Secure Cognitive Radio Communication via Intelligent Reflecting Surface

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Abstract—In this paper, an intelligent reflecting surface (IRS) assisted spectrum sharing underlay cognitive radio (CR) wiretap channel (WTC) is studied, and we aim at enhancing the secrecy rate of secondary user in this channel subject to total power constraint at secondary transmitter (ST), interference power constraint (IPC) at primary receiver (PR) as well as unit modulus constraint at IRS. Due to extra IPC and eavesdropper (Eve) are considered, all the existing solutions for enhancing secrecy rate of IRS-assisted non-CR WTC as well as enhancing transmission rate in IRS-assisted CR channel without eavesdropper fail in this work. Therefore, we propose new numerical solutions to optimize the secrecy rate of this channel under full primary, secondary users' channel state information (CSI) and three different cases of Eve's CSI: full CSI, imperfect CSI with bounded estimation error, and no CSI. To solve the difficult non-convex optimization problem, an efficient alternating optimization (AO) algorithm is proposed to jointly optimize the beamformer at ST and phase shift coefficients at IRS. In particular, when optimizing the phase shift coefficients during each iteration of AO, a Dinkelbach based solution in combination with successive approximation and penalty based solution is proposed under full CSI and a penalty convex-concave procedure solution is proposed under imperfect Eve's CSI. For no Eve's CSI case, artificial noise (AN) aided approach is adopted to help enhancing the secrecy rate. Simulation results show that our proposed solutions for the IRS-assisted design greatly enhance the secrecy performance compared with the existing numerical solutions with and without IRS under full and imperfect Eve's CSI. And positive secrecy rate can be achieved by our proposed AN aided approach given most channel realizations under no Eve's CSI case so that secure communication also can be guaranteed. All of the proposed AO algorithms are guaranteed to monotonic convergence.

Index Terms—Cognitive radio, intelligent reflecting surface, MISO, secrecy rate, CSI.

I. INTRODUCTION

Due to exponential growth of wireles systems and services in the past two decades, spectrum has become a very scarce resource. Cognitive radio (CR) concept has been proposed and is treated as one of the most promising technologies. Using the spectrum sensing and sharing technology, the growth of wireless devices and the scarcity of spectrum resources can be effectively alleviated. However, CR networks is suffering from lots of security threads, such as primary user emulation, jamming and eavesdropping in the physical layer, and spectrum sensing data falsification in the network layer as well as cross layer attacks [1]. Eavesdropping is a kind of passive attack in the physical layer that brings great security risks due to the broadcast nature of wireless channels. Physical layer security (PLS) approach has emerged as a very valuable complement to cryptography-based approaches. The key idea of this approach is that by exploiting the properties of wireless channels, the transmitted information for legitimate users can be completely "hidden" from eavesdropping, resulting secrecy of communication [2]. And the secrecy rate, namely as the difference of mutual information of legitimate user and eavesdropper, is the key performance metric for secrecy communications, and various works were established to enhance the secrecy rate of CR channels analytically or numerically.

A. Related work

A number of research results for secure multi-antenna spectrum sharing CR communication based on PLS were established [3]-[11]. In [3], the secrecy rate maximization of CR multi-input single-output (MISO) wiretap channel (WTC) under full channel state information (CSI) subject to total power constraint (TPC) at secondary transmitter as well as interference power constraint (IPC) at primary receiver were studied, and the imperfect CSI case was also established in [4]. In [5]-[7], artificial noise (AN) aided approach was also proposed to maximize the secrecy rate. Apart from the MISO case, secure CR multi-input multi-output (MIMO) WTC was also considered in [8]-[11], and the secrecy rate maximization of this channel was investigated either analytically or numerically. However, there is an inevitable problem in spectrum sharing CR networks: as primary receiver is located close to the secondary transmitter, the IPC is becoming tight so that the transmitter is unable to allocate full power for signaling. Therefore, the achievable secrecy rate at secondary user is likely to saturate with transmit power [8]. Hence, how to eliminate the restrictions brought by IPC on enhancing the secrecy performance in CR channels is still an open problem.

Recently, intelligent reflecting surface (IRS), has been proposed and it has drawn wide attention due to its extraodinary advantages. IRS is a metasurface consisting of low complexity passive reflecting elements [12]. These elements could change the propagation channels by inducing certain phase shift for the incident electromagnetic signal waves via the software in the controller so that the quality of communications at user can be greatly improved. Since IRS is a passive device, it does not consume any power for signal reflection, and can be easily deployed on many areas such as buildings, ceilings or indoor spaces. Furthermore, IRS also does not produce any extra noise to users since it is not equipped with A/D, D/A converter, power amplifiers or other signal processing devices. Therefore,

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these great benefits make IRS as a promising green energyefficient technique in beyond 5G or even 6G communications [13]-[15].

Inspired by these advantages brought by IRS, several studies of IRS-assisted multi-antenna communication were proposed, and lots of results were shown that IRS greatly enhance the transmission rate under either full CSI [16]-[18] or imperfect CSI [19][20]. In [21], it was shown that the IRS-assisted design also greatly improves the energy efficiency. Motivated by these works, IRS was also applied to enhance the transmission in multi-antenna CR channels [22]-[28]. In [22]-[24], the transmission rate optimization of IRS-assisted MISO CR channel subject to TPC, IPC and unit modulus constraint (UMC) was studied, and it was later extended to MIMO case [25]. In [26][27], the power minimization optimization algorithm of IRS-assisted MISO CR channel subject to IPC, UMC as well as target quality-of-service (QoS) for secondary user under full and statistical CSI were proposed. The sum rate of a full-duplex IRS-assisted MISO CR channel was also investigated in [28]. All these works again validated that IRS greatly improved the system performance of CR channels.

Furthermore, IRS was also combined with PLS to enhance the secrecy of communication in MISO/MIMO WTCs [29]-[38]. In [29]-[32], secure IRS-assisted MISO WTC subject to TPC at transmitter and UMC at IRS was studied, and the simulation results showed that proposed numerical solutions for this IRS-asssited desgin greatly boosted the user's secrecy rate compared with existing solutions for no IRS case. In [33], a double IRS-assisted design was considered, and a product Riemmanian manifold based algorithm was investigated to solve the non-convex secrecy rate problem. In [34], an efficient AN-aided method was proposed to enhance the secrecy rate when there is completely no eavesdropper's CSI. In [35], the IRS-assisted multi-user MISO downlink wiretap channel was also investigated under full eavesdropper's CSI, and it was later extended to the case of imperfect eavesdropper's CSI [36]. In addition to MISO case, the numerical solutions for enhancing the IRS-assisted MIMO WTC was recently established [37][38]. Same with the non-secure case, all these current literatures for secure IRS-assisted multi-antenna system indicated that IRS greatly boosted the secrecy rate compared with traditional solutions.

However, all the studies [29]-[38] for secure IRS-assisted design didn't consider CR-setting in which extra IPC is involved in addition to TPC and UMC. Therefore, all the solutions in the current literatures may fail to CR case (unless the IPC is a relaxed ignorable constraint). Furthermore, all the existing solutions for the IRS-assisted CR channels [22]-[28] did not consider security issues. When eavesdropper exists in the system, the secrecy rate optimization problem becomes complicated due to the new structure of objective function, which is significantly more complex than the single log formular for the non-secure case. Hence, new efficient numerical solutions is necessary to develop in the secure CR setting.

B. Contributions

Against the above background, in this paper, we consider an IRS-assisted spectrum sharing underlay CR MISO WTC, and focus on enhancing the secrecy rate at secondary user subject to TPC at secondary transmitter, IPC at primary receiver as well as UMC at IRS. The key motivation for applying IRS to secure CR system in this work is of two aspects: firstly, to the best of our knowledge, the study of IRS-assisted secure CR communication has never appeared in the literature, and all the existing numerical solutions cannot be directly applied to this setting; secondly, with IRS, full power allocation at secondary transmitter for signaling can be realized so that the secrecy rate can grow unbounded with transmit power. This is significantly different from those studies without IRS [3]-[11] in which the IPC becomes tight as the transmit power increases so that the secrecy rate saturates eventually. Specifically, we assume that full CSI of legitimate primary and secondary user are available, and consider three conditions of eavesdropper's CSI: full CSI, imperfect CSI with bounded estimation error and completely no CSI. And numerical algorithms are developed to enhance the secrecy rate under each considered CSI condition. The following summarizes the key contributions of our work.

1). Firstly, we assume that the eavesdropper's CSI is perfectly available, and propose an efficient alternating optimization (AO) algorithm to jointly optimize the beamformer \mathbf{w} and phase shift coefficients \mathbf{s} in the non-convex secrecy rate optimization problem. The main dificulty of this work is of optimizing the \mathbf{s} given \mathbf{w} in the non-convex fractional programming sub-problem. In particular, we propose a Dinkelbach method in combination with successive convex approximation (SCA) and penalty based (PB) approach to optimize the secrecy rate. As the convergence of AO algorithm is reached, a limit point solution for the problem can be obtained.

2). Secondly, we assume that the eavesdropper's CSI is imperfectly available due to the bounded channel estimation errors. To solve the complicated non-convex secrecy rate optimization problem, we firstly transform the infinite nonconvex constraints to convex one by adding auxiliary variables, and then apply AO algorithm to jointly optimize w and s. When optimizing w given s, SCA algorithm is applied to solve the sub-problem, and when optimizing s given w, a penalty convex concave procedure (P-CCP) approach is proposed. The key idea of P-CCP is to relax the problem by adding slack variables so that the non-convex UMC can be violated, and then penalizing the sum of the violations. As the convergence is reached, the solution returned by the P-CCP is an approximate first-order optimal solution for the original sub-problem.

3). Thirdly, we assume a more practical case that the eavesdropper's CSI is completely unavailable at transmitter. To enhance the secrecy performance under this case, we propose an artificial noise (AN) aided approach, in which a minimum power is firstly optimized to meet a target QoS constraint at secondary receiver, and then the residual power at secondary transmitter is applied for AN signaling so as to decrease the quality of communication at eavesdropper. Furthermore, to

guarantee that the target QoS at secondary receiver is not affected by the AN, we set the directions for AN signaling to both null space of the aggregated channels of secondary and primary receiver so that only eavesdropper is interfered by AN.

