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A Unified Performance Optimization for Secrecy Wireless Information and Power Transfer Over Interference Channels

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ABSTRACT In this paper, we give a unified performance optimization for secrecy wireless information and power transfer over interference channels, where an external eavesdropper is also interested in the confidential message. We propose to perform cooperative energy beamforming between two sources to confuse the eavesdropper while satisfying the requirements on the minimum amounts of individual harvested energy, and the minimum signal-to-interference-plus-noise ratio at the wiretap-free node, even under an adverse condition that there exist channel uncertainties at the transmitters. Considering the maximization of secrecy rate subject to a power constraint and the minimization of power consumption with a minimum secrecy rate requirement are two commonly used design objectives for secure communications, we give a unified performance optimization from the both perspectives. Especially, since there exists channel uncertainty, we propose to optimize the worst performance, so as to satisfy the performance requirements under all channel conditions. To achieve a balance between system performance and implementation complexity, we present a robust cooperative beamforming and power splitting scheme for each secrecy problem while confining the information signal in the null space of the interference channel. Finally, simulation results validate the effectiveness of the proposed schemes.

INDEX TERMS Cooperative energy beamforming, power splitting, secrecy wireless information and power transfer, interference channel.

I. INTRODUCTION

Wireless information and power transfer has been widely recognized as a promising technology for realizing *completely* wireless communications in processes of both battery charging and information transmission [1]–[3]. More importantly, it is likely to jointly optimize energy harvesting and information transmission by adjusting the parameters of radio frequency (RF) signal, i.e., transmit power and beam direction, so as to increase the utilization efficiency of limited radio resources [4]–[6].

Due to the broadcast nature of wireless medium, wireless communication is susceptible to eavesdropping [7], [8]. Especially in wireless information and power transfer, in order to balance power transfer and information transmission, wireless information security is a more critical issue [9], [10]. In general, wireless nodes powered by wireless power transfer have limited energy, and thus it is difficult to adopt traditional complicated encryption technology to guarantee secure communication. To solve this problem, physical layer security (PHY-security) technology is naturally applied to achieve secrecy wireless information and power transfer (SWIPT) [11]–[13]. By simply exploiting the characteristics of wireless channel, i.e., fading, noise and interference, PHY-security might degrade the performance of the eavesdropper, and hence makes it fail to decode the interception signal [14]–[16]. In particular, there is an extra advantage of PHY-layer security for SWIPT. Specifically, the energy signal that originally facilitates energy harvesting at the power receiver can be used to confuse the eavesdropper [17]. In other words, the energy signal also plays a role of the artificial noise (AN), which is a commonly used security enhancement technique in PHY-security [18]–[20].

Since the energy signal simultaneously carries out charging the power receiver and confusing the eavesdropper, it is necessary to achieve a tradeoff between the two functions. A feasible and powerful way is to perform spatial beamforming at a multiple-antenna transmitter [21]–[24]. By adjusting the beam direction, it is possible to achieve the both goals properly.

It is well known that the performance of multiple-antenna spatial beamforming is heavily dependent of available channel state information (CSI) at the transmitter [25]. Especially in SWIPT, the design of spatial beamforming requires multiple copies of CSI about information transmission channel, power transfer channel, and eavesdropper channel, which is a nontrivial task in practical systems [26]–[28]. This is because the eavesdropper is usually passive, and thus it is difficult for the transmitter to obtain full eavesdropper CSI. In the case of partial CSI, it is only possible to guarantee the performance in the worst case. As such, it makes sense to design the beamforming for optimizing the performance in the worst case, namely robust beamforming [29]. In general, the optimization objectives in SWIPT includes the maximization of secrecy rate and the minimization of total power consumption. For instance, Zhang *et al.* [30] formulated the problem of robust beamforming as the minimization of the total power subject to the secrecy rate constraint for legitimate information receivers and the harvested energy constraint for energy harvesting receivers. A similar problem was addressed in [31] by replacing the constraint conditions with outage probabilities of secrecy rate and harvesting energy, such that the required minimum power can be further reduced. On the other hand, robust beamforming was designed from the perspective of maximizing the secrecy rate in [32] and [33]. Moreover, the application of external jamming combing with robust beamforming was proposed in [34] to simultaneously enhance wireless security and increase harvesting energy. It was shown that compared with internal energy signal, external jamming had more degrees of freedom to improve the performance at the cost of a high overhead on CSI exchange.

A common of the above works on robust beamforming for SWIPT is that they all consider a single transmitter. As shown in [35]–[37], if there are multiple transmitters, cooperative beamforming can be adopted to enhance the performance of wireless information and power transfer. It was reported in [38] that multiple-transmitter cooperative beamforming is able to dramatically reduce the power consumption while satisfying a given performance requirement. Inspired by this idea, we aim to utilize cooperative energy beamforming to boost power transfer efficiency and information transmission security in SWIPT over interference channels. The contributions of this paper are two folds:

1) We propose to exploit the benefits of two-transmitter cooperation to enhance the performance of SWIPT over interference channels. To be more specific, the inter-channel interference is utilized to confuse the eavesdropper and improve the amount of harvested energy.

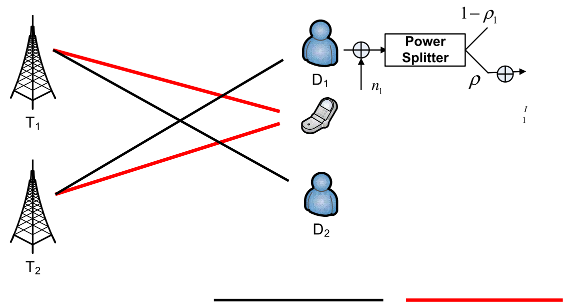

FIGURE 1. SWIPT in two-user interference network with an eavesdropper.

2) We give a unified performance optimization for SWIPT over interference channels from the perspectives of the maximization of secrecy rate and the minimization of total power consumption, and present the corresponding robust optimization schemes.
3) We show that the proposed framework can be extended to optimize the other metrics of SWIPT over interference channels.

The rest of this paper is organized as follows: Section II gives a brief introduction of the considered SWIPT over interference channels. Section III proposes robust cooperative beamforming and power splitting schemes for minimizing the power consumption and maximizing the secrecy rate, respectively. Section IV presents some simulation results to validate the effectiveness of the proposed schemes. Finally, Section V concludes the whole paper.

Notations: We use bold upper (lower) letters to denote matrices (column vectors), $(\cdot)^H$ to denote conjugate transpose, $\|\cdot\|$ to denote the L_2-norm of a vector, $|\cdot|$ to denote the absolute value, $\mathrm{tr}(\cdot)$ to denote the trace of a matrix, $\mathrm{rank}(\cdot)$ to denote the rank of a matrix, and $\mathcal{CN}(\mathbf{A}, \mathbf{B})$ to denote complex Gaussian distribution with mean $\mathbf{A}$ and variance $\mathbf{B}$.

II. SYSTEM MODEL

Let us consider a wiretap two-user MISO interference network as shown in Fig. 1, where two transmitters, denoted by T_1 and T_2, convey information and energy simultaneously to the corresponding receivers represented as D_1 and D_2, while an eavesdropper (Eve) attempts to overhear the confidential message. The two receivers adopt a power splitting (PS) strategy to divide the received signal into two separated parts, one for energy harvesting (EH), and the other for information decoding (ID) [39]. Both T_1 and T_2 deploy N_t antennas, while the other nodes are equipped with a single antenna each due to the size limitation of mobile devices. We use $\mathbf{h}_{ij}$ to represent the N_t-dimensional channel vectors from node i to j, where $i \in \{1, 2\}$ and $j \in \{1, 2, e\}$. We consider quasi-static fading channels, where the channels remain unchanged during one time slot, and independently fade over time slots. At each transmitter, an energy signal is transmitted together with an information signal, with the purpose of simultaneously facilitating the energy harvesting at the energy receivers and suppressing the interception from the Eve. Thus, the actual transmit signal at T_i, $i \in \{1, 2\}$, is given by

$$\mathbf{x}_i = \mathbf{w}_i s_i + \mathbf{v}_i, \tag{1}$$

where s_i, $i \in \{1, 2\}$, is the information signal with $\mathbb{E}[|s_i|^2] = 1$, $\mathbf{w}_i$ is the corresponding transmit beam, and $\mathbf{v}_i$ is the energy signal. Following the previous related work [33], we assume that $\mathbf{v}$ is pseudo-random noise, whose random seed is known at the transmitter and the corresponding receiver. Thus, the receiver is able to generate the same noise. In other words, $\mathbf{v}_i$ is perfectly known at the corresponding receiver D_i, but not at the eavesdropper. In general, $\mathbf{v}_i$ is modeled as a complex Gaussian pseudo-random vector with a distribution

$$\mathbf{v}_i \sim \mathcal{CN}(0, \mathbf{V}_i), \tag{2}$$

where $\mathbf{V}_i$ is a $N_t \times N_t$ covariance matrix. Given the transmit signal $\mathbf{x}_i$, the total transmit power of the two transmitters is given by

$$P = \|\mathbf{w}_1\|^2 + \|\mathbf{w}_2\|^2 + \|\mathbf{v}_1\|^2 + \|\mathbf{v}_2\|^2, \tag{3}$$

and the received signal at D_i can be expressed as

$$\begin{aligned} y_i &= \mathbf{h}_{1i}^H \mathbf{x}_1 + \mathbf{h}_{2i}^H \mathbf{x}_2 + n_i \\ &= \mathbf{h}_{1i}^H \mathbf{w}_1 s_1 + \mathbf{h}_{1i}^H \mathbf{v}_1 + \mathbf{h}_{2i}^H \mathbf{w}_2 s_2 + \mathbf{h}_{2i}^H \mathbf{v}_2 + n_i, \end{aligned} \tag{4}$$

