Outage Constrained Robust Secrecy Energy Efficiency Maximization for EH Cognitive Radio Networks

Lei Ni, Xinyu Da, Hang Hu, Miao Zhang, and Kanapathippillai Cumanan

***Abstract*—In this letter, we investigate the outage-constrained robust secure design in a multiple-input single-output (MISO) energy harvesting (EH) cognitive radio network (CRN), where the malicious energy receivers (ERs) may wiretap the desired information and hence can be treated as potential eavesdroppers (Eves). In particular, considering a non-linear energy harvesting (EH) model, our objective is to design the transmit covariance matrix to maximize the secrecy energy efficiency (SEE) under the given outage probability and transmit power constraints, while satisfying the EH and quality-of-service (QoS) requirements. To tackle the original non-convex problem, we resort to semi-definite relaxation (SDR) and Bernstein-type inequality (BTI)-based approximations to reformulate it into a tractable form. Then, the original problem becomes decomposable and can be efficiently solved by handling a two-stage optimization problem. At last, numerical results are provided to demonstrate the effectiveness and superior performance of the proposed design in comparisons with the existing schemes.**

***Index Terms*—Cognitive radio network (CRN), energy harvesting, secrecy energy efficiency (SEE), outage probability.**

I. Introduction

Nowadays, the exponential growth of data traffic and mobile computing have brought the increasing demands for wireless communication, such as scarce spectrum resources and energy supply [1]. As a promising approach to simultaneously improving both spectrum efficiency (SE) and energy efficiency (EE) in fifth generation (5G) and beyond wireless networks, the energy harvesting (EH) cognitive radio network (CRN) has recently attracted great research attention [2]. In contrast to other natural-resource EH techniques (such as solar, wind and thermal), the radio frequency (RF)-based EH technology is more suitable for stable energy provision [3]. Furthermore, RF signals have the capability to transfer information and energy through the same electromagnetic waves, which facilitates the implementation of simultaneous wireless information and power transfer (SWIPT) [4].

Due to the broadcast nature of wireless medium, communications in a EH-CRN is vulnerable to be intercepted by external eavesdroppers (Eves). Hence, it is crucial to design green communication systems that could achieve both secure transmission and efficient EH. To handle this challenge, physical layer security (PLS) has attracted paramount interest in recent years [5]. By exploiting the physical characteristics of wireless channels, e.g., fading, noise and interference, PLS has considerable potential capabilities to achieve "perfect secrecy" without using any encryption keys, and is widely pursued in different communication scenarios, such as relay networks [6], SWIPT networks [7], CRNs [8]-[10], multiple-input single-output (MISO) [11]-[13] and multiple-input multiple-output (MIMO) [14] systems.

It is worth noting that, the existing works on PLS in the literature [5]-[10] are under the assumption of perfect channel state information (CSI) or imperfect CSI with norm-bounded uncertainty model. However, due to the channel estimation and quantization errors, they may rarely occur in practice and can be seen as absolute safe designs. Thus, probability-based robust design becomes a better approach for handling the CSI errors. Furthermore, for secure EH-CRNs, most existing research efforts concentrate only on improving either secrecy rate or EE. To achieve a better trade-off between the secrecy rate and EE, secrecy energy efficiency (SEE) has been proposed as a novel design criterion in secure communication systems. Moreover, the resource allocation designs in wireless powered communication systems mainly rely on the ideal linear EH model. In fact, non-linear EH model can capture a better practical circuit feature [15] and yield a significant improvement on the system performance. To the authors' best knowledge, the outage-constrained SEE optimization for CRNs with practical EH model has not been investigated yet.

Motivated by the aforementioned aspects, in this letter, we study the outage-constrained SEE maximization (OC-SEEM) for MISO EH-CRNs with external energy receivers (ERs). In particular, the non-linear EH model is employed. By assuming that only statistical CSI of the illegitimate ERs is available at the transmitter, the formulated OC-SEEM problem is shown to be non-convex and cannot be solved directly. With the aid of semi-definite relaxation (SDR) and Bernstein-type inequality (BTI), we transform the original non-convex problem into an equivalent two-stage problem, where the associated transmit design is bounded to fulfill the outage constraints.