4). Simulation results have validated the monotonic convergence of the proposed algorithm. And when full CSI and imperfect Eve's CSI are assumed, our proposed AO algorithm for the IRS-assisted design greatly enhances the secrecy rate compared with the existing solutions for no IRS case. And even when the primary receiver is located close to secondary transmitter, allocating full power for signaling is still possible and the secrecy rate can grow unbounded with transmit power as if there is no IPC. This is significantly different from no IRS case in which the secrecy rate is likely to saturate since full power cannot be allocated for signaling. When no Eve's CSI is assumed, positive secrecy rate can be achieved by our proposed AN aided scheme under most scenarios and hence secure communications also can be guaranteed.

The rest of the paper is organized as follows: Section II describes the channel model. In Section III, the algorithm for secrecy rate maximization under full Eve's CSI is proposed. In Section IV, the algorithm for secrecy rate maximization under imperfect eavesdropper's CSI is proposed. Section V gives solution for enhancing the secrecy rate under no eavesdropper's CSI. Simulation results have been carried out to evaluate the performance and convergence of proposed algorithm in Section VI. Finally, Section VII concludes the paper.

Notations: Bold lower-case letters (a) and capitals (A) denote the vector and matrix respectively; \mathbf{A}^{T} , \mathbf{A}^{*} and \mathbf{A}^{H} denote transpose, conjugate and Hermitian conjugate of A, respectively; $\mathbf{A} \geq \mathbf{0}$ means positive semi-definite; $E\{\cdot\}$ is statistical expectation, $\lambda_i(\mathbf{A})$ denotes eigenvalues of \mathbf{A} , which are in decreasing order unless indicated otherwise, i.e. $\lambda_1 \geq \lambda_2 \geq \lambda_3...; tr(\mathbf{A})$ and $|\mathbf{A}|$ are the trace and determinant of **A**; **I** is an identity matrix with appropriate size; $\mathbb{C}^{M \times N}$ and $\mathbb{R}^{M \times N}$ are the space of $M \times N$ matrix with complex-valued elements and real-valued elements, respectively; $diag(\mathbf{a})$ is to transform the vector a to a diagonal matrix in which all diagonal entries are in a; $arg\{a\}$ denotes the phase of each entry of a; rank(A) is the rank of A; || a || denotes the Euclidian norm of vector **a**, and $|| \mathbf{A} ||_F$ denotes the F-norm of matrix A; $Re\{a\}$ denotes the real element of a; \odot denotes Hadamard product; $\mathcal{N}(A)$ denotes the null space of **A**.

II. CHANNEL MODEL

Considering an IRS-assisted spectrum sharing underlay CR Gaussian WTC model shown in Fig.1, in which an IRS, a secondary transmitter (Alice), secondary receiver (Bob), eavesdropper (Eve) as well as a primary receiver (PR) are included. In this model, Alice is equipped with m antennas and Bob, Eve, PR are all equipped with single antenna, the IRS is equipped with n reflecting elements. To help Alice enhancing the secrecy performance, the task of IRS in this model is to adjust the phase of the incident signals via the reflecting elements. And there is a controller connected with both IRS and Alice which is used to control the phase shift



Fig. 1. A block diagram of IRS-assisted Gaussian CR MISO wiretap channel

coefficient of reflecting elements as well as other coordination tasks for channel acquisition and data transmission [29].

Denote x as the information signals to Bob following $E\{|x|^2\} = 1$, let $\bar{\mathbf{h}}_{AB} \in \mathbb{C}^{1 \times m}$, $\bar{\mathbf{h}}_{AE} \in \mathbb{C}^{1 \times m}$, $\mathbf{h}_{IB} \in \mathbb{C}^{1 \times n}$, $\mathbf{h}_{IE} \in \mathbb{C}^{1 \times n}$, $\bar{\mathbf{H}}_{AI} \in \mathbb{C}^{n \times m}$, $\mathbf{h}_{AP} \in \mathbb{C}^{1 \times m}$ and $\mathbf{h}_{IP} \in \mathbb{C}^{1 \times n}$ be as the communication link of Alice-Bob, Alice-Eve, IRS-Bob, IRS-Eve, Alice-IRS, Alice-PR and IRS-PR respectively, then the received signals at Bob y_B and Eve y_E are

$$y_B = (\mathbf{h}_{AB} + \mathbf{h}_{IB} diag(\mathbf{s}^*) \mathbf{H}_{AI}) \mathbf{w} x + \xi_B$$
$$y_E = (\mathbf{h}_{AE} + \mathbf{h}_{IE} diag(\mathbf{s}^*) \mathbf{H}_{AI}) \mathbf{w} x + \xi_E$$

respectively where $\mathbf{w} \in \mathbb{C}^{m \times 1}$ is the beamformer at Alice, $\mathbf{s} = [e^{j\theta_1}, e^{j\theta_2}, ..., e^{j\theta_n}]^H$, θ_i is the phase shift coefficient at the *i*-th reflecting element, $\xi_B \sim \mathcal{CN}(0, \sigma_B^2)$ and $\xi_E \sim \mathcal{CN}(0, \sigma_E^2)$ represent complex noise at Bob and Eve respectively, σ_B^2, σ_E^2 denote the noise power. After some manipulations, y_B and y_E can be further equivalently expressed as

$$y_B = (\bar{\mathbf{h}}_{AB} + \mathbf{s}^{\mathrm{H}} \bar{\mathbf{H}}_B) \mathbf{w} x + \xi_B,$$

$$y_E = (\bar{\mathbf{h}}_{AE} + \mathbf{s}^{\mathrm{H}} \bar{\mathbf{H}}_E) \mathbf{w} x + \xi_E$$

respectively, where $\bar{\mathbf{H}}_B = diag(\mathbf{h}_{IB}^T)\bar{\mathbf{H}}_{AI}$, $\bar{\mathbf{H}}_E = diag(\mathbf{h}_{IE}^T)\bar{\mathbf{H}}_{AI}$ denote the effective cascaded channels of the reflecting communication link Alice-IRS-Bob, Alice-IRS-Eve respectively. We assume that the CSI of $\bar{\mathbf{h}}_{AB}$, $\bar{\mathbf{H}}_B$ are fully known at Alice throughout the paper. Based on this signal model, the transmission rate C_B at Bob and C_E at Eve are expressed as

$$C_B = \log_2(1 + |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_B)\mathbf{w}|^2),$$

$$C_E = \log_2(1 + |(\mathbf{h}_{AE} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_E)\mathbf{w}|^2),$$

respectively, where for $i \in \{B, E\}$, $\mathbf{h}_{Ai} = \bar{\mathbf{h}}_{Ai}/\sigma_i$, $\mathbf{H}_i = \bar{\mathbf{H}}_i/\sigma_i$. Since primary user is the licensed spectrum holder in spectrum sharing network, the interference generated from Alice to PR should keep below a certain pre-defined threshold. Therefore, the design of \mathbf{w} and \mathbf{s} should satisfy both TPC and IPC, i.e., $\|\mathbf{w}\|^2 \leq P_T$ and $|(\mathbf{h}_{AP} + \mathbf{s}^H \mathbf{H}_P)\mathbf{w}|^2 \leq P_I$, where P_T is the total power budget at Alice, P_I is the maximum interference power threshold at PR and where $\mathbf{H}_P = diag(\mathbf{h}_{IP}^T)\mathbf{H}_{AI}$ is the effective cascaded channel of the reflecting communication link Alice-IRS-PR. Since PR is also a legitimate user, we assume that PR shares its CSI of \mathbf{H}_P and \mathbf{h}_{AP} with Alice. IRS is only capable of adjusting the phase of the signals without changing the amplitudes so that s follows the UMC $|s_i| = 1$ where s_i is the *i*-th entry of s. Furthermore, the interference power generated by primary transmitter to Bob and Eve are treated as complex Gaussian noise mixed in ξ_B and ξ_E , and secondary user has no privilege to make primary transmitter changes its signaling strategy, which are also standard settings being widely accepted in the literature [3]-[11], [22]-[28].

Therefore, based on the key concept of informationtheoretic PLS, to guarantee secure communication for this channel, the achievable secrecy rate $C_B - C_E$ should be positive, and larger secrecy rate indicates better secrecy performance [2]. In the following sections, we focus on enhancing the secrecy performance of this IRS-assisted channel by jointly optimizing w and s under three conditions of the Eve's CSI \mathbf{H}_E and \mathbf{h}_{AE} : full CSI, imperfect CSI with bounded estimation error, and completely no CSI.

III. ALGORITHM FOR MAXIMIZING SECRECY RATE UNDER FULL EVE'S CSI

Firstly, we consider an ideal assumption that Eve's CSI $\bar{\mathbf{h}}_{AE}$ in the direct link and $\bar{\mathbf{H}}_E$ in the reflecting link are perfectly known at Alice. This can be realized since Eve is just other user in the system and it also shares its CSI with Alice but is untrusted by Bob. For how to estimate the CSI of all the channel links, we consider that the channel is with quasi-static block fading, and focus on one particular fading block with length T symbols over which all the channels remain approximately constant. Then, T is divided into three successive time slots, and Bob, Eve, PR send pilot signals to Alice in each time slot so as to estimate the CSI. Finally, each time slot can be further divided into two smaller time slots, and we apply the existing channel estimation solutions (see e.g. [39]) to estimate the direct and cascaded channel in each smaller time slot.

Given full CSI, we formulate the secrecy rate optimization problem for this IRS-assisted CR MISO WTC as follows.

$$(P1) \max_{\mathbf{w},\mathbf{s}} C_B - C_E$$

s.t. $\|\mathbf{w}\|^2 \leq P_T, |(\mathbf{h}_{AP} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_P)\mathbf{w}|^2 \leq P_I, \quad (1)$
 $|s_i| = 1, i = 1, 2, ..., n.$ (2)

$$P1$$
 is a non-convex optimization problem due to non-convex
objective function and constraints, and currently there is no
closed-form or numerical solutions for this problem in the
literature. Since the variable w and s are coupled in both
the objective function and IPC constraints, it is difficult to
simultaneously optimize them. Therefore, in this subsection,

Firstly, given fixed s, we formulate the sub-problem for optimizing w as

we propose an AO algorithm to jointly optimize w and s in

two sub-problems.

$$(P2) \max_{\mathbf{w}} C_B - C_E \quad s.t. \quad (1).$$

It can be known that P2 is a standard secrecy capacity of CR Gaussian wiretap channel optimization problem, which can be directly solved via the existing solutions in [3]. By setting

 $\mathbf{R} = \mathbf{w}\mathbf{w}^{H}$, and $\mathbf{h}_{B} = \mathbf{h}_{AB} + \mathbf{s}^{H}\mathbf{H}_{B}$, $\mathbf{h}_{E} = \mathbf{h}_{AE} + \mathbf{s}^{H}\mathbf{H}_{E}$, $\mathbf{h}_{P} = \mathbf{h}_{AP} + \mathbf{s}^{H}\mathbf{H}_{P}$, P2 can be expressed as

$$\begin{aligned} (P2') \max_{\mathbf{R}} & (1 + \mathbf{h}_B \mathbf{R} \mathbf{h}_B^{\mathrm{H}}) (1 + \mathbf{h}_E \mathbf{R} \mathbf{h}_E^{\mathrm{H}})^{-1} \\ s.t. \quad tr(\mathbf{R}) \leq P_T, \mathbf{h}_P \mathbf{R} \mathbf{h}_P^{\mathrm{H}} \leq P_I, \mathbf{R} \geq \mathbf{0} \end{aligned}$$

To solve P2', the existing Charnes-Cooper transformation illustrated in [3] can be directly applied to globally optimize **R**, from which the details is omitted here.

