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Secure Downlink Transmission for Integrated Sensing, Energy, and Communication Systems

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***Abstract*—This paper proposes an integrated sensing, energy, and communication (ISEAC) system that considers secure communication. In this system, the base station (BS) is serving as one legitimate single-antenna information receiver (IR) whose position is known and multiple single-antenna energy receivers (ERs) that are considered as eavesdroppers whose locations are unknown and need to be detected. First, we propose a framework for designing transmitter beamforming to maximize the system secrecy rate under the energy-harvesting constraint and the sensing constraints. Next, we study the beamforming design of the system under imperfect channel status information (CSI). For the non-convex equations in these two cases, we use semidefinite relaxation (SDR) and Taylor expansion to transform the problem to the convex form. Finally, the simulation results verify the effective performance of the proposed optimal beamforming design.**

***Index Terms*—Integrated sensing, energy, and communication (ISEAC), secrecy rate, imperfect channel status information (CSI), Taylor series expansion.**

I. Introduction

INTEGRATED sensing and communication (ISAC) has been a vital technique for the next-generation wireless communication system since it is expected to improve spectrum utilization. The authors of [1] designed dual-function waveforms by weighted optimization, thus acquiring a flexible implementation tradeoff between sensing and communication. The advantages of deploying reconfigurable intelligent surfaces (RIS) in ISAC systems were studied in [2] by designing dual-function transmission waveforms jointly.

Furthermore, simultaneous wireless information and power transfer (SWIPT) has been an attractive approach for 6G systems. SWIPT is a crucial component of green communication and can ensure the continuous power supply of wireless communication equipment. Transmitting information and energy simultaneously was first proposed in [3]. The authors of [4] studied the weighted sum rate maximization in RIS-assisted SWIPT systems. They verified that RIS improves the performance of SWIPT systems by proposing an effective block coordinate descent (BCD) algorithm.

Regarding the broadcast character of wireless media, wireless communication systems may have security vulnerabilities, and both ISAC and SWIPT further increase vulnerability to eavesdropping. The authors of [5] investigated the beamforming design in an ISAC system to minimize the performance of eavesdroppers while ensuring the requirements of secure communication. The authors of [6] proposed suboptimal beamforming designs in the SWIPT systems with eavesdroppers and compared their performance regarding rate-energy tradeoffs.

Building upon the current research status of the aforementioned cutting-edge technologies, we have identified a research gap concerning the repurposing of residual resources within the domain of ISAC. The originality of our proposed integrated sensing, energy, and communication (ISEAC) system is demonstrated in its capability to not only harvest and store energy from residual transmission signals but also to innovate within the SWIPT framework. Traditionally, energy receivers (ERs) in SWIPT systems are perceived as eavesdroppers. Our proactive approach to eavesdropper detection has yielded evidence that such sensing mechanisms can markedly improve the security performance of the system. Our study, contrasting with the current research landscape, pioneers a novel perspective that is instrumental in optimizing the performance of systems susceptible to eavesdropping. Therefore, we propose a framework for designing transmitter beamforming of an ISEAC system. The contents of this paper are as follows, we aim to: 1) maximize the system secrecy rate ensuring the performance of sensing and ERs as well as the transmit power budget, where ERs are treated as eavesdroppers with perfect channel status information (CSI) and imperfect CSI, respectively; 2) use semidefinite relaxation (SDR), S-procedure, and Taylor expansion to transform the original problems to the convex form; 3) numerical results confirm the performance of proposed designs for systems.

II. System Model

Consider an ISEAC system shown in Fig. 1, where there is an ISEAC base station (BS) equipped with N transmit/receive antennas serving one single-antenna information receiver (IR) and K single-antenna ERs. We consider that there exists secret information transmission to the IR, and the energy signals also realize the role of artificial noise (AN) to reduce the information rate eavesdropped by ERs. We assume that the

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ISAEC BS could acquire part of the CSI by detecting the position of eavesdroppers with the Angle of Arrival (AOA). The baseband signal transmitted from the BS can be given as

$$\boldsymbol{x} = \boldsymbol{w}s_0 + \sum\nolimits_{k=1}^{K} \boldsymbol{v}_k s_k, \tag{1}$$

where $\boldsymbol{w}\in\mathbb{C}^{N\times 1}$ and $\boldsymbol{v}_k\in\mathbb{C}^{N\times 1}$ are the information beamforming vector and the kth energy beamforming vector, while s_0 and s_k are IR's information-bearing signal and kth ER's energy-carrying signal, respectively. Without loss of generality, $\mathbb{E}\{|s_k s_k^H|\} = 1, k = 0, 1, ..., K$. The signal received by the IR is expressed as

$$y_I = \boldsymbol{h}^H \boldsymbol{w} s_0 + \sum\nolimits_{k=1}^{K} \boldsymbol{h}^H \boldsymbol{v}_k s_k + z_I, \tag{2}$$

where $\boldsymbol{h}\in\mathbb{C}^{N\times 1}$ is the channel vector between the BS and the IR, and $z_I \sim \mathcal{CN}(0, \sigma_I^2)$. The signal-to-interference-plus-noise ratio (SINR) of the IR can be written as

$$\gamma_I = \frac{|\boldsymbol{h}^H \boldsymbol{w}|^2}{\sum_{k=1}^{K} |\boldsymbol{h}^H \boldsymbol{v}_k|^2 + \sigma_I^2}. \tag{3}$$

