Secure Beamforming Designs for Secrecy MIMO SWIPT Systems

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***Abstract*—In this letter, secure beamforming designs are investigated in a multiple-input multiple-output secrecy channels with simultaneous wireless information and power transfer. In order to achieve fairness among different multiple energy harvesting receivers, the minimum harvested energy is maximized under the secrecy rate requirements. In particular, in order to reduce the computational complexity of the semidefinite programming problem, a successive convex approximation (SCA) iterative algorithm is proposed in the perfect channel state information (CSI) case to obtain a near-optimal rank-one solution. Moreover, the original problem is extended to the imperfect CSI case by incorporating a norm-bounded error model, where an SCA-based iterative algorithm is also proposed. Simulation results reveal that the SCA-based iterative algorithm achieves the same performance as the semidefinite relaxation method with reduced complexity.**

***Index Terms*—SWIPT, MIMO system, secure beamforming, successive convex approximation, semidefinite relaxation.**

I. Introduction

SIMULTANEOUS wireless information and power transfer (SWIPT) which harvests energy for wireless devices and increases the durability of wireless networks [1]. Meanwhile, because of the openness of wireless networks, the information security is a key issue for SWIPT system. Physical-layer security (PLS), has become more crucial in 5G wireless networks to increase the security of wireless channels [2]–[5]. Moreover, PLS has recently been pursued in different SWIPT systems, such as relay network [6], multiple-input-multiple-output (MIMO) channel [7], cognitive radio network [8], and multiple-input-single-output (MISO) systems [9], [10].

In many investigations [7]–[12], with the help of the semidefinite relaxation (SDR) method, a rank relaxation method has widely employed in various PLS-SWIPT design problems, where a semi-definite programming (SDP) problem was generated. Unfortunately, SDP problem can not be guaranteed to get a rank-one solution, which serve as a performance upper bound of the original problem in general. Specifically, since the proof of rank-two solution was presented, the works [9], [10] have generated a suboptimal rank-one solution by applying a Gaussian randomization (GR) method, which may not be correct. In addition, if SDP returns a high-rank solution, the GR method may give rise to poor performance or even may not obtain the optimal beamforming. Besides, solving a SDP problem requires higher computational complexity [15].

It is worth noting that these previous works referring to PLS-SWIPT were either focus on transmit power minimization or secrecy rate maximization problem. As another important issue of PLS-SWIPT, the research of the max-min fair energy harvesting (EH) problem still remains infrequent, which brought extensive attention of academia. So far, only several literatures [11], [12] studied the max-min fair EH problem. However, [11] and [12] only considered the signal-to-interference and noise ratio (SINR) constraint at the information receiver. Also, Khandaker and Wong [12] only studied the case with single-antenna energy harvesting receivers (EHR). In addition, the SDR method is applied to some works [11], [12], which results of the higher complexity.

Motivated by these issues, in this letter, the energy harvested by EH receivers under the rule of a max-min fairness criterion is optimized while guaranteing the secrecy transmission. The contributions of this letter are summarized as follows:

- For the perfect channel state information (CSI) case, to solve a non-convex problem, we present a novel secrecy rate reformulation as a second-order cone (SOC), and utilize a first-order Taylor approximation to convert the minimum harvested energy into a linear constraint. To circumvent rank relaxation, a novel iterative algorithm based on successive convex approximation (SCA) is proposed to obtain a near-optimal beamforming.
- For the imperfect CSI case, we extend the max-min EH fairness problem with deterministic channel uncertainties. According to the SCA method, a robust problem can be relaxed as a second order cone programming (SOCP). Thus, a SCA-based iterative algorithm is applied to compute the near-optimal secure beamforming vector.

Simulation results demonstrate that our proposed algorithms can achieve the same secrecy performance as the SDR method with much low complexity.

Notation: $\Re\{\cdot\}$ stands for the real part of a complex number. The operator $\otimes$ is the Kronecker product. $[x]^+$ represents $\max\{x, 0\}$. $\mathbf{A} \succeq \mathbf{0}$ indicates that $\mathbf{A}$ is positive semi-definite, tr $(\mathbf{A})$, $\|\mathbf{A}\|_F$ and $vec(\mathbf{A})$ means the trace, Frobenius norm and a column vector where elements of $\mathbf{A}$ are stacked, respectively.

