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Joint Robust Design for Secure AF Relay Networks With SWIPT

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ABSTRACT In this paper, we investigate the physical layer security for amplify-and-forward relay networks with simultaneous wireless information and power transfer. Specifically, by considering the dual-functional desired receiver, which is capable of decoding information and energy harvesting (EH), and assuming that only imperfect eavesdroppers' channel state information can be attained, we propose a joint robust cooperative beamforming, artificial noise, and power splitting scheme. We formulate the relay power minimization problem under both the secrecy rate constraint and the EH constraint, which is non-convex and hard to tackle. To tackle this problem, we propose a two-level optimization approach, which involves 1-D search and the semi-definite relaxation. In addition, we testify that the SDR can obtain the rank-one optimal solution. Simulation results show that the proposed robust scheme achieves better secrecy performance than other schemes.

INDEX TERMS Simultaneous wireless information and power transfer (SWIPT), AF relay, cooperative beamforming (CB), artificial noise (AN), power splitting (PS).

I. INTRODUCTION

The demand for high data rate in wireless communications networks coupled with the fact that mobile devices are power-limited by batteries, has driven the notion of energy harvesting (EH) to become a promising resolution for low power applications such as sensors networks [1]. Among the varied available resources for EH, radio-frequency (RF) signals can be a sustainable new source for EH, which motivates the paradigm of simultaneous wireless information and power transfer (SWIPT), e.g., [2], [3]. Specifically, the authors in [2] investigated the SWIPT for multiput-input single-out (MISO) channel while the optimal beamforming scheme for SWIPT in multiple-input multiple-output (MIMO) channel was studied in [3], which showed that beamforming could control the transmission directions of information and power effectively.

Security is a critical issue for SWIPT since the wireless information in SWIPT systems is susceptible to be eavesdropped due to the open nature of wireless channel. Recently, physical layer security (PLS) technique in [4], which exploits the characteristics of wireless channels, such as fading, noise and interference to fulfill secure communication, has been proved to be an effective way to improve the security in SWIPT systems [5]–[7]. Specifically, in [5], the authors studied the problem of secrecy SWIPT in a SISO fading wiretap channel. While in [6], the authors investigated the secrecy rate maximization (SRM) problem in a multiuser MISO SWIPT system. Later, the system model in [6] was extended to MIMO wiretap channel in [7]. Among these literatures, artificial noise (AN) is an effective way to improve secure performance, which can enhance the received signals at both IR and ER while degrade the received signals at eavesdroppers simultaneously.

However, all these literatures assume that perfect knowledge of eavesdropper's channel state information (CSI) can be obtained. For a more practical case, e.g., the eavesdropper's CSI can not be perfectly obtained or even unavailable at the transmitters. The robust design has been widely applied to handle the CSI's uncertainties in [8]–[12], among which the worst-case secrecy rate maximization (WCSRM) is commonly employed to formulate the robust optimization problem. Specifically, the authors in [8] and [9] investigated the WCSRM problems for a MISO SWIPT system without/with AN, respectively.

It should be noted that all the above literatures focus on the scenario of individual information receiver (IR) and energy receiver (ER), while recently several literatures investigated the case of dual-functional receiver, e.g., the receiver is capable to decode confidential information and harvest energy simultaneously. Specifically, in [10], the author investigated the scheme to jointly design the beamforming vector, energy signal (ES) and AN to minimize the transmit power under the Quality of Service (QoS) constraint. In [11], the authors investigated the robust power minimization in MISO downlink channel with single-antenna EH eavesdroppers. While in [12], the authors investigated the WCSRM problem for MISO downlink with multiple colluding ERs. While in [13], the authors proposed a joint robust design of the transmit beamforming vector, AN covariance and the power splitting (PS) ratio at the desired receiver (DR) to maximize the secure rate. In [14], the authors investigated the WCSRM problem in MIMO SWIPT channels and proposed a successive convex approximation (SCA)-based optimization method to design the transmit precoding matrix, AN covariance and the PS ratio.

Relaying is recognized as a popular approach to extend network coverage and provide spatial degrees of freedom (DoF), which is beneficial to PLS as well as wireless energy transfer (see [15] and [16], respectively). Recently, secure SWIPT problem in relay systems has aroused great concerns in [17]–[23]. Specifically, the SRM problem in AF relay SWIPT networks subject to the relay power budget and the EH constraints was investigated in [17], where the authors proposed a constrained concave convex procedure (CCCP)-based iterative algorithm. While in [18], the authors proposed a new scheme to improve wireless security using EH-enabled self-sustaining AF relay. A joint design of the signal beamforming and AN at the source and the beamforming at the relay to maximizing the secrecy rate while subject to the EH constraint was investigated in [19]. While in [20], the authors proposed a novel destination aided AN scheme and analyzed the secrecy capacity of a half-duplex EH-based multi-antenna AF relay network in the presence of a passive eavesdropper.

For the scenario of imperfect CSI, in [21], the authors investigated the use of wireless EH-enabled friendly jammer in AF-relaying networks to improve the security. While in [22], the authors considered unavailable eavesdroppers CSI and proposed a null space based cooperative beamforming (CB) and AN scheme in two-way AF relay networks with SWIPT, which is a simple but suboptimal strategy. Recently in [23], a joint CB and ES scheme for providing both secure communication and efficient wireless energy transfer in AF relay networks was proposed. However all of these works did not consider PS.

Motivated by these works, in this paper, we investigate the PLS for SWIPT in AF relay networks. Specifically, we focus on the following settings: 1) multiple relays employ CB and AN scheme to fulfill secure communication and wireless energy transmission; 2) the source has perfect CSI of the relays, while relays have perfect CSI of the DR but imperfect CSI of the Eves; 3) the DR apply PS to extract information and harvest energy simultaneously. Based on these settings, we formulate the problem of joint robust CB, AN and PS design to minimize the power consumption at the relays, subject to the secure rate constraint and EH requirements. To the best of our knowledge, such a joint robust design for secure SWIPT in AF relay networks has not been investigated in related literatures. To solve the formulated non-convex problem, we proposed a two-level optimization approach where the outer problem is tackled by a one-dimensional search and the inner one can be efficiently solved by the semi-definite relaxation (SDR) [25] and S-procedure [26]. In addition, with the help of the Karush-Kuhn-Tucker (KKT) optimality, the tightness of the SDR is established.

Notably, there have some similar works [10], [11], [23], however, the differences of our work are summarized as: Firstly, we consider AN rather than the ES scheme in [10] and [23], in which the authors assumed that a pseudo-random ES is priori known and can be totally cancelled at the DR, thus the ES would not interference the DR but can interference the Eves. But the total cancellation of the ES at the DR need to use the reciprocity of the channels between the transmitter and the DR, which is not always satisfied especially for frequency division duplexing (FDD) system. Secondly, both [10] and [23] investigated the case of individual IR and ER and did not consider PS. The combination of PS ratio makes the problem more hard to tackle since the objective and constraints are highly non-convex. Thirdly, although [10] and [11] consider the power minimization problem, but the constraints in both the two papers are QoS, while our constraints are the secure rate and the EH threshold, which makes our problem more general and hard than the problems in [10] and [11].

The rest of this paper is organized as follows. The system model and problem statement are given in Section II. Section III investigates the power minimization problem, wherein the SDR-based optimization approach is established and the tightness of the SDR is analysed. Simulation results are provided in Section IV. Section V concludes this paper.

