Robust MISO Beamforming With Cooperative Jamming for Secure Transmission From Perspectives of QoS and Secrecy Rate

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***Abstract*— Robust quality-of-service (QoS)-based and secrecy rate-based secure transmission designs are investigated for a multiple-input single-output system with multiple eavesdroppers and a cooperative jammer. Two scenarios are considered: (a) eavesdroppers' channel state information (ECSI) is available and (b) ECSI is unavailable. In scenario (a), a QoS-based design is considered to minimize the worst case signal-to-interference-and-noise ratio at the eavesdroppers and to guarantee the QoS of the legitimate receiver. A secrecy rate-based design is also studied where the worst case secrecy rate is maximized. In scenario (b), a QoS-based design is considered to maximize the power of jamming signals under the QoS constraint of the legitimate receiver, and the secrecy rate-based design is not applicable. In all these designs, we jointly optimize the transmit beamforming vector and the covariance matrix of jamming signals under individual power constraints. As the optimization problems are non-convex, we propose an algorithm for each problem through semidefinite relaxation. Our analysis and simulation results show that, even though the linear precoding scheme in our designs is transmit beamforming rather than the general rank transmit covariance, this does not cause any loss of optimality.**

***Index Terms*— Cooperative jamming, multiple-input single-output, quality of service, secrecy rate, secure transmit beamforming, semidefinite programming.**

I. Introduction

PHYSICAL layer security, which aims at providing information security by employing the physical layer characteristics, has attracted much research attention. This research area was initiated by Wyner, who introduced and studied the wiretap channel by considering one legitimate receiver's single-input-single-output (SISO) channel and one eavesdropper's SISO channel [1]. Wyner claimed that information can be reliably transmitted to the legitimate receiver at a positive rate and achieve perfect secrecy from the eavesdropper when the eavesdropper's channel is a degraded version of the legitimate receiver's channel. This rate is defined as the secrecy rate. Motivated by the wide application of multi-antenna technique, recent research in physical layer security has focused on multi-antenna transmission.

In multi-antenna communication systems, linear precoding has been proven to be an effective transmit strategy to concentrate the information signal and control the power leakage [2]–[8]. Consequently, optimizing the linear precoding scheme (i.e., optimize the transmit beamforming vector or the transmit covariance[1]) is an effective approach in the secure transmission design for multi-antenna systems [9]–[13]. In addition, the security performance of multi-antenna systems can be further enhanced by artificial noise (AN), in which part of the power at the information transmitter is used to generate artificial jamming signals to confuse the eavesdroppers [14]–[20]. Recently, an alternative approach of AN, namely cooperative jamming (CJ), where the artificial jamming signals are generated by friendly helpers of the transmitter, also attracts much attention.

In the study of secure transmission designs for CJ aided multi-antenna systems, it is commonly assumed that both the legitimate receiver's channel state information (LCSI) and eavesdroppers' CSI (ECSI) are available at the transmitter and helpers [21]–[29]. Under this assumption, it is popular to consider secrecy rate based secure transmission designs, which aim at perfectly secret information transmission. In [21]–[23], secure transmission designs for the maximum achievable secrecy rate were studied with the help of perfect channel state information (CSI). However, the CSI error is inevitable in practice. To accommodate the imperfect CSI, in [24]–[26], robust secrecy rate maximization design problems were formulated and solved for multiple-input-single-output (MISO) systems. Nevertheless, to achieve perfectly secret information transmission, secrecy rate based secure transmission designs have to incorporate complicated secrecy coding

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[1]The transmit beamforming vector refers to the beamforming vector for the information signal vector, and the transmit covariance refers to the covariance matrix of the information signal vector.

techniques [1], [30]. Consequently, secure transmission designs for the scenario where both LCSI and ECSI are available were also considered from the perspective of quality-of-service (QoS)[2] [24], [28], [29]. In these designs, the signal-to-interference-and-noise ratios (SINRs) at eavesdroppers are controlled so that the eavesdroppers can only retrieve a small amount of information from their observations. For such a security strategy, secrecy coding is not required. Moreover, the secrecy rate based secure transmission designs cannot satisfy the data rate demand which exceeds the maximum achievable secrecy rate. By contrast, the QoS based secure transmission designs avoid this drawback at the expense of limited information leakage. In [24] and [28], robust QoS based secure transmission designs were considered for CJ aided MISO systems. Most previous works on robust secure transmission designs for CJ aided MISO systems focused on optimizing the transmit covariance and seldom discussed the existence of rank-one transmit covariance solutions. However, linear precoding with rank-one transmit covariance, i.e., transmit beamforming, is the most implementable linear precoding scheme. This motivates us to consider robust secure transmission designs for CJ aided MISO channels, where the transmit beamforming vector and the jamming signal covariance are jointly optimized with imperfect LCSI and ECSI, from the perspectives of QoS and secrecy rate.

However, it is impractical to assume ECSI is available when the eavesdroppers are purely passive. Without ECSI, neither the secrecy rate nor the SINRs at the eavesdroppers can be calculated. Therefore, we further consider a QoS based robust secure transmission design with unknown ECSI for the CJ aided MISO system, where the QoS of the legitimate receiver is guaranteed at first, and then the transmit power of jamming signals is maximized for crippling eavesdroppers' interceptions. This work follows the approaches in [21], [31], and [32]. But, to our best knowledge, the research on robust secure transmission designs with unknown ECSI for CJ aided MISO systems is still missing.

In this paper, we investigate robust secure transmission designs for a CJ aided MISO system with multiple eavesdroppers from both the perspectives of QoS and secrecy rate. The transmit beamforming vector and the covariance of the jamming signals are jointly optimized in our designs. We formulate the robust secure transmission design problems by the worst-case approach, where the bounded CSI error model is used [24], [25], [27]. The worst case robust secure transmission designs are mainly applicable for the case where the CSI errors are dominantly caused by quantization [19], [33]. Moreover, the worst-case robust design problems can also be used to approximate probabilistic-constrained robust designs in which the statistic CSI error model is applied [17], [18]. In this paper, we consider two scenarios: (a) ECSI is available, which is possible when eavesdroppers are participating users but attempt to access unauthorized services [14], [17], [27]; and (b) ECSI is unavailable[3], which occurs when eavesdroppers are passive. For scenario (a), we first consider a QoS based robust secure transmission design problem where the worst-case SINR at eavesdroppers is minimized under the QoS constraint of the legitimate receiver. After that, the secrecy rate based transmission design is studied where the worst-case secrecy rate is maximized. For scenario (b), the secrecy rate based design is not applicable and we consider a QoS based robust secure transmission design to provide security. Our strategy here is to maximize the power of jamming signals while ensuring the SINR at the legitimate receiver. The main contributions of this paper are summarized as follows.

- To solve the robust QoS based secure transmission design problem under scenario (a), we use the semidefinite relaxation (SDR) approach [34] to relax the linear precoding scheme to be the general rank transmit covariance and construct a convex semidefinite programming (SDP) problem. We prove that the solution to the original design problem can be obtained through the constructed convex SDP problem. Moreover, our analysis shows that the relaxation is tight, which implies that transmit beamforming is the optimal linear precoding scheme.
- For the robust secrecy rate maximization design problem under scenario (a), it is first relaxed by the SDR approach. We demonstrate that the optimal transmit covariance in the SDR problem must be rank-one. Thus the relaxation is tight and the original design problem can be solved through the SDR problem. In addition, our proof reveals that the non-convex SDR problem can be handled via the help of one-dimensional line search and a sequence of convex SDPs which are built according to the Charnes-Cooper method.
- For the robust QoS based secure transmission design under scenario (b), the SDR approach is used at first. Then we construct a new convex SDP problem which can assist us to find out an optimal solution to the original design problem. Furthermore, simulation results demonstrate that our design where the linear precoding scheme is fixed as the transmit beamforming performs better than its SDR counterpart in suppressing the worst-case SINR at eavesdroppers.
- A new criterion is proposed through which we can check the feasibility of the QoS based transmission design problems.

Notations: Vectors are denoted by boldface lowercase letters while matrices are denoted by boldface uppercase letters. $(\cdot)^T$ represents the transpose; $(\cdot)^H$ represents the conjugate transpose; $\|\cdot\|$ represents the Euclidean norm; $\mathrm{E}[\cdot]$ represents the expectation; $\mathrm{diag}(\cdot)$ is to put matrices or scalars into a block diagonal matrix in order; and $\mathrm{tr}(\cdot)$ denotes the trace operator. The notation $\mathbf{A} \succeq \mathbf{B}$ ($\mathbf{A} \succ \mathbf{B}$) implies $\mathbf{A} - \mathbf{B}$ is positive semidefinite (positive definite). $\mathbf{0}$ represents a null matrix with suitable dimension, and $\mathbf{I}$ is an identity matrix with suitable dimension. For a Hermitian matrix $\mathbf{A}$, $\partial \mathbf{A}/\partial a$ is the entry wise partial derivative with respect to a; $\mathrm{vec}(\mathbf{A})$ is

[2]QoS refers to SINR and these two words are used equivalently in this paper.

[3]By assuming both ECSI and Eve's channel statistics are unavailable, the secure transmission design based on probabilistic constraint in [12] is not applicable.

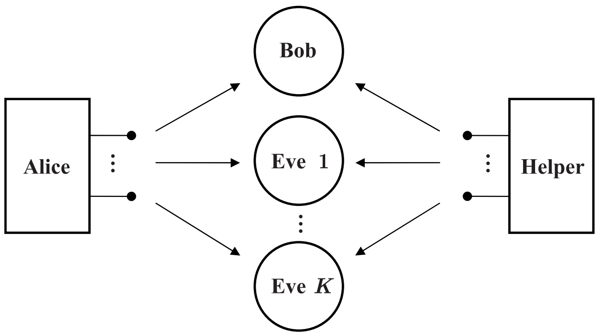

Fig. 1. System model of secure transmission with K eavesdroppers.

to put the real and imaginary parts of the entries which are in the upper triangular part of $\mathbf{A}$ into a vector by a certain order[4]; $\ker(\mathbf{A})$ denotes its null space and $\mathrm{rank}(\mathbf{A})$ is the rank of $\mathbf{A}$. $\dim(Y)$ stands for the dimension of a subspace Y.

II. System Model and Robust Transmission Designs Goals

We consider a CJ aided MISO system in Fig. 1 where a source node (Alice) sends information to a legitimate receiver (Bob) and a Helper sends Gaussian noise signals to confuse K eavesdroppers (Eves). We assume Alice and the Helper are equipped, respectively, with N_a and N_h transmit antennas, while both Bob and Eves have single antenna.

Denote the information signal vector transmitted from Alice and the jamming vector generated by the Helper as $\mathbf{x}(t) \in \mathbb{C}^{N_a}$ and $\mathbf{z}(t) \in \mathbb{C}^{N_h}$ respectively, where t is the time variable. The received signals at Bob and Eves can be expressed as

$$y_b(t) = \mathbf{h}_b\mathbf{x}(t) + \mathbf{g}_b\mathbf{z}(t) + n_b(t) \tag{1}$$

and

$$y_{e,k}(t) = \mathbf{h}_{e,k}\mathbf{x}(t) + \mathbf{g}_{e,k}\mathbf{z}(t) + n_{e,k}(t), \quad k = 1, \ldots, K \tag{2}$$

respectively, where the row vectors[5] $\{\mathbf{h}_b, \mathbf{h}_{e,k}\}$ denote the channels from Alice to Bob and the kth Eve, the row vectors $\{\mathbf{g}_b, \mathbf{g}_{e,k}\}$ denote the channels from the Helper to Bob and the kth Eve. All the channels are assumed to be quasi-static flat fading channels. In (1) and (2), $n_b(t)$ and $n_{e,k}(t)$ represent the zero-mean complex circular Gaussian noises with variances σ_b^2 and $\sigma_{e,k}^2$ respectively. The jamming vector $\mathbf{z}(t)$ follows zero-mean complex Gaussian distribution with covariance matrix $\mathbf{Q}_z \succeq \mathbf{0}$. In the robust secure transmission designs in this work, we assume the information signal vector takes the form of $\mathbf{x}(t) = \mathbf{w}x(t)$ where the column vector $\mathbf{w}$ is the transmit beamforming vector and $x(t) \in \mathbb{C}$ is the information bearing signal intended for Bob with $\mathrm{E}[|x(t)|^2] = 1$. Therefore, the SINRs at Bob and the k-th Eve can be, respectively, expressed as

$$SINR_b(\mathbf{w}, \mathbf{Q}_z) = \frac{\mathbf{h}_b\mathbf{w}\mathbf{w}^H\mathbf{h}_b^H}{\mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b^H + \sigma_b^2} \tag{3}$$

and

$$SINR_{e,k}(\mathbf{w}, \mathbf{Q}_z) = \frac{\mathbf{h}_{e,k}\mathbf{w}\mathbf{w}^H\mathbf{h}_{e,k}^H}{\mathbf{g}_{e,k}\mathbf{Q}_z\mathbf{g}_{e,k}^H + \sigma_{e,k}^2}. \tag{4}$$

Since the CSI error is inevitable, the channel vectors $\mathbf{h}_b, \mathbf{h}_{e,k}, \mathbf{g}_b, \mathbf{g}_{e,k}$ cannot be perfectly known. In addition, for Eve's channels $\mathbf{h}_{e,k}, \mathbf{g}_{e,k}$, it is even possible that no channel knowledge can be obtained. Consequently, we consider the following two scenarios in this work.

1) Scenario (a): ECSI is available. This scenario arises when Eves are participating users of the system but attempt to access unauthorized services [14], [17], [27]. In this scenario, imperfect estimates of both Bob's and Eves' channels are available at Alice and the Helper. To describe the imperfect CSI, we have

$$\begin{aligned} \mathbf{h}_b &= \tilde{\mathbf{h}}_b + \mathbf{e}_{h,b}, \quad \mathbf{g}_b = \tilde{\mathbf{g}}_b + \mathbf{e}_{g,b}, \\ \mathbf{h}_{e,k} &= \tilde{\mathbf{h}}_{e,k} + \mathbf{e}_{h,e,k}, \quad \mathbf{g}_{e,k} = \tilde{\mathbf{g}}_{e,k} + \mathbf{e}_{g,e,k}, \quad k = 1, \ldots, K \end{aligned} \tag{5}$$

where $\tilde{\mathbf{h}}_b$, $\tilde{\mathbf{g}}_b$, $\tilde{\mathbf{h}}_{e,k}$ and $\tilde{\mathbf{g}}_{e,k}$ are the estimates for each channel and $\mathbf{e}_{h,b}$, $\mathbf{e}_{g,b}$, $\mathbf{e}_{h,e,k}$ and $\mathbf{e}_{g,e,k}$ represent the corresponding CSI errors. We assume that the CSI errors are bounded by spheres, i.e., they lie in the bounded sets as follows [24], [27], [35],

$$\begin{aligned} \varepsilon_{h,b} &= \{\mathbf{e}_{h,b} : \|\mathbf{e}_{h,b}\|^2 \le \xi_{h,b}^2\}, \\ \varepsilon_{g,b} &= \{\mathbf{e}_{g,b} : \|\mathbf{e}_{g,b}\|^2 \le \xi_{g,b}^2\}, \\ \varepsilon_{h,e,k} &= \{\mathbf{e}_{h,e,k} : \|\mathbf{e}_{h,e,k}\|^2 \le \xi_{h,e,k}^2\}, \\ \varepsilon_{g,e,k} &= \{\mathbf{e}_{g,e,k} : \|\mathbf{e}_{g,e,k}\|^2 \le \xi_{g,e,k}^2\} \end{aligned}$$

where $\xi_{h,b}$, $\xi_{g,b}$, $\xi_{h,e,k}$ and $\xi_{g,e,k}$ are known radius of the uncertainty regions. In addition, we further define sets $\mathcal{H}_e = \{\tilde{\mathbf{h}}_{e,1}, \ldots, \tilde{\mathbf{h}}_{e,K}\}$, $\mathcal{G}_e = \{\tilde{\mathbf{g}}_{e,1}, \ldots, \tilde{\mathbf{g}}_{e,K}\}$, $\mathcal{N}_e = \{\sigma_{e,1}^2, \ldots, \sigma_{e,K}^2\}$, $\mathcal{B}_{h,e} = \{\xi_{h,e,1}^2, \ldots, \xi_{h,e,K}^2\}$ and $\mathcal{B}_{g,e} = \{\xi_{g,e,1}^2, \ldots, \xi_{g,e,K}^2\}$.

