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Outage Constraint Robust Transmission Design for Secrecy MIMO SWIPT System with Time Switching

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Abstract—In this paper, we investigate a robust secrecy transmission design for a multiple-input multiple-output simultaneous wireless information and power transfer system. Specifically, considering time switching at the transmitter, we aim to maximize the outage secrecy rate by jointly designing the information signal, energy signal, and time switching ratio, under the constraints of transmit power and harvested energy. The formulated problem is highly non-convex due to the difference of two log-det functions and probabilistic constraints. To overcome this obstacle, we divide the original problem into three convex subproblems. Then, an alternative optimization method is proposed. Finally, numerical results are presented to verify the performance of the proposed scheme.

1. INTRODUCTION

Simultaneous wireless information and power transfer (SWIPT) has been proposed as a promising solution to improve the energy efficiency of wireless networks [1], which has been widely investigated in different scenarios [2–4].

However, due to the inherent nature of SWIPT and the openness of wireless channel, transmitting information and energy simultaneously makes it vulnerable to security attacks [5]. An emerging technique named physical layer security (PLS), which exploits the characteristics of wireless channels to improve the security, has aroused great attention to handle this problem [6]. Specifically, secrecy SWIPT has been investigated in [7] for single-input-single-output (SISO) wiretap channel, in [8] for multiple-input-single-output (MISO) channel, and in [9] and [10] for multiple-input-multiple-output (MIMO) channel, respectively.

One of the most important challenges in secure SWIPT design is the acquirement of channel state information (CSI). In practice, it is hard to obtain perfect CSI due to channel estimation error and feedback delay. When CSI errors have certain statistical properties, probabilistically robust method is commonly used to formulate an optimization problem [11–16]. Specifically, the outage constrained robust methods were investigated for secrecy MISO SWIPT systems in [11–13] and for secrecy MIMO SWIPT systems in [14–16], respectively. Among them, Bernstein-type inequality (BTI) has been proved to be an effective method to transform probabilistic constraints into solvable form.

However, most of these works focus on power splitting (PS) scheme. Compared with PS, time switching (TS) is more feasible due to simplicity of the circuit structure [17–20]. Specifically, in [17], the authors investigated the sum rate maximization design for a multiuser MISO system with transmit TS scheme. In [18], the authors compared the sum rate performance in a multi-cell SWIPT system using PS and TS. Recently in [19] and [20], the authors investigated a novel TS scheme in two-user downlink

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SWIPT channel. However, all of them only consider perfect CSI case and do not fit for the secrecy design.

Motivated by this observation, in this paper, we investigate the PLS design in MIMO SWIPT channel, where TS is adapted by the transmitter to coordinate the information and energy transmission. Specifically, we aim to maximize the outage secrecy rate by jointly optimizing the information signal covariance, energy signal covariance and TS ratio, subject to the transmit power constraint and the harvested energy threshold at the energy receivers (ERs). The formulated problem is highly non-convex due to the difference of the logarithmic determinant (log-det) functions, while the probabilistic constraints make the problem harder to handle. To overcome this obstacle, we propose an effective linearization method and divide the original problem into several convex subproblems. Then, an alternating optimization (AO) method is proposed to obtain the solution. Numerical results demonstrate the secrecy performance of the proposed method.

The rest of this paper is organized as follows. A system model and problem statement are given in Section 2. Section 3 investigates the joint design problem, wherein an AO based approach is established. Simulation results are illustrated in Section 4. Section 5 concludes this paper.

Table 1 summarizes the used notations and the corresponding definitions in this paper.

Table 1. List of notations.

Notation	Definition
$\mathbf{A}^T$	Transpose of matrix $\mathbf{A}$
$\mathbf{A}^H$	Conjugate transpose of matrix $\mathbf{A}$
$\mathrm{Tr}(\mathbf{A})$	Trace of matrix $\mathbf{A}$
$\mathbf{a}= \mathrm{vec}(\mathbf{A})$	Stack the columns of matrix $\mathbf{A}$ into a vector $\mathbf{a}$
$\mathbf{A} \succeq \mathbf{0}$	$\mathbf{A}$ is a positive semi-definite matrix
$\|\cdot\|$	Euclidean norm
$\|\cdot\|_F$	Frobenius norm
$\otimes$	Kronecker product
$\mathbf{I}$	Identity matrix with proper dimension
$\mathrm{Re}\{a\}$	The real part of a complex variable a
$\mathcal{CN}(\mathbf{0},\mathbf{I})$	A circularly symmetric complex Gaussian random vector with mean $\mathbf{0}$ and covariance $\mathbf{I}$
$[x]^+$	$\max(0,x)$
$\mathcal{CN}(\mathbf{0},\mathbf{I})$	A circularly symmetric complex Gaussian random vector with mean $\mathbf{0}$ and covariance $\mathbf{I}$
$\mathbb{E}[.]$	Statistical expectation