Notations: Throughout this paper, boldface lowercase and uppercase letters denote vectors and matrices, respectively. The conjugate, transpose, conjugate transpose, trace and rank of matrix $\mathbf{A}$ are denoted as $\mathbf{A}^{\dagger}$, $\mathbf{A}^{T}$, $\mathbf{A}^{H}$, $Tr\left(\mathbf{A}\right)$ and $rank\left(\mathbf{A}\right)$ respectively. $\mathbf{a}= vec\left(\mathbf{A}\right)$ denotes to stack the columns of matrix $\mathbf{A}$ into a vector $\mathbf{a}$. $\mathbb{H}_{+}^{N}$ denotes the set of all $N \times N$ Hermitian positive semi-definite matrices. $\mathbf{A} \succeq \mathbf{0}$ indicates that $\mathbf{A}$ is a positive semi-definite matrix. $|\cdot|$ and $\|\mathbf{a}\|$ denotes the absolute value and Euclidean norm of vector $\mathbf{a}$, respectively. $\otimes$ denotes Kronecker product. $\mathbf{D}\left(\mathbf{a}\right)$ represents a diagonal matrix with $\mathbf{a}$ on the main diagonal. $\mathbf{I}$ is an identity matrix with proper dimension. $\lambda_{\max}\left(\mathbf{A}, \mathbf{B}\right)$ denotes the largest generalized eigenvalue of the matrices $\mathbf{A}$ and $\mathbf{B}$. $Re\left\{a\right\}$ denotes the real part of a complex variable a. $\mathcal{CN}\left(\mathbf{0}, \mathbf{I}\right)$ denotes a circularly symmetric complex Gaussian random vector with mean $\mathbf{0}$ and covariance $\mathbf{I}$. $[x]^{+}$ indicates $\max\left(0, x\right)$ and $\mathbb{E}\left[.\right]$ stands for the statistical expectation.

II. SYSTEM MODEL AND PROBLEM STATEMENT

A. SYSTEM MODEL

We consider a cooperative relay wiretap channel for SWIPT as shown in Fig. 1, in which a transmitter, sending

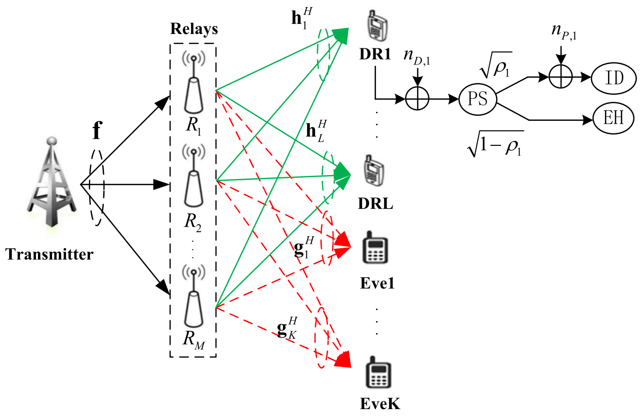

FIGURE 1. **The secure AF relay SWIPT system model.**

confidential messages to the L DRs, in the presence of K eavesdroppers (Eves), with the aid of M AF relays. We assume that each node is equipped with single antenna and the channels between the relays and the Eves can not be perfectly known, which is a common assumption in related literatures [17] and [21]–[23]. Let $\mathbf{f} \in \mathbb{C}^{M\times 1}$, $\mathbf{h}_l \in \mathbb{C}^{M\times 1}$ and $\mathbf{g}_k \in \mathbb{C}^{M\times 1}$ denote the channel vectors from the transmitter to the relays, from the relays to the l-th DR and the k-th Eve, respectively. In addition, similar to the consideration in [17]–[19], [21], and [23], we assumed that the Eves are close to the DRs, and there is no direct link from the transmitter to the DRs as well as the Eves, thus the information leakage happens in the second phase. Since the relays operate in a half-duplex mode, one transmission round is composed of two phases.

In the first phase, the transmitter broadcasts its information s satisfying $\mathbb{E}\left[ss^H\right] = 1$ to the relays. Hence, the received signal at the relays is given by

$$\mathbf{y}_r = \sqrt{P_s}\mathbf{f}s + \mathbf{n}_r, \tag{1}$$

where P_s is the transmit power at the transmitter and $\mathbf{n}_r \sim \mathcal{CN}\left(\mathbf{0}, \sigma_r^2\mathbf{I}\right)$ is the additive noise at the relays.

In the second phase, the relays employ the CB vector $\mathbf{w} \in \mathbb{C}^{M\times 1}$ to forward the information. In the meantime, the relays emit artificial noise $\mathbf{z} \in \mathbb{C}^{M\times 1}$ obeying $\mathbf{z} \sim \mathcal{CN}(\mathbf{0}, \mathbf{Q})$ to confuse the Eves as well as improve energy harvesting at the DRs. Thus the signal transmitted by the relays can be expressed as

$$\mathbf{x}_r = \mathbf{D}(\mathbf{y}_r)\,\mathbf{w} + \mathbf{z}. \tag{2}$$

Then, the received signals at the l-th DR and the k-th Eve are given, respectively, by

$$y_{D,l} = \sqrt{P_s}\mathbf{h}_l^H\mathbf{D}(\mathbf{f})\,\mathbf{w}s + \mathbf{n}_r^T\mathbf{D}^H(\mathbf{h}_l)\,\mathbf{w} + \mathbf{h}_l^H\mathbf{z} + n_{D,l}, \tag{3a}$$

$$y_{E,k} = \sqrt{P_s}\mathbf{g}_k^H\mathbf{D}(\mathbf{f})\,\mathbf{w}s + \mathbf{n}_r^T\mathbf{D}^H(\mathbf{g}_k)\,\mathbf{w} + \mathbf{g}_k^H\mathbf{z} + n_{E,k}, \tag{3b}$$

where $n_{D,l}$ and $n_{E,k}$ are additive noises at the l-th DR and the k-th Eve with variance $\sigma_{D,l}^2$ and $\sigma_{E,k}^2$, respectively.

We assume that each DR is equipped with a power splitter as shown in Fig. 1, thus the received signals are divided into two streams. One is used to ID and the other is for EH. Then, the signal received for ID at the l-th DR can be expressed as

$$y_{D,l}^I = \sqrt{\rho_l}\left(\sqrt{P_s}\mathbf{h}_l^H\mathbf{D}(\mathbf{f})\,\mathbf{w}s + \mathbf{n}_r^T\mathbf{D}^H(\mathbf{h}_l)\,\mathbf{w} + \mathbf{h}_l^H\mathbf{z} + n_{D,l}\right) + n_{P,l}, \tag{4}$$

where $\rho_{D,l}$ denotes the PS ratio at the l-th DR, $n_{P,l}$ is the additional processing noise at the l-th DR with variance $\sigma_{P,l}^2$.