II. System Model and Problem Statement

A. System Model

We consider the downlink transmission of an underlay MISO-CRN system, which consists of one secondary transmitter (ST), one primary receiver (PR), one secondary receiver (SR), N legitimate ERs and K illegitimate ERs. Since the

This work was supported in part by the National Natural Science Foundation of China (No. 61571460, No. 61901509, No. 61901490), in part by the Natural Science Foundation of Shaanxi Province of China (No. 2018JQ6042), and in part by the H2020-MSCA-RISE-2015 under grant 690750. (*Corresponding author: Xinyu Da.*)

L. Ni and H. Hu are with the Information and Navigation College, Air Force Engineering University, Xi'an 710077, China, and X. Da is with the College of Artificial Intelligence, Yango University, Fuzhou 350015, China (e-mail: {nileikgd, kgddxy2008}@163.com, xd_huhang@126.com).

M. Zhang and K. Cumanan are with the Department of Electronic Engineering, University of York, York YO10 5DD, United Kingdom (e-mail: {mz1022, kanapathippillai.cumanan}@york.ac.uk).

ERs are usually located closer to the ST than the SR, the illegitimate ERs may abandon the opportunity of EH, and attempt to decode the received signal that sent by the ST. For ease of exposition, we name the malicious ER as "Eve" in this letter. It is assumed that the ST is equipped with N_t antennas, whereas all the other users consist of a single antenna. The slow frequency-flat fading channels from the ST to the PR, the SR, the j-th legitimate ER as well as the k-th Eve are denoted by $\mathbf{h}_p \in \mathbb{C}^{N_t \times 1}$, $\mathbf{h}_s \in \mathbb{C}^{N_t \times 1}$, $\mathbf{h}_{r,j} \in \mathbb{C}^{N_t \times 1}$ and $\mathbf{g}_{e,k} \in \mathbb{C}^{N_t \times 1}$, respectively. Then, the corresponding received signals at the SR and k-th Eve are given by

$$y_s = \mathbf{h}_s^H \mathbf{w} s + n_s, \tag{1}$$

$$y_{e,k} = \mathbf{g}_{e,k}^H \mathbf{w} s + n_{e,k}, \forall k \in \mathcal{K}, \tag{2}$$

where $\mathcal{K} \triangleq \{1, 2, 3, ..., K\}$, $\mathbf{w} \in \mathbb{C}^{N_t}$ defines the transmit beamforming vector, and s with $\mathbb{E}\{|s|^2\} = 1$ is the confidential information-bearing signal intended to SR. Furthermore, n_s and $n_{e,k}$ are independent identically distributed complex Gaussian noise with zero mean and unit variance. Accordingly, the achievable secrecy rate of the SR is therefore expressed as

$$R_s(\mathbf{W}) = \min_{k \in \mathcal{K}} f_k(\mathbf{W}), \tag{3}$$

where $f_k(\mathbf{W}) = \log\left(1 + \mathbf{h}_s^H \mathbf{W} \mathbf{h}_s\right) - \log\left(1 + \mathbf{g}_{e,k}^H \mathbf{W} \mathbf{g}_{e,k}\right)$, and $\mathbf{W} = \mathbf{w}\mathbf{w}^H$ with $\mathrm{Rank}\,(\mathbf{W}) = 1$.

Similarly to the power consumption model available in the literature [16], the total power consumption at ST is denoted by $P_t = \frac{1}{\xi}\mathrm{Tr}(\mathbf{W}) + P_c$, in which $\xi \in (0, 1]$ is the power amplifier efficiency, and P_c represents fixed circuit power consumption. Without loss of generality, ξ is assumed to be one in this letter.