In this scenario, we first study a QoS based secure transmission design problem with the goal to minimize Eves' worst-case SINR while guaranteeing Bob's worst-case SINR[6] no less than a target value. Then, a secrecy rate based secure transmission design problem is considered where the worst-case secrecy rate is maximized with constrained power.

2) Scenario (b): ECSI is not available. This scenario occurs when Eves are passive and not part of the legitimate system. In this scenario, Alice and the Helper can only know the estimates of Bob's channels, $\tilde{\mathbf{h}}_b$ and $\tilde{\mathbf{g}}_b$, and the CSI error uncertainty radius, $\xi_{h,b}$ and $\xi_{g,b}$, but have no knowledge of Eves' channels.

Since there is no information about Eves' channels, secrecy rate is not achievable and the best approach for information security is to allocate as much power as possible to transmit the jamming signals while ensuring the QoS of Bob [31], [36]. Thus, a robust QoS based secure transmission design is studied

[4]The order is established as follows. Suppose the entry at the l-th row and the n-th column of matrix $\mathbf{A}$ is represented by $a_{l,n}$. Since $a_{1,1}$ is on the main diagonal, it does not have imaginary part. The real part of $a_{1,1}$ is placed at the first position of the vector. The real part of $a_{1,2}$ is placed at the second position of the vector; the imaginary part of $a_{1,2}$ is placed at the third position and so forth.

[5]For brevity, all channel vectors are row vectors.

[6]Eves' worst-case SINR refers to the largest SINR at Eves with CSI errors, and Bob's worst-case SINR refers to the smallest SINR at Bob with CSI errors.

for the CJ aided MISO system to maximize the transmit power of jamming signals with the QoS requirement of Bob.

Note that all the secure transmission design problems in this work are investigated under individual power constraints. However, our results can be easily extended to global power constraint cases. We comment that, if the more general ellipsoidally bounded CSI error model [31], [37] is used instead of the spherically bounded one, the methods and conclusions in this work are still applicable.

III. Robust QoS Based Transmission Design for Scenario A

Based on (3)-(5), we can formulate the robust QoS based design problem as

$$\begin{aligned}
\text{P-QoS-A:}\quad & \min_{\mathbf{w},\mathbf{Q}_z} \max_{\substack{\mathbf{e}_{h,e,k}\in\varepsilon_{h,e,k}\\ \mathbf{e}_{g,e,k}\in\varepsilon_{g,e,k}\\ k=1,\ldots,K}} SINR_{e,k}(\mathbf{w},\mathbf{Q}_z)\\
&\text{s.t.} \min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b}\\ \mathbf{e}_{g,b}\in\varepsilon_{g,b}}} SINR_b(\mathbf{w},\mathbf{Q}_z)\geq\gamma_b\\
&\qquad \|\mathbf{w}\|^2\leq P_s,\quad \mathrm{tr}(\mathbf{Q}_z)\leq P_c,\ \mathbf{Q}_z\succeq\mathbf{0}
\end{aligned}$$

where γ_b is the minimum SINR requirement at Bob, P_s and P_c are the power constraints for Alice and the Helper respectively. To make the design problem meaningful, we must have $\gamma_b > 0$ and $P_s > 0$.

It is natural to ask under what condition the robust design problem P-QoS-A is feasible. Motivated by [14, Lemma 1], the following proposition provides a verifiable criterion.

Proposition 1: Assume that

$$\|\tilde{\mathbf{h}}_b\|\geq\xi_{h,b}, \tag{6}$$

$$\|\tilde{\mathbf{h}}_b\|^2(\|\tilde{\mathbf{h}}_b\|-\xi_{h,b})^2\geq\gamma_b(\xi_{g,b}^2+\sigma_b^2), \tag{7}$$

$$\|\tilde{\mathbf{h}}_b\|^2\leq P_s \quad\text{and } (N_h-1)\leq P_c. \tag{8}$$

Then the robust design problem P-QoS-A is feasible.

Proof: See Appendix A.

In the following, we will discuss how to solve P-QoS-A under the assumption that it is feasible. In fact, the infeasible case implies that the given parameters are too stringent. In this case, we should raise the power constraints P_s and P_c or reduce the minimum SINR requirement γ_b to make P-QoS-A feasible.

The optimization problem described in P-QoS-A is non-convex; therefore, we relax it by using the SDR approach at first. According to SDR, we consider a transmit covariance based design problem

$$\min_{\mathbf{Q}_x,\mathbf{Q}_z,\gamma_e}\ \gamma_e \tag{9a}$$

$$\text{s.t.} \max_{\substack{\mathbf{e}_{h,e,k}\in\varepsilon_{h,e,k}\\ \mathbf{e}_{g,e,k}\in\varepsilon_{g,e,k}\\ k=1,\ldots,K}} \frac{\mathbf{h}_{e,k}\mathbf{Q}_x\mathbf{h}_{e,k}{}^H}{\mathbf{g}_{e,k}\mathbf{Q}_z\mathbf{g}_{e,k}{}^H+\sigma_{e,k}^2}\leq\gamma_e \tag{9b}$$

$$\min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b}\\ \mathbf{e}_{g,b}\in\varepsilon_{g,b}}} \frac{\mathbf{h}_b\mathbf{Q}_x\mathbf{h}_b{}^H}{\mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b{}^H+\sigma_b^2}\geq\gamma_b \tag{9c}$$

$$\mathrm{tr}(\mathbf{Q}_x)\leq P_s,\ \mathrm{tr}(\mathbf{Q}_z)\leq P_c,\ \mathbf{Q}_x\succeq\mathbf{0},\ \mathbf{Q}_z\succeq\mathbf{0},\ \gamma_e\geq 0 \tag{9d}$$

where $\mathbf{Q}_x$ can be explained as the transmit covariance. It is obvious if $\mathbf{Q}_x$ is restricted to be rank-one, the optimization problem described in (9) is equivalent to that of P-QoS-A. Since P-QoS-A is feasible, problem (9) must be feasible. Problem (9) is also non-convex, because both the constraints (9b) and (9c) are non-convex.

By introducing the slack variables υ, ϱ, $u_1,\ldots,u_K$ and $z_1,\ldots,z_K$, we now rewrite (9) as

$$\begin{aligned}
&\min_{\substack{\mathbf{Q}_x,\ \mathbf{Q}_z,\upsilon,\varrho,\gamma_e\\ u_1,\ldots,u_K,z_1,\ldots,z_K}} \gamma_e\\
&\text{s.t. } \mathbf{h}_b\mathbf{Q}_x\mathbf{h}_b{}^H\geq\upsilon,\quad\forall\,\mathbf{e}_{h,b}\in\varepsilon_{h,b} && (10a)\\
&\quad \mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b{}^H+\sigma_b^2\leq\varrho,\quad\forall\,\mathbf{e}_{g,b}\in\varepsilon_{g,b} && (10b)\\
&\quad \upsilon\geq\gamma_b\varrho,\ \upsilon\geq 0,\ \varrho\geq 0\\
&\quad \mathbf{h}_{e,k}\mathbf{Q}_x\mathbf{h}_{e,k}{}^H\leq u_k,\quad\forall\,\mathbf{e}_{h,e,k}\in\varepsilon_{h,e,k} && (10c)\\
&\quad \mathbf{g}_{e,k}\mathbf{Q}_z\mathbf{g}_{e,k}{}^H+\sigma_{e,k}^2\geq z_k,\quad\forall\,\mathbf{e}_{g,e,k}\in\varepsilon_{g,e,k} && (10d)\\
&\quad u_k\leq z_k\gamma_e,\ u_k\geq 0,\ z_k\geq 0,\ \gamma_e\geq 0,\ k=1,\ldots,K\\
&\quad \mathrm{tr}(\mathbf{Q}_x)\leq P_s,\ \mathrm{tr}(\mathbf{Q}_z)\leq P_c,\ \mathbf{Q}_x\succeq\mathbf{0},\ \mathbf{Q}_z\succeq\mathbf{0}.
\end{aligned}$$

Through the S-procedure (see [38, p. 655] or [39]), we know (10a)–(10d) are equivalent to

$$T_{h,b}(\mathbf{Q}_x,\psi,\upsilon)=\begin{pmatrix}\psi\mathbf{I}+\mathbf{Q}_x & \mathbf{Q}_x\tilde{\mathbf{h}}_b^H\\ \tilde{\mathbf{h}}_b\mathbf{Q}_x & \tilde{\mathbf{h}}_b\mathbf{Q}_x\tilde{\mathbf{h}}_b^H-\upsilon-\psi\xi_{h,b}^2\end{pmatrix}\succeq\mathbf{0},\quad\psi\geq 0 \tag{11}$$

$$T_{g,b}(\mathbf{Q}_z,\alpha,\varrho,\sigma_b^2)=\begin{pmatrix}\alpha\mathbf{I}-\mathbf{Q}_z & -\mathbf{Q}_z\tilde{\mathbf{g}}_b^H\\ -\tilde{\mathbf{g}}_b\mathbf{Q}_z & \varrho-\sigma_b^2-\tilde{\mathbf{g}}_b\mathbf{Q}_z\tilde{\mathbf{g}}_b^H-\alpha\xi_{g,b}^2\end{pmatrix}\succeq\mathbf{0},\quad\alpha\geq 0 \tag{12}$$

$$T_{h,e,k}(\mathbf{Q}_x,\varphi_k,u_k)=\begin{pmatrix}\varphi_k\mathbf{I}-\mathbf{Q}_x & -\mathbf{Q}_x\tilde{\mathbf{h}}_{e,k}^H\\ -\tilde{\mathbf{h}}_{e,k}\mathbf{Q}_x & u_k-\tilde{\mathbf{h}}_{e,k}\mathbf{Q}_x\tilde{\mathbf{h}}_{e,k}^H-\varphi_k\xi_{h,e,k}^2\end{pmatrix}\succeq\mathbf{0},\quad\varphi_k\geq 0 \tag{13}$$

$$T_{g,e,k}(\mathbf{Q}_z,\beta_k,z_k,\sigma_{e,k}^2)=\begin{pmatrix}\beta_k\mathbf{I}+\mathbf{Q}_z & \mathbf{Q}_z\tilde{\mathbf{g}}_{e,k}^H\\ \tilde{\mathbf{g}}_{e,k}\mathbf{Q}_z & \tilde{\mathbf{g}}_{e,k}\mathbf{Q}_z\tilde{\mathbf{g}}_{e,k}^H-z_k+\sigma_{e,k}^2-\beta_k\xi_{g,e,k}^2\end{pmatrix}\succeq\mathbf{0},\quad\beta_k\geq 0. \tag{14}$$

Replacing (10a)–(10d) with (11)–(14), we convert problem (10) into

$$\min_{\substack{\mathbf{Q}_x,\mathbf{Q}_z,\upsilon,t,\psi,\alpha,\gamma_e,u_1,\ldots,u_K\\ z_1,\ldots,z_K,\varphi_1,\ldots,\varphi_K,\beta_1,\ldots,\beta_K}} \gamma_e \tag{15a}$$

$$\text{s.t. } (11)-(14),\ \upsilon\geq\gamma_b\varrho,\ \upsilon\geq 0,\ \varrho\geq 0 \tag{15b}$$

$$u_k\leq\gamma_e z_k,\ u_k\geq 0,\ z_k\geq 0,\ \gamma_e\geq 0,\quad k=1,\ldots,K \tag{15c}$$

$$\mathrm{tr}(\mathbf{Q}_x)\leq P_s,\ \mathrm{tr}(\mathbf{Q}_z)\leq P_c,\ \mathbf{Q}_x\succeq\mathbf{0},\ \mathbf{Q}_z\succeq\mathbf{0}. \tag{15d}$$

The feasibility problem of (15) for fixed γ_e, i.e.,

$$\min_{\substack{\mathbf{Q}_x,\mathbf{Q}_z,\upsilon,t,\psi,\alpha,u_1,\ldots,u_K\\ z_1,\ldots,z_K,\varphi_1,\ldots,\varphi_K,\beta_1,\ldots,\beta_K}} 0\quad\text{s.t. } (15b)-(15d), \tag{16}$$

is convex.

Because problem (9) is feasible and (15) is equivalent to (9), we can always find a sufficient large value $\bar{\gamma}_e$ such that problem (16) is feasible when $\gamma_e = \bar{\gamma}_e$. Let γ_e^* denote the optimal value of (15), we have $\gamma_e^* \le \bar{\gamma}_e$. According to (15c), we know $0 \le \gamma_e^*$. Thus, γ_e^* is included in the finite interval $[0, \bar{\gamma}_e]$. In addition, we know the feasibility problem (16) is convex. Therefore, problem (15) can be solved by the bisection method [38, pp. 144–146], in which γ_e^* is searched over $[0, \bar{\gamma}_e]$ by solving the feasibility problem (16) for different values of γ_e.

Through the quasi-convex problem in (15), problem (9) can be solved, but the rank profile of the optimal solutions cannot be guaranteed, which will be demonstrated in our simulation. To solve the original design problem P-QoS-A, we need to further discuss how to obtain a rank-one solution to (9).