Now, from (4) and (3b), the signal-interference to noise ratios (SINRs) at the l-th DR and the k-th Eve are derived, respectively, as

$$\Gamma_{D,l} \triangleq \frac{\rho_l\mathbf{w}^H\mathbf{A}_l\mathbf{w}}{\rho_l\left(\mathbf{w}^H\mathbf{B}_l\mathbf{w} + \mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l + \sigma_{D,l}^2\right) + \sigma_{P,l}^2}, \tag{5a}$$

$$\Gamma_{E,k} \triangleq \frac{\mathbf{w}^H\mathbf{C}_k\mathbf{w}}{\mathbf{w}^H\mathbf{D}_k\mathbf{w} + \mathbf{g}_k^H\mathbf{Q}\mathbf{g}_k + \sigma_{E,k}^2}, \tag{5b}$$

where $\mathbf{A}_l = P_s\mathbf{D}^H(\mathbf{f})\,\mathbf{h}_l\mathbf{h}_l^H\mathbf{D}(\mathbf{f})$, $\mathbf{B}_l = \sigma_r^2\mathbf{D}(\mathbf{h}_l)\,\mathbf{D}^H(\mathbf{h}_l)$, $\mathbf{C}_k = P_s\mathbf{D}^H(\mathbf{f})\,\mathbf{g}_k\mathbf{g}_k^H\mathbf{D}(\mathbf{f})$, and $\mathbf{D}_k = \sigma_r^2\mathbf{D}(\mathbf{g}_k)\,\mathbf{D}^H(\mathbf{g}_k)$. Hence, the information rates at the l-th DR and the k-th Eve are given, respectively, by

$$C_{D,l}(\mathbf{w}, \mathbf{Q}, \rho_l) = \frac{1}{2}\log_2\left(1 + \Gamma_{D,l}\right), \tag{6a}$$

$$C_{E,k}(\mathbf{w}, \mathbf{Q}) = \frac{1}{2}\log_2\left(1 + \Gamma_{E,k}\right), \tag{6b}$$

where the scaling factor $1/2$ is due to the half-duplex operation of relays. Hence, the achievable secrecy rate is

$$R_s = \left[\min_{\forall l\in\mathcal{L}, \forall k\in\mathcal{K}}\left\{C_{D,l}(\mathbf{w}, \mathbf{Q}, \rho_l) - C_{E,k}(\mathbf{w}, \mathbf{Q})\right\}\right]^+, \tag{7}$$

where $\mathcal{L} \triangleq \{1, \ldots, L\}$ and $\mathcal{K} \triangleq \{1, \ldots, K\}$ stands for the set of DRs and Eves.

On the other hand, the harvested energy at the l-th DR is given as

$$E_l = \eta_l(1 - \rho_l)\left(\mathbf{w}^H(\mathbf{A}_l + \mathbf{B}_l)\,\mathbf{w} + \mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l + \sigma_{D,l}^2\right), \tag{8}$$

where η_l is the energy transfer efficiency for the l-th DR. In the following, without loss of generality (w.l.o.g), we assume that $\eta_l = 1, \forall l \in \mathcal{L}$.

For the imperfect Eves' CSI, we use the deterministic spherical model [21]–[23] to characterize the CSI uncertainties. Specifically, the uncertainties of channel responses $\mathbf{g}_k$ are expressed as

$$\mathcal{G}_k = \left\{\mathbf{g}_k | \mathbf{g}_k = \bar{\mathbf{g}}_k + \Delta\mathbf{g}_k, \|\Delta\mathbf{g}_k\| \le \varepsilon_k\right\}, \quad \forall k \in \mathcal{K}, \tag{9}$$

where ε_k denotes the uncertainty level, $\bar{\mathbf{g}}_k$ denotes the estimates of $\mathbf{g}_k$ and $\Delta\mathbf{g}_k$ represents the channel uncertainties, respectively.

B. PROBLEM STATEMENT

Our objective is to minimize the total power consumption at the relays by joint designing the CB vector $\mathbf{w}$, AN covariance $\mathbf{Q}$ and the PS ratio ρ_l subject to the secrecy rate constraint and energy harvesting constraints. Specifically, the power minimization problem is formulated as

$$\min_{\mathbf{w},\mathbf{Q},\rho_l} \ \mathbf{w}^H\mathbf{\Phi}\mathbf{w} + Tr\left(\mathbf{Q}\right) \tag{10a}$$

$$s.t. \ \min_{\forall l\in\mathcal{L},\|\Delta\tilde{\mathbf{g}}_k\|\le\varepsilon_k,\forall k\in\mathcal{K}} \left\{C_{D,l}\left(\mathbf{w},\mathbf{Q},\rho_l\right) - C_{E,k}\left(\mathbf{w},\mathbf{Q}\right)\right\} \ge R, \tag{10b}$$

$$\left(1-\rho_l\right)\left(\mathbf{w}^H\left(\mathbf{A}_l+\mathbf{B}_l\right)\mathbf{w} + \mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l + \sigma_{D,l}^2\right) \ge E_{D,l}, \tag{10c}$$

$$\mathbf{e}_m^T\left(\mathbf{w}^H\Phi\mathbf{w}+\mathbf{Q}\right)\mathbf{e}_m \le P_m, \forall m\in\mathcal{M}, \tag{10d}$$

where $\mathbf{\Phi} = P_s\mathbf{D}^H\left(\mathbf{f}\right)\mathbf{D}\left(\mathbf{f}\right) + \sigma_r^2\mathbf{I}$, R denotes the worst-case secrecy rate and $E_{D,l}$ denotes the EH threshold for the l-th DR. $\mathbf{e}_m$ is the $M\times 1$ unit vector with the m-th entry being equal to one, P_m is the transmit power constraint at the m-th relay and $\mathcal{M} \triangleq \{1,\ldots,M\}$ stands for the set of relays.

Notably, we find that the problem in (10) is a non-convex, which is hard to solve. In the next section, we will develop a tractable solution to (10) through convex relaxation.

III. JOINT ROBUST CB, AN AND PS DESIGN

In this section, we will first reformulate (10) into a two-level optimization problem, then show (10) can be handled by solving a sequence of convex optimization problems.

A. A SINGLE VARIABLE REFORMATION OF (10)

Firstly we introduce an auxiliary variable β to decouple the secrecy rate constraint (10b), then (10) can be reformulated as

$$\min_{\mathbf{w},\mathbf{Q},\rho_l,\beta_{\min}\le\beta\le\beta_{\max}} \ \varphi\left(\beta\right), \tag{11}$$

where $\varphi\left(\beta\right)$ is the optimal value for the following problem

$$\min_{\mathbf{w},\mathbf{Q},\rho_l} \ \mathbf{w}^H\Phi\mathbf{w} + Tr\left(\mathbf{Q}\right) \tag{12a}$$

$$s.t. \ \frac{\rho_l\mathbf{w}^H\mathbf{A}_l\mathbf{w}}{\rho_l\left(\mathbf{w}^H\mathbf{B}_l\mathbf{w}+\mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l+\sigma_{D,l}^2\right)+\sigma_{P,l}^2} \ge \beta 2^{2R}-1, \quad \forall l\in\mathcal{L}, \tag{12b}$$

$$\frac{\mathbf{w}^H\mathbf{C}_k\mathbf{w}}{\mathbf{w}^H\mathbf{D}_k\mathbf{w}+\mathbf{g}_k^H\mathbf{Q}\mathbf{g}_k+\sigma_{E,k}^2} \le \beta - 1, \quad \left\|\Delta\tilde{\mathbf{g}}_k\right\| \le \varepsilon_k, \forall k\in\mathcal{K}, \tag{12c}$$

$$\left(1-\rho_l\right)\left(\mathbf{w}^H\left(\mathbf{A}_l+\mathbf{B}_l\right)\mathbf{w} + \mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l + \sigma_{D,l}^2\right) \ge E_{D,l}, \quad \forall l\in\mathcal{L}, \tag{12d}$$

$$\mathbf{e}_m^T\left(\mathbf{w}^H\Phi\mathbf{w}+\mathbf{Q}\right)\mathbf{e}_m \le P_m, \quad \forall m\in\mathcal{M}, \tag{12e}$$

$$\mathbf{Q}\succeq\mathbf{0}, 0\le\rho_l\le 1, \quad \forall l\in\mathcal{L}. \tag{12f}$$