The received signal at the kth ER can be expressed as

$$y_k = \boldsymbol{g}_k \boldsymbol{w} s_0 + \boldsymbol{g}_k \boldsymbol{v}_k s_k + \sum\nolimits_{i=1, i\neq k}^{K} \boldsymbol{g}_k \boldsymbol{v}_i s_i + z_k, \tag{4}$$

where $\boldsymbol{g}_k\in\mathbb{C}^{N\times 1}$ is the channel vector between the BS and the kth ER, and $z_k \sim \mathcal{CN}(0, \sigma_k^2)$. For the SWIPT, the energy is carried by $s_k, \forall k$. Hence, the energy harvested by all the ERs is expressed as

$$Q = \zeta \sum\nolimits_{k=1}^{K} \left(|\boldsymbol{g}_k^H \boldsymbol{w}|^2 + \sum\nolimits_{l=1}^{K} |\boldsymbol{g}_k \boldsymbol{v}_l|^2 \right), \tag{5}$$

where ζ denotes the energy harvesting efficiency. Since $\boldsymbol{v}_l$ denotes the beamforming vector of AN, the received SINR at the kth ER is

$$\gamma_k = \frac{|\boldsymbol{g}_k^H \boldsymbol{w}|^2}{\sum_{l=1}^{K} |\boldsymbol{g}_k \boldsymbol{v}_l|^2 + \sigma_k^2}. \tag{6}$$

The system secrecy rate is expressed by

$$r = \log_2(1+\gamma_I) - \sum\nolimits_{k=1}^{K} \log_2(1+\gamma_k). \tag{7}$$

The echo signal received at the BS can be expressed as

$$\begin{aligned} \boldsymbol{y}_e = \sum\nolimits_{k=1}^{K} \Bigg(& \boldsymbol{G}_k \boldsymbol{w} s_0 + \sum\nolimits_{k=1}^{K} \boldsymbol{G}_k \boldsymbol{v}_k s_k \\ & + \sum\nolimits_{i=1, i\neq k}^{K} \boldsymbol{G}_i \left(\boldsymbol{w} s_0 + \sum\nolimits_{l=1}^{K} \boldsymbol{v}_l s_l \right) \Bigg) + \boldsymbol{z}_r, \end{aligned} \tag{8}$$

where α is reflection coefficient, $\boldsymbol{G}_k = \boldsymbol{g}_k \boldsymbol{g}_k^H$, $\boldsymbol{z}_r = \sum_{k=1}^{K} \boldsymbol{z}_{r,k}$, and $\boldsymbol{z}_{r,k} \sim \mathcal{CN}(0, \sigma_{r,k}^2 \mathbf{I}_N)$. Since eavesdroppers receive IR-specific beams of information and decode them to get the message, the sensing SINR of the kth ER is expressed as

$$\begin{aligned} \gamma_{r,k} &= \frac{||\boldsymbol{G}_k^H \boldsymbol{w}||^2}{\sum\limits_{l=1}^{K} ||\boldsymbol{G}_k \boldsymbol{v}_l||^2 + \sum\limits_{i=1, i\neq k}^{K} ||\boldsymbol{G}_i \boldsymbol{x}||^2 + \sigma_{r,k}^2} \\ &= \frac{\mathrm{tr}\left(\boldsymbol{G}_k \boldsymbol{G}_k^H \boldsymbol{w}\boldsymbol{w}^H\right)}{\sum\limits_{i\neq k}^{K} \mathrm{tr}\left(\boldsymbol{G}_i \boldsymbol{G}_i^H \boldsymbol{w}\boldsymbol{w}^H\right) + \sum\limits_{k=1}^{K} \sum\limits_{l=1}^{K} \mathrm{tr}\left(\boldsymbol{G}_k \boldsymbol{G}_k^H \boldsymbol{v}_l \boldsymbol{v}_l^H\right) + \sigma_{r,k}^2}. \end{aligned} \tag{9}$$

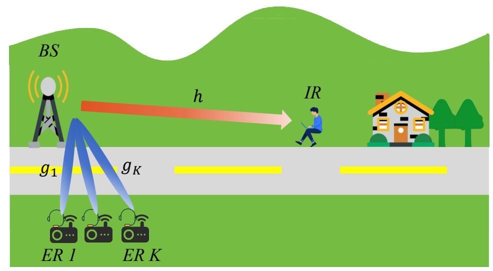

Fig. 1. An ISEAC system.

