Role of Interference-Outage Constraint and Binary Power Control for RIS-Assisted Spectrum Sharing

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***Abstract*—Considering an reconfigurable intelligent surface (RIS)-assisted underlay spectrum sharing network, our goal is to minimize an average symbol error probability (SEP) of a secondary user while adhering to an interference-outage constraint imposed by a primary user. We first derive an optimal rule for on-off power control at a secondary source and passive beamforming at the RIS to minimize the average SEP at a secondary destination. We derive novel analytical expressions for the probability density functions of the effective interference channel power gains at the primary receiver and primary interference-outage probability. Building upon those analyses, we subsequently propose two simpler, yet near-optimal rules for on-off power control and RIS passive beamforming with lower complexity. Finally, simulation results corroborate the efficacy of the proposed framework and show the impact of different system parameters on the SEP.**

***Keywords*—Reconfigurable intelligent surface, underlay spectrum sharing, interference-outage constraint, on-off power control, symbol error probability.**

I. Introduction

Spectrum sharing is essential to support large number of wireless connections with high data rates in the overcrowded spectrum [1]. In an underlay spectrum sharing, a secondary user can concurrently transmit with a higher priority primary user in the same frequency band. However, the interference experienced by the primary user due to transmissions from the secondary user must be constrained [2], which can limit the performance of the secondary users significantly.

Reconfigurable intelligent surface (RIS) has been envisioned as a revolutionary technology to enhance energy efficiency cost-effectively for 6G wireless communication systems [3]. By dynamically controlling the reflection coefficient of each RIS element, it enables to increase the received signal power at the intended destination as well as interference suppression towards an unintended direction. Hence, RIS passive beamforming is an efficient solution to control the interference in an underlay spectrum sharing network (SSN) [4]. We now discuss the relevant literature based on objective function and constraints considered in underlay SSN.

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Literature on RIS-Assisted Spectrum Sharing Network: In [5], an alternating optimization (AO)-based algorithm for continuous power control of a secondary source (S) and passive beamforming of an RIS is proposed. It aims to maximize an achievable rate at a secondary destination (D) while meeting a constraint on the signal-to-interference-plus-noise ratio (SINR) at a primary receiver (X). Incorporating discrete phase shifts of the RIS under imperfect channel state information (CSI) assumption, similar optimization problem is studied in [6]. An optimal rule for joint on-off power control of S and RIS phase shift design is investigated in [7]. It aims to minimize an average symbol error probability (SEP) at D while meeting an average interference constraint at X. Considering a multiple-input single-output SSN, the authors in [8], [9] propose AO-based algorithm for optimizing beamforming at S and RIS phase shifts to maximize the data rate at D under a peak interference constraint at X. The work in [9] is extended for multiple RIS-assisted SSN in [4].

Motivation and Our Contributions: We consider on-off power control (PC), in which S chooses to transmit either with zero power (off) or a fixed power $P_{\max}$ (on). It is practically motivated as it enables the use of power amplifiers with high efficiency and reduces the design complexity of transmit radio frequency chain [2]. Also, it helps in reducing the interference at X. The above literature survey shows that different combinations of objective functions and constraints have been studied for RIS-assisted underlay spectrum sharing with continuous power control. However, to the best of our knowledge, on-off PC has not been studied for an *interference-outage constrained* secondary network. This interference constraint states that the instantaneous interference power at X can exceed a threshold τ but for utmost $O_{\max}$ fraction of time. It has not been explored in RIS literature. Furthermore, we focus on minimizing the average SEP metric unlike maximizing achievable rate at D [5] or minimizing transmit power of S [10]. SEP is an important performance metric characterizing the reliability of communication [2]. Altogether, our PC, interference-constraint, and objective are different from what is considered in the literature.

Our novel contributions in this paper are as follows:

1) We develop an *optimal rule* for joint on-off PC at S and passive beamforming at the RIS to minimize the average

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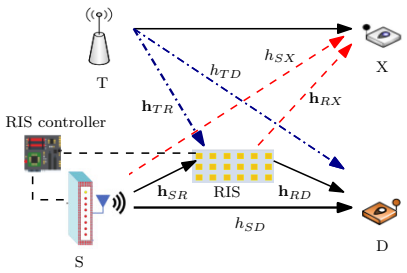


Fig. 1: RIS-assisted underlay spectrum sharing network.

SEP at D under the interference-outage constraint imposed by X. We further provide an algorithm to compute optimal Lagrange parameter.

2) To reduce computational complexity, we further develop two near-optimal rules: (i) Minimum SEP (MSEP) rule and (ii) Low interference (LI) rule. For the MSEP rule, the RIS phases are adjusted to obtain the minimum SEP at D. However for the LI rule, the RIS phases are adjusted to reduce the interference at X. The source employs on-off PC to meet the interference constraint.
3) We provide exact expressions for the probability density function (PDF) of the effective channel power gains from S to X for the above two cases. We further analyze the interference-outage probability (IOP) at X when S transmits at power $P_{\max}$ and RIS phases are adjusted to obtain minimum SEP at D. These results help characterizing the optimal rule, MSEP, and LI rules.
4) Our benchmarking results show that the MSEP rule and the optimal rule are identical when the interference constraint is inactive. However, when the interference constraint is active, the LI rule is near-optimal and outperforms the MSEP rule.

II. System Model

Fig. 1 shows the system model of an RIS-assisted underlay spectrum sharing network. A source S transmits data to a destination D with the assistance of an RIS having M reflective elements in the secondary network. It coexists with a primary network, in which a primary transmitter T communicates with a primary receiver X. We assume single-antenna model at each node.[1] The complex baseband channel gains for the links from S to D, from S to X, and from T to D are labeled as h_{SD}, h_{SX}, and h_{TD}, respectively. We assume independent Rayleigh fading for these links. Therefore, $h_{SD} \sim \mathcal{CN}(0, \mu_{SD})$, $h_{SX} \sim \mathcal{CN}(0, \mu_{SX})$, and $h_{TD} \sim \mathcal{CN}(0, \mu_{TD})$ where μ_{SD}, μ_{SX}, and μ_{TD} denote their mean channel power gains, respectively. Here, $h \sim \mathcal{CN}(0, \mu)$ implies that h is a circularly-symmetric complex Gaussian random variable with covariance μ.

[1]We focus on single input single output model to develop the optimal rule for on-off PC and RIS phase design. Extension to multiple-input multiple-output system is considered as part of our future work.