where $n_i \sim \mathcal{CN}(0, \sigma_i^2)$ is the antenna noise at D_i. As mentioned earlier, D_i splits the received signal y_i into two power streams with power splitting ratios ρ_i and $1 - \rho_i$ for EH and ID, respectively. First, the harvested energy at D_1 and D_2 can be written as

$$E_1 = \rho_1 \eta_1 (|\mathbf{h}_{11}^H \mathbf{w}_1|^2 + |\mathbf{h}_{11}^H \mathbf{v}_1|^2 + |\mathbf{h}_{21}^H \mathbf{w}_2|^2 + |\mathbf{h}_{21}^H \mathbf{v}_2|^2), \tag{5}$$

and

$$E_2 = \rho_2 \eta_2 (|\mathbf{h}_{12}^H \mathbf{w}_1|^2 + |\mathbf{h}_{12}^H \mathbf{v}_1|^2 + |\mathbf{h}_{22}^H \mathbf{w}_2|^2 + |\mathbf{h}_{22}^H \mathbf{v}_2|^2), \tag{6}$$

respectively, where $\eta_i \in (0, 1]$ is the energy conversion efficiency from signal power to circuit power [40]. Note that the contribution of thermal noise to the harvested energy is negligible compared to the information and energy signals, and thus is neglected in (5) and (6). Second, the signal for ID at D_i is given by

$$\begin{aligned} y_i^{ID} = \sqrt{1-\rho_i}\big(&\mathbf{h}_{1i}^H \mathbf{w}_1 s_1 + \mathbf{h}_{1i}^H \mathbf{v}_1 + \mathbf{h}_{2i}^H \mathbf{w}_2 s_2 + \mathbf{h}_{2i}^H \mathbf{v}_2 \\ &+ n_i\big) + n_i^{ID}, \end{aligned} \tag{7}$$

where $n_i^{ID} \sim \mathcal{CN}(0, \delta_i^2)$ is the additive white Gaussian noise (AWGN) produced during the conversion from a RF signal to a baseband signal, and δ_i^2 is the noise variance. Since the energy signal from T_i is perfectly known at D_i, it can be completely cancelled at D_i via interference cancellation before attempting to decode the desired information signal. As a result, the signal to interference plus noise ratio (SINR) for ID at the receivers can be expressed as

$$\Gamma_1 = \frac{(1-\rho_1)|\mathbf{h}_{11}^H \mathbf{w}_1|^2}{(1-\rho_1)(|\mathbf{h}_{21}^H \mathbf{w}_2|^2 + |\mathbf{h}_{21}^H \mathbf{v}_2|^2 + \sigma_1^2) + \delta_1^2}, \tag{8}$$

and

$$\Gamma_2 = \frac{(1-\rho_2)|\mathbf{h}_{22}^H \mathbf{w}_2|^2}{(1-\rho_2)(|\mathbf{h}_{12}^H \mathbf{w}_1|^2 + |\mathbf{h}_{12}^H \mathbf{v}_1|^2 + \sigma_2^2) + \delta_2^2}, \tag{9}$$

respectively. Hence, the legitimate channel capacity can be computed as

$$C_i = \log_2(1 + \Gamma_i). \tag{10}$$

Similarly, the received signal at Eve is given by

$$\begin{aligned} y_e &= \mathbf{h}_{1e}^H \mathbf{x}_1 + \mathbf{h}_{2e}^H \mathbf{x}_2 + n_e \\ &= \mathbf{h}_{1e}^H \mathbf{w}_1 s_1 + \mathbf{h}_{1e}^H \mathbf{v}_1 + \mathbf{h}_{2e}^H \mathbf{w}_2 s_2 + \mathbf{h}_{2e}^H \mathbf{v}_2 + n_e, \end{aligned} \tag{11}$$

where $n_e \sim \mathcal{CN}(0, \sigma_e^2)$ is the AWGN introduced by the receiver antenna at Eve, and σ_e^2 is the noise variance. As for the eavesdropper, we consider that it is only interested in one of the transmitters. Without loss of generality, we assume that the eavesdropping target is T_1. In this case, the eavesdropper channel capacity can be calculated as

$$C_e = \log_2(1 + \Gamma_e), \tag{12}$$

where $\Gamma_e = \frac{|\mathbf{h}_{1e}^H \mathbf{w}_1|^2}{|\mathbf{h}_{1e}^H \mathbf{v}_1|^2 + |\mathbf{h}_{2e}^H \mathbf{w}_2|^2 + |\mathbf{h}_{2e}^H \mathbf{v}_2|^2 + \sigma_e^2}$. Therefore, from an information-theoretic viewpoint, the secrecy rate at D_1 can be expressed as

$$\begin{aligned} R &= [0, C_1 - C_e]^+ \\ &= \left[0, \log_2\left(\frac{1 + \frac{(1-\rho_1)|\mathbf{h}_{11}^H \mathbf{w}_1|^2}{(1-\rho_1)(|\mathbf{h}_{21}^H \mathbf{w}_2|^2 + |\mathbf{h}_{21}^H \mathbf{v}_2|^2 + \sigma_1^2) + \delta_1^2}}{1 + \frac{|\mathbf{h}_{1e}^H \mathbf{w}_1|^2}{|\mathbf{h}_{1e}^H \mathbf{v}_1|^2 + |\mathbf{h}_{2e}^H \mathbf{w}_2|^2 + |\mathbf{h}_{2e}^H \mathbf{v}_2|^2 + \sigma_e^2}}\right)\right]^+. \end{aligned} \tag{13}$$

In this paper, we assume that T_1 and T_2 have perfect legitimate channel state information (CSI) about $\mathbf{h}_{ij}$ with $i, j \in \{1, 2\}$ through channel estimation and feedback. However, considering the eavesdropper might be passive, full eavesdropper CSI is difficult to be obtained. In this paper, it is assumed that the Eve is an idle receiver, thus the transmitter has partial CSI according to the feedback in previous communication due to channel correlation over time. Following previous related literature [33], we model eavesdropper CSI as

$$\mathbf{h}_{ie} = \overline{\mathbf{h}}_{ie} + \Delta \mathbf{h}_{ie}, \quad i \in \{1, 2\}, \tag{14}$$

where $\overline{\mathbf{h}}_{ie} \in \mathbb{C}^{N_t \times 1}$ is erroneous CSI available at the transmitters at the beginning of a scheduling slot, and $\Delta \mathbf{h}_{ie}$ represents the unknown channel uncertainty due to the time varying nature of the channel during transmission, which is assumed to lie in the following uncertainty region:

$$\hbar_i = \{\mathbf{h}_{ie} \in \mathbb{C}^{N_t \times 1} | \|\mathbf{h}_{ie} - \overline{\mathbf{h}}_{ie}\|^2 \le \varepsilon_i^2\}, \quad i \in \{1, 2\}, \tag{15}$$

where $\varepsilon_i > 0$ defines the size of the uncertainty region.

In general, due to the existence of channel uncertainty, the performance of SWIPT might be unsatisfactory. Especially, there are multiple unaligned or even conflicting performance requirements in SWIPT. To resolve this challenge, we propose to make use of two-transmitter cooperative beamforming to simultaneously enhance wireless security, improve the received SINR, and increase the harvested energy with limited transmit power for the wiretap interference network. Specifically, the two transmitters coordinate the transmit beams for information and energy signals, so as to reduce the impact of channel uncertainty on the multiple performance metrics. Meanwhile, power splitting ratios at the two receivers are carefully selected to further improve the performance.

III. ROBUST COOPERATIVE BEAMFORMING AND POWER SPLITTING SCHEME

In this section, we give a unified performance optimization for SWIPT over interference channels in the context of two-transmitter cooperation. As is well known, the maximization of secrecy rate and the minimization of the total power are two common objectives in PHY-security. Thus, we aim to design robust cooperative beamforming and power splitting schemes for SWIPT over interference channels from the perspectives of minimizing the total transmit power and maximizing the secrecy rate, respectively.

A. THE TOTAL TRANSMIT POWER MINIMIZATION PROBLEM

First, we consider the total transmit power minimization problem, which jointly designs cooperative beamforming and power splitting to minimize the total power consumption subject to a minimum secrecy rate requirement and a minimum EH constraint at D_1, a minimum SINR requirement, and a minimum EH constraint at D_2. Mathematically, the optimization problem can be described as

$$\begin{aligned}
\text{OP1}: \quad \min_{\mathbf{w}_i,\mathbf{v}_i,\rho_i} \quad & \|\mathbf{w}_1\|^2 + \|\mathbf{w}_2\|^2 + \|\mathbf{v}_1\|^2 + \|\mathbf{v}_2\|^2 \\
\text{s.t.} \quad & \text{C1}: R \geq R_{\min}, \quad \forall \mathbf{h}_{1e} \in \hbar_1,\ \mathbf{h}_{2e} \in \hbar_2, \\
& \text{C2}: \Gamma_2 \geq \gamma_2, \\
& \text{C3}: E_1 \geq q_1, \\
& \text{C4}: E_2 \geq q_2, \\
& \text{C5}: 0 < \rho_1 \leq 1, \quad 0 < \rho_2 \leq 1,
\end{aligned}$$

where $R_{\min}$ is a required minimum secrecy rate for all possible eavesdropper CSI, γ_2 represents a required minimum SINR at D_2, q_1 and q_2 denote required minimum amounts of EH at D_1 and D_2, respectively. Unfortunately, OP1 is not convex due to the complicated fractional objective function, the nonconvex constraints, and especially C1 contains infinite nonlinear functions. To settle such a problem, we propose a two-stage optimization approach. Prior to discussing this approach, we provide the following statement:

Lemma 1: Denote $\beta^* = (\mathbf{w}_1^*, \mathbf{w}_2^*, \mathbf{v}_1^*, \mathbf{v}_2^*, \rho_1^*, \rho_2^*)$ as the optimal solution to the original problem OP1, and define $\gamma_e^* = \max_{\forall \mathbf{h}_{ie} \in \hbar_i} \frac{|\mathbf{h}_{1e}^H \mathbf{w}_1^*|^2}{(|\mathbf{h}_{1e}^H \mathbf{v}_1^*|^2 + |\mathbf{h}_{2e}^H \mathbf{w}_2^*|^2 + |\mathbf{h}_{2e}^H \mathbf{v}_2^*|^2 + \sigma_e^2) + \delta_1^2}$. Then, β^* is also optimal for the following problem OP2 with $\gamma_e = \gamma_e^*$.

$$\begin{aligned}
\text{OP2}: \quad \min_{\mathbf{w}_i,\mathbf{v}_i,\rho_i} \quad & \|\mathbf{w}_1\|^2 + \|\mathbf{w}_2\|^2 + \|\mathbf{v}_1\|^2 + \|\mathbf{v}_2\|^2 \\
\text{s.t.} \quad & \text{C2, C3, C4, C5}, \\
& \text{C6}: \Gamma_1 \geq \gamma_1, \\
& \text{C7}: \Gamma_e \leq \gamma_e, \quad \forall \mathbf{h}_{1e} \in \hbar_1,\ \mathbf{h}_{2e} \in \hbar_2,
\end{aligned}$$

where γ_e is the maximum tolerable wiretap SINR at Eve, $\gamma_1 = 2^{R_{\min}}(1+\gamma_e) - 1$ is the minimum SINR requirement at D_1.

