Robust Secure Transmission Scheme in MISO Interference Channel with Simultaneous Wireless Information and Power Transfer

Chong Xue[1(✉)], Jian Xiao[1], Sai Zhao[2], Jingrong Zhou[3], and Maoxin Tian[1]

[1] School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou 510006, Guangdong, China
xuech6@mail2.sysu.edu.cn

[2] School of Mechanical and Electrical Engineering, Guangzhou University, Guangzhou 510006, Guangdong, China

[3] Huawei Technologies Co. Ltd., Shenzhen 518129, Guangdong, China

Abstract. Considering simultaneous wireless information and power transfer (SWIPT), we investigate robust secure transmission scheme in two-user multiple-input-single-output interference channels, where channel uncertainties are modeled by worst-case model. Our objective is to maximize the worst-case sum secrecy rate under individual transmit power constraints and worst-case energy harvest (EH) constraints. We propose an alternative optimization (AO) based algorithm to solve the robust secure transmission problem, and we can obtain a closed form solution in the process of AO algorithm. Simulation results demonstrate that our proposed robust secure transmission scheme has significant performance gain over the non-robust one.

Keywords: Simultaneous wireless information and power transfer (SWIPT) · Energy harvest (EH) · Security · Interference channel (IFC) · Multiple-input-single-output (MISO)

1 Introduction

Recently, a unified study on simultaneous wireless information and power transfer (SWIPT) has drawn significant attention, which is not only theoretically intricate but also practically valuable for enabling both the wireless data and wireless energy access to mobile terminals at the same time. For two-user single-input-single-output (SISO), MISO, and multiple-input-multiple-output (MIMO) interference channels (IFCs), SWIPT schemes were invested in [1,2].

Due to the openness of wireless transmission medium and the inherent randomness of wireless channel, radio transmission is vulnerable to attacks from unexpected eavesdroppers [3,4]. Secure communications in MISO SWIPT systems were derived in [4,5] where perfect channel state information (CSI) was considered. In practice, it is difficult to obtain perfect CSI because of channel

Q. Chen et al. (Eds.): ChinaCom 2016, Part I, LNICST 209, pp. 14–23, 2018.
DOI: 10.1007/978-3-319-66625-9_2

estimation and quantization errors. Considering the worst-case channel uncertainties, the robust secure beamforming scheme with SWIPT in MISO channels was proposed in [6].

In this paper, we investigate robust secure transmission scheme in two-user multiple-input-single-output (MISO) interference channels, where channel uncertainties are modeled by worst-case model. Our objective is to maximize the worst-case sum secrecy rate under individual transmit power constraints and worst-case energy harvest (EH) constraints. The formulated optimization problem is nonconvex and we propose an alternative optimization (AO) based algorithm to solve the robust secure transmission problem, and we can obtain a closed form solution in the process of AO algorithm.

2 System Model and Problem Formulation

A. *System Model*

Consider a two-user MISO IFC system with SWIPT which consists of two transmitters, two ID receivers, a eavesdropper and K EH receivers. Each transmitter is equipped with N antennas. Each energy receiver and the eavesdropper are equipped with single antenna. Each ID receiver decodes the information sent from its correspondence transmitter whereas each EH receiver harvests energy from both transmitters. The eavesdropper decodes the information sent from the two transmitters. Denote the channel responses from transmitter i to ID receiver j, energy receiver k and eavesdropper e as $\mathbf{h}_{ij} \in \mathbb{C}^N \times 1$, $\mathbf{g}_{ik} \in \mathbb{C}^N \times 1$ and $\mathbf{h}_{ie} \in \mathbb{C}^N \times 1$.

Denote the confidential signal sent by transmitter i as $\mathbf{x}_i \in \mathbb{C}^{N\times 1}$, $i \in \{1, 2\}$, where $\mathbb{E}[\mathbf{x}_i\mathbf{x}_i^\dagger] = \mathbf{I}$ and $\mathbb{E}[\mathbf{x}_i\mathbf{x}_j^\dagger] = \mathbf{I}$ for $i \neq j$. Thus, the received signals at the ID receiver j and the eavesdropper e, denoted as y_j and y_e, respectively, are

$$y_j = \sum_{i=1}^{2} \mathbf{h}_{ji}^\dagger \mathbf{x}_i + n_j \text{ and } y_e = \sum_{i=1}^{2} \mathbf{h}_{ie}^\dagger \mathbf{x}_i + n_e \tag{1}$$

where $n_j \sim \mathcal{CN}(\mathbf{0}, \sigma^2\mathbf{I})$ and $n_e \sim \mathcal{CN}(\mathbf{0}, \sigma^2\mathbf{I})$ are the additive Gaussian noises at the ID receiver j and the eavesdropper e, respectively. Without loss of generality, we assume that the noise variance is $\sigma^2 = 1$ in this paper. Therefore, the achievable rate of the ID receiver 1, 2 can be expressed as

$$I_1(\mathbf{x}_1, \mathbf{x}_2) = \log_2(1 + \frac{\mathbf{h}_{11}^\dagger \mathbf{x}_1 \mathbf{x}_1^\dagger \mathbf{h}_{11}}{\mathbf{h}_{21}^\dagger \mathbf{x}_2 \mathbf{x}_2^\dagger \mathbf{h}_{21} + 1}), \tag{2}$$

$$I_2(\mathbf{x}_1, \mathbf{x}_2) = \log_2(1 + \frac{\mathbf{h}_{22}^\dagger \mathbf{x}_2 \mathbf{x}_2^\dagger \mathbf{h}_{22}}{\mathbf{h}_{12}^\dagger \mathbf{x}_1 \mathbf{x}_1^\dagger \mathbf{h}_{12} + 1}) \tag{3}$$

