Secrecy Energy Efficiency Optimization for Artificial Noise Aided Physical-Layer Security in OFDM-Based Cognitive Radio Networks

Yuhan Jiang, Yulong Zou, Senior Member, IEEE, Jian Ouyang, Member, IEEE, and Jia Zhu

Abstract-In this paper, we investigate the power allocation of primary base station (PBS) and cognitive base station (CBS) across different orthogonal frequency division multiplexing (OFDM) subcarriers for energy-efficient secure downlink communication in OFDM-based cognitive radio networks (CRNs) with the existence of an eavesdropper having multiple antennas. For the sake of defending against eavesdropping, artificial noise is used to confuse the eavesdropper at the cost of extra power consumption. For the purpose of improving the energy efficiency (EE) of secure communications, we propose a secrecy energy efficiency maximization (SEEM) scheme by exploiting the instantaneous channel state information (ICSI) of the eavesdropper, called ICSI based SEEM (ICSI-SEEM) scheme with a given total transmit power budget for different OFDM subcarriers of both PBS and CBS while guaranteeing a certain secrecy rate (SR) for a cognitive user, where a primary user' SR is also taken into consideration for limiting the interference in CRNs at each subcarrier. As for the case when the eavesdropper's ICSI is unknown, we also propose an SEEM scheme through using the statistical CSI (SCSI) of the eavesdropper, namely SCSI based SEEM (SCSI-SEEM) scheme. Since the ICSI-SEEM and SCSI-SEEM problems are fractional and non-convex, we first transform them into equivalent subtractive problems, and then achieve approximate convex problems through employing the difference of two-convex functions approximation method. Finally, new two-tier power allocation algorithms are proposed to achieve ε -optimal solutions of our formulated ICSI-SEEM and SCSI-SEEM problems. Simulation results illustrate that the ICSI-SEEM has a better secrecy energy efficiency (SEE) performance than SCSI-SEEM, and moreover, the proposed ICSI-SEEM and SCSI-SEEM schemes outperform conventional SR maximization and EE maximization approaches in terms of their SEE performance.

Index Terms—Power allocation, artificial noise, energy efficiency, secure communication, cognitive radio networks.

I. INTRODUCTION

In order to make full use of radio spectrum resources [1], extensive works have been devoted to investigating cognitive radio networks (CRNs), including cellular networks [2] and

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satellite networks [3]. In CRNs, the spectrum resources licensed to primary users (PUs) can be also allowed to cognitive users (CUs). Since the primary transmission dynamically changes with time between busy and idle states, the orthogonal frequency division multiplexing (OFDM) has been employed in CRNs by advantage of its flexibility in dynamic spectrum access [4]. However, even though CUs transmit over their detected spectrum holes in OFDM-based CRNs, the mutual interference between primary networks and CRNs still exists due to the occurrence of false alarm of a spectrum hole. Therefore, it is important to investigate power allocation for OFDM-based CRNs to control and limit such mutual interference below a tolerable level.

Besides, due to the broadcast nature of wireless networks, eavesdroppers (EDs) can overhear the confidential information transmitted over CRNs [5], which endangers the physicallayer security (PLS) of wireless communications seriously [6]. To defend against eavesdropping, many technologies have been utilized to ensure the secure transmission, including beamforming (BF) [7], artificial noise (AN) [8] and cooperative jamming [9], especially. Jamming can be used by the legitimate nodes to interfere with the EDs. Thus, it has a great potential in improving the transmission secrecy of wireless networks. For example, a cooperative jamming scheme has been presented for multi-antenna systems in [10]. Moreover, the authors also have optimized the power allocation between cooperative jammers to further improve the PLS. However, the improvement of secrecy performance is marginal when friendly jammers are near to legitimate receivers [11]. In such cases, the secrecy performance can be enhanced by employing BF technology [12], [13]. The secure BF design for multiuser multiple-input single-output (MISO) interference channel with an ED was investigated in [12]. The authors of [13] designed the secure BF to maximize the secrecy rate (SR) of secondary transmissions in an underlay MISO CRN, where broadcast channels are assumed to be overhead by massive EDs. The PLS of massive multiple-input multipleoutput (MIMO) systems was enhanced in [14] by injecting the AN at the transmitter to interfere with the EDs at the cost of extra power consumption and exploiting the spatial degrees of freedom to guarantee the secure communication. In [15], AN was used in wiretap channels to improve the secrecy performance of three schemes, namely, the partially adaptive, fully adaptive, and ON-OFF schemes. The authors of [16] have studied the optimal power allocation for AN in wiretap channels with transmitter-side correlation to minimize the secrecy outage probability. In MISO wiretap channels with multiple antennas transmitter and single-antenna receiver and ED, AN was used for optimizing the secrecy performance in [17].

Also, since the energy resources are limited and most of them are not renewable, energy efficiency (EE) has been considered to be more and more important in CRNs, which is regarded as an efficient metric to balance the spectral efficiency (SE) and the power consumption [18]. In [19], the authors have studied a joint ergodic capacity maximization and average transmission power minimization problem for the secondary networks by employing spectrum sharing and spectrum sensing while satisfying PUs' quality-of-service (QoS). With the aid of cooperative jamming, EE was maximized through allocating power optimally under the constraints of secure transmission [20]. The authors of [21] investigated the physical layer power allocation and network layer delay in energy harvesting CRNs. For the aim of balancing the delay and EE, the delay power allocation was proposed and optimized. Considering the total power of CUs and interference of PUs, resource allocation problem in a multicarrier-based CRN was proposed to obtain the maximum CUs' EE in the condition of cooperative and uncooperative CUs [22].

Overall, the aforementioned research efforts [5]-[22] address either the case only concerned about SR or the case focused on EE. To this end, for the purpose of balancing the SR and EE better, the secrecy energy efficiency (SEE), has attracted considerable attention. To be specific, the SEE maximization (SEEM) problem was investigated in an underlay CRN which takes into account the transmit power constraint of cognitive base station (CBS) and SR of CU, at the same time, the QoS requirement of PU was also considered in [23]. The authors of [24] maximized the SEE of OFDM access (OFDMA) downlink network through allocating power, secrecy date rate and subcarrier resources subject to power consumption constraint and different QoS requirement. To take advantages of the cognitive radio and OFDM techniques, we study an SEEM problem for both instantaneous and statistical CSI of ED in a downlink OFDM-based CRN and propose an AN aided power allocation algorithm. The main contributions of this paper can be summarized as follows.

- We present a maximum ratio transmission (MRT) based confidential signal beamformer at CBS and propose an SEE optimization scheme for OFDM-based cognitive radio downlink transmissions. It is to maximize the SEE at the CBS by optimizing the power allocation between confidential and AN signals across different OFDM subcarriers with the total transmit power constraints for the primary base station (PBS) and CBS, while guaranteeing a required SR for the CU and PU.
- We propose an SEEM scheme by exploiting the instantaneous CSI (ICSI) of the ED, namely ICSI based SEEM (ICSI-SEEM) scheme. However, the ICSI of ED may be unavailable in some cases. Therefore, we also propose an SEEM scheme by using the statistical CSI (SCSI) of the ED, called SCSI based SEEM (SCSI-SEEM) scheme.
- Considering that our formulated ICSI-SEEM and SCSI-SEEM problems are fractional and non-convex, the orig-

- inal problems are converted into equivalent subtractive forms, and then they are transformed to convex problems by employing the difference of two-convex functions (D.C.) approximation method. Since there are no closed-form solutions for the proposed problems, new two-tier algorithms are proposed to achieve the corresponding ε -optimal power allocation solutions to our formulated problems.
- Simulation results are given to prove the superiority of the proposed ICSI-SEEM and SCSI-SEEM schemes as well as the proposed MRT beamforming scheme with ε -optimal power allocation. Numerical results indicate that the proposed ICSI-SEEM and SCSI-SEEM schemes can balance the relationship between SR and EE better compared with the previous SR maximization (SRM) and EEM schemes. Moreover, the proposed schemes with ε -optimal power allocation algorithms obtain higher SEE than the other power allocation approaches.

The rest of the paper is organized as follows. In Section II, we describe the system model and introduce the performance metric used in this paper. Next, Section III formulates an SEE optimization problem with instantaneous CSI of ED for OFDM-based CRN systems and presents a two-tier algorithm to solve our formulated optimization problem. Then, in Section IV, we propose an SEEM problem with statistical CSI of ED and gives the corresponding solution, followed by Section V, where numerical simulation results are given to show the advantage of proposed SEEM schemes. Finally, a brief summary of our results are provided in Section V.

Notation: Vectors or matrices are represented in bold letters. $E(\cdot)$ represents the statistical expectation. $(\cdot)^H$ denotes the conjugate transpose. The Euclidean norm of a vector is expressed as $\|\cdot\|$. $[x]^+$ is defined as $\max\{x,0\}$. $\mathrm{Tr}(\mathbf{A})$ is the trace of \mathbf{A} . \mathbf{I}_k denotes the $k\times k$ identity matrix. $\mathbb{C}^{N\times M}$ is the space of all $N\times M$ matrices with complex entries. $\mathcal{CN}\left(0,\sigma^2\right)$ represents a complex Gaussian random variable with zero mean and variance σ^2 .

II. SYSTEM MODEL AND PERFORMANCE METRIC

In this section, after presenting the system model used in this paper, we introduce the SEE as performance metric.

A. System Model

We consider a downlink OFDM-based CRN having a CBS with N_C antennas, a single-antenna CU and an ED with N_E antennas coexists with a primary network (PN) having a PBS equipped with N_P antennas and a single-antenna PU, as shown in Fig. 1. There are I subcarriers in each OFDM symbol. On subcarrier $i \in \{1,...,I\}$, CBS transmits confidential messages to CU with the same spectrum used by PN, where ED attempts to intercept the CBS-CU transmissions. To improve the PLS of cognitive transmissions, we adopt AN signals to confuse the ED.

At the i_{th} subcarrier, the transmit signals of PBS and CBS can be respectively expressed by

$$\mathbf{x}_{p,i} = \mathbf{v}_{p,i} p_i, \tag{1}$$

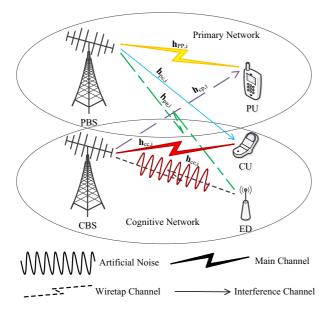


Fig. 1. System model for secure communication in OFDM-based CRN.

$$\mathbf{x}_{c,i} = \mathbf{v}_{s,i} s_i + \mathbf{v}_{z,i} z_i, \tag{2}$$

where p_i is the transmit signal of PBS and $P_{p,i} = \mathbb{E}\{|p_i|^2\}$ is the transmit power of PBS at the i_{th} subcarrier, $\mathbf{v}_{p,i}$ is the BF weight vector of the PBS' signal on subcarrier i, s_i is the confidential signal, satisfying $\mathbb{E}\{|s_i|^2\} = P_{s,i}$ at the i_{th} subcarrier, z_i represents the AN signal with $\mathbb{E}\{|z_i|^2\} = P_{z,i}$ on subcarrier i, $\mathbf{v}_{s,i}$ and $\mathbf{v}_{z,i}$ are the BF weight vectors of the confidential and AN signals at the i_{th} subcarrier, respectively.