Based on the above settings, the SEE in terms of bits per Joule per Hertz, which is defined as the ratio between the achievable secrecy rate and the total power consumption, can be computed by

$$\eta_s(\mathbf{W}) = \frac{R_s(\mathbf{W})}{\mathrm{Tr}(\mathbf{W}) + P_c}. \tag{4}$$

In addition, to characterize the practical energy conversion property, we consider employing the newly proposed non-linear EH model, which is similar to [15]. Therefore, the output direct current (DC) power at the j-th ER, denoted by E_j^{nl}, can be expressed as

$$E_j^{nl} = \frac{\Psi_j - M\Omega}{1 - \Omega},\ \Psi_j = \frac{M}{1 + e^{-a(P_j - b)}},\ \forall j \in \mathcal{J}, \tag{5}$$

where $\mathcal{J} \triangleq \{1, 2, 3, ..., N\}$ and $\Omega = \frac{1}{1+e^{ab}}$. M represents the maximum harvested energy when the circuit becomes saturated. P_j is the received RF power at the j-th ER, while a together with b are the parameters that describe the joint effects of various non-linear phenomenons caused by hardware limit, circuit sensitivity and leakage currents, etc.

B. Outage-Constrained SEE Maximization

Notably, we assume a practical scenario that the ST has perfect knowledge of all the legitimate channels but only imperfect CSI about the potential Eves. Specifically, the complex circular Gaussian CSI error model is applied, i.e.,

$$\mathbf{g}_{e,k} = \tilde{\mathbf{g}}_{e,k} + \Delta\mathbf{g}_{e,k},\ \forall k \in \mathcal{K}, \tag{6}$$

where $\tilde{\mathbf{g}}_{e,k}$ is the estimation of the true CSI, $\Delta\mathbf{g}_{e,k}$ denotes the associated CSI errors, which satisfies $\Delta\mathbf{g}_{e,k} \sim \mathcal{CN}(\mathbf{0}, \mathbf{R}_k)$, and $\mathbf{R}_k \succeq \mathbf{0}$. Moreover, $\Delta\mathbf{g}_{e,k}$ and $\Delta\mathbf{g}_{e,j}$ are independent for any $k \neq j$. Note that this partial channel uncertainty assumption has been widely considered in the current literature about PLS [9]-[10].

In this paper, we aim to maximize the SEE of CRN with energy harvesting, subject to the constraints of the outage secrecy rate, the outage SEE, the total transmit power, the EH and the quality-of-service (QoS) at the PR. Hence, the OC-SEEM problem can be formulated as follows:

$$\max_{\mathbf{W}}\ \eta \tag{7a}$$

$$\mathrm{s.t.}\ \ \mathrm{Pr}_{\mathbf{g}_{e,k}}\{\eta_s(\mathbf{W}) \geq \eta\} \geq 1 - \varphi,\ \forall k \in \mathcal{K}, \tag{7b}$$

$$\mathrm{Pr}_{\mathbf{g}_{e,k}}\{R_s(\mathbf{W}) \geq R\} \geq 1 - \delta,\ \forall k \in \mathcal{K}, \tag{7c}$$

$$E_j^{nl} \geq \gamma,\ \forall j \in \mathcal{J}, \tag{7d}$$

$$\mathbf{h}_p^H \mathbf{W} \mathbf{h}_p \leq \Gamma, \tag{7e}$$

$$\mathrm{Tr}(\mathbf{W}) \leq P, \tag{7f}$$

$$\mathbf{W} \succeq \mathbf{0},\ \mathrm{Rank}(\mathbf{W}) = 1, \tag{7g}$$

where φ is the given parameter defining the required SEE outage probability, e.g., the chance of the achievable SEE falling below the target threshold η due to random CSI uncertainty. R and δ are the predetermined target rate and the maximal secrecy rate outage probability, respectively. Furthermore, γ is the minimum harvested energy constraint for the legitimate ERs. In addition, Γ denotes tolerable interference power caused to the PR, and P represents the maximum transmit power at the ST.

III. Proposed Robust OC-SEEM Problem Design

A. A Tractable Approach to the OC-SEEM Problem

The original OC-SEEM problem defined in (7) is highly non-convex in nature and difficult to solve. Moreover, the non-convex rank-one constraint in (7g) makes the optimization problem even more challenging. To circumvent these issues, our strategy is to pursue convex restriction approaches, also known as safe tractable approximations, to deal with the non-convex constraints. First, by noting the independence between the Eves' channels, the probabilistic constraint in (7b) can be decoupled into the following constraint:

$$\begin{aligned}(7\mathrm{b}) \Leftrightarrow \prod_{k=1}^{K} \mathrm{Pr}_{\mathbf{g}_{e,k}}\{f_k(\mathbf{W}) \geq \eta\left(\mathrm{Tr}(\mathbf{W}) + P_c\right)\} \geq 1 - \varphi \\ \Leftarrow \mathrm{Pr}_{\mathbf{g}_{e,k}}\{f_k(\mathbf{W}) \geq \eta\left(\mathrm{Tr}(\mathbf{W}) + P_c\right)\} \geq 1 - \bar{\varphi},\end{aligned} \tag{8}$$

where $\bar{\varphi} = 1 - (1 - \varphi)^{1/K}$. In fact, (8) can be physically regarded as a per-Eve SEE outage probability. Notice that (8) is still not convenient to process, since the constraint has no closed-form expression. To make the robust problem more tractable, by invoking the identity $\Delta\mathbf{g}_{e,k} = \mathbf{R}_k^{\frac{1}{2}}\mathbf{e}_k$ such that $\mathbf{e}_k \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$, the channel error defined in (6) can be rewritten as

$$\mathbf{g}_{e,k} = \tilde{\mathbf{g}}_{e,k} + \mathbf{R}_k^{\frac{1}{2}}\mathbf{e}_k,\ \forall k \in \mathcal{K}. \tag{9}$$

By substituting (9) into (8) and performing some mathematical manipulations, we have

$$\Pr_{\mathbf{e}_k}\left\{\mathbf{e}_k^H\mathbf{W}_k\mathbf{e}_k+2\Re\left\{\mathbf{e}_k^H\mathbf{r}_k\right\}+s_k\geq 0\right\}\geq 1-\bar{\varphi}, \quad (10)$$

where $\mathbf{W}_k \triangleq -\mathbf{R}_k^{\frac{1}{2}}\mathbf{W}\mathbf{R}_k^{\frac{1}{2}}$, $\mathbf{r}_k \triangleq -\mathbf{R}_k^{\frac{1}{2}}\mathbf{W}\tilde{\mathbf{g}}_{e,k}$, $s_k \triangleq -1-\tilde{\mathbf{g}}_{e,k}^H\mathbf{W}\tilde{\mathbf{g}}_{e,k}+(1+\mathbf{h}_s^H\mathbf{W}\mathbf{h}_s)\lambda$, and $\lambda = 2^{-\eta(\mathrm{Tr}(\mathbf{W})+P_c)}$.

It is obvious that the chance constraint in (10) can be characterized by the quadratic inequality with respect to (w.r.t) $\mathbf{e}_k$. Therefore, the efficient computable upper bounds on the rate outage probabilities are derived by using Bernstein-type inequality (BTI) in the following lemma:

Lemma 1 (BTI) [16]: Suppose the chance constraint

$$\Pr\left\{\mathbf{x}^H\mathbf{A}\mathbf{x}+2\Re\{\mathbf{x}^H\mathbf{u}\}+\theta\geq 0\right\}\geq 1-\alpha, \quad (11)$$

where $(\mathbf{A},\mathbf{u},\theta)\in\mathbb{R}^N\times\mathbb{C}^N\times\mathbb{R}$ is an arbitrary 3-tuple of (deterministic) variables, $\mathbf{x}\sim\mathcal{CN}(\mathbf{0},\mathbf{I})$, and $\alpha\in(0,1]$. With any slack variables ψ and ω, the following relationship will always hold:

$$\begin{cases}\mathrm{Tr}(\mathbf{A})-\sqrt{-2\ln(\alpha)}\psi+\ln(\alpha)\omega+\theta\geq 0,\\ \left\|\begin{bmatrix}\mathrm{vec}(\mathbf{A})\\ \sqrt{2}\mathbf{u}\end{bmatrix}\right\|\leq\psi,\\ \omega\mathbf{I}+\mathbf{A}\succeq\mathbf{0},\ \omega\geq 0.\end{cases} \quad (12)$$

By applying Lemma 1 to (10), we rewrite the probabilistic constraint as a set of inequalities as follows:

$$\mathrm{Tr}\big(\mathbf{W}_k\big)-\sqrt{-2\ln(\bar{\varphi})}\psi_k+\ln(\bar{\varphi})\omega_k+s_k\geq 0,\ \forall k\in\mathcal{K}, \quad (13a)$$

$$\left\|\begin{bmatrix}\mathrm{vec}(\mathbf{W}_k)\\ \sqrt{2}\mathbf{r}_k\end{bmatrix}\right\|\leq\psi_k,\ \forall k\in\mathcal{K}, \quad (13b)$$

$$\omega_k\mathbf{I}-\mathbf{W}_k\succeq\mathbf{0},\ \omega_k\geq 0,\ \forall k\in\mathcal{K}, \quad (13c)$$

where ψ_k and ω_k are slack variables.