We model the complex baseband channel gains between node A and node B following *Rician* fading, where A-B belongs to S-R, R-D, R-X, and T-R and node R represents the RIS. Hence, the baseband channel gains for the m^{th} RIS reflective element is given as $h_{AB}^m = \sqrt{\mu_{AB}}\left(\sqrt{K_{AB}/(1+K_{AB})}\bar{h}_{AB}^m + \sqrt{1/(1+K_{AB})}\tilde{h}_{AB}^m\right)$, for $1 \le m \le M$, where K_{AB} denotes the Rician factor and μ_{AB} represents the mean channel power gain. Furthermore, $\bar{h}_{AB}^m$ denotes the fixed channel associated with the line-of-sight (LoS) component, while $\tilde{h}_{AB}^m$ denotes the non-LoS channel following independent $\mathcal{CN}(0,1)$ distribution [4], [9].

Let $\theta_{h_{SX}}$, $\theta_{h_{SD}}$, $\theta_{h_{SR}^m}$, $\theta_{h_{RD}^m}$, $\theta_{h_{RX}^m}$ denote the phases of the baseband channel gains h_{SX}, h_{SD}, h_{SR}^m, h_{RD}^m, and h_{RX}^m, for $1 \le m \le M$, respectively. The RIS reflection coefficient can be expressed as $\Phi_m = \beta_m e^{j\theta_m}$, where $\beta_m \in [0,1]$ is loss due to reflection and $\theta_m \in [0, 2\pi)$ is the phase shift of the m^{th} RIS reflective element. For maximizing the reflection power of the RIS, we set $\beta_m = 1$, for all m, as typically assumed in [5] and [10]. The signal powers that are reflected by the RIS more than one time is ignored due to high path loss [5]. Let $\mathbf{\Theta} \triangleq [\theta_1, \theta_2, \ldots, \theta_M]$ denote the RIS phase shift vector.

A. Signal and Interference Model

We assume that S sends a data symbol x to D, where $\mathbb{E}[|x^2|] = 1$. According to on-off PC policy $P_S \in \{P_{\max}, 0\}$ represents the transmit power of S. We assume flat-fading and quasi-static channel model. Additionally, when data is being transmitted from S to D, the RIS is always presumed to be on. The combined received signal at D from the RIS-reflected link and direct link is given as

$$y_D = \sqrt{P_S}\left(h_{SD} + \sum_{m=1}^{M} h_{RD}^m e^{j\theta_m} h_{SR}^m\right) x + n_D + n_P, \quad (1)$$

where, $n_D \sim \mathcal{CN}(0, \sigma_D^2)$ is the Gaussian noise at D and n_P is the combined interference signal received at D from T.

Interference from T to D: The following two interference power models are typically considered in the literature:

- *Instantaneous Interference Model [5]:* In this model, combined interference power from T to D is given by $|n_P|^2 = P_T\left|h_{TD} + \sum_{m=1}^{M} h_{RD}^m e^{j\theta_m} h_{TR}^m\right|^2$, where P_T is the fixed transmit power of T. The SINR at D as a function of P_S and $\mathbf{\Theta}$ is then expressed as $\gamma_S(P_S, \mathbf{\Theta}) = P_S\left|h_{SD} + \sum_{m=1}^{M} h_{RD}^m e^{j\theta_m} h_{SR}^m\right|^2 \Big/ \left(\sigma_D^2 + |n_P|^2\right)$.
- *Average Interference Model [2], [7]:* This model instead considers the average interference power from T to D, which is given by $\mathbb{E}\left[|n_P|^2\right] = P_T\mathbb{E}\left[\left|h_{TD} + \sum_{m=1}^{M} h_{RD}^m e^{j\theta_m} h_{TR}^m\right|^2\right]$, and then writes the SINR at D as a function of P_S and $\mathbf{\Theta}$ as $\gamma_S(P_S, \mathbf{\Theta}) = P_S\left|h_{SD} + \sum_{m=1}^{M} h_{RD}^m e^{j\theta_m} h_{SR}^m\right|^2 \Big/ \left(\sigma_D^2 + \mathbb{E}\left[|n_P|^2\right]\right)$.

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We note that the denominator of $\gamma_S(P_S, \mathbf{\Theta})$ in the average interference model depends on the mean channel power gains μ_{TD}, μ_{TR}, and μ_{RD}, and not on the instantaneous channel states.

Remark: The choice of $\mathbf{\Theta}$ for the instantaneous interference model impacts both the numerator and denominator of $\gamma_S(P_S, \mathbf{\Theta})$. However, in the average interference model, $\mathbf{\Theta}$ impacts only the numerator term. To ensure insightful results, we consider the average interference model. The SEP using the two interference models shall be compared in Fig. 5(b).[2]

Interference from S to X: The combined interference signal received at X due to transmissions by S is $\sqrt{P_S}(h_{SX} + \sum_{m=1}^{M} h_{RX}^m e^{j\theta_m} h_{SR}^m)x$. Therefore, instantaneous interference power at X as a function of P_S and $\mathbf{\Theta}$ can be written as

$$I(P_S, \mathbf{\Theta}) = P_S \left| h_{SX} + \sum_{m=1}^{M} h_{RX}^m e^{j\theta_m} h_{SR}^m \right|^2. \quad (2)$$

An interference-outage constraint is imposed on S by the primary network. It states that $I(P_S, \mathbf{\Theta})$ can exceed an interference threshold τ but for utmost $O_{\max}$ fraction of time. By it, $\Pr(I(P_S, \mathbf{\Theta}) > \tau) \leq O_{\max}$. The choice of τ and $O_{\max}$ are determined by the primary network's quality of service requirements. When $O_{\max} = 0$, it reduces to the peak interference constraint: $I(P_S, \mathbf{\Theta}) \leq \tau$.