2. SYSTEM MODEL AND PROBLEM STATEMENT

2.1. System Model

Let us consider a MIMO SWIPT system as shown in Fig. 1, which consists of one multi-antenna transmitter, one multi-antenna information receiver (IR) and multiple multi-antenna ERs, which may act as potential eavesdroppers (Eves). We assume that the transmitter, IR and each ER are equipped with N_t, N_i and N_e antennas, respectively. In addition, all the links are assumed to undergo flat fading, and the channel matrices from the transmitter to IR and m-th ER are denoted as $\mathbf{H} \in \mathbb{C}^{N_t \times N_i}$ and $\mathbf{G}_m \in \mathbb{C}^{N_t \times N_e}$, respectively.

Since TS scheme is used by the transmitter, the entire information and energy transmission slot can be divided into two parts. Specifically, assuming a normalized transmitting time, in the first phase τT, the transmitter sends the information signal to the IR, which may be eavesdropped by the ER. In the remaining time, the transmitter transmits energy signal to power the ER over $(1-\tau)T$ duration, where $0 \leq \tau \leq 1$ is the TS ratio.

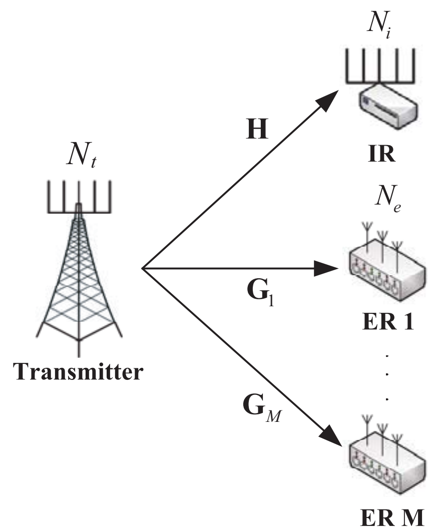

Figure 1. The secrecy MIMO SWIPT system.

In the first block, the received signal at IR and the m-th ER can be expressed as

$$\mathbf{y}_i = \mathbf{H}^H \mathbf{x} + \mathbf{n}_i, \tag{1a}$$

$$\mathbf{y}_{e,m} = \mathbf{G}_m^H \mathbf{x} + \mathbf{n}_{e,m}, \tag{1b}$$

respectively, where $\mathbf{x} \sim \mathcal{CN}(\mathbf{0}, \mathbf{W})$ denotes the signal vector with $\mathbf{W}$ being the information signal covariance. In addition, $\mathbf{n}_i \sim \mathcal{CN}(\mathbf{0}, \sigma_i^2 \mathbf{I})$ and $\mathbf{n}_{e,m} \sim \mathcal{CN}(\mathbf{0}, \sigma_{e,m}^2 \mathbf{I})$ are the additive noises at the IR and m-th ER, respectively.

Thus, the achievable secrecy rate can be expressed as

$$R = \min_{m=1,\ldots,M} f_m(t, \mathbf{W}), \tag{2}$$

where

$$f_m(t, \mathbf{W}) = t \left(\ln \left| \mathbf{I} + \sigma_i^{-2} \mathbf{H}^H \mathbf{W} \mathbf{H} \right| - \ln \left| \mathbf{I} + \sigma_{e,m}^{-2} \mathbf{G}_m^H \mathbf{W} \mathbf{G}_m \right| \right). \tag{3}$$

In the second block, the harvested energy at the m-th ER is

$$E_m = (1 - t) \operatorname{Tr}\left(\mathbf{G}_m^H \mathbf{Q} \mathbf{G}_m \right), \tag{4}$$

where $\mathbf{Q}$ is the covariance of the energy signal.

Based on the transmit method, the total transmit power at the transmitter is

$$P_{tot} = t \operatorname{Tr}(\mathbf{W}) + (1 - t) \operatorname{Tr}(\mathbf{Q}). \tag{5}$$

2.2. Problem Statement

In this paper, we assume that only partial ERs' CSI can be obtained. Similar to the considerations in [12] and [14], the imperfect ERs' CSI is modeled as

$$\operatorname{vec}(\mathbf{G}_m) \sim \mathcal{CN}(\bar{\mathbf{g}}_m, \mathbf{C}_m), \quad m = 1, \ldots, M, \tag{6}$$

where $\bar{\mathbf{g}}_m = \operatorname{vec}\left(\bar{\mathbf{G}}_m\right)$ is the estimate of the m-th ER channel $\mathbf{G}_m$, and $\mathbf{C}_m \in \mathbb{H}_+^{N_t}$ is the associated CSI uncertainty covariance. Besides, we assume that $\mathbf{G}_m$ is independent with $\mathbf{G}_k$ for any $k \neq m$.