Similarly, with BTI, the outage secrecy rate constraint in (7c) can be transformed into the following deterministic form:

$$\mathrm{Tr}\big(\mathbf{W}_k\big)-\sqrt{-2\ln(\bar{\rho})}x_k+\ln(\bar{\rho})y_k+p_k\geq 0,\ \forall k\in\mathcal{K}, \quad (14a)$$

$$\left\|\begin{bmatrix}\mathrm{vec}(\mathbf{W}_k)\\ \sqrt{2}\mathbf{r}_k\end{bmatrix}\right\|\leq x_k,\ \forall k\in\mathcal{K}, \quad (14b)$$

$$y_k\mathbf{I}-\mathbf{W}_k\succeq\mathbf{0},\ y_k\geq 0,\ \forall k\in\mathcal{K}, \quad (14c)$$

where $p_k \triangleq -1-\tilde{\mathbf{g}}_{e,k}^H\mathbf{W}\tilde{\mathbf{g}}_{e,k}+2^{-R}(1+\mathbf{h}_s^H\mathbf{W}\mathbf{h}_s)$, $\bar{\rho}=1-(1-\rho)^{1/K}$, x_k and y_k are slack variables.

At last, we remove the the rank one constraint by employing SDR technique. Then, the problem (7) is equivalent to the following problem:

$$\max_{\substack{\mathbf{W},\nu,\\ \{\psi_k,\omega_k,x_k,y_k\}_{k\in\mathcal{K}}}} \frac{\log\lambda^{-1}}{\mathrm{Tr}\left(\mathbf{W}\right)+P_c} \quad (15a)$$

$$\mathrm{s.t.}\ \mathbf{h}_{r,j}^H\mathbf{W}\mathbf{h}_{r,j}\geq\Upsilon,\ \forall j\in\mathcal{J}, \quad (15b)$$

$$\mathbf{h}_p^H\mathbf{W}\mathbf{h}_p\leq\Gamma, \quad (15c)$$

$$\mathrm{Tr}(\mathbf{W})\leq P, \quad (15d)$$

$$\mathbf{W}\succeq\mathbf{0}, \quad (15e)$$

$$(13a)-(13c),\ (14a)-(14c), \quad (15f)$$

where $\Upsilon \triangleq b-\frac{1}{a}\ln\left(\frac{M}{(1-\Omega)\gamma+M\Omega}-1\right)$. In (15), due to the definition of λ, the optimization objective η can be discarded as a slack variable. In the next subsection, we propose a two-stage optimization method to handle the problem in (15).

B. A Two-stage Optimization for the Problem (15)

The problem defined in (15) still remains non-convex due to the fractional objective function. We note that the resulting problem in (15) becomes primal decomposable, which could be further recast as a two-stage optimization problem. i.e., the outer problem (16), shown as follows

$$\max_{\lambda}\ \varpi(\lambda)\log\lambda^{-1} \quad (16a)$$

$$\mathrm{s.t.}\ \tau_{\min}\leq\lambda\leq\tau_{\max}, \quad (16b)$$

where $\tau_{\min}$ and $\tau_{\max}$ are the value boundary of λ such that (16) is feasible. As can be seen, the outer problem (16) is a single-variable optimization problem, whose optimal solution can be obtained through performing an one dimensional search such as golden section search.