II. System Model

Considering a secrecy MIMO system with SWIPT which include one legitimate transmitter (named Alice) equipped

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with N_T transmit antenna, one single antenna legitimate user (Bob), K eavesdroppers (Eves) with N_R antenna, and L single antenna EHRs. Then, the received signals at Bob, the k-th Eve and the l-th EHR, denoted by y_s, $\mathbf{y}_{e,k}$ and y_l, can be given, respectively, as

$$\begin{aligned} y_s &= \mathbf{h}_s^H \mathbf{w} s + n_s, \\ \mathbf{y}_{e,k} &= \mathbf{H}_{e,k}^H \mathbf{w} s + \mathbf{n}_{e,k}, \text{ for } k = 1, \ldots, K, \\ y_l &= \mathbf{h}_l^H \mathbf{w} s, \text{ for } l = 1, \ldots, L, \end{aligned}$$

where $\mathbf{h}_s \in \mathbb{C}^{N_T \times 1}$, $\mathbf{H}_{e,k} \in \mathbb{C}^{N_T \times N_R}$ and $\mathbf{h}_l \in \mathbb{C}^{N_T \times 1}$ are the channel vectors between Alice and Bob, the k-th Eve and the l-th EHR, respectively, s and $\mathbf{w} \in \mathbb{C}^{N_T \times 1}$ represent the information-bearing signal with $\mathbb{E}\{s^2\} = 1$ and the corresponding beamforming. Also, $n_s \sim \mathcal{CN}(0, \sigma_s^2)$ and $\mathbf{n}_{e,k} \sim \mathcal{CN}(0, \sigma_{e,k}^2)$ indicate the complex Gaussian noise at Bob and the k-th Eve, respectively.

Accordingly, the achieved secrecy rate of Bob is given as

$$R_s = \left[\log\left(1 + \frac{|\mathbf{h}_s^H \mathbf{w}|^2}{\sigma_s^2}\right) - \max_k \log\left| \mathbf{I} + \frac{\mathbf{H}_{e,k}^H \mathbf{w}\mathbf{w}^H \mathbf{H}_{e,k}}{\sigma_{e,k}^2} \right| \right]^+ .$$

In addition, the energy harvested at the l-th EHR, denoted by E_l, is written as $E_l = \zeta_l |\mathbf{h}_l^H \mathbf{w}|^2, \ \forall l$, where $0 < \zeta_l \leq 1$ means the energy conversion efficiency which is a constant.

III. Max-Min EH Fairness for Perfect CSI Case

We assume that perfect CSI of all receivers is available at Alice. Our aim is to maximize the minimum harvested energy such that the achieved secrecy rate is above a certain threshold. Hence, the max-min EH fairness problem is formulated as

$$\begin{aligned} \mathbf{P1}: \ & \max_{\mathbf{w}} \ \min_{l} \ E_l && \text{(1a)} \\ & s.t. \ \min_k R_s \geq R, \ \forall k, && \text{(1b)} \\ & \|\mathbf{w}\|^2 \leq P, && \text{(1c)} \end{aligned}$$

where R indicates the minimum secrecy rate and P stands for the available transmit power budget.

Owing to the non-convex constraint, **P1** is a non-convex problem and cannot be solved directly [13]. In order to get a rank-one covariance matrix solution, Zhang *et al.* [9] and Feng *et al.* [10] presented suboptimal algorithms by utilizing the SDR method. In this letter, we propose a novel relaxation method for **P1** to circumvent the SDR method. First, by applying the matrix inequality $|\mathbf{I} + \mathbf{A}| \geq 1 + \text{tr}(\mathbf{A})$ [5], (1b) can be relaxed as

$$\log\left(1 + \frac{|\mathbf{h}_s^H \mathbf{w}|^2}{\sigma_s^2}\right) - \log\left(1 + \frac{\text{tr}(\mathbf{H}_{e,k}^H \mathbf{w}\mathbf{w}^H \mathbf{H}_{e,k})}{\sigma_{e,k}^2}\right) \geq R, \forall k. \quad (2)$$