III. Problem Formulation and Proposed Solutions

This section considers a secrecy beamforming design problem that aims to maximize the system secrecy rate while ensuring the constraints: 1) the lower bound of energy harvested by all ERs; 2) the lower bound of the sensing SINR of each ER; 3) the upper bound of the overall power. The problem is thus given by

$$\max_{\boldsymbol{w}, \boldsymbol{v}_k, \forall k} \quad r \tag{10a}$$

$$\text{s.t.} \quad Q \geq \overline{Q}, \tag{10b}$$

$$\gamma_{r,k} \geq \overline{\gamma_{r,k}}, \forall k, \tag{10c}$$

$$||\boldsymbol{w}||^2 + \sum_{k=1}^{K} ||\boldsymbol{v}_k||^2 \leq P. \tag{10d}$$

We set $\boldsymbol{W} = \boldsymbol{w}\boldsymbol{w}^H$, $\boldsymbol{V}_k = \boldsymbol{v}_k \boldsymbol{v}_k^H$, $\boldsymbol{H} = \boldsymbol{h}\boldsymbol{h}^H$, $\boldsymbol{U}_k = \boldsymbol{G}_k \boldsymbol{G}_k^H$, $\forall k$. In the following, we assume that $\{\boldsymbol{g}_k\}_{k=1}^{K}$ are perfect and imperfect, respectively.

A. Perfect CSI

Because of the non-convexity of the target value, we use the Taylor series extension method to transform it into the convex form.

Proposition 1. The first order Taylor expansion of the secrecy rate at a feasible point $(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)$ gives the following approximate formula

$$\begin{aligned} \widetilde{r} = & \log_2 \left(\mathrm{tr}(\boldsymbol{H}\boldsymbol{W}) + \sum_{k=1}^{K} \mathrm{tr}(\boldsymbol{H}\boldsymbol{V}_k) + \sigma_I^2 \right) \\ & - \left(\log_2 \left| \sum_{k=1}^{K} \mathrm{tr}(\boldsymbol{H}\tilde{\boldsymbol{V}}_k) + \sigma_I^2 \right| + \frac{\sum_{l=1}^{K} \mathrm{tr}(\boldsymbol{H}(\boldsymbol{V}_l - \tilde{\boldsymbol{V}}_l))}{\ln 2 \sum_{k=1}^{K} \mathrm{tr}(\boldsymbol{H}\tilde{\boldsymbol{V}}_k) + \sigma_I^2} \right) \\ & - \sum_{k=1}^{K} \log_2 \left| \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{W}}) + \sum_{i=1}^{K} \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{V}}_i) + \sigma_k^2 \right| \\ & - \frac{1}{\ln 2} \cdot \sum_{k=1}^{K} \frac{\mathrm{tr}(\boldsymbol{G}_k(\boldsymbol{W} - \tilde{\boldsymbol{W}}))}{\mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{W}}) + \sum_{i=1}^{K} \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{V}}_i) + \sigma_k^2} \\ & - \frac{1}{\ln 2} \cdot \sum_{l=1}^{K} \sum_{k=1}^{K} \frac{\mathrm{tr}(\boldsymbol{G}_k(\boldsymbol{V}_l - \tilde{\boldsymbol{V}}_l))}{\mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{W}}) + \sum_{i=1}^{K} \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{V}}_i) + \sigma_k^2} \\ & + \sum_{k=1}^{K} \log_2 \left(\sum_{i=1}^{K} \mathrm{tr}(\boldsymbol{G}_k \boldsymbol{V}_i) + \sigma_k^2 \right) \end{aligned} \tag{11}$$

Proof: Please refer to Appendix A.

Therefore, (10) can be written as

$$\max_{\boldsymbol{W},\boldsymbol{V}_k,\forall k} \quad \widetilde{r} \tag{12a}$$

s.t.

$$\zeta \sum_{k=1}^{K} \left(\mathrm{tr}(\boldsymbol{G}_k \boldsymbol{W}) + \sum_{l=1}^{K} \mathrm{tr}(\boldsymbol{G}_k \boldsymbol{V}_l) \right) \geq \overline{Q}, \tag{12b}$$

$$\frac{\mathrm{tr}\,(\boldsymbol{U}_k \boldsymbol{W})}{\sum\limits_{i=1,i\neq k}^{K} \mathrm{tr}\,(\boldsymbol{U}_i \boldsymbol{W}) + \sum\limits_{k=1}^{K} \sum\limits_{l=1}^{K} \mathrm{tr}\,(\boldsymbol{U}_k \boldsymbol{V}_l) + \sigma_{r,k}^2} \geq \gamma_k, \forall k, \tag{12c}$$

$$\mathrm{tr}(\boldsymbol{W}) + \sum_{k=1}^{K} \mathrm{tr}(\boldsymbol{V}_k) \leq P, \tag{12d}$$

$$\mathrm{rank}(\boldsymbol{W}) = \mathrm{rank}(\boldsymbol{V}_k) = 1, \forall k. \tag{12e}$$

By removing (12e), Problem (12) can be transformed into a standard semidefinite programming (SDP) [6], which can be solved by the CVX tool. The rank-1 constraint can be achieved by using the Gaussian randomization method [7].