For (16), it is readily known that $\lambda\leq 1$, and less obvious is the lower bound on λ. Moreover, we find that if problem (7) is feasible, $(1+\mathbf{h}_s^H\mathbf{W}\mathbf{h}_s)\lambda\geq 1$ will always be satisfied. Otherwise, $\mathbf{e}_k\mathbf{W}_k\mathbf{e}_k^H+2\Re\{\mathbf{e}_k\mathbf{r}_k\}+s_k\leq 0$ holds for arbitrary $\mathbf{e}_k$, which contradicts (11). As a result, we can derive

$$\left(1+P\left\|\mathbf{h}_s\right\|^2\right)^{-1}\leq\lambda\leq 1, \quad (17)$$

in which the left hand side (LHS) of (17) is due to the relation $\mathbf{h}_s^H\mathbf{W}\mathbf{h}_s\leq\mathrm{Tr}\left(\mathbf{W}\right)\left\|\mathbf{h}_s\right\|^2$ for any $\mathrm{Tr}(\mathbf{W})\leq P$ and $\mathbf{W}\succeq\mathbf{0}$.

In the sequel, we will describe our approach for solving the inner problem (18), which is expressed as

$$\beta(\lambda)=\min_{\substack{\mathbf{W},\{\psi_k,\omega_k\}_{k\in\mathcal{K}},\\ \{x_k,y_k\}_{k\in\mathcal{K}}}}\mathrm{Tr}\left(\mathbf{W}\right)+P_c \quad (18a)$$

$$\mathrm{s.t.}\ (15\mathrm{b})-(15\mathrm{f}), \quad (18b)$$

where $\beta^{-1}(\lambda)=\varpi(\lambda)$. The inner problem defined in problem (18) is a convex optimization problem which includes positive semidefinite (PSD) and second order cone (SOC) constraints, and can be efficiently solved by applying the convex programming tool, such as CVX [17]. Next, we present the computational complexity analysis of the proposed method. Defining T as the number of searches involved in seeking the optimal $\lambda^\star$ in (16), we can conclude that the complexity for an ϵ-optimal solution to (15) is on the order of $T\ln(1/\epsilon)\sqrt{\beta}\zeta$, where $\beta=(2N_t+8)K+N_t+N+2$, $\zeta=n\left(N_t^3(2K+1)+N+4K+2\right)+2nK\left(N_t^2+N_t+1\right)^2+n^2\left(N_t^2(2K+1)+4K+2\right)+n^3$, and $n=\mathcal{O}(N_t^2)$.

Provided that the problem (18) is feasible, the optimal solution $\mathbf{W}^\star$ will be always rank-one, i.e., $\mathrm{Rank}(\mathbf{W}^\star)=1$. In other words, the SDR is tight and the global optimal solution to the primal problem (7) can be guaranteed. The rank-profile can be proved via a similar way in [16] and [18], this part is omitted due to the limited space in this letter.

IV. Numerical results

In this section, we provide numerical results to validate the performance of our proposed design. Unless specified, similar to [19]-[25], the simulation setting is assumed as follows: $N_t=4$, $K=N=2$, $P_c=3\,\mathrm{dBW}$, $R=0.5\,\mathrm{bps/Hz}$, $\varphi=\delta=0.1$, $\gamma=-40\,\mathrm{dBW}$, $\Gamma=0\,\mathrm{dBW}$. Each entry of $\mathbf{h}_p$, $\mathbf{h}_s$, and $\mathbf{h}_{r,j}$ are randomly generated by $\mathcal{CN}\left(0,10^{-2}\right)$, and the associated channel uncertainty of $\mathbf{g}_{e,k}$ is $\mathbf{R}_k = \sigma^2\mathbf{I}$, $\forall k \in \mathcal{K}$. Regarding the non-linear EH model parameters, we adopt $M = 24\,\mathrm{mW}$, $a = 160$ and $b = 0.014$. Moreover, to show the efficacy of the proposed method, we compare our design with the conventional OC-SRM optimal strategies [18].

Fig. 1 shows the achieved outage SEE versus maximum available transmit power at the ST. Specially, the case of perfect CSI can be seen as a benchmark of our robust design. As observed, in the low-power range, the proposed OC-SEEM scheme achieves a similar performance to that of the OC-SRM scheme with the CSI uncertainty $\sigma = 0.1$, since both schemes use all the available transmit power to obtain the maximum SEE, and the SEE performance of null space beamforming (BF) is the worst due to the limited degree of freedom. Then, as P continues to increase, one can notice a remarkable performance gap between these different designs. This can be explained as follows, the performance gain of our proposed scheme remains the same due to the fact that it ceases consuming more transmit power to avoid sacrificing the SEE; furthermore, exceedingly large transmit power can cause saturation in EH circuits. In contrast, the conventional OC-SRM optimal strategies will continue to allocate more transmit power to achieve a higher secrecy rate, which will result in reduction on the SEE.