Proof: Please refer to Appendix A. ∎

Denote the minimum value of the objective function for OP2 as $f(\gamma_e)$, which is a function of γ_e. Then, we further have the following statement:

Lemma 2: The original problem OP1 is equivalent to the following problem

$$\text{OP3}: \min_{\gamma_e \geq 0} f(\gamma_e).$$

Proof: Please refer to Appendix B. ∎

Consequently, according to Lemma 2, OP1 can be solved via resolving OP3 instead. Furthermore, based on Lemma 1, we can solve OP3 with the following two steps. In the first step, we solve OP2 with a given γ_e, and obtain the optimal value $f(\gamma_e)$. Whereafter, in the second step, we find the optimal γ_e^* of OP3 through a one-dimensional searching. In what follows, we concentrate on solving OP2 for a given γ_e.

Note that OP2 still cannot be solved directly. To tackle this problem, we define $\mathbf{W}_i = \mathbf{w}_i\mathbf{w}_i^H$ and $\mathbf{H}_{ij} = \mathbf{h}_{ij}\mathbf{h}_{ij}^H$. Then, OP2 can be equivalently rewritten as

$$\begin{aligned}
\text{OP4}: \quad \min_{\mathbf{W}_i,\mathbf{V}_i,\rho_i} \quad & \text{tr}(\mathbf{W}_1) + \text{tr}(\mathbf{W}_2) + \text{tr}(\mathbf{V}_1) + \text{tr}(\mathbf{V}_2) \\
\text{s.t.} \quad & \text{C5, C8}: \text{tr}(\mathbf{H}_{11}\mathbf{W}_1) - \gamma_1 p_1 \geq \frac{\delta_1^2 \gamma_1}{1-\rho_1}, \\
& \text{C9}: \mathbf{h}_{1e}^H \mathbf{W}_1 \mathbf{h}_{1e} - \gamma_e \mathbf{h}_{1e}^H \mathbf{V}_1 \mathbf{h}_{1e} \\
& \qquad \leq \gamma_e (\mathbf{h}_{2e}^H \mathbf{W}_2 \mathbf{h}_{2e} + \mathbf{h}_{2e}^H \mathbf{V}_2 \mathbf{h}_{2e} + \sigma_e^2), \\
& \qquad\qquad \forall \mathbf{h}_{1e} \in \hbar_1,\ \mathbf{h}_{2e} \in \hbar_2, \\
& \text{C10}: \text{tr}(\mathbf{H}_{22}\mathbf{W}_2) - \gamma_2 p_2 \geq \frac{\delta_2^2 \gamma_2}{1-\rho_2}, \\
& \text{C11}: \eta_1 P_1 \geq q_1/\rho_1, \\
& \text{C12}: \eta_2 P_2 \geq q_2/\rho_2, \\
& \text{C13}: \mathbf{W}_i \succeq 0, \quad \mathbf{V}_i \succeq 0,\ i \in \{1,2\}, \\
& \text{C14}: \text{rank}(\mathbf{W}_i) = 1, \quad i \in \{1,2\},
\end{aligned}$$

where

$$\begin{aligned}
p_1 &= \text{tr}(\mathbf{H}_{21}\mathbf{W}_2) + \text{tr}(\mathbf{H}_{21}\mathbf{V}_2) + \sigma_1^2, \\
p_2 &= \text{tr}(\mathbf{H}_{12}\mathbf{W}_1) + \text{tr}(\mathbf{H}_{12}\mathbf{V}_1) + \sigma_2^2, \\
P_1 &= \text{tr}(\mathbf{H}_{11}\mathbf{W}_1) + \text{tr}(\mathbf{H}_{11}\mathbf{V}_1) + \text{tr}(\mathbf{H}_{21}\mathbf{V}_2) + \text{tr}(\mathbf{H}_{21}\mathbf{V}_2), \\
P_2 &= \text{tr}(\mathbf{H}_{12}\mathbf{W}_1) + \text{tr}(\mathbf{H}_{12}\mathbf{V}_1) + \text{tr}(\mathbf{H}_{22}\mathbf{V}_2) + \text{tr}(\mathbf{H}_{22}\mathbf{V}_2).
\end{aligned}$$

Substituting (14) and (15) into the constraint C9, we have

$$\max_{\|\Delta\mathbf{h}_{1e}\|^2\le\varepsilon_1^2}(\overline{\mathbf{h}}_{1e}+\Delta\mathbf{h}_{1e})^H\mathbf{S}_1(\overline{\mathbf{h}}_{1e}+\Delta\mathbf{h}_{1e})$$
$$\le\min_{\|\Delta\mathbf{h}_{2e}\|^2\le\varepsilon_2^2}\gamma_e((\overline{\mathbf{h}}_{2e}+\Delta\mathbf{h}_{2e})^H\mathbf{S}_2(\overline{\mathbf{h}}_{2e}+\Delta\mathbf{h}_{2e})+\sigma_e^2), \tag{16}$$

where $\mathbf{S}_1=\mathbf{W}_1-\gamma_e\mathbf{V}_1$ and $\mathbf{S}_2=\mathbf{W}_2+\mathbf{V}_2$. Moreover, by introducing two slack variables m and n, (16) can be transformed as

$$m\le\gamma_e(n+\sigma_e^2), \tag{17}$$
$$(\overline{\mathbf{h}}_{1e}+\Delta\mathbf{h}_{1e})^H\mathbf{V}_1(\overline{\mathbf{h}}_{1e}+\Delta\mathbf{h}_{1e})\le m,\quad\forall\|\Delta\mathbf{h}_{1e}\|^2\le\varepsilon_1^2, \tag{18}$$
$$(\overline{\mathbf{h}}_{2e}+\Delta\mathbf{h}_{2e})^H\mathbf{V}_2(\overline{\mathbf{h}}_{2e}+\Delta\mathbf{h}_{2e})\ge n,\quad\forall\|\Delta\mathbf{h}_{2e}\|^2\le\varepsilon_2^2, \tag{19}$$

Although (18) and (19) are convex with respect to the optimization variables, they contain semi-infinite constraints that are generally intractable for beamforming design. To facilitate the solution, (18) and (19) can be further converted to the following linear matrix inequalities (LMIs) form by using S-procedure

$$\Omega_1=\begin{bmatrix}\lambda_1\mathbf{I}-\mathbf{S}_1 & -\mathbf{S}_1\overline{\mathbf{h}}_{1e}\\ -\overline{\mathbf{h}}_{1e}^H\mathbf{S}_1 & -\lambda_1\varepsilon_1^2-\overline{\mathbf{h}}_{1e}^H\mathbf{S}_1\overline{\mathbf{h}}_{1e}+m\end{bmatrix},$$
$$\Omega_2=\begin{bmatrix}\lambda_2\mathbf{I}+\mathbf{S}_2 & \mathbf{S}_2\overline{\mathbf{h}}_{2e}\\ \overline{\mathbf{h}}_{2e}^H\mathbf{S}_2 & -\lambda_2\varepsilon_2^2+\overline{\mathbf{h}}_{2e}^H\mathbf{S}_2\overline{\mathbf{h}}_{2e}-n\end{bmatrix},$$
$$\lambda_1\ge 0,\quad\lambda_2\ge 0, \tag{20}$$