B. Imperfect CSI

We consider Problem (10) with the additional assumption that the BS has imperfect CSI on ERs' links. Channel vector errors can adversely affect the system's security capabilities, given that the efficacy of beamforming techniques depends on the precision of CSI to accurately steer signals towards authorized recipients. We consider Problem (10) with the additional assumption that the BS has imperfect CSI on ERs' links. To achieve secure beamforming design under the worst-case scenario, we consider the bounded error model. Let

$$\boldsymbol{g}_k = \hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k, \forall k, \tag{13}$$

where $\hat{\boldsymbol{g}}_k$ denotes the contaminated channel vector and $\Delta \boldsymbol{g}_k$ denotes the corresponding channel error vector. We adopt the channel error bounded model, i.e., $||\Delta \boldsymbol{g}_k||^2 \leq \epsilon_k$, where $\epsilon_k, \forall k$ is the radius of the uncertainty region known by the BS. For simplicity, we ignore the imperfect CSI of other channels when calculating the sensing SINR of the kth ER. By taking β_k as an upper bound on the sum rate of the kth ER, we formulate the beamforming design problem as follows

$$\max_{\boldsymbol{W},\boldsymbol{V},\beta} \quad \log_2 \left(1 + \frac{\boldsymbol{h}^H \boldsymbol{W} \boldsymbol{h}}{\boldsymbol{h}^H \left(\sum_{l=1}^{k} \boldsymbol{V}_l \right) \boldsymbol{h} + \sigma_I^2} \right) - \sum_{k=1}^{K} \beta_k \tag{14a}$$

s.t.

$$\log_2 \left(1 + \frac{(\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)^H \boldsymbol{W} (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)}{(\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)^H \sum\limits_{l=1}^{K} \boldsymbol{V}_l (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k) + \sigma_k^2} \right) \leq \beta_k, \forall k, \tag{14b}$$

$$\zeta (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)^H \boldsymbol{W} (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k) + \zeta \sum_{l=1}^{K} (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)^H \boldsymbol{V}_l (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k) \geq \overline{Q}_k, \forall k, \tag{14c}$$

$$\frac{X_k}{Y_k + \sigma_{r,k}^2} \geq \overline{\gamma}_{r,k}, \forall k, \tag{14d}$$

$$||\Delta \boldsymbol{g}_k||^2 \leq \epsilon_k, (12d), (12e), \tag{14e}$$

where $X_k = \mathrm{tr}\,(\boldsymbol{t}_k \boldsymbol{W} \boldsymbol{t}_k)$, $\boldsymbol{t}_k = (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)(\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)^H$, $Y_k = \sum\limits_{i=1,i\neq k}^{K} \mathrm{tr} \left(\boldsymbol{G}_i \boldsymbol{G}_i^H \left(\boldsymbol{W} + \sum\limits_{l=1}^{K} \boldsymbol{V}_l \right) \right) + \sum\limits_{l=1}^{K} \mathrm{tr}\,(\boldsymbol{t}_k \boldsymbol{V}_l \boldsymbol{t}_k)$.

Lemma 1. (Generalized S-Procedure) Consider the quadratic functions:

$$f_i(\boldsymbol{x}) = \boldsymbol{x}^H \mathbf{W}_i \boldsymbol{x} + 2\mathrm{Re}\{\mathbf{w}_i \boldsymbol{x}\} + w_i, i = 0, ..., P, \tag{15}$$

where $\mathbf{W}_i = \mathbf{W}_i^H$, $\boldsymbol{x} \in \mathbb{C}^{n\times 1}$. $\{f_i(\boldsymbol{x}) \geq 0\}_{i=1}^{P} \Rightarrow f_0(\boldsymbol{x}) \geq 0$ is satisfied if and only if there exist $\forall i$, $p_i \geq 0$ such that

$$\begin{bmatrix} \mathbf{W}_0 & \mathbf{w}_0 \\ \mathbf{w}_0^H & w_0 \end{bmatrix} - \sum_{i=1}^{P} p_i \begin{bmatrix} \mathbf{W}_i & \mathbf{w}_i \\ \mathbf{w}_i^H & w_i \end{bmatrix} \succeq 0.$$

We define that $\boldsymbol{U}_1 = \sum_{l=1}^{K} (2^{\beta_k} - 1) \boldsymbol{V}_l - \boldsymbol{W}$, $\boldsymbol{U}_2 = \boldsymbol{W} + \sum_{l=1}^{K} \boldsymbol{V}_l$, $m_1 = \sigma_k^2 (2^{\beta_k} - 1)$, $m_2 = \frac{\overline{Q}_k}{\zeta}$.