The received signals at PU, CU and ED on subcarrier i can be respectively given by

$$y_{p,i} = \mathbf{h}_{pp,i} \mathbf{v}_{p,i} p_i + \mathbf{h}_{cp,i} \mathbf{v}_{s,i} s_i + \mathbf{h}_{cp,i} \mathbf{v}_{z,i} z_i + n_{p,i}, \quad (3)$$

$$y_{c,i} = \mathbf{h}_{pc,i} \mathbf{v}_{p,i} p_i + \mathbf{h}_{cc,i} \mathbf{v}_{s,i} s_i + \mathbf{h}_{cc,i} \mathbf{v}_{z,i} z_i + n_{c,i}, \quad (4)$$

$$\mathbf{y}_{e,i} = \mathbf{h}_{pe,i} \mathbf{v}_{p,i} p_i + \mathbf{h}_{ce,i} \mathbf{v}_{s,i} s_i + \mathbf{h}_{ce,i} \mathbf{v}_{z,i} z_i + \mathbf{n}_{e,i}, \quad (5)$$

where $\mathbf{h}_{pp,i} \in \mathbb{C}^{1 \times N_P}$, $\mathbf{h}_{pc,i} \in \mathbb{C}^{1 \times N_P}$ and $\mathbf{h}_{pe,i} \in \mathbb{C}^{N_E \times N_P}$ denote fading coefficients of the channel from PBS to PU, CU and ED at the i_{th} subcarrier, respectively, $\mathbf{h}_{cp,i} \in \mathbb{C}^{1 \times N_C}$, $\mathbf{h}_{cc,i} \in \mathbb{C}^{1 \times N_C}$ and $\mathbf{h}_{ce,i} \in \mathbb{C}^{N_E \times N_C}$ are fading coefficients of the channel from CBS to PU, CU and ED, respectively at the i_{th} subcarrier, $n_{p,i} \sim \mathcal{CN}\left(0,\sigma_{p,i}^2\right)$, $n_{c,i} \sim \mathcal{CN}\left(0,\sigma_{c,i}^2\right)$ and $\mathbf{n}_{e,i} \sim \mathcal{CN}\left(0,\sigma_{e,i}^2\mathbf{I}_{N_E}\right)$ denote additive white Gaussian noises (AWGN) at PU, CU and ED on subcarrier i, respectively, with the same variance $\sigma_{p,i}^2 = \sigma_{c,i}^2 = \sigma_{e,i}^2 = \Delta f N_0$, wherein Δf and N_0 are the system bandwidth and single-sided noise spectral density, respectively.

From (3)-(4), the instantaneous signal-to-interference-plusnoise ratios (SINRs) at PU and CU on subcarrier i, respectively, can be written as

$$\gamma_{p,i} = \frac{|\mathbf{h}_{pp,i}\mathbf{v}_{p,i}|^2 P_{p,i}}{|\mathbf{h}_{cp,i}\mathbf{v}_{s,i}|^2 P_{s,i} + |\mathbf{h}_{cp,i}\mathbf{v}_{z,i}|^2 P_{z,i} + \sigma_{p,i}^2}, \quad (6)$$

$$\gamma_{c,i} = \frac{|\mathbf{h}_{cc,i}\mathbf{v}_{s,i}|^2 P_{s,i}}{|\mathbf{h}_{pc,i}\mathbf{v}_{p,i}|^2 P_{p,i} + |\mathbf{h}_{cc,i}\mathbf{v}_{z,i}|^2 P_{z,i} + \sigma_{c,i}^2}, \quad (7)$$

where the BF vector $\mathbf{v}_{p,i}$ and $\mathbf{v}_{s,i}$ are designed by MRT [25], i.e., $\mathbf{v}_{p,i} = \frac{\mathbf{h}_{pp,i}^H}{\|\mathbf{h}_{pp,i}\|}$ and $\mathbf{v}_{s,i} = \frac{\mathbf{h}_{cc,i}^H}{\|\mathbf{h}_{cc,i}\|}$. Meanwhile, for the purpose of guaranteeing that AN only degrades the channel condition of ED, we design $\mathbf{v}_{z,i}$ at the null space of $\mathbf{h}_{cc,i}$ and $\mathbf{h}_{cp,i}$, namely $\mathbf{h}_{cc,i}\mathbf{v}_{z,i} = 0$ and $\mathbf{h}_{cp,i}\mathbf{v}_{z,i} = 0$. Thus, the BF vector $\mathbf{v}_{z,i}$ is given by [26]

$$\mathbf{v}_{z,i} = \frac{\Psi \mathbf{h}_{ce,i}^{H}}{\|\Psi \mathbf{h}_{ce,i}^{H}\|} \mathbf{w}, \tag{8}$$

where $\Psi = \mathbf{I}_{N_C} - \frac{\mathbf{h}_i^H \mathbf{h}_i}{\|\mathbf{h}_i\|^2}$, $\mathbf{h}_i = [\mathbf{h}_{cp,i}; \mathbf{h}_{cc,i}]$ and \mathbf{w} is the AN vector $\mathbf{w} \sim \mathcal{CN}\left(0, \sigma_{e,i}^2 \mathbf{I}_{N_E}\right)$.

According to [27], the channel rates of PBS-ED and CBS-ED transmissions at the i_{th} subcarrier can be respectively expressed as (9) and (10) at the top of the next page.

B. Performance Metric

The achievable SR of the CRN [28] is defined as

$$R_{\text{sec}}(\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z}) = \sum_{i=1}^{I} \left[R_{cc}(P_{p,i}, P_{s,i}, P_{z,i}) - R_{ce}(P_{p,i}, P_{s,i}, P_{z,i}) \right]^{+},$$
(11)

where $\mathbf{P}_p = [P_{p,1} \, P_{p,2} \, \cdots P_{p,I}], \; \mathbf{P}_s = [P_{s,1} \, P_{s,2} \, \cdots P_{s,I}]$ and $\mathbf{P}_z = [P_{z,1} \, P_{z,2} \, \cdots P_{z,I}].$

Besides, the total power consumption at the CBS can be modelled as [29]

$$P_{\text{tot}}(\mathbf{P}_s, \mathbf{P}_z) = \sum_{i=1}^{I} (P_{s,i} + P_{z,i}) + P_b,$$
 (12)

where P_b is a constant circuit power consumed by the CBS.

Therefore, the SEE η_{SEE} which measures the number of available secret bits transferred from the transmitter to receiver per unit energy and bandwidth of OFDM-based CRN systems can be expressed by [30]

$$\eta_{\text{SEE}} = \frac{R_{\text{sec}}(\mathbf{P}_p, \mathbf{P}_s, \mathbf{P}_z)}{P_{\text{tot}}(\mathbf{P}_s, \mathbf{P}_z)}.$$
 (13)

III. SECRECY ENERGY EFFICIENCY OPTIMIZATIONS WITH INSTANTANEOUS CSI OF ED

In this section, we assume that the instantaneous CSI of ED is known, this CSI can be estimated by some technologies in some cases [31]-[33]. For example, we can estimate this CSI through local oscillator power leakage from the ED's radio frequency front-end [31]. Besides, if there exists an active ED in the wireless network, the CSI regarding the ED will be acquired [32]. Furthermore, due to the openness of wireless communications, some legal users may be captured by Trojan and then become EDs to wiretap the confidential transmissions. In this case, it is available to achieve the instantaneous CSI of the ED [33]. Therefore, we propose the eavesdropper's instantaneous CSI based SEEM (ICSI-SEEM) scheme. Then, due to the non-convexity of the proposed problem, we introduce the problem transformation. Finally, a two-tier power allocation algorithm is designed to obtain the ε -optimal SEE solution.

$$R_{pe}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) = \log_{2} \frac{\left|\mathbf{h}_{pe,i}\mathbf{v}_{p,i}\mathbf{h}_{pe,i}^{H}\mathbf{p}_{p,i} + \mathbf{h}_{ce,i}\mathbf{v}_{s,i}\mathbf{v}_{s,i}^{H}\mathbf{h}_{ce,i}^{H}P_{s,i} + \mathbf{h}_{ce,i}\mathbf{v}_{z,i}\mathbf{v}_{z,i}^{H}\mathbf{h}_{ce,i}^{H}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right|}{\left|\mathbf{h}_{ce,i}\mathbf{v}_{s,i}\mathbf{v}_{s,i}^{H}\mathbf{h}_{ce,i}^{H}P_{s,i} + \mathbf{h}_{ce,i}\mathbf{v}_{z,i}\mathbf{v}_{z,i}^{H}\mathbf{h}_{ce,i}^{H}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right|},$$

$$(9)$$

$$R_{ce}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) = \log_{2} \frac{\left|\mathbf{h}_{pe,i}\mathbf{v}_{p,i}\mathbf{v}_{p,i}^{H}\mathbf{h}_{pe,i}^{H}P_{p,i} + \mathbf{h}_{ce,i}\mathbf{v}_{s,i}\mathbf{v}_{s,i}^{H}\mathbf{h}_{ce,i}^{H}P_{s,i} + \mathbf{h}_{ce,i}\mathbf{v}_{z,i}\mathbf{v}_{z,i}^{H}\mathbf{h}_{ce,i}^{H}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right|}{\left|\mathbf{h}_{pe,i}\mathbf{v}_{p,i}\mathbf{v}_{p,i}^{H}\mathbf{h}_{pe,i}^{H}P_{p,i} + \mathbf{h}_{ce,i}\mathbf{v}_{z,i}\mathbf{v}_{z,i}^{H}\mathbf{h}_{ce,i}^{H}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right|}.$$

$$(10)$$

$$\begin{aligned} & \max_{\mathbf{P}_{p},\mathbf{P}_{s},\mathbf{P}_{z}} \quad \eta_{\mathrm{SEE}} = \frac{\sum_{i=1}^{I} \left[\log_{2} \left(1 + \frac{e_{i}P_{s,i}}{b_{i}P_{p,i} + \sigma_{c,i}^{2}} \right) - \log_{2} \frac{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{c,i}^{2} \mathbf{I}_{N_{E}} \right|}{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{c,i}^{2} \mathbf{I}_{N_{E}} \right|} \right]} \\ & s.t. \quad & C1 : \log_{2} \left(1 + \frac{e_{i}P_{s,i}}{b_{i}P_{p,i} + \sigma_{c,i}^{2}} \right) - \log_{2} \frac{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{c,i}^{2} \mathbf{I}_{N_{E}} \right|}{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{c,i}^{2} \mathbf{I}_{N_{E}} \right|} \ge R_{CU}^{\min}, \quad \forall i, \\ & C2 : \log_{2} \left(1 + \frac{a_{i}P_{p,i}}{d_{i}P_{s,i} + \sigma_{p,i}^{2}} \right) - \log_{2} \frac{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{c,i}^{2} \mathbf{I}_{N_{E}} \right|}{\left| \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{c,i}^{2} \mathbf{I}_{N_{E}} \right|} \ge R_{PU}^{\min}, \quad \forall i, \\ & C3 : \sum_{i=1}^{I} P_{p,i} \le P_{\mathrm{PBS}}^{\mathrm{total}}, \\ & C4 : \sum_{i=1}^{I} (P_{s,i} + P_{z,i}) \le P_{\mathrm{CBS}}^{\mathrm{total}}, \end{aligned} \tag{15}$$