For the feasible region of β, it is easy to know that the lower bound $\beta_{\min} = 1$ from (12c). On the other hand, since

$$\frac{\mathbf{w}^H\mathbf{A}_l\mathbf{w}}{\mathbf{w}^H\mathbf{B}_l\mathbf{w}+\mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l+\sigma_{D,l}^2+\sigma_{P,l}^2/\rho_l} \ge \frac{\mathbf{w}^H\mathbf{A}_l\mathbf{w}}{\mathbf{w}^H\mathbf{B}_l\mathbf{w}} \ge \lambda_{\max}\left(\mathbf{A}_l,\mathbf{B}_l\right), \tag{13}$$

the upper bound $\beta_{\max}$ can be calculated as $\beta_{\max} = \min_{l\in\mathcal{L}}\left(\left(1+\lambda_{\max}\left(\mathbf{A}_l,\mathbf{B}_l\right)\right)/2^{2R}\right)$.

The key merit of the reformulation is that the outer-level problem (11) is a single-variable optimization problem, which can be solved by performing a one-dimensional line search over β. However the inner-level problem (12) is still non-convex. In what follows, we focus on solving (12) by developing an SDR approach.

B. AN SDR METHOD TO (12)

By denoting $t_l = 1/\rho_l$, $\mathbf{W} = \mathbf{w}\mathbf{w}^H$ and dropping the non-convex constraint $rank\left(\mathbf{W}\right) = 1$, we can convert (12) into the SDR formulation as follows:

$$\min_{\mathbf{W},\mathbf{Q},t_l} \ Tr\left(\Phi\mathbf{W}+\mathbf{Q}\right) \tag{14a}$$

$$s.t. \ \left(\beta 2^{2R}-1\right)\left(Tr\left(\mathbf{B}_l\mathbf{W}\right)+\mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l + \sigma_{D,l}^2 + t_l\sigma_{P,l}^2\right) \le Tr\left(\mathbf{A}_l\mathbf{W}\right), \quad \forall l\in\mathcal{L}, \tag{14b}$$

$$\left(1-\beta\right)\left(Tr\left(\mathbf{D}_k\mathbf{W}\right)+\mathbf{g}_k^H\mathbf{Q}\mathbf{g}_k+\sigma_{E,k}^2\right) + Tr\left(\mathbf{C}_k\mathbf{W}\right) \le 0, \ \left\|\Delta\tilde{\mathbf{g}}_k\right\| \le \varepsilon_k, \forall k\in\mathcal{K}, \tag{14c}$$

$$Tr\left(\left(\mathbf{A}_l+\mathbf{B}_l\right)\mathbf{W}\right) + \mathbf{h}_l^H\mathbf{Q}\mathbf{h}_l + \sigma_{D,l}^2 \ge E_{D,l}\left(1+1/\left(t_l-1\right)\right), \quad \forall l\in\mathcal{L}, \tag{14d}$$

$$\mathbf{e}_m^T\left(\Phi\mathbf{W}+\mathbf{Q}\right)\mathbf{e}_m \le P_m, \quad \forall m\in\mathcal{M}, \tag{14e}$$

$$\mathbf{W}\succeq\mathbf{0}, \mathbf{Q}\succeq\mathbf{0}, t_l\ge 1, \quad \forall l\in\mathcal{L}. \tag{14f}$$

Please noted, (14) is still non-convex due to the infinite constraint (14c), which can be transformed to linear matrix inequalities (LMI) using the S-Procedure [26].

In order to make the transformation tractable, we first define $\mathbf{G}_k \triangleq \mathbf{D}\left(\mathbf{g}_k\right)$, $\Delta\mathbf{G}_k \triangleq \mathbf{D}\left(\Delta\mathbf{g}_k\right)$, $\bar{\mathbf{G}}_k \triangleq \mathbf{D}\left(\bar{\mathbf{g}}_k\right)$, $\tilde{\mathbf{g}}_k \triangleq vec\left(\mathbf{G}_k\right)$, $\Delta\tilde{\mathbf{g}}_k \triangleq vec\left(\Delta\mathbf{G}_k\right)$ and $\hat{\mathbf{g}}_k \triangleq vec\left(\bar{\mathbf{G}}_k\right)$. In addition, it is easily known that $\left\|\Delta\mathbf{g}_k\right\| \le \varepsilon_k \Rightarrow \left\|\Delta\tilde{\mathbf{g}}_k\right\| \le \varepsilon_k, \forall k\in\mathcal{K}$.

Furthermore, by using the following identities

$$\left.\begin{array}{c} \left(\mathbf{AB}\right)^T = \mathbf{B}^T\mathbf{A}^T, \\ Tr\left(\mathbf{AB}\right) = Tr\left(\mathbf{BA}\right), \\ \mathbf{a}^H\mathbf{D}\left(\mathbf{b}\right) = \mathbf{b}^T\mathbf{D}^{\dagger}\left(\mathbf{a}\right), \\ Tr\left(\mathbf{ABCE}\right) = vec^T\left(\mathbf{E}^T\right)\left(\mathbf{C}^T\otimes\mathbf{A}\right)vec\left(\mathbf{B}\right), \end{array}\right\} \tag{15}$$

we have

$$\begin{aligned} Tr\left(\mathbf{C}_k\mathbf{W}\right) &= Tr\left(P_s\mathbf{W}\mathbf{D}^H\left(\mathbf{f}\right)\mathbf{g}_k\mathbf{g}_k^H\mathbf{D}\left(\mathbf{f}\right)\right) \\ &= Tr\left(P_s\mathbf{W}\mathbf{G}_k^T\mathbf{f}^{\dagger}\mathbf{f}^T\mathbf{G}_k^{\dagger}\right) = Tr\left(\mathbf{W}\mathbf{G}_k\left(P_s\mathbf{f}\mathbf{f}^H\right)^T\mathbf{G}_k^H\right) \\ &= \tilde{\mathbf{g}}_k^H\left(P_s\mathbf{f}\mathbf{f}^H\otimes\mathbf{W}\right)\tilde{\mathbf{g}}_k. \end{aligned} \tag{16}$$

Similarly, we have

$$Tr(\mathbf{D}_k\mathbf{W}) = Tr\left(\sigma_r^2\mathbf{G}_k\mathbf{G}_k^H\mathbf{W}\right) = \tilde{\mathbf{g}}_k^H\left(\left(\sigma_r^2\mathbf{I}\right)\otimes\mathbf{W}\right)\tilde{\mathbf{g}}_k,$$
$$\mathbf{g}_k^H\mathbf{Q}\mathbf{g}_k = \tilde{\mathbf{g}}_k^H(\mathbf{I}\otimes\mathbf{Q})\tilde{\mathbf{g}}_k. \quad (17)$$