The upper bound of the eavesdropper information rate is

$$I_e(\mathbf{x}_1, \mathbf{x}_2) = \log_2(1 + \mathbf{h}_{1e}^\dagger \mathbf{x}_1 \mathbf{x}_1^\dagger \mathbf{h}_{1e} + \mathbf{h}_{2e}^\dagger \mathbf{x}_2 \mathbf{x}_2^\dagger \mathbf{h}_{2e}) \tag{4}$$

According to [7], the worst-case sum secrecy rate of the system can be expressed as

$$I_S = I_1(\mathbf{x}_1, \mathbf{x}_2) + I_2(\mathbf{x}_1, \mathbf{x}_2) - I_e(\mathbf{x}_1, \mathbf{x}_2) \tag{5}$$

The transmit power constraint at the transmitter i is

$$\|\mathbf{x}_i\|^2 \leq P_i, \ \forall\, i \in \{1, 2\} \tag{6}$$

The harvested energy at energy receiver k should be constrained as

$$\rho(\mathbf{g}_{1k}^{\dagger}\mathbf{x}_1\mathbf{x}_1^{\dagger}\mathbf{g}_{1k} + \mathbf{g}_{2k}^{\dagger}\mathbf{x}_2\mathbf{x}_2^{\dagger}\mathbf{g}_{2k}) \geq Q_k \tag{7}$$

where ρ is the EH efficiency that accounts for the loss in energy transducer and Q_k is the threshold of the harvested energy at EH receiver k. Without loss of generality, the EH efficiency is assumed to be $\rho = 1$ in this paper.

B. *Problem Formulation*

We assume that the two transmitters know the imperfect CSI on $\mathbf{h}_{ij}$, $\mathbf{g}_{ik}$ and $\mathbf{h}_{ie}$. This assumption is valid because of channel estimation and quantization errors. In this paper, we model the channel uncertainties by worst-case model as in [6] which can be expressed as

$$\mathcal{H}_{ij} = \{\mathbf{h}_{ij} | \mathbf{h}_{ij} = \hat{\mathbf{h}}_{ij} + \Delta\mathbf{h}_{ij}, \Delta\mathbf{h}_{ij}^{\dagger}\mathbf{V}_{ij}\Delta\mathbf{h}_{ij} \leq 1\}, \tag{8}$$

$$\mathcal{G}_{ik} = \{\mathbf{g}_{ik} | \mathbf{g}_{ik} = \hat{\mathbf{g}}_{ik} + \Delta\mathbf{g}_{ik}, \Delta\mathbf{g}_{ik}^{\dagger}\mathbf{V}_{ik}\Delta\mathbf{g}_{ik} \leq 1\}, \tag{9}$$

$$\mathcal{H}_{ie} = \{\mathbf{h}_{ie} | \mathbf{h}_{ie} = \hat{\mathbf{h}}_{ie} + \Delta\mathbf{h}_{ie}, \Delta\mathbf{h}_{ie}^{\dagger}\mathbf{V}_{ie}\Delta\mathbf{h}_{ie} \leq 1\} \tag{10}$$

where $\hat{\mathbf{h}}_{ij}$, $\hat{\mathbf{g}}_{ik}$ and $\hat{\mathbf{h}}_{ie}$ denote the estimates of channels $\mathbf{h}_{ij}$, $\mathbf{g}_{ik}$ and $\mathbf{h}_{ie}$, respectively; $\Delta\mathbf{h}_{ij}$, $\Delta\mathbf{g}_{ik}$ and $\Delta\mathbf{h}_{ie}$ denote the channel uncertainties; $\mathbf{V}_{ij} \succ 0$, $\mathbf{V}_{ik} \succ 0$ and $\mathbf{V}_{ie} \succ 0$ determine the qualities of CSI.

Considering worst-case channel uncertainties, our objective is to maximize worst-case sum secrecy rate subject to individual transmit power constraints at two transmitters and worst-case EH constraints at EH receivers. Thus, the optimization problem is formulated as

$$\max_{\mathbf{x}_1, \mathbf{x}_2} \min_{\Delta\mathbf{h}_{ij} \in \mathcal{H}_{ij}, \Delta\mathbf{h}_{ie} \in \mathcal{H}_{ie}} I_S \tag{11a}$$

$$\text{s.t.} \quad \|\mathbf{x}_i\|^2 \leq P_i, \ \forall\, i \in \{1, 2\}, \tag{11b}$$

$$\sum_{i=1}^{2} \mathbf{g}_{ik}^{\dagger}\mathbf{x}_i{\mathbf{x}_i}^{\dagger}\mathbf{g}_{ik} \geq Q_k, \ \forall\, \Delta\mathbf{g}_{ik} \in \mathcal{G}_{ik}, \forall\, k \in \mathcal{K} \tag{11c}$$

where $\mathcal{K} = \{1, 2, \ldots, K\}$. The robust problem (11) is non-convex which is difficult to solve. Thus, we propose an alternative iteration (AO) algorithm to solve the worst-case sum secrecy rate maximization problem.