Therefore, OP4 can be reformulated as a standard semi-definite programming (SDP) problem as follows

$$\begin{aligned}\text{OP5}:\ &\min_{\mathbf{W}_i,\mathbf{V}_i,\rho_i}\ \mathrm{tr}(\mathbf{W}_1)+\mathrm{tr}(\mathbf{W}_2)+\mathrm{tr}(\mathbf{V}_1)+\mathrm{tr}(\mathbf{V}_2)\\ &\text{s.t. C5, C13, C15}: m\le\gamma_e(n+\sigma_e^2),\\ &\quad\text{C16}:\Omega_i\succeq 0,\quad i\in\{1,2,3,4,5,6\},\\ &\quad\text{C17}:\lambda_i\ge 0,\quad i\in\{1,2\},\end{aligned}$$

where

$$\Omega_3=\begin{bmatrix}1-\rho_1 & \delta_1\sqrt{\gamma_1}\\ \delta_1\sqrt{\gamma_1} & \mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1)-\gamma_1p_1\end{bmatrix},$$
$$\Omega_4=\begin{bmatrix}1-\rho_2 & \delta_2\sqrt{\gamma_2}\\ \delta_2\sqrt{\gamma_2} & \mathrm{tr}(\mathbf{H}_{22}\mathbf{W}_2)-\gamma_2p_2\end{bmatrix},$$
$$\Omega_5=\begin{bmatrix}\rho_1 & \sqrt{q_1}\\ \sqrt{q_1} & \eta_1P_1\end{bmatrix},\quad\Omega_6=\begin{bmatrix}\rho_2 & \sqrt{q_2}\\ \sqrt{q_2} & \eta_2P_2\end{bmatrix},$$

are converted from C8, C10, C11 and C12 according to Schur complement [41], respectively. It is worth pointing out that with respect to OP4, OP5 relaxes the rank-one constraints C14 to make it tractable. Therefore, we formulate a robust total power minimization problem as a semi-definite relaxed programming, where the objective function is a liner function and the constraints are defined by LMIs involving $\mathbf{W}_i$, $\mathbf{V}_i$ and ρ_i. Hence, it can be solved efficiently via some optimization softwares, i.e., CVX. We denote the optimal solution to OP5 as $\alpha^*=(\mathbf{W}_i^*,\mathbf{V}_i^*,\rho_i^*)$, $i\in\{1,2\}$. Note that in order to obtain the optimal beamforming vectors $\mathbf{w}_i$ of OP2, $\mathbf{W}_i^*$ must be rank-one. Check the rank of $\mathbf{W}_i^*$, we have the following lemma:

Lemma 3: The rank of the optimal $\mathbf{W}_1^*$ and $\mathbf{W}_2^*$ of OP5 satisfies $\mathrm{rank}(\mathbf{W}_1^*)\le 2$ and $\mathrm{rank}(\mathbf{W}_2^*)\le 2$.

Proof: Please refer to Appendix C. ∎

Thus, if $\mathrm{rank}(\mathbf{W}_i^*)=1$, it is easy to get the optimal beamforming vector $\mathbf{w}_i^*$ exactly via eigenvalue decomposition (EVD). Otherwise, if $\mathrm{rank}(\mathbf{W}_i^*)=2$, some rank-one approximation procedures, e.g., Gaussian randomization, need to be employed to obtain $\mathbf{w}_i^*$. Since OP2 is equivalent to OP5 with a given γ_e, $\mathbf{w}_i^*$ is also the solution to OP2. Finally, in order to get the solution to the original problem OP1, we need to compare the total transmit powers related to multiple γ_e's via a one-dimensional searching.

In the case of $\mathrm{rank}(\mathbf{W}_i^*)=2$, a rank-one approximation method should be utilized to get the beamforming vectors, resulting in performance loss and complexity increasing. To avoid the use of rank-one approximation, we provide a zero-forcing beamforming (ZFBF) scheme at the transmitters. Specifically, the information signal is transmitted in the orthogonal space of the interference channel, i.e., $\mathbf{h}_{12}^H\mathbf{w}_1=0$ and $\mathbf{h}_{21}^H\mathbf{w}_2=0$, such that the inter-link interference can be cancelled completely. In this context, the SINRs at D_1, D_2 and Eve are changed as

$$\Gamma_1'=\log_2\left(1+\frac{(1-\rho_1)|\mathbf{h}_{11}^H\mathbf{w}_1|^2}{(1-\rho_1)(|\mathbf{h}_{21}^H\mathbf{v}_2|^2+\sigma_1^2)+\delta_1^2}\right), \tag{21}$$
$$\Gamma_2'=\log_2\left(1+\frac{(1-\rho_2)|\mathbf{h}_{22}^H\mathbf{w}_2|^2}{(1-\rho_2)(|\mathbf{h}_{12}^H\mathbf{v}_1|^2+\sigma_2^2)+\delta_2^2}\right), \tag{22}$$

and

$$\Gamma_e'=\log_2\left(1+\frac{|\mathbf{h}_{1e}^H\mathbf{w}_1|^2}{|\mathbf{h}_{1e}^H\mathbf{v}_1|^2+|\mathbf{h}_{2e}^H\mathbf{w}_2|^2+|\mathbf{h}_{2e}^H\mathbf{v}_2|^2+\sigma_e^2}\right). \tag{23}$$

To satisfy the requirement of ZFBF, we let $\mathbf{w}_1=\mathbf{H}_{12}^{\perp}\mathbf{w}_3$ and $\mathbf{w}_2=\mathbf{H}_{21}^{\perp}\mathbf{w}_4$, where $\mathbf{H}_{12}^{\perp}=\mathbf{I}-\mathbf{h}_{12}(\mathbf{h}_{12}^H\mathbf{h}_{12})^{-1}\mathbf{h}_{12}^H$ and $\mathbf{H}_{21}^{\perp}=\mathbf{I}-\mathbf{h}_{21}(\mathbf{h}_{21}^H\mathbf{h}_{21})^{-1}\mathbf{h}_{21}^H$ are the orthogonal projectors of $\mathbf{h}_{12}$ and $\mathbf{h}_{21}$, respectively. As a result, OP5 is transformed as

$$\begin{aligned}\text{OP6}:\ &\min_{\mathbf{W}_i,\mathbf{V}_i,\rho_i}\ \mathrm{tr}((\mathbf{H}_{12}^{\perp})^H\mathbf{H}_{12}^{\perp}\mathbf{W}_3)+\mathrm{tr}((\mathbf{H}_{21}^{\perp})^H\mathbf{H}_{21}^{\perp}\mathbf{W}_4)\\ &\qquad+\mathrm{tr}(\mathbf{V}_1)+\mathrm{tr}(\mathbf{V}_2)\\ &\text{s.t. C5, C18}: m'\le\gamma_e(n'+\sigma_e^2),\\ &\quad\text{C19}:\Omega_i'\succeq 0,\quad i\in\{1,2,3,4,5,6\},\\ &\quad\text{C20}:\lambda_1'\ge 0,\quad\lambda_2'\ge 0,\\ &\quad\text{C21}:\mathbf{W}_3\succeq 0,\quad\mathbf{W}_4\succeq 0,\ \mathbf{V}_1\succeq 0,\ \mathbf{V}_2\succeq 0,\end{aligned}$$

where $\mathbf{W}_3=\mathbf{w}_3\mathbf{w}_3^H$, $\mathbf{W}_4=\mathbf{w}_4\mathbf{w}_4^H$,

$$\Omega_1'=\begin{bmatrix}\lambda_1'\mathbf{I}-\mathbf{S}_1' & -\mathbf{S}_1'\overline{\mathbf{h}}_{1e}\\ -\overline{\mathbf{h}}_{1e}^H\mathbf{S}_1' & -\lambda_1'\varepsilon_1^2-\overline{\mathbf{h}}_{1e}^H\mathbf{S}_1'\overline{\mathbf{h}}_{1e}+m'\end{bmatrix}, \tag{24}$$

$$\Omega_2' = \begin{bmatrix} \lambda_2'\mathbf{I}+\mathbf{S}_2' & \mathbf{S}_2'\bar{\mathbf{h}}_{2,e} \\ \bar{\mathbf{h}}_{2e}^H\mathbf{S}_2' & -\lambda_2'\varepsilon_2^2+\bar{\mathbf{h}}_{2e}^H\mathbf{S}_2'\bar{\mathbf{h}}_{2e}-n' \end{bmatrix}, \tag{25}$$

$$\Omega_3' = \begin{bmatrix} 1-\rho_1 & \delta_1\sqrt{\gamma_1} \\ \delta_1\sqrt{\gamma_1} & \mathrm{tr}(\mathbf{H}_{11}'\mathbf{W}_3)-\gamma_1(\mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2)+\sigma_1^2) \end{bmatrix},$$

$$\Omega_4' = \begin{bmatrix} 1-\rho_2 & \delta_2\sqrt{\gamma_2} \\ \delta_2\sqrt{\gamma_2} & \mathrm{tr}(\mathbf{H}_{22}'\mathbf{W}_4)-\gamma_2(\mathrm{tr}(\mathbf{H}_{12}\mathbf{V}_1)+\sigma_2^2) \end{bmatrix},$$

$$\Omega_5' = \begin{bmatrix} \rho_1 & \sqrt{q_1} \\ \sqrt{q_1} & \eta_1(\mathrm{tr}(\mathbf{H}_{11}'\mathbf{W}_3)+\mathrm{tr}(\mathbf{H}_{11}\mathbf{V}_1)+\mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2)) \end{bmatrix},$$

$$\Omega_6' = \begin{bmatrix} \rho_2 & \sqrt{q_2} \\ \sqrt{q_2} & \eta_2(\mathrm{tr}(\mathbf{H}_{12}\mathbf{V}_1)+\mathrm{tr}(\mathbf{H}_{22}'\mathbf{W}_4)+\mathrm{tr}(\mathbf{H}_{22}\mathbf{V}_2)) \end{bmatrix},$$

$\mathbf{H}_{11}' = (\mathbf{H}_{12}^{\perp})^H\mathbf{h}_{11}\mathbf{h}_{11}^H\mathbf{H}_{12}^{\perp}$, $\mathbf{H}_{22}' = (\mathbf{H}_{21}^{\perp})^H\mathbf{h}_{22}\mathbf{h}_{22}^H\mathbf{H}_{21}^{\perp}$, $\mathbf{S}_1' = \mathbf{H}_{12}^{\perp}\mathbf{W}_3(\mathbf{H}_{12}^{\perp})^H-\gamma_e\mathbf{V}_1$, and $\mathbf{S}_2' = \mathbf{H}_{21}^{\perp}\mathbf{W}_4(\mathbf{H}_{21}^{\perp})^H+\mathbf{V}_2$.

It is clear that OP6 is a convex problem, and thus can be solved by some optimization softwares directly. Assume that the optimal solution to OP6 is $\xi' = (\mathbf{W}_3', \mathbf{W}_4', \mathbf{V}_i', \rho_i')$, $i \in \{1, 2\}$, we have the following theorem:

Theorem 1: The ranks of $\mathbf{W}_3'$ and $\mathbf{W}_4'$ obtained by solving OP6 are one.