Consider the following optimization problem[7]

$$\min_{\mathbf{Q}_x, \mathbf{Q}_z, \theta_b, \theta_e} \; f(\theta_b, \theta_e) \tag{17a}$$

$$\text{s.t.} \max_{\substack{\mathbf{e}_{h,e,k} \in \mathcal{E}_{h,e,k} \\ \mathbf{e}_{g,e,k} \in \mathcal{E}_{g,e,k} \\ k=1,\ldots,K}} \frac{\mathbf{h}_{e,k} \mathbf{Q}_x \mathbf{h}_{e,k}{}^H}{\mathbf{g}_{e,k} \mathbf{Q}_z \mathbf{g}_{e,k}{}^H + \sigma_{e,k}^2} \le \theta_e \tag{17b}$$

$$\min_{\substack{\mathbf{e}_{h,b} \in \mathcal{E}_{h,b} \\ \mathbf{e}_{g,b} \in \mathcal{E}_{g,b}}} \frac{\mathbf{h}_b \mathbf{Q}_x \mathbf{h}_b{}^H}{\mathbf{g}_b \mathbf{Q}_z \mathbf{g}_b{}^H + \sigma_b^2} \ge \theta_b \tag{17c}$$

$$\text{tr}(\mathbf{Q}_x) \le P_s, \; \text{tr}(\mathbf{Q}_z) \le P_c \tag{17d}$$

$$\mathbf{Q}_x \succeq \mathbf{0}, \; \mathbf{Q}_z \succeq \mathbf{0}, \; \theta_b \ge 0, \; \theta_e \ge 0 \tag{17e}$$

where $f(\theta_b, \theta_e)$ is a $\mathbb{R}^2 \to \mathbb{R}$ function of variables θ_b and θ_e. For fixed θ_b and θ_e which are feasible in problem (17) and $\theta_b > 0$, we have the following lemma and theorem.

Lemma 1: Define $\mathbf{F} = \text{diag}\{T_{h,b}(\mathbf{Q}_x, \psi, \upsilon), T_{g,b}(\mathbf{Q}_z, \alpha, \varrho, \sigma_b^2), T_{h,e,k}(\mathbf{Q}_x, \varphi_k, u_k)|_{k=1,\ldots,K}, T_{g,e,k}(\mathbf{Q}_z, \beta_k, z_k, \sigma_{e,k}^2)|_{k=1,\ldots,K}, \mathbf{Q}_x, \mathbf{Q}_z, P_c - \text{tr}(\mathbf{Q}_z), \upsilon - \theta_b \varrho, \theta_e z_k - u_k|_{k=1,\ldots,K}, \psi, \alpha, \varphi_k|_{k=1,\ldots,K}, \beta_k|_{k=1,\ldots,K}\}$ and consider the following convex SDP problem

$$\min_{\mathbf{s}} \sum_{i=1}^{n_\mathbf{s}} c_i s_i$$
$$\text{s.t.} \; \mathbf{F}_0 + \sum_{i=1}^{n_\mathbf{s}} s_i \mathbf{F}_i \succeq \mathbf{0} \tag{18}$$

where s_i is the i-th element in the $n_\mathbf{s}$ dimensional vector $\mathbf{s} = [\text{vec}(\mathbf{Q}_x), \text{vec}(\mathbf{Q}_z), \upsilon, \varrho, \psi, \alpha, u_1, \ldots, u_K, z_1, \ldots, z_K, \varphi_1, \ldots, \varphi_K, \beta_1, \ldots, \beta_K]$, matrix $\mathbf{F}_i = \partial \mathbf{F} / \partial s_i, i = 1, \ldots, n_\mathbf{s}$, $\mathbf{F}_0 = \mathbf{F} - \sum_{i=1}^{n_\mathbf{s}} s_i \mathbf{F}_i$ and c_i is defined as follows. We have $c_i = 1$ when s_i corresponds to a diagonal entry of matrix $\mathbf{Q}_x$; $c_i = 0$ otherwise. Then,

(i) Let $\mathbf{s}^*$=[vec($\mathbf{Q}_x^*$), vec($\mathbf{Q}_z^*$), υ^*, ϱ^*, ψ^*, α^*, u_1^*,…, u_K^*, z_1^*,…, z_K^*, φ_1^*,…, φ_K^*, β_1^*,…, β_K^*] be an optimal solution to (18). Then, $\mathbf{Q}_x^*$ and $\mathbf{Q}_z^*$, together with the fixed θ_b and θ_e, must be in the feasible set of (17).

(ii) Strong duality holds for (18).

[7]We consider Lemma 1 and Theorem 1 for problem (17) rather than dealing with problem (9) (or its equivalent problem (15)) directly. In this way, Lemma 1 and Theorem 1 take general forms; therefore, we can use them in Section IV to make the presentation more concise.

Proof: See Appendix B.

With the help of Lemma 1, we have Theorem 1.

Theorem 1[8]*:* For the fixed θ_b and θ_e which are feasible in problem (17) and the corresponding optimal solution $\mathbf{s}^*$ to (18), if $\theta_b > 0$, we have $\text{rank}(\mathbf{Q}_x^*) = 1$.

Proof: See Appendix C.

Based on Lemma 1 and Theorem 1, we have the following proposition for P-QoS-A.

Proposition 2: Let $\theta_b = \gamma_b$ and $\theta_e = \gamma_e^*$. Then for the corresponding optimal solution $\mathbf{s}^*$ to (18), we have $\{\mathbf{Q}_x^*, \mathbf{Q}_z^*, \gamma_e^*\}$ as an optimal solution to (9) with $\text{rank}(\mathbf{Q}_x^*) = 1$, and we have $\{\mathbf{w}^*, \mathbf{Q}_z^*\}$ as an optimal solution to the original design problem P-QoS-A, where the optimal beamforming vector $\mathbf{w}^*$ is decomposed from $\mathbf{Q}_x^*$, i.e., $\mathbf{Q}_x^* = \mathbf{w}^*(\mathbf{w}^*)^H$.

Proof: Since (15) is equivalent to (9), γ_e^* is also the optimal value of (9). Thus, by letting $\theta_b = \gamma_b$ and $\theta_e = \gamma_e^*$, it is easy to see $\theta_b > 0$; and θ_b and θ_e must be feasible in (17). Then, we can observe that, for any feasible point $\{\mathbf{Q}_x, \mathbf{Q}_z, \gamma_b, \gamma_e^*\}$ in (17), $\{\mathbf{Q}_x, \mathbf{Q}_z, \gamma_e^*\}$ is an optimal solution to (9). Thus, by applying Lemma 1(i), we know $\{\mathbf{Q}_x^*, \mathbf{Q}_z^*, \gamma_e^*\}$ must be an optimal solution to (9). Furthermore, because of Theorem 1, there must be $\text{rank}(\mathbf{Q}_x^*) = 1$. Since (9) is an SDR of P-QoS-A, $\{\mathbf{w}^*, \mathbf{Q}_z^*\}$ must be an optimal solution to P-QoS-A.

Remark: The existence of rank-one optimal $\mathbf{Q}_x$ in (9) *means that the transmit covariance based design problem* (9) *is a tight relaxation of the transmit beamforming based original design problem P-QoS-A. Therefore, transmit beamforming is the optimal linear precoding approach.*

Based on Proposition 2, the details of solving P-QoS-A is summarized in Algorithm 1.

Algorithm 1 Algorithm of Robust QoS Based Transmission Design for Scenario(a)

Input: $\tilde{\mathbf{h}}_b$, $\mathcal{H}_e$, $\tilde{\mathbf{g}}_b$, $\mathcal{G}_e$, σ_b^2, $\mathcal{N}_e$, γ_b, $\xi_{h,b}^2$, $\xi_{g,b}^2$, $\mathcal{B}_{h,e}$, $\mathcal{B}_{g,e}$, P_s, P_c.

1. Use bisection method to solve the quasi-convex problem (15) to obtain an optimal solution $\{\bar{\mathbf{Q}}_x^*, \bar{\mathbf{Q}}_z^*, \bar{\upsilon}^*, \bar{\varrho}^*, \bar{\psi}^*, \bar{\alpha}^*, \gamma_e^*, \bar{u}_1^*, \ldots, \bar{u}_K^*, \bar{z}_1^*, \ldots, \bar{z}_K^*, \bar{\varphi}_1^*, \ldots, \bar{\varphi}_K^*, \bar{\beta}_1^*, \ldots, \bar{\beta}_K^*\}$.
2. If $\text{rank}(\bar{\mathbf{Q}}_x^*) = 1$, let $\mathbf{Q}_x^* = \bar{\mathbf{Q}}_x^*$ $\mathbf{Q}_z^* = \bar{\mathbf{Q}}_z^*$ and go to step 4. Otherwise, go to step 3.
3. Solve the SDP problem (18) and obtain $\mathbf{Q}_x^*$ and $\mathbf{Q}_z^*$ which is contained in solution $\mathbf{s}^*$.
4. Obtain $\mathbf{w}^*$ by performing eigenvalue decomposition for $\mathbf{Q}_x^*$.

Output: $\mathbf{w}^*$, $\mathbf{Q}_z^*$.

Since only linear matrix inequality (LMI) constraints are involved, the feasibility problem (16) can be solved through the interior-point method (IPM). The complexity of

[8]Compared with the system in [6] and [7] where a source node sends different information to multiple users, we assume that Alice only intends to serve one user (the legitimate receiver) and the service is wiretapped by eavesdroppers. Therefore, different from the rank-one conclusions made in [6] and [7], this rank-one result does not rely on any assumption on the radii of the uncertainty regions. Moreover, the rank-one result in [8] also holds with any radii of the uncertainty regions. However, the system model in this paper is different from the one in [8] and the ways to achieve the rank-one results are different as well.

Algorithm 1 is due to the bisection search and the complexity of IPM which contains the iteration complexity and the per-iteration computation cost [40]. Assuming that the number of iterations in the bisection search is B_1 and ϵ is the accuracy of IPM, the complexity of Algorithm 1 is on the order of

$$\begin{aligned}&B_1\sqrt{(K+2)(N_a+N_h)+7K+9}\ln(1/\epsilon)\mathcal{O}(N_a^2+N_h^2+K)\\&\times(((K+1)((N_a+1)^3+(N_h+1)^3)+N_a^3+N_h^3+5K+7)\\&+\mathcal{O}(N_a^2+N_h^2+K)((K+1)((N_a+1)^2+(N_h+1)^2)+N_a^2\\&+N_h^2+5K+7)+\mathcal{O}^2(N_a^2+N_h^2+K))\end{aligned}$$

where $\mathcal{O}(\cdot)$ is the big-O operator.

IV. Robust Secrecy Rate Based Transmission Design for Scenario A

The worst-case secrecy rate maximization design problem described in Section II can be mathematically expressed as

P-SRM-A:

$$\begin{aligned}\max_{\mathbf{w},\mathbf{Q}_z}\ \min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b},\mathbf{e}_{g,b}\in\varepsilon_{g,b}\\ \mathbf{e}_{h,e,k}\in\varepsilon_{h,e,k},\mathbf{e}_{g,e,k}\in\varepsilon_{g,e,k}\\ k=1,\ldots,K}}\ &\log(1+SINR_b(\mathbf{w},\mathbf{Q}_z))\\ &-\log(1+SINR_{e,k}(\mathbf{w},\mathbf{Q}_z))\\ \text{s.t. } \|\mathbf{w}\|^2\le P_s,\ &\operatorname{tr}(\mathbf{Q}_z)\le P_c,\ \mathbf{Q}_z\succeq\mathbf{0}.\end{aligned}$$

Note that the optimal value R^+ of problem P-SRM-A must be greater or equal to 0, because $\{\mathbf{w}=\mathbf{0},\mathbf{Q}_z=\mathbf{0}\}$ exits in the feasible set.

To solve P-SRM-A, we first use the SDR approach to relax it into

$$\begin{aligned}\max_{\mathbf{Q}_x,\mathbf{Q}_z}\ &\min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b}\\ \mathbf{e}_{g,b}\in\varepsilon_{g,b}}}\log\left(1+\frac{\mathbf{h}_b\mathbf{Q}_x\mathbf{h}_b{}^H}{\mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b{}^H+\sigma_b^2}\right)\\ &-\max_{\substack{\mathbf{e}_{h,e,k}\in\varepsilon_{h,e,k}\\ \mathbf{e}_{g,e,k}\in\varepsilon_{g,e,k}\\ k=1,\ldots,K}}\log\left(1+\frac{\mathbf{h}_{e,k}\mathbf{Q}_x\mathbf{h}_{e,k}{}^H}{\mathbf{g}_{e,k}\mathbf{Q}_z\mathbf{g}_{e,k}{}^H+\sigma_{e,k}^2}\right)\\ \text{s.t. } &\operatorname{tr}(\mathbf{Q}_x)\le P_s,\ \operatorname{tr}(\mathbf{Q}_z)\le P_c,\ \mathbf{Q}_x\succeq\mathbf{0},\ \mathbf{Q}_z\succeq\mathbf{0}.\end{aligned}\quad(19)$$

Problem (19) can be further rewritten as

$$\max_{\mathbf{Q}_x,\mathbf{Q}_z,\phi_b,\phi_e}\ \log(1+\phi_b)-\log(1+\phi_e)\quad(20a)$$

$$\text{s.t. }\max_{\substack{\mathbf{e}_{h,e,k}\in\varepsilon_{h,e,k}\\ \mathbf{e}_{g,e,k}\in\varepsilon_{g,e,k}\\ k=1,\ldots,K}}\frac{\mathbf{h}_{e,k}\mathbf{Q}_x\mathbf{h}_{e,k}{}^H}{\mathbf{g}_{e,k}\mathbf{Q}_z\mathbf{g}_{e,k}{}^H+\sigma_{e,k}^2}\le\phi_e\quad(20b)$$

$$\min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b}\\ \mathbf{e}_{g,b}\in\varepsilon_{g,b}}}\frac{\mathbf{h}_b\mathbf{Q}_x\mathbf{h}_b{}^H}{\mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b{}^H+\sigma_b^2}\ge\phi_b\quad(20c)$$

$$\operatorname{tr}(\mathbf{Q}_x)\le P_s,\operatorname{tr}(\mathbf{Q}_z)\le P_c\quad(20d)$$

$$\mathbf{Q}_x\succeq\mathbf{0},\ \mathbf{Q}_z\succeq\mathbf{0},\ \phi_b\ge0,\ \phi_e\ge0.\quad(20e)$$

Even though (20) is a relaxation of the original design problem P-SRM-A, it can be shown that this relaxation is tight and P-SRM-A can thus be solved.

Proposition 3: Let ϖ^+ denote the optimal value of (20) and assume $\{\mathbf{Q}_x^+,\ \mathbf{Q}_z^+,\ \phi_b^+,\ \phi_e^+\}$ is an optimal solution to it. If $\varpi^+>0$, we have $\operatorname{rank}(\mathbf{Q}_x^+)=1$ with $\mathbf{Q}_x^+=\mathbf{w}^+(\mathbf{w}^+)^H$, and $\{\mathbf{w}^+,\mathbf{Q}_z^+\}$ is an optimal solution to P-SRM-A. Otherwise, $\varpi^+=0$ and $\{\mathbf{w}^+=\mathbf{0},\mathbf{Q}_z^+=\mathbf{0}\}$ is an optimal solution to P-SRM-A.

Proof: See Appendix D.