We set the parameters as follows

$$P = 1, \mathbf{W}_0 = \boldsymbol{U}_i, \mathbf{w}_0 = \boldsymbol{U}_i \hat{\boldsymbol{g}}_k, w_0 = \hat{\boldsymbol{g}}_k^H \boldsymbol{U}_i \hat{\boldsymbol{g}}_k - m_i,$$
$$\boldsymbol{x} = \Delta \boldsymbol{g}_k, \mathbf{W}_1 = -\mathbf{I}, w_1 = \xi_k^2, i = 1, 2, \forall k.$$

Thus, (14b) and (14c) can be transformed into the following equivalent linear matrix inequalities (LMIs) as

$$\boldsymbol{T}_i = \begin{bmatrix} \boldsymbol{U}_i + p_i \mathbf{I}_N & \hat{\boldsymbol{g}}_k^H \boldsymbol{U}_i \\ \boldsymbol{U}_i \hat{\boldsymbol{g}}_k & \hat{\boldsymbol{g}}_k^H \boldsymbol{U}_i \hat{\boldsymbol{g}}_k - m_i - p_i \xi_k^2 \end{bmatrix} \succeq 0, i = 1, 2, \forall k. \tag{16}$$

Lemma 2. By defining $\boldsymbol{U}_3 = \boldsymbol{W} - \gamma_{r,k}^2 \sum_{l=1}^{K} \boldsymbol{V}_l$, (14d) can be expressed as

$$T_3 = \begin{bmatrix} \mathrm{tr}(\boldsymbol{U}_3) & 2\mathrm{tr}(\boldsymbol{U}_3) & 2\mathrm{tr}(\boldsymbol{U}_3) \\ 2\mathrm{tr}(\boldsymbol{U}_3) & 2\mathrm{tr}(\boldsymbol{U}_3) + p_3/|\hat{\boldsymbol{g}}_k|^2 & 2\mathrm{tr}(\boldsymbol{U}_3) \\ 2\mathrm{tr}(\boldsymbol{U}_3) & 2\mathrm{tr}(\boldsymbol{U}_3) & \mathrm{tr}(\boldsymbol{U}_3) - B_k \end{bmatrix} \succeq 0, \tag{17}$$

where $B_k = \frac{A_{-k} - p_3 \xi_k |\hat{\boldsymbol{g}}_k|^2}{|\hat{\boldsymbol{g}}_k|^2}$.

Proof: Please refer to Appendix B.

By using Taylor expansion, Problem (14) can be finally rewritten as the following convex SDP problem

$$\max_{\boldsymbol{W},\boldsymbol{V}_l,\beta_k,p_1,p_2,p_3} \quad \log_2 \left(\boldsymbol{h}^H \boldsymbol{W} \boldsymbol{h} + \sum_{l=1}^{K} \boldsymbol{h}^H \boldsymbol{V}_l \boldsymbol{h} + \sigma_I^2 \right) - \sum_{l=1}^{K} \log_2 \left| \boldsymbol{h}^H \tilde{\boldsymbol{V}} \boldsymbol{h} \right| - \sum_{l=1}^{K} \frac{1}{\ln 2} \cdot \frac{\boldsymbol{h}^H (\boldsymbol{V} - \tilde{\boldsymbol{V}}) \boldsymbol{h}}{\boldsymbol{h}^H \tilde{\boldsymbol{V}} \boldsymbol{h} + \sigma_I^2} - \sum_{k=1}^{K} \beta_k \tag{18a}$$

$$\text{s.t.} \quad \boldsymbol{T}_i \succeq 0, i = 1, 2, 3, \tag{18b}$$

$$(12d), (12e), \tag{18c}$$

where $p_i > 0, \forall i$. The problem still ignores the rank-1 constraint, which could be solved by the Gaussian randomization method.

Problems (12) and (18) are solved via SDR technique, the computational complexity are $\mathcal{O}(\max\{K + 2, N\}^4 p N^{1/2} \log(1/\epsilon))$ and $\mathcal{O}(\max\{3K + 1, N\}^4 p N^{1/2} \log(1/\epsilon))$, respectively.

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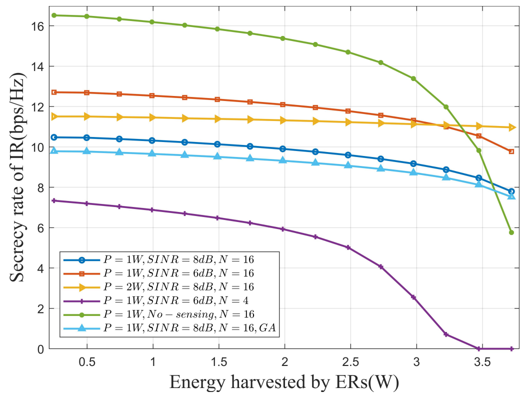

Fig. 2. The system secrecy rate versus the predefined value of energy harvesting.

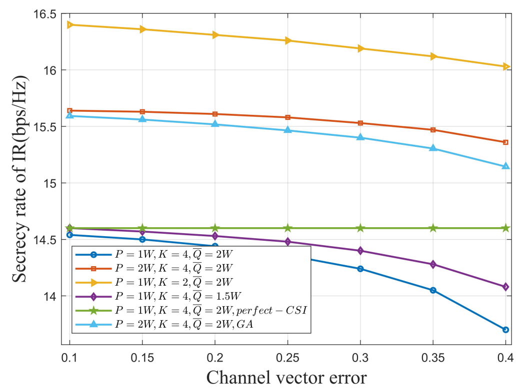

Fig. 3. The system secrecy rate versus the predefined value of energy harvesting with different channel vector errors.