B. Problem Formulation

Let $\text{SEP}(\gamma_S)$ represents the instantaneous SEP at D, which depends on the SINR γ_S that has been received. For all modulation techniques, it can be expressed in the following generic form $\text{SEP}(\gamma_S) \approx c_1 \exp(-c_2 \gamma_S)$, where c_1 and c_2 are modulation dependent constants [3], [7]. Our goal is to jointly optimize transmit power P_S of S and the phase shift vector $\mathbf{\Theta}$ of the RIS for minimizing the average SEP at D subject to the interference-outage constraint. The optimization problem $\mathcal{P}$ can be formulated as

$$\mathcal{P}: \min_{P_S, \mathbf{\Theta}} \quad \mathbb{E}[c_1 \exp(-c_2\, \gamma_S(P_S, \mathbf{\Theta}))], \quad (3)$$

$$\text{s.t.} \quad \Pr(I(P_S, \mathbf{\Theta}) > \tau) \leq O_{\max}, \quad (4)$$

$$P_S \in \{P_{\max}, 0\}. \quad (5)$$

III. Analysis of Interference-Outage Probability

To solve $\mathcal{P}$, we now analyze the interference-outage probability at X, denoted by IOP_{un}, which achieves the minimum SEP at D when no interference-outage constraint is active. In this case, $P_S = P_{\max}$ and $\theta_m = \theta_{h_{SD}} - \left(\theta_{h_{SR}^m} + \theta_{h_{RD}^m}\right)$, for $1 \leq m \leq M$. Using this, the power gain g of the effective channel from S to X can be expressed as

$$g = \left| h_{SX} + e^{j\theta_{h_{SD}}} \sum_{m=1}^{M} |h_{RX}^m||h_{SR}^m| e^{j\left(\theta_{h_{RX}^m} - \theta_{h_{RD}^m}\right)} \right|^2. \quad (6)$$

[2]We note that the interference from T to D is even neglected in [8]–[10] assuming that T is deployed far enough from the secondary network.

Lemma *1:* The PDF of g, $f_g(x)$, for $x \geq 0$ is given by

$$f_g(x) = \frac{\exp\left[\frac{\left(\frac{2\sqrt{x}}{\mu_{SX}}\right)^2 + \left(\frac{\mu_R}{\sigma_R^2}\right)^2}{4\omega} - \left(\frac{x}{\mu_{SX}} + \frac{\mu_R^2}{2\sigma_R^2}\right)\right] I_0\left(\frac{\sqrt{x}\mu_R}{\mu_{SX}\omega\sigma_R^2}\right)}{2\mu_{SX}\omega\sigma_R^2}, \quad (7)$$

where $\mu_R = \frac{M\pi}{4}\sqrt{\frac{\mu_{SR}\mu_{RX}}{(K_{SR}+1)(K_{RX}+1)}} L_{1/2}(-K_{SR})\, L_{1/2}(-K_{RX})\, \zeta(K_{RX})\zeta(K_{RD})$, $\sigma_R^2 = \frac{M}{2}\mu_{SR}\mu_{RX}\left[1 - \frac{\pi^2}{16(K_{SR}+1)(K_{RX}+1)}\left(L_{1/2}(-K_{SR})\, L_{1/2}(-K_{RX})\, \zeta(K_{RX})\zeta(K_{RD})\right)^2\right]$, $\zeta(K) = \sqrt{\frac{K}{\pi}} \int_0^{\pi} \cos^2\theta e^{-K\sin^2\theta}\left(1 + \text{erf}\left(\sqrt{K}\cos\theta\right)\right) d\theta$, $\omega = \left(\frac{1}{\mu_{SX}} + \frac{1}{2\sigma_R^2}\right)$, and $\text{erf}(.)$ denotes the error function [11, (7.1.1)], $L_{\frac{1}{2}}(.)$ denotes the Laguerre Polynomial [11, (22.2.13)], and $I_0(z)$ denotes the modified Bessel function of the first kind with order zero [11, (9.6.16)].

Proof: The proof is relegated to Appendix A. ∎

The accuracy of the PDF shall be verified in Fig. 3. The corresponding interference-outage probability at X is $\text{IOP}_{\text{un}} = \Pr(g > \tau/P_{\max})$. Using (7), closed-form exact expression of IOP_{un} is difficult to obtain, to the best of our knowledge. Using Gauss Quadrature rule [11, (25.4.30)], it is approximated as

$$\text{IOP}_{\text{un}} = 1 - \int_0^{\tau/P_{\max}} f_g(x)\, dx \approx 1 - \frac{\tau}{2P_{\max}} \sum_{i=1}^{N} w_i f_g\left(\frac{\tau(1+y_i)}{2P_{\max}}\right), \quad (8)$$

where y_i and w_i, for $1 \leq i \leq N$, are abscissas and weights, respectively. It is verified that $N = 5$ terms are sufficient to compute IOP_{un} accurately.

IV. Optimal ON-OFF PC and RIS Phase Design

We now derive the optimal rule that solves $\mathcal{P}$. Let $\bar{P}_S \in \{P_{\max}, 0\}$ denote the optimal transmit power of S and $\bar{\mathbf{\Theta}} = \left[\bar{\theta}_1, \bar{\theta}_2, \ldots, \bar{\theta}_M\right]$ denote the optimal phase shift vector of the RIS reflective elements. A feasible rule is the one that meets the interference-outage constraint (4). Let $\text{SEP}(P_S, \mathbf{\Theta})$ denote the instantaneous SEP for a specific choice of P_S and $\mathbf{\Theta}$. It is given by the term inside the expectation operator in (3). We characterize the optimal rule as follows:

- *Region I ($\text{IOP}_{un} \leq O_{max}$)*: Here, the optimal values of P_S and $\mathbf{\Theta}$ that solves $\mathcal{P}$ are given by

$$\bar{P}_S = P_{\max} \text{ and } \bar{\mathbf{\Theta}} \triangleq \mathbf{\Theta}_{\text{un}} = \theta_{h_{SD}}\mathbb{I} - (\mathbf{\Theta}_{h_{SR}} + \mathbf{\Theta}_{h_{RD}}), \quad (9)$$

where $\mathbf{\Theta}_{h_{SR}} \triangleq \left[\theta_{h_{SR}^1}, \theta_{h_{SR}^2}, \ldots, \theta_{h_{SR}^M}\right]$, $\mathbf{\Theta}_{h_{RD}} \triangleq \left[\theta_{h_{RD}^1}, \theta_{h_{RD}^2}, \ldots, \theta_{h_{RD}^M}\right]$, and $\mathbb{I} \triangleq [1, 1, \ldots, 1]$. We shall refer the rule in (9) as the *unconstrained rule*. Its interference-outage probability is equal to IOP_{un}. The average interference power $\mathbb{E}\left[|n_P|^2\right]$ in the denominator of $\gamma_S(P_S, \mathbf{\Theta})$ depends on the mean channel power gains and Rician factors. Hence, $\bar{P}_S$ and $\bar{\mathbf{\Theta}}$

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are independent of $\mathbb{E}\left[|n_P|^2\right]$. In Region I, by following Lemma 2 of [7], we can show that $\mathbb{E}\left[|n_P|^2\right] = P_T\left(\mu_{TD} + M\mu_{TR}\mu_{RD} + \frac{M(M-1)\pi^2\mu_{TR}\mu_{RD}}{16(K_{TR}+1)(K_{RD}+1)} \times \left[L_{1/2}(-K_{TR})\, L_{1/2}(-K_{RD})\, \zeta(K_{TR})\zeta(K_{SR})\right]^2\right)$.