Remark: Proposition 3 implies that the transmit beamforming based design P-SRM-A must perform as well as the transmit covariance based design (20) *in terms of maximizing the secrecy rate, which gives a theoretical justification for using transmit beamforming.*

In the following, we will focus on solving problem (20). Our method to solve (20) is to divide it into two layers. The outer layer is an one-dimensional optimization problem and the inner layer is a sequence of convex SDPs.

In the inner layer, we consider solving problem (20) with fixed ϕ_e. By the Charnes-Cooper method [41], we have the following proposition.

Proposition 4: When ϕ_e is fixed, let $\varpi(\phi_e)$ denote the optimal value of problem (20) and assume $\{\tilde{\mathbf{Q}}_x(\phi_e),\ \tilde{\mathbf{Q}}_z(\phi_e),\ \tilde{\phi_b}(\phi_e)\}$ is an optimal solution to it. Consider a convex SDP problem

$$\begin{aligned}\chi(\phi_e)&=\max_{\substack{\mathbf{X}_\eta,\mathbf{Z}_\eta,\eta,\phi_b,\psi,\alpha,u_{\eta,1},\ldots,u_{\eta,K}\\ z_{\eta,1},\ldots,z_{\eta,K},\varphi_1,\ldots,\varphi_K,\beta_1,\ldots,\beta_K}}\log(1+\phi_b)-\log(1+\phi_e)\\ \text{s.t. }&T_{h,b}(\mathbf{X}_\eta,\psi,\phi_b)\succeq\mathbf{0},\ \psi\ge0\\ &T_{g,b}(\mathbf{Z}_\eta,\alpha,1,\sigma_b^2\eta)\succeq\mathbf{0},\ \alpha\ge0\\ &T_{h,e,k}(\mathbf{X}_\eta,\varphi_k,u_{\eta,k})\succeq\mathbf{0},\ \varphi_k\ge0\\ &T_{g,e,k}(\mathbf{Z}_\eta,\beta_k,z_{\eta,k},\sigma_{e,k}^2\eta)\succeq\mathbf{0},\ \beta_k\ge0\\ &u_{\eta,k}\ge0,\ z_{\eta,k}\ge0,\ u_{\eta,k}\le\phi_e z_{\eta,k},\\ &\qquad k=1,\ldots,K\\ &\operatorname{tr}(\mathbf{X}_\eta)\le P_s\eta,\ \operatorname{tr}(\mathbf{Z}_\eta)\le P_c\eta\\ &\mathbf{X}_\eta\succeq\mathbf{0},\ \mathbf{Z}_\eta\succeq\mathbf{0},\ \eta\ge0,\ \phi_b\ge0\end{aligned}\quad(21)$$

where $\chi(\phi_e)$ denotes the optimal value of (21). If $\chi(\phi_e)>0$, there must be $\chi(\phi_e)=\varpi(\phi_e)$. Moreover, for $\tilde{\mathbf{X}}_\eta(\phi_e)$, $\tilde{\mathbf{Z}}_\eta(\phi_e)$ and $\tilde{\eta}(\phi_e)$ which are involved in an optimal solution to (21), we have $\tilde{\mathbf{Q}}_x(\phi_e)=\tilde{\mathbf{X}}_\eta(\phi_e)/\tilde{\eta}(\phi_e)$, $\tilde{\mathbf{Q}}_z(\phi_e)=\tilde{\mathbf{Z}}_\eta(\phi_e)/\tilde{\eta}(\phi_e)$. Otherwise, $\varpi(\phi_e)\le\chi(\phi_e)\le0$.

Proof: See Appendix E.

In the outer layer, we first note that

$$\phi_e\le\max_{\substack{\mathbf{Q}_x\succeq\mathbf{0},\mathbf{Q}_z\succeq\mathbf{0}\\ \operatorname{tr}(\mathbf{Q}_x)\le P_s,\operatorname{tr}(\mathbf{Q}_z)\le P_c}}\ \min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b}\\ \mathbf{e}_{g,b}\in\varepsilon_{g,b}}}\frac{\mathbf{h}_b\mathbf{Q}_x\mathbf{h}_b{}^H}{\mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b{}^H+\sigma_b^2}\quad(22a)$$

$$\le\max_{\mathbf{Q}_x\succeq\mathbf{0},\operatorname{tr}(\mathbf{Q}_x)\le P_s}\ \min_{\mathbf{e}_{h,b}\in\varepsilon_{h,b}}\frac{\mathbf{h}_b\mathbf{Q}_x\mathbf{h}_b{}^H}{\sigma_b^2}\quad(22b)$$

where (22a) holds because there must be $\varpi(\phi_e)\le\chi(\phi_e)<0$ otherwise. Assuming the value of the optimization problem in (22b) is denoted by $\bar{\phi}_e$, by the similar manner as that in Section III, we can see $\bar{\phi}_e$ can be calculated through

$$\begin{aligned}\max_{\mathbf{Q}_x,\phi_e,\psi}\ &\phi_e\\ \text{s.t. }&T_{h,b}(\mathbf{Q}_x,\psi,\phi_e\sigma_b^2)\succeq\mathbf{0},\ \mathbf{Q}_x\succeq\mathbf{0}\\ &\operatorname{tr}(\mathbf{Q}_x)\le P_s,\ \psi\ge0,\ \phi_e\ge0\end{aligned}\quad(23)$$

which is convex. Then, we solve (20) by

$$\max_{\phi_e} \chi(\phi_e) \quad \text{s.t. } 0 \le \phi_e \le \bar{\phi}_e. \tag{24}$$

The function $\chi(\phi_e)$ is not analytically tractable, but can be efficiently computed for every fixed ϕ_e by solving (21). Therefore, the one-dimensional optimization problem (24) can be handled by any line search method, e.g., uniform sampling or the golden search [42].

Remark: It can be shown that problem (20) *can be simplified into problem* (9) *if ϕ_b is fixed. Thus, it is natural to consider solving problem* (20) *on the basis of the discussion in Section III for solving (9), i.e., consider a two-layer method, which is similar to the proposed ϕ_e fixed method, with fixing ϕ_b in the inner layer. However, compared with this ϕ_b fixed method, the proposed ϕ_e fixed method is superior in computational complexity. Since solving the inner layer problem of the ϕ_e fixed method (i.e., the convex problem* (21)*) is much more efficient than solving the inner layer problem of the ϕ_b fixed method (i.e., the quasi-convex problem* (15)*). On the other hand, while the ϕ_e fixed method has lower complexity in solving (20), it cannot be applied to problem (9) in Section III since γ_b is constant in (9).*

Suppose $\chi(\phi_e)$ is maximized at a point ϕ_e^* in (24). Through Proposition 4, if $\chi(\phi_e^*) > 0$, we have $\chi(\phi_e^*) = \varpi(\phi_e^*) = \varpi^+$ and $\mathbf{Q}_x^+ = \tilde{\mathbf{Q}}_x(\phi_e^*) = \tilde{\mathbf{X}}_\eta(\phi_e^*)/\tilde{\eta}(\phi_e^*)$, $\mathbf{Q}_z^+ = \tilde{\mathbf{Q}}_z(\phi_e^*) = \tilde{\mathbf{Z}}_\eta(\phi_e^*)/\tilde{\eta}(\phi_e^*)$. Otherwise, since $\varpi(\phi_e) \le \chi(\phi_e) \le \chi(\phi_e^*) \le 0$, we know $\varpi^+ = 0$. Thus, by Proposition 3, problem P-SRM-A can be solved. More specifically, the steps for solving the original design problem P-SRM-A are described in Algorithm 2.

Algorithm 2 Algorithm of Robust Secrecy Rate Based Transmission Design for Scenario(a)

Input: $\tilde{\mathbf{h}}_b$, $\mathcal{H}_e$, $\tilde{\mathbf{g}}_b$, $\mathcal{G}_e$, σ_b^2, $\mathcal{N}_e$, $\xi_{h,b}^2$, $\xi_{g,b}^2$, $\mathcal{B}_{h,e}$, $\mathcal{B}_{g,e}$, P_s, P_c.
1. Solve problem (23) and take the optimal value as $\bar{\phi}_e$.
2. Apply a suitable line search method to solve (24) and obtain ϕ_e^* by selecting specific ϕ_e over the interval $[0, \bar{\phi}_e]$ and calculating $\chi(\phi_e)$ through (21) iteratively.
3. If $\chi(\phi_e^*) > 0$, go to step 4. Otherwise, let $\mathbf{w}^+ = \mathbf{0}$, $\mathbf{Q}_z^+ = \mathbf{0}$ and go to **Output**.
4. Obtain $\tilde{\mathbf{X}}_\eta(\phi_e^*)$, $\tilde{\mathbf{Z}}_\eta(\phi_e^*)$, $\tilde{\eta}(\phi_e^*)$ by solving problem (21) with $\phi_e = \phi_e^*$.
5. Let $\mathbf{Q}_x^+ = \tilde{\mathbf{X}}_\eta(\phi_e^*)/\tilde{\eta}(\phi_e^*)$, $\mathbf{Q}_z^+ = \tilde{\mathbf{Z}}_\eta(\phi_e^*)/\tilde{\eta}(\phi_e^*)$.
6. Obtain $\mathbf{w}^+$ by performing eigenvalue decomposition for $\mathbf{Q}_x^+$.
Output: $\mathbf{w}^+$, $\mathbf{Q}_z^+$.

In Algorithm 2, the convex SDP problems with only LMI constraints can be solved by IPM efficiently. Similar to the analysis of Algorithm 1, the complexity of Algorithm 2 comes from the line search method and complexity of IPM. Suppose the number of iterations in the line search method is L_1. The complexity of Algorithm 2 can be shown on the order of

$$\begin{aligned}&L_1\sqrt{(K+2)(N_a+N_h)+7K+8}\ln(1/\epsilon)\mathcal{O}(N_a^2+N_h^2+K)\\&\times(((K+1)((N_a+1)^3+(N_h+1)^3)+N_a^3+N_h^3+5K+6)\\&+\mathcal{O}(N_a^2+N_h^2+K)((K+1)((N_a+1)^2+(N_h+1)^2)+N_a^2\\&+N_h^2+5K+6)+\mathcal{O}^2(N_a^2+N_h^2+K)).\end{aligned}$$

V. Robust QoS Based Transmission Design for Scenario b

According to the discussion in Section II, the QoS based transmission design problem for scenario (b) can be derived as

$$\begin{aligned}\text{P-QoS-B:}\ &\max_{\mathbf{w},\mathbf{Q}_z} \operatorname{tr}(\mathbf{Q}_z)\\&\text{s.t.} \min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b}\\ \mathbf{e}_{g,b}\in\varepsilon_{g,b}}} SINR_b(\mathbf{w},\mathbf{Q}_z)\ge\gamma_b\\&\qquad\|\mathbf{w}\|^2\le P_s,\ \operatorname{tr}(\mathbf{Q}_z)\le P_c,\ \mathbf{Q}_z\succeq\mathbf{0}.\end{aligned}$$

For the feasibility of P-QoS-B, because P-QoS-A and it have the same constraints, Proposition 1 can also be applied.

Similar to Section III, the following discussion is based on the assumption that $P_s > 0$, $\gamma_b > 0$ and problem P-QoS-B is feasible.

The SDR problem of P-QoS-B is

$$\begin{aligned}&\max_{\mathbf{Q}_x,\mathbf{Q}_z} \operatorname{tr}(\mathbf{Q}_z)\\&\text{s.t.} \min_{\substack{\mathbf{e}_{h,b}\in\varepsilon_{h,b}\\ \mathbf{e}_{g,b}\in\varepsilon_{g,b}}} \frac{\mathbf{h}_b\mathbf{Q}_x\mathbf{h}_b{}^H}{\mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b{}^H+\sigma_b^2}\ge\gamma_b\\&\qquad\operatorname{tr}(\mathbf{Q}_x)\le P_s,\ \operatorname{tr}(\mathbf{Q}_z)\le P_c,\ \mathbf{Q}_x\succeq\mathbf{0},\ \mathbf{Q}_z\succeq\mathbf{0}.\end{aligned}\tag{25}$$

Through the discussion for problem (9), we know (25) can be transformed into

$$\begin{aligned}&\max_{\mathbf{Q}_x,\mathbf{Q}_z,\psi,\alpha,\upsilon,\varrho} \operatorname{tr}(\mathbf{Q}_z)\\&\text{s.t. } T_{h,b}(\mathbf{Q}_x,\psi,\upsilon)\succeq\mathbf{0},\quad T_{g,b}(\mathbf{Q}_z,\alpha,\varrho,\sigma_b^2)\succeq\mathbf{0}\\&\qquad\upsilon\ge\gamma_b\varrho,\ \psi\ge0,\ \alpha\ge0,\ \upsilon\ge0,\ \varrho\ge0\\&\qquad\operatorname{tr}(\mathbf{Q}_x)\le P_s,\ \operatorname{tr}(\mathbf{Q}_z)\le P_c,\ \mathbf{Q}_x\succeq\mathbf{0},\ \mathbf{Q}_z\succeq\mathbf{0}\end{aligned}\tag{26}$$

which is a convex SDP. The SDR problem (25) can be solved through (26). However, the rank profile of its optimal solutions cannot be guaranteed, which will be shown in our simulation. To solve P-QoS-B, we need a method to find out a rank-guaranteed solution in (26).

Proposition 5: Suppose problem P-QoS-B is feasible. By letting $\{\mathbf{Q}_x^-, \mathbf{Q}_z^-, \psi^-, \alpha^-, \upsilon^-, \varrho^-\}$ denote an optimal solution to problem (26), we construct a convex SDP problem as

$$\min_{\mathbf{s}} \sum_{i=1}^{n_\mathbf{s}} c_i s_i \tag{27a}$$

$$\text{s.t. } \mathbf{G}_0+\sum_{i=1}^{n_\mathbf{s}} s_i\mathbf{G}_i\succeq\mathbf{0}. \tag{27b}$$

Here s_i is the i-th element in the $n_\mathbf{s}$ dimensional vector $\mathbf{s} = [\operatorname{vec}(\mathbf{Q}_x), \upsilon, \psi]$. c_i is 1 when s_i represents a

Algorithm 3 Algorithm of Robust QoS Based Transmission Design for Scenario(b)

Input: $\tilde{\mathbf{h}}_b$, $\tilde{\mathbf{g}}_b$, σ_b^2, γ_b, $\xi_{h,b}^2$, $\xi_{g,b}^2$, P_s, P_c.
1. Obtain $\{\mathbf{Q}_x^-$, $\mathbf{Q}_z^-$, $\psi^-, \alpha^-, \upsilon^-, \varrho^-\}$ by solving problem (26).
2. If $\mathrm{rank}(\mathbf{Q}_x^-) = 1$, let $\ddot{\mathbf{Q}}_x = \mathbf{Q}_x^-$ and go to step 4. Otherwise, go to step 3.
3. Solve (27) and obtain $\ddot{\mathbf{Q}}_x$ which is contained in solution $\ddot{\mathbf{s}}$.
4. Obtain $\ddot{\mathbf{w}}$ by performing eigenvalue decomposition for $\ddot{\mathbf{Q}}_x$.
Output: $\ddot{\mathbf{w}}$, $\mathbf{Q}_z^-$.

diagonal entry of $\mathbf{Q}_x$; otherwise, it is 0. For matrices, $\mathbf{G}_i = \partial \mathbf{G}/\partial s_i, i = 1, \ldots, n_{\mathbf{s}}$, $\mathbf{G}_0 = \mathbf{G} - \sum_{i=1}^{n_{\mathbf{s}}} s_i \mathbf{G}_i$ and $\mathbf{G} = \mathrm{diag}\{T_{h,b}(\mathbf{Q}_x, \psi, \upsilon), \mathbf{Q}_x, \upsilon - \gamma_b \varrho^-, \psi\}$. For each optimal solution $\ddot{\mathbf{s}} = [\mathrm{vec}(\ddot{\mathbf{Q}}_x), \ddot{\upsilon}, \ddot{\psi}]$ to (27), we have $\{\ddot{\mathbf{Q}}_x, \mathbf{Q}_z^-, \ddot{\psi}, \alpha^-, \ddot{\upsilon}, \varrho^-\}$ is an optimal solution to (26) and $\ddot{\mathbf{Q}}_x$ must be rank-one. Thus, $\ddot{\mathbf{Q}}_x$ can be decomposed as $\ddot{\mathbf{w}}\ddot{\mathbf{w}}^H$ and $\{\ddot{\mathbf{w}}, \mathbf{Q}_z^-\}$ is an optimal solution to P-QoS-B.