By pulling the above equations together, (14) can be transformed as follows

$$\min_{\mathbf{W},\mathbf{Q},t_l} \; Tr(\Phi\mathbf{W}+\mathbf{Q}) \quad (18a)$$
$$s.t.\; \tilde{\mathbf{g}}_k^H\left(P_s\mathbf{f}\mathbf{f}^H\otimes\mathbf{W}\right)\tilde{\mathbf{g}}_k + (1-\beta)\tilde{\mathbf{g}}_k^H\left(\left(\sigma_r^2\mathbf{I}\right)\otimes\mathbf{W}\right)\tilde{\mathbf{g}}_k$$
$$+(1-\beta)\tilde{\mathbf{g}}_k^H(\mathbf{I}\otimes\mathbf{Q})\tilde{\mathbf{g}}_k + (1-\beta)\sigma_{E,k}^2 \le 0,$$
$$\left\|\Delta\tilde{\mathbf{g}}_k\right\| \le \varepsilon_k, \forall k\in\mathcal{K}, \quad (18b)$$
$$(14b), (14d), (14e), (14f). \quad (18c)$$

To handle the infinite constraints (18b), we first present the S-Procedure [26] in the following lemma.

Lemma 1 (S-lemma [26]): Define the function

$$f_j(\mathbf{x}) = \mathbf{x}^H\mathbf{A}_j\mathbf{x} + 2Re\left\{\mathbf{b}_j^H\mathbf{x}\right\} + c_j, \quad j=1,2$$

where $\mathbf{A}_j = \mathbf{A}_j^H \in \mathbb{C}^{n\times n}$, $\mathbf{b}_j \in \mathbb{C}^{n\times 1}$, and $c_j \in \mathbb{R}$. The implication $f_1(\mathbf{x}) \le 0 \Rightarrow f_2(\mathbf{x}) \le 0$ holds if and only if there exists $\lambda \ge 0$ such that

$$\lambda\begin{bmatrix}\mathbf{A}_1 & \mathbf{b}_1\\ \mathbf{b}_1^H & c_1\end{bmatrix} - \begin{bmatrix}\mathbf{A}_2 & \mathbf{b}_2\\ \mathbf{b}_2^H & c_2\end{bmatrix} \succeq \mathbf{0}$$

provided that there exists a point $\mathbf{x}_0$ such that $f_1(\mathbf{x}_0) < 0$.

Proof: The proof can be found in [26]. ■

Now, to apply S-Procedure on the constraint (18b), we rewrite it as follows

$$\begin{cases}\tilde{\mathbf{g}}_k^H\mathbf{\Psi}\tilde{\mathbf{g}}_k + (1-\beta)\sigma_{E,k}^2 \le 0;\\ \left\|\Delta\tilde{\mathbf{g}}_k\right\| \le \varepsilon_k,\end{cases} \quad (19)$$

where $\mathbf{\Psi} = P_s\mathbf{f}\mathbf{f}^H\otimes\mathbf{W} + (1-\beta)\sigma_r^2\mathbf{I}\otimes\mathbf{W} + (1-\beta)\mathbf{I}\otimes\mathbf{Q}$.

Applying S-Procedure with respect to (w.r.t) $\Delta\tilde{\mathbf{g}}_k$, we convert (19) into an LMI as followsčž

$$\mathbf{\Omega}_k(\mathbf{W},\mathbf{Q},\lambda_k) \triangleq \begin{bmatrix}\lambda_k\mathbf{I}_M - \mathbf{\Psi} & -\mathbf{\Psi}\hat{\mathbf{g}}_k\\ -\hat{\mathbf{g}}_k^H\mathbf{\Psi} & \eta_k\end{bmatrix} \succeq \mathbf{0}, \quad (20)$$

for given $\lambda_k \ge 0$, where $\eta_k = -\lambda_k\varepsilon_k^2 - \hat{\mathbf{g}}_k^H\mathbf{\Psi}\hat{\mathbf{g}}_k + (\beta-1)\sigma_{E,k}^2$.

By combining these equations together, we obtain the following problem

$$\min_{\mathbf{W},\mathbf{Q},t_l} \; Tr(\Phi\mathbf{W}+\mathbf{Q}) \quad (21a)$$
$$s.t.\; \mathbf{\Omega}_k(\mathbf{W},\mathbf{Q},\lambda_k) \succeq \mathbf{0}, \forall k\in\mathcal{K}, \quad (21b)$$
$$(14b), (14d), (14e), (14f). \quad (21c)$$

Now, (21) is a convex problem w.r.t $(\mathbf{W},\mathbf{Q},t_l)$, which can be efficiently solved by the convex programming toolbox CVX [28].

Since the rank-one constraint on $\mathbf{W}$ has been dropped in the reformulation, the solution to (21) may not be feasible for the original problem (12). In fact for (21), we have the following proposition 1.

Proposition 1: The optimal $\mathbf{W}^\star$ to (21) must satisfy $rank(\mathbf{W}^\star) = 1$.

The proof is detailed in the Appendix and Proposition 1 shows the SDR is tight for (12).

For the complexity of the proposed algorithm, by following a similar way as [23], we concluded that with given κ which denotes the accuracy requirement, the complexity for an κ-optimal solution to (21) is on the order of $\ln(1/\kappa)\sqrt{\psi}\varsigma$, where $\psi = LK\left(M^2+1\right)+2(L+2)$, $\varsigma = 2nM^3+2n^2M^2+nLK\left(M^2+1\right)^3+n^2LK\left(M^2+1\right)^2+n(M+3L)+n^3$, and $n=\mathcal{O}\left(2M^2+L\right)$.

IV. SIMULATION RESULTS

In this section, simulation results are presented to evaluate the performance of the proposed joint CB, AN and PS scheme. In addition, to highlight the superiority of the proposed scheme, we also compare our design with the existing methods: 1) the design without the aid of AN, e.g., $\mathbf{Q}=\mathbf{0}$ by only optimizes $\mathbf{w}$ and ρ_l in (10); 2) the zero force beamforming in [6], e.g., choosing the beamforming vector $\mathbf{w}$ to lie in the null space of the estimated Eves' channel $\bar{\mathbf{G}} = [\bar{\mathbf{g}}_1,\ldots,\bar{\mathbf{g}}_K]^H \in \mathbb{C}^{M\times K}$. Specifically, we set $\mathbf{w} = \mathbf{U}\mathbf{x}$, where $\mathbf{x} \in \mathbb{C}^{(M-K)\times 1}$ is an arbitrary matrix to be designed, and $\mathbf{U} \in \mathbb{C}^{M\times(M-K)}$ is a semi-unitary matrix consisting of the orthogonal basis of the null space of $\bar{\mathbf{G}}$ which satisfies $\bar{\mathbf{g}}_k^H\mathbf{U} = \mathbf{0}$. Then, we minimize the relay power consumption by joint optimizing $\mathbf{x}$, $\mathbf{Q}$ and ρ_l subject to the same constraint as (10); 3) the fixed PS ratio, e.g., a fixed PS ratio $\rho_l = 0.5$ by only optimizes $\mathbf{w}$ and $\mathbf{Q}$ in (10).