Here, we aim to maximize the outage secrecy rate subject to the transmit power and the harvested energy constraints. Mathematically, this problem can be formulated as

$$\max_{\mathbf{W}, \mathbf{Q}, t, R_s} \quad R_s, \tag{7a}$$

$$\text{s.t.} \quad \Pr_{\mathbf{G}_m} \left\{ \min_{m=1,\ldots,M} f_m(t, \mathbf{W}) \geq R_s \right\} \geq 1 - \rho, \tag{7b}$$

$$\Pr\{E_m \geq \eta_m\} \geq 1 - r_m, \tag{7c}$$

$$t\text{Tr}\left(\mathbf{W}\right)+\left(1-t\right)\text{Tr}\left(\mathbf{Q}\right)\leq P_s, \tag{7d}$$

where P_s is the maximal transmit power at the transmitter; ρ denotes the probability of the achievable secrecy rate falling below the target rate R_s; and r_m denotes the probability of the harvested energy E_m at the m-th ER falling below the target threshold η_m. Notably, the objective and constraints in Eq. (7) are highly non-convex, thus, it is hard to obtain the solution directly. In the next section, we will propose an AO algorithm to solve Eq. (7).

3. AN AO METHOD TO THE OUTAGE SRM PROBLEM

The formulation of the AO method consists of the following three steps:

Step 1: Decouple the probabilistic constraint.

Since $\mathbf{G}_m$ and $\mathbf{G}_k, \forall m \neq k$ are independent, based on the analysis in [21], we have

$$\begin{aligned}(7\text{b}) \Leftrightarrow &\prod\nolimits_{m=1}^{M}\Pr\nolimits_{\mathbf{G}_m}\left\{f_m\left(t,\mathbf{W}\right)\geq R_s\right\}\geq 1-\rho\\ \Leftarrow &\Pr\nolimits_{\mathbf{G}_m}\left\{f_m\left(t,\mathbf{W}\right)\geq R_s\right\}\geq 1-\bar{\rho},\forall m,\end{aligned} \tag{8}$$

where $\bar{\rho}=1-(1-\rho)^{1/M}$.

Owing to the difference of two log-det functions in $f_m(t,\mathbf{W})$, Eq. (8) is still non-convex. In the following, we aim to turn $f_m(t,\mathbf{W})$ into a more tractable form.

Step 2: A convenient approximation of $f_m(t,\mathbf{W})$.

Firstly we introduce the following Lemma.

Lemma 1 [21]: Let $\mathbf{E}\in\mathbb{C}^{N\times N}$ be any matrix such that $\mathbf{E}\succ\mathbf{0}$, consider the function $\gamma(\mathbf{S},\mathbf{E})=-\text{Tr}(\mathbf{SE})+\ln|\mathbf{S}|+N$, then we have

$$-\ln\left|\mathbf{E}\right|=\max_{\mathbf{S}\in\mathbb{C}^{N\times N},\mathbf{S}\succ\mathbf{0}}\gamma\left(\mathbf{S},\mathbf{E}\right). \tag{9}$$

Via Lemma 1, we rewrite the term $\ln|\mathbf{I}+\sigma_{e,m}^{-2}\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m|$ as

$$\begin{aligned}\ln\left|\mathbf{I}+\sigma_{e,m}^{-2}\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m\right| &= -\max_{\mathbf{S}_m\succeq\mathbf{0}}\gamma\left(\mathbf{S}_m,\mathbf{I}+\sigma_{e,m}^{-2}\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m\right)\\ &=\min_{\mathbf{S}_m\succeq\mathbf{0}}-\gamma\left(\mathbf{S}_m,\mathbf{I}+\sigma_{e,m}^{-2}\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m\right).\end{aligned} \tag{10}$$

To simplify the notations, we denote

$$\begin{aligned}\bar{\gamma}\left(\mathbf{S}_m,\mathbf{W}\right) &\triangleq -\gamma\left(\mathbf{S}_m,\mathbf{I}+\sigma_{e,m}^{-2}\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m\right)\\ &=\text{Tr}\left(\mathbf{S}_m\left(\mathbf{I}+\sigma_{e,m}^{-2}\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m\right)\right)-\ln\left|\mathbf{S}_m\right|-N_e,\end{aligned} \tag{11}$$

where the last equality is obtained from Lemma 1.