Proof: See Appendix F.

Based on Proposition 5, the original design problem in P-QoS-B can be exactly solved as shown in Algorithm 3.

IPM can be applied to solve the convex SDPs (26) and (27) which have only LMI constraints. The complexity of Algorithm 3 consists of the iteration complexity and the per-iteration computation cost of IPM for solving (26) and (27). It can be shown the complexity of Algorithm 3 is on order of

$$\begin{aligned}
&\sqrt{2(N_a+N_h)+9}\ln(1/\epsilon)\mathcal{O}(N_a^2+N_h^2)(((N_a+1)^3\\
&\quad+(N_h+1)^3+N_a^3+N_h^3+7)+\mathcal{O}(N_a^2+N_h^2)((N_a+1)^2\\
&\quad+(N_h+1)^2+N_a^2+N_h^2+7)+\mathcal{O}^2(N_a^2+N_h^2))\\
&\quad+\sqrt{2N_a+3}\ln(1/\epsilon)\mathcal{O}(N_a^2)(((N_a+1)^3+N_a^3+2)\\
&\quad+\mathcal{O}(N_a^2)((N_a+1)^2+N_a^2+2)+\mathcal{O}^2(N_a^2)).
\end{aligned}$$

VI. Simulation Results

In this section, we first demonstrate numerical results on the performance of the robust secrecy rate maximization design (SRMD) proposed in Section IV. Then, we present simulation experiments to illustrate the performance of the robust QoS based secure transmission designs for scenarios (a) and (b) (which are referred to as QoSD(a) and QoSD(b)). For comparison, we also examine the robust and non-robust individual power constrained SRMDs discussed in [24] and the relaxed counterparts of QoSD(a) and QoSD(b) (which are referred to as QoSD(a)-SDR and QoSD(b)-SDR), i.e., the transmit covariance based designs in (9) and (25) respectively.

For all the examples in this section, we assume Alice and the Helper both have four antennas, i.e., $N_a = 4$, $N_h = 4$. Elements of channel estimates are independent, zero-mean complex Gaussian random variables with unit variance and the channel uncertainty are given by $\xi_{h,b}^2 = \xi_{g,b}^2 = \xi_b^2$ and $\xi_{h,e,k}^2 = \xi_{g,e,k}^2 = \xi_e^2$, $k = 1, \ldots, K$. The noise power at Bob and Eves is assumed to be unity, i.e., $\sigma_d^2 = \sigma_{e,k}^2 = 1$. For the power bounds for Alice and the Helper, we assume they are the same, $P_s = P_c$, and their sum $P = P_s + P_c$ is defined in dB.

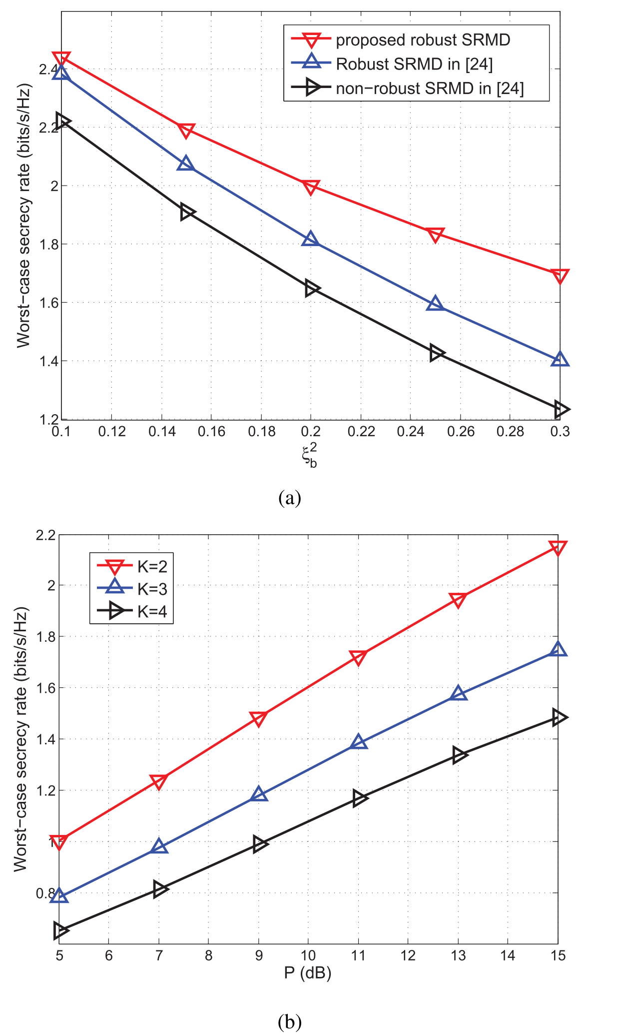

Fig. 2. (a) Average worst-case secrecy rates for proposed SRMD and SRMDs in existing work versus ξ_b^2 with $K = 1$; (b) average worst-case secrecy rates in multiple eavesdroppers scenarios for proposed SRMD versus P.

Convex optimization problems are solved by using CVX [43] and the number of trials for Monte Carlo simulations is 1, 000.

In Fig. 2(a), we compare the impacts of increasing ξ_b^2 on the proposed SRMD and its counterparts. Because SRMDs in [24] is only for the one eavesdropper scenario, we assume that $K = 1$. Moreover, we set $P = 10$ dB and $\xi_e^2 = 0.3$ in this case. During the aggregation of channel uncertainty in LCSI, the secrecy rate gaps between the the proposed SRMD and the SRMDs in [24] are widen significantly. The reason behind this is that both the robust and non-robust SRMDs in [24] are based on zero-forcing and the zero-forcing approach is sensitive to LCSI errors. Fig. 2(b) shows the optimal worst-case secrecy rates achieved by the proposed SRMD in multiple eavesdroppers cases as functions of P, with $\xi_b^2 = 0.2$ and $\xi_e^2 = 0.3$. We can observe that the increase of the number of eavesdroppers causes performance degradation, which can be overcome by increasing P.

Fig. 3(a) represents the average worst-case SINRs at both Bob and Eves versus the channel uncertainty in ECSI for QoSD(a) and QoSD(a)-SDR with $K = 2$, $P = 10$dB, $\xi_b^2 = 0.2$ and $\gamma_b = 5$dB. We can observe that the performance of

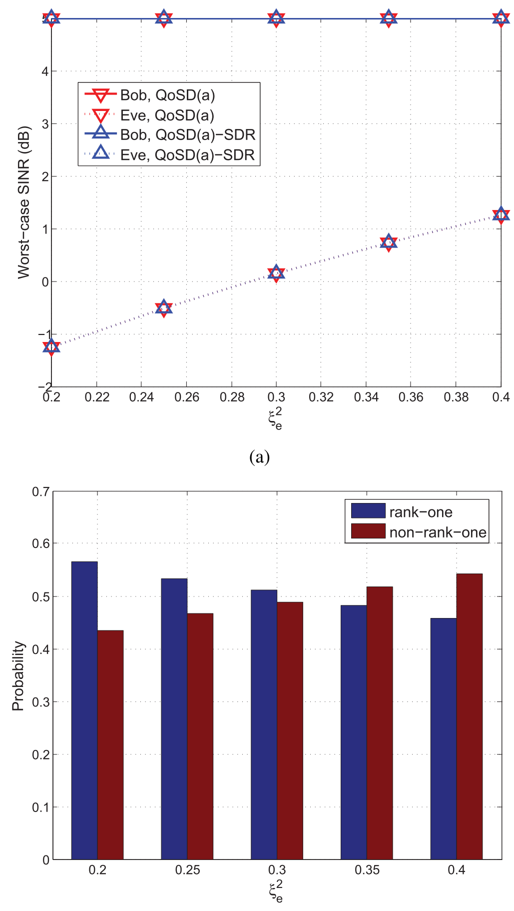

Fig. 3. (a) Average worst-case SINRs at Bob and Eves for QoSD(a) and QoSD(a)-SDR versus ξ_e^2; (b) probabilities of rank-one and non-rank-one optimal $\mathbf{Q}_x$ in QoSD(a)-SDR versus ξ_e^2.

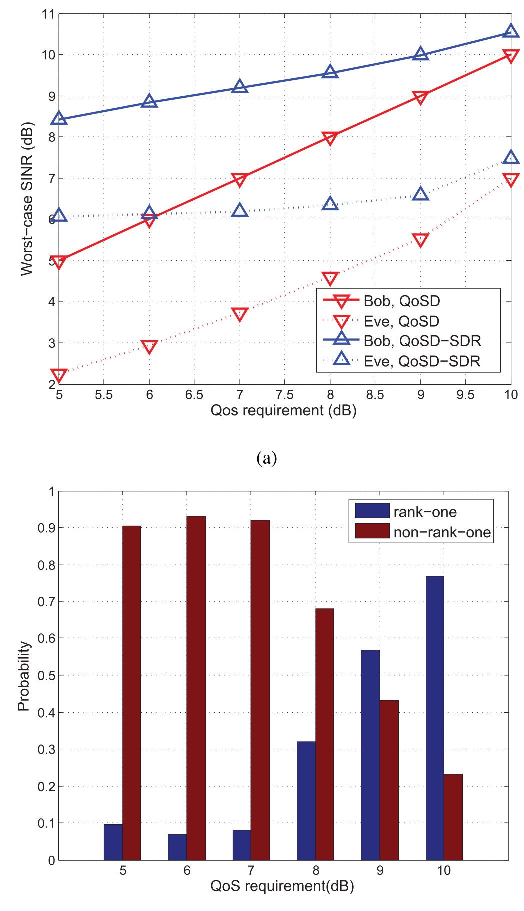

Fig. 4. (a) Average worst-case SINRs at Bob and Eves for QoSD(b) and QoSD(b)-SDR versus QoS requirement at Bob; (b) probabilities of rank-one and non-rank-one optimal $\mathbf{Q}_x$ in QoSD(b)-SDR versus the QoS requirement at Bob.

QoSD(a) coincides with that of QoSD(a)-SDR. This verifies our analysis that beamforming is the best transmission strategy. Compared with Fig. 2(b), Fig. 3(a) also shows that Alice can transmit information to Bob at a speed higher than the maximum achievable secrecy rate with limited SINR leakage to Eves. Thus, when the achievable secrecy rate cannot meet the data rate demand, QoS based transmission design can be used to help information security from physical layer by crippling eavesdroppers' interceptions. In Fig. 3(b), we examine the probabilities of obtaining rank-one and non-rank-one optimal $\mathbf{Q}_x$ in QoSD(a)-SDR with the same parameters as those in Fig. 3(a). It can be observed that the chance of directly obtaining rank-one optimal $\mathbf{Q}_x$ through QoSD(a)-SDR is no more than 60% and this chance decreases when ξ_e^2 is increased.

In Fig. 4(a), the worst-case SINRs at both Bob and Eves[9] are plotted against increasing γ_b for QoSD(b) and QoSD(b)-SDR, when $\xi_b^2 = 0.2$ and $P = 10$dB. In addition, the probabilities of obtaining rank-one and non-rank-one optimal $\mathbf{Q}_x$ in QoSD(b)-SDR are demonstrated in Fig. 4(b) for different values of γ_b. In Fig. 4(a), we can see that, even though there is no knowledge about ECSI, the proposed design QoSD(b) can suppress the SINR at Eves and impose a 3dB gap with respect to the worst-case SINR at Bob. It can also be observed for QoSD(b)-SDR that the QoS provided at Bob exceeds the requirement while signals with higher SINR are leaked to Eves in comparison with QoSD(b). This can be explained by the fact that the non-unique-rank solutions in QoSD(b)-SDR usually maximize the power of jamming signals at the expense of enhancing the power of information transmission and non-unique-rank solutions are obtained in QoSD(b)-SDR with high probability, which is shown in Fig. 4(b). Since the QoS requirement is met by both QoSD(b) and QoSD(b)-SDR, QoSD(b) shows a performance improvement by suppressing the SINR at Eves.

[9]ECSI is unknown in QoSD(b) and QoSD(b)-SDR. To calculate the worst-case SINR at Eves, we randomly generate channel estimates for Eves ($\tilde{\mathbf{h}}_{e,k}$ and $\tilde{\mathbf{g}}_{e,k}$) and assume $\sigma_{e,k}^2 = 1$, $K = 2$, $\xi_e^2 = 0.3$.

VII. Conclusions

We studied robust secure transmission designs from both QoS based and secrecy rate based perspectives for a CJ aided MISO system with norm bounded channel uncertainties. Two scenarios were considered: (a) ECSI is available and (b) ECSI is unavailable. For scenario (a), a QoS based design and a secrecy rate based design were investigated. For scenario (b), only the QoS based design was considered since the secrecy rate based design is not applicable. In all the designs, we optimized the transmit beamforming vector and the covariance matrix of jamming signals under individual power constraints. To solve the non-convex design problems, we use the SDR approach to obtain the transmit covariance based counterparts. We demonstrated that rank-one optimal transmit covariance solutions can always be found in the transmit covariance based problems and similar results do not exist in previous works on robust secure transmission designs for CJ aided MISO systems. The simulation results revealed that, when the ECSI is available, the secrecy rate based design outperformed previously proposed designs based on transmit covariance optimization. The effectiveness and robustness of the QoS based designs were also demonstrated by the simulation results. All the robust secure transmission designs are considered in worst-case sense in this paper. The probabilistic-constrained robust secure transmission designs will be studied in our future work.