After optimizing \mathbf{w} given \mathbf{s} , the next step is to optimize \mathbf{s} in the following sub-problem

(P3) max
$$h_B(\mathbf{s})/h_E(\mathbf{s}), \ s.t. \ (2), h_P(\mathbf{s}) \le P_I,$$

where for $j \in \{B, E, P\}$, $h_j(\mathbf{s}) = 1 + \mathbf{s}^H \bar{\mathbf{H}}_{Ij}\mathbf{s} + 2Re\{\mathbf{s}^H \tilde{\mathbf{h}}_{Ij}\} + \bar{h}_{Aj}, \bar{h}_{Aj} = \mathbf{h}_{Aj}\mathbf{R}\mathbf{h}_{Aj}^H, \tilde{\mathbf{h}}_{Ij} = \mathbf{H}_j\mathbf{R}\mathbf{h}_{Aj}^H, \mathbf{H}_{Ij} = \mathbf{H}_j\mathbf{R}\mathbf{H}_{j}^H$. P3 is a fractional programming problem, and we propose Dinkelbach based method [30][40] in combination with SCA and PB algorithm to solve this problem. The key idea of this algorithm is summarized as three aspects: firstly, using Dinkelbach method to transform the problem to a more tractable non-fractional programming problem by adding extra variable; secondly, using SCA to approximate the non-convex objective function and constraints in the transformed problem to simpler linear formular; finally, PB approach is adopted to globally solve this approximated problem.

Remark 1. Here we point out that the Dinkelbach method should be applied ahead of the SCA method when optimizing *P*3. The main reason is that the there are extra terms 1, $2Re\{\mathbf{s}^{H}\tilde{\mathbf{h}}_{IB}\}, \bar{h}_{AB}$ in the numerator of $h(\mathbf{s})$, and extra terms 1, $2Re\{\mathbf{s}^{H}\tilde{\mathbf{h}}_{IE}\}, \bar{h}_{AE}$ in the denominator of $h(\mathbf{s})$, which fail to directly approximate $h(\mathbf{s})$ using Lemma 1 in [23]. Hence, motivated by this issue, the solution we apply is to firstly transform the problem via Dinkelbach method to a new one, and then use SCA to approximate the new problem to more tractable form (see e.g. [30]). Although a first-order optimal solution of P3 is out of reach by this method, the algorithm is guaranteed to converge so that a limit point solution can be obtained.

Specifically, by adding a non negative u, P3 can be transformed to

(P4)
$$\min_{\mathbf{s}} f(\mathbf{s}/u) = h_E(\mathbf{s}) - uh_B(\mathbf{s}), \ s.t. \ (2), h_P(\mathbf{s}) \le P_I.$$

Let s(u) be as the optimal value of P4 given fixed u, according to the key idea of Dinkelbach method [40], finding the optimal solution of P3 is equivalent to searching for the optimal usuch that the value of objective function f(s(u)/u) = 0, which can be obtained via BS algorithm since f(s(u)/u) is monotonically decreasing in u.

P4 is still non-convex due to the objective function and non-convex IPC. In the following, we propose SCA method to deal with P4, in which the key idea is to firstly approximate the non-convex (concave) objective function and constraint to more simpler linear formular given a feasible starting point, and then iteratively optimize the approximated problem. As the convergence is reached, the solutions returned by SCA is a first-order optimal point for the original problem [21][41].

To approximate the objective function and IPC in P4, the following key lemma is needed, from which the proof can be seen in [42].

Lemma 1. Let \mathbf{A} be an $n \times n$ Hermitian matrix, then for any point $\tilde{\mathbf{x}} \in \mathbb{C}^{n \times 1}$, $\mathbf{x}^{H} \mathbf{A} \mathbf{x}$ is upper bounded by $\mathbf{x}^{H} \mathbf{A} \mathbf{x} \leq \mathbf{x}^{H} \lambda_{1}(\mathbf{A}) \mathbf{I} \mathbf{x} - 2Re\{\mathbf{x}^{H}(\lambda_{1}(\mathbf{A})\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}}\} + \tilde{\mathbf{x}}^{H}(\lambda_{1}(\mathbf{A})\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}}$.

Therefore, denote \tilde{s} as a feasible point for P4, using this lemma, the objective function f(s/u) can be linearly approximated as

$$\begin{aligned} f(\mathbf{s}/u) &\leq c_1(u) + c_2(u) \\ &+ 2Re\{\mathbf{s}^{\mathrm{H}}[\tilde{\mathbf{h}}_{EB}(u) - (\lambda_1(\bar{\mathbf{H}}_{EB}(u))\mathbf{I} - \bar{\mathbf{H}}_{EB}(u))\tilde{\mathbf{s}}]\} \end{aligned}$$

where $\tilde{\mathbf{h}}_{EB}(u) = \tilde{\mathbf{h}}_{IE} - u\tilde{\mathbf{h}}_{IB}$, $\bar{\mathbf{H}}_{EB}(u) = \bar{\mathbf{H}}_{IE} - u\bar{\mathbf{H}}_{IB}$, $c_1(u) = 1 + \bar{h}_{AE} - u(1 + \bar{h}_{AB}) + n\lambda_1(\bar{\mathbf{H}}_{EB}(u))$, $c_2(u) = n\lambda_1(\bar{\mathbf{H}}_{EB}(u)) - \tilde{\mathbf{s}}^{\mathrm{H}}\bar{\mathbf{H}}_{EB}(u)\tilde{\mathbf{s}}$. Similarly, the IPC in P4 can also be linearly approximated as $h_P(\mathbf{s}) \leq c_3 + \tilde{h}_P(\mathbf{s}/\tilde{\mathbf{s}}) \leq P_I$ where $c_3 = \bar{h}_{AP} + 2n\lambda_1(\bar{\mathbf{H}}_{IP}) - \tilde{\mathbf{s}}^{\mathrm{H}}\bar{\mathbf{H}}_{IP}\tilde{\mathbf{s}}$, $\tilde{h}_P(\mathbf{s}/\tilde{\mathbf{s}}) = 2Re\{\mathbf{s}^{\mathrm{H}}[\tilde{\mathbf{h}}_{IP} - (\lambda_1(\bar{\mathbf{H}}_{IP})\mathbf{I} - \bar{\mathbf{H}}_{IP})\tilde{\mathbf{s}}]\}$. Hence, after dropping the constant terms, P4 can be approximated to a new optimization problem P5.

$$(P5) \min_{\mathbf{s}} \tilde{f}(\mathbf{s}/(u,\tilde{\mathbf{s}})) = Re\{\mathbf{s}^{\mathrm{H}}[\tilde{\mathbf{h}}_{EB}(u) - (\lambda_{1}(\bar{\mathbf{H}}_{EB}(u))\mathbf{I} - \bar{\mathbf{H}}_{EB}(u))\tilde{\mathbf{s}}]\} \ s.t. \ (2), \ \tilde{h}_{P}(\mathbf{s}/\tilde{\mathbf{s}}) \leq P_{I} - c_{3} = \tilde{P}_{I}.$$

Therefore, by setting a feasible starting point \tilde{s} and iteratively solve P5, the solution of s is treated as a new starting point \tilde{s} . As the convergence is reached, the solution returned by SCA algorithm is a first-order optimal point for P4.

However, P5 is still difficult to directly solve due to nonconvex (2). But note that even when the problem is nonconvex, the complementary slackness condition

$$\mu(\hat{h}_P(\mathbf{s}(\mu)/\tilde{\mathbf{s}}) - \tilde{P}_I) = 0.$$
(3)

is always the necessary condition for optimality [43], where μ is the Lagrange multiplier respect to IPC $\tilde{h}_P(\mathbf{s}(\mu)/\tilde{\mathbf{s}}) \leq \tilde{P}_I$. Hence, based on this key property, the optimal solution s for P5 can be optimized based on two cases.

Considering the first case that $\mu = 0$, i.e., IPC is an inactive constraint so that P5 reduces to the following P5'

$$(P5'): \max_{\mathbf{s}} - \tilde{f}(\mathbf{s}/(u,\tilde{\mathbf{s}})) \ s.t. \ (2).$$

Hence, it can be directly known that the global optimal solution of P5' is

$$\mathbf{s}(\mu=0) = \arg\{[\lambda_1(\bar{\mathbf{H}}_{EB}(u))\mathbf{I} - \bar{\mathbf{H}}_{EB}(u)]\tilde{\mathbf{s}} - \tilde{\mathbf{h}}_{EB}(u)\}.$$
(4)

Next, we consider the second case that $\mu > 0$, i.e., IPC is a tight active constraint. Note that when IPC is tight, it is difficult to directly obtain a closed-form solution of s as in the first case. Therefore, inspired by the solution illustrated in [18], we propose a PB approach to globally optimize s in this case. The key idea of this approach is of two aspects: firstly, we keep (2) unchanged and transform P5 to a new problem in which the IPC is absorbed by the objective function via adding a penalty variable; secondly, we give the closed-form solution of s in the transformed problem given fixed penalty variable. If a proper value of penalty variable is found, the corresponding solution of s for the transformed problem is a global optimal solution for the original problem P5. Specifically, we set the dual variable $\mu > 0$ for the IPC as a penalty variable, and transform P5 to a new problem P5" as follows.

$$(P5'') \max_{\mathbf{s}} - \tilde{f}(\mathbf{s}/(u,\tilde{\mathbf{s}})) - \mu \tilde{h}_P(\mathbf{s}(\mu)/\tilde{\mathbf{s}}) \quad s.t. \ (2),$$

Then, the global optimal solution of P5'' can be obtained as

$$\mathbf{s}(\mu > 0) = arg\{[(\lambda_1(\bar{\mathbf{H}}_{EB}(u))\mathbf{I} - \bar{\mathbf{H}}_{EB}(u)]\tilde{\mathbf{s}} \\ -\tilde{\mathbf{h}}_{EB}(u) - \mu(\tilde{\mathbf{h}}_{IP} - (\lambda_1(\bar{\mathbf{H}}_{IP})\mathbf{I} - \bar{\mathbf{H}}_{IP})\tilde{\mathbf{s}})\}.$$
 (5)

To find the optimal value of μ , the following lemma is needed

Lemma 2. Let $\mathbf{s}(\mu)$ be as the optimal solution of P5 given μ , then $\tilde{h}_P(\mathbf{s}(\mu)/\tilde{\mathbf{s}})$ is monotonically non-increasing in μ .