Then, by substituting Eq. (11) into Eq. (7b), we obtain

$$\begin{aligned}&\Pr\left\{f_m\left(t,\mathbf{W}\right)\geq R_s\right\}\geq 1-\bar{\rho}\Leftrightarrow\\ &\Pr\left\{\min_{\mathbf{S}_m\succeq\mathbf{0}}t\bar{\gamma}\left(\mathbf{S}_m,\mathbf{W}\right)\leq t\ln\left|\mathbf{I}+\sigma_i^{-2}\mathbf{H}^H\mathbf{W}\mathbf{H}\right|-R_s\right\}\geq 1-\bar{\rho}\\ &\Leftarrow\Pr\left\{t\text{Tr}\left(\mathbf{S}_m\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m\right)\leq\theta_m-\sigma_{e,m}^2R_s\right\}\geq 1-\bar{\rho}\end{aligned} \tag{12}$$

where

$$\theta_m=\sigma_{e,m}^2t\left(\ln\left|\mathbf{I}+\sigma_i^{-2}\mathbf{H}^H\mathbf{W}\mathbf{H}\right|+\ln\left|\mathbf{S}_m\right|+N_e-\text{Tr}\left(\mathbf{S}_m\right)\right). \tag{13}$$

Note that Eq. (12) is still intractable due to the probability constraints. In the following, we will focus on how to transform these probabilistic constraints into solvable convex constraints.

Based on the matrix equation $\text{Tr}(\mathbf{A}\mathbf{B}^H\mathbf{C}\mathbf{D})=\text{vec}(\mathbf{B})^H(\mathbf{A}^T\otimes\mathbf{C})\text{vec}(\mathbf{D})$ [22], we have $\text{Tr}(\mathbf{S}_m\mathbf{G}_m^H\mathbf{W}\mathbf{G}_m)=\mathbf{g}_m^H(\mathbf{S}_m^T\otimes\mathbf{W})\mathbf{g}_m$. By denoting $\mathbf{g}_m=\text{vec}(\mathbf{G}_m)=\bar{\mathbf{g}}_m+\Delta\mathbf{g}_m$, where $\bar{\mathbf{g}}_m=\text{vec}(\bar{\mathbf{G}}_m)$, Eq. (12) can be recast as

$$\begin{aligned}\Pr\big\{&t\Delta\mathbf{g}_m^H\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\Delta\mathbf{g}_m+2t\Re\left\{\Delta\mathbf{g}_m^H\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m\right\}\\ &+t\bar{\mathbf{g}}_m^H\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m\leq\theta-\sigma_{e,m}^2R_s\big\}\geq 1-\bar{\rho}\end{aligned} \tag{14}$$

The remaining task is to transform Eq. (14) into convex constraint. Firstly, we introduce the following BTI.

Lemma 2 [23, 24] (BTI): For any $(\mathbf{A}, \mathbf{u}, c) \in \mathbb{H}^N \times \mathbb{C}^N \times \mathbb{R}$, $\mathbf{v} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ and $\beta \in (0, 1]$, the following inequalities hold:

$$\begin{aligned} &\Pr_{\mathbf{v}}\left\{\mathbf{v}^H\mathbf{A}\mathbf{v} + 2\Re\left\{\mathbf{v}^H\mathbf{u}\right\} + c \geq 0\right\} \geq 1-\beta \\ &\Leftarrow \begin{cases} \mathrm{Tr}\left(\mathbf{A}\right) - \sqrt{-2\ln\left(\beta\right)}\mathrm{x} + \ln\left(\beta\right)\mathrm{y} + \mathrm{c} \geq 0, \\ \left\|\begin{bmatrix} \mathrm{vec}\left(\mathbf{A}\right) \\ \sqrt{2}\mathbf{u} \end{bmatrix}\right\| \leq x, \\ y\mathbf{I} + \mathbf{A} \succeq \mathbf{0}, \quad y \geq 0, \end{cases} \end{aligned} \tag{15}$$

where x and y are the slack variables. Moreover, Eq. (15) is convex w.r.t all the variables $(\mathbf{A}, \mathbf{u}, c, x, y)$.

Step 3: A BTI-based approximation.