Appendix

A. Proof of Proposition 1

Take

$$\mathbf{w} = \tilde{\mathbf{h}}_b^H \text{ and } \mathbf{Q}_z = \mathbf{I} - \frac{\tilde{\mathbf{g}}_b^H \tilde{\mathbf{g}}_b}{\|\tilde{\mathbf{g}}_b\|^2}. \tag{28}$$

Due to (6), it can be seen that

$$\begin{aligned}\min_{\mathbf{e_{h,b}} \in \varepsilon_{h,b}} & (\tilde{\mathbf{h}}_b + \mathbf{e_{h,b}})\mathbf{w}^H\mathbf{w}(\tilde{\mathbf{h}}_b + \mathbf{e_{h,b}})^H \\ &= \min_{\mathbf{e_{h,b}} \in \varepsilon_{h,b}} |\tilde{\mathbf{h}}_b\tilde{\mathbf{h}}_b^H + \mathbf{e_{h,b}}\tilde{\mathbf{h}}_b^H|^2 \\ &\geq (\|\tilde{\mathbf{h}}_b\|^2 - \xi_{h,b}\|\tilde{\mathbf{h}}_b\|)^2 = (\|\tilde{\mathbf{h}}_b\| - \xi_{h,b})^2\|\tilde{\mathbf{h}}_b\|^2. \end{aligned} \tag{29}$$

Then, we employ $\mathbf{Q}_z\tilde{\mathbf{g}}_b^H = 0$, $\tilde{\mathbf{g}}_b\mathbf{Q}_z = 0$ and $\|\mathbf{Q}_z\| = 1$ to have

$$\begin{aligned}\max_{\mathbf{e_{g,b}} \in \varepsilon_{g,b}} & (\tilde{\mathbf{g}}_b + \mathbf{e_{g,b}})\mathbf{Q}_z(\tilde{\mathbf{g}}_b + \mathbf{e_{g,b}})^H + \sigma_b^2 \\ &= \max_{\mathbf{e_{g,b}} \in \varepsilon_{g,b}} (\tilde{\mathbf{g}}_b + \mathbf{e_{g,b}})\mathbf{Q}_z\mathbf{e_{g,b}}^H + \sigma_b^2 \\ &= \max_{\mathbf{e_{g,b}} \in \varepsilon_{g,b}} \mathbf{e_{g,b}}\mathbf{Q}_z\mathbf{e_{g,b}}^H + \sigma_b^2 \\ &\leq \max_{\mathbf{e_{g,b}} \in \varepsilon_{g,b}} \|\mathbf{e_{g,b}}\|^2 + \sigma_b^2 = \xi_{g,b}^2 + \sigma_b^2 \end{aligned} \tag{30}$$

which, together with (29), lead to

$$\begin{aligned}\min_{\mathbf{e_{h,b}} \in \varepsilon_{h,b}, \mathbf{e_{g,b}} \in \varepsilon_{h,b}} & \frac{(\tilde{\mathbf{h}}_b + \mathbf{e_{h,b}})\mathbf{w}^H\mathbf{w}(\tilde{\mathbf{h}}_b + \mathbf{e_{h,b}})^H}{(\tilde{\mathbf{g}}_b + \mathbf{e_{g,b}})\mathbf{Q}_z(\tilde{\mathbf{g}}_b + \mathbf{e_{g,b}})^H + \sigma_b^2} \\ &\geq \frac{(\|\tilde{\mathbf{h}}_b\| - \xi_{h,b}\|)^2\|\tilde{\mathbf{h}}_b\|^2}{\xi_{g,b}^2 + \sigma_b^2} \geq \gamma_b \end{aligned} \tag{31}$$

by (7). Furthermore, according to the assumption (8), it is easy to have

$$\|\mathbf{w}\|^2 = \left\|\tilde{\mathbf{h}}_b\right\|^2 \leq P_s \tag{32}$$

and

$$\begin{aligned}\mathrm{tr}(\mathbf{Q}_z) &= N_h - \mathrm{tr}(\frac{\tilde{\mathbf{g}}_b^H \tilde{\mathbf{g}}_b}{\|\tilde{\mathbf{g}}_b\|^2}) \\ &= N_h - \mathrm{tr}(\frac{\tilde{\mathbf{g}}_b \tilde{\mathbf{g}}_b^H}{\|\tilde{\mathbf{g}}_b\|^2}) = N_h - 1 \leq P_c. \end{aligned} \tag{33}$$

Because of (31)–(33) and $\mathbf{Q}_z \succeq \mathbf{0}$, $(\mathbf{w}, \mathbf{Q}_z)$ given by (28) is a feasible point and problem P-QoS-A is feasible.

B. Proof of Lemma 1

Recall that we have $\mathrm{diag}\{\boldsymbol{\Omega}, \boldsymbol{\Upsilon}\} \succeq \mathbf{0}$ if and only if $\boldsymbol{\Omega} \succeq \mathbf{0}$ and $\boldsymbol{\Upsilon} \succeq \mathbf{0}$. Therefore, $\mathbf{F} = \mathbf{F}_0 + \sum_{i=1}^{n_\mathbf{s}} s_i\mathbf{F}_i \succeq \mathbf{0}$ is equivalent to

$$(11) - (14), \quad \upsilon \geq \theta_b \varrho \tag{34a}$$

$$u_k \leq \theta_e z_k, \quad k = 1, \ldots, K \tag{34b}$$

$$\mathrm{tr}(\mathbf{Q}_z) \leq P_c, \ \mathbf{Q}_x \succeq \mathbf{0}, \ \mathbf{Q}_z \succeq \mathbf{0}. \tag{34c}$$

Furthermore, it can be observed that $\sum_{i=1}^{n_\mathbf{s}} c_i s_i = \mathrm{tr}(\mathbf{Q}_x)$. Consequently, problem in (18) can be equivalently expressed as

$$\begin{aligned}\min_{\substack{\mathbf{Q}_x, \mathbf{Q}_z, \upsilon, \varrho, \psi, \alpha, u_1, \ldots, u_K \\ z_1, \ldots, z_K, \varphi_1, \ldots, \varphi_K, \beta_1, \ldots, \beta_K}} & \mathrm{tr}(\mathbf{Q}_x) \\ \text{s.t. } & (34a) - (34c). \end{aligned} \tag{35}$$

Since (12) implies (10b), in problem (35) there must be $\varrho \geq 0$. Hence $\upsilon \geq \theta_b \varrho$ forces $\upsilon \geq 0$. Similarly, we also have $u_k, z_k \geq 0$ in (35). Therefore, by replacing (11)-(14) with their equivalent counterparts, problem (35) can be rewritten as

$$\begin{aligned}\min_{\substack{\mathbf{Q}_x, \mathbf{Q}_z, \upsilon, \varrho, \\ u_1, \ldots, u_K, z_1, \ldots, z_K}} & \mathrm{tr}(\mathbf{Q}_x) \\ \text{s.t. } & (10a) - (10d), \ \upsilon \geq \theta_b \varrho, \ \upsilon \geq 0, \ \varrho \geq 0 \\ & u_k \leq \theta_e z_k, \ u_k \geq 0, \ z_k \geq 0, \ k = 1, \ldots, K \\ & \mathrm{tr}(\mathbf{Q}_z) \leq P_c, \ \mathbf{Q}_x \succeq \mathbf{0}, \ \mathbf{Q}_z \succeq \mathbf{0} \end{aligned} \tag{36}$$

which can be further converted into

$$\begin{aligned}\min_{\mathbf{Q}_x, \mathbf{Q}_z} & \mathrm{tr}(\mathbf{Q}_x) \\ \text{s.t. } & (17b), \ (17c), \ (34c). \end{aligned} \tag{37}$$

Due to the equivalent relationship between (18) and (37), $\{\mathbf{Q}_x^*, \mathbf{Q}_z^*\}$ is an optimal solution of (37). Since problem (17) is feasible for the fixed θ_b and θ_e, there exists a feasible point in (37) such that $\mathrm{tr}(\mathbf{Q}_x) \leq P_s$. Thus we have $\mathrm{tr}(\mathbf{Q}_x^*) \leq P_s$, from which we can see $\{\mathbf{Q}_x^*, \mathbf{Q}_z^*, \theta_b, \theta_e\}$ lies in the feasible set of (17).

Because $\mathbf{s}^*$ is optimal to (18), $\{\mathbf{Q}_x^*, \mathbf{Q}_z^*, \upsilon^*, \varrho^*, \psi^*, \alpha^*, u_1^*, \ldots, u_K^*, z_1^*, \ldots, z_K^*, \varphi_1^*, \ldots, \varphi_K^*, \beta_1^*, \ldots, \beta_K^*\}$ is an optimal solution to (35). Thus, υ^*, ϱ^*, u_k^* and z_k^* must be greater or equal to 0. Through the inequalities $\mathrm{tr}(\mathbf{Q}_x^*) \leq P_s$, $\mathrm{tr}(\mathbf{Q}_z^*) \leq P_c$, we know that $\mathbf{Q}_x^*$ and $\mathbf{Q}_z^*$ are in bounded sets. Together this with $\upsilon \geq \theta_b \varrho$ and (10a) which is equivalent to (11), we can show that υ^* and ϱ^* lie in bounded sets. Then, using (12), we see that α^* is in a bounded set. Because of (11), ψ^* lies in a bounded set. By (10d), the equivalent counterpart of (14), z_k^* lies in a bounded set; consequently, by $u_k \leq \theta_e z_k$, u_k^* is bounded. The boundedness of φ_k^* and β_k^* follows from (13) and (14). Therefore $\mathbf{s}^*$ must be in a bounded set and the set of optimal solutions of (18) is bounded. Then, we consider the dual problem of (18)

$$\begin{aligned}\max_{\mathbf{E}} & -\mathrm{tr}(\mathbf{F}_0\mathbf{E}) \\ \text{s.t. } & \mathrm{tr}(\mathbf{F}_i\mathbf{E}) = c_i, \quad i = 1, \ldots, n_\mathbf{s}, \ \mathbf{E} \succeq \mathbf{0} \end{aligned} \tag{38}$$

where matrix $\mathbf{E}$ is the Lagrangian multiplier corresponding to the constraint of (18). Suppose that (38) is not strictly feasible, i.e. $\nexists \mathbf{E}^0$ s.t. $\mathrm{tr}(\mathbf{F}_i\mathbf{E}^0) = c_i, i = 1, \ldots, n_{\mathbf{s}}, \mathbf{E}^0 \succ \mathbf{0}$. Then, we know the set $\Theta = \{\mathbf{h}|\mathrm{tr}(\mathbf{F}_i\mathbf{E}^0) = h_i; \forall \mathbf{E}^0 \succ \mathbf{0}, \text{ or } \mathbf{E}^0 = \mathbf{0}\}$ and the set $\Phi = \{\mathbf{c}\}$ are disjoint, where $\mathbf{h}$ and $\mathbf{c}$ are column vectors composed of h_i and c_i respectively. Because Θ is a convex cone and Φ is also convex, by the separating hyperplane theorem [38], a vector $\mathbf{d} \neq \mathbf{0}$ can be found to make $\mathbf{h}^T\mathbf{d} \geq 0$, $\forall \mathbf{h} \in \Theta$ and $\mathbf{c}^T\mathbf{d} \leq 0$. From $\mathbf{h}^T\mathbf{d} \geq 0$, $\forall \mathbf{h} \in \Theta$, we have $\sum_{i=1}^{n_{\mathbf{s}}} d_i \mathrm{tr}(\mathbf{F}_i\mathbf{E}^0) = \mathrm{tr}(\mathbf{E}^0 \sum_{i=1}^{n_{\mathbf{s}}} d_i\mathbf{F}_i) \geq 0, \forall \mathbf{E}^0 \succ \mathbf{0}$, where d_i is the i-th entry in the vector $\mathbf{d}$. This implies $\sum_{i=1}^{n_{\mathbf{s}}} d_i\mathbf{F}_i \succeq \mathbf{0}$. Then consider $\mathbf{y} = \mathbf{s}^* + \tau\mathbf{d}$, $\tau > 0$. $\mathbf{y}$ is feasible in (18) since $\mathbf{F}_0 + \sum_{i=1}^{n_{\mathbf{s}}}(s_i^* + \tau d_i)\mathbf{F}_i \succeq \mathbf{0}$. If $\mathbf{c}^T\mathbf{d} < 0$, then $\mathbf{c}^T\mathbf{y} < \mathbf{c}^T\mathbf{s}^*$ which contradicts with the statement $\mathbf{s}^*$ is the optimality in (18). Otherwise, if $\mathbf{c}^T\mathbf{d} = 0$, then we know a ray $\{\mathbf{y} = \mathbf{s}^* + \tau\mathbf{d}|\forall\tau > 0\}$ lies in the set of optimal solutions of (18) which is bounded. This, of course, is a paradox. Therefore, problem (38) is strictly feasible. Since (18) and (38) are self-dual, by using Slater's condition, we conclude that strong duality holds for them.

C. Proof of Theorem 1

Lemma 1 (ii) implies $\mathbf{s}^*$ must satisfy the KKT conditions [38, p. 267] showing below

$$\mathbf{F}_0 + \sum_{i=1}^{n_{\mathbf{s}}} s_i^*\mathbf{F}_i \succeq \mathbf{0}, \tag{39}$$

$$\mathbf{E}^* \succeq \mathbf{0}, \tag{40}$$

$$\mathrm{tr}(\mathbf{E}^*(\mathbf{F}_0 + \sum_{i=1}^{n_{\mathbf{s}}} s_i^*\mathbf{F}_i)) = 0, \tag{41}$$

$$\mathrm{tr}(\mathbf{F}_i\mathbf{E}^*) = c_i, \quad i = 1, \ldots, n_{\mathbf{s}} \tag{42}$$

where $\mathbf{E}^*$ is an optimal dual variable.