Proof: Please refer to Appendix D. ∎

Hence, we can get the optimal solution to OP6 exactly by EVD as follows

$$\mathbf{W}_3' = \mathbf{w}_3\mathbf{w}_3^H, \quad \mathbf{W}_4' = \mathbf{w}_4\mathbf{w}_4^H. \tag{26}$$

Then, the cooperative beams based on the ZFBF criterion can be constructed by letting $\mathbf{w}_1 = \mathbf{H}_{12}^{\perp}\mathbf{w}_3$ and $\mathbf{w}_2 = \mathbf{H}_{21}^{\perp}\mathbf{w}_4$. Furthermore, the solution to the original problem OP1 can be obtained by comparing the total transmit powers related to multiple γ_e's via a one-dimensional searching. Since the solution to OP6 can be directly obtained by optimization softwares, the complexity of the whole scheme is determined by the step of the one-dimensional searching.

B. THE SECRECY RATE MAXIMIZATION PROBLEM

In this section, we consider the secrecy rate maximization problem under the total transmit power constraint, a minimum EH constraint at D_1, a minimum SINR requirement, and a minimum EH constraint at D_2. Since the case of $R = 0$ is trivial, we consider a general case that D_1 has a nonzero secrecy rate. Thus, the secrecy rate maximization problem in the worst-case of channel uncertainties can be formulated as

$$\begin{aligned} \mathrm{OP7}: \ & \max_{\mathbf{w}_i,\mathbf{v}_i,\rho_i} \min_{\forall \mathbf{h}_{ie}\in\hbar_i} \ \log_2(1+\Gamma_1)-\log_2(1+\Gamma_e) \\ & \text{s.t. C2, C3, C4, C5,} \\ & \quad \mathrm{C22}: \|\mathbf{w}_1\|^2+\|\mathbf{w}_2\|^2+\|\mathbf{v}_1\|^2+\|\mathbf{v}_2\|^2 \le P_{\max}, \end{aligned} \tag{27}$$

where $P_{\max}$ is the maximum tolerance total transmit power. Note that the two transmitter may have individual power constraints. Since joint power constraint can achieve the performance upper of individual power constraint, we consider joint power constraint in this paper. In fact, the proposed scheme can be easily extended to the case of individual power constraint. Obviously, OP7 is not in general a convex optimization problem, since its objective function in terms of the difference of two logarithmic functions is non-concave. In order to obtain a tractable solution to such a kind of challenging problem of the maximization of secrecy rate in PHY-security, an alternative optimization algorithm was proposed through reformulating the objective function in [42]. It is proved that maximizing the secrecy rate is equivalent to maximizing the legitimate channel rate subject to an upper bound on the eavesdropper channel rate. Furthermore, due to $\log_2(x)$ is a monotonically increasing function that has no effect on the optimization problem, we omit it here and transform OP7 into the maximization of the SINR at T_1 under the constraint of the SINR at Eve, namely

$$\begin{aligned} \mathrm{OP8}: \ & \max_{\mathbf{w}_i,\mathbf{v}_i,\rho_i} \frac{(1-\rho_1)|\mathbf{h}_{11}^H\mathbf{w}_1|^2}{(1-\rho_1)(|\mathbf{h}_{21}^H\mathbf{w}_2|^2+|\mathbf{h}_{21}^H\mathbf{v}_2|^2+\sigma_1^2)+\delta_1^2} \\ & \text{s.t. C2, C3, C4, C5, C7, C22,} \end{aligned}$$

Similar to Lemma 1, we can prove that there exists a γ_e^* that makes the optimal solution of OP8 identical to that of OP7. In other words, let $g(\gamma_e)$ represent the optimal value of OP8, OP7 is equivalent to the following problem

$$\mathrm{OP9}: \max_{\gamma_e\ge 0} g(\gamma_e)$$

Therefore, it is possible to obtain the optimal γ_e^* by a one-dimensional searching method. In what follows, we turn our attention on solving OP8. In order to make OP8 tractable, we apply a semi-definite relaxation technique by setting $\mu_1 = \frac{1}{1-\rho_1}$, and remove the rank-one constraints on $\mathbf{W}_1$ and $\mathbf{W}_2$. Then, we can obtain the following relaxed SDP problem

$$\begin{aligned} \mathrm{OP10}: \ & \max_{\mathbf{W}_i,\mathbf{V}_i,\mu_1,\rho_2} \frac{\mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1)}{p_1+\mu_1\delta_1^2} \\ & \text{s.t. C9, C10, C12, C13,} \\ & \quad \mathrm{C23}: \eta_1 P_1 - q_1 \ge \frac{q_1}{\mu_1-1}, \\ & \quad \mathrm{C24}: \mu_1 > 1, \quad 0 < \rho_2 < 1, \\ & \quad \mathrm{C25}: \mathrm{tr}(\mathbf{W}_1)+\mathrm{tr}(\mathbf{W}_2)+\mathrm{tr}(\mathbf{V}_1) \\ & \qquad\quad +\mathrm{tr}(\mathbf{V}_2) \le P_{\max}, \end{aligned}$$

Note that OP10 is a fractional programming problem, such that we can get the optimal solution $\alpha^* = (\mathbf{W}_i^*, \mathbf{V}_i^*, \mu_1^*, \rho_2^*)$ and the maximum value of the objective function τ^* by using the following property of fractional programming [43]:

Lemma 4: The maximum value τ^* is achieved if and only if $\max_{\mathbf{W}_i,\mathbf{V}_i,\mu_1,\rho_2} \mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1) - \tau^*(p_1+\mu_1\delta_1^2) = \mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1^*) - \tau^*(\mathrm{tr}(\mathbf{H}_{21}\mathbf{W}_2^*)+\mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2^*)+\sigma_1^2+\mu_1^*\delta_1^2) = 0$ for $\mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1) > 0$ and $p_1+\mu_1\delta_1^2 > 0$.

According to Lemma 4, the objective function of OP10 is equivalent to $\mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1)-\tau(p_1+\mu_1\delta_1^2)$. Moreover, the constraint C23 hinders us to further solve this problem. As similar to the transformation of C8, C10, C11 and C12, we convert C23 into an LMI according to Schur complement, namely

$$\mathrm{C26} \Rightarrow \Omega_7 = \begin{bmatrix} \mu_1-1 & \sqrt{q_1} \\ \sqrt{q_1} & \eta_1 P_1 - q_1 \end{bmatrix}.$$

Therefore, for a given τ, OP10 can be reexpressed as

$$\begin{aligned} \mathrm{OP11}: \quad & \max_{\mathbf{W}_i, \mathbf{V}_i, \mu_1, \rho_2} \quad \mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1) - \tau(p_1 + \mu_1 \delta_1^2) \\ & \quad \text{s.t. } \mathrm{C27}: \Omega_i \succeq 0, \quad i \in \{1, 2, 4, 6, 7\}, \\ & \qquad \mathrm{C13}, \mathrm{C24}, \mathrm{C25}, \mathrm{C26}, \end{aligned}$$

which is convex, and hence can be efficiently solved by some convex optimization solvers, such as CVX. In order to get the solutions to OP10, it is necessary to update $\tau = \frac{\mathrm{tr}(\mathbf{H}_{11}\mathbf{W}_1)}{p_1+\mu_1\delta_1^2}$ based on the last solutions to OP11 until τ converges to its maximum value as mentioned in Lemma 4.

A potential problem is that the optimal $\mathbf{W}_i^*$ of OP10 might be not rank-one. Similarly, to solve this problem, we carry out ZFBF at the transmitters by replacing $\mathbf{w}_1$ and $\mathbf{w}_2$ with $\mathbf{H}_{12}^{\perp}\mathbf{w}_3$ and $\mathbf{H}_{21}^{\perp}\mathbf{w}_4$, respectively. In this context, OP11 is transformed as

$$\begin{aligned} \mathrm{OP12}: \quad & \max_{\mathbf{W}_i, \mathbf{V}_i, \mu_1, \rho_2} \quad \mathrm{tr}(\mathbf{H}_{11}'\mathbf{W}_3) - \tau(\mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2)+\sigma_1^2+\mu_1\delta_1^2) \\ & \text{s.t. } \mathrm{C28}: \Omega_i' \succeq 0, i \in \{1, 2, 4, 6, 7\}, \\ & \text{s.t. } \mathrm{C29}: \mathrm{tr}((\mathbf{H}_{12}^{\perp})^H \mathbf{H}_{12}^{\perp}\mathbf{W}_3)+\mathrm{tr}((\mathbf{H}_{21}^{\perp})^H \mathbf{H}_{21}^{\perp}\mathbf{W}_4) \\ & \qquad + \mathrm{tr}(\mathbf{V}_1) + \mathrm{tr}(\mathbf{V}_2) \leq P_{\max}, \\ & \quad \mathrm{C18}, \mathrm{C20}, \mathrm{C21}, \end{aligned}$$

where

$$\Omega_7' = \begin{bmatrix} \mu_1 - 1 & \sqrt{q_1} \\ \sqrt{q_1} & \eta_1(\mathrm{tr}(\mathbf{H}_{11}'\mathbf{W}_3)+\mathrm{tr}(\mathbf{H}_{11}\mathbf{V}_1)+\mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2)) - q_1 \end{bmatrix}.$$

Fortunately, the obtained transmit beams of OP12 are all rank-one, i.e., $\mathrm{rank}(\mathbf{W}_3) = \mathrm{rank}(\mathbf{W}_4) = 1$. This is because the constraints of OP12 are almost the same as that of OP6. Hence, we omit the proof here for simplicity. Furthermore, the solutions to the original problem OP7 can be obtained by updating τ and then conducting a one-dimensional searching on γ_e. The complexity of such a scheme is also determined by the step of the one-dimensional searching.