Proof. Specifically, the Lagrangian of P5 is as $L(\mathbf{s}, \mu, v_i) = \tilde{f}(\mathbf{s}/(u, \tilde{\mathbf{s}})) + \mu(\tilde{h}_P(\mathbf{s}/\tilde{\mathbf{s}}) - \tilde{P}_I) + \sum_{i=1}^n v_i(|q_i| - 1)$, where μ and v_i denote the Lagrange multipliers responsible for the IPC and UMC respectively. Considering that $\mu_1 > \mu_2 > 0$, and let $\mathbf{s}(\mu_1)$, $\mathbf{s}(\mu_2)$ denote the solution of P5 with μ_1, μ_2 . Assume $\mathbf{s}(\mu_1)$ and $\mathbf{s}(\mu_2)$ are both the global optimal solution of P5, then $L(\mathbf{s}(\mu_1), \mu_1, v_i) \leq L(\mathbf{s}(\mu_2), \mu_1, v_i), L(\mathbf{s}(\mu_2), \mu_2, v_i) \leq L(\mathbf{s}(\mu_1), \mu_2, v_i)$. Combining these two inequalities, one obtains $(\mu_1 - \mu_2)\tilde{h}_P(\mathbf{s}(\mu_1)/\tilde{\mathbf{s}}) \leq (\mu_1 - \mu_2)\tilde{h}_P(\mathbf{s}(\mu_2)/\tilde{\mathbf{s}})$. Since $\mu_1 > \mu_2$, then $\tilde{h}_P(\mathbf{s}(\mu_1)/\tilde{\mathbf{s}}) \leq \tilde{h}_P(\mathbf{s}(\mu_2)/\tilde{\mathbf{s}})$, from which the lemma holds.

Therefore, BS algorithm can be applied to optimize the optimal μ satisfying $\tilde{h}_P(\mathbf{s}(\mu)/\tilde{\mathbf{s}}) = \tilde{P}_I$. The global convergence of this proposed method is analyzed as follows.

Proposition 1. If IPC is tight and active, the output solution $\mathbf{s}(\mu)$ for P5'' via (5) in which μ is returned by BS is the global optimal solution of P5 given $\tilde{\mathbf{s}}$.

Proof. The proof is similar with the proof of Theorem 2 in [18]. Denote the global optimal solution for P5 as \hat{s} , then

$$h_P(\hat{\mathbf{s}}/\tilde{\mathbf{s}}) = P_I. \tag{6}$$

Then, denote the optimal μ returned by BS as $\hat{\mu}$, and the corresponding solution of s given $\hat{\mu}$ as $s(\hat{\mu})$, one observes that $\hat{\mu}$ satisfies

$$\hat{h}_P(\mathbf{s}(\hat{\mu})/\tilde{\mathbf{s}}) = \hat{P}_I.$$
 (7)

Now Proposition 1 can be proved via contradiction. Assume that $\mathbf{s}(\hat{\mu})$ is not the global optimal solution of P5, then we have $-\tilde{f}(\mathbf{s}(\hat{\mu})/(u,\tilde{\mathbf{s}})) \leq -\tilde{f}(\hat{\mathbf{s}}/(u,\tilde{\mathbf{s}}))$. Note that $\mathbf{s}(\hat{\mu})$ is the global optimal solution of P5'' under $\mu = \hat{\mu}$, then

$$-f(\mathbf{s}(\hat{\mu})/(u,\tilde{\mathbf{s}})) - \mu h_P(\mathbf{s}(\hat{\mu})/\tilde{\mathbf{s}})$$

$$\geq -\tilde{f}(\hat{\mathbf{s}}/(u,\tilde{\mathbf{s}})) - \mu \tilde{h}_P(\hat{\mathbf{s}}/\tilde{\mathbf{s}}).$$
(8)

By substituting (6) and (7) into (8) and after some manipulations, one obtains $-\tilde{f}(\mathbf{s}(\hat{\mu})/(u,\tilde{\mathbf{s}})) \geq -\tilde{f}(\hat{\mathbf{s}}/(u,\tilde{\mathbf{s}}))$, from which $-\tilde{f}(\mathbf{s}(\hat{\mu})/(u,\tilde{\mathbf{s}})) = -\tilde{f}(\hat{\mathbf{s}}/(u,\tilde{\mathbf{s}}))$ follows so that $\mathbf{s}(\hat{\mu}) = \hat{\mathbf{s}}$, i.e., $\mathbf{s}(\hat{\mu})$ in which $\hat{\mu}$ is returned by BS is the global optimal solution of *P*5.

Using this proposition, a global optimal solution of s can also be obtained for P5 under active IPC case. Therefore, during each iteration of SCA algorithm, s is optimized either via (4) or (5). As the convergence of SCA algorithm is reached, a first-order optimal s given fixed u in P4 can be obtained.

Hence, once the optimal u returned by BS is obtained, the corresponding s is a sub-optimal solution for original P1 given fixed w. The Dinkelbach based method in combination with SCA and PB algorithm for optimizing s given w in P3 is summarized as Algorithm 1. In this algorithm, there are three loops from the outer layer to inner layer. The outer-most loop is the BS algorithm for optimizing u, the second middle layer loop is the SCA algorithm for solving P5, and the inner layer loop is the BS algorithm for optimizing μ in P5'' if IPC is tight and active.

Algorithm 1 (Algorithm for optimizing s in P3)
Require u_l, u_u, μ_l, μ_u .
repeat
1. Initialize \tilde{s} , set $u = (u_l + u_u)/2$, start BS algorithm.
repeat
2. If IPC is inactive, optimize s according to (4),
and go to step 4, else go to step 3.
repeat
3. Set $\mu = (\mu_l + \mu_u)/2$, optimize $s(\mu)$ via (5).
If $\tilde{g}(\mathbf{s}(\mu)/\tilde{\mathbf{s}}) \geq \tilde{P}_I$, set $\mu_l = \mu$, otherwise set $\mu_u = \mu$.
until $ \mu_u - \mu_l $ converges
4. Set s as new starting point \tilde{s} .
until $\tilde{f}(\mathbf{s}/(u,\tilde{\mathbf{s}}))$ converges
5. Output s and compute $f(s/u)$.
6. If $f(\mathbf{s}/u) \ge 0$, set $u_l = u$, otherwise set $u_u = u$.
until $ u_u - u_l $ converges
Finally, since w and s are optimized alternatively in AO algorithm, $C(\mathbf{w}_1, \mathbf{s}_1) \leq C(\mathbf{w}_2, \mathbf{s}_2) \leq \dots \leq C(\mathbf{w}_k, \mathbf{s}_k)$

algorithm, $C(\mathbf{w}_1, \mathbf{s}_1) \leq C(\mathbf{w}_2, \mathbf{s}_2) \leq \ldots \leq C(\mathbf{w}_k, \mathbf{s}_k)$ where $C(\mathbf{w}_k, \mathbf{s}_k)$ is the objective value of P1 and $\mathbf{w}_k, \mathbf{s}_k$ are the solutions during the iteration k. Furthermore, since \mathbf{w} is bounded by the inequality TPC, and \mathbf{s} is bounded by the equality IPC, $C(\mathbf{w}_k, \mathbf{s}_k)$ is guaranteed to converge to a limit point $C(\mathbf{w}_{opt}, \mathbf{s}_{opt})$. In the AO algorithm, the main computational complexity on optimizing \mathbf{w} given \mathbf{s} is about $O(m^{3.5})$ [43]. Given \mathbf{w} , the main computational complexity of computing $\lambda_1(\tilde{\mathbf{H}}_{IE} - u\tilde{\mathbf{H}}_{IB})$ and $\lambda_1(\tilde{\mathbf{H}}_{IP})$ when optimizing \mathbf{s} are about $O(n^3)$, and the main computational complexity in each iteration of SCA with PB approach is about $O(n^2)$.