Unless specified, the simulation setting are assumed as follows: $K=3$, $M=5$, $L=3$, $P_s = 10dBW$, $P_m = 10dBW$, $R=5$, $E_{D,l} = -30dBm$ and $\sigma_r^2 = \sigma_{d,l}^2 = \sigma_{p,l}^2 = \sigma_{e,k}^2 = 10^{-8}$. All the entries of channel responses $\mathbf{f}$, $\mathbf{h}_l$, $\bar{\mathbf{g}}_k$ are randomly generated following an independent and identically distributed (i.i.d) complex Gaussian distribution with zero mean and unit variance 10^{-2}. Regarding the CSI uncertainty model in (9), we use a similar way as [21]. Specifically, we introduce the uncertainty ratios υ_k associated with ε_k and υ_k is defined as $\upsilon_k^2 = \frac{\varepsilon_k^2}{E\left[\|\bar{\mathbf{g}}_k\|^2\right]}$. In addition the CSI uncertainties regions are assumed to be norm-bound, i.e., $\mathbf{\Lambda}_k = \mathbf{I}/\varepsilon_k^2$, and we set $\upsilon_k^2 = 0.1, \forall k$. Our design and the other three designs are labeled as proposed design, no AN scheme, zero force scheme in [6] and fixed PS ratio scheme, respectively.

A. THE RELAY POWER VERSUS THE SECRECY RATE R

Fig. 2 illustrates the relay transmit power of four different schemes versus the secrecy rate R. It is observed from Fig. 2 that the relay power increases with the growth of R for all the schemes. Our proposed design outperforms the other schemes while the no AN scheme is the worst design. This phenomenon suggest that AN is beneficial for secure

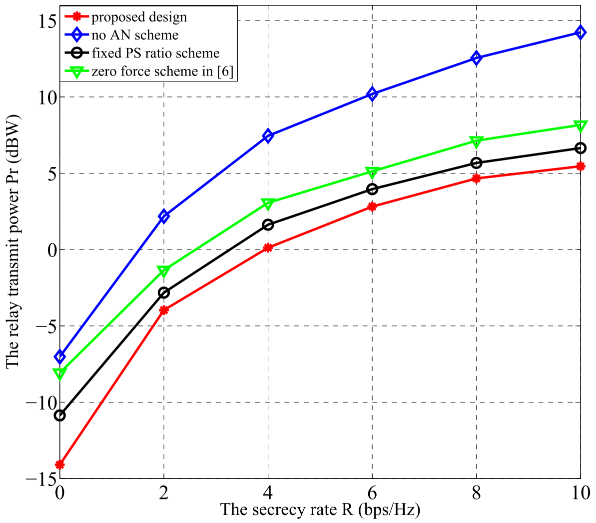

FIGURE 2. **The relay power versus the secrecy rate.**

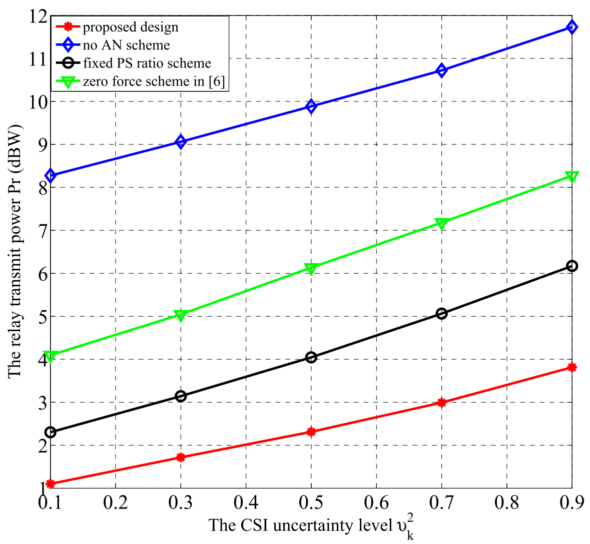

FIGURE 3. **The relay power versus the Eves' CSI uncertainty level.**

SWIPT system. In addition, we can see from the figure that when the secrecy rate is small, the relay power increases fast, whereas when the secrecy rate is large, the power relay increases slower. This will be further explained by the following examples.

B. THE RELAY POWER VERSUS THE EVES' CSI UNCERTAINTY LEVEL υ_k^2

Fig. 3 shows the relay transmit power of four different schemes versus the Eves' CSI uncertainty level υ_k^2. It is observed from the figure that the relay power increases with the increase of υ_k^2 for all the schemes, while our proposed scheme achieves the best performance. In addition, the relay transmit power shows an approximately linear relationship with the Eves' CSI uncertainty level υ_k^2, which is different with the phenomenons in Fig. 2.

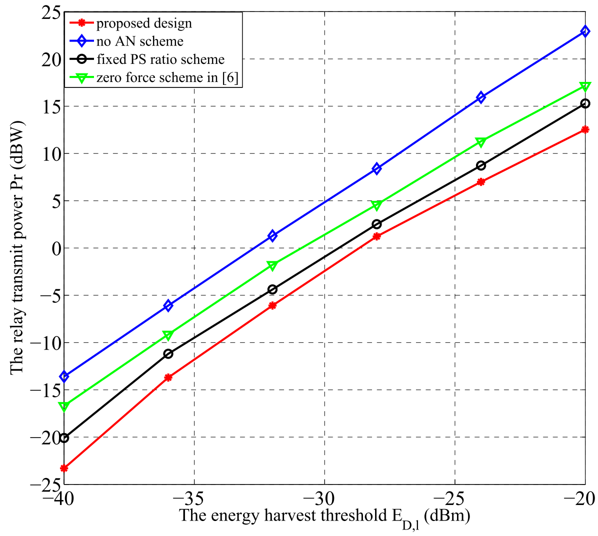

FIGURE 4. **The relay power versus the EH threshold.**

C. THE RELAY POWER VERSUS THE EH THRESHOLD $E_{D,l}$

Fig. 4 investigates the relay transmit power of four different schemes versus the EH threshold $E_{D,l}$. It can been seen that the relay power budget increase with the increase of $E_{D,l}$ for all the schemes while our proposed scheme achieves better performance than the other schemes. In addition, the relay transmit power shows an approximately linear relationship with the EH threshold, which is different with the phenomenons in Fig. 2 but similar with the result in Fig. 3. The result suggests that the when the secrecy rate is small, the Eves' CSI uncertainty level υ_k^2 and the EH threshold $E_{D,l}$ are more prominent to the relay power consumption. However when the secrecy rate is high, the secrecy rate becomes the major factor for the relay power consumption.

D. THE RELAY POWER VERSUS THE NUMBER OF RELAYS M

Fig. 5 plots the relay power consumption of four different schemes versus the number of relays M. From this figure, we can see that the power budget decreases with the increase of M for all the methods due to the increased spatial DoF, while our scheme outperforms other schemes. It should be noted that the zero force scheme can only work when M is larger than the number of Eves. In this particular example, when $M \leq 3$, the zero force scheme is invalid since there is no enough DoF left for the DR after nulling the Eve's channel.