A. Problem Formulation

Our interest is to maximize SEE of the cognitive transmission under the SR constraints of CU and PU at each subcarrier and the total transmit power of PBS and CBS. Thus, the ICSI-SEEM can be formulated as

$$\max_{\mathbf{P}_{p},\mathbf{P}_{s},\mathbf{P}_{z}} \frac{\sum_{i=1}^{I} \left[R_{cc} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) - R_{ce} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) \right]}{\sum_{i=1}^{I} \left(P_{s,i} + P_{z,i} \right) + P_{b}}$$

$$s.t.C1: R_{cc} (P_{p,i}, P_{s,i}, P_{z,i}) - R_{ce} (P_{p,i}, P_{s,i}, P_{z,i}) \ge R_{CU}^{\min}, \forall i,$$

$$C2: R_{pp} (P_{p,i}, P_{s,i}, P_{z,i}) - R_{pe} (P_{p,i}, P_{s,i}, P_{z,i}) \ge R_{PU}^{\min}, \forall i,$$

$$C3: \sum_{i=1}^{I} P_{p,i} \le P_{\text{PBS}}^{\text{total}},$$

$$C4: \sum_{i=1}^{I} \left(P_{s,i} + P_{z,i} \right) \le P_{\text{CBS}}^{\text{total}},$$
(14)

where $R_{pp}(P_{p,i},P_{s,i},P_{z,i}) = \log_2(1+\gamma_{p,i})$ and $R_{cc}(P_{p,i},P_{s,i},P_{z,i}) = \log_2(1+\gamma_{c,i})$, C1 specifies the minimum SR requirement R_{CU}^{\min} to ensure the security performance for CU at each subcarrier. For the sake of satisfying the SR requirement of PU, C2 gives a predefined threshold R_{PU}^{\min} at the i_{th} subcarrier to guarantee the PU' secure communications. Additionally, C3 and C4 are the transmit power constraints for PBS and CBS in the downlink OFDM-based CRN, where $P_{\text{PBS}}^{\text{total}}$ and $P_{\text{CBS}}^{\text{total}}$ represent the maximum total transmit power of PBS and CBS, respectively.

Following [34]-[36], we can readily obtain the non-convexity of (14) due to its fractional form and logarithmic

function, as shown from the objective function and constraint conditions in (14). It is challenging to solve a non-convex problem of (14). To this end, we introduce the following transformation.

B. Problem Transformation

Let $a_i = |\mathbf{h}_{pp,i}\mathbf{v}_{p,i}|^2$, $b_i = |\mathbf{h}_{pc,i}\mathbf{v}_{p,i}|^2$, $\mathbf{c}_i = |\mathbf{h}_{pe,i}\mathbf{v}_{p,i}\mathbf{v}_{p,i}^H\mathbf{h}_{pe,i}^H$, $d_i = |\mathbf{h}_{cp,i}\mathbf{v}_{s,i}|^2$, $e_i = |\mathbf{h}_{cc,i}\mathbf{v}_{s,i}|^2$, $\mathbf{f}_i = |\mathbf{h}_{ce,i}\mathbf{v}_{s,i}\mathbf{h}_{ce,i}^H\mathbf{h}_{ce,i}^H$ and $\mathbf{g}_i = |\mathbf{h}_{ce,i}\mathbf{v}_{z,i}\mathbf{v}_{z,i}^H\mathbf{h}_{ce,i}^H$, problem (14) can be formulated into (15) at the top of this page. Then, we are ready to introduce the following theorem.

Theorem 1: The optimal $\eta_{\rm SEE}^*$ for (15) can be acquired through the following optimization problem (16) if and only if $f(\eta_{\rm SEE}^*) = 0$.

$$f(\eta_{\text{SEE}}) = \max_{\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z_{i=1}}} \sum_{i=1}^{I} \left[f_{1}(P_{p,i}, P_{s,i}, P_{z,i}) - f_{2}(P_{p,i}, P_{s,i}, P_{z,i}) \right]$$
$$- \eta_{\text{SEE}} \left[\sum_{i=1}^{I} \left(P_{s,i} + P_{z,i} \right) + P_{b} \right]$$

$$s.t. \ C1: f_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - f_{2}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) \ge R_{CU}^{\min}, \ \forall i,$$

$$C2: g_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - g_{2}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) \ge R_{PU}^{\min}, \ \forall i,$$

$$C3, \ C4,$$

$$(16)$$

where $f_1(P_{p,i}, P_{s,i}, P_{z,i}) = \log_2(b_i P_{p,i} + e_i P_{s,i} + \sigma_{c,i}^2) + \log_2 \left| \mathbf{c}_i P_{p,i} + \mathbf{g}_i P_{z,i} + \sigma_{e,i}^2 \mathbf{I}_{N_E} \right|, \ f_2(P_{p,i}, P_{s,i}, P_{z,i}) = \log_2(b_i P_{p,i} + \sigma_{c,i}^2) + \log_2 \left| \mathbf{c}_i P_{p,i} + \mathbf{f}_i P_{s,i} + \mathbf{g}_i P_{z,i} + \sigma_{e,i}^2 \mathbf{I}_{N_E} \right|, \ g_1(P_{p,i}, P_{s,i}, P_{z,i}) = \log_2(a_i P_{p,i} + d_i P_{s,i} + \sigma_{p,i}^2) + \log_2 \left| \mathbf{f}_i P_{s,i} + \mathbf{g}_i P_{z,i} + \sigma_{e,i}^2 \mathbf{I}_{N_E} \right| \ \text{and} \ g_2(P_{p,i}, P_{s,i}, P_{z,i}) = \log_2(d_i P_{s,i} + \sigma_{p,i}^2) + \log_2 \left| \mathbf{c}_i P_{p,i} + \mathbf{f}_i P_{s,i} + \mathbf{g}_i P_{z,i} + \sigma_{e,i}^2 \mathbf{I}_{N_E} \right|. \ Proof: \ \text{Please see Appendix A}.$

From Theorem 1, it is observed that the optimal solution of an optimization problem in fractional form can be solved by that in subtractive form. To this end, we will concentrate on solving the problem (16) in the rest of this paper.

C. D.C. Programming

Since the logarithmic functions $f_1(P_{p,i},P_{s,i},P_{z,i})$, $f_2(P_{p,i},P_{s,i},P_{z,i})$, $g_1(P_{p,i},P_{s,i},P_{z,i})$ and $g_2(P_{p,i},P_{s,i},P_{z,i})$ of (16) are concave, the functions f_1-f_2 and g_1-g_2 are D.C. functions, which become non-convex. For the purpose of solving the non-convex objective function, we apply the Taylor formula to approximate concave functions $f_2(P_{p,i},P_{s,i},P_{z,i})$ and $g_2(P_{p,i},P_{s,i},P_{z,i})$ into linear forms, which is the so-called D.C. approximation method [37]. The gradients of $f_2(P_{p,i},P_{s,i},P_{z,i})$ and $g_2(P_{p,i},P_{s,i},P_{z,i})$ are respectively given by

$$df_{2}(P_{p,i}, P_{s,i}, P_{z,i}) = \frac{b_{i}}{(b_{i}P_{p,i} + \sigma_{c,i}^{2})\ln 2} dP_{p,i}$$

$$+ \frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}dP_{p,i}\right]}{\ln 2}$$

$$+ \frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}dP_{s,i}\right]}{\ln 2}$$

$$+ \frac{\operatorname{Tr}\left[\mathbf{g}_{i}(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}dP_{z,i}\right]}{\ln 2},$$

and

$$dg_{2}(P_{p,i}, P_{s,i}, P_{z,i}) = \frac{d_{i}}{(d_{i}P_{s,i} + \sigma_{p,i}^{2}) \ln 2} dP_{s,i}$$

$$+ \frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1} dP_{p,i}\right]}{\ln 2}$$

$$+ \frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1} dP_{s,i}\right]}{\ln 2}$$

$$+ \frac{\operatorname{Tr}\left[\mathbf{g}_{i}(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1} dP_{z,i}\right]}{\ln 2},$$
(18)