Defining $\mathbf{h}_{e,k} \triangleq vec(\mathbf{H}_{e,k})$ and $\tilde{\mathbf{W}} \triangleq \mathbf{I}_{N_R} \otimes \mathbf{w}$, we rewrite the secrecy rate constraint as

$$\|\mathbf{a}_k\|^2 \leq \frac{1}{\sigma_s^2} |\mathbf{w}^H \mathbf{h}_s|^2, \forall k, \quad (3)$$

where $\mathbf{a}_k = \left[\frac{2^{\frac{R}{2}}}{\sigma_{e,k}} \tilde{\mathbf{W}}^H \mathbf{h}_{e,k} \quad \sqrt{2^R - 1} \right]^T$. Thus, (3) can be further recast to a SOC as

$$\|\mathbf{a}_k\| \leq \sigma_s^{-1} \Re\{\mathbf{w}^H \mathbf{h}_s\}, \forall k. \quad (4)$$

Then, by introducing a variable $r > 0$, **P1** can be equivalently rewritten as

$$\begin{aligned} \mathbf{P2}: \ & \max_{\mathbf{w}, r} \ r \\ & s.t. \ \min_l \ |\mathbf{w}^H \mathbf{h}_l|^2 \geq r/\zeta_l, \ \forall l, \\ & \|\mathbf{w}\| \leq \sqrt{P}, \ r \geq 0, \ (4). \end{aligned} \quad (5)$$

It is observed that $|\mathbf{w}^H \mathbf{h}_l|^2$ is the exact concave part of EH constraint. Next, the SCA technique is employed for the concave constraints [16] to obtain convex approximations. First, we denote $\tilde{\mathbf{w}}$ as a feasible initial point which is assumed to be found. Defining $\mathbf{w} \triangleq \tilde{\mathbf{w}} + \Delta\mathbf{w}$. Then, by substituting $\tilde{\mathbf{w}} + \Delta\mathbf{w}$ into the left-hand side (LHS) of the EH constraint, we can obtain

$$\begin{aligned} |\mathbf{w}^H \mathbf{h}_l|^2 = (\tilde{\mathbf{w}} + \Delta\mathbf{w})^H \mathbf{H}_l (\tilde{\mathbf{w}} + \Delta\mathbf{w}) \geq \tilde{\mathbf{w}}^H \mathbf{H}_l \tilde{\mathbf{w}} \\ + 2\Re\{\tilde{\mathbf{w}}^H \mathbf{H}_l \Delta\mathbf{w}\}, \end{aligned} \quad (6)$$

where $\mathbf{H}_l = \mathbf{h}_l \mathbf{h}_l^H$ and the inequality is given by dropping the quadratic term $\Delta\mathbf{w}^H \mathbf{H}_l \Delta\mathbf{w}$. According to (6), the EH constraint is expressed as

$$\tilde{\mathbf{w}}^H \mathbf{H}_l \tilde{\mathbf{w}} + 2\Re\{\tilde{\mathbf{w}}^H \mathbf{H}_l \Delta\mathbf{w}\} \geq r/\zeta_l, \ \forall l. \quad (7)$$

Thus, **P2** is rewritten as

$$\mathbf{P3}: \ \max_{\mathbf{w}, r} \ r \ \ s.t. \ (4), \ (7), \ \|\mathbf{w}\| \leq \sqrt{P}, \ r \geq 0. \quad (8)$$

Then, **P3** becomes a SOCP problem and can be solved by the CVX tool [14]. Let us randomly generate an initial value of the beamforming vector $\tilde{\mathbf{w}}^{(0)}$, and update $\tilde{\mathbf{w}}$ at each iteration. Also, due to the power constraint (1c), r always has a upper bound, and thus the proposed SCA algorithm can be guaranteed to converge to a global optimal rank-one solution [16].

IV. Robust Max-Min EH Fairness With Deterministic Channel Uncertainty

When the channel estimation and quantization errors exist, it is not always possible to realize the perfect CSI case.[1] In this section, by incorporating norm-bounded channel uncertainties, a robust secure beamforming design is investigated. Assuming that perfect CSI is not available at Alice, the channel uncertainties are modelled to the norm-bounded form as

$$\begin{aligned} \mathbf{h}_s &= \bar{\mathbf{h}}_s + \mathbf{e}_s, \ \|\mathbf{e}_s\|_2 \leq \varepsilon_s, \ \text{for } \varepsilon_s \geq 0, \\ \mathbf{H}_{e,k} &= \bar{\mathbf{H}}_{e,k} + \mathbf{E}_{e,k}, \ \|\mathbf{E}_{e,k}\|_F \leq \varepsilon_{e,k}, \ \text{for } \varepsilon_{e,k} \geq 0, \forall k, \\ \mathbf{h}_l &= \bar{\mathbf{h}}_l + \mathbf{e}_l, \ \|\mathbf{e}_l\|_2 \leq \varepsilon_l, \ \text{for } \varepsilon_l \geq 0, \forall l, \end{aligned}$$