- *Region II ($IOP_{un} > O_{max}$)*: Here, the unconstrained rule does not satisfy the interference-outage constraint and is not optimal. The following result states the optimal rule. **Result** *1:* The optimal on-off PC and RIS passive beamforming rule that minimizes the average SEP subject to the interference-outage constraint in Region II is

$$(\bar{P}_S, \bar{\boldsymbol{\Theta}}) = \underset{P_S, \boldsymbol{\Theta}}{\operatorname{argmin}} \left\{\text{SEP}(P_S, \boldsymbol{\Theta}) + \lambda \mathbf{1}_{\{I(P_S,\boldsymbol{\Theta})>\tau\}}\right\}, \quad (10)$$

where $\mathbf{1}_{\{a\}}$ denotes an indicator function; it is 1 if a is true and is 0 otherwise. The Lagrange parameter $0 \le \lambda \le c_1$ is chosen such that the secondary network satisfies the interference-outage constraint with equality. Hence, the IOP caused by the optimal rule, denoted by IOP(λ), is

$$\text{IOP}(\lambda) \triangleq \Pr\left(I\left(\bar{P}_S, \bar{\boldsymbol{\Theta}}\right) > \tau\right) = O_{\max}. \quad (11)$$

Proof: The proof is relegated to Appendix B. ■

The optimal rule in (10) is novel and differs from the rule proposed in [7] subject to an average interference constraint. To understand its behavior, let $\sigma^2 = \left(\sigma_D^2 + \mathbb{E}\left[|n_P|^2\right]\right)$, $h_{\text{eq}}(\boldsymbol{\Theta}) \triangleq |h_{SD} + \sum_{m=1}^{M} h_{RD}^m e^{j\theta_m} h_{SR}^m|^2$ and $g_{\text{eq}}(\boldsymbol{\Theta}) \triangleq |h_{SX} + \sum_{m=1}^{M} h_{RX}^m e^{j\theta_m} h_{SR}^m|^2$ denote the power gain of the effective channel from S to D and from S to X, respectively. We shall refer to $c_1 \exp\left(-c_2 P_S h_{\text{eq}}(\boldsymbol{\Theta})/\sigma^2\right) + \lambda \mathbf{1}_{\{P_S g_{\text{eq}}(\boldsymbol{\Theta})>\tau\}}$ as an *instantaneous metric*. Thus, the optimal rule selects P_S and $\boldsymbol{\Theta}$ that minimize the instantaneous metric. Further, we shall refer the RIS phase shift vector $\boldsymbol{\Theta}$ for which $P_{\max} g_{\text{eq}}(\boldsymbol{\Theta}) \le \tau$ as an *outage-consistent phase shift vector*. Otherwise, we shall refer it as an *outage-inconsistent phase shift vector*.

A. Behaviour of the Optimal Rule for Different λ:

1) Instantaneous metric is $c_1 \exp\left(-c_2 P_S h_{\text{eq}}(\boldsymbol{\Theta})/\sigma^2\right)$, for $\lambda = 0$. The unconstrained rule in (9) is clearly optimal as it minimizes the average SEP.
2) If $0 < \lambda < c_1$, the instantaneous metric is a combination of an exponentially decaying function of $h_{\text{eq}}(\boldsymbol{\Theta})$ and the indicator function dependent on $g_{\text{eq}}(\boldsymbol{\Theta})$, weighted by the Lagrange parameter λ. Fig 2 shows 3-D plot of the instantaneous metric versus $g_{\text{eq}}(\boldsymbol{\Theta})$ and $h_{\text{eq}}(\boldsymbol{\Theta})$. We see its discontinuous nature at $g_{\text{eq}}(\boldsymbol{\Theta}) = \tau/P_{\max}$. The optimal rule behaviour can be explained as follows:
   - *Case 1:* When $g_{\text{eq}}(\boldsymbol{\Theta}_{\text{un}}) \le \tau/P_{\max}$, the optimal rule in (10) simplifies to $\bar{\boldsymbol{\Theta}} = \boldsymbol{\Theta}_{\text{un}}$ and $\bar{P}_S = P_{\max}$.
   - *Case 2:* When $g_{\text{eq}}(\boldsymbol{\Theta}_{\text{un}}) > \tau/P_{\max}$, the optimal phase shift vector will be selected from the set of outage-consistent phase shift vectors that satisfies $\text{SEP}(P_{\max}, \boldsymbol{\Theta}) < \text{SEP}(P_{\max}, \boldsymbol{\Theta}_{\text{un}}) + \lambda$ and maximizes $h_{\text{eq}}(\boldsymbol{\Theta})$. If no such $\boldsymbol{\Theta}$ is found, the optimal rule selects $\bar{P}_S = 0$ if $c_1 < \text{SEP}(P_{\max}, \boldsymbol{\Theta}_{\text{un}}) + \lambda$; otherwise, it selects $\bar{P}_S = P_{\max}$ and $\bar{\boldsymbol{\Theta}} = \boldsymbol{\Theta}_{\text{un}}$.
3) If $\lambda = c_1$, the instantaneous metric of any outage-inconsistent phase shift vector for $P_S = P_{\max}$ is $c_1\left(\exp\left(-c_2 P_S h_{\text{eq}}(\boldsymbol{\Theta})/\sigma^2\right) + 1\right)$, which is greater than c_1. Therefore, the optimal rule will select $\bar{P}_S = P_{\max}$ and $\bar{\boldsymbol{\Theta}}$ that maximizes $h_{\text{eq}}(\boldsymbol{\Theta})$ from the set of outage-consistent phase shift vectors. Otherwise, it will select $\bar{P}_S = 0$ if this set is empty.