Then, according to the first-order Taylor series expansions of $f_2(P_{p,i}, P_{s,i}, P_{z,i})$ and $g_2(P_{p,i}, P_{s,i}, P_{z,i})$, we have

$$\begin{split} &f_{2}(P_{p,i},P_{s,i},P_{z,i}) \leq f_{2}(\bar{P}_{p,i},\bar{P}_{s,i},\bar{P}_{z,i}) + \frac{b_{i}(P_{p,i} - \bar{P}_{p,i})}{(b_{i}\bar{P}_{p,i} + \sigma_{c,i}^{2})\ln 2} \\ &+ \frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\mathbf{c}_{i}\bar{P}_{p,i} + \mathbf{f}_{i}\bar{P}_{s,i} + \mathbf{g}_{i}\bar{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}(P_{p,i} - \bar{P}_{p,i})\right]}{\ln 2} \\ &+ \frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\mathbf{c}_{i}\bar{P}_{p,i} + \mathbf{f}_{i}\bar{P}_{s,i} + \mathbf{g}_{i}\bar{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}(P_{s,i} - \bar{P}_{s,i})\right]}{\ln 2} \\ &+ \frac{\operatorname{Tr}\left[\mathbf{g}_{i}(\mathbf{c}_{i}\bar{P}_{p,i} + \mathbf{f}_{i}\bar{P}_{s,i} + \mathbf{g}_{i}\bar{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}(P_{z,i} - \bar{P}_{z,i})\right]}{\ln 2}, \end{split}$$

and

$$g_{2}(P_{p,i}, P_{s,i}, P_{z,i}) \leq g_{2}(\bar{P}_{p,i}, \bar{P}_{s,i}, \bar{P}_{z,i}) + \frac{d_{i}(P_{s,i} - \bar{P}_{s,i})}{\left(d_{i}\bar{P}_{s,i} + \sigma_{p,i}^{2}\right) \ln 2} \qquad -\frac{b_{i}(P_{p,i} - \bar{P}_{p,i}^{n})}{\left(b_{i}\bar{P}_{p,i}^{n} + \sigma_{c,i}^{2}\right) \ln 2} - \frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\bar{\Omega}_{i}^{\mathbf{n}})^{-1}(P_{p,i} - \bar{P}_{p,i}^{n})\right]}{\ln 2}$$

$$+\frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\mathbf{c}_{i}\bar{P}_{p,i}+\mathbf{f}_{i}\bar{P}_{s,i}+\mathbf{g}_{i}\bar{P}_{z,i}+\sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}(P_{p,i}-\bar{P}_{p,i})\right]}{\ln 2}$$

$$+\frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\mathbf{c}_{i}\bar{P}_{p,i}+\mathbf{f}_{i}\bar{P}_{s,i}+\mathbf{g}_{i}\bar{P}_{z,i}+\sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}(P_{s,i}-\bar{P}_{s,i})\right]}{\ln 2}$$

$$+\frac{\operatorname{Tr}\left[\mathbf{g}_{i}(\mathbf{c}_{i}\bar{P}_{p,i}+\mathbf{f}_{i}\bar{P}_{s,i}+\mathbf{g}_{i}\bar{P}_{z,i}+\sigma_{e,i}^{2}\mathbf{I}_{N_{E}})^{-1}(P_{z,i}-\bar{P}_{z,i})\right]}{\ln 2},$$

$$(20)$$

where $(\bar{P}_{p,i}, \bar{P}_{s,i}, \bar{P}_{z,i})$ is a feasible solution of $f_2(P_{p,i}, P_{s,i}, P_{z,i})$ and $g_2(P_{p,i}, P_{s,i}, P_{z,i})$. By substituting (19) and (20) into the problem (16), and denoting $\bar{\Omega}_i = \mathbf{c}_i \bar{P}_{p,i} + \mathbf{f}_i \bar{P}_{s,i} + \mathbf{g}_i \bar{P}_{z,i} + \sigma_{e,i}^2 \mathbf{I}_{N_E}$, we can reformulate (16) as

$$\max_{\mathbf{P}_{p},\mathbf{P}_{s},\mathbf{P}_{z}} \sum_{i=1}^{I} \left\{ f_{1}\left(P_{p,i},P_{s,i},P_{z,i}\right) - f_{2}(\bar{P}_{p,i},\bar{P}_{s,i},\bar{P}_{z,i}) \right. \\
- \frac{b_{i}\left(P_{p,i} - \bar{P}_{p,i}\right)}{\left(b_{i}\bar{P}_{p,i} + \sigma_{c,i}^{2}\right)\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\bar{\Omega}_{i})^{-1}\left(P_{p,i} - \bar{P}_{p,i}\right)\right]}{\ln 2} \\
- \frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\bar{\Omega}_{i})^{-1}\left(P_{s,i} - \bar{P}_{s,i}\right)\right]}{\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{g}_{i}(\bar{\Omega}_{i})^{-1}\left(P_{z,i} - \bar{P}_{z,i}\right)\right]}{\ln 2} \right\} \\
- \eta_{\text{SEE}}\left[\sum_{i=1}^{I}\left(P_{s,i} + P_{z,i}\right) + P_{b}\right] \\
s.t. f_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - f_{2}\left(\bar{P}_{p,i}, \bar{P}_{s,i}, \bar{P}_{z,i}\right) - \frac{b_{i}\left(P_{p,i} - \bar{P}_{p,i}\right)}{\left(b_{i}\bar{P}_{p,i} + \sigma_{c,i}^{2}\right)\ln 2} \\
- \frac{\operatorname{Tr}\left[\mathbf{c}_{i}\bar{\Omega}_{i}^{-1}\left(P_{p,i} - \bar{P}_{p,i}\right)\right]}{\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{f}_{i}\bar{\Omega}_{i}^{-1}\left(P_{s,i} - \bar{P}_{s,i}\right)\right]}{\ln 2} \\
- \frac{\operatorname{Tr}\left[\mathbf{g}_{i}\bar{\Omega}_{i}^{-1}\left(P_{z,i} - \bar{P}_{z,i}\right)\right]}{\ln 2} \geq R_{CU}^{\min}, \, \forall i, \\
g_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - g_{2}\left(\bar{P}_{p,i}, \bar{P}_{s,i}, \bar{P}_{z,i}\right) - \frac{d_{i}\left(P_{s,i} - \bar{P}_{s,i}\right)}{\left(d_{i}\bar{P}_{s,i} + \sigma_{p,i}^{2}\right)\ln 2} \\
- \frac{\operatorname{Tr}\left[\mathbf{c}_{i}\bar{\Omega}_{i}^{-1}\left(P_{p,i} - \bar{P}_{p,i}\right)\right]}{\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{f}_{i}\bar{\Omega}_{i}^{-1}\left(P_{s,i} - \bar{P}_{s,i}\right)\right]}{\ln 2} \\
- \frac{\operatorname{Tr}\left[\mathbf{g}_{i}\bar{\Omega}_{i}^{-1}\left(P_{p,i} - \bar{P}_{p,i}\right)\right]}{\ln 2} \geq R_{PU}^{\min}, \, \forall i, \\
C3, \, C4. \tag{21}$$

Following [38] and [39], it is obvious that the problem (21) is convex, which results from the convexity of the objective function as well as that of the constraints C1, C2, C3 and C4. Therefore, it is simple and straightforward to obtain the optimal solution to (21) by using existing convex software tools, e.g., CVX [40].

Based on (21), we propose the following iterative procedure, which converges to the optimal solutions of problem (16).

$$\begin{split} &(\bar{\mathbf{P}}_{p}^{n+1}, \bar{\mathbf{P}}_{s}^{n+1}, \bar{\mathbf{P}}_{z}^{n+1}) = \\ &= \arg\max_{\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z}} \sum_{i=1}^{I} \left\{ f_{1} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) - f_{2} (\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) \right. \\ &\left. - \frac{b_{i} (P_{p,i} - \bar{P}_{p,i}^{n})}{(b_{i}\bar{P}_{s}^{n} + \sigma_{s}^{2}) \ln 2} - \frac{\operatorname{Tr} \left[\mathbf{c}_{i} (\bar{\mathbf{\Omega}}_{i}^{n})^{-1} (P_{p,i} - \bar{P}_{p,i}^{n}) \right]}{\ln 2} \right] \end{split}$$

$$-\frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\bar{\mathbf{\Omega}}_{i}^{\mathbf{n}})^{-1}(P_{s,i}-\bar{P}_{s,i}^{n})\right]}{\ln 2}-\frac{\operatorname{Tr}\left[\mathbf{g}_{i}(\bar{\mathbf{\Omega}}_{i}^{\mathbf{n}})^{-1}(P_{z,i}-\bar{P}_{z,i}^{n})\right]}{\ln 2}\right\}$$

$$-\eta_{\text{SEE}} \left[\sum_{i=1}^{I} \left(P_{s,i} + P_{z,i} \right) + P_b \right]$$

$$s.t. f_{1}(P_{p,i}, P_{s,i}, P_{z,i}) - f_{2}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) - \frac{b_{i} (P_{p,i} - P_{p,i}^{n})}{(b_{i}\bar{P}_{p,i}^{n} + \sigma_{c,i}^{2}) \ln 2} - \frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(P_{p,i} - \bar{P}_{p,i}^{n})\right]}{\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(P_{s,i} - \bar{P}_{s,i}^{n})\right]}{\ln 2}$$

$$-\frac{\operatorname{Tr}\left[\mathbf{g}_{i}\left(\bar{\mathbf{\Omega}}_{i}^{n}\right)^{-1}\left(P_{z,i}-\bar{P}_{z,i}^{n}\right)\right]}{\ln 2} \geq R_{CU}^{\min}, \forall i,$$

$$g_{1}(P_{p,i}, P_{s,i}, P_{z,i}) - g_{2}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) - \frac{d_{i}\left(P_{s,i} - \bar{P}_{s,i}^{n}\right)}{\left(d_{i}\bar{P}_{s,i}^{n} + \sigma_{p,i}^{2}\right)\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{c}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(P_{p,i} - \bar{P}_{p,i}^{n})\right]}{\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{f}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(P_{s,i} - \bar{P}_{s,i}^{n})\right]}{\ln 2}$$

$$-\frac{\ln 2}{\ln 2} - \frac{\operatorname{Tr}\left[\mathbf{g}_{i}(\bar{\boldsymbol{\Omega}}_{i}^{n})^{-1}(P_{z,i} - \bar{P}_{z,i}^{n})\right]}{\ln 2} \ge R_{PU}^{\min}, \forall i,$$

where $\bar{\mathbf{\Omega}}_i^n = \mathbf{c}_i \bar{P}_{p,i}^n + \mathbf{f}_i \bar{P}_{s,i}^n + \mathbf{g}_i \bar{P}_{z,i}^n + \sigma_{e,i}^2 \mathbf{I}_{N_E}, \ (\bar{\mathbf{P}}_p^n, \bar{\mathbf{P}}_s^n, \bar{\mathbf{P}}_z^n)$ and $(\bar{\mathbf{P}}_p^{n+1}, \bar{\mathbf{P}}_s^{n+1}, \bar{\mathbf{P}}_z^{n+1})$ the optimal solutions in (22) at iterations n and n + 1, respectively.

Proof: Please see Appendix B for the proof of conver-

D. Two-tier Iterative Algorithm for ICSI-SEEM

In this section, we propose a two-tier iterative power allocation algorithm to obtain an ε -optimal power allocation solution to our formulated ICSI-SEEM problem. The proposed algorithm is summarized in Table I. First of all, we initialize the maximum SEE $\eta_{\text{SEE}}^m=0$ and iteration index m=0, n=0. Based on the given maximum SEE η_{SEE}^m at the outer tier, the D.C. approximation method is applied to solve problem (16) for obtaining the ε -optimal solution $(\mathbf{P}_{p}^{n}, \mathbf{P}_{s}^{n}, \mathbf{P}_{z}^{n})$ at the inner tier. The ε -optimal solution $(\mathbf{P}_p^n, \mathbf{P}_s^n, \mathbf{P}_z^n)$ will be used to update the value of $f(\eta_{\text{SEE}})$ for the next outer tier. Meanwhile, $\eta_{\rm SEE}$ is found to satisfy $f(\eta_{\rm SEE})=0$ by using the Dinkelbach's method [41] at this tier. When all the updated data nearly keeps unchanged or the number of iterations approaches to the maximization, the iteration stops; otherwise, another round of iteration starts.