where $\bar{\mathbf{h}}_s$, $\bar{\mathbf{H}}_{e,k}$ and $\bar{\mathbf{h}}_l$ denote the channel estimation values of Bob, the k-th Eve and the l-th EHR, respectively, $\mathbf{e}_s$, $\mathbf{E}_{e,k}$ and $\mathbf{e}_l$ represent the corresponding channel errors, and ε_s, $\varepsilon_{e,k}$ and ε_l indicate the norm bounds of the channel errors.

Taking the channel uncertainties into account, the robust max-min EH fairness problem is written as

$$\begin{aligned} \mathbf{P4}: \ & \max_{\mathbf{w}} \ \min_{\mathbf{e}_l} \ \zeta_l |(\bar{\mathbf{h}}_l + \mathbf{e}_l)^H \mathbf{w}|^2 && \text{(9a)} \\ s.t. \ & \min_{\mathbf{e}_s} \log\left(1 + |(\bar{\mathbf{h}}_s + \mathbf{e}_s)^H \mathbf{w}|^2 \big/ \sigma_s^2\right) - \\ & \max_{\mathbf{e}_{e,k}} \log\left(1 + \frac{\text{tr}((\bar{\mathbf{H}}_{e,k} + \mathbf{E}_{e,k})^H \mathbf{w}\mathbf{w}^H (\bar{\mathbf{H}}_{e,k} + \mathbf{E}_{e,k}))}{\sigma_{e,k}^2}\right) \geq R, && \text{(9b)} \\ & \|\mathbf{w}\|^2 \leq P. && \text{(9c)} \end{aligned}$$

[1] In this letter, we can use an MMSE-based channel estimation method to obtain the estimated CSI [18].

In terms of channel uncertainties, **P4** is non-convex and cannot be solved directly [13]. First, we consider the reformulation of (9b), which can be relaxed as

$$\max_{\mathbf{e}_{e,k}} \frac{2^R}{\sigma_{e,k}^2}\mathrm{tr}((\bar{\mathbf{H}}_{e,k}+\mathbf{E}_{e,k})^H\mathbf{w}\mathbf{w}^H(\bar{\mathbf{H}}_{e,k}+\mathbf{E}_{e,k}))+2^R-1 \le \min_{\mathbf{e}_s}\frac{1}{\sigma_s^2}|\mathbf{w}^H(\mathbf{h}_s+\mathbf{e}_s)|^2. \tag{10}$$

By introducing a slack variable r_2 and denoting $\hat{\mathbf{H}}_{e,k} = \bar{\mathbf{H}}_{e,k}\bar{\mathbf{H}}_{e,k}^H$ and $\bar{\mathbf{H}}_s = \bar{\mathbf{h}}_s\bar{\mathbf{h}}_s^H$, we can convert the secrecy rate constraint into

$$\max_{\Delta_{e,k}} \frac{2^R}{\sigma_{e,k}^2}\mathbf{w}^H(\hat{\mathbf{H}}_{e,k}+\Delta_{e,k})\mathbf{w}+2^R-1 \le r_2,\ \forall k, \tag{11a}$$

$$\min_{\Delta_s}\mathbf{w}^H(\bar{\mathbf{H}}_s+\Delta_s)\mathbf{w} \ge \sigma_s^2 r_2, \tag{11b}$$

where $\Delta_{e,k} = \bar{\mathbf{H}}_{e,k}\mathbf{E}_{e,k}^H+\mathbf{E}_{e,k}\bar{\mathbf{H}}_{e,k}^H+\mathbf{E}_{e,k}\mathbf{E}_{e,k}^H$ and $\Delta_s = \bar{\mathbf{h}}_s\mathbf{e}_s^H+\mathbf{e}_s\bar{\mathbf{h}}_s^H+\mathbf{e}_s\mathbf{e}_s^H$ stand for the CSI uncertainty. It is straightforward to show that