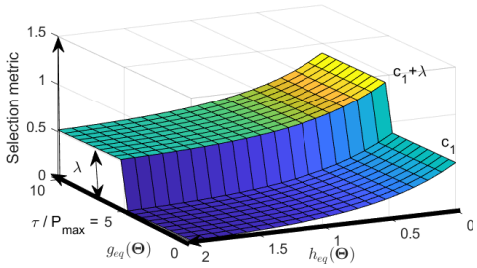


Fig. 2: Instantaneous metric as a function of $h_{\text{eq}}(\boldsymbol{\Theta})$ and $g_{\text{eq}}(\boldsymbol{\Theta})$ for $P_S = P_{\max}$ ($c_1 = 0.5$, $c_2 = 0.17$).

B. Calculating Optimal λ, $\bar{P}_S$ and $\bar{\boldsymbol{\Theta}}$ in Region II:

We note that for $\lambda = 0$, $\text{IOP}(0) = \text{IOP}_{\text{un}}$. Further, we can show that as λ increases from 0 to c_1, IOP(λ) monotonically decreases and reaches zero. We find the optimal value for λ using bisection search approach. Given λ, we obtain $\bar{P}_S$, and $\bar{\boldsymbol{\Theta}}$ using (10) along with its simplified form discussed in Section IV-A. The algorithm to compute optimal value for λ, $\bar{P}_S$, and $\bar{\boldsymbol{\Theta}}$ is demonstrated in Algorithm 1.

Discussion on CSI Assumptions: S needs to know perfect knowledge about direct S-D channel gain h_{SD} and the cascaded channel gain matrix $\mathbf{H}_{RD}\mathbf{h}_{SR}$ of S-RIS-D link, where $\mathbf{H}_{RD} = \text{diag}\left(\mathbf{h}_{RD}\right)$, $\mathbf{h}_{RD} = [h_{RD}^1, \ldots, h_{RD}^M]^T$, and $\mathbf{h}_{SR} = [h_{SR}^1, \ldots, h_{SR}^M]^T$ [3]. Similarly, the direct S-X channel gain h_{SX} and the cascaded channel gain matrix of S-RIS-X link can be estimated. Based on this CSI, the source selects P_S and $\boldsymbol{\Theta}$. It then communicates to the RIS controller via a control link. Furthermore, no CSI is assumed at the RIS. The detailed channel estimation scheme that considers a time-division duplex protocol by exploiting channel reciprocity has been omitted for brevity.

V. Low-Complexity Rules

The optimal rule involves solving a system of M non-linear equations (see Case 2), which requires numerical methods such as Newton-Raphson with a complexity $\mathcal{O}(M^3)$. To reduce this complexity, we now propose two rules, which we shall refer as the LI rule and MSEP rule. They require $\mathcal{O}(M)$ computations to find $\boldsymbol{\Theta}$.

A. LI Rule

When S transmits with power $P_S = P_{\max}$, the primary receiver will experience lower interference when direct S-X

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Algorithm 1 Algorithm to obtain Optimal λ, $\bar{P}_S$, and $\bar{\boldsymbol{\Theta}}$

1: **Initialize** $\lambda = \lambda_l = \lambda_u = 0$
2: **Initialize** $\bar{P}_S$ and $\bar{\boldsymbol{\Theta}}$ according to (9) for $\lambda = 0$. Compute IOP(λ) by (11).
3: Until IOP(λ) $\leq O_{\max}$, find λ_u by updating $\lambda_u \leftarrow \lambda + 0.01$ and obtaining $\bar{P}_S$ and $\bar{\boldsymbol{\Theta}}$ using (10) for $\lambda = \lambda_u$.
4: **while** $|\text{IOP}(\lambda) - O_{\max}| > \epsilon$ and $\lambda \leq c_1$ **do**
5: Calculate $\lambda = \frac{\lambda_l + \lambda_u}{2}$. Find $\bar{P}_S$ and $\bar{\boldsymbol{\Theta}}$ using (10).
6: Compute IOP(λ) $= \Pr\left(I\left(\bar{P}_S, \bar{\boldsymbol{\Theta}}\right) > \tau\right)$.
7: If IOP(λ) $< O_{\max}$, $\lambda_u \leftarrow \lambda$; otherwise $\lambda_l \leftarrow \lambda$.
8: **end while**
9: **return** The optimal solutions for λ, $\bar{P}_S$, and $\bar{\boldsymbol{\Theta}}$.

link is 180° out of phase with the effective S-RIS-X link. Therefore, LI rule sets $\theta_m = \pi + \theta_{h_{SX}} - \left(\theta_{h_{SR}^m} + \theta_{h_{RX}^m}\right)$, for $1 \leq m \leq M$. Consequently, the power gain of the effective channel from S-X is $g_{\text{eq}}(\boldsymbol{\Theta}) \triangleq g_{\min} = \left(|h_{SX}| - \sum_{m=1}^{M} |h_{RX}^m||h_{SR}^m|\right)^2$.

We use the following on-off PC policy for the LI rule. Let $\beta > 0$ be the unique solution of the equation

$$\Pr(P_{\max} g_{\min} > \tau, g_{\min} > \beta) = O_{\max}. \tag{12}$$

If $\tau/P_{\max} \geq \beta$, then $P_S = P_{\max}$, else if $\tau/P_{\max} < \beta$, then $P_S = P_{\max}$, if $g_{\min} < \frac{\tau}{P_{\max}}$ or $g_{\min} > \beta$; otherwise, $P_S = 0$. A special case of conventional SSN without RIS is considered in [2]. To calculate β, we now derive the PDF of $g_{\min}$.

Lemma *2:* The PDF of $g_{\min}$, $f_{g_{\min}}(g)$, for $g \geq 0$ is given by

$$f_{g_{\min}}(g) = \frac{f_R\left(\sqrt{g}\right) + f_R\left(-\sqrt{g}\right)}{2\sqrt{g}}, \tag{13}$$

where

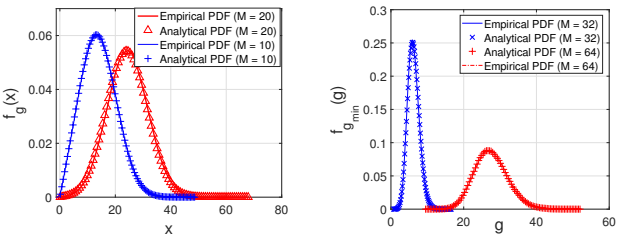
$$f_R(z) = \nu e^{\left(\frac{\mu_Y}{\sigma_Y^2} - \frac{2z}{\mu_{SX}}\right)^2 / (4a)} e^{-\left(\frac{z^2}{\mu_{SX}} + \frac{\mu_Y^2}{2\sigma_Y^2}\right)} I_R(z), \tag{14}$$

$$I_R(z) = \begin{cases} \left(\frac{z}{\sqrt{a}} + \frac{b}{2a\sqrt{a}}\right)\Gamma\left(\frac{1}{2}, \frac{b^2}{4a}\right) + \frac{1}{a}e^{-\frac{b^2}{4a}}, & z \geq 0, \\ \left(\frac{z}{\sqrt{a}} + \frac{b}{2a\sqrt{a}}\right)\Gamma\left(\frac{1}{2}, a\left(z + \frac{b}{2a}\right)^2\right) + \frac{1}{a}e^{-a\left(z+\frac{b}{2a}\right)^2}, & z < 0, \end{cases} \tag{15}$$