In above, we provide a unified performance optimization framework for SWIPT over interference channels. Based on such a framework, it is likely to optimize the other performance metrics. For instance, energy efficiency has received more and more attentions recently. However, it is not a trivial task to optimize the energy efficiency in SWIPT. With the above framework, we can search the maximum energy efficiency through the minimization of total power consumption or the maximization of secrecy rate. Specifically, give a total power constraint, it is possible to obtain a cooperative beamforming and power splitting scheme with the maximum secrecy rate. Finally, we can find a solution with the maximum energy efficiency by comparing the cases of difference total power constraints. Similarly, we can optimize the energy efficiency from the perspective of minimizing the total power consumption.

IV. NUMERICAL RESULTS

In this section, simulation results are presented to illustrate the performance of the proposed robust cooperative beamforming and power splitting schemes over interference channels. For convenience and without loss of generality, the simulation scenario is set as: $\sigma_1^2 = \sigma_2^2 = \delta_1^2 = \delta_2^2 = 1$, $\eta_1 = \eta_2 = 1, q_1 = q_2 = q$, and $\gamma_2 = 2$. All simulation results are obtained by averaging over 1000 randomly generated channel realizations.

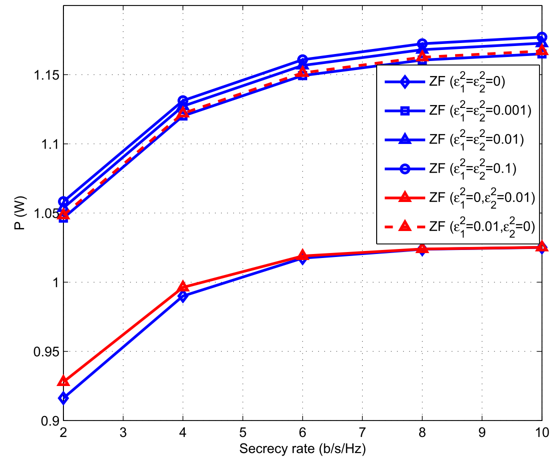

FIGURE 2. Total transmit power comparison of the proposed ZF scheme with different channel uncertainties.

Firstly, we show the effect of CSI accuracy on the total transmit power of the proposed ZF scheme with $N_t = 4$ and $q = 1$. As seen in Fig. 2, from the case of $\varepsilon_1^2 = \varepsilon_2^2 = 0.001$ to that of $\varepsilon_1^2 = \varepsilon_2^2 = 0.1$, the proposed scheme nearly consumes the same power to satisfy the performance requirements. Thus, the proposed scheme has a strong robustness. On the other hand, it is found that the accuracy of $\mathbf{h}_{1e}$ has a great impact on the power consumption. With respect to the case of perfect $\mathbf{h}_{1e}$, a slight channel uncertainty leads to an obvious performance loss. This is because imperfect $\mathbf{h}_{1e}$ would result in more information leakage to the eavesdropper. In order to fulfill the same performance requirement, more power should be used at the transmitters.

Secondly, we investigate the impact of minimum EH requirements on the total transmit power with $R_{\min} = 2$ b/s/Hz and $\varepsilon_1^2 = \varepsilon_2^2 = 10^{-3}$. Note that we compare the proposed ZF scheme with a commonly used artificial noise (AN) aided scheme in PHY-security. Specifically, the AN aided scheme replaces the energy signal with an AN signal, but the receivers cannot cancel the random AN signal. As depicted in Fig. 3, the total transmit power for both schemes increases as minimum EH requirement q adds, but the AN scheme always consumes more power than the proposed scheme. It is seen that the proposed ZF scheme with 4 antennas consumes the same power as the AN scheme with 6 antennas. Thus, the proposed scheme can effectively reduce the cost.

Then, we check the effect of the eavesdropper channel uncertainty on the secrecy rate with $N_t = 4$ and $q = 1$. In particular, the case of perfect eavesdropper CSI is also considered for comparison. From Fig. 4, it is observed that, when the the eavesdropper CSI changes from perfect to imperfect, even though the channel uncertainty is very slight,

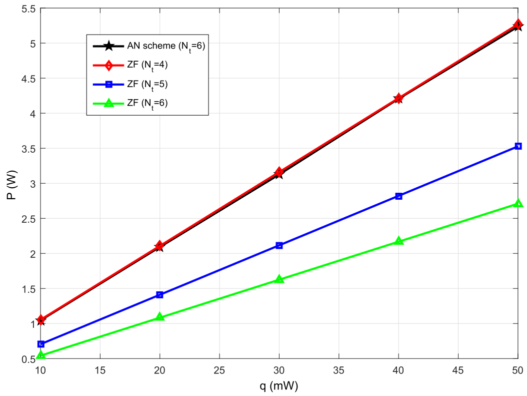

FIGURE 3. **Total transmit power comparison of the proposed scheme and the AN aided scheme with different energy harvesting constraints.**

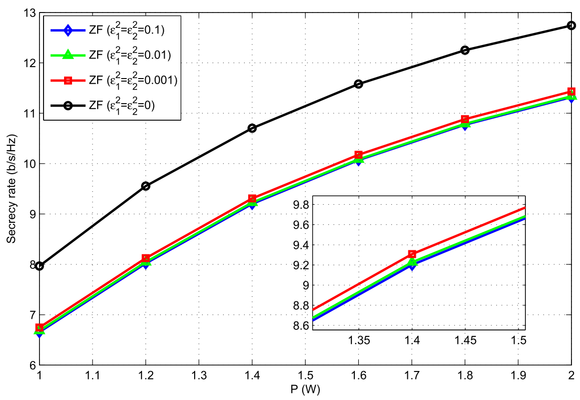

FIGURE 4. **Secrecy rate comparison of the proposed ZF scheme with different maximum tolerance power constraints.**

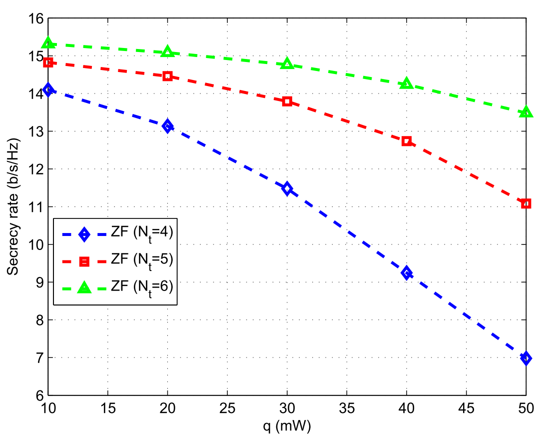

FIGURE 5. **Secrecy rate comparison of the proposed ZF scheme with different energy harvesting constraints.**

$\varepsilon_1^2 = \varepsilon_2^2 = 10^{-3}$, the secrecy rates decrease significantly. However, when the channel uncertainties change from $\varepsilon_1^2 = \varepsilon_2^2 = 10^{-3}$ to $\varepsilon_1^2 = \varepsilon_2^2 = 10^{-2}$, the secrecy rate is nearly unchanged. Thus, the proposed scheme is highly robust to channel uncertainty.

Next, we investigate the impact of the number of transmit antennas on the secrecy rate performance with a fixed maximum total transmit power constraint $P_{\max} = 30$ dB

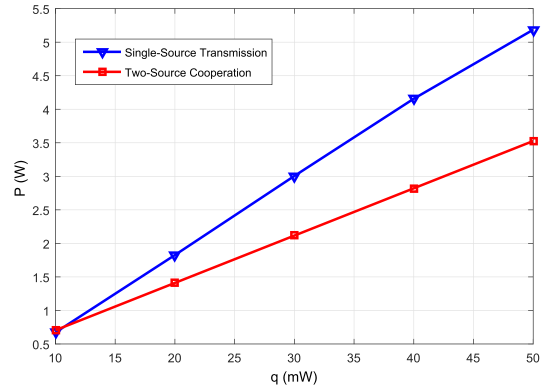

FIGURE 6. **Total transmit power comparison of two-source cooperation and single-source transmission.**

and channel uncertainty $\varepsilon_1^2 = \varepsilon_2^2 = 10^{-3}$. It can be found that the secrecy rate obviously increases as the number of transmit antennas adds, especially at a large q. Thus, it is possible to improve the secrecy rate performance by adding more antennas (Fig. 5).

Finally, we show the performance gain of the proposed two-source cooperative scheme over a single-source transmission scheme. To be more specific, the single-source transmission scheme design the transmit beams and power splitting ratio of the two links individually. As seen in Fig. 6, when the required amount of harvested energy q is low, the consumed power of the single-source transmission scheme is nearly equal to that of the two-source cooperation scheme. However, as q increases, the single-source scheme consumes much more power than the two-source cooperation scheme. Especially, the gap of the consumed power of the two schemes becomes larger as q increases. Thus, the proposed two-source cooperation scheme can effectively reduce the power consumption.

V. CONCLUSION

In this paper, we propose to use two-transmitter cooperation to enhance the performance of secrecy wireless information and power transfer over interference channels. We formulate the problems from the perspectives of both maximizing the secrecy rate and minimizing the total power consumption. For each problem, we provide a robust cooperative beamforming and power splitting scheme.

APPENDIX A
PROOF OF LEMMA 1

We prove lemma 1 by contradiction. Suppose that $\hat{\beta} = (\hat{\mathbf{w}}_1, \hat{\mathbf{w}}_2, \hat{\mathbf{v}}_1, \hat{\mathbf{v}}_2, \hat{\rho}_1, \hat{\rho}_2)$ is also an optimal solution to OP2 with $\gamma_e = \gamma_e^*$, which is different from the optimal solution β^* to OP1. On the one hand, if $\|\hat{\mathbf{w}}_1\|^2 + \|\hat{\mathbf{w}}_2\|^2 + \|\hat{\mathbf{v}}_1\|^2 + \|\hat{\mathbf{v}}_2\|^2 > \|\mathbf{w}_1^*\|^2 + \|\mathbf{w}_2^*\|^2 + \|\mathbf{v}_1^*\|^2 + \|\mathbf{v}_2^*\|^2$, then β^* is a better solution to OP2, since it also satisfies all constraints of OP2. Thus, it is a contradiction that $\hat{\beta}$ is optimal for OP2.