3 Robust Secure Transmission Scheme

It is observed that the optimization problem (11) is a fractional quadratically constrained quadratic (QCQP) problem, which is non-convex and difficult to solve. Employing the semidefinite relaxation method [8], the problem (11) is equivalently rewritten as

$$\max_{\mathbf{X}_1,\mathbf{X}_2} \min_{\Delta\mathbf{h}_{ij}\in\mathcal{H}_{ij},\Delta\mathbf{h}_{ie}\in\mathcal{H}_{ie}} \eta_1+\eta_2+\eta_3+\eta_4+\eta_5 \tag{12a}$$

$$\text{s.t. } \operatorname{tr}(\mathbf{X}_i)\le P_i,\ \forall\, i\in\{1,2\} \tag{12b}$$

$$\operatorname{rank}(\mathbf{X}_i)=1,\ \forall\, i\in\{1,2\} \tag{12c}$$

$$\sum_{i=1}^{2}\operatorname{tr}\left(\mathbf{g}_{ik}\mathbf{X}_i\mathbf{g}_{ik}^{\dagger}\right)\ge Q_k,\ \forall\Delta\mathbf{g}_{ik}\in\mathcal{G}_{ik},\forall k\in\mathcal{K} \tag{12d}$$

where

$$\eta_1=\log_2(1+\mathbf{h}_{11}^{\dagger}\mathbf{X}_1\mathbf{h}_{11}+\mathbf{h}_{21}^{\dagger}\mathbf{X}_2\mathbf{h}_{21}), \tag{13}$$

$$\eta_2=-\log_2(1+\mathbf{h}_{21}^{\dagger}\mathbf{X}_2\mathbf{h}_{21}), \tag{14}$$

$$\eta_3=\log_2(1+\mathbf{h}_{12}^{\dagger}\mathbf{X}_1\mathbf{h}_{12}+\mathbf{h}_{22}^{\dagger}\mathbf{X}_2\mathbf{h}_{22}), \tag{15}$$

$$\eta_4=-\log_2(1+\mathbf{h}_{12}^{\dagger}\mathbf{X}_1\mathbf{h}_{12}), \tag{16}$$

$$\eta_5=-\log_2(1+\mathbf{h}_{1e}^{\dagger}\mathbf{X}_1\mathbf{h}_{1e}+\mathbf{h}_{2e}^{\dagger}\mathbf{X}_2\mathbf{h}_{2e}), \tag{17}$$

$$\mathbf{X}_1=\mathbf{x}_1\mathbf{x}_1^{\dagger} \text{ and } \mathbf{X}_2=\mathbf{x}_2\mathbf{x}_2^{\dagger} \tag{18}$$

In (12a), since η_1,η_3 are concave and η_2,η_4,η_5 are convex, (12a) is non-convex. In order to deal with (12a), we have the following proposition.

Proposition 1. *Let $a\in\mathcal{R}^{1\times1}$ be a positive scalar and $f(a)=\frac{-ab}{\ln 2}+\log_2 a+\frac{1}{\ln 2}$. We have*

$$-\log_2 b=\max_{a\in\mathcal{R}^{1\times1},a\ge0} f(a) \tag{19}$$

and the optimal solution to the right-hand side of (19) is $a=\frac{1}{b}$.

Proof. Since $f(a)$ is concave, the partial derivative of $f(a)$ with respect to a is

$$\frac{\partial f(a)}{\partial a}=-\frac{b}{\ln 2}+\frac{1}{a\ln 2} \tag{20}$$

In order to maximize $f(a)$, let $\frac{\partial f(a)}{\partial a}=0$, we can obtain $b=\frac{1}{a}$. Substituting b into $f(a)$, (19) can be obtained. □

Using Proposition 1, we transform η_2,η_4,η_5 into convex optimization problems

$$\eta_2=\max_{a_1\in\mathcal{R}^{1\times1},a_1\ge0}\zeta_1(a_1), \tag{21}$$

$$\eta_4=\max_{a_2\in\mathcal{R}^{1\times1},a_2\ge0}\zeta_2(a_2), \tag{22}$$

$$\eta_5=\max_{a_3\in\mathcal{R}^{1\times1},a_3\ge0}\zeta_3(a_3) \tag{23}$$

where

$$\zeta_1(a_1) = -\frac{a_1}{\ln 2}(\mathbf{h}_{21}^{\dagger}\mathbf{X}_2\mathbf{h}_{21} + 1) + \log_2 a_1 + \frac{1}{\ln 2}, \tag{24}$$

$$\zeta_2(a_2) = -\frac{a_2}{\ln 2}(\mathbf{h}_{12}^{\dagger}\mathbf{X}_1\mathbf{h}_{12} + 1) + \log_2 a_2 + \frac{1}{\ln 2}, \tag{25}$$

$$\zeta_1(a_3) = -\frac{a_3}{\ln 2}(\mathbf{h}_{1e}^{\dagger}\mathbf{X}_1\mathbf{h}_{1e} + \mathbf{h}_{2e}^{\dagger}\mathbf{X}_2\mathbf{h}_{2e} + 1) + \log_2 a_3 + \frac{1}{\ln 2} \tag{26}$$