$\mu_Y = \frac{M\pi}{4}\sqrt{\frac{\mu_{SR}\mu_{RX}}{(K_{SR}+1)(K_{RX}+1)}} L_{1/2}(-K_{SR}) L_{1/2}(-K_{RX})$, $\sigma_Y^2 = M\mu_{SR}\mu_{RX}\left(1 - \frac{\pi^2\left[L_{1/2}(-K_{SR})L_{1/2}(-K_{RX})\right]^2}{16(K_{SR}+1)(K_{RX}+1)}\right)$, $\nu = \frac{2\psi}{\mu_{SX}\sqrt{2\pi\sigma_Y^2}}$, $a = \left(\frac{1}{2\sigma_Y^2} + \frac{1}{\mu_{SX}}\right)$, $b = \left(\frac{\mu_Y}{\sigma_Y^2} - \frac{2z}{\mu_{SX}}\right)$, $\psi = 1/Q\left(-\mu_Y/\sigma_Y\right)$. Here, $Q(.)$ is the Gaussian-Q function [12], and $\Gamma(n, x)$ is the upper incomplete Gamma function [13, (8.350.2)].

Proof: The proof is relegated to Appendix C. ∎

The accuracy of the PDF expressions for $g_{\min}$ (c.f. (13)) and g (c.f. (7)) is verified in Fig. 3 by plotting analytical PDF and empirical PDF by Monte-Carlo simulations for different values of M. We see that our analytical PDF matches with that obtained from the simulations.



(a) PDF of g (b) PDF of $g_{\min}$

Fig. 3: PDF of g and $g_{\min}$ for different values of M.

We note that the PDF for $g_{\min}$ in (13) is quite involved and a closed-form solution for β is difficult to obtain. Using Gauss Quadrature rule [11, (25.4.30)], (12) can be approximated as $\int_{\beta}^{\infty} f_{g_{\min}}(g)\, dg \approx 1 - \frac{\beta}{2}\sum_{i=1}^{\mathcal{N}} \eta_i f_{g_{\min}}\left(\frac{\beta}{2}(1 + y_i)\right) = O_{\max}$, where y_i and η_i, for $1 \leq i \leq \mathcal{N}$, are abscissas and weights, respectively. We have observed that $\mathcal{N} = 5$ terms are sufficient to compute the integral accurately. Now β is the solution of the above equation and is computed numerically.

B. MSEP Rule

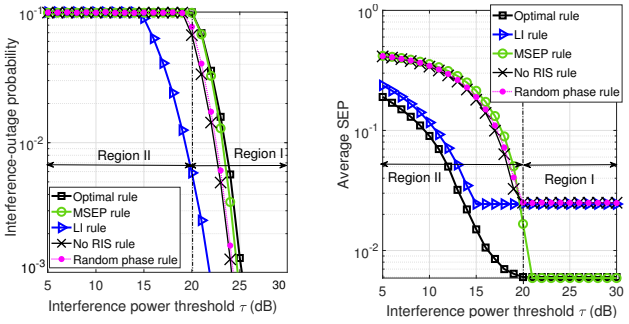
When S transmits with power $P_S = P_{\max}$, D experiences the minimum SEP when the direct S-D link is in phase with the cascaded S-RIS-D link. Therefore, the MSEP rule sets $\theta_m = \theta_{h_{SD}} - \left(\theta_{h_{SR}^m} + \theta_{h_{RD}^m}\right)$, for $1 \leq m \leq M$. The effective channel power gain from S to X is given by g in (6). To meet the interference-outage constraint, the MSEP rule uses similar on-off PC policy as that of the LI rule, where $g_{\min}$ will now be replaced by g. The parameter β in (12) can be computed by solving $\frac{\beta}{2}\sum_{i=1}^{\mathcal{N}} \eta_i f_g\left(\frac{\beta}{2}(1 + y_i)\right) = 1 - O_{\max}$, where $f_g(x)$ is given in (7).

VI. NUMERICAL RESULTS

We now provide simulation results. For any two nodes A $\in \{S, \text{RIS}, T\}$ and B $\in \{D, \text{RIS}, X\}$, the mean channel power gain $\mu_{AB} = \delta\left(d_0/d_{\text{AB}}\right)^{\kappa_{\text{AB}}}$ [10]. Here, $\delta = -30$ dB denotes the path loss at reference point $d_0 = 1$ m with a carrier frequency of 750 MHz, d_{AB} denotes the distance between the nodes A and B, and κ_{AB} denotes the path loss exponent, which is considered as 3.5 for the direct S-D, S-X, and T-D channels and 2.5 for the RIS-assisted channels. We set the Rician factors as 2 and noise power as $\sigma_D^2 = -100$ dBm. Unless mentioned otherwise, we assume that S, D, RIS, T, and X are located at $(0, 0, 0)$, $(100, 0, 0)$, $(98, 0, 10)$, $(0, 50, 0)$, $(95, 5, 0)$ in meter, in 3-D plane, respectively. Therefore, $d_{SD} = 100$ m, $d_{SX} = 95.1$ m, $d_{SR} = 98.5$ m, $d_{RD} = 10.2$ m, $d_{RX} = 11.5$ m, $d_{TD} = 111.8$ m, and $d_{TR} = 110.4$ m.