E. THE RELAY POWER VERSUS THE NUMBER OF EVES K

Fig. 6 depicts the relay transmit power of four different schemes versus the number of Eves K. It is seen from the figure that the relay power consumption increase with the increase of K for all the methods due to the decreased spatial DoF while our scheme has a significant performance gain over the other schemes. The zero force scheme is invalid when $K \geq 5$ in this particular example, which further suggests that

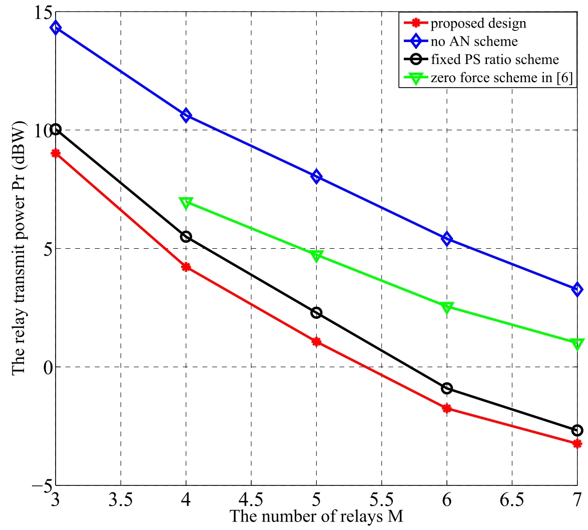

FIGURE 5. The relay power versus the number of relays.

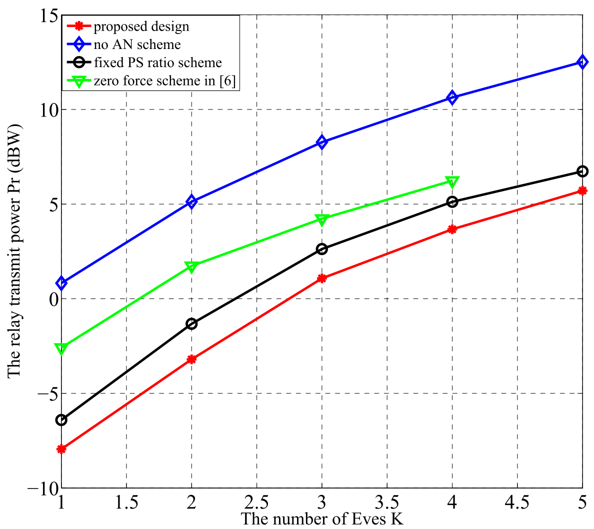

FIGURE 6. The relay power versus the number of Eves.

the spatial DoF has great influence on the performance of the zero force scheme.

V. CONCLUSION

In this paper, we investigated a joint robust scheme for secure SWIPT in AF relay networks with considering dual-functional DR. Specifically, we formulate the robust power minimization problem subject to both secrecy rate and EH constraint. To obtain the optimal CB vector, AN covariance and PS ratio, a two-level optimization which combining one-dimensional search and SDR has been proposed to find the optimal solution. Furthermore, we provided a tightness analysis for this SDR method, which shows the optimal solution must be rank-one. Simulation results demonstrated the effectiveness of our proposed design.

APPENDIX

We consider the Lagrangian dual function of problem (21), which can be expressed in (22), shown at the bottom of this page, where $\Xi_k \in \mathbb{H}_+^{M\times M+1}$, $u_l \geq 0$, $\eta_l \geq 0$, $\lambda_m \geq 0$, $\mathbf{Z} \in \mathbb{H}_+^M$, $\mathbf{Y} \in \mathbb{H}_+^M$ and $\phi_l \geq 0$ are the dual variables associated with (21b), (14b), (14d), (14e), $\mathbf{W}$, $\mathbf{Q}$ and t, respectively.

According to the Karush-Kuhn-Tucker (KKT) condition [27], we have

$$\begin{aligned}\mathbf{Z} &= \Phi + \sum_{l=1}^{L} u_l \left(\left(\beta 2^{2R} - 1\right)\mathbf{B}_l - \mathbf{A}_l\right) \\ &\quad + (1-\beta)\sum_{k=1}^{K} \sigma_r^2 \mathbf{I} \otimes \mathbf{\Pi}_k + \sum_{k=1}^{K} P_s \mathbf{F}^H \mathbf{\Pi}_k \mathbf{F} \\ &\quad - \sum_{l=1}^{L} \eta_l \left(\mathbf{A}_l + \mathbf{B}_l\right) + \sum_{m=1}^{M} \lambda_m \mathbf{e}_m \mathbf{e}_m^T \Phi, \end{aligned} \tag{23a}$$

$$\begin{aligned}\mathbf{Y} &= \mathbf{I} + \sum_{l=1}^{L} u_l \left(\beta 2^{2R} - 1\right) \mathbf{h}_l^H \mathbf{h}_l + (1-\beta)\sum_{k=1}^{K} \mathbf{I} \otimes \mathbf{\Pi}_k \\ &\quad - \sum_{l=1}^{L} \eta_l \mathbf{h}_l^H \mathbf{h}_l + \sum_{m=1}^{M} \lambda_m \mathbf{e}_m \mathbf{e}_m^T, \end{aligned} \tag{23b}$$

with $\mathbf{\Pi}_k = \left[\mathbf{I}\ \tilde{\mathbf{g}}_k\right] \Xi_k \left[\mathbf{I}\ \tilde{\mathbf{g}}_k\right]^H$.

From the above relationship, we obtain that

$$\begin{aligned}\mathbf{Z} &= \sigma_r^2 \mathbf{I} \odot \mathbf{Y} + P_s \mathbf{F}^H \mathbf{F} - \sum_{l=1}^{L} u_l \mathbf{A}_l + \sum_{k=1}^{K} P_s \mathbf{F}^H \mathbf{\Pi}_k \mathbf{F} \\ &\quad - \sum_{l=1}^{L} \eta_l \mathbf{A}_l + P_s \mathbf{F}^H \mathbf{F} \sum_{m=1}^{M} \lambda_m \mathbf{e}_m \mathbf{e}_m^T, \end{aligned} \tag{24}$$

$$\begin{aligned}\mathcal{L}(\chi) &= Tr\left(\mathbf{\Phi W} + \mathbf{Q}\right) + \sum_{l=1}^{L} u_l \left(\left(\beta 2^{2R} - 1\right)\left(Tr\left(\mathbf{B}_l \mathbf{W}\right) + \mathbf{h}_l^H \mathbf{Q} \mathbf{h}_l + \sigma_{D,l}^2 + t_l \sigma_{P,l}^2\right) - Tr\left(\mathbf{A}_l \mathbf{W}\right)\right) \\ &\quad - \sum_{k=1}^{K} Tr\left(\Xi_k \Omega_k\right) + \sum_{l=1}^{L} \eta_l \left(E_l \left(1 + 1/(t_l - 1)\right) - Tr\left(\left(\mathbf{A}_l + \mathbf{B}_l\right)\mathbf{W}\right) - \mathbf{h}_l^H \mathbf{Q} \mathbf{h}_l - \sigma_{D,l}^2\right) \\ &\quad + \sum_{m=1}^{M} \lambda_m \left(\mathbf{e}_m^T \left(\mathbf{\Phi W} + \mathbf{Q}\right)\mathbf{e}_m - P_m\right) - Tr\left(\mathbf{ZW}\right) - Tr\left(\mathbf{YQ}\right) + \sum_{l=1}^{L} \phi_l \left(1 - t_l\right) \end{aligned} \tag{22}$$

then we have the following relationship

$$\left(\sigma_r^2\mathbf{I}\odot\mathbf{Y}+P_s\mathbf{F}^H\mathbf{F}+\sum_{k=1}^{K}P_s\mathbf{F}^H\mathbf{\Pi}_k\mathbf{F}+P_s\mathbf{F}^H\mathbf{F}\sum_{m=1}^{M}\lambda_m\mathbf{e}_m\mathbf{e}_m^T\right)\mathbf{W}=\left(\sum_{l=1}^{L}u_l\mathbf{A}_l+\sum_{l=1}^{L}\eta_l\mathbf{A}_l\right)\mathbf{W}. \tag{25}$$