On the other hand, if $\|\hat{\mathbf{w}}_1\|^2 + \|\hat{\mathbf{w}}_2\|^2 + \|\hat{\mathbf{v}}_1\|^2 + \|\hat{\mathbf{v}}_2\|^2 < \|\mathbf{w}_1^*\|^2 + \|\mathbf{w}_2^*\|^2 + \|\mathbf{v}_1^*\|^2 + \|\mathbf{v}_2^*\|^2$, which also contradicts the assumption that β^* is the optimal solution to OP1. As a result, we must have $\hat{\beta} = \beta^*$. Thus, the proof is completed.

APPENDIX B
PROOF OF LEMMA 2

Denote P_t^* and $\tilde{P}_t$ as the minimum values of OP1 and OP3, respectively. The proof includes two parts. First, we show that OP3 can achieve the minimum value of OP1, i.e., $\tilde{P}_t \leq P_t^*$. According to Lemma 1, we can conclude that

$$f(\gamma_e^*) = P_t^*. \tag{28}$$

In addition, due to the fact that $\tilde{P}_t = \min_{\gamma_e} f(\gamma_e) \leq f(\gamma_e^*)$, we have

$$\tilde{P}_t \leq P_t^*. \tag{29}$$

Then, we prove that OP1 can achieve the minimum value of OP3, i.e., $P_t^* \leq \tilde{P}_t$. Assume that $\tilde{\gamma}_e$ is the optimal solution to OP3, such that $\tilde{P}_t$ is the minimum value of OP2 with $\gamma_e = \tilde{\gamma}_e$. Since $\tilde{P}_t$ is a possible minimum value of OP1, it is obtained that

$$\tilde{P}_t \geq P_t^*. \tag{30}$$

Consequently, combining (29) and (30), we have $\tilde{P}_t = P_t^*$. Thus, the proof is completed.

APPENDIX C
PROOF OF LEMMA3

For proving Lemma 3 more clearly, we define

$$a = -\lambda_1 \varepsilon_1^2 + m \tag{31}$$
$$b = -\gamma_1(\mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2^*) + \sigma_1^2) \tag{32}$$
$$c = -\gamma_2(\mathrm{tr}(\mathbf{H}_{12}\mathbf{V}_1^*) + \sigma_2^2) \tag{33}$$
$$d = \eta_1(\mathrm{tr}(\mathbf{H}_{11}\mathbf{V}_1^*) + \mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2^*)) \tag{34}$$
$$e = \eta_2(\mathrm{tr}(\mathbf{H}_{12}\mathbf{V}_1^*) + \mathrm{tr}(\mathbf{H}_{22}\mathbf{V}_2^*)) \tag{35}$$

and rewrite Ω_i, $i \in \{1, 3, \ldots, 6\}$ as the following form

$$\begin{aligned}
\Omega_1 &= \begin{bmatrix} \lambda_1 \mathbf{I} & \mathbf{0} \\ \mathbf{0}^H & a \end{bmatrix} - \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix} [\mathbf{W}_1^* - \gamma_e \mathbf{V}_1^*] \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right] \\
\Omega_3 &= \begin{bmatrix} 1-\rho_1^* & \delta_1\sqrt{\gamma_1} \\ \delta_1\sqrt{\gamma_1} & b \end{bmatrix} + \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H \end{bmatrix} \mathbf{W}_1^* \left[\mathbf{0}, \mathbf{h}_{11}\right] \\
&\quad - \gamma_1 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{21}^H \end{bmatrix} \mathbf{W}_2^* \left[\mathbf{0}, \mathbf{h}_{21}\right] \\
\Omega_4 &= \begin{bmatrix} 1-\rho_2^* & \delta_2\sqrt{\gamma_2} \\ \delta_2\sqrt{\gamma_2} & c \end{bmatrix} - \gamma_2 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{12}^H \end{bmatrix} \mathbf{W}_1^* \left[\mathbf{0}, \mathbf{h}_{12}\right] \\
&\quad + \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{22}^H \end{bmatrix} \mathbf{W}_2^* \left[\mathbf{0}, \mathbf{h}_{22}\right] \\
\Omega_5 &= \begin{bmatrix} \rho_1^* & \sqrt{q_1} \\ \sqrt{q_1} & d \end{bmatrix} + \eta_1 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H \end{bmatrix} \mathbf{W}_1^* \left[\mathbf{0}, \mathbf{h}_{11}\right] \\
&\quad + \eta_1 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{21}^H \end{bmatrix} \mathbf{W}_2^* \left[\mathbf{0}, \mathbf{h}_{21}\right] \\
\Omega_6 &= \begin{bmatrix} \rho_2^* & \sqrt{q_2} \\ \sqrt{q_2} & e \end{bmatrix} + \eta_2 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{12}^H \end{bmatrix} \mathbf{W}_1^* \left[\mathbf{0}, \mathbf{h}_{12}\right] \\
&\quad + \eta_2 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{22}^H \end{bmatrix} \mathbf{W}_2^* \left[\mathbf{0}, \mathbf{h}_{22}\right]
\end{aligned}$$

Then, the Lagrangian function for OP5 is given by

$$\begin{aligned}
\mathcal{L} &= \mathrm{tr}(\mathbf{A}\mathbf{W}_1^*) + \mathrm{tr}(\mathbf{B}\mathbf{W}_2^*) + \mathrm{tr}(\mathbf{V}_1^*) + \mathrm{tr}(\mathbf{V}_2^*) \\
&\quad + \Theta_1 (\begin{bmatrix} \lambda_1 \mathbf{I} & \mathbf{0} \\ \mathbf{0}^H & a \end{bmatrix} + \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix} \gamma_e \mathbf{V}_1 \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right]) + \Theta_2 \Omega_2 \\
&\quad + \Theta_3 \begin{bmatrix} 1-\rho_1^* & \delta_1\sqrt{\gamma_1} \\ \delta_1\sqrt{\gamma_1} & b \end{bmatrix} + \Theta_4 \begin{bmatrix} 1-\rho_2^* & \delta_2\sqrt{\gamma_2} \\ \delta_2\sqrt{\gamma_2} & c \end{bmatrix} \\
&\quad + \Theta_5 \begin{bmatrix} \rho_1^* & \sqrt{q_1} \\ \sqrt{q_1} & d \end{bmatrix} + \Theta_6 \begin{bmatrix} \rho_2^* & \sqrt{q_2} \\ \sqrt{q_2} & e \end{bmatrix} \\
&\quad + \nu_1(m - n - \gamma_e \sigma_e^2)
\end{aligned} \tag{36}$$

where

$$\begin{aligned}
\mathbf{A} &= \mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right] \Theta_1 \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix} - \left[\mathbf{0}, \mathbf{h}_{11}\right] [\Theta_3 + \eta_1 \Theta_5] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H \end{bmatrix} \\
&\quad + \left[\mathbf{0}, \mathbf{h}_{12}\right] [\gamma_2 \Theta_4 - \eta_2 \Theta_6] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{12}^H \end{bmatrix}, \\
\mathbf{B} &= \mathbf{I} + \left[\mathbf{0}, \mathbf{h}_{21}\right] [\gamma_1 \Theta_3 - \eta_1 \Theta_5] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{21}^H \end{bmatrix} \\
&\quad - \left[\mathbf{0}, \mathbf{h}_{22}\right] [\Theta_4 + \eta_2 \Theta_6] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{22}^H \end{bmatrix},
\end{aligned}$$

and $\{\Theta_i\}$, ν_1 are the Lagrange multipliers associated with the LMIs and inequality constraints in OP5. The complementary slackness condition yields to $\mathbf{A}\mathbf{W}_1^* = 0$, i.e.,

$$\begin{aligned}
&(\mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right] \Theta_1 \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix} - \left[\mathbf{0}, \mathbf{h}_{11}\right] [\Theta_3 + \eta_1 \Theta_5] \left[\mathbf{0}^H \mathbf{h}_{11}^H\right] \\
&\quad + \left[\mathbf{0}, \mathbf{h}_{12}\right] [\gamma_2 \Theta_4 - \eta_2 \Theta_6] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{12}^H \end{bmatrix}) \mathbf{W}_1^* = 0.
\end{aligned} \tag{37}$$

Then, the rank of $\mathbf{W}_1^*$ can be computed as follows

$$\begin{aligned}
\mathrm{rank}(\mathbf{W}_1^*) &= \mathrm{rank}((\mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right] \Theta_1 \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix}) \mathbf{W}_1^*) \\
&= \mathrm{rank}((\left[\mathbf{0}, \mathbf{h}_{11}\right] [\Theta_3 + \eta_1 \Theta_5] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H \end{bmatrix} \\
&\quad - \left[\mathbf{0}, \mathbf{h}_{12}\right] [\gamma_2 \Theta_4 - \eta_2 \Theta_6] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{12}^H \end{bmatrix}) \mathbf{W}_1^*) \\
&\leq \mathrm{rank}(\left[\mathbf{0}, \mathbf{h}_{11}\right] [\Theta_3 + \eta_1 \Theta_5] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H \end{bmatrix} \\
&\quad - \left[\mathbf{0}, \mathbf{h}_{12}\right] [\gamma_2 \Theta_4 - \eta_2 \Theta_6] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{12}^H \end{bmatrix}) \\
&\quad + \mathrm{rank}(\left[\mathbf{0}, \mathbf{h}_{12}\right] [\gamma_2 \Theta_4 - \eta_2 \Theta_6] \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{12}^H \end{bmatrix}) \\
&\leq 2,
\end{aligned} \tag{38}$$

where the first equality follows the fact that $\mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right] \Theta_1 \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix} \succ 0$, and the second equality is obtained according to (37). The first inequality holds due to $\mathrm{rank}(\mathbf{A}_1\mathbf{A}_2) \leq \min\{\mathrm{rank}(\mathbf{A}_1), \mathrm{rank}(\mathbf{A}_2)\}$, and the last inequality is true because of $\mathrm{rank}(\mathbf{A}_1 + \mathbf{A}_2) \leq \mathrm{rank}(\mathbf{A}_1) + \mathrm{rank}(\mathbf{A}_2)$. The proof about the rank of $\mathbf{W}_2^*$ is similar to the above and omitted for brevity.