IV. Algorithm for maximizing secrecy rate under imperfect Eve's CSI

In this section, we consider a second assumption that the CSI of Eve is imperfectly known at Alice due to estimation errors. Denote $\tilde{\mathbf{h}}_{AE}$ and $\tilde{\mathbf{H}}_E$ as the estimated channels and $\tilde{\Delta}_E$, $\tilde{\Delta}_{AE}$ as the estimation errors, then the direct and cascaded channels between Alice and Eve are modeled as $\tilde{\mathbf{h}}_{AE} = \tilde{\mathbf{h}}_{AE} + \tilde{\Delta}_{AE}$, $\bar{\mathbf{H}}_E = \tilde{\mathbf{H}}_E + \tilde{\Delta}_E$ so that $\mathbf{h}_{AE} = \hat{\mathbf{h}}_{AE} + \Delta_{AE}$, $\mathbf{H}_E = \hat{\mathbf{H}}_E + \Delta_E$ where $\hat{\mathbf{h}}_{AE} = \tilde{\mathbf{h}}_{AE}/\sigma_E$, $\hat{\mathbf{H}}_E = \tilde{\mathbf{H}}_E/\sigma_E$, $\Delta_{AE} = \tilde{\Delta}_{AE}/\sigma_E$, $\Delta_E = \tilde{\Delta}_E/\sigma_E$. In particular, we assume that the errors are bounded as $\|\Delta_E\|_F = \|\tilde{\Delta}_E\|_F/\sigma_E \le$

 $\tilde{\epsilon}_E/\sigma_E = \epsilon_E$, $\|\Delta_{AE}\| = \|\tilde{\Delta}_{AE}\|/\sigma_E \le \tilde{\epsilon}_{AE}/\sigma_E = \epsilon_{AE}$, where $\tilde{\epsilon}_E$ and $\tilde{\epsilon}_{AE}$ are the uncertainty region of estimation errors known at Alice. Based on these settings, the corresponding secrecy rate maximization problem can be formulated as follows.

$$(P6) \max_{\substack{\mathbf{s},\mathbf{w} \ \Delta_E, \Delta_{AE}}} C_B - C_E$$

s.t. (1), (2), $\| \Delta_E \|_F \le \epsilon_E, \| \Delta_{AE} \| \le \epsilon_{AE}.$

Note that this is also a difficult non-convex problem with nonconvex IPC, UMC and infinite non-convex bounded estimation error constraints. Before solving this problem, we firstly transform the object function and the constraints to a more tractable form. By dropping the log function in both C_B and C_E and adding an auxiliary variable τ , P6 can be equivalently transformed to

$$(P7) \max_{\mathbf{s}, \mathbf{w}, \tau, \Delta_E, \Delta_{AE}} \frac{1 + |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_B) \mathbf{w}|^2}{1 + \tau}$$

s.t. (1), (2), $\tau \ge 0$, $|(\mathbf{h}_{AE} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_E) \mathbf{w}|^2 \le \tau$,
 $\|\Delta_E\|_F \le \epsilon_E$, $\|\Delta_{AE}\| \le \epsilon_{AE}$. (9)

Then, by adopting Schur's complement [43], the constraint $|(\mathbf{h}_{AE} + \mathbf{s}^H \mathbf{H}_E)\mathbf{w}|^2 \leq \tau$ as well as the IPC in (1) can be equivalently transformed to

$$\begin{bmatrix} \tau & (\mathbf{h}_{AE} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_{E}) \mathbf{w} \\ \mathbf{w}^{\mathrm{H}} (\mathbf{h}_{AE}^{\mathrm{H}} + \mathbf{H}_{E}^{\mathrm{H}} \mathbf{s}) & 1 \end{bmatrix} \ge \mathbf{0}, \qquad (10)$$

$$\begin{bmatrix} P_I & (\mathbf{h}_{AP} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_P) \mathbf{w} \\ \mathbf{w}^{\mathrm{H}} (\mathbf{h}_{AP}^{\mathrm{H}} + \mathbf{H}_P^{\mathrm{H}} \mathbf{s}) & 1 \end{bmatrix} \ge \mathbf{0}.$$
(11)

Then, substituting $\mathbf{H}_E = \mathbf{H}_E + \Delta_E$, $\mathbf{h}_{AE} = \mathbf{h}_{AE} + \Delta_{AE}$ into (10) and after some manipulations, one obtains that

$$\begin{bmatrix} \tau & (\hat{\mathbf{h}}_{AE} + \mathbf{s}^{\mathrm{H}} \hat{\mathbf{H}}_{E}) \mathbf{w} \\ \mathbf{w}^{\mathrm{H}} (\hat{\mathbf{h}}_{AE}^{\mathrm{H}} + \hat{\mathbf{H}}_{E}^{\mathrm{H}} \mathbf{s}) & 1 \end{bmatrix} \\ + \begin{bmatrix} \mathbf{0}_{1 \times m} \\ \mathbf{w}^{\mathrm{H}} \end{bmatrix} \begin{bmatrix} \Delta_{AE}^{\mathrm{H}} & \mathbf{0}_{m \times 1} \end{bmatrix} \mathbf{I} + \mathbf{I} \begin{bmatrix} \Delta_{AE} \\ \mathbf{0}_{1 \times m} \end{bmatrix} \begin{bmatrix} \mathbf{0}_{m \times 1} & \mathbf{w} \end{bmatrix} \\ + \begin{bmatrix} \mathbf{0}_{1 \times m} \\ \mathbf{w}^{\mathrm{H}} \end{bmatrix} \Delta_{E}^{\mathrm{H}} \begin{bmatrix} \mathbf{s} & \mathbf{0}_{n \times 1} \end{bmatrix} + \begin{bmatrix} \mathbf{s}^{\mathrm{H}} \\ \mathbf{0}_{1 \times n} \end{bmatrix} \Delta_{E} \begin{bmatrix} \mathbf{0}_{m \times 1} & \mathbf{w} \end{bmatrix} \ge \mathbf{0}.$$

To make further manipulations, we apply the following key lemma of general sign-definiteness principle, from which the proof can be seen in [44].

Lemma 3. Given matrices \mathbf{A}_i , \mathbf{B}_i , i = 1, 2, ..., n, and $\mathbf{Y} = \mathbf{Y}^{\mathrm{H}}$, the linear matrix inequality (LMI) $\mathbf{Y} \geq \sum_{i=1}^{n} (\mathbf{A}_i^{\mathrm{H}} \mathbf{X}_i \mathbf{B}_i + \mathbf{B}_i^{\mathrm{H}} \mathbf{X}_i \mathbf{A}_i), \forall i, || \mathbf{X}_i ||_F \leq \epsilon_i$ holds only if there exists $u_i \geq 0$, $\forall i$ such that

$$\begin{bmatrix} \mathbf{Y} - \sum_{i=1}^{n} u_i \mathbf{B}_i^{\mathrm{H}} \mathbf{B}_i & -\epsilon_1 \mathbf{A}_1^{\mathrm{H}} & \cdots & -\epsilon_n \mathbf{A}_n^{\mathrm{H}} \\ -\epsilon_1 \mathbf{A}_1 & u_1 \mathbf{I} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ -\epsilon_n \mathbf{A}_n & \mathbf{0} & \cdots & u_n \mathbf{I} \end{bmatrix} \ge \mathbf{0}.$$

Using this lemma, by introducing u_1 and u_2 , and combing

 $\| \Delta_E \|_F \le \epsilon_E, \| \Delta_{AE} \| \le \epsilon_{AE}$, we obtain the LMI as

$$\begin{bmatrix} \tau - u_1 n - u_2 & (\hat{\mathbf{h}}_{AE} + \mathbf{s}^{\mathrm{H}} \hat{\mathbf{H}}_E) \mathbf{w} & \mathbf{0}_{1 \times m} & \mathbf{0}_{1 \times m} \\ \mathbf{w}^{\mathrm{H}} (\hat{\mathbf{h}}_{AE}^{\mathrm{H}} + \hat{\mathbf{H}}_{E}^{\mathrm{H}} \mathbf{s}) & 1 - u_2 & \epsilon_E \mathbf{w}^{\mathrm{H}} & \epsilon_{AE} \mathbf{w}^{\mathrm{H}} \\ \mathbf{0}_{m \times 1} & \epsilon_E \mathbf{w} & u_1 \mathbf{I} & \mathbf{0}_{m \times m} \\ \mathbf{0}_{m \times 1} & \epsilon_{AE} \mathbf{w} & \mathbf{0}_{m \times m} & u_2 \mathbf{I} \end{bmatrix} \\ \geq \mathbf{0}. \tag{12}$$

Therefore, using these aforementioned manipulations, the infinite non-convex constraints in (9) and $|(\mathbf{h}_{AE} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_{E})\mathbf{w}|^{2} \leq \tau$ can be equivalently integrated to a single convex constraint (12) so that *P*7 can be equivalently transformed to

(P8)
$$\max_{\substack{\mathbf{s},\mathbf{w},\tau,u_1,u_2}} \frac{1 + |(\mathbf{h}_{AB} + \mathbf{s}^{\mathbf{H}}\mathbf{H}_B)\mathbf{w}|^2}{1 + \tau}$$

s.t. $\|\mathbf{w}\|^2 \le P_T, (2), (11), (12), \tau \ge 0, u_1 \ge 0, u_2 \ge 0.$

We note that in P8, the secrecy rate is determined only by \mathbf{w} , \mathbf{s} and τ , which are difficult to optimize simultaneously. To optimize P8, in this paper, we firstly obtain a proper region of τ numerically, and then apply AO algorithm to jointly optimize \mathbf{w} and \mathbf{s} by fixing τ . Lastly, the optimal τ corresponding to the largest objective value in P8 can be found via searching algorithm in its region.

Specifically, the upper bound of τ can be formulated as

$$\tau \le |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_B) \mathbf{w}|^2 \le P_T J(\mathbf{s})$$
(13)

where $J(\mathbf{s}) = \| \mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_{B} \|^{2} = \mathbf{h}_{AB}\mathbf{h}_{AB}^{\mathrm{H}} + 2Re\{\mathbf{s}^{\mathrm{H}}\mathbf{H}_{B}\mathbf{h}_{AB}^{\mathrm{H}}\} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_{B}\mathbf{H}_{B}^{\mathrm{H}}\mathbf{s}$. In (13), the first inequality holds since the secrecy rate is non-negative, and the second inequality follows from the lemma [45]: for any $\mathbf{W} \ge \mathbf{0}$ and $tr(\mathbf{W}) \le P_{T}$, $\mathbf{h}\mathbf{W}\mathbf{h}^{\mathrm{H}} \le tr(\mathbf{W}) \| \mathbf{h} \|^{2}$ holds. Hence, the work reduces to maximize $J(\mathbf{s})$, which corresponds to the following problem

$$(P9) \min_{\mathbf{s}} \mathbf{s}^{\mathrm{H}} (-\mathbf{H}_{B} \mathbf{H}_{B}^{\mathrm{H}}) \mathbf{s} - 2Re \{ \mathbf{s}^{\mathrm{H}} \mathbf{H}_{B} \mathbf{h}_{AB}^{\mathrm{H}} \} s.t. (2).$$

P9 can be maximized via SCA algorithm, in which the objective function can be approximated to a linear formula using Lemma 1 so that a first-order optimal closed-form solution of s can be obtained. Hence, assume that the optimized solution for P9 is s_{opt} , the upper bound of τ can be finally obtained as $P_T J(\mathbf{s}_{opt})$. Therefore, P8 can be equivalently expressed as

$$\max_{\tau} \varphi(\tau) \ s.t. \ 0 \le \tau \le P_T J(\mathbf{s}_{opt}) \tag{14}$$

where $\varphi(\tau)$ is defined as

$$(P10) \ \varphi(\tau) \triangleq \max_{\mathbf{s}, \mathbf{w}, u_1, u_2} \frac{1 + |(\mathbf{h}_{AB} + \mathbf{s}^H \mathbf{H}_B)\mathbf{w}|^2}{1 + \tau}$$

s.t. $\|\mathbf{w}\|^2 \le P_T, (2), (11), (12), u_1 \ge 0, u_2 \ge 0.$

To optimize w and s given τ in P10, we firstly fix s and optimize w in the following sub-problem