IV. Simulation

This section provides numerical results to indicate the performance of the proposed design. We consider an ISEAC BS equipped with 16 transmit/receive antennas serving 1 IR and 4 ERs, where ERs are considered eavesdroppers, and their respective locations require detection. The noise variances are set as $\sigma_I^2 = \sigma_k^2 = \sigma_{r,k}^2 = 0$ dBm. Without loss of generality, the channel vectors $\boldsymbol{h}$ and $\{\boldsymbol{g}_k\}_{k=1}^K$ obey i.i.d. complex Gaussian distribution. Considering the robustness of Genetic Algorithm (GA), we use it as benchmark against our proposed solutions using CVX. The MATLAB GA toolbox applied to obtain the secrecy rate, where we set the probability of crossover and mutation probability at 0.8 and 0.02, respectively. Unless otherwise stated, the other parameters are set as follows: $P = 30$ dBm, $\zeta = 0.5$, $\alpha = 1$, $\overline{Q} = 1.5$ W.

Fig. 2 presents the system secrecy rate versus the predefined value of energy harvesting by ERs. It could be seen from Fig. 2 that the system secrecy rate decreases with increasing predefined values of energy harvesting. When the energy threshold at ERs increases, the power allocated by the BS to the IR decreases, thereby reducing the secrecy rate and increasing the risk of eavesdropping. Benchmarked against GA, it can be observed that the Taylor approximation employed in our proposed scheme exhibits a high degree of accuracy. It is also observed from Fig. 2 that the secrecy rate is higher with a lower sensing SINR bound. However, the secrecy rate without sensing decreases rapidly with extremely high energy harvesting requirements, which demonstrates that the scheme with sensing is effective.

Fig. 3 provides the system secrecy rate versus the channel uncertainty level. It can be seen from Fig. 3 that the schemes with higher transmission power and fewer eavesdroppers are more robust when the CSI is imperfect. However, the secrecy rate without sensing decreases rapidly with extremely high energy harvesting requirements. The reason is that we can strategically employ beamforming techniques to concentrate the transmission of confidential signals towards our legitimate users with the sensing of the eavesdropper's location, which demonstrates that the scheme with sensing is effective. It can be seen from Fig. 3 that the schemes with higher transmission power and fewer eavesdroppers are more robust when the CSI is imperfect. The occurrence of this phenomenon can be attributed to the fact that elevated transmission power enables a more concentrated delivery of signals to legitimate users, subsequently amplifying the quality of their communications. Concurrently, a diminished count of eavesdroppers correlates with a decrease in potential interception endeavors, thereby bolstering the system's security measures.

V. Conclusion

In this paper, we proposed a beamforming design in an ISEAC system. In particular, we formulated an optimization problem to design the beamforming vectors by maximizing the secrecy rate at the IR while ensuring the sensing SINR constraints and the ERs' energy harvesting constraint. Considering the non-convex optimization problems with perfect CSI and imperfect CSI, we transformed them into the convex form through Taylor expansion, S-procedure, and the SDR approach, where we used the Gaussian randomization algorithm to solve the rank-one constraint. Numerical results demonstrated the performance of the proposed ISEAC beamforming design and trade-offs between secrecy rates and other factors.

Appendix A
Derivation of First Order Taylor Expansion of Secure Rate

Equation (7) can be express as

$$\begin{aligned}
&\log_2\left(\operatorname{tr}(\boldsymbol{H}\boldsymbol{W}) + \sum_{k=1}^{K}\operatorname{tr}(\boldsymbol{H}\boldsymbol{V}_k) + \sigma_I^2\right) \\
&- \log_2\left(\sum_{k=1}^{K}\operatorname{tr}(\boldsymbol{H}\boldsymbol{V}_k) + \sigma_I^2\right) \\
&- \sum_{k=1}^{K}\log_2\left(\operatorname{tr}(\boldsymbol{G}_k\boldsymbol{W}) + \sum_{i=1}^{K}\operatorname{tr}(\boldsymbol{G}_k\boldsymbol{V}_i) + \sigma_k^2\right) \\
&+ \sum_{k=1}^{K}\log_2\left(\sum_{i=1}^{K}\operatorname{tr}(\boldsymbol{G}_k\boldsymbol{V}_i) + \sigma_k^2\right)
\end{aligned} \tag{19}$$

To transform the target value to the convex form, we approximate the second term and the third term to affine functions based on the Taylor series at $(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)$, an arbitrary feasible point. Defining $f_2 = \log_2\left(\sum_{k=1}^{K}\operatorname{tr}(\boldsymbol{H}\boldsymbol{V}_k) + \sigma_I^2\right)$