Since $\Delta\mathbf{g}_m \sim \mathcal{CN}(\mathbf{0}, \mathbf{C}_m)$, $\Delta\mathbf{g}_m$ can be reexpressed as $\Delta\mathbf{g}_m = \mathbf{C}_m^{1/2}\mathbf{v}_m$, where $\mathbf{v}_m \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$. Thus Eq. (14) can be recast as

$$\begin{aligned} \Pr\Big\{&-t\mathbf{v}_m^H\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\mathbf{C}_m^{1/2}\mathbf{v}_m - 2t\Re\left\{\mathbf{v}_m^H\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m\right\} \\ &-t\bar{\mathbf{g}}_m^H\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m + \theta - \sigma_{e,m}^2 R_s \geq 0\Big\} \geq 1-\bar{\rho} \end{aligned} \tag{16}$$

Via Lemma 1, we turn Eq. (16) into the following convex constraints

$$\begin{cases} t\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\mathbf{C}_m^{1/2} + \sqrt{-2\ln\bar{\rho}}\cdot x_m - \ln\bar{\rho}\cdot y_m + t\bar{\mathbf{g}}_m^H\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m + \sigma_{e,m}^2 R_s - \theta_m \leq 0, \forall m \\ \left\|\begin{bmatrix} t\mathrm{vec}\left(\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\mathbf{C}_m^{1/2}\right) \\ t\sqrt{2}\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m \end{bmatrix}\right\| \leq x_m, \forall m, \\ y_m\mathbf{I} - t\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\mathbf{C}_m^{1/2} \succeq \mathbf{0}, \forall m, \end{cases} \tag{17}$$

with $\{x_m, y_m \geq 0\}$ bing the introduced auxiliary variables.

Similarly, the outage harvested energy constraint in Eq. (7c) can be reformulated as

$$\begin{cases} \mathrm{Tr}\left(\mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\mathbf{C}_m^{1/2}\right) + \bar{\mathbf{g}}_m^H\left(\mathbf{I}\otimes\mathbf{Q}\right)\bar{\mathbf{g}}_m - \eta_m/(1-t) - \sqrt{-2\ln r_m}\cdot p_m + \ln r_m\cdot q_m \geq 0, \forall m, \\ \left\|\begin{bmatrix} \mathrm{vec}\left(\mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\mathbf{C}_m^{1/2}\right) \\ \sqrt{2}\mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\bar{\mathbf{g}}_m \end{bmatrix}\right\| \leq p_m, \forall m, \\ q_m\mathbf{I} + \mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\mathbf{C}_m^{1/2} \succeq \mathbf{0}, \forall m, \end{cases} \tag{18}$$

with $\{p_m, q_m \geq 0\}$ being the introduced auxiliary variables.

Combining the above steps, we recast Eq. (7) into the following problem

$$\max_{\mathbf{W},\mathbf{Q},t,R_s,\mathbf{S}_m,x_m,y_m,p_m,q_m} \quad R_s \tag{19a}$$

$$\begin{aligned} \text{s.t.}\quad & t\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\mathbf{C}_m^{1/2} + \sqrt{-2\ln\bar{\rho}}\cdot x_m - \ln\bar{\rho}\cdot y_m \\ & + t\bar{\mathbf{g}}_m^H\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m + \sigma_{e,m}^2 R_s - \theta_m \leq 0, \forall m, \end{aligned} \tag{19b}$$

$$\left\|\begin{bmatrix} t\mathrm{vec}\left(\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\mathbf{C}_m^{1/2}\right) \\ t\sqrt{2}\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\bar{\mathbf{g}}_m \end{bmatrix}\right\| \leq x_m, \forall m, \tag{19c}$$

$$y_m\mathbf{I} - t\mathbf{C}_m^{1/2}\left(\mathbf{S}_m^T\otimes\mathbf{W}\right)\mathbf{C}_m^{1/2} \succeq \mathbf{0}, \forall m, \tag{19d}$$

$$\begin{aligned} & \mathrm{Tr}\left(\mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\mathbf{C}_m^{1/2}\right) + \bar{\mathbf{g}}_m^H\left(\mathbf{I}\otimes\mathbf{Q}\right)\bar{\mathbf{g}}_m - \eta_m/(1-t) \\ & - \sqrt{-2\ln r_m}\cdot p_m + \ln r_m\cdot q_m \geq 0, \forall m, \end{aligned} \tag{19e}$$

$$\left\|\begin{bmatrix} \mathrm{vec}\left(\mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\mathbf{C}_m^{1/2}\right) \\ \sqrt{2}\mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\bar{\mathbf{g}}_m \end{bmatrix}\right\| \leq p_m, \forall m, \tag{19f}$$

$$q_m\mathbf{I} + \mathbf{C}_m^{1/2}\left(\mathbf{I}\otimes\mathbf{Q}\right)\mathbf{C}_m^{1/2} \succeq \mathbf{0}, \forall m, \tag{19g}$$
$$\mathbf{S}_m \succeq \mathbf{0}, y_m \geq 0, q_m \geq 0, \forall m, \tag{19h}$$
$$\mathbf{W} \succeq \mathbf{0}, \mathbf{Q} \succeq \mathbf{0}, 0 \leq t \leq 1, (7\text{d}). \tag{19i}$$