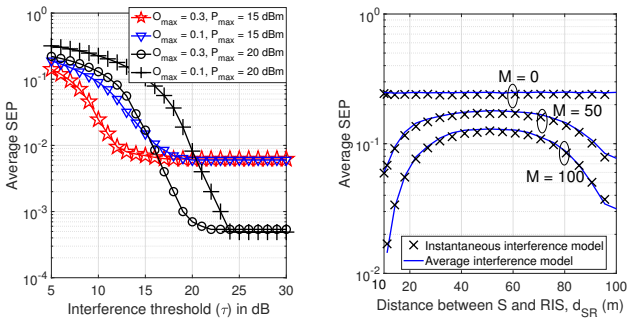
Performance Benchmarking: Fig. 4(a) and Fig. 4(b) plot the IOP at X and the average SEP at D, respectively, caused by the optimal, MSEP, and LI rules as a function of τ. They are compared with two other rules: (i) no RIS rule, in which no RIS ($M = 0$) is used [2] and (ii) random phase rule, in which

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(a) IOP (b) Average SEP

Fig. 4: IOP at X and average SEP at D as a function of interference threshold τ ($M = 10$, $O_{\max} = 0.1$, $P_{\max} = 15$ dBm, $P_T = 5$ dBm, and QPSK).



(a) Effect of $O_{\max}$ and $P_{\max}$ (b) Effect of distance, d_{SR}

Fig. 5: (a) Average SEP vs. τ ($M = 10$, $P_T = 5$ dBm, and QPSK); (b) Average SEP vs. distance between S and RIS ($P_{\max} = 10$ dBm, $P_T = 0$ dBm, $\tau = 15$ dB, $O_{\max} = 0.1$, and 8PSK).

the phase of each reflective element is uniformly and randomly generated between 0 and 2π. For them, we set $P_S = P_{\max}$ in Region I. However, in Region II, we adopt on-off PC similar as the LI rule except that $g_{\min}$ will be replaced by $g_{\text{eq}}(\boldsymbol{\Theta})$.

We first discuss the behaviour of the optimal rule. (a) For $\text{IOP}_{\text{un}} > O_{\max}$ ($\tau \leq 20$ dB), the SSN operates in Region II and the optimal rule in (10) is active. As τ increases, IOP initially remains constant at $O_{\max} = 0.1$ by the choice of optimal λ and the average SEP monotonically decreases. (b) For $\text{IOP}_{\text{un}} \leq O_{\max}$ ($\tau > 20$ dB), the SSN operates in Region I and the unconstrained rule in (9) is active. As τ increases, the IOP decreases. We notice that the average SEP saturates and becomes independent of τ. This is because S always transmits at fixed power $P_{\max}$ in this region.

The LI rule provides near-optimal SEP in Region II. However, in Region I, its SEP reaches to an error floor that is one order of magnitude higher than the optimal rule. The IOP of the LI rule is lower than all the other rules. The MSEP, random phase, and no RIS rules incur high average SEP in Region II due to on-off PC to meet the interference constraint. However, in Region I, the MSEP rule minimizes the average SEP.

Effect of O_{max}, P_{max}, and RIS Location: Fig. 5(a) plots the average SEP for the optimal rule as a function of τ for different values of $O_{\max}$ and $P_{\max}$. For a fixed $P_{\max}$, as $O_{\max}$ increases, the SEP decreases due to relaxed interference-outage constraint. Notice that the error floor is independent of $O_{\max}$. For a fixed $O_{\max}$, as $P_{\max}$ increases, the SEP increases for low-to-mid values of τ. This is because optimal λ increases and S transmits with zero power more often to satisfy the interference-outage constraint. However, for higher values of τ, the SEP decreases as $P_{\max}$ increases, thereby following interference-unconstrained behaviour. Fig. 5(b) plots the average SEP of the optimal rule as a function of S-RIS distance d_{SR} for two different interference models from T to D. We see that as the minimum SEP is obtained when the RIS is located close to S or close to D. Note that as M decreases, the average SEP increases. For no RIS case, the SEP attains the maximum value, which is independent of d_{SR}. Note also that SEP trend using the instantaneous interference model and the average interference model are almost similar except that average interference model results slightly higher SEP.

VII. CONCLUSION

We developed a novel SEP-optimal rule for joint on-off PC and RIS passive beamforming for an underlay SSN subject to an interference-outage constraint. We also proposed two simpler rules – LI and MSEP rules in closed-form with lower complexity. We derived the PDF of the effective channel power gains from S to X for two choices of the RIS phase shift vector and analyzed the IOP. These helped to characterize the proposed rules. The optimal rule provided the lowest average SEP. The LI rule reduced the average SEP than the MSEP rule for low-to-mid values of τ. However, for higher τ, the MSEP rule outperformed the LI rule. Altogether, these results would be useful to design practical RIS-assisted spectrum-sharing networks. Extension to multiple concurrent secondary and primary transmissions can be our potential future work.

APPENDIX

A. Proof of Lemma 1

Define $Z \triangleq \sum_{m=1}^{M} |h_{RX}^m||h_{SR}^m| e^{j\left(\theta_{h_{RX}^m} - \theta_{h_{RD}^m}\right)} = Z_R + jZ_I$. By central-limit-theorem (CLT), the real and imaginary parts of Z follow $Z_R \sim \mathcal{N}(\mu_R, \sigma_R^2)$ and $Z_I \sim \mathcal{N}(0, \sigma_R^2)$, respectively, for large M. Here μ_R and σ_R^2 are defined in Lemma 1 statement. Since Z_R is independent of Z_I, we can write the joint PDF of Z_R and Z_I as

$$f_{Z_R,Z_I}(Z_R, Z_I) = \frac{1}{2\pi\sigma_R^2} e^{-\frac{(Z_R-\mu_R)^2}{2\sigma_R^2}} e^{-\frac{Z_I^2}{2\sigma^2}}. \quad (16)$$

Converting from cartesian to polar coordinate using $Z = Re^{j\phi}$, $Z_R = R\cos\phi$, $Z_I = R\sin\phi$, and noting that Jacobian determinant of the transformation is $J(r, \phi) = r$, we can write the joint PDF in polar coordinate as [12, p.201]

$$f_{R,\phi}(r, \phi) = \frac{r}{2\pi\sigma_R^2} e^{-\frac{\left(r^2+\mu_R^2-2r\mu_R\cos\phi\right)}{2\sigma_R^2}}. \quad (17)$$

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From this, the PDF of R can be shown to be Rician distributed:

$$f_R(r) = \frac{r}{\sigma_R^2} e^{-\frac{\left(r^2+\mu_R^2\right)}{2\sigma_R^2}} I_0\left(\frac{r\mu_R}{\sigma_R^2}\right), \quad r \geq 0, \tag{18}$$

where $I_0(z)$ is the modified Bessel function of the first kind with order zero [11, (9.6.16)].