Since $\sigma_r^2\mathbf{I}\odot\mathbf{Y}+P_s\mathbf{F}^H\mathbf{F}+\sum_{k=1}^{K}P_s\mathbf{F}^H\mathbf{\Pi}_k\mathbf{F}+P_s\mathbf{F}^H\mathbf{F}\sum_{m=1}^{M}\lambda_m\mathbf{e}_m\mathbf{e}_m^T\succ\mathbf{0}$, we attain the following rank equation

$$\begin{aligned}&rank\left(\mathbf{W}\right)\\&=rank\left(\left(\sigma_r^2\mathbf{I}\odot\mathbf{Y}+P_s\mathbf{F}^H\mathbf{F}+\sum_{k=1}^{K}P_s\mathbf{F}^H\mathbf{\Pi}_k\mathbf{F}\right.\right.\\&\qquad\left.\left.P_s\mathbf{F}^H\mathbf{F}\sum_{m=1}^{M}\lambda_m\mathbf{e}_m\mathbf{e}_m^T\right)\mathbf{W}\right)\\&=rank\left(\left(\sum_{l=1}^{L}\left(u_l+\eta_l\right)\mathbf{A}_l\right)\mathbf{W}\right)\\&\leq\min\left(rank\left(\sum_{l=1}^{L}\left(u_l+\eta_l\right)\mathbf{A}_l\right),rank\left(\mathbf{W}\right)\right)\leq 1,\end{aligned} \tag{26}$$

thus completes the proof.

REFERENCES

[1] 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.

[2] J. Xu, L. Liu, and R. Zhang, "Multiuser MISO beamforming for simultaneous wireless information and power transfer," *IEEE Trans. Signal Process.*, vol. 62, no. 18, pp. 4798–4810, Sep. 2014.

[3] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[4] X. Chen, D. W. K. Ng, and H.-H. Chen, "Secrecy wireless information and power transfer: Challenges and opportunities," *IEEE Commun. Mag.*, vol. 23, no. 2, pp. 51–61, Apr. 2016.

[5] H. Xing, L. Liu, and R. Zhang, "Secrecy wireless information and power transfer in fading wiretap channel," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 180–190, Jan. 2016.

[6] L. Liu, R. Zhang, and K.-C. Chua, "Secrecy wireless information and power transfer with MISO beamforming," *IEEE Trans. Signal Process.*, vol. 62, no. 7, pp. 1850–1863, Apr. 2014.

[7] Q. Shi, W. Xu, J. Wu, E. Song, and Y. Wang, "Secure beamforming for MIMO broadcasting with wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 14, no. 5, pp. 2841–2853, May 2015.

[8] R. Feng, Q. Li, Q. Zhang, and J. Qin, "Robust secure transmission in MISO simultaneous wireless information and power transfer system," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 400–405, Jan. 2015.

[9] M. Tian, X. Huang, Q. Zhang, and J. Qin, "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.

[10] D. W. K. Ng, E. S. Lo, and R. Schober, "Robust beamforming for secure communication in systems with wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4599–4615, Aug. 2014.

[11] M. R. A. Khandaker and K.-K. Wong, "Robust secrecy beamforming with energy-harvesting eavesdroppers," *IEEE Wireless Commun. Lett.*, vol. 4, no. 1, pp. 10–13, Feb. 2015.

[12] M. R. A. Khandaker and K.-K. Wong, "Masked beamforming in the presence of energy-harvesting eavesdroppers," *IEEE Trans. Inf. Forensics Security*, vol. 10, no. 1, pp. 40–54, Jan. 2015.

[13] Z. Chu, Z. Zhu, and J. Hussein, "Robust optimization for AN-aided transmission and power splitting for secure MISO SWIPT system," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1571–1574, Aug. 2016, doi: 10.1109/LCOMM.2016.2572684.

[14] S.-H. Wang and B.-Y. Wang, "Robust secure transmit design in MIMO channels with simultaneous wireless information and power transfer," *IEEE Signal Process. Lett.*, vol. 22, no. 11, pp. 2147–2151, Nov. 2015.

[15] L. J. Rodriguez, N. H. Tran, T. Q. Duong, T. Le-Ngoc, M. Elkashlan, and S. Shetty, "Physical layer security in wireless cooperative relay networks: State of the art and beyond," *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 32–39, Dec. 2015.

[16] X. Chen, Z. Zhang, H.-H. Chen, and H. Zhang, "Enhancing wireless information and power transfer by exploiting multi-antenna techniques," *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 133–141, Apr. 2015.

[17] Q. Li, Q. Zhang, and J. Qin, "Secure relay beamforming for simultaneous wireless information and power transfer in nonregenerative relay networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2462–2467, Jun. 2014.

[18] H. Xing, K.-K. Wong, and A. Nallanathan, "Secure wireless energy harvesting-enabled AF-relaying SWIPT networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 2307–2312.

[19] G. Zhang, X. Li, M. Cui, G. Li, and L. Yang, "Signal and artificial noise beamforming for secure simultaneous wireless information and power transfer multiple-input multiple-output relaying systems," *IET Commun.*, vol. 10, no. 7, pp. 796–804, Apr. 2016.

[20] A. Salem, K. A. Hamdi, and K. M. Rabie, "Physical layer security with RF energy harvesting in AF multi-antenna relaying networks," *IEEE Trans. Commun.*, vol. 64, no. 7, pp. 3025–3038, Jul. 2016, doi: 10.1109/TCOMM.2016.2573829.

[21] H. Xing, K.-K. Wong, Z. Chu, and A. Nallanathan, "To harvest and jam: A paradigm of self-sustaining friendly jammers for secure AF relaying," *IEEE Trans. Signal Process.*, vol. 63, no. 24, pp. 6616–6631, Dec. 2015.

[22] Q. Li, Q. Zhang, and J. Qin, "Secure relay beamforming for SWIPT in amplify-and-forward two-way relay networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9006–9019, Nov. 2016, doi: 10.1109/TVT.2016.2519339.

[23] Y. Feng, Y. Zhen, W.-P. Zhu, Q. Li, and B. Lv, "Robust cooperative secure beamforming for simultaneous wireless information and power transfer in amplify-and-forward relay networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2354–2366, Mar. 2017, doi: 10.1109/TVT.2016.2578313.

[24] X. Zhang, *Matrix Analysis and Applications*. Beijing, China: Tsinghua Univ. Press, Sep. 2004.

[25] Z.-Q. Luo, W.-K. Ma, A. M.-C. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Process. Mag.*, vol. 27, no. 3, pp. 20–34, May 2010.

[26] Z.-Q. Luo, J. F. Sturm, and S. Zhang, "Multivariate nonnegative quadratic mappings," *SIAM J. Optim.*, vol. 14, no. 4, pp. 1140–1162, 2004.

[27] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[28] M. Grant and S. Boyd. *CVX: MATLAB Software for Disciplined Convex Programming*. [Online]. Available: http://cvxr.com/cvx

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