$$
\begin{aligned}
&\mathrm{tr}\left(\boldsymbol{J}_k \boldsymbol{U}_3\right) - A_{-k} \geq 0 \\
\Rightarrow &\mathrm{tr}\left(\hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H + \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H + \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H + \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \right.\\
&+ \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H + \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H + \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H + \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \\
&+ \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H + \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H + \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H + \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \\
&\left. + \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H + \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \hat{\boldsymbol{g}}_k \Delta \boldsymbol{g}_k^H + \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H + \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \boldsymbol{U_3} \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \right) - A_{-k} \geq 0 \\
\Rightarrow &\mathrm{tr}(\boldsymbol{U_3}) \left(\Delta \boldsymbol{g}_k^H \Delta \boldsymbol{g}_k \Delta \boldsymbol{g}_k^H \Delta \boldsymbol{g}_k + 4 \Delta \boldsymbol{g}_k^H \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H \Delta \boldsymbol{g}_k + 6 \Delta \boldsymbol{g}_k^H \Delta \boldsymbol{g}_k \hat{\boldsymbol{g}}_k^H \hat{\boldsymbol{g}}_k + 4 \hat{\boldsymbol{g}}_k^H \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H \Delta \boldsymbol{g}_k + \hat{\boldsymbol{g}}_k^H \hat{\boldsymbol{g}}_k \hat{\boldsymbol{g}}_k^H \hat{\boldsymbol{g}}_k \right) - A_{-k} \geq 0 \\
\Rightarrow &\left[\Delta \boldsymbol{g}_k^H \Delta \boldsymbol{g}_k \quad \Delta \boldsymbol{g}_k^H \hat{\boldsymbol{g}}_k \quad \hat{\boldsymbol{g}}_k^H \hat{\boldsymbol{g}}_k \right] \begin{bmatrix} \mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) \\ 2\mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) \\ 2\mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) & \mathrm{tr}(\boldsymbol{U_3}) - \boldsymbol{A}_{-k}/|\hat{\boldsymbol{g}}_k|^4 \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{g}_k^H \Delta \boldsymbol{g}_k \\ \hat{\boldsymbol{g}}_k^H \Delta \boldsymbol{g}_k \\ \hat{\boldsymbol{g}}_k^H \hat{\boldsymbol{g}}_k \end{bmatrix} \geq 0 \overset{\triangle}{\Rightarrow} \boldsymbol{b}_k^H \boldsymbol{F}_k \boldsymbol{b}_k \geq 0. \qquad (23)
\end{aligned}
$$

and $f_3 = \sum_{k=1}^K \log_2 \left(\mathrm{tr}(\boldsymbol{G}_k \boldsymbol{W}) + \sum_{l=1}^K \mathrm{tr}(\boldsymbol{G}_k \boldsymbol{V}_l) + \sigma_k^2 \right)$, the functions obtained by Taylor expansion at this point are as follows

$$
\begin{aligned}
&f_2(\boldsymbol{W}, \boldsymbol{V}_k) = f_2(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k) \\
&+ \left[\frac{\partial f_2}{\partial \mathrm{Re}\,[\boldsymbol{W}]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)}, \frac{\partial f_2}{\partial \mathrm{Re}\,[\boldsymbol{V}_k]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)} \right] \begin{bmatrix} \boldsymbol{W} - \tilde{\boldsymbol{W}} \\ \boldsymbol{V}_k - \tilde{\boldsymbol{V}}_k \end{bmatrix} \\
&+ \left[\frac{\partial f_2}{\partial \mathrm{Im}\,[\boldsymbol{W}]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)}, \frac{\partial f_2}{\partial \mathrm{Im}\,[\boldsymbol{V}_k]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)} \right] \begin{bmatrix} \boldsymbol{W} - \tilde{\boldsymbol{W}} \\ \boldsymbol{V}_k - \tilde{\boldsymbol{V}}_k \end{bmatrix} \\
&= \log_2 \left| \sum_{k=1}^K \mathrm{tr}(\boldsymbol{H} \tilde{\boldsymbol{V}}_k) + \sigma_I^2 \right| + \frac{1}{\ln 2} \cdot \frac{\sum_{l=1}^K \mathrm{tr}(\boldsymbol{H}(\boldsymbol{V}_l - \tilde{\boldsymbol{V}}_l))}{\sum_{k=1}^K \mathrm{tr}(\boldsymbol{H} \tilde{\boldsymbol{V}}_k) + \sigma_I^2}, \qquad (20)
\end{aligned}
$$