The computational complexity of the proposed scheme depends on the number of iterations, variable size and the number of constraints at the outer and inner tiers. Based on the given tolerance ε , we can give the iterations as $O\left(\log\left(\eta_{\rm SEE}^{up}/\varepsilon\right)\log\left(g_{\rm SEE}^{up}/\varepsilon\right)\right), \text{ where } \eta_{\rm SEE}^{up}=\left(\frac{\max(e_i)P_{\rm CBS}^{\rm total}}{\Delta f N_0 \ln 2}\right)/P_b$ and $g_{\rm SEE}^{up}=\frac{\max(e_i)P_{\rm CBS}^{\rm total}}{\Delta f N_0 \ln 2}.$ Given 3I scalar variables in problem (22), so we need at most $O((3I)^{3.5}\log(1/\varepsilon))$ calculations at each inner iteration [42]. Finally, the overall computational complexity of the proposed scheme can be roughly written as

$$O\left(\log\left(\frac{1}{\varepsilon}\right)\log\left(\frac{\eta_{\text{SEE}}^{up}}{\varepsilon}\right)\log\left(\frac{g_{\text{SEE}}^{up}}{\varepsilon}\right)(3I)^{3.5}\right).$$
 (23)

Algorithm 1: Two-tier Iterative ε -optimal Power Allocation Algorithm.

Function Outer_ Iteration

Step 1: Initialize the maximum number of iterations $m_{\rm max}$, $n_{\rm max}$ and the maximum tolerance ε .

Step 2: Set maximum SEE $\eta_{\rm SEE}^0=0$ and iteration index m=0. Step 3: Call **Function** Inner_Iteration with $\eta_{\rm SEE}^m$ to obtain the ε -optimal solution $({\bf P}_p^n,{\bf P}_s^n,{\bf P}_z^n)$.

$$\begin{aligned} & \text{Step 4: Update } \eta_{\text{SEE}}^{m+1} = \\ & \underbrace{\sum_{i=1}^{I} \left[\log_2 \left(1 + \frac{1}{b_i P_{p,i}^n + \sigma_{c,i}^2} \right) - \log_2 \left(\frac{\left| \mathbf{c}_i P_{p,i}^n + \mathbf{f}_i P_{s,i}^n + \mathbf{g}_i P_{z,i}^n + \sigma_{c,i}^2 \mathbf{I}_{N_E} \right|}{\left| \mathbf{c}_i P_{p,i}^n + \mathbf{g}_i P_{z,i}^n + \sigma_{c,i}^2 \mathbf{I}_{N_E} \right|} \right) \right]} \\ & \underbrace{\sum_{i=1}^{I} \left(P_{i}^n + P_{i}^n \right) + P_{b}}_{I} \end{aligned}$$

Step 5: Set m = m + 1

Step 6: **if** $|\eta_{\text{SEE}}^m - \eta_{\text{SEE}}^{m-1}| \ge \varepsilon$ or $m \le m_{\text{max}}$

Step 7: goto Step 3.

Step 8: end if

Step 9: **return** \mathbf{P}_p^n , \mathbf{P}_s^n , \mathbf{P}_z^n .

Step 10: Obtain the ε -optimal solution $\mathbf{P}_p^* = \mathbf{P}_p^n$, $\mathbf{P}_s^* = \mathbf{P}_s^n$ and $\mathbf{P}_z^* = \mathbf{P}_z^n$ for problem (15).

Function Inner_Iteration $(\eta_{\rm SEE})$ Step 11: Initialize $(\mathbf{P}_p^0, \mathbf{P}_s^0, \mathbf{P}_z^0) = (0,0,0)$ and $f^0 = 0$.

Step 12: Set n = 0.

Step 13: Find the ε -optimal solution $(\mathbf{P}_p^{n+1}, \mathbf{P}_s^{n+1}, \mathbf{P}_z^{n+1})$ of (22) for given $(\mathbf{P}_p^n, \mathbf{P}_s^n, \mathbf{P}_z^n)$ and η_{SEE}^m by using CVX.

Step 14: Compute

$$\begin{split} f^{n+1} &= \sum_{i=1}^{I} \left[f_1 \left(P_{p,i}^{n+1}, P_{s,i}^{n+1}, P_{z,i}^{n+1} \right) - f_2 \left(P_{p,i}^{n+1}, P_{s,i}^{n+1}, P_{z,i}^{n+1} \right) \right] \\ &- \eta_{\text{SEE}}^m \left[\sum_{i=1}^{I} \left(P_{s,i}^{n+1} + P_{z,i}^{n+1} \right) + P_b \right]. \end{split}$$
 Step 15: Set $n = n + 1$. Step 16: **if** $|f^n - f^{n-1}| \geq \varepsilon$ or $n \leq n_{\text{max}}$

Step 17: goto Step 13.

Step 18: end if

Step 19: **return** \mathbf{P}_p^n , \mathbf{P}_s^n , \mathbf{P}_s^n

IV. SECRECY ENERGY EFFICIENCY OPTIMIZATIONS WITH STATISTICAL CSI OF ED

For the reason that the instantaneous CSI of ED may be unavailable in some cases, we propose an SEEM scheme through using the statistical CSI of the ED [43], [44], namely the eavesdropper's statistical CSI based SEEM (SCSI-SEEM) scheme in this section. Then, we give the solution of our formulated SCSI-SEEM problem. Finally, a two-tier iterative ε -optimal power allocation algorithm is presented for SCSI-SEEM scheme.

A. SCSI-SEEM Problem Formulation

We formulate the SCSI-SEEM problem in OFDM-based CRNs as

$$\max_{\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z}} \frac{\sum_{i=1}^{I} \left\{ R_{cc}(P_{p,i}, P_{s,i}, P_{z,i}) - \mathbb{E}[R_{ce}(P_{p,i}, P_{s,i}, P_{z,i})] \right\}}{\sum_{i=1}^{I} \left(P_{s,i} + P_{z,i} \right) + P_{b}}$$

$$s.t.C1:R_{cc}(P_{p,i},P_{s,i},P_{z,i}) - \mathbb{E}[R_{ce}(P_{p,i},P_{s,i},P_{z,i})] \ge R_{CU}^{\min}, \forall i,$$

$$C2:R_{pp}(P_{p,i},P_{s,i},P_{z,i}) - \mathbb{E}[R_{pe}(P_{p,i},P_{s,i},P_{z,i})] \ge R_{PU}^{\min}, \forall i,$$

$$C3: \sum_{i=1}^{I} P_{p,i} \leq P_{\text{PBS}}^{\text{total}},$$

$$C4: \sum_{i=1}^{I} (P_{s,i} + P_{z,i}) \leq P_{\text{CBS}}^{\text{total}}.$$
(24)

After some operations, problem (24) can be rewritten as (25) at top of the next page.

B. SCSI-SEEM Solution

According to Theorem 1, we can achieve the optimal solution $\varphi_{\rm SEE}^*$ of (25) through problem (26) if and only if $h(\varphi_{\rm SEE}^*)=0$.

$$h(\varphi_{\text{SEE}}) = \max_{\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z}} \sum_{i=1}^{I} \left[h_{1}(P_{p,i}, P_{s,i}, P_{z,i}) - h_{2}(P_{p,i}, P_{s,i}, P_{z,i}) \right]$$

$$- \varphi_{\text{SEE}} \left[\sum_{i=1}^{I} \left(P_{s,i} + P_{z,i} \right) + P_{b} \right]$$

$$s.t. \ C1: h_{1} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) - h_{2} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) \ge R_{CU}^{\min}, \ \forall i,$$

$$C2: r_{1} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) - r_{2} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) \ge R_{PU}^{\min}, \ \forall i,$$

$$C3, \ C4,$$

$$(26)$$
where $h_{1} \left(P_{p,i}, P_{s,i}, P_{z,i} \right) = \log_{2} \left(b_{i} P_{p,i} + e_{i} P_{s,i} + \sigma_{c,i}^{2} \right) +$

where $h_1\left(P_{p,i},P_{s,i},P_{z,i}\right) = \log_2\left(b_iP_{p,i} + e_iP_{s,i} + \sigma_{c,i}^2\right) + \mathrm{E}[\log_2\left|\mathbf{c_i}\mathrm{P_{p,i}} + \mathbf{g_i}\mathrm{P_{z,i}} + \sigma_{e,i}^2\mathbf{I_{N_E}}\right|], \quad h_2\left(P_{p,i},P_{s,i},P_{z,i}\right) = \log_2\left(b_iP_{p,i} + \sigma_{c,i}^2\right) + \mathrm{E}[\log_2\left|\mathbf{c_i}\mathrm{P_{p,i}} + \mathbf{f_i}\mathrm{P_{s,i}} + \mathbf{g_i}\mathrm{P_{z,i}} + \sigma_{e,i}^2\mathbf{I_{N_E}}\right|], \quad r_1\left(P_{p,i},P_{s,i},P_{z,i}\right) = \log_2\left(a_iP_{p,i} + d_iP_{s,i} + \sigma_{p,i}^2\right) + \mathrm{E}[\log_2\left|\mathbf{f_i}\mathrm{P_{s,i}} + \mathbf{g_i}\mathrm{P_{z,i}} + \sigma_{e,i}^2\mathbf{I_{N_E}}\right|] \quad \mathrm{and} \quad r_2\left(P_{p,i},P_{s,i},P_{z,i}\right) = \log_2\left(d_iP_{s,i} + \sigma_{p,i}^2\right) + \mathrm{E}[\log_2\left|\mathbf{c_i}\mathrm{P_{p,i}} + \mathbf{f_i}\mathrm{P_{s,i}} + \mathbf{g_i}\mathrm{P_{z,i}} + \sigma_{e,i}^2\mathbf{I_{N_E}}\right|]. \quad \mathrm{The gradients of} \quad h_2\left(P_{p,i},P_{s,i},P_{z,i}\right) \quad \mathrm{and} \quad r_2\left(P_{p,i},P_{s,i},P_{z,i}\right) \quad \mathrm{are} \quad \mathrm{respectively} \quad \mathrm{written} \quad \mathrm{as} \quad \mathrm{The gradients} \quad \mathrm{The gradi$