Eq. (19) is non-convex w.r.t all the optimization variables, However, Eq. (19) can be decoupled into the following three subproblems.

$$\text{P1}: \max_{\mathbf{W},\mathbf{Q},R_s,x_m,y_m,p_m,q_m} \quad R_s \tag{20a}$$
$$\text{s.t.} \quad (19\text{b}) - (19\text{g}), \tag{20b}$$
$$\mathbf{W} \succeq \mathbf{0}, \mathbf{Q} \succeq \mathbf{0}, y_m \geq 0, q_m \geq 0, \forall m, (7\text{d}). \tag{20c}$$

$$\text{P2}: \max_{\mathbf{S}_m,R_s,x_m,y_m} \quad R_s \tag{21a}$$
$$\text{s.t.} \quad (19\text{b}) - (19\text{d}), \tag{21b}$$
$$\mathbf{S}_m \succeq \mathbf{0}, y_m \geq 0, \forall m. \tag{21c}$$

$$\text{P3}: \max_{t,R_s,x_m,y_m} \quad R_s \tag{22a}$$
$$\text{s.t.} \quad (19\text{b}) - (19\text{e}), \tag{22b}$$
$$0 \leq t \leq 1, y_m \geq 0, \forall m, (7\text{d}). \tag{22c}$$

P1, P2, and P3 are all convex problem w.r.t to the respectively optimizing variables when the other variables are fixed. Specifically, P1 is convex w.r.t $\{\mathbf{W},\mathbf{Q}\}$ when $\{t,\{\mathbf{S}_m\}_{m=1}^M\}$ is fixed. P2 is convex w.r.t $\{\{\mathbf{S}_m\}_{m=1}^M\}$ when $\{\mathbf{W},\mathbf{Q},t\}$ is fixed. P3 is convex w.r.t t when $\{\mathbf{W},\mathbf{Q},\{\mathbf{S}_m\}_{m=1}^M\}$ is fixed [25]. All these subproblems can be solved by the convex optimization tool CVX [26].

Motivated by this observation, AO can be utilized to handle Eq. (19), and the entire algorithm is given in Algorithm 1, where κ denotes the stopping criterion.

Algorithm 1 : AO Algorithm for problem in Eq. (19).

1: Initialization: $n = 1$, set P_s, $\mathbf{H}$, $\bar{\mathbf{g}}_m$, $\mathbf{C}_m$, ρ, η_m and r_m.
2: **repeat**
[a)]
(i) Fix $\mathbf{S}_m = \mathbf{S}_m^{(n-1)}$ and $t = t^{(n-1)}$, get $\{\mathbf{W}^{(n)},\mathbf{Q}^{(n)}\}$ via solving P1.
(ii) Fix $\mathbf{W} = \mathbf{W}^{(n)}$, $\mathbf{Q} = \mathbf{Q}^{(n)}$, $t = t^{(n-1)}$, get $\mathbf{S}_m^{(n)}$ via solving P2.
(iii) Fix $\mathbf{W} = \mathbf{W}^{(n)}$, $\mathbf{Q} = \mathbf{Q}^{(n)}$ and $\mathbf{S}_m = \mathbf{S}_m^{(n)}$, get $t^{(n)}$ via solving P3.
(iv) $n = n + 1$.
3: **until** $R_s^n - R_s^{n-1} < \kappa$.
4: **Output** $(\mathbf{W}^\star,\mathbf{Q}^\star,t^\star,R_s^\star)$.

4. SIMULATION RESULTS

In this section, we will provide some numerical results to testify the performance of our proposed scheme. Unless specified, the simulation setting is assumed as follows: $N_t = 5$, $N_i = 3$, $N_e = 3$, $M = 2$, $P_s = 10\,\text{dBW}$, $\rho = 0.01$, $\eta_m = -30\,\text{dBW}, \forall m$ and $r_m = 0.01\,, \forall m$. Each entry of $\mathbf{H}$ and $\mathbf{G}_m$ is randomly generated by $\mathcal{CN}(0, 10^{-2})$, and the channel uncertainty is $\mathbf{C}_m = 10^{-5}, \forall m$. In addition, we compare our design with the following methods: 1) the proposed design in the case of perfect ER's CSI, which can be seen as the upper bound of the outage design; 2) the fixed TS ratio scheme, e.g., setting a fixed TS ratio $\tau = 0.5$ while only optimizing $\{\mathbf{W},\mathbf{Q}\}$; 3) the previously proposed power splitting method in [13] and [15]. The four methods are called as "the proposed design", "perfect CSI case", "the fixed TS scheme" and "the PS scheme", respectively.