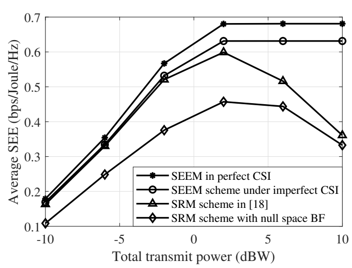

Fig. 1. The average outage SEE versus the transmit power.

Fig. 2 depicts the effect of the Eves' CSI uncertainty level σ on the achieved SEE with $P = 10\,\mathrm{dBW}$. The general trend is that, the average SEE decreases with the increasement of the CSI uncertainties. In addition, our design significantly outperforms the OC-SRM optimal strategies, and the simulation result suggests that in PLS design, acquiring perfect CSI of the Eves is helpful to improve security performance.

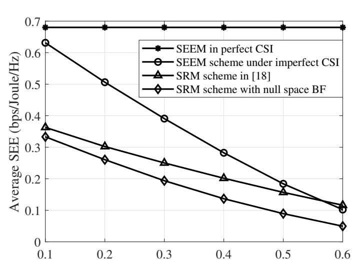

Fig. 2. The average outage SEE versus the CSI uncertainty level.

V. Conclusion

In this letter, we designed the robust secure beamforming strategy for MISO CRNs with practical non-linear EH. In particular, we formulated this original design as an outage probability constrained SEE optimization problem. Assuming that the malicious ERs' CSI is only partially available at the ST, we proposed a novel two-stage algorithm based on SDR and BTI to determine a safe approximated solution. Simulation results were provided to demonstrate that our proposed design achieves better performance than that of the existing OC-SRM optimization schemes in the literature.

References

[1] F. Zhou, N. C. Beaulieu, Z. Li, J. Si, and P. Qi, "Energy-efficient optimal power allocation for fading cognitive radio channels: Ergodic capacity, outage capacity, and minimum-rate capacity," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2741-2755, Apr. 2016.

[2] M. Zhang, K. Cumanan, J. Thiyagalingam, W. Wang, A. G. Burr, Z. Ding, and O. A. Dobre, "Energy efficiency optimization for secure transmission in MISO cognitive radio network with energy harvesting", *IEEE Access*, Accepted for publication, Aug. 2019.

[3] M. Zhang, K. Cumanan, L. Ni, H. Hu, A. Burr, and Z. Ding, "Robust beamforming for AN aided MISO SWIPT system with unknown eavesdroppers and non-linear EH model," *in Proc. IEEE GLOBECOM WORKSHOP*, Abu Dahbi, United Arab Emirates, Dec. 2018, pp. 1-7.

[4] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," *IEEE Commun. Mag.*, vol.52, no.11, pp.104-110, Nov. 2014.

[5] W. Mei, Z. Chen, J. Fang, and S. Li, "Physical layer service integration in 5G: potentials and challenges," *IEEE Access*, vol. 6, pp. 16563-16575, Feb. 2018.

[6] H. Niu, B. Zhang, D. Guo, and Y. Huang, "Joint robust design for secure AF relay networks with SWIPT," *IEEE Access*, vol. 5, pp. 9369-9377, Apr. 2017.

[7] Z. Zhu, Z. Chu, F. Zhou, H. Niu, Z. Wang, and I. Lee, "Secure beamforming designs for secrecy MIMO SWIPT systems," *IEEE Wireless Commun. Lett.*, vol. 7, no. 3, pp. 424-427, Jun. 2018.

[8] F. Zhou, Z. Chu, H. Sun, R. Hu, and L. Hanzo, "Artificial noise aided secure cognitive beamforming for cooperative MISO-NOMA using SWIPT," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 4, pp. 918-931, Apr. 2018.