Since $\mathbf{F}_0 + \sum_{i=1}^{n_{\mathbf{s}}} s_i^*\mathbf{F}_i$ is positive semidefinite, the diagonal matrices or scalars of it must be positive semidefinite or nonnegative. Similarly, the diagonal matrices and scalars of $\mathbf{E}^*$ are also positive semidefinite and nonnegative respectively. Without loss of generality, we let the diagonal matrices or scalars of $\mathbf{E}^*$ be sequentially denoted by $\mathbf{A}^*$, $\mathbf{C}^*$, $\mathbf{B}_1^*, \ldots, \mathbf{B}_K^*$, $\mathbf{D}_1^*, \ldots, \mathbf{D}_K^*$, $\mathbf{Y}^*$, $\mathbf{Z}^*$, $\lambda_{P_c}^*$, λ_1^*, $\lambda_{2,1}^*, \ldots, \lambda_{2,K}^*$, λ_ψ^*, λ_α^*, $\lambda_{\varphi_1}^*, \ldots, \lambda_{\varphi_K}^*$, $\lambda_{\beta_1}^*, \ldots, \lambda_{\beta_K}^*$, where $\mathbf{A}^* \in \mathbb{S}^{(N_a+1)\times(N_a+1)}$, $\mathbf{C}^* \in \mathbb{S}^{(N_h+1)\times(N_h+1)}$, $\mathbf{B}_k^* \in \mathbb{S}^{(N_a+1)\times(N_a+1)}, k = 1, \ldots, K$, $\mathbf{D}_k^* \in \mathbb{S}^{(N_h+1)\times(N_h+1)}, k = 1, \ldots, K$, $\mathbf{Y}^* \in \mathbb{S}^{N_a\times N_a}$, $\mathbf{Z}^* \in \mathbb{S}^{N_h\times N_h}$, $\mathbb{S}^{n\times n}$ denotes the set of positive semidefinite $n \times n$ matrices and the other variables are nonnegative scalars. Then, according to (41), we have

$$\begin{aligned}
&\mathrm{tr}(\mathbf{E}^*(\mathbf{F}_0 + \sum_{i=1}^{n_{\mathbf{s}}} s_i^*\mathbf{F}_i)) = \mathrm{tr}(\mathbf{A}^*T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*))\\
&\quad + \mathrm{tr}(\mathbf{C}^*T_{g,b}(\mathbf{Q}_z^*, \alpha^*, \varrho^*, \sigma_b^2)) + \sum_{k=1}^{K}\mathrm{tr}(\mathbf{B}_k^*T_{h,e,k}(\mathbf{Q}_x^*, \varphi_k^*, u_k^*))\\
&\quad + \sum_{k=1}^{K}\mathrm{tr}(\mathbf{D}_k^*T_{g,e,k}(\mathbf{Q}_z^*, \beta_k^*, z_k^*, \sigma_{e,k}^2)) + \mathrm{tr}(\mathbf{Y}^*\mathbf{Q}_x^*) + \mathrm{tr}(\mathbf{Z}^*\mathbf{Q}_z^*)\\
&\quad + \lambda_{P_c}^*(P_c - \mathrm{tr}(\mathbf{Q}_z^*)) + \lambda_1^*(\upsilon^* - \theta_b\varrho^*) + \sum_{k=1}^{K}\lambda_{2,k}^*(\theta_e z_k^* - u_k^*)\\
&\quad + \lambda_\psi^*\psi^* + \lambda_\alpha^*\alpha^* + \sum_{k=1}^{K}\lambda_{\varphi_k}^*\varphi_k^* + \sum_{k=1}^{K}\lambda_{\beta_k}^*\beta_k^* = 0.
\end{aligned} \tag{43}$$

Consider that if $\mathbf{\Omega} \succeq \mathbf{0}$, $\mathbf{\Upsilon} \succeq \mathbf{0}$ then $\mathrm{tr}(\mathbf{\Omega}\mathbf{\Upsilon}) \geq 0$. From (43), it can be known that

$$\mathrm{tr}(\mathbf{A}^*T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*)) = 0, \tag{44}$$

$$\mathrm{tr}(\mathbf{Y}^*\mathbf{Q}_x^*) = 0. \tag{45}$$

Recall that, when $\mathbf{\Omega} \succeq \mathbf{0}$ and $\mathbf{\Upsilon} \succeq \mathbf{0}$, $\mathrm{tr}(\mathbf{\Omega}\mathbf{\Upsilon}) = \mathbf{0}$ is equivalent to $\mathbf{\Omega}\mathbf{\Upsilon} = \mathbf{0}$. Hence, eqs.(44)-(45) can be re-written as

$$\mathbf{A}^*T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*) = \mathbf{0}, \tag{46}$$

$$\mathbf{Y}^*\mathbf{Q}_x^* = \mathbf{0}. \tag{47}$$

Let $q_{l,n}^x$ denote the entry at the l-th row and n-th column of matrix $\mathbf{Q}_x$ with $l \leq n$. When $l = n$, $q_{l,n}^x$ is on the diagonal of $\mathbf{Q}_x$ and the KKT condition in (42) which is corresponding to $q_{l,n}^x$ can be denoted as $\mathrm{tr}(\mathbf{F}_{q_{l,n}^x}\mathbf{E}^*) = c_{q_{l,n}^x}$. Suppose $\mathrm{tr}(\mathbf{F}_{q_{l,n}^x}\mathbf{E}^*)$ is in the l-th position of the diagonal of a matrix which is on the left side of an equation (left matrix) and $c_{q_{l,n}^x}$ is in the l-th position of the diagonal of a matrix which is on the right side of an equation (right matrix). When $l < n$, let $q_{l,n}^{x,R}$ and $q_{l,n}^{x,I}$ be the real part and imaginary part of $q_{l,n}^x$ respectively. The KKT condition in (42) which are associated with $q_{l,n}^{x,R}$ and $q_{l,n}^{x,I}$ can be denoted as $\mathrm{tr}(\mathbf{F}_{q_{l,n}^{x,R}}\mathbf{E}^*) = c_{q_{l,n}^{x,R}}$ and $\mathrm{tr}(\mathbf{F}_{q_{l,n}^{x,I}}\mathbf{E}^*) = c_{q_{l,n}^{x,I}}$. Let $j = \sqrt{-1}$. Suppose $(\mathrm{tr}(\mathbf{F}_{q_{l,n}^{x,R}}\mathbf{E}^*) + \mathrm{tr}(\mathbf{F}_{q_{l,n}^{x,I}}\mathbf{E}^*)j)/2$ is at the l-th row and n-th column of the left matrix; $(\mathrm{tr}(\mathbf{F}_{q_{l,n}^{x,R}}\mathbf{E}^*) + \mathrm{tr}(\mathbf{F}_{q_{l,n}^{x,I}}\mathbf{E}^*/j))/2$ is at the n-th row and l-th column of the left matrix; $(c_{q_{l,n}^{x,R}} + c_{q_{l,n}^{x,I}}j)/2$ is at the l-th row and n-th column of the right matrix; and $(c_{q_{l,n}^{x,R}} + c_{q_{l,n}^{x,I}}/j)/2$ is at the n-th row and l-th column of the right matrix. Then all such conditions form a matrix equation

$$\mathbf{Y}^* + (\mathbf{I}, \tilde{\mathbf{h}}_b^H)\mathbf{A}^*(\mathbf{I}, \tilde{\mathbf{h}}_b^H)^H - \sum_{k=1}^{K}(\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H)\mathbf{B}_k^*(\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H)^H = \mathbf{I}. \tag{48}$$

According to (39), we know $T_{g,b}(\mathbf{Q}_z^*, \alpha^*, \varrho^*, \sigma_b^2) \succeq \mathbf{0}$ which leads to $\varrho^* \geq \sigma_b^2 + \tilde{\mathbf{g}}_b\mathbf{Q}_z^*\tilde{\mathbf{g}}_b^H + \alpha\xi_{g,b}^2 > 0$. As $\theta_b > 0$, we have $\upsilon^* \geq \theta_b\varrho^* > 0$. Then assume $\psi^* = 0$, we have

$$\begin{aligned}
&(-\tilde{\mathbf{h}}_b, 1)T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*)(-\tilde{\mathbf{h}}_b, 1)^H\\
&\quad = (-\tilde{\mathbf{h}}_b, 1)\begin{pmatrix} \mathbf{Q}_x^* & \mathbf{Q}_x^*\tilde{\mathbf{h}}_b^H \\ \tilde{\mathbf{h}}_b\mathbf{Q}_x^* & \tilde{\mathbf{h}}_b\mathbf{Q}_x^*\tilde{\mathbf{h}}_b^H - \upsilon^* \end{pmatrix}(-\tilde{\mathbf{h}}_b, 1)^H\\
&\quad = -\upsilon^* < 0.
\end{aligned} \tag{49}$$

This contradicts that $T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*) \succeq \mathbf{0}$. Consequently, $\psi^* > 0$, which leads to $\psi^*\mathbf{I} + \mathbf{Q}_x^* \succ \mathbf{0}$. This implies that $\mathrm{rank}(T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*)) \geq N_a$ according to (11). Because of (46), $T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*)\ (\mathbf{A}^*)^H = \mathbf{0}$. The column space of $(\mathbf{A}^*)^H$ lies in the null space of $T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*)$. Then

$$\begin{aligned}\mathrm{rank}(\mathbf{A}^*) &= \mathrm{rank}(\mathbf{A}^{*H})\\ &\leq \dim(\ker(T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*)))\\ &= N_a + 1 - \mathrm{rank}(T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*))\\ &\leq N_a + 1 - N_a = 1. \end{aligned} \tag{50}$$

Multiplying (48) by $\mathbf{Q}_x^*$ and using (47), we have

$$\left(\mathbf{I} + \sum_{k=1}^{K} (\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H)\mathbf{B}_k^*(\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H)^H\right)\mathbf{Q}_x^* = (\mathbf{I}, \tilde{\mathbf{h}}_b^H)\mathbf{A}^*(\mathbf{I}, \tilde{\mathbf{h}}_b^H)^H\mathbf{Q}_x^*. \tag{51}$$

As $\left(\mathbf{I} + \sum_{k=1}^{K} (\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H)\mathbf{B}_k^*(\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H)^H\right)$ is positive definite, we must have

$$\begin{aligned}\mathrm{rank}(\mathbf{Q}_x^*) &= \mathrm{rank}\left(\left(\mathbf{I} + \sum_{k=1}^{K}\left(\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H\right)\mathbf{B}_k^*\left(\mathbf{I}, \tilde{\mathbf{h}}_{e,k}^H\right)^H\right)\mathbf{Q}_x^*\right)\\ &= \mathrm{rank}\left(\left(\mathbf{I}, \tilde{\mathbf{h}}_b^H\right)\mathbf{A}^*\left(\mathbf{I}, \tilde{\mathbf{h}}_b^H\right)^H\mathbf{Q}_x^*\right)\\ &\leq \mathrm{rank}(\mathbf{A}^*) \leq 1. \end{aligned} \tag{52}$$

Assume $\mathbf{Q}_x^* = \mathbf{0}$, then

$$T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*) = \begin{pmatrix}\psi^*\mathbf{I} & \mathbf{0}\\ \mathbf{0} & -\upsilon^* - \psi^*\xi_{h,b}^2\end{pmatrix} \not\succeq \mathbf{0} \tag{53}$$

because $\upsilon^* > 0$. This contradicts with $T_{h,b}(\mathbf{Q}_x^*, \psi^*, \upsilon^*) \succeq \mathbf{0}$. So $\mathrm{rank}(\mathbf{Q}_x^*) = 1$.

D. Proof of Proposition 3

We first prove the conclusion which is under the condition $\varpi^+ > 0$. When we let $\theta_b = \phi_b^+$ and $\theta_e = \phi_e^+$, $\{\mathbf{Q}_x^+, \mathbf{Q}_z^+\}$ is feasible in problem (37). Assume $\{\mathbf{Q}_x^+, \mathbf{Q}_z^+\}$ is not optimal. Then, for an optimal solution $\{\bar{\mathbf{Q}}_x^+, \bar{\mathbf{Q}}_z^+\}$ to (37), there must be $\mathrm{tr}(\bar{\mathbf{Q}}_x^+) < \mathrm{tr}(\mathbf{Q}_x^+) \leq P_s$. Thus, we can see $\{\bar{\mathbf{Q}}_x^+, \bar{\mathbf{Q}}_z^+, \phi_b^+, \phi_e^+\}$ satisfies all the constraints in (20) and becomes an optimal solution to (20). Consequently, $\{\bar{\mathbf{Q}}_x^+, \bar{\mathbf{Q}}_z^+\}$ is an optimal solution to (19). By denoting $\{\bar{\mathbf{e}}_{h,b}^+, \bar{\mathbf{e}}_{g,b}^+, \bar{\mathbf{e}}_{h,e,k}^+|_{k=1,\dots,K}, \bar{\mathbf{e}}_{g,e,k}^+|_{k=1,\dots,K}, k^+\}$ as an optimal solution of the objective function in (19) when $\mathbf{Q}_x = \bar{\mathbf{Q}}_x^+$, $\mathbf{Q}_z = \bar{\mathbf{Q}}_z^+$ and letting

$$\begin{aligned}a^+ &= (\tilde{\mathbf{h}}_b + \bar{\mathbf{e}}_{h,b}^+)\bar{\mathbf{Q}}_x^+(\tilde{\mathbf{h}}_b + \bar{\mathbf{e}}_{h,b}^+)^H,\\ b^+ &= (\tilde{\mathbf{g}}_b + \bar{\mathbf{e}}_{g,b}^+)\bar{\mathbf{Q}}_z^+(\tilde{\mathbf{g}}_b + \bar{\mathbf{e}}_{g,b}^+)^H + \sigma_b^2,\\ c_k^+ &= (\tilde{\mathbf{h}}_{e,k} + \bar{\mathbf{e}}_{h,e,k}^+)\bar{\mathbf{Q}}_x^+(\tilde{\mathbf{h}}_{e,k} + \bar{\mathbf{e}}_{h,e,k}^+)^H,\\ d_k^+ &= (\tilde{\mathbf{g}}_{e,k} + \bar{\mathbf{e}}_{g,e,k}^+)\bar{\mathbf{Q}}_z^+(\tilde{\mathbf{g}}_{e,k} + \bar{\mathbf{e}}_{g,e,k}^+)^H + \sigma_{e,k}^2,\end{aligned}$$

we can express the optimal value of problem (19) as $r^+ = \log((1+a^+/b^+)/(1+c_{k^+}^+/d_{k^+}^+))$. Owing to $\mathrm{tr}(\bar{\mathbf{Q}}_x^+) < P_s$, there must be some $\rho > 1$ such that $\mathrm{tr}(\rho\bar{\mathbf{Q}}_x^+) \leq P_s$. Therefore, $\{\rho\bar{\mathbf{Q}}_x^+, \bar{\mathbf{Q}}_z^+\}$ is feasible in (19). For $\{\rho\bar{\mathbf{Q}}_x^+, \bar{\mathbf{Q}}_z^+\}$, because of $\log((1+\rho a^+/b^+)/(1+\rho c_{k^+}^+/d_{k^+}^+)) \leq \log((1+\rho a^+/b^+)/(1+\rho c_k^+/d_k^+))\forall 1 \leq k \leq K$ and $k \neq k^+$, we can see $\{\bar{\mathbf{e}}_{h,b}^+, \bar{\mathbf{e}}_{g,b}^+, \bar{\mathbf{e}}_{h,e,k}^+|_{k=1,\dots,K}, \bar{\mathbf{e}}_{g,e,k}^+|_{k=1,\dots,K}, k^+\}$ is still optimal in the objective function of (19). Thus, when $\mathbf{Q}_x = \rho\bar{\mathbf{Q}}_x^+$, $\mathbf{Q}_z = \bar{\mathbf{Q}}_z^+$, the value of the objective function of (19) is $r_\rho = \log((1+\rho a^+/b^+)/(1+\rho c_{k^+}^+/d_{k^+}^+))$. Since $\varpi^+ > 0$ and problem (19) is equivalent to (20), we have $a^+d_{k^+}^+ > b^+c_{k^+}^+$ from $r^+ > 0$. Thus, the function $f(x) = \log((1+a^+x/b^+)/(1+c_{k^+}^+x/d_{k^+}^+))$ is strictly increasing. Through $f(x)$ and $\rho > 1$, we have $r_\rho > r^+$, which leads to a contradiction. Therefore $\{\mathbf{Q}_x^+, \mathbf{Q}_z^+\}$ is an optimal solution to problem (37) for $\theta_b = \phi_b^+$ and $\theta_e = \phi_e^+$. Since $\{\mathbf{Q}_x^+, \mathbf{Q}_z^+, \phi_b^+, \phi_e^+\}$ is optimal in (20), we must have $\theta_b = \phi_b^+$ and $\theta_e = \phi_e^+$ are feasible in (17). In addition, because of $\varpi^+ > 0$, we know $\theta_b = \phi_b^+ > 0$. By applying the equivalent relationship between (37) and (18) and Theorem 1, we can see $\mathrm{rank}(\mathbf{Q}_x^+) = 1$. Thus, $\mathbf{Q}_x^+$ can be decomposed as $\mathbf{Q}_x^+ = \mathbf{w}^+(\mathbf{w}^+)^H$ and $\{\mathbf{w}^+, \mathbf{Q}_z^+\}$ is an optimal solution to P-SRM-A.