Let $h^{'} \triangleq Ze^{j\theta_{h_{SD}}} = Re^{j\left(\phi+\theta_{h_{SD}}\right)} = Re^{j\Theta}$. The PDF of phase $\Theta = \phi + \theta_{h_{SD}}$ can now be computed by using convolution formula of the PDF of ϕ and $\theta_{h_{SD}}$. It can be shown to be uniformly distributed. Since magnitude and phase of $h^{'}$ are independent RVs, the joint PDF of R and Θ is

$$f_{R,\Theta}(r,\theta) = \frac{r}{2\pi\sigma_R^2} e^{-\frac{\left(r^2+\mu_R^2\right)}{2\sigma_R^2}} I_0\left(\frac{r\mu_R}{\sigma_R^2}\right). \tag{19}$$

Let $X \triangleq \left(h_{SX} + e^{j\theta_{h_{SD}}} Z\right)$. Using polar-to-cartesian transformation followed by 2-D convolution formula given in [14, (4)], the joint PDF of the real (X_R) and imaginary (X_I) parts of X can be obtained after mathematical simplification as

$$f_{X_R,X_I}(x_R,x_I) = \frac{e^{-\left(\frac{x^2}{\mu_{SX}}+\frac{\mu_R^2}{2\sigma_R^2}\right)}}{\pi\mu_{SX}\sigma_R^2} \int_0^\infty h e^{-h^2\left(\frac{1}{\mu_{SX}}+\frac{1}{2\sigma_R^2}\right)} \times I_0\left(\frac{2xh}{\mu_{SX}}\right) I_0\left(\frac{h\mu_R}{\sigma_R^2}\right) dh, \tag{20}$$

where $x^2 = x_R^2 + x_I^2$. Finally, using [13, (6.633.4)] and [11, (9.6.3)], the PDF of $g = |X|^2$ can be derived as (7).

B. Proof of Result 1

A selection rule that always chooses the zero transmit power option causes zero interference to X. It is, therefore, a feasible rule. Therefore, the set of all feasible selection rules is a non-empty set. Let ϕ be a feasible rule, for which $\mathbf{\Theta}$ be the RIS phase shift vector and P_S be the transmit power of S. For $\lambda > 0$, we define an auxiliary function $\mathfrak{L}_\phi(\lambda)$ as follows:

$$\mathfrak{L}_\phi(\lambda) \triangleq \mathbb{E}\left[\text{SEP}(P_S,\mathbf{\Theta}) + \lambda \mathbf{1}_{\{I(P_S,\mathbf{\Theta})>\tau\}}\right]. \tag{21}$$

Note that $\mathfrak{L}_\phi(\lambda)$ is a function of both ϕ and λ.

We further define $\overline{\phi}$ to be another feasible rule which selects $\bar{P}_S$ and $\bar{\mathbf{\Theta}}$ as

$$\left(\bar{P}_S,\bar{\mathbf{\Theta}}\right) = \underset{P_S,\mathbf{\Theta}}{\text{argmin}} \left\{\text{SEP}(P_S,\mathbf{\Theta}) + \lambda \mathbf{1}_{\{I(P_S,\mathbf{\Theta})>\tau\}}\right\}, \tag{22}$$

Here, λ is chosen such that $\Pr\left(I\left(\bar{P}_S,\bar{\mathbf{\Theta}}\right)>\tau\right) = O_{\max}$.[3] Thus, $\bar{\mathbf{\Theta}}$ is a feasible rule. From the definition of $\overline{\phi}$, it follows that $\mathfrak{L}_{\overline{\phi}}(\lambda) \leq \mathfrak{L}_\phi(\lambda)$. Therefore, using (21), we get

$$\mathbb{E}\left[\text{SEP}\left(\bar{P}_S,\bar{\mathbf{\Theta}}\right)\right] \leq \mathbb{E}[\text{SEP}(P_S,\mathbf{\Theta})] + \lambda\left(\Pr(I\left(P_S,\mathbf{\Theta}\right)>\tau) - O_{\max}\right). \tag{23}$$

[3]It can be proved using the intermediate value theorem that such a unique choice of λ exists. The theorem can be applied on the basis of the following two facts: (i) $0 \leq O_{\max} < \text{IOP}_{\text{un}}$ and (ii) It can be shown that the interference-outage probability is a continuous and monotonically decreasing function of λ for $0 < \lambda \leq c_1$.

Since ϕ is a feasible rule, $\Pr(I\left(P_S,\mathbf{\Theta}\right)>\tau) - O_{\max} \leq 0$. As $\lambda > 0$, this inequality implies $\mathbb{E}\left[\text{SEP}\left(\bar{P}_S,\bar{\mathbf{\Theta}}\right)\right] \leq \mathbb{E}\left[\text{SEP}\left(P_S,\mathbf{\Theta}\right)\right]$. Thus, $\overline{\phi}$ results the lowest average SEP among all feasible rules. Therefore, it is the optimal rule.

C. Proof of Lemma 2

Define $Y \triangleq \sum_{m=1}^{M} |h_{RX}^m||h_{SR}^m|$. Its PDF can be shown to be one-sided Gaussian by CLT for large M. Therefore, $f_Y(y) = \frac{\psi}{\sqrt{2\pi\sigma_Y^2}} \exp\left(-\frac{(y-\mu_Y)^2}{2\sigma_Y^2}\right)$, $y \geq 0$. Further, $f_{|h_{SX}|}(x) = \frac{2x}{\mu_{SX}} e^{-\frac{x^2}{\mu_{SX}}}$, $x \geq 0$. Using [12, (6.55)], the PDF of $R \triangleq |h_{SX}| - Y$ can be shown as $f_R(z) = \nu e^{\frac{b^2}{4a}} e^{-\left(\frac{z^2}{\mu_{SX}}+\frac{\mu_Y^2}{2\sigma_Y^2}\right)} I_R(z)$, for $z \geq 0$. Here, $I_R(z) = \int_0^\infty (z+y)\, e^{-a\left(y-\frac{b}{2a}\right)^2} dy$. Substituting $\sqrt{a}\left(y-\frac{b}{2a}\right) = t$ and using [13, (2.33.10)] and [13, (8.350.2)], $I_R(z)$ simplifies to the first case in (15). Similarly, for $z < 0$, $I_R(z)$ can be derived as the second case in (15). Finally, the CDF of $g_{\min} = R^2$ is $F_{g_{\min}}(z) = F_R(\sqrt{z}) - F_R(-\sqrt{z})$. Differentiating this w.r.t. z yields the desired expression for the PDF of $g_{\min}$ in (13).

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