In the following, we propose to decouple (12) into four optimization problems and employ AO algorithm to iteratively optimize $a_1, a_2, a_3, \mathbf{X}_1$ and $\mathbf{X}_2$. Our design concept is based on the fact that for fixed $\mathbf{X}_1$ and $\mathbf{X}_2$ the optimal solution of a_1, a_2, a_3 can be derived, and vice versa.

Given $\mathbf{X}_1^{(n-1)}$ and $\mathbf{X}_2^{(n-1)}$ which are optimal in the $(n-1)$th iteration, we solve

$$a_1^{(n)} = \arg\max_{a_1 \geq 0} -\frac{a_1}{\ln 2}(\max_{\Delta\mathbf{h}_{21}} \mathbf{h}_{21}^{\dagger}\mathbf{X}_2^{(n-1)}\mathbf{h}_{21} + 1) + \log_2 a_1 + \frac{1}{\ln 2}, \tag{27}$$

$$a_2^{(n)} = \arg\max_{a_2 \geq 0} -\frac{a_2}{\ln 2}(\max_{\Delta\mathbf{h}_{12}} \mathbf{h}_{12}^{\dagger}\mathbf{X}_1^{(n-1)}\mathbf{h}_{12} + 1) + \log_2 a_2 + \frac{1}{\ln 2}, \tag{28}$$

$$a_3^{(n)} = \arg\max_{a_3 \geq 0} -\frac{a_3}{\ln 2}(\max_{\Delta\mathbf{h}_{ie}} \sum_{i=1}^{2} \mathbf{h}_{ie}^{\dagger}\mathbf{X}_i^{(n-1)}\mathbf{h}_{ie} + 1) + \log_2 a_3 + \frac{1}{\ln 2} \tag{29}$$

We first solve the problem (27). It is noted that the problem (27) is convex with respect to a_1 and $\Delta\mathbf{h}_{21}$, respectively. They are also decoupled. Therefore, we can optimize them respectively. Before solving the problem (27), we first solve the following problem

$$\mathbf{F}_1 = \max_{\Delta\mathbf{h}_{21} \in \mathcal{H}_{21}} (\hat{\mathbf{h}}_{21} + \Delta\mathbf{h}_{21})^{\dagger}\mathbf{X}_2^{(n-1)}(\hat{\mathbf{h}}_{21} + \Delta\mathbf{h}_{21}) \tag{30a}$$

$$\text{s.t. } \Delta\mathbf{h}_{21}^{\dagger}\mathbf{V}_{21}\Delta\mathbf{h}_{21} \leq 1 \tag{30b}$$

The Lagrange function of the problem (30) is

$$\varsigma_1 = (\hat{\mathbf{h}}_{21} + \Delta\mathbf{h}_{21})^{\dagger}\mathbf{X}_2^{(n-1)}(\hat{\mathbf{h}}_{21} + \Delta\mathbf{h}_{21}) + \lambda_1(\Delta\mathbf{h}_{21}^{\dagger}\mathbf{V}_{21}\Delta\mathbf{h}_{21} - 1) \tag{31}$$

where ς_1 is non-negative Lagrangian multiplier. Obviously, ς_1 is convex with respect to $\Delta\mathbf{h}_{21}$. Thus, the KKT condition is satisfied when we solve the problem (27). Therefore, we have

$$\mathbf{F}_1 = \mathrm{tr}\left[(\mathbf{X}_2^{(n-1)}\hat{\mathbf{h}}_{21}\hat{\mathbf{h}}_{21}^{\dagger} + \mathbf{V}_{21}^{-1} + 2\sqrt{\kappa_1}\mathbf{V}_{21}^{-1})\right] \tag{32}$$

where

$$\kappa_1 = \frac{\mathrm{tr}(\hat{\mathbf{h}}_{21}\hat{\mathbf{h}}_{21}^{\dagger}\mathbf{X}_2^{(n-1)})}{\mathrm{tr}(\mathbf{X}_2^{(n-1)}\mathbf{V}_{21}^{-1})} \tag{33}$$