$$\begin{aligned}\|\Delta_{e,k}\|_F &\le \|\bar{\mathbf{H}}_{e,k}\mathbf{E}_{e,k}^H\|_F+\|\mathbf{E}_{e,k}\bar{\mathbf{H}}_{e,k}^H\|_F+\|\mathbf{E}_{e,k}\mathbf{E}_{e,k}^H\|_F\\ &\le \|\bar{\mathbf{H}}_{e,k}\|_F\|\mathbf{E}_{e,k}^H\|_F+\|\mathbf{E}_{e,k}\|_F\|\bar{\mathbf{H}}_{e,k}^H\|_F+\|\mathbf{E}_{e,k}\|_F^2\\ &= \varepsilon_{c,l}^2+2\varepsilon_{c,l}\|\bar{\mathbf{H}}_{e,k}\|_F,\end{aligned} \tag{12}$$

$$\begin{aligned}\|\Delta_s\|_F &\le \|\bar{\mathbf{h}}_s\mathbf{e}_s^H\|_F+\|\mathbf{e}_s\bar{\mathbf{h}}_s^H\|_F+\|\mathbf{e}_s\mathbf{e}_s^H\|_F\\ &\le \|\bar{\mathbf{h}}_s\|\|\mathbf{e}_s^H\|+\|\mathbf{e}_s\|\|\bar{\mathbf{h}}_s^H\|+\|\mathbf{e}_s\|^2\\ &= \varepsilon_s^2+2\varepsilon_s\|\bar{\mathbf{h}}_s\|.\end{aligned} \tag{13}$$

Note that $\Delta_{e,k}$ and Δ_s are norm-bounded matrices as $\|\Delta_{e,k}\|_F \le \xi_{e,k}$ and $\|\Delta_s\|_F \le \xi_s$ where $\xi_{e,k} = \varepsilon_{e,k}^2+2\varepsilon_{e,k}\|\bar{\mathbf{H}}_{e,k}\|_F$ and $\xi_s = \varepsilon_s^2+2\varepsilon_s\|\bar{\mathbf{h}}_s\|_F$. In order to maximize the LHS of (11a) and minimize the LHS of (11b), a loose approximation [7] is applied, which gives

$$\max_{\Delta_{e,k}}\frac{2^R}{\sigma_{e,k}^2}\mathbf{w}^H(\hat{\mathbf{H}}_{e,k}+\Delta_{e,k})\mathbf{w}+2^R-1 \le \frac{2^R}{\sigma_{e,k}^2}\mathbf{w}^H(\hat{\mathbf{H}}_{e,k}+\xi_{e,k}\mathbf{I})\mathbf{w}+2^R-1 \le r_2, \tag{14}$$

$$\min_{\Delta_s}\mathbf{w}^H(\bar{\mathbf{H}}_s+\Delta_s)\mathbf{w} \ge \mathbf{w}^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})\mathbf{w} \ge \sigma_s^2 r_2. \tag{15}$$

By introducing a slack variable r_3, **P4** can be rewritten as

$$\mathbf{P5}:\ \max_{\mathbf{w},r_2,r_3} r_3 \tag{16a}$$

$$\begin{aligned}s.t.\ &\min_{\mathbf{e}_l}\ |(\bar{\mathbf{h}}_l+\mathbf{e}_l)^H\mathbf{w}|^2 \ge r_3/\zeta_l,\ \forall l,\\ &r_3 \ge 0,\ (14),\ (15),\ (9c).\end{aligned} \tag{16b}$$

Denoting $\bar{\mathbf{H}}_l = \bar{\mathbf{h}}_l\bar{\mathbf{h}}_l^H$ and $\xi_l = \varepsilon_l^2+2\varepsilon_l\|\bar{\mathbf{h}}_l\|_F$. Similarly, the constraint (16b) can be equivalently given as

$$\min_{\Delta_l}\ \mathbf{w}^H(\bar{\mathbf{H}}_l+\Delta_l)\mathbf{w} \ge \mathbf{w}^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})\mathbf{w} \ge r_3/\zeta_l,\ \forall l, \tag{17}$$

where $\|\Delta_l\|_F \le \xi_l$.