$$dh_{2} (P_{p,i}, P_{s,i}, P_{z,i}) = \frac{b_{i}}{\left(b_{i}P_{p,i} + \sigma_{c,i}^{2}\right) \ln 2} dP_{p,i}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{c}_{i}\left(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1} dP_{p,i}\right]\right\}}{\ln 2}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{f}_{i}\left(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1} dP_{s,i}\right]\right\}}{\ln 2}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{g}_{i}\left(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1} dP_{z,i}\right]\right\}}{\ln 2},$$

$$\ln 2$$

$$(27)$$

and

$$dr_{2} (P_{p,i}, P_{s,i}, P_{z,i}) = \frac{d_{i}}{\left(d_{i}P_{s,i} + \sigma_{p,i}^{2}\right) \ln 2} dP_{s,i}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{c}_{i}\left(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1} dP_{p,i}\right]\right\}}{\ln 2}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{f}_{i}\left(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1} dP_{s,i}\right]\right\}}{\ln 2}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{g}_{i}\left(\mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1} dP_{z,i}\right]\right\}}{\ln 2}.$$

$$+ \frac{1}{\ln 2}$$

$$(28)$$

Then, assuming $(\widetilde{P}_{p,i},\widetilde{P}_{s,i},\widetilde{P}_{z,i})$ is a feasible solution of $h_2\left(P_{p,i},P_{s,i},P_{z,i}\right)$ and $r_2\left(P_{p,i},P_{s,i},P_{z,i}\right)$, the first-order Taylor series expansions of $h_2\left(P_{p,i},P_{s,i},P_{z,i}\right)$ and $r_2\left(P_{p,i},P_{s,i},P_{z,i}\right)$ can be obtained as

$$h_{2}(P_{p,i}, P_{s,i}, P_{z,i}) \leq h_{2}(\widetilde{P}_{p,i}, \widetilde{P}_{s,i}, \widetilde{P}_{z,i}) + \frac{b_{i}(P_{p,i} - P_{p,i})}{(b_{i}\widetilde{P}_{p,i} + \sigma_{c,i}^{2}) \ln 2}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{c}_{i}(\mathbf{c}_{i}\widetilde{P}_{p,i} + \mathbf{f}_{i}\widetilde{P}_{s,i} + \mathbf{g}_{i}\widetilde{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1}(P_{p,i} - \widetilde{P}_{p,i})\right]\right\}}{\ln 2}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{f}_{i}(\mathbf{c}_{i}\widetilde{P}_{p,i} + \mathbf{f}_{i}\widetilde{P}_{s,i} + \mathbf{g}_{i}\widetilde{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1}(P_{s,i} - \widetilde{P}_{s,i})\right]\right\}}{\ln 2}$$

$$+ \frac{E\left\{\operatorname{Tr}\left[\mathbf{g}_{i}(\mathbf{c}_{i}\widetilde{P}_{p,i} + \mathbf{f}_{i}\widetilde{P}_{s,i} + \mathbf{g}_{i}\widetilde{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1}(P_{z,i} - \widetilde{P}_{z,i})\right]\right\}}{\ln 2}$$

$$+ \frac{1}{\ln 2}$$

$$(29)$$

and

$$r_{2}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) \leq r_{2}(\widetilde{P}_{p,i}, \widetilde{P}_{s,i}, \widetilde{P}_{z,i}) + \frac{d_{i}(P_{s,i} - \widetilde{P}_{s,i})}{(b_{i}\widetilde{P}_{s,i} + \sigma_{p,i}^{2}) \ln 2} + \frac{E\left\{\operatorname{Tr}\left[\mathbf{c}_{i}(\mathbf{c}_{i}\widetilde{P}_{p,i} + \mathbf{f}_{i}\widetilde{P}_{s,i} + \mathbf{g}_{i}\widetilde{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1}(P_{p,i} - \widetilde{P}_{p,i})\right]\right\}}{\ln 2} + \frac{E\left\{\operatorname{Tr}\left[\mathbf{f}_{i}(\mathbf{c}_{i}\widetilde{P}_{p,i} + \mathbf{f}_{i}\widetilde{P}_{s,i} + \mathbf{g}_{i}\widetilde{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1}(P_{s,i} - \widetilde{P}_{s,i})\right]\right\}}{\ln 2} + \frac{E\left\{\operatorname{Tr}\left[\mathbf{g}_{i}(\mathbf{c}_{i}\widetilde{P}_{p,i} + \mathbf{f}_{i}\widetilde{P}_{s,i} + \mathbf{g}_{i}\widetilde{P}_{z,i} + \sigma_{e,i}^{2}\mathbf{I}_{N_{E}}\right)^{-1}(P_{z,i} - \widetilde{P}_{z,i})\right]\right\}}{\ln 2}$$

$$= \frac{\ln 2}{\ln 2}$$
(30)

Denoting $\widetilde{\Omega}_i = \mathbf{c}_i \widetilde{P}_{p,i} + \mathbf{f}_i \widetilde{P}_{s,i} + \mathbf{g}_i \widetilde{P}_{z,i} + \sigma_{e,i}^2 \mathbf{I}_{N_E}$ and according to Section III-C, we employ the D.C. approximation method [37] to transform (26) into an approximate convex problem (31) at top of the next page. As a result, assuming that $(\widetilde{P}_{p,i}^n,\widetilde{P}_{s,i}^n,\widetilde{P}_{z,i}^n)$ and $(\widetilde{P}_{p,i}^{n+1},\widetilde{P}_{s,i}^{n+1},\widetilde{P}_{z,i}^{n+1})$ are the optimal solutions to (31) at iterations n and n+1, and letting $\Omega_i^n =$ $\mathbf{c}_i \widetilde{P}_{p,i}^n + \mathbf{f}_i \widetilde{P}_{s,i}^n + \mathbf{g}_i \widetilde{P}_{z,i}^n + \sigma_{e,i}^2 \mathbf{I}_{N_E}$, the solution of (26) can be obtained through the iterative procedure at (32). According to Appendix B, the convergence of the iterative procedure can be guaranteed. Then, the optimization problem (31) can be easily solved by CVX [40]. Finally, a two-tier iterative ε optimal power allocation algorithm for SCSI-SEEM scheme is summarized in Table II. The φ_{SEE} satisfying $h(\varphi_{\text{SEE}}) = 0$ is found with the help of Dinkelbach's method [41] at the outer tier, meanwhile, the solution is achieved for a given $\varphi_{\rm SEE}$ at the inner tier.

In addition, the computational complexity of proposed SCSI-SEEM scheme is determined by the number of iterations, variable size and the number of constraints at the outer and inner tiers. The iterations excluding convex programming can be given by $O\left(\log\left(\varphi_{\text{SEE}}^{up}/\varepsilon\right)\log\left(\varphi_{\text{SEE}}^{up}/\varepsilon\right)\right)$, where $\varphi_{\text{SEE}}^{up}=\left(\frac{\max(e_i)P_{\text{CBS}}^{\text{total}}}{\Delta f N_0 \ln 2}\right)/P_b, \ \phi_{\text{SEE}}^{up}=\frac{\max(e_i)P_{\text{CBS}}^{\text{total}}}{\Delta f N_0 \ln 2}$, and ε is the tolerance level. Since the problem (32) has 3I variables, we need at most $O((3I)^{3.5}\log(1/\varepsilon))$ calculations at each inner iteration [42]. Thus, the overall computational complexity of the SCSI-SEEM scheme can be given by

$$O\left(\log\left(\frac{1}{\varepsilon}\right)\log\left(\frac{\varphi_{\text{SEE}}^{up}}{\varepsilon}\right)\log\left(\frac{\varphi_{\text{SEE}}^{up}}{\varepsilon}\right)(3I)^{3.5}\right). \tag{33}$$

$$\max_{\mathbf{P}_{p},\mathbf{P}_{s},\mathbf{P}_{z}} \varphi_{\mathrm{SEE}} = \frac{\sum_{i=1}^{I} \left\{ \log_{2} \left(1 + \frac{e_{i}P_{s,i}}{b_{i}P_{p,i} + \sigma_{c,i}^{2}} \right) - \mathrm{E} \left[\log_{2} \frac{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2} \mathbf{I}_{N_{E}} \right|}{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2} \mathbf{I}_{N_{E}} \right|} \right] \right\}} \\
s.t. \quad C1 : \log_{2} \left(1 + \frac{e_{i}P_{s,i}}{b_{i}P_{p,i} + \sigma_{c,i}^{2}} \right) - \mathrm{E} \left[\log_{2} \frac{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2} \mathbf{I}_{N_{E}} \right|}{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2} \mathbf{I}_{N_{E}} \right|} \right] \ge R_{CU}^{\min}, \quad \forall i,$$

$$C2 : \log_{2} \left(1 + \frac{a_{i}P_{p,i}}{d_{i}P_{s,i} + \sigma_{p,i}^{2}} \right) - \mathrm{E} \left[\log_{2} \frac{\left| \mathbf{c}_{i}P_{p,i} + \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2} \mathbf{I}_{N_{E}} \right|}{\left| \mathbf{f}_{i}P_{s,i} + \mathbf{g}_{i}P_{z,i} + \sigma_{e,i}^{2} \mathbf{I}_{N_{E}} \right|} \right] \ge R_{PU}^{\min}, \quad \forall i,$$

$$C3 : \sum_{i=1}^{I} P_{p,i} \le P_{\mathrm{PBS}}^{\mathrm{total}},$$

$$C4 : \sum_{i=1}^{I} (P_{s,i} + P_{z,i}) \le P_{\mathrm{CBS}}^{\mathrm{total}},$$

$$\begin{split} & \max_{\mathbf{P}_{p},\mathbf{P}_{s},\mathbf{P}_{z}} \sum_{i=1}^{I} \left\{ h_{1}\left(P_{p,i},P_{s,i},P_{z,i}\right) - h_{2}(\tilde{P}_{p,i},\tilde{P}_{s,i},\tilde{P}_{z,i}) - \frac{b_{i}(P_{p,i} - \tilde{P}_{p,i})}{(b_{i}\tilde{P}_{p,i} + \sigma_{c,i}^{2}) \ln 2} - \frac{\mathbb{E}\left\{ \operatorname{Tr}\left[\mathbf{c}_{i}(\tilde{\mathbf{\Omega}}_{i})^{-1}(P_{p,i} - \tilde{P}_{p,i})\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{ \operatorname{Tr}\left[\mathbf{f}_{i}(\tilde{\mathbf{\Omega}}_{i})^{-1}(P_{z,i} - \tilde{P}_{z,i})\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{ \operatorname{Tr}\left[\mathbf{g}_{i}(\tilde{\mathbf{\Omega}}_{i})^{-1}(P_{z,i} - \tilde{P}_{z,i})\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{ \operatorname{Tr}\left[\mathbf{f}_{i}(\tilde{\mathbf{\Omega}}_{i})^{-1}(P_{z,i} - \tilde{P}_{z,i})\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{ \operatorname{Tr}\left[\mathbf{f}_{i}(\tilde{\mathbf{\Omega}}_{i})^{-1}(P_{z,i} - \tilde{P}_{z,i})\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{ \operatorname{Tr}\left[\mathbf{g}_{i}(\tilde{\mathbf{\Omega}}_{i})^{-1}(P_{z,i} - \tilde{P}_{z,i}\right]\right\}}{\ln 2} - \frac{\mathbb$$

V. SIMULATION RESULTS

In this section, we present numerical results to evaluate the performance of our proposed schemes. The simulation parameters can be found in Table III. All simulation results were averaged over 100 random channel realizations.