Problem (20) is a relaxation of P-SRM-A, which implies $\varpi^+ \geq R^+$. Since $\{\mathbf{Q}_x = \mathbf{0}, \mathbf{Q}_z = \mathbf{0}, \phi_b = 0, \phi_e = 0\}$ lies in the feasible set of (20), we have $\varpi^+ \geq 0$. If ϖ^+ is not greater than 0, there must be $R^+ \leq \varpi^+ = 0$. Together with $R^+ \geq 0$, we know $R^+ = 0$ and $\{\mathbf{w}^+ = \mathbf{0}, \mathbf{Q}_z^+ = \mathbf{0}\}$ is an optimal solution to P-SRM-A.

E. Proof of Proposition 4

By introducing the slack variables u_k and z_k, constraint (20b) can be reformulated as

$$\mathbf{h}_{e,k}\mathbf{Q}_x\mathbf{h}_{e,k}{}^H \leq u_k, \quad \forall\ \mathbf{e}_{h,e,k} \in \varepsilon_{h,e,k} \tag{54}$$

$$\mathbf{g}_{e,k}\mathbf{Q}_z\mathbf{g}_{e,k}{}^H + \sigma_{e,k}^2 \geq z_k, \quad \forall\ \mathbf{e}_{g,e,k} \in \varepsilon_{g,e,k} \tag{55}$$

$$u_k \leq z_k\phi_e,\ u_k \geq 0,\ z_k \geq 0,\ k = 1, \dots, K. \tag{56}$$

Then, according to the Charnes-Cooper method, we let $\mathbf{X}_\eta = \mathbf{Q}_x\eta$, $\mathbf{Z}_\eta = \mathbf{Q}_z\eta$, $u_{\eta,k} = u_k\eta$, $z_{\eta,k} = z_k\eta$ and

$$\eta = \frac{1}{\max_{\mathbf{e}_{g,b}\in\varepsilon_{g,b}}\mathbf{g}_b\mathbf{Q}_z\mathbf{g}_b{}^H + \sigma_b^2}. \tag{57}$$

Through (54)–(57), we have another form of (20) for fixed ϕ_e

$$\max_{\substack{\mathbf{X}_\eta,\mathbf{Z}_\eta,\eta,\phi_b,u_{\eta,1},\dots,u_{\eta,K}\\ z_{\eta,1},\dots,z_{\eta,K}}} \log(1+\phi_b) - \log(1+\phi_e) \tag{58a}$$

$$\text{s.t. } \mathbf{h}_{e,k}\mathbf{X}_\eta\mathbf{h}_{e,k}{}^H \leq u_{\eta,k}, \quad \forall \mathbf{e}_{h,e,k} \in \varepsilon_{h,e,k} \tag{58b}$$

$$\mathbf{g}_{e,k}\mathbf{Z}_\eta\mathbf{g}_{e,k}{}^H + \sigma_{e,k}^2\eta \geq z_{\eta,k}, \quad \forall \mathbf{e}_{g,e,k} \in \varepsilon_{g,e,k} \tag{58c}$$

$$u_{\eta,k} \leq z_{\eta,k}\phi_e,\ u_{\eta,k} \geq 0,\ z_{\eta,k} \geq 0,\ k = 1, \dots, K \tag{58d}$$

$$\min_{\mathbf{e}_{h,b}\in\varepsilon_{h,b}} \mathbf{h}_b\mathbf{X}_\eta\mathbf{h}_b{}^H \geq \phi_b \tag{58e}$$

$$\max_{\mathbf{e}_{g,b}\in\varepsilon_{g,b}} \mathbf{g}_b\mathbf{Z}_\eta\mathbf{g}_b{}^H + \sigma_b^2\eta = 1 \tag{58f}$$

$$\mathrm{tr}(\mathbf{X}_\eta) \leq P_s\eta,\ \mathrm{tr}(\mathbf{Z}_\eta) \leq P_c\eta \tag{58g}$$

$$\mathbf{X}_\eta \succeq \mathbf{0},\ \mathbf{Z}_\eta \succeq \mathbf{0},\ \eta > 0,\ \phi_b \geq 0. \tag{58h}$$

Then, consider a convex SDP problem

$$\begin{aligned}&\max_{\substack{\mathbf{X}_\eta,\mathbf{Z}_\eta,\eta,\phi_b,u_{\eta,1},\dots,u_{\eta,K}\\ z_{\eta,1},\dots,z_{\eta,K}}} \log(1+\phi_b) - \log(1+\phi_e)\\ &\quad\text{s.t. } (58b) - (58e)\\ &\qquad\quad \max_{\mathbf{e}_{g,b}\in\varepsilon_{g,b}} \mathbf{g}_b\mathbf{Z}_\eta\mathbf{g}_b{}^H + \sigma_b^2\eta \leq 1\\ &\qquad\quad \mathrm{tr}(\mathbf{X}_\eta) \leq P_s\eta,\ \mathrm{tr}(\mathbf{Z}_\eta) \leq P_c\eta\\ &\qquad\quad \mathbf{X}_\eta \succeq \mathbf{0},\ \mathbf{Z}_\eta \succeq \mathbf{0},\ \eta \geq 0,\ \phi_b \geq 0. \end{aligned} \tag{59}$$

which can be equivalently rewritten as (21) by the S-procedure. Obviously, the optimal values of (58) and (59) are $\varpi(\phi_e)$ and $\chi(\phi_e)$, respectively. Let $\{\mathbf{X}_\eta^*, \mathbf{Z}_\eta^*, \eta^*, \phi_b^*, u_{\eta,1}^*, \ldots, u_{\eta,K}^*, z_{\eta,1}^*, \ldots, z_{\eta,K}^*\}$ denote an optimal solution to (59). Assume $\chi(\phi_e) > 0$. Because of $\chi(\phi_e) = \log(1+\phi_b^*) - \log(1+\phi_e)$, we have $\phi_b^* > 0$. Suppose $\max_{\mathbf{e}_{g,b}\in\varepsilon_{g,b}} \mathbf{g}_b \ \mathbf{Z}_\eta^* \mathbf{g}_b{}^H + \sigma_b^2 \eta^* < 1$. Then there must be some $\kappa > 1$ which can make $\{\kappa\mathbf{X}_\eta^*, \kappa\mathbf{Z}_\eta^*, \kappa\eta^*, \kappa\phi_b^*, \kappa_{\eta,1}^*, \ldots, \kappa u_{\eta,K}^*, \kappa z_{\eta,1}^*, \ldots, \kappa z_{\eta,K}^*\}$ be feasible in (59). However, due to $\phi_b^* > 0$, we know $\log(1+\kappa\phi_b^*) - \log(1+\phi_e) > \chi(\phi_e) = \log(1+\phi_b^*) - \log(1+\phi_e)$, which is a contradiction. Therefore, $\mathbf{Z}_\eta^*$ and η^* must satisfy (58f). In addition, we have $\eta^* > 0$. Otherwise, constraints (58e), $\mathrm{tr}(\mathbf{X}_\eta) \le P_s\eta$ and $\mathbf{X}_\eta \succeq \mathbf{0}$ cannot be met at the same time. Therefore, eqs.(58) and (59) are equivalent, through which we have $\varpi(\phi_e) = \chi(\phi_e)$ and (21) is equivalent to (58). Since (58) is converted from (20) through the Charnes-Cooper method, we have $\tilde{\mathbf{Q}}_x(\phi_e) = \tilde{\mathbf{X}}_\eta(\phi_e)/\tilde{\eta}(\phi_e)$, $\tilde{\mathbf{Q}}_z(\phi_e) = \tilde{\mathbf{Z}}_\eta(\phi_e)/\tilde{\eta}(\phi_e)$. Because (59) is a relaxation of (58), there must be $\varpi(\phi_e) \le \chi(\phi_e)$. Thus, when $\chi(\phi_e) \le 0$, we conclude that $\varpi(\phi_e) \le \chi(\phi_e) \le 0$.

F. Proof of Proposition 5

Because $\ddot{\mathbf{s}} = [\mathrm{vec}(\ddot{\mathbf{Q}}_x), \ddot{\upsilon}, \ddot{\psi}]$ is optimal in (27), $\ddot{\mathbf{s}}$ must satisfy the constraint (27b). Due to the properties of semidefinite matrix, we know

$$T_{h,b}(\ddot{\mathbf{Q}}_x, \ddot{\psi}, \ddot{\upsilon}) \succeq \mathbf{0}, \quad \ddot{\mathbf{Q}}_x \succeq \mathbf{0}, \ \ddot{\upsilon} \ge \gamma_b \varrho^-, \ \ \ddot{\psi} \ge 0. \quad (60)$$

The assumption that $\{\mathbf{Q}_x^-, \mathbf{Q}_z^-, \psi^-, \alpha^-, \upsilon^-, \varrho^-\}$ is an optimal solution to (26) implies

$$\begin{aligned} &T_{g,b}(\mathbf{Q}_z^-, \alpha^-, \varrho^-, \sigma_b^2) \succeq \mathbf{0}, \quad \alpha^- \ge 0, \\ &\varrho^- > 0, \ \mathrm{tr}(\mathbf{Q}_z^-) \le P_c, \ \mathbf{Q}_z^- \succeq \mathbf{0}, \end{aligned} \quad (61)$$

where $\varrho^- > 0$ is owing to $T_{g,b}(\mathbf{Q}_z^-, \alpha^-, \varrho^-, \sigma_b^2) \succeq \mathbf{0}$. Furthermore, it can be also known that $\mathbf{Q}_x^-$ is feasible in (27). Therefore, there must be

$$\mathrm{tr}(\ddot{\mathbf{Q}}_x) \le \mathrm{tr}(\mathbf{Q}_x^-) \le P_s. \quad (62)$$

From $\ddot{\upsilon} \ge \gamma_b\varrho^-$, $\varrho^- > 0$ and $\gamma_b > 0$, we have $\ddot{\upsilon} > 0$ which together with (60), (61) and (62) leads to the result that $\{\ddot{\mathbf{Q}}_x, \mathbf{Q}_z^-, \ddot{\psi}, \alpha^-, \ddot{\upsilon}, \varrho^-\}$ satisfies the constraints of (26) and is an optimal solution to it.

The inequality in (62) implies the boundedness of $\ddot{\mathbf{Q}}_x$. Because of $T_{h,b}(\ddot{\mathbf{Q}}_x, \ddot{\psi}, \ddot{\upsilon}) \succeq \mathbf{0}$, $\ddot{\upsilon}$ and $\ddot{\psi}$ must be bounded. Therefore, $\ddot{\mathbf{s}}$ lies in a bounded set and strong duality can be proved to be valid for (27) through the similar method as the one used in Appendix A.

The remaining part of this proof follows the logic line in Appendix B and we briefly describe it. Through the KKT conditions that $\ddot{\mathbf{s}}$ must satisfy, we can obtain the following useful equations

$$\ddot{\mathbf{A}} T_{h,b}(\ddot{\mathbf{Q}}_x, \ddot{\psi}, \ddot{\upsilon}) = \mathbf{0}, \quad (63)$$

$$\ddot{\mathbf{Y}}\ddot{\mathbf{Q}}_x = \mathbf{0}, \quad (64)$$

$$\mathbf{I} - (\mathbf{I}, \tilde{\mathbf{h}}_b^H)\ddot{\mathbf{A}}(\mathbf{I}, \tilde{\mathbf{h}}_b^H)^H = \ddot{\mathbf{Y}} \quad (65)$$

where $\ddot{\mathbf{A}}$ and $\ddot{\mathbf{Y}}$ are positive semidefinite optimal dual variables. Because of $\ddot{\upsilon} > 0$, we have $\ddot{\psi} > 0$. Otherwise, $(-\tilde{\mathbf{h}}_b, 1) T_{h,b}(\ddot{\mathbf{Q}}_x, \ddot{\psi}, \ddot{\upsilon})(-\tilde{\mathbf{h}}_b, 1)^H = -\ddot{\upsilon} < 0$ contradicts $T_{h,b}(\ddot{\mathbf{Q}}_x, \ddot{\psi}, \ddot{\upsilon}) \succeq \mathbf{0}$. Thus, we know $\mathrm{rank}(T_{h,b}(\ddot{\mathbf{Q}}_x, \ddot{\psi}, \ddot{\upsilon})) \ge N_a$. This, together with (63), leads to $\mathrm{rank}(\ddot{\mathbf{A}}) \le 1$. Then, by multiplying both sides of equation (65) by $\ddot{\mathbf{Q}}_x$ and employing (64), we can see $\mathrm{rank}(\ddot{\mathbf{Q}}_x) = \mathrm{rank}((\mathbf{I}, \tilde{\mathbf{h}}_b^H)\ddot{\mathbf{A}}(\mathbf{I}, \tilde{\mathbf{h}}_b^H)^H \ddot{\mathbf{Q}}_x) \le \mathrm{rank}(\ddot{\mathbf{A}}) \le 1$. Since $T_{h,b}(\ddot{\mathbf{Q}}_x, \ddot{\psi}, \ddot{\upsilon}) \succeq \mathbf{0}$ forces $\ddot{\mathbf{Q}}_x \ne \mathbf{0}$, we have $\mathrm{rank}(\ddot{\mathbf{Q}}_x) = 1$ and $\ddot{\mathbf{Q}}_x$ can be decomposed into $\ddot{\mathbf{w}}\ddot{\mathbf{w}}^H$. Since $\{\ddot{\mathbf{Q}}_x, \mathbf{Q}_z^-, \ddot{\psi}, \alpha^-, \ddot{\upsilon}, \varrho^-\}$ is optimal to (26) and (26) is equivalent to the SDR of P-QoS-B, we see $\{\ddot{\mathbf{w}}, \mathbf{Q}_z^-\}$ is an optimal solution to the original design problem P-QoS-B.

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