In order to approximate the concave constraints (15) and (17) to convex constraints, we apply an alterative SCA-based iterative method. By substituting $\mathbf{w} \triangleq \tilde{\mathbf{w}}+\Delta\mathbf{w}$ into the LHS of (15) and (17), we obtain

$$\begin{aligned}\mathbf{w}^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})\mathbf{w} &= (\tilde{\mathbf{w}}+\Delta\mathbf{w})^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})(\tilde{\mathbf{w}}+\Delta\mathbf{w})\\ &\ge \tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})\tilde{\mathbf{w}}+2\Re\{\tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})\Delta\mathbf{w}\},\end{aligned} \tag{18}$$

$$\begin{aligned}\mathbf{w}^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})\mathbf{w} &= (\tilde{\mathbf{w}}+\Delta\mathbf{w})^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})(\tilde{\mathbf{w}}+\Delta\mathbf{w})\\ &\ge \tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})\tilde{\mathbf{w}}+2\Re\{\tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})\Delta\mathbf{w}\},\end{aligned} \tag{19}$$

where (18) and (19) are derived by removing $\Delta\mathbf{w}^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})\Delta\mathbf{w}$ and $\Delta\mathbf{w}^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})\Delta\mathbf{w}$, respectively. Based on (18) and (19), we then acquire the linear approximations of (15) and (17), respectively, as

$$\tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})\tilde{\mathbf{w}}+2\Re\{\tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_s-\xi_s\mathbf{I})\Delta\mathbf{w}\} \ge \sigma_s^2 r_2, \tag{20}$$

$$\tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})\tilde{\mathbf{w}}+2\Re\{\tilde{\mathbf{w}}^H(\bar{\mathbf{H}}_l-\xi_l\mathbf{I})\Delta\mathbf{w}\} \ge r_3/\zeta_l,\ \forall l. \tag{21}$$

According to (9)-(21), **P4** is expressed as

$$\begin{aligned}\mathbf{P6}:\ &\max_{\mathbf{w},r_2,r_3}\quad r_3\\ &s.t.\ \|\mathbf{w}\|_2 \le \sqrt{P},\ r_2 \ge 0,\ r_3 \ge 0,\ (14),\ (20),\ (21).\end{aligned} \tag{22}$$

P6 is a SOCP problem. Thus, we can solve problem (22) by using the CVX tool [14]. It is easily observed that $\tilde{\mathbf{w}}$ is updated when the algorithm converges.

V. Computational Complexity

The computational complexity of the proposed algorithms are compared with the conventional methods [11], [12]. By using the analysis in [15], the complexity comparison are listed in Table I, where, n denotes the number of variables, and $N_1^{\max}$ and $N_2^{\max}$ stand for the iteration number of the proposed algorithms, respectively. *1) SCA algorithm with perfect CSI* in problem (8) involves $K+1$ SOCs of dimension N_T and $L+1$ linear constraints (LCs). *2) SDR method with perfect CSI* with AN vector $\boldsymbol{\nu} = \mathbf{0}$ in [11] contains one LMI constraint of size N_T and $K+L+2$ LCs. *3) SCA algorithm with imperfect CSI* in problem (22) consists of K SOC constraints of dimension N_T+1, one SOC constraint of dimension N_T, and $L+3$ LCs. *4) SDR method with imperfect CSI* which is similar to the one in [12] has K LMI constraints of size $N_R N_T+N_T+1$, L LMI constraints of size N_T+1, one LMI constraint of size N_T, and $2K+L+2$ LCs.

Considering a secure MIMO system[2] with $K = 3, L = 2, N_T = 6, N_R = 2$, and $N_1^{\max} = N_2^{\max} = 5$, the complexity of the SCA algorithm with perfect CSI, the SDR method with perfect CSI [11], the SCA algorithm with imperfect CSI, and the SDR method with imperfect CSI [12], are $O(2.27\times10^4)$, $O(3.66\times10^5)$, $O(3.49\times10^4)$, and $O(3.24\times10^7)$, respectively.

VI. Simulation Results

In this section, we show the effectiveness of the SCA-based iterative algorithms by simulation results. The simulation parameters are set to be $K = 4, L = 3$, $N_T = 6$ and $N_R = 2$. It is assumed that the large-scale fading and small-scale fading are included in the channel models. First, we denote $D = \left(\frac{d}{d_0}\right)^{-\alpha}$ as the large-scale fading model, where d is the distance between Alice and the receiver, d_0 equals a reference distance which is 10 m, and $\alpha = 3$ represents the path loss exponent. Thus, the distance between Alice and Bob, Eves and EHRs are defined as $d_s = 40, d_e = 20, d_r = 10$ m. Also, we model the small-scale fading as the Rician fading. For example, let the Rician factor K_R equal 3, $\mathbf{h}_s$ is described as $\mathbf{h}_s = \sqrt{\frac{K_R}{1+K_R}}\mathbf{h}_s^{LOS}+\sqrt{\frac{1}{1+K_R}}\mathbf{h}_s^{NLOS}$, where $\mathbf{h}_s^{LOS}$

[2]When the system setting is larger (such as the number of transmit antennas N_T, eavesdroppers K, and EHRs L is large), the proposed algorithms is available since problem (8) and problem (22) can be solved by the CVX tool.