[9] F. Zhou, Z. Li, J. Cheng, Q. Li, and J. Si, "Robust AN-aided beamforming and power splitting design for secure MISO cognitive radio with SWIPT," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2450-2464, Apr. 2017.

[10] D. W. K. Ng, E. S. Lo, and R. Schober, "Multiobjective resource allocation for secure communication in cognitive radio networks with wireless information and power transfer," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3166-3184, May 2016.

[11] W. Mei, Z. Chen, J. Fang, and B. Ning. "Energy efficiency optimization for MISO wiretap channels with statistical and imperfect CSI," in *Proc. IEEE SPAWC*, Hokkaido, Japan, Jul. 2017, pp. 1-6.

[12] Z. Chu, X. Hong, M. Johnston, and S. L. Goff, "Secrecy rate optimizations for a MISO secrecy channel with multiple multiantenna eavesdroppers," *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 283-297, Jan. 2016.

[13] M. Tian, X. Huang, and Q. Zhang, "Robust AN-aided secure transmission scheme in MISO channels with simultaneous wireless information and power transfer," *IEEE Signal Process. Lett.*, vol. 22, no. 6, pp. 723-727, Jun. 2015.

[14] K. Cumanan, Z. Ding, B. Sharif, G. Y. Tian, and K. K. Leung, "Secrecy rate optimization techniques for a MIMO secrecy channel with a multiple-antenna eavesdropper," *IEEE Trans. Veh. Technol.*, vol. 63, no. 4, pp 1678-1690, May 2014.

[15] E. Boshkovska, D. W. K. Ng, N. Zlatanov, A. Koelpin, and R. Schober, "Robust resource allocation for MIMO wireless powered communication networks based on a non-linear EH model," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 1984-1999, May 2017.

[16] L. Ni, X. Da, H. Hu, Y. Huang, R. Xu, and M. Zhang, "Outage constrained robust transmit design for secure cognitive radio with practical energy harvesting," *IEEE Access*, vol. 6, pp. 71444-71454, Dec. 2018.

[17] M. Grant and S. Boyd, *CVX: Matlab software for disciplined convex programming, version 2.0 beta*, Sep. 2012. Available: http://cvxr.com/cvx.

[18] H. Niu, B. Zhang and D. Guo, "Outage constrained robust beamforming and power splitting for secure MISO SWIPT channel," *IEEE Wireless Commun. Lett.*, vol. 6, no. 6, pp. 826-829, Sep. 2017.

[19] F. Alavi, K. Cumanan, M. Fozooni, Z. Ding, S. Lambotharan, and O. A. Dobre, "Robust energy-efficient design for MISO non-orthogonal multiple access systems," *IEEE Trans. Commun.*, Accepted for publication, Jul. 2019.

[20] H. Alobiedollah, K. Cumanan, J. Thiyaglingam, A. G. Burr, Z. Ding, and O. A. Dobre, "Energy efficient beamforming design for MISO non-orthogonal multiple access systems," *IEEE Trans. Commun.*, vol. 67, no. 6, pp. 4117-4131, Jun. 2019.

[21] F. Alavi, K. Cumanan, Z. Ding, and A. G. Burr, "Robust beamforming techniques for non-orthogonal multiple access systems with bounded channel uncertainties," *IEEE Commun. Lett.*, vol. 21, no. 9, pp. 2033-2036, Sep. 2017.

[22] F. Alavi, N. M. Yamchi, M. R. Javan, and K. Cumanan, "Limited feedback scheme for device to device communications in 5G cellular networks with reliability and secrecy outage constraints," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8072-8085, Sep. 2017.

[23] K. Cumanan, R. Zhang, and S. Lambotharan, "A new design paradigm for MIMO cognitive radio with primary user rate constraint", *IEEE Commun. Lett.*, vol. 16, No. 5, pp. 706-709, May 2012.

[24] K. Cumanan, Z. Ding, Y. Rahulamathavan, M. M. Molu, and H. H. Chen, "Robust MMSE beamforming for multiantenna relay networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 3900-3912, May 2017.

[25] K. Cumanan, G. C. Alexandropolous, Z. Ding, and G. K. Karagiannidis, "Secure communications with cooperative jamming: power allocation and secrecy outage analysis," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7495-7505, Aug. 2017.