(P11)
$$\max_{\mathbf{w}, u_1, u_2} |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_B) \mathbf{w}|^2$$

s.t. $||\mathbf{w}||^2 \le P_T, (11), (12), u_1 \ge 0, u_2 \ge 0.$

Note that the objective function in P11 is not concave respect to w, however, it can be approximated via SCA. By applying the lemma that for any complex x and \tilde{x} ,

$$|x|^2 \ge 2Re\{\tilde{x}^*x\} - \tilde{x}^*\tilde{x},\tag{15}$$

 $|(\mathbf{h}_{AB} + \mathbf{s}^{H}\mathbf{H}_{B})\mathbf{w}|^{2}$ can be lower bounded by $2Re\{(\mathbf{h}_{AB} + \mathbf{s}^{H}\mathbf{H}_{B})\mathbf{\tilde{w}}\mathbf{w}^{H}(\mathbf{h}_{AB}^{H} + \mathbf{H}_{B}^{H}\mathbf{s})\} - (\mathbf{h}_{AB} + \mathbf{s}^{H}\mathbf{H}_{B})\mathbf{\tilde{w}}\mathbf{\tilde{w}}^{H}(\mathbf{h}_{AB}^{H} + \mathbf{H}_{B}^{H}\mathbf{s})\}$ where $\mathbf{\tilde{w}}$ is a feasible point. Therefore, after dropping the constant term, the problem transforms to

$$(P11') \max_{\mathbf{w}, u_1, u_2} Re\{\mathbf{w}^{\mathrm{H}}(\mathbf{h}_{AB}^{\mathrm{H}} + \mathbf{H}_{B}^{\mathrm{H}}\mathbf{s})(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_{B})\tilde{\mathbf{w}}\}$$

s.t. $\|\mathbf{w}\|^{2} \leq P_{T}, (11), (12), u_1, u_2 \geq 0,$

which can be directly solved via CVX solver since the objective function and all the constraints are convex. Hence, by solving P10 via SCA until convergence, a first-order optimal solution of w given s can be obtained.

The next step is to optimize s given w when fixing τ in the following problem

$$(P12)\min_{\mathbf{s},u_1,u_2} r(\mathbf{s}) = -|(\mathbf{h}_{AB} + \mathbf{s}^{\mathbf{H}}\mathbf{H}_B)\mathbf{w}|$$

s.t. (11), (12), $u_1 \ge 0, u_2 \ge 0, (2).$

Different from P11, P12 is difficult to solve, since although the objective function r(s) can be approximated to linear expression, the non-convex strict equality (2) can not be approximated. Therefore, inspired by [46], we propose a P-CCP approach to optimize s in P12, in which the key idea is to relax the problem by adding slack variables so as to make (2) to be violated, and then penalizing the sum of the violations. Note that a significant difference between P-CCP and the aforementioned PB approach for solving P5 is that in P-CCP, the non-convex (2) is relaxed to a convex one so that the optimized $|s_i|$ may not equal but infinitely close to 1, but in PB, (2) is unchanged so that the solution $|s_i| = 1$ always holds.

Firstly, following (15), r(s) is upper bounded by

$$r(\mathbf{s}) \leq \tilde{r}(\mathbf{s}, \tilde{\mathbf{s}}) = -2Re\{(\mathbf{h}_{AB} + \tilde{\mathbf{s}}^{\mathrm{H}}\mathbf{H}_{B})\mathbf{w}\mathbf{w}^{\mathrm{H}}(\mathbf{h}_{AB}^{\mathrm{H}} + \mathbf{H}_{B}^{\mathrm{H}}\mathbf{s})\} + (\mathbf{h}_{AB} + \tilde{\mathbf{s}}^{\mathrm{H}}\mathbf{H}_{B})\mathbf{w}\mathbf{w}^{\mathrm{H}}(\mathbf{h}_{AB}^{\mathrm{H}} + \mathbf{H}_{B}^{\mathrm{H}}\tilde{\mathbf{s}}).$$

Then, by introducing auxiliary real vectors $\mathbf{b} = [b_1, b_2, ..., b_n]^T$, $\mathbf{c} = [c_1, c_2, ..., c_n]^T$ (where $b_i, c_i > 0, \forall i$), we formulate the following constraint

$$1 - b_i \le |s_i|^2 \le 1 + c_i, \forall i = 1, 2, ..., n.$$
(16)

so that the feasible set of $|s_i|$ changes to a continuous region. Although this violates the strict equality UMC, the sum of the violations $\sum_{i=1}^{n} b_i^k + \sum_{i=1}^{n} c_i^k$ can be penalized so that the value of b_i and c_i (i = 1, 2, ..., n) is guaranteed to converge to zero. Hence, $|s_i|$ returned by P-CCP is infinitely close to 1.

Note that (16) can be further divided into a convex constraint $|s_i|^2 \leq 1 + c_i$ and non-convex constraint $|s_i|^2 \geq 1 - b_i$. The non-convex one can also be approximated (according to (15)) as $|s_i|^2 \geq 2Re\{\tilde{s}_i^*s_i\} - |\tilde{s}_i|^2 \geq 1 - b_i$ where \tilde{s}_i is a feasible point. Based on the key concept of P-CCP [46], we introduce a penalty parameter γ and construct the following optimization

problem

$$(P12') \min_{\mathbf{s}, u_1, u_2, \mathbf{b}, \mathbf{c}} \tilde{r}(\mathbf{s}, \tilde{\mathbf{s}}) + \gamma(\sum_{i=1}^n b_i + \sum_{i=1}^n c_i)$$

s.t. (11), (12), $u_1 \ge 0, u_2 \ge 0, b_i \ge 0, c_i \ge 0,$
 $2Re\{\tilde{s}_i^* s_i\} - |\tilde{s}_i|^2 \ge 1 - b_i, |s_i|^2 \le 1 + c_i, \forall i.$

Therefore, given fixed γ , P12' is a convex problem which can be directly solved via CVX. The algorithm of P-CCP for optimizing s in P12 is summarized as Algorithm 2. In this algorithm, γ is refreshed during each iteration, which is used to scale the impact of the penalty term $\sum_{i=1}^{n} b_i + \sum_{i=1}^{n} c_i$ and control the feasibility of the constraints. And the upper limit γ_{max} is used to avoid numerical problems if γ grows too large and to provide convergence if a feasible region is not found. Following [46], Algorithm 2 is not a strictly descent algorithm (mostly when $\gamma < \gamma_{max}$), but the value of objective function $r(s) + \gamma(\sum_{i=1}^{n} b_i + \sum_{i=1}^{n} c_i)$ is always guaranteed to converge. The reason is that as γ reaches to γ_{max} ,

$$\sum_{i=1}^{n} b_i^k + \sum_{i=1}^{n} c_i^k \approx 0$$
 (17)

where b_i^k and c_i^k are optimized at iteration k. Therefore, b_i and c_i both converge to zero so that the objective value of P12' is only affected by $\tilde{r}(\mathbf{s}, \tilde{\mathbf{s}})$. Furthermore, since $r(\mathbf{s})$ is also approximately upper bounded by $\tilde{r}(\mathbf{s}, \tilde{\mathbf{s}})$, one obtains that

$$(r(\mathbf{s}_{k}) + \gamma_{max}(\sum_{i=1}^{n} b_{i}^{k} + \sum_{i=1}^{n} c_{i}^{k})) - (r(\mathbf{s}_{k+1}) + \gamma_{max}(\sum_{i=1}^{n} b_{i}^{k+1} + \sum_{i=1}^{n} c_{i}^{k+1})) \le \epsilon_{violation}$$

can be achieved where $\epsilon_{violation}$ is the target accuracy for convergence. As the convergence is reached, the optimized solution satisfying (16) (where $b_i, c_i \approx 0$) returned by Algorithm 2 can be as an approximate first-order optimal solution for the original problem *P*12.

Algorithm 2 (*P-CCP algorithm for solving* P12)
Require
$$\gamma > 0$$
, $\gamma_{max} > 0$, $t > 1$, \tilde{s} , set $k = 0$.
repeat
1. Set $k = k+1$, optimize s_k in the convex optimization

problem P12' given \tilde{s} . 2. Update the penalty parameter: $\gamma = \min(t\gamma, \gamma_{max})$. 3. Set $\tilde{s} = s_k$.

until The objective value $r(\mathbf{s}_k) + \gamma(\sum_{i=1}^n b_i^k + \sum_{i=1}^n c_i^k)$ converges

Hence, using AO algorithm to jointly optimize w and s in the sub-problem P11 and P12 until converge, a limit point solution for the original problem P10 can be obtained. Since τ lies in the interval $[0, P_T J(\mathbf{s}_{opt})]$, the optimization problem in (14) can be solved by performing one-dimensional line search (such as uniform sampling or golden search [45]) over τ , and choosing the optimal one τ_{opt} that achieves the maximum value of objective function. In this paper, we apply uniform sampling method to search for τ_{opt} . Based on our extensive simulations, the searched point τ_{opt} is usually a very small value ranging from 0 to 1 in most channel realizations. Once τ_{opt} is found, the corresponding w and s returned by AO algorithm is a final limit point solution of original problem P6. In this algorithm, given fixed τ , the main computational complexity of optimizing w given s in each iteration of SCA and optimizing s given w in each iteration of P-CCP are $O((m+2)^2)$ and $O((3n+2)^2)$ respectively. And the main computational complexity of solving P9 via SCA in each iteration is about $O(n^2)$.

In addition, we point out that when the CSI of \mathbf{H}_P and \mathbf{h}_{AP} between Alice and PR link are also imperfectly known due to bounded estimation errors as with the settings for \mathbf{H}_E and \mathbf{h}_{AE} , our proposed AO algorithm shown above also can be extended to enhance the secrecy rate under this condition. This can be easily achieved by applying Schur's complement and Lemma 3 so that the infinite non-convex constraints can be directly transformed to single convex LMI constraint by adding auxiliary variables. Hence, AO algorithm can be directly applied to jointly optimize the beamformer and phase shift.