According to the Proposition 1 and (30)–(33), the closed form of the problem (27) is

$$a_1^{(n)} = (\mathbf{F}_1 + 1)^{-1} \tag{34}$$

Then, we can use the similar method to solve (28) and (29). Thus, the closed form of $a_2^{(n)}, a_3^{(n)}$ are

$$a_2^{(n)} = (\mathbf{F}_2 + 1)^{-1} \text{ and } a_3^{(n)} = (\mathbf{F}_3 + 1)^{-1} \tag{35}$$

where

$$\mathbf{F}_2 = \mathrm{tr}\left[(\mathbf{X}_1^{(n-1)}\hat{\mathbf{h}}_{12}\hat{\mathbf{h}}_{12}^{\dagger} + \mathbf{V}_{12}^{-1} + 2\sqrt{\kappa_2}\mathbf{V}_{12}^{-1})\right], \tag{36}$$

$$\mathbf{F}_3 = \sum_{i=1}^{2} \mathrm{tr}\left[(\mathbf{X}_i^{(n-1)}\hat{\mathbf{h}}_{ie}\hat{\mathbf{h}}_{ie}^{\dagger} + \mathbf{V}_{ie}^{-1} + 2\sqrt{\varpi_i}\mathbf{V}_{ie}^{-1})\right], \tag{37}$$

$$\kappa_2 = \frac{\mathrm{tr}(\hat{\mathbf{h}}_{12}\hat{\mathbf{h}}_{12}^{\dagger}\mathbf{X}_1^{(n-1)})}{\mathrm{tr}(\mathbf{X}_1^{(n-1)}\mathbf{V}_{12}^{-1})},\ \varpi_i = \frac{\mathrm{tr}(\hat{\mathbf{h}}_{ie}\hat{\mathbf{h}}_{ie}^{\dagger}\mathbf{X}_i^{(n-1)})}{\mathrm{tr}(\mathbf{X}_i^{(n-1)}\mathbf{V}_{ie}^{-1})}, \forall i \in \{1,2\} \tag{38}$$

After obtaining $a_1^{(n)}, a_2^{(n)}, a_3^{(n)}$, we solve

$$\max_{\mathbf{X}_1 \succeq 0, \mathbf{X}_2 \succeq 0} \omega \tag{39a}$$

$$\text{s.t.}\quad \mathrm{tr}(\mathbf{X}_i) \le P_i,\ \mathrm{rank}(\mathbf{X}_i) = 1,\ i \in \{1,2\} \tag{39b}$$

$$\mathrm{tr}(\mathbf{h}_{21}\mathbf{h}_{21}^{\dagger}\mathbf{X}_2) \le \tau_1,\ \forall \Delta\mathbf{h}_{21} \in \mathcal{H}_{21} \tag{39c}$$

$$\mathrm{tr}(\mathbf{h}_{11}\mathbf{h}_{11}^{\dagger}\mathbf{X}_1) \ge \tau_2,\ \forall \Delta\mathbf{h}_{11} \in \mathcal{H}_{11} \tag{39d}$$

$$\mathrm{tr}(\mathbf{h}_{12}\mathbf{h}_{12}^{\dagger}\mathbf{X}_1) \le \tau_3,\ \forall \Delta\mathbf{h}_{12} \in \mathcal{H}_{12} \tag{39e}$$

$$\mathrm{tr}(\mathbf{h}_{22}\mathbf{h}_{22}^{\dagger}\mathbf{X}_2) \ge \tau_4,\ \forall \Delta\mathbf{h}_{22} \in \mathcal{H}_{22} \tag{39f}$$

$$\mathrm{tr}(\mathbf{h}_{1e}\mathbf{h}_{1e}^{\dagger}\mathbf{X}_1) \le \tau_5,\ \forall \Delta\mathbf{h}_{1e} \in \mathcal{H}_{1e} \tag{39g}$$

$$\mathrm{tr}(\mathbf{h}_{2e}\mathbf{h}_{2e}^{\dagger}\mathbf{X}_2) \le \tau_6,\ \forall \Delta\mathbf{h}_{2e} \in \mathcal{H}_{2e} \tag{39h}$$

$$\sum_{i=1}^{2} \mathrm{tr}(\mathbf{g}_{ik}\mathbf{g}_{ik}^{\dagger}\mathbf{X}_i) \ge Q_k,\ \forall \Delta\mathbf{g}_{ik} \in \mathcal{G}_{ik}, i \in \{1,2\} \tag{39i}$$

where

$$\omega = \log_2(\tau_1 + \tau_2 + 1) - \frac{a_1^{(n)}(\tau_1 + 1)}{\ln 2} + \log_2 a_1^{(n)} + \log_2(\tau_3 + \tau_4 + 1) - \frac{a_2^{(n)}(\tau_3 + 1)}{\ln 2} + \log_2 a_2^{(n)} - \frac{a_3^{(n)}(\tau_5 + \tau_6 + 1)}{\ln 2} + \log_2 3 + \frac{3}{\ln 2} \tag{40}$$

The problem (39) is a semidefinite programming (SDP). However, the problem has semi-infinite constraints (39c)–(39i) and the rank-one constraint $\mathrm{rank}(\mathbf{X}_i) = 1$, $i \in \{1,2\}$, which are difficult to solve. To make the problem tractable, we convert the constraints (39c)–(39i) into linear matrix inequalities (LMIs) [9] equivalently, using $\mathcal{S}$-Procedure [10].