Firstly, we investigate the convergency performance of our proposed AO method by comparing the outage secrecy rate R_s with iterative numbers. Fig. 2 shows six examples of the convergence behavior with random channel realizations. From Fig. 2, it is observed that the AO algorithm can always converge to the optimal solution in limited iterative numbers.

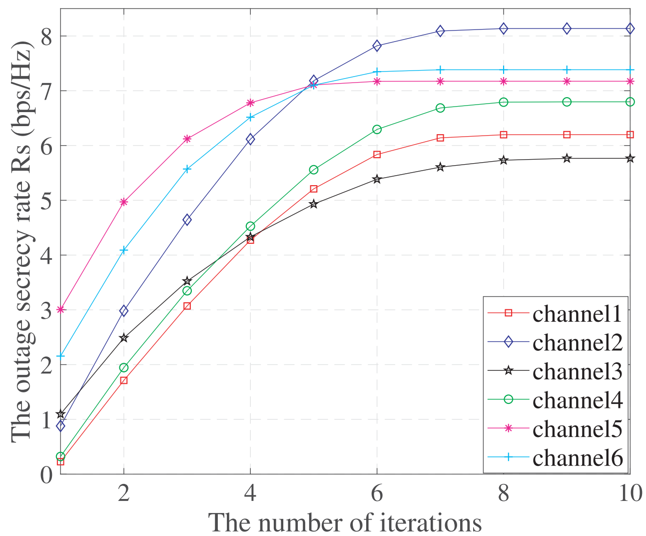

Figure 2. The outage secrecy rate versus the iterative numbers.

Figure 3 plots the outage secrecy rate R_s versus the transmit power P_s. As seen in this figure, the proposed scheme outperforms the fixed TS and PS scheme over the whole power range, especially the fixed TS scheme, since the fixed TS scheme cannot adapt to the rapidly changing channel condition. On the other hand, the PS scheme in [13] and [15] only considers the information signal design, while we consider both the information and energy signal design in our TS scheme, thus lead to better performance. Besides, the gap between the perfect and imperfect CSI cases cannot be neglected, especially in large P_s region, which shows the negative impact of the imperfect CSI case.

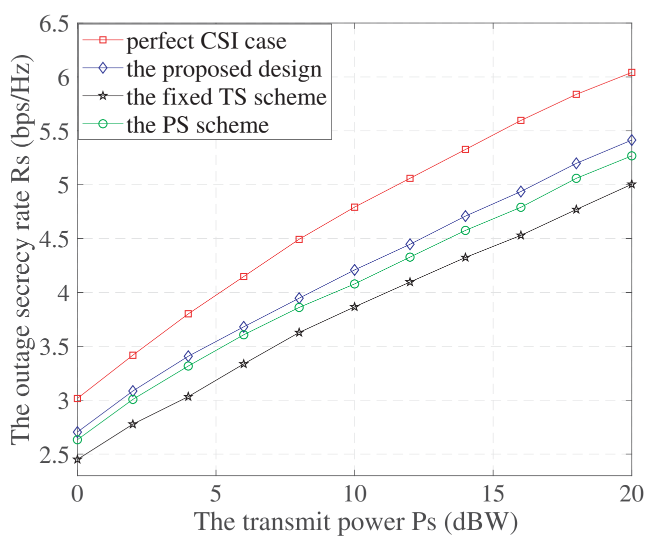

Figure 3. The outage secrecy rate versus the transmit power.

Figure 4 shows the outage secrecy rate R_s versus harvested energy threshold η_m. From Fig. 4, we can see that R_s declines with the increase of η_m, while our design outperforms the other schemes. In addition, there is a remarkable phenomenon that R_s tends to be flat in the low η_m region but declines quickly when η_m exceeds a certain value for all these methods. In this case, most transmit power is used to generate the energy signal $\mathbf{Q}$, and only a little power can be used to generate the information signal $\mathbf{W}$, which suggests the significant effect of η_m on the secrecy rate.