APPENDIX D
PROOF OF THEOREM 1

Similarly, we define

$$a_1 = -\lambda_1'\varepsilon_1^2 + m', \tag{39}$$
$$a_2 = -\lambda_2'\varepsilon_2^2 - n', \tag{40}$$
$$b_1 = -\gamma_1(\mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2') + \sigma_1^2), \tag{41}$$
$$b_2 = -\gamma_2(\mathrm{tr}(\mathbf{H}_{12}\mathbf{V}_1') + \sigma_2^2), \tag{42}$$
$$c_1 = \eta_1(\mathrm{tr}(\mathbf{H}_{11}\mathbf{V}_1') + \mathrm{tr}(\mathbf{H}_{21}\mathbf{V}_2')), \tag{43}$$
$$c_2 = \eta_2(\mathrm{tr}(\mathbf{H}_{12}\mathbf{V}_1') + \mathrm{tr}(\mathbf{H}_{22}\mathbf{V}_2')), \tag{44}$$

and rewrite Ω_i', $i \in \{1, 2, \ldots, 6\}$ as

$$\Omega_1' = \begin{bmatrix} \lambda_1'\mathbf{I} & \mathbf{0} \\ \mathbf{0}^H & a_1 \end{bmatrix} - \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix} [\mathbf{H}_{12}^{\perp}\mathbf{W}_3'(\mathbf{H}_{12}^{\perp})^H - \gamma_e\mathbf{V}_1'] [\mathbf{I}, \bar{\mathbf{h}}_{1e}],$$
$$\Omega_2' = \begin{bmatrix} \lambda_2'\mathbf{I} & \mathbf{0} \\ \mathbf{0}^H & a_2 \end{bmatrix} + \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{2e}^H \end{bmatrix} [\mathbf{H}_{21}^{\perp}\mathbf{W}_4'(\mathbf{H}_{21}^{\perp})^H + \mathbf{V}_2'] [\mathbf{I}, \bar{\mathbf{h}}_{2e}],$$
$$\Omega_3' = \begin{bmatrix} 1-\rho_1' & \delta_1\sqrt{\gamma_1} \\ \delta_1\sqrt{\gamma_1} & b_1 \end{bmatrix} + \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H\mathbf{H}_{12}^{\perp} \end{bmatrix} \mathbf{W}_3' \left[\mathbf{0}, (\mathbf{H}_{12}^{\perp})^H\mathbf{h}_{11}\right],$$
$$\Omega_4' = \begin{bmatrix} 1-\rho_2' & \delta_2\sqrt{\gamma_2} \\ \delta_2\sqrt{\gamma_2} & b_2 \end{bmatrix} + \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{22}^H\mathbf{H}_{21}^{\perp} \end{bmatrix} \mathbf{W}_4' \left[\mathbf{0}, (\mathbf{H}_{21}^{\perp})^H\mathbf{h}_{22}\right],$$
$$\Omega_5' = \begin{bmatrix} \rho_1' & \sqrt{q_1} \\ \sqrt{q_1} & c_1 \end{bmatrix} + \eta_1 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H\mathbf{H}_{12}^{\perp} \end{bmatrix} \mathbf{W}_3' \left[\mathbf{0}, (\mathbf{H}_{12}^{\perp})^H\mathbf{h}_{11}\right],$$
$$\Omega_6' = \begin{bmatrix} \rho_2' & \sqrt{q_2} \\ \sqrt{q_2} & c_2 \end{bmatrix} + \eta_2 \begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{22}^H\mathbf{H}_{21}^{\perp} \end{bmatrix} \mathbf{W}_4' \left[\mathbf{0}, (\mathbf{H}_{21}^{\perp})^H\mathbf{h}_{22}\right].$$

Therefore, the Lagrangian dual function of OP6 is given by

$$\begin{aligned}\mathcal{L}' &= \mathrm{tr}(\mathbf{A}'\mathbf{W}_3') + \mathrm{tr}(\mathbf{B}'\mathbf{W}_4') + \mathrm{tr}(\mathbf{V}_1') + \mathrm{tr}(\mathbf{V}_2') \\ &\quad - \Theta_1\left(\begin{bmatrix} \lambda_1'\mathbf{I} & \mathbf{0} \\ \mathbf{0}^H & a_1 \end{bmatrix} + \gamma_e\begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix}\mathbf{V}_1'\left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right]\right) \\ &\quad - \Theta_2\left(\begin{bmatrix} \lambda_2'\mathbf{I} & \mathbf{0} \\ \mathbf{0}^H & a_2 \end{bmatrix} + \begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{2e}^H \end{bmatrix}\mathbf{V}_2'\left[\mathbf{I}, \bar{\mathbf{h}}_{2e}\right]\right) \\ &\quad - \Theta_3\begin{bmatrix} 1-\rho_1' & \delta_1\sqrt{\gamma_1} \\ \delta_1\sqrt{\gamma_1} & b_1 \end{bmatrix} - \Theta_4\begin{bmatrix} 1-\rho_2' & \delta_2\sqrt{\gamma_2} \\ \delta_2\sqrt{\gamma_2} & b_2 \end{bmatrix} \\ &\quad - \Theta_5\begin{bmatrix} \rho_1' & \sqrt{q_1} \\ \sqrt{q_1} & c_1 \end{bmatrix} - \Theta_6\begin{bmatrix} \rho_2' & \sqrt{q_2} \\ \sqrt{q_2} & c_2 \end{bmatrix} \\ &\quad + d_1(m' - \gamma_e(n' + \sigma_e^2)),\end{aligned} \tag{45}$$

where $\mathbf{A}'$ and $\mathbf{B}'$ are given by

$$\begin{aligned}\mathbf{A}' &= (\mathbf{H}_{12}^{\perp})^H\left(\mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right]\Theta_1\begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix}\right)\mathbf{H}_{12}^{\perp} \\ &\quad - \left[\mathbf{0}, (\mathbf{H}_{12}^{\perp})^H\mathbf{h}_{11}\right](\Theta_3 + \eta_1\Theta_5)\begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H\mathbf{H}_{12}^{\perp} \end{bmatrix},\end{aligned} \tag{46}$$

$$\begin{aligned}\mathbf{B}' &= (\mathbf{H}_{21}^{\perp})^H\left(\mathbf{I} - \left[\mathbf{I}, \bar{\mathbf{h}}_{2e}\right]\Theta_2\begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{2e}^H \end{bmatrix}\right)\mathbf{H}_{21}^{\perp} \\ &\quad - \left[\mathbf{0}, (\mathbf{H}_{21}^{\perp})^H\mathbf{h}_{22}\right](\Theta_4 + \eta_2\Theta_6)\begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{22}^H\mathbf{H}_{21}^{\perp} \end{bmatrix},\end{aligned} \tag{47}$$

and $\{\Theta_i\}$ and d_1 are the Lagrange multipliers associated with the LMIs and inequality constraints in OP6. According to the KKT conditions, we have $\mathbf{A}'\mathbf{W}_3' = 0$, i.e.,

$$\begin{aligned}&\left((\mathbf{H}_{12}^{\perp})^H\left(\mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right]\Theta_1\begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix}\right)\mathbf{H}_{12}^{\perp} - \left[\mathbf{0}, (\mathbf{H}_{12}^{\perp})^H\mathbf{h}_{11}\right]\right. \\ &\qquad\left.(\Theta_3 + \eta_1\Theta_5)\begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H\mathbf{H}_{12}^{\perp} \end{bmatrix}\right)\mathbf{W}_3' = 0.\end{aligned} \tag{48}$$

Accordingly, the following relation holds

$$\begin{aligned}&\mathrm{rank}(\mathbf{W}_3') \\ &= \mathrm{rank}\left(\left((\mathbf{H}_{12}^{\perp})^H\left(\mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right]\Theta_1\begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix}\right)\mathbf{H}_{12}^{\perp}\right)\mathbf{W}_3'\right) \\ &= \mathrm{rank}\left(\left(\left[\mathbf{0}, (\mathbf{H}_{12}^{\perp})^H\mathbf{h}_{11}\right](\Theta_3 + \eta_1\Theta_5)\begin{bmatrix} \mathbf{0}^H \\ \mathbf{h}_{11}^H\mathbf{H}_{12}^{\perp} \end{bmatrix}\right)\mathbf{W}_3'\right) \\ &= 1,\end{aligned} \tag{49}$$

where the first equality holds due to the fact that $(\mathbf{H}_{12}^{\perp})^H\left(\mathbf{I} + \left[\mathbf{I}, \bar{\mathbf{h}}_{1e}\right]\Theta_1\begin{bmatrix} \mathbf{I} \\ \bar{\mathbf{h}}_{1e}^H \end{bmatrix}\right)\mathbf{H}_{12}^{\perp} \succ 0$, and the second equality is obtained from (48). Thus, the rank-one proof of $\mathbf{W}_3'$ is completed. The proof about the rank of $\mathbf{W}_4'$ is similar to the above and omitted for brevity here.

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