$$
\begin{aligned}
&f_3(\boldsymbol{W}, \boldsymbol{V}_k) = f_3(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k) \\
&+ \left[\frac{\partial f_3}{\partial \mathrm{Re}\,[\boldsymbol{W}]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)}, \frac{\partial f_3}{\partial \mathrm{Re}\,[\boldsymbol{V}_k]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)} \right] \begin{bmatrix} \boldsymbol{W} - \tilde{\boldsymbol{W}} \\ \boldsymbol{V}_k - \tilde{\boldsymbol{V}}_k \end{bmatrix} \\
&+ \left[\frac{\partial f_3}{\partial \mathrm{Im}\,[\boldsymbol{W}]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)}, \frac{\partial f_3}{\partial \mathrm{Im}\,[\boldsymbol{V}_k]} \bigg|_{(\tilde{\boldsymbol{W}}, \tilde{\boldsymbol{V}}_k)} \right] \begin{bmatrix} \boldsymbol{W} - \tilde{\boldsymbol{W}} \\ \boldsymbol{V}_k - \tilde{\boldsymbol{V}}_k \end{bmatrix} \\
&= \sum_{k=1}^K \log_2 \left| \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{W}}) + \sum_{i=1}^K \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{V}}_i) + \sigma_k^2 \right| \\
&+ \frac{1}{\ln 2} \cdot \sum_{k=1}^K \frac{\mathrm{tr}(\boldsymbol{G}_k(\boldsymbol{W} - \tilde{\boldsymbol{W}}))}{\mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{W}}) + \sum_{i=1}^K \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{V}}_i) + \sigma_k^2} \\
&+ \frac{1}{\ln 2} \cdot \sum_{l=1}^K \sum_{k=1}^K \frac{\mathrm{tr}(\boldsymbol{G}_k(\boldsymbol{V}_l - \tilde{\boldsymbol{V}}_l))}{\mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{W}}) + \sum_{i=1}^K \mathrm{tr}(\boldsymbol{G}_k \tilde{\boldsymbol{V}}_i) + \sigma_k^2}. \qquad (21)
\end{aligned}
$$

Appendix B
Proof of Lemma 2

By defining $\boldsymbol{U}_3 = \boldsymbol{W} - \gamma_{r,k}^2 \sum_{l=1}^K \boldsymbol{V}_l$, (14d) can be written as

$$
\mathrm{tr}\left(\boldsymbol{J}_k \boldsymbol{U}_3\right) - A_{-k} \geq 0, \forall k, \qquad (22)
$$

where $\boldsymbol{J}_k = (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)(\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)^H (\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)(\hat{\boldsymbol{g}}_k + \Delta \boldsymbol{g}_k)^H$, $A_{-k} = \gamma_{r,k} \sum_{i=1, i \neq k}^K \mathrm{tr}\left(\boldsymbol{G}_i \boldsymbol{G}_i^H \left(\boldsymbol{W} + \sum_{l=1}^K \boldsymbol{V}_l \right) \right) + \gamma_{r,k} \sigma_{r,k}^2$.

By processing $\mathrm{tr}\left(\boldsymbol{J}_k \boldsymbol{U}_3\right)$, we have (23). $|\Delta \boldsymbol{g}_k|^2 \leq \epsilon_k$ can be transformed as

$$
\boldsymbol{b}_k^H \begin{bmatrix} 0 & 0 & 0 \\ 0 & -1/|\hat{\boldsymbol{g}}_k|^2 & 0 \\ 0 & 0 & \epsilon_k/|\hat{\boldsymbol{g}}_k|^2 \end{bmatrix} \boldsymbol{b}_k \geq 0. \qquad (24)
$$

With (23) and Lemma 1, (14) is reformulated as

$$
\begin{aligned}
\boldsymbol{T}_3 &= F_k - \begin{bmatrix} 0 & 0 & 0 \\ 0 & -p_3/|\hat{\boldsymbol{g}}_k|^2 & 0 \\ 0 & 0 & \epsilon_k/|\hat{\boldsymbol{g}}_k|^2 \end{bmatrix} \\
&= \begin{bmatrix} \mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) \\ 2\mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) + p_3/|\hat{\boldsymbol{g}}_k|^2 & 2\mathrm{tr}(\boldsymbol{U_3}) \\ 2\mathrm{tr}(\boldsymbol{U_3}) & 2\mathrm{tr}(\boldsymbol{U_3}) & \mathrm{tr}(\boldsymbol{U_3}) - B_k \end{bmatrix} \succeq 0, \qquad (25)
\end{aligned}
$$

where $B_k = \frac{\boldsymbol{A}_{-k} - p_3 \epsilon_k |\hat{\boldsymbol{g}}_k|^2}{|\hat{\boldsymbol{g}}_k|^2}$.

References

[1] F. Liu et al., "Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728-1767, June 2022.

[2] R. Liu, M. Li, Y. Liu, Q. Wu and Q. Liu, "Joint Transmit Waveform and Passive Beamforming Design for RIS-Aided DFRC Systems," *IEEE J. Sel. Topics Signal Process.*, vol. 16, no. 5, pp. 995-1010, Aug. 2022.

[3] L. R. Varshney, "Transporting information and energy simultaneously," *2008 IEEE International Symposium on Information Theory*, 2008, pp. 1612-1616.

[4] C. Pan et al., "Intelligent Reflecting Surface Aided MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1719-1734, Aug. 2020.

[5] N. Su, F. Liu, and C. Masouros, "Secure radar-communication systems with malicious targets: Integrating radar, communications and jamming functionalities," *IEEE Trans. Wireless Commun.*, vol. 20, no. 1, pp. 83–95, Jan. 2021.

[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, April1, 2014.

[7] 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.

[8] 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, Sept.15, 2014.

[9] Z. -M. Jiang, P. Zhang, L. Huang, M. Rihan and J. Zhang, "A Novel Energy Harvesting-Enabled Design for Radar and Communication Coexistence," *2019 6th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR)*, 2019, pp. 1-5.

[10] F. Liu et al., "Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728-1767, June 2022.