Applying $\mathcal{S}$-Procedure, and introducing slack variables $\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6$ and μ_7, the constraints (39c)–(39i) can be equivalently transformed into the following LMIs

$$\mathbf{W}_1 \triangleq \begin{bmatrix} \mu_1 \mathbf{V}_{21} - \mathbf{X}_2 & -\mathbf{X}_2 \hat{\mathbf{h}}_{21} \\ -\hat{\mathbf{h}}_{21}^\dagger \mathbf{X}_2 & -\mu_1 - \hat{\mathbf{h}}_{21}^\dagger \mathbf{X}_2 \hat{\mathbf{h}}_{21} + \tau_1 \end{bmatrix} \succeq 0 \tag{41}$$

$$\mathbf{W}_2 \triangleq \begin{bmatrix} \mu_2 \mathbf{V}_{11} + \mathbf{X}_1 & \mathbf{X}_1 \hat{\mathbf{h}}_{11} \\ \hat{\mathbf{h}}_{11}^\dagger \mathbf{X}_1 & -\mu_2 + \hat{\mathbf{h}}_{11}^\dagger \mathbf{X}_1 \hat{\mathbf{h}}_{11} - \tau_2 \end{bmatrix} \succeq 0 \tag{42}$$

$$\mathbf{W}_3 \triangleq \begin{bmatrix} \mu_3 \mathbf{V}_{12} - \mathbf{X}_1 & -\mathbf{X}_1 \hat{\mathbf{h}}_{12} \\ -\hat{\mathbf{h}}_{12}^\dagger \mathbf{X}_1 & -\mu_3 - \hat{\mathbf{h}}_{12}^\dagger \mathbf{X}_1 \hat{\mathbf{h}}_{12} + \tau_3 \end{bmatrix} \succeq 0 \tag{43}$$

$$\mathbf{W}_4 \triangleq \begin{bmatrix} \mu_4 \mathbf{V}_{22} + \mathbf{X}_2 & \mathbf{X}_2 \hat{\mathbf{h}}_{22} \\ \hat{\mathbf{h}}_{22}^\dagger \mathbf{X}_2 & -\mu_4 + \hat{\mathbf{h}}_{22}^\dagger \mathbf{X}_2 \hat{\mathbf{h}}_{22} - \tau_4 \end{bmatrix} \succeq 0 \tag{44}$$

$$\mathbf{W}_5 \triangleq \begin{bmatrix} \mu_5 \mathbf{V}_{1e} - \mathbf{X}_1 & -\mathbf{X}_1 \hat{\mathbf{h}}_{1e} \\ -\hat{\mathbf{h}}_{1e}^\dagger \mathbf{X}_1 & -\mu_5 - \hat{\mathbf{h}}_{1e}^\dagger \mathbf{X}_1 \hat{\mathbf{h}}_{1e} + \tau_5 \end{bmatrix} \succeq 0 \tag{45}$$

$$\mathbf{W}_6 \triangleq \begin{bmatrix} \mu_6 \mathbf{V}_{2e} - \mathbf{X}_2 & -\mathbf{X}_2 \hat{\mathbf{h}}_{2e} \\ -\hat{\mathbf{h}}_{2e}^\dagger \mathbf{X}_2 & -\mu_6 - \hat{\mathbf{h}}_{2e}^\dagger \mathbf{X}_2 \hat{\mathbf{h}}_{2e} + \tau_6 \end{bmatrix} \succeq 0 \tag{46}$$

$$\mathbf{W}_7 \triangleq \begin{bmatrix} \mu_7 \mathbf{V}_{1k} + \mathbf{X}_1 & \mathbf{X}_1 \hat{\mathbf{g}}_{1k} \\ \hat{\mathbf{g}}_{1k}^\dagger \mathbf{X}_1 & -\mu_7 - Q_k + \hat{\mathbf{g}}_{1k}^\dagger \mathbf{X}_1 \hat{\mathbf{g}}_{1k} + \mathbf{g}_{2k}^\dagger \mathbf{X}_2 \mathbf{g}_{2k} \end{bmatrix} \succeq 0 \tag{47}$$

We need the extensions of $\mathcal{S}$-Procedure [11] to convert (47) into an LMI. Introducing slack variables μ_8, we equivalently transformed (47) into

$$\mathbf{W}_8 \triangleq \begin{bmatrix} \mu_7 \mathbf{V}_{1k} + \mathbf{X}_1 & \mathbf{X}_1 \hat{\mathbf{g}}_{1k} & \mathbf{0} \\ \hat{\mathbf{g}}_{2k}^\dagger \mathbf{X}_1 & \hat{\varphi} & \hat{\mathbf{g}}_{2k}^\dagger \mathbf{X}_2 \\ \mathbf{0} & \mathbf{X}_2 \hat{\mathbf{g}}_{2k} & \mathbf{X}_2 + \mu_8 \mathbf{V}_{2k} \end{bmatrix} \succeq 0 \tag{48}$$

where

$$\hat{\varphi} = \hat{\mathbf{g}}_{1k}^\dagger \mathbf{X}_1 \hat{\mathbf{g}}_{1k} + \hat{\mathbf{g}}_{2k}^\dagger \mathbf{X}_2 \hat{\mathbf{g}}_{2k} - \mu_7 - \mu_8 - Q_k \tag{49}$$