V. AN AIDED SOLUTION FOR ENHANCING SECRECY RATE UNDER NO EVE'S CSI

In this section, we consider a third assumption that the Eve's CSI is completely unknown at Alice so that both the direct channel $\bar{\mathbf{h}}_{AE}$ and cascaded channel $\bar{\mathbf{H}}_E$ cannot be obtained. Compared with the full and imperfect Eve's CSI cases in the previous sections, no Eve's CSI is a more practical assumption since Eve is usually a hidden passive malicious user, and it does not actively exchange its CSI with Alice. Therefore, it is unlikely to formulate an optimization problem as P1 or P6 to maximize the secrecy rate. Although the transmission rate at Bob can be optimized given full CSI of Bob and PR, the information leakage at Eve may be large so that $C_B < C_E$, i.e., secure communication may not achievable according to the key concept of information-theoretic PLS.

Therefore, following our previous work for the non-CR setting in [34][38], in this paper, we propose an AN aided scheme to enhance the secrecy rate under no Eve's CSI. To achieve secure communication (i.e., $C_B > C_E$), the key idea of this scheme is summarized as two aspects. Firstly, we optimize a minimum power P_S subject to the IPC at PR and a QoS constraint at Bob in which the signal-to-noise ratio (SNR) meets the lowest pre-defined threshold. Secondly, we use the residual power $P_T - P_S$ available at Alice to transmit AN signals so as to decrease the SNR at Eve.

Based on this aforementioned setting, the signals received at Bob and Eve are represented as

$$y_B = (\mathbf{h}_{AB} + \mathbf{h}_{IB} diag(\mathbf{s}^*) \mathbf{H}_{AI})(\mathbf{w}x + \mathbf{z}) + \xi_B,$$

$$y_E = (\bar{\mathbf{h}}_{AE} + \mathbf{h}_{IE} diag(\mathbf{s}^*) \bar{\mathbf{H}}_{AI})(\mathbf{w}x + \mathbf{z}) + \xi_E$$

respectively where z is the AN signals. In order to determine how much power of the total power P_T can be dominated for transmitting the information signal x satisfying the QoS constraint at Bob, we formulate a power minimization problem as

$$(P13) \min_{\mathbf{w},\mathbf{s}} \| \mathbf{w} \|^2 \quad s.t. \ (11), |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_B) \mathbf{w}|^2 \ge T, (2),$$

where T is the pre-defined lowest SNR threshold at Bob. To solve this problem, we apply AO algorithm again to jointly optimize w and s in two sub-problems.

Firstly, when s is fixed, the sub-problem for optimizing w is expressed as

(P14)
$$\min_{\mathbf{w}} \| \mathbf{w} \|^2$$

s.t. $|(\mathbf{h}_{AP} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_P)\mathbf{w}|^2 \leq P_I, |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_B)\mathbf{w}|^2 \geq T.$

Note that except for QoS constraint $|(\mathbf{h}_{AB} + \mathbf{s}^{H}\mathbf{H}_{B})\mathbf{w}|^{2} \geq T$, the objective function and IPC are all convex in \mathbf{w} . Using (15), the QoS constraint can be approximated to a linear formular so that a first-order optimal \mathbf{w} can be obtained via SCA algorithm. Furthermore, it is straightforward to obtain that the solution of \mathbf{w} makes the QoS constraint always hold with equality.

Secondly, when w is fixed, the sub-problem of optimizing s is expressed as

(P15) Find
$$\mathbf{s}$$
 s.t.
 $|(\mathbf{h}_{AP} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_{P})\mathbf{w}|^{2} \leq P_{I}, |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_{B})\mathbf{w}|^{2} \geq T, (2).$

Note that there is no objective function in this problem, and any feasible s satisfying the QoS and UMC can be as the optimal solution. In fact, if the feasible solution s obtained for P15 achieves a strictly larger SNR than the target T, then the minimum transmit power in P14 returned by SCA can be properly reduced without violating the QoS constraint. Hence, the work can be reduced to maximize the SNR at Bob as large as possible in the following problem P15'.

$$(P15') \max_{\mathbf{s}} |(\mathbf{h}_{AB} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_{B})\mathbf{w}|^{2}$$

s.t. (2), $|(\mathbf{h}_{AP} + \mathbf{s}^{\mathrm{H}}\mathbf{H}_{P})\mathbf{w}|^{2} \leq P_{I}$

Using the key idea of solving P4 given fixed u, P15' also can be solved via SCA so as to obtain a first-order optimal solution, in which the objective function can be approximated via (15) given a feasible point \tilde{s} and the IPC $|(\mathbf{h}_{AP} + \mathbf{s}^{H}\mathbf{H}_{P})\mathbf{w}|^{2} \leq P_{I}$ can be approximated via Lemma 1. And during each iteration of SCA algorithm, the global optimal solution of s given \tilde{s} can be obtained analytically under inactive IPC case and via the PB approach under active IPC case.

Collectively, since w and s are optimized alternatively, the objective value $\|\mathbf{w}\|^2$ is non-increasing with iteration k, i.e., $\|\mathbf{w}_1\|^2 \ge \|\mathbf{w}_2\|^2 \ge ... \ge \|\mathbf{w}_k\|^2$. Furthermore, since w and s are both bounded by the constraints, a limit point solution of w and s for P13 can be obtained as the AO algorithm converges. For optimizing w given s and optimizing s given w in each iteration of SCA, the main computational complexity are $O(m^2)$ and $O(n^2)$ respectively.

After obtaining the solution w, we obtain the minimum power $P_S = || \mathbf{w} ||^2$ used for information signal transmission, then the residual power $P_T - P_S$ is used to send AN signal z to jam Eve. Since the Eve's channels are unknown at Alice, it is unlikely to optimize the transmit covariance of AN signal $\mathbf{R}_{AN} = E\{\mathbf{z}\mathbf{z}^{H}\}$. Therefore, we apply equal power allocation strategy to transmit AN signals to each dimension of $\mathcal{N}(\mathbf{H}_{eff})$ where

$$\mathbf{H}_{eff} \in \mathbb{C}^{m \times m} = \begin{bmatrix} \bar{\mathbf{h}}_{AB} + \mathbf{s}^{\mathrm{H}} \bar{\mathbf{H}}_{B} \\ \mathbf{h}_{AP} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_{P} \end{bmatrix}^{\mathrm{H}} \begin{bmatrix} \bar{\mathbf{h}}_{AB} + \mathbf{s}^{\mathrm{H}} \bar{\mathbf{H}}_{B} \\ \mathbf{h}_{AP} + \mathbf{s}^{\mathrm{H}} \mathbf{H}_{P} \end{bmatrix}$$

with $rank(\mathbf{H}_{eff}) = 2$ so that the transmit covariance \mathbf{R}_{AN} is expressed as

$$\mathbf{R}_{AN} = \frac{P_T - P_S}{m - 2} \mathbf{U}_{AN} \mathbf{U}_{AN}^{\mathrm{H}}$$

where the columns in the semi-unitary matrix U_{AN} are all m-2 eigenvectors corresponding to zero eigenvalues of H_{eff} . Using this way, the AN generated by Alice could only interfere Eve, and does not affect the quality of communication at both Bob and PR so that the QoS constraint at Bob and IPC at PR can be satisfied simultaneously. Hence, given target SNR threshold T, the actual achievable secrecy rate C_s by this scheme at Bob is finally expressed as

$$C_s = \log_2(1+T) - \log_2 |1 + \frac{|(\bar{\mathbf{h}}_{AE} + \mathbf{s}^{\mathrm{H}}\bar{\mathbf{H}}_E)\mathbf{w}|^2}{\sigma_E^2 + (\bar{\mathbf{h}}_{AE} + \mathbf{s}^{\mathrm{H}}\bar{\mathbf{H}}_E)\mathbf{R}_{AN}(\bar{\mathbf{h}}_{AE} + \mathbf{s}^{\mathrm{H}}\bar{\mathbf{H}}_E)^{\mathrm{H}}}|.$$

Based on our extensive numerical simulations, a positive secrecy rate $C_s > 0$ can be achieved via the proposed scheme in most channel realizations given finite T and hence secure communication can be guaranteed.

VI. SIMULATION RESULTS

To validate the performance of our proposed numerical solutions, extensive simulation results have been carried out in this section. Following [29], all the channels are assumed to be independent Rayleigh fading, and each channel vector and matrix are formulated as the product of large scale fading and small scale fading. For the location of each node, we consider a three dimensional coordinate space, and let Alice, Bob, IRS to be fixed in a coordinate, Eve and PR are randomly located in certain areas (see Fig.1). For all the AO algorithms illustrated in the paper, the starting point of w and s are randomly generated satisfying the corresponding constraints in each optimization problem. And the sampling interval for finding the optimal τ in the feasible interval $[0, P_T J(\mathbf{s}_{ont})]$ are set as 10^{-2} . Some main parameter settings of channels, locations of each node as well as algorithms for the simulation are summarized in Table 1. All the results plotted in Fig.2 to Fig.5 are averaged over 100 channel realizations, and all the results plotted in Fig.6 to Fig.9 are generated based on single channel realization.

Fig.2 shows the average secrecy rate performance returned by our proposed AO algorithm for the IRS-assisted design under full Eve's CSI. We also compare the results with those by other benchmark schemes: 1). only optimizing w given random s at IRS; 2).optimal solutions in [3] without IRS; 3).AN aided solutions in [11] without IRS. Observe that the performance via the proposed algorithm is significantly better than the those benchmark schemes without IRS. The main

 TABLE I

 Summary of Parameter Settings for Simulation

Symbol	Definition and setting
$\alpha_{AB}, \alpha_{AE}, \alpha_{AP}$	The path loss exponents of Alice-Bob, Alice-Eve and Alice-PR links respectively, all of them are set as 3.
$\alpha_{AI}, \alpha_{IB}, \alpha_{IE}, \alpha_{IP}$	The path loss exponents of Alice-IRS, IRS-Bob, IRS-Eve and IRS-PR links respectively, all of them are set as 2.5.
(0, 0, 0), (100, 0, 0), (50, 0, 50)	The coordinates of Alice, Bob and IRS respectively, their locations are all fixed.
$(d_{x1}, d_{y1}, 0), (d_{x2}, d_{y2}, 0)$	The coordinates of Eve and PR respectively. PR is randomly located in a circle with Alice as the center and a radius of 50 meters, i.e. $d_{x1}, d_{y1} \in [-50, 50]$. Eve is randomly located in a circle with Bob as the center and a radius of 50 meters, i.e., $d_{x2} \in [50, 150]$, $d_{y2} \in [-50, 50]$.
$\epsilon_{BS}, \epsilon_{AO}, \epsilon_{SCA}$	The target accuracy of all the bisection search algorithms, AO algorithms and SCA algorithms, respectively. All these accuracy are set as 10^{-3} .
t	The update of γ in P-CCP algorithm, $t = 5$.
γ, γ_{max}	$\gamma = 10$ and $\gamma_{max} = 10^3$ are the initial and maximum value of penalty parameter respectively in P-CCP algorithm.
σ_B^2,σ_E^2	The noise power at Bob and Eve respectively, they are both set as -100dBm.