TABLE I
COMPLEXITY ANALYSIS OF THE PROPOSED METHODS

Schemes	Complexity Comparisons
SCA algorithm with perfect CSI	$O(nN_1^{max}\sqrt{2K+L+3}((K+1)N_T^2+L+1+n^2))$ where $n=O(N_T+1)$
SDR method with perfect CSI [11]	$O(n\sqrt{N_T+K+L+2}(N_T^3+nN_T^2+K+L+2+n^2))$ where $n=O(N_T^2+1)$
SCA algorithm with imperfect CSI	$O\big(nN_2^{max}\sqrt{2K+L+4}(K(N_T+1)^2+N_T^2+L+3+n^2)\big)$ where $n=O(N_T+2)$
SDR method with imperfect CSI [12]	$O\big(n\sqrt{(KN_R+K+L+1)N_T+3K+L+2}[K((N_RN_T+N_T+1)^3+n(N_RN_T+N_T+1)^2)$ $+L((N_T+1)^3+n(N_T+1)^2)+N_T^3+nN_T^2+n^2]\big)$where $n=O(N_T^2+2K+L+1)$

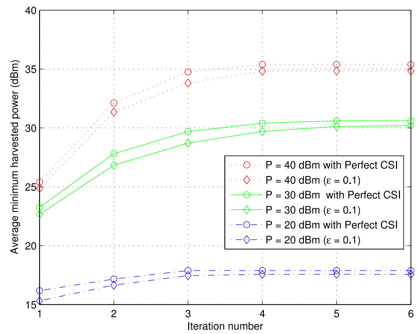

Fig. 1. Convergence behavior of the proposed SCA algorithm.

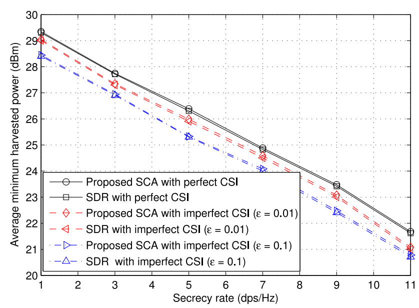

Fig. 2. Average minimum harvested energy versus secrecy rate.

stands for the line-of-sight (LOS) deterministic component with $\|\mathbf{h}_s^{LOS}\|_2^2 = D$ [17], and $\mathbf{h}_s^{NLOS}$ indicates the Rayleigh fading component as $\mathbf{h}_s^{NLOS} \sim \mathcal{CN}(\mathbf{0}, D\mathbf{I})$. In addition, we set $\sigma_s^2 = -60$ dBm and $\sigma_{e,k}^2 = \sigma_e^2 = -10$ dBm, $\forall k$, $\varepsilon_s = \varepsilon_{e,k} = \varepsilon_l = \varepsilon, \forall l, k$, and $\zeta_l = 0.3$.

Fig. 1 shows the convergence behavior of our proposed SCA algorithms. It can be observed that the convergence of the proposed SCA algorithms are quickly achieved after 5 iterations for all transmit power P. Also, we can see that the minimum harvested energy increases with P.

Fig. 2 evaluates the trade-off between average minimum harvested power and secrecy rate with $P = 50$ dBm. From this result, one can observe that the harvested power decreases with the secrecy rate. For all the cases, the proposed SCA method can achieve the same performance as the conventional schemes, but with much lower complexity. Moreover, the performance gaps between the perfect CSI case and the case with $\varepsilon = 0.01$ and 0.1 equal 0.4 dB and 1.2 dB, respectively.

VII. CONCLUSION

In this letter, secure beamforming designs have been studied under a max-min fairness criterion in a secrecy MIMO SWIPT channel. To this end, a SCA-based iterative algorithm has been proposed to relax this original problem for perfect CSI and imperfect CSI cases. Simulation results have demonstrated the SCA algorithms arrive the same performance of the conventional SDR methods with reduced complexity.

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