Fig. 2 presents the convergence behavior of proposed algorithms for ICSI-SEEM and SCSI-SEEM schemes versus the number of iterations in terms of average SEE, with I=8, $N_P=N_C=4$, $N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$, $P_{\rm CBS}^{\rm total}=40{\rm dBm}$. As observed, the average SEE results obtained by proposed algorithms converge to the optimal SEE of ICSI-SEEM and SCSI-SEEM schemes respectively after sufficient iterations, which confirms that proposed algorithms are able to achieve the optimal solutions of ICSI-SEEM and SCSI-SEEM schemes by simply increasing the number of iterations.

Fig. 3 shows the average SEE results of proposed ICSI-SEEM and SCSI-SEEM as well as conventional SRM, EEM and SEEM without AN schemes versus the CBS transmit power constraint $P_{\rm CBS}^{\rm total}$ with $I=8,\ N_P=N_C=4,\ N_E=3,$ and the maximum transmit power of PBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$.

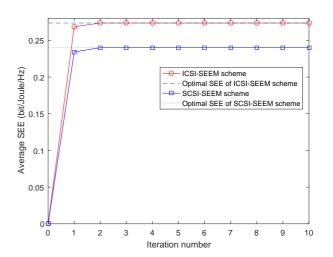


Fig. 2. Covergence behavior of proposed algorithms for ICSI-SEEM and SCSI-SEEM schemes versus the number of iterations in terms of average SEE, with I=8, $N_P=N_C=4$, $N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$, $P_{\rm CBS}^{\rm total}=40{\rm dBm}$.

The average SEE performance of proposed ICSI-SEEM, SCSI-

$$\begin{split} & (\tilde{\mathbf{P}}_{p}^{n+1}, \tilde{\mathbf{P}}_{s}^{n+1}, \tilde{\mathbf{P}}_{z}^{n+1}) = \arg\max_{\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z}} \sum_{i=1}^{I} \left\{ h_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - h_{2}\left(\tilde{P}_{p,i}^{n}, \tilde{P}_{s,i}^{n}\right) - \frac{b_{i}\left(P_{p,i} - \tilde{P}_{p,i}^{n}\right)}{\left(b_{i}\tilde{P}_{p,i}^{n} + \sigma_{c,i}^{2}\right)\ln 2} - \frac{\mathbb{E}\left\{\mathrm{Tr}\left[\mathbf{f}_{i}\left(\tilde{\mathbf{Q}}_{i}^{n}\right)^{-1}\left(P_{s,i} - \tilde{P}_{p,i}^{n}\right)\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{\mathrm{Tr}\left[\mathbf{g}_{i}\left(\tilde{\mathbf{Q}}_{i}^{n}\right)^{-1}\left(P_{z,i} - \tilde{P}_{z,i}^{n}\right)\right]\right\}\right\}}{\ln 2} - \varphi_{\mathrm{SEE}}\left[\sum_{i=1}^{I}\left(P_{s,i} + P_{z,i}\right) + P_{b}\right] \\ s.t. C1: h_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - h_{2}\left(\tilde{P}_{p,i}^{n}, \tilde{P}_{s,i}^{n}, \tilde{P}_{z,i}^{n}\right) - \frac{b_{i}\left(P_{p,i} - \tilde{P}_{z,i}^{n}\right)}{\left(b_{i}\tilde{P}_{p,i}^{n} + \sigma_{c,i}^{2}\right)\ln 2} - \frac{\mathbb{E}\left\{\mathrm{Tr}\left[\mathbf{c}_{i}\left(\tilde{\mathbf{Q}}_{i}^{n}\right)^{-1}\left(P_{p,i} - \tilde{P}_{p,i}^{n}\right)\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{\mathrm{Tr}\left[\mathbf{f}_{i}\left(\tilde{\mathbf{Q}}_{i}^{n}\right)^{-1}\left(P_{p,i} - \tilde{P}_{p,i}^{n}\right)\right]\right\}}{\ln 2} - \frac{\mathbb{E}\left\{\mathrm{Tr}\left[\mathbf{f}_{i}\left(\tilde{\mathbf{Q}$$

TABLE II Two-tier Iterative ε -optimal Power Allocation Algorithm for SCSI-SEEM SCHEME

Algorithm 2: Two-tier Iterative ε -optimal Power Allocation Algorithm.
Function Outer_ Iteration
Step 1: Initialize the maximum number of iterations m_{max} , n_{max}
and the maximum tolerance ε .
Step 2: Set maximum SEE $\varphi_{\text{SEE}}^0 = 0$ and iteration index $m = 0$.
Step 3: Call Function Inner_Iteration with φ_{SEE}^m to obtain the
continual solution ($\mathbf{D}^n \ \mathbf{D}^n \ \mathbf{D}^n$)

$$\begin{aligned} & \text{Step 4: Update } \varphi_{\text{SEE}}^{m+1} = \\ & \underbrace{\sum\limits_{i=1}^{I} \left\{ \log_2 \left(1 + \frac{e_i P_{s,i}^n}{b_i P_{p,i}^n + \sigma_{c,i}^2} \right) - \text{E} \left[\log_2 \frac{\left| \mathbf{c}_i P_{p,i}^n + \mathbf{f}_i P_{s,i}^n + \mathbf{g}_i P_{z,i}^n + \sigma_{e,i}^2 \mathbf{I}_{N_E} \right|}{\left| \mathbf{c}_i P_{p,i}^n + \mathbf{g}_i P_{z,i}^n + \sigma_{e,i}^2 \mathbf{I}_{N_E} \right|} \right] \right\}} \\ & \underbrace{\sum\limits_{i=1}^{I} \left(P_{s,i}^n + P_{z,i}^n \right) + P_b} \end{aligned}}_{}. \end{aligned}$$

Step 6: **if** $\varphi_{\text{SEE}}^m - \varphi_{\text{SEE}}^{m-}$

Step 7: goto Step 3.

Step 8: end if

Step 9: **return** \mathbf{P}_p^n , \mathbf{P}_s^n , \mathbf{P}_z^n

Step 10: Obtain the ε -optimal solution $\mathbf{P}_p^* = \mathbf{P}_p^n$, $\mathbf{P}_s^* = \mathbf{P}_s^n$ and $\mathbf{P}_z^* = \mathbf{P}_z^n$ for problem (25).

Function *Inner*_ *Iteration* (φ_{SEE})

Step 11: Initialize $(\mathbf{P}_p^0, \mathbf{P}_s^0, \mathbf{P}_z^0) = (0, 0, 0)$ and $h^0 = 0$.

Step 12: Set n = 0.

Step 13: Find the ε -optimal solution $(\mathbf{P}_p^{n+1}, \mathbf{P}_s^{n+1}, \mathbf{P}_z^{n+1})$ of (30) for given $(\mathbf{P}_p^n, \mathbf{P}_s^n, \mathbf{P}_z^n)$ and φ_{SEE}^m by using CVX.

$$h^{n+1} = \sum_{i=1}^{I} \left[h_1 \left(P_{p,i}^{n+1}, P_{s,i}^{n+1}, P_{z,i}^{n+1} \right) - h_2 \left(P_{p,i}^{n+1}, P_{s,i}^{n+1}, P_{z,i}^{n+1} \right) \right]$$

$$-\varphi_{\text{SEE}}^m \left[\sum_{i=1}^{I} \left(P_{s,i}^{n+1} + P_{z,i}^{n+1} \right) + P_b \right]$$

Step 15: Set n = n + 1. Step 16: **if** $\left| h^n - h^{n-1} \right| \ge \varepsilon$ or $n \le n_{\max}$

Step 17: goto Step 13.

Step 18: end if

end

Step 19: **return** \mathbf{P}_p^n , \mathbf{P}_s^n , \mathbf{P}_z^n .

SEEM and conventional SRM schemes all improve with an increasing $P_{\mathrm{CBS}}^{\mathrm{total}}$ in the $20-40\mathrm{dBm}$ region of transmit power. This means that ICSI-SEEM, SCSI-SEEM and SRM schemes

TABLE III SYSTEM PARAMETERS

Parameters	Values
Path loss model, $\log_{10}(\vartheta)$	$-34.5 - 38\log_{10}(d[m])$
SR threshold for PU, $R_{\rm PU}^{\rm min}$	0 bit/s/Hz
SR threshold for CU, $R_{\mathrm{CU}}^{\mathrm{min}}$	0 bit/s/Hz
Corresponding distance, d	500 m
Bandwidth, Δf	10 MHz
Noise spectral density, N_0	-174 dBm/Hz
Basic power consumption of CBS, P_b	40 dBm
Maximum iteration, i_{max}	100
Convergence threshold, ε	10^{-3}

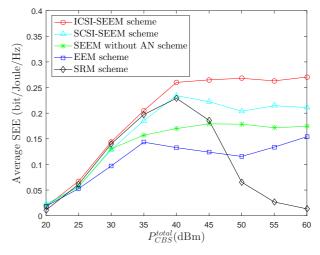


Fig. 3. Average SEE versus maximum transmit power of CBS, $P_{\mathrm{CBS}}^{\mathrm{total}}$, with $I=8, N_P=N_C=4, N_E=3$, and the maximum transmit power of PBS, $P_{\text{PBS}}^{\text{total}} = 30 \text{dBm}.$

can obtain the maximum SEE with the full transmit power. Then, as $P_{\text{CBS}}^{\text{total}}$ continues to increase after 40dBm, the average SEE performance of proposed ICSI-SEEM and SCSI-SEEM schemes approach to a constant, while the SRM scheme begins to degrade in terms of its SEE performance. This is because that in the proposed ICSI-SEEM and SCSI-SEEM schemes, the power allocator would not consume more transmit power when the maximum SEE has been achieved. By contrast, in order to achieve a higher SR, the SRM scheme will continue to allocate more transmit power, which will result in the drop of the average SEE. In addition, as observed, the proposed ICSI-SEEM and SCSI-SEEM schemes significantly outperform the EEM scheme in terms of the average SEE, and ICSI-SEEM achieves a higher SEE than the SCSI-SEEM scheme. In the SEEM without AN scheme, CBS only transmits the confidential signal to the destination without considering AN, besides, the powers of CBS' and PBS' OFDM subcarriers are optimized with a given total power consumption for CBS and PBS, respectively. As can be seen from Fig. 2, the proposed ICSI-SEEM and SCSI-SEEM schemes achieve a higher SEE than SEEM without AN scheme, which indicates the advantage of AN to wiretap the ED.