Fig. 2. The average secrecy rate performance versus P_T returned by proposed algorithm with other benchmark schemes under full Eve's CSI. P_I is fixed at 30dBm, m = 4, n = 8.



Fig. 3. The average secrecy rate and average actual power consumption returned by proposed algorithm with IRS and existing optimal solution in [3] without IRS when PR is located at (20, 0, 0). P_I is fixed at 25dBm, m = n = 3.

reason is that IRS helps adjust the propagation channels, and via jointly optimizing s and w, the signals transmitted via the direct link Alice-Bob (Eve) and reflecting link Alice-IRS-Bob (Eve) can be constructively (destructively) added at Bob (Eve), thereby boosting the secrecy rate. Although the random phase shift scheme has better performance than those without IRS, it still achieves significantly less performance than the proposed one. This indicates that only by the signal cooperation between Alice and IRS can the better performance gain be achieved.

To further exploit how the secrecy rate changes with P_T as PR is located close to Alice under IRS-assisted and no IRS cases, we set the location of PR at (20, 0, 0) between Alice and Bob so that the direct link of channels \mathbf{h}_{AB} , \mathbf{h}_{AP} are strongly correlated, and the quality of \mathbf{h}_{AP} is better than \mathbf{h}_{AB} (since the signals transmitted via the channel \mathbf{h}_{AP} suffers from less attenuation), and we show the average secrecy rate as well as the average actual power consumption (i.e., the value of $||\mathbf{w}||^2$) via the proposed algorithm for IRS-assisted case and existing solutions [3] for no IRS case under this location setting.

Observe that in (a), as P_T is increasing, the secrecy rate gradually saturate under no IRS case, since the interference generated to PR gradually reach the maximum threshold P_I so that Alice cannot allocate all the power for signaling. On the contrary, when IRS exists, the secrecy rate increases with P_T as if the IPC is relaxed. The main reason is that IRS helps providing new communication link of Alice-IRS-Bob so that full power can be allocated for signal transmission. This can be validated in (b), in which the red curve representing $||\mathbf{w}||^2$ by the proposed algorithm coincides with the black curve representing total power P_T . For no IRS case, $||\mathbf{w}||^2 < P_T$ returned by [3] appears as $P_T > 30$ dBm, which indicates that full power allocation is not optimal due to tight IPC. Hence, we remark that IRS effectively eliminates the restriction brought by IPC on the unbounded growth of secrecy rate with P_T even when the PR's channel is strongly corelated with Bob's channel. which can never be achieved in the conventional CR system without IRS.

ϵ=0.04, without IRS ϵ =0.01, without IRS (bit/s/Hz full CSI, without IRS 2.5 =0.04, with IRS random phase shift secrecy rate e=0.01, with IRS random phase shift full CSI, with IRS random phase shif Average 0.5 32 33 34 35 P_{τ} (dBm)

-e=0.04, proposed with IRS re=0.01, proposed with IRS

full CSI, proposed with IRS

3.5

Fig. 4. The robust average secrecy rate returned by proposed algorithm with IRS, random phase shift with IRS and no IRS case under imperfect Eve's CSI condition. $\tilde{\epsilon}_E = \tilde{\epsilon}_{AE} = \epsilon$, P_I is fixed at 30dBm, m = 3, n = 4.

Fig.4 shows the robust average secrecy rate returned by the proposed AO algorithm under imperfect Eve's CSI. Same with the results illustrated in Fig.2, our proposed solution also achieves significantly better performance than that for no IRS case as well as random phase shifts solution with IRS under different channel estimation errors. And with larger settings of m, n, larger secrecy rate can be achieved due to the increased degree of freedom. Furthermore, as expected, the achievable secrecy rate is decreased when the estimation error of Eve's CSI exists compared with perfect CSI case, since the signal power from the direct Alice-Bob link and reflected Alice-IRS-Bob link cannot accurately focus on Bob. And as the region of estimation error is larger, more reduction in secrecy rate appears due to more power loss when transmitting and reflecting the signals. Apart from this simulation, we also have made comparison about the secrecy rate between IRS-assisted and no IRS design by setting the location of PR at (20, 0, 0) given imperfect Eve's CSI. Same with the results illustrate in Fig.3, full power allocation is always optimal under IRSassisted design so that secrecy rate keeps growing with P_T , from which the results are omitted here for brevity.

Fig.5 shows the actual achievable average secrecy rate versus target SNR T at Bob returned by the proposed AN aided scheme with IRS, random phase shift with IRS and no IRS case when Eve's CSI is completely unknown. Based on the results, one observes that given a finite SNR ranging from 25dBm to 35dBm, a positive secrecy rate $C_s > 0$ still can be achieved by our scheme so that secure communication also can be guaranteed. Also note that the performance returned by our proposed solution with IRS is better than the other two solutions. The main reason is that more sufficient power can be saved for Alice to achieve the same target SNR via jointly optimizing w and s than that by simply optimizing w given random phase shifts at IRS or without IRS. Hence, for IRSassisted design, Alice can use more residual power for AN signaling so as to decrease the SNR at Eve as much as possible, resulting higher secrecy rate. Here we remark that based on our extensive simulations, as long as T is set properly, positive actual secrecy rate can be achieved in most scenarios.



Fig. 5. The actual average secrecy rate returned by the proposed AN aided scheme for IRS-assisted case, random phase shift for IRS-assisted case and no IRS case under no Eve's CSI. P_T is fixed at 40dBm, P_I is fixed at 30dBm. m = n = 4.

But sometimes the actual secrecy rate becomes zero especially when Eve is located close to Alice. Therefore, to guarantee positive secrecy rate under this unfavorable environment, Bob needs to lower the value of T so that Alice could save more power used to decrease the SNR at Eve via AN signaling.

To further exploit the secrecy performance returned by our proposed scheme when increasing the target SNR T to larger under no Eve's CSI case, Fig.6 shows the actual secrecy rate C_s versus T under different settings of total power P_T . Note that for all settings of P_T , C_s firstly increases with T since the transmission rate $C_B = T$ at Bob dominates. However, as T grows to higher, C_s starts to decrease sharply, since the sufficient residual power $P_T - P_S$ for AN signaling is reduced significantly so that the information leakage to Eve C_E dominates. Finally, as T grows to high enough, the total power P_T can not support to meet the QoS constraint so that P13 becomes infeasible and hence secure communication is not achievable (e.g., the secrecy rate stops at T=24 dB when $P_T \ge 55$ dBm in the red curve). Therefore, we see that there is a trade off between improving QoS at Bob and enhancing the secrecy rate. Hence, based on the results in Fig.5 and 6, one concludes that it is better to balance the setting between T and the residual power $P_T - P_S$ for AN signaling so as to achieve a good secrecy performance.

Fig.7 and Fig.8 illustrates the convergence of the objective function $C_s(\mathbf{w}_k, \mathbf{s}_k)$ in P1 under full CSI and imperfect Eve's CSI given fixed τ respectively. Observe that it requires about 4 to 16 iterations for $C_s(\mathbf{w}_k, \mathbf{s}_k)$ to converge to the target accuracy 10^{-3} under full CSI case, and 15 to 50 iterations are required to converge under imperfect Eve's CSI case. Also for both two CSI cases, the convergence is monotonically increasing. Based on our other extensive simulations, our proposed AO algorithms under both full and imperfect Eve's CSI are guaranteed to monotonic convergence.

Finally, Fig.9 gives the convergence of the proposed AO algorithm for solving power minimization problem P13 when no Eve's CSI is assumed. We plot the objective value $\| \mathbf{w}_k \|^2$ in P13 versus the number of iterations k under several ran-



Fig. 6. The actual secrecy rate versus T returned by the proposed scheme under no Eve's CSI given different total power P_T . P_I is fixed at 30dBm. m = 4, n = 6.



Fig. 7. Convergence of the objective value $C_s(\mathbf{w}_k, \mathbf{s}_k)$ in P1 returned by the proposed AO algorithm for solving P1 under full CSI. P_T, P_I are fixed at 30dBm.

domly generated channels with different settings of m, n. Note that a monotonically non-increasing convergence is guaranteed for all the channel realizations. And same with the results in Fig.7 and Fig.8, larger settings of m, n results in slower convergence since more iterations is required to optimize w and s with larger dimensions.

VII. CONCLUSION

In this paper, an IRS-assisted spectrum sharing underlay Gaussian CR WTC is studied, and we focus on enhancing the secrecy rate of this channel under full CSI, imperfect Eve's CSI and completely no Eve's CSI cases. To solve the nonconvex optimization problem, AO algorithm is proposed to jointly optimize the beamformer at secondary transmitter and phase shift vector at IRS. When no Eve's CSI is assumed, an AN aided approach is proposed to enhance the secrecy rate. Simulation results have shown that given full and imperfect CSI, our proposed solutions for the IRS-assisted design greatly enhance the secrecy rate compared with other benchmark solutions. When no Eve's CSI is assumed, positive secrecy rate also can be achieved by our proposed AN aided scheme



Fig. 8. Convergence of the objective value $C_s(\mathbf{w}_k, \mathbf{s}_k)$ in P10 returned by the proposed AO algorithm given fixed τ under imperfect Eve's CSI. P_T, P_I are fixed at 30dBm. $\tilde{\epsilon}_E = 0.02, \tilde{\epsilon}_{AE} = 0.005$.



Fig. 9. Convergence of the objective value $\parallel \mathbf{w}_k \parallel^2$ in *P*13 returned by the proposed AO algorithm given no Eve's CSI. *T* is fixed at 0dB.

in most scenarios and hence secure communication can be guaranteed.

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