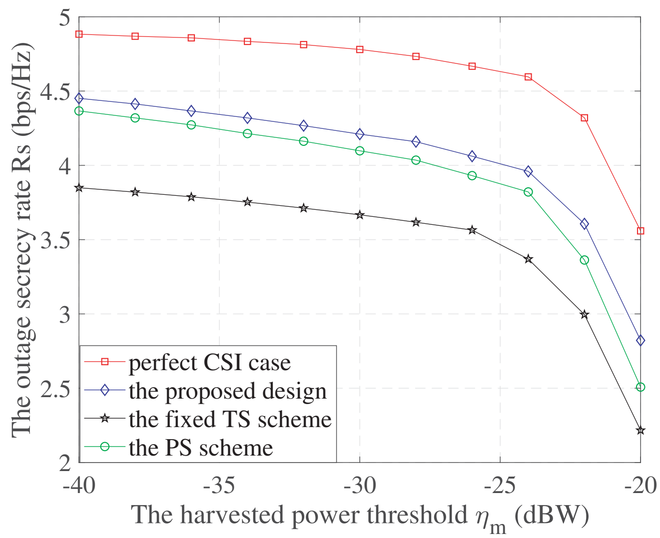

Figure 4. The outage secrecy rate versus the harvested energy threshold.

Figure 5 shows the outage secrecy rate R_s versus the ER's channel uncertainty level $\mathbf{C}_m$. From Fig. 5, we can see that R_s declines with the increase of $\mathbf{C}_m$. Due to larger $\mathbf{C}_m$, the system has to reduce the outage secrecy rate in order to satisfy the outage probability constraint, which further shows the negative impact of the imperfect CSI case.

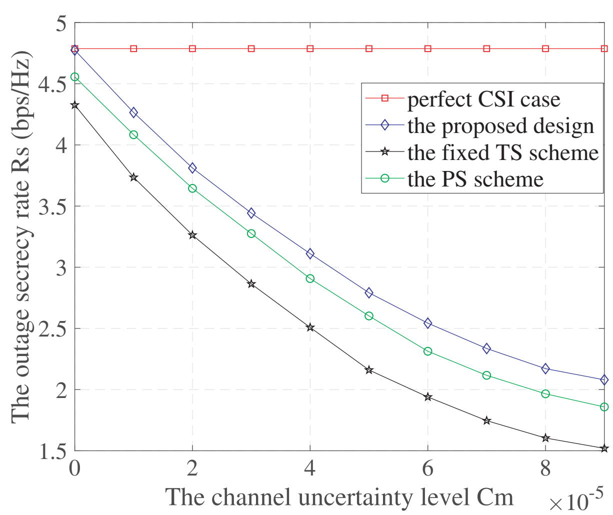

Figure 5. The outage secrecy rate versus the channel uncertainty level.

Figure 6 shows the outage secrecy rate R_s versus the secrecy outage probability ρ. From Fig. 6, we can see that R_s increases with the increase of ρ for all these methods. Due to the increase of ρ, the system can permit more possibility of outage, thus lead to higher outage secrecy rate.

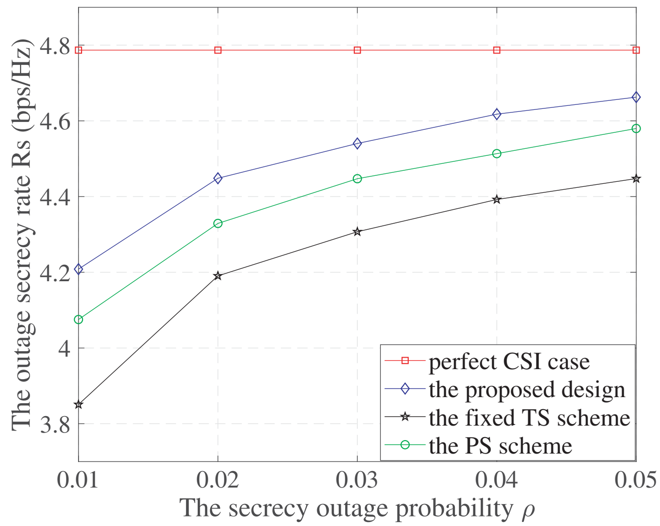

Figure 6. The outage secrecy rate versus the secrecy outage probability.

5. CONCLUSION

In this paper, we have addressed an outage constrained SRM problem for a secrecy MIMO SWIPT channel with transmit TS scheme. Specifically, we aim to maximize the outage secrecy rate by jointly optimizing the information signal covariance, energy signal covariance and TS ratio. We transform the non-convex outage SRM problem into three convex subproblems and propose an AO method. Finally, numerical results have demonstrated the performance of our method.

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