Combing (41)–(46) and (48) and omitting the rank-one constraint, the optimization problem (39) can be recast as

$$\max_{\mathbf{X}_1 \succeq 0, \mathbf{X}_2 \succeq 0, \mu_j} \omega \tag{50a}$$

$$\text{s.t.} \quad \mathrm{tr}(\mathbf{X}_i) \leq P_i, i \in \{1, 2\} \tag{50b}$$

$$\mathbf{W}_l \succeq 0, \mu_j \geq 0, l \in \{1, \ldots, 8\}/7, j \in \{1, \ldots, 8\} \tag{50c}$$

Obviously, (50) is a convex SDP problem which can be solved by existing software, e.g., CVX. It is noted that (50) is a rank-one relaxation of the original problem (39). If the optimal solution of (50) is rank-one, it is also the optimal solution of the original problem (39). If the rank of the optimal solution of (50) is greater than 1, we employ the Gaussian randomization (GR) method to generate the suboptimal rank-one solution.

4 Simulation Results

In this section, we evaluate the performance of our proposed robust secure transmission scheme through computer simulations. We assume that two-user MISO IFC system consists of two transmitters, two ID receivers, $K = 1$ EH receiver and a eavesdropper. The entries in the channel estimates $\mathbf{h}_{ii}$, $\mathbf{h}_{i\bar{i}}$, $\mathbf{h}_{ie}$, $\mathbf{g}_{ik}$, $i \in \{1, 2\}$, $\bar{i} \in \{1, 2\} - i$, are independent and identically distributed complex Gaussian random variables whose variances are 1, 0.1, 1 and 1 respectively. We assume that the maximum allowable transmit powers of two transmitters are $P_1 = P_2$. The worst-case EH constraint is $Q_k = 0.3P_1$. We produce 500 randomly generated channel realizations and compute the worst-case sum secrecy rate.

The channel uncertainty regions are assumed to be norm-bounded, i.e.,

$$\mathbf{V}_{ij} = \frac{1}{(\tilde{\delta}_{ij}^h)^2}\mathbf{I}, \ \mathbf{V}_{ik} = \frac{1}{(\tilde{\delta}_{ik}^g)^2}\mathbf{I}, \ \text{ and } \mathbf{V}_{ie} = \frac{1}{(\tilde{\delta}_{ie}^h)^2}\mathbf{I} \tag{51}$$

where $(\tilde{\delta}_{ij}^h)^2$, $(\tilde{\delta}_{ik}^g)^2$ and $(\tilde{\delta}_{ie}^h)^2$ are normalized radii of the uncertainty regions which can be expressed as

$$(\tilde{\delta}_{ij}^h)^2 = \frac{N(\delta_{ij}^h)^2}{\mathbb{E}\left[\|\hat{\mathbf{h}}_{ij}\|_F^2\right]}, \ (\tilde{\delta}_{ik}^g)^2 = \frac{N(\delta_{ik}^g)^2}{\mathbb{E}\left[\|\hat{\mathbf{g}}_{ik}\|_F^2\right]}, \ \text{ and } (\tilde{\delta}_{ie}^h)^2 = \frac{N(\delta_{ie}^h)^2}{\mathbb{E}\left[\|\hat{\mathbf{h}}_{ie}\|_F^2\right]} \tag{52}$$

We assume that $\delta = (\tilde{\delta}_{ij}^h)^2 = (\tilde{\delta}_{ik}^g)^2 = (\tilde{\delta}_{ie}^h)^2$ in this paper.

For our proposed robust secure transmission scheme, the optimal solution to the rank-relaxed problem of (12) serves as a performance upper bound. In Fig. 1, we present the worst-case sum secrecy rate comparison of the proposed robust secure transmission scheme after GR (denoted as "Robust-GR" in the legend), the performance upper bound (denoted as "Robust") and the non-robust secure transmission scheme (denoted as "Non-Robust" in the legend) for different maximum allowable transmit power to noise power ratios, i.e., $P_i/\sigma^2, i \in \{1, 2\}$ and different channel uncertainty of the radius, i.e., δ^2. Each transmitter is equipped with $N = 4$ antennas. The non-robust secure transmission scheme is obtained by solving (12) where $\Delta\mathbf{h}_{ij} = 0, \Delta\mathbf{g}_{ik} = 0$ and $\Delta\mathbf{h}_{ie} = 0$, $i \in \{1, 2\}, j \in \{1, 2\}$ and $k \in \mathcal{K}$. After obtaining $\mathbf{X}_1$ and $\mathbf{X}_2$, if the worst-case EH constraint at each EH receiver is not satisfied, an outage occurs and the worst-case sum secrecy rate is 0. If otherwise, the worst-case sum secrecy rate is computed by using the similar method proposed in Sect. 2. From Fig. 1, we can conclude that the performance of the "Robust" secure transmission scheme outperform the performance of the "Non-Robust" secure transmission scheme. It is also found that with the increase of δ^2, the performance gaps between the "Robust" secure transmission scheme and the "Non-Robust" secure transmission scheme become larger, especially at the high $P_i/\sigma^2, i \in \{1, 2\}$. This is because when the channel uncertainty of the radius is larger, the "Non-Robust" secure transmission scheme is difficult to steer its antenna beam towards the direction which increases the sum secrecy rate. From Fig. 1, it is observed that the performance of the "Robust-GR" close to

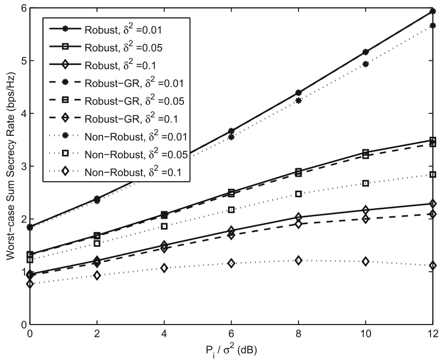

Fig. 1. Worst-case sum secrecy rate versus $P_i/\sigma^2, i \in \{1, 2\}$; performance comparison of proposed robust secure transmission scheme and the non-robust one, $N = 4$, $K = 1$, $\alpha = 0.3$

the upper bound, and the performance of the "Robust-GR" is better than the "Non-Robust" secure transmission scheme.

In Fig. 2, we compare the outage probability of the proposed robust secure transmission scheme (denoted as "Robust" in the legend) and the non-robust secure transmission scheme (denoted as "Non-Robust" in the legend) for different maximum allowable transmit power to noise power ratios, i.e., $P_i/\sigma^2, i \in \{1, 2\}$ and different channel uncertainty of the radius, i.e., δ^2. Each transmitter is equipped with $N = 4$ antennas. From Fig. 2, it is observed that the outage in the proposed "Robust" secure transmission scheme doesn't occur. However, the outage probability of the "Non-Robust" secure transmission scheme becomes larger with the increase of the channel uncertainty of the radius δ^2.

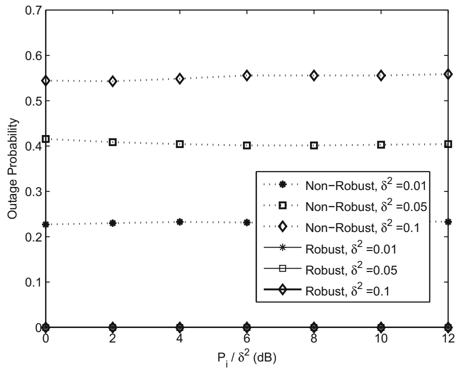

Fig. 2. Outage probability versus $P_i/\sigma^2, i \in \{1, 2\}$; performance comparison of proposed robust secure transmission scheme and the non-robust one, $N = 4$, $K = 1$, $\alpha = 0.3$

5 Conclusion

In this paper, we have invested robust secure transmission scheme for two-user MISO IFC system with SWIPT. Considering the worst-case channel uncertainty model, we propose alternative iteration algorithm to design the transmit convariance matrix. Simulation results demonstrate that our proposed robust secure transmission scheme has significant performance gain over the non-robust one.

References

1. Shen, C., Li, W-C., Chang, T-H.: Simultaneous information and energy transfer: a two-user MISO interference channel case. In: Proceedings of GLOBECOM, pp. 3862–3867 (2012)
2. Park, J., Clerckx, B.: Joint wireless information and energy transfer in a two-user MIMO interference channel. IEEE Trans. Wirel. Commun. **12**(8), 4210–4221 (2013)
3. Ng, D.W.K., Schober, R.: Resource allocation for secure communication in systems with wireless information and power transfer. In: Proceedings of IEEE Globecom, pp. 1251–1257 (2013)
4. Ng, D.W.K., Xiang, L., Schober, R.: Multi-objective beamforming for secure communication in systems with wireless information and power transfer. In: Proceedings of IEEE PIMRC, pp. 7–12 (2013)
5. Liu, L., Zhang, R., Chua, K.C.: Secrecy wireless information and power transfer with MISO beamforming. IEEE Trans. Signal Process. **62**(7), 1850–1863 (2014)
6. Ng, D.W.K., Lo, E.S., Schober, R.: Robust beamforming for secure communication in systems with wireless information and power transfer. IEEE Trans. Wirel. Commun. **13**(8), 4599–4615 (2014)
7. Somekh-Baruch, A.: On the secure interference channel. In: Proceedings of 51st Annual Allerton Conference on Communication, Control, and Computing, pp. 770–773 (2013)
8. Luo, Z.-Q., Ma, W.-K., So, A.M.-C., Ye, Y., Zhang, S.: Semidefinite relaxation of quadratic optimization problems. IEEE Sig. Process. Mag. **27**(3), 20–34 (2010)
9. Boyd, S., Vandenberghe, L.: Convex Optimization. Cambridge University Press, Cambridge (2004)
10. Beck, A., Eldar, Y.: Strong duality in nonconvex quadratic optimization with two quadratic constraints. SIAM J. Optim. **17**(3), 844–860 (2006)
11. Luo, Z.-Q., Sturm, J.F., Zhang, S.: Multivariate nonnegative quadratic mapping. SIAM J. Optim. **14**(4), 1140–1162 (2004)