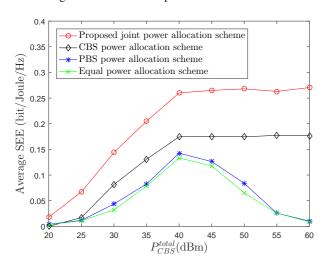


Fig. 4. Average SEE versus maximum transmit power of CBS, $P_{\rm CBS}^{\rm total}$, for different power allocation schemes with I=8, $N_P=N_C=4$, $N_E=3$, and the maximum transmit power of PBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$.

Fig. 4 shows the average SEE versus maximum transmit power of CBS, $P_{\mathrm{CBS}}^{\mathrm{total}}$, for the proposed joint power allocation of PBS and CBS, pure power allocation of CBS' OFDM subcarriers (denoted by CBS power allocation for short), pure power allocation of PBS' OFDM subcarriers (called PBS power allocation) and equal power allocation schemes with $I=8, N_P=N_C=4, N_E=3$, and the maximum transmit power of PBS, $P_{\rm PBS}^{\rm total} = 30 {\rm dBm}$. In the CBS power allocation scheme, the powers of CBS' OFDM subcarriers are optimized with a given total power consumption for CBS $P_{\mathrm{CBS}}^{\mathrm{total}}$ and a fixed power allocation is used for PBS' OFDM subcarriers, namely the power of each PBS' subcarrier is given by 10dBm. Similarly, the PBS power allocation scheme only considers the optimal power allocation for PBS' OFDM subcarriers with a constrained total power P_{PBS}^{total} , while the equal power allocation is used for CBS' subcarriers. Moreover, in the equal power allocation scheme, CBS' OFDM subcarriers are equally allocated with their respective total transmit power constraints while the PBS' OFDM subcarriers are allocated with fixed transmit power, namely, $P_{s,i} = P_{\text{CBS}}^{\text{total}}/(2I)$, $P_{z,i} = P_{\text{CBS}}^{\text{total}}/(2I)$ and $P_{p,i} = 10 \text{dBm}$.

As can be seen from Fig. 4, the average SEE of proposed joint power allocation and CBS power allocation scheme

approach a constant in the high CBS transmit power regime. This is because both the proposed joint power allocation and CBS power allocation schemes stop assuming more CBS transmit power when the maximal SEE is achieved. However, the PBS power allocation and equal power allocation schemes begin to drop in the regime of $P_{\rm CBS}^{\rm total} \geq 40 {\rm dBm}$. This is due to the fact that they allocate all the available CBS transmit power even without much secrecy rate improvement. On the other hand, the proposed joint power allocation scheme can achieve a higher average SEE than other power allocation methods, which indicates the superiority of proposed joint power allocation scheme.

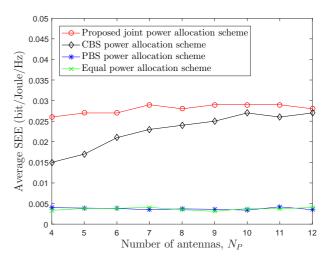


Fig. 5. Average SEE versus the number of PBS' antennas, N_P , for different power allocation schemes with $I=8,\,N_C=4,\,N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm hotal}=30{\rm dBm},\,P_{\rm CGB}^{\rm total}=20{\rm dBm}$.

Fig. 5 illustrates the average SEE versus the number of PBS' antennas, N_P , for the proposed joint power allocation, CBS power allocation, PBS power allocation, and equal power allocation schemes with I=8, $N_C=4$, $N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$, $P_{\rm CBS}^{\rm total}=20{\rm dBm}$. It can be observed that as N_P increases, the CBS power allocation schemes begin to increase in terms of the average SEE, however, the proposed joint power allocation, PBS power allocation and equal power allocation methods converge to their respective SEE floors. This means that given sufficiently high number of PBS's antennas, the proposed joint power allocation, PBS power allocation and equal power allocation can sophisticatedly stop consuming additional power resources when the resultant secrecy rate improvement is marginal.

Fig. 6 depicts the average SEE results of the proposed joint power allocation scheme, CBS power allocation, PBS power allocation and equal power allocation schemes versus the number of CBS's antennas, N_C , in the cases of I=8, $N_P=4$, $N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$, $P_{\rm CBS}^{\rm total}=20{\rm dBm}$. As shown in Fig. 5, the average SEE of the all schemes increases as N_C increases, which means that the average SEE of OFDM-based CRNs can be further enhanced by employing more antennas of the CBS. Besides, the growth rate of proposed joint power allocation scheme is higher than the other power

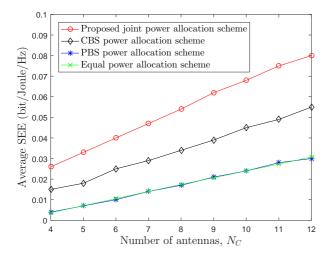


Fig. 6. Average SEE versus the number of CBS's antennas, N_C , for different power allocation schemes with I=8, $N_P=4$, $N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$, $P_{\rm CBS}^{\rm total}=20{\rm dBm}$.

allocation schemes, showing that the number of antennas for joint optimal power allocation scheme has a more impact on the average SEE than the other power allocation schemes.

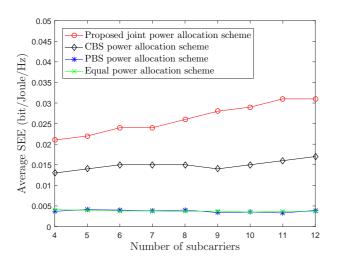


Fig. 7. Average SEE versus the number of subcarriers, I, for different power allocation schemes with $N_P=N_C=4$, $N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm hotal}=30{\rm dBm}$, $P_{\rm CBS}^{\rm total}=20{\rm dBm}$.

Fig. 7 shows the average SEE results of the proposed joint power allocation scheme versus the number of subcarriers, I, for different power allocation schemes with $N_P=N_C=4$, $N_E=3$, and the maximum transmit power of PBS and CBS, $P_{\rm PBS}^{\rm total}=30{\rm dBm}$, $P_{\rm CBS}^{\rm total}=20{\rm dBm}$. As observed, the proposed joint power allocation outperforms the other power allocation methods in terms of average SEE. Futhermore, giving the transmit power of PBS and CBS, as the number of subcarrier I increases, the average SEE of the PBS power allocation and equal power allocation schemes almost keep unchanged. However, the average SEE of proposed joint power allocation and CBS power allocation approaches increase slightly. Besides, the proposed joint power allocation and CBS power allocation schemes obtain a higher average SEE than the PBS power allocation and equal power allocation methods,

which indicates that the CBS transmit power allocation is more important than PBS power allocation in OFDM-based CRNs.

VI. CONCLUSION

In this paper, we studied the power allocation of PBS and CBS across different OFDM subcarries in downlink OFDMbased CRNs. We first employed AN to improve the PLS of OFDM-based CRNs, and then formulated a power allocation problem to maximize the SEE based on instantaneous and statistical CSI of ED, where the circuit power consumption, minimum SR constraint, and minimum SR requirement were taken into consideration. New two-tier power allocation algorithms were presented to optimize the power allocation of PBS and CBS across different OFDM subcarriers. To be specific, with the help of the Dinkelbach's method and D.C. approaches, we converted the originally formulated non-convex problems into convex problems. Finally, numerical results showed that the proposed ε -optimal power allocation scheme obtains a higher SEE than conventional power allocation methods. Also, the proposed ICSI-SEEM and SCSI-SEEM schemes can improve the SEE of CRNs significantly compared with conventional SRM and EEM approaches.

APPENDIX A

PROOF OF THEOREM 1

It is obvious that the problems (15) and (16) have the same feasible region \Re_1 for their same constraint conditions C1-C4. Firstly, we denote $(\widehat{\mathbf{P}}_p,\widehat{\mathbf{P}}_s,\widehat{\mathbf{P}}_z)\in\Re_1$ and $(\widehat{\mathbf{P}}_p^*,\widehat{\mathbf{P}}_s^*,\widehat{\mathbf{P}}_z^*)\in\Re_1$ as the feasible and optimal solution of problem (15), respectively, so the maximum SEE η_{SEE}^* can be achieved by the following formula

$$\eta_{\text{SEE}}^{*} = \max_{\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z}} \frac{\sum_{i=1}^{I} \left[f_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - f_{2}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) \right]}{\sum_{i=1}^{I} \left(P_{s,i} + P_{z,i}\right) + P_{b}}$$

$$= \frac{\sum_{i=1}^{I} \left[f_{1}(\widehat{P}_{p,i}^{*}, \widehat{P}_{s,i}^{*}, \widehat{P}_{z,i}^{*}) - f_{2}(\widehat{P}_{p,i}^{*}, \widehat{P}_{s,i}^{*}, \widehat{P}_{z,i}^{*}) \right]}{\sum_{i=1}^{I} \left(\widehat{P}_{s,i}^{*} + \widehat{P}_{z,i}^{*}\right) + P_{b}}$$

$$\geq \frac{\sum_{i=1}^{I} \left[f_{1}(\widehat{P}_{p,i}, \widehat{P}_{s,i}, \widehat{P}_{z,i}) - f_{2}(\widehat{P}_{p,i}, \widehat{P}_{s,i}, \widehat{P}_{z,i}) \right]}{\sum_{i=1}^{I} \left(\widehat{P}_{s,i} + \widehat{P}_{z,i}\right) + P_{b}}.$$
(A.1)

Based on the fact that $\sum\limits_{i=1}^{I} \left(\widehat{P}_{s,i} + \widehat{P}_{z,i}\right) + P_b > 0$, (A.1) can be further transmitted into the following form

$$\sum_{i=1}^{I} \left[f_1(\widehat{P}_{p,i}^*, \widehat{P}_{s,i}^*, \widehat{P}_{z,i}^*) - f_2(\widehat{P}_{p,i}^*, \widehat{P}_{s,i}^*, \widehat{P}_{z,i}^*) \right] - \eta_{\text{SEE}}^* \left[\sum_{i=1}^{I} (\widehat{P}_{s,i}^* + \widehat{P}_{z,i}^*) + P_b \right] = 0,$$
(A.2)

$$\sum_{i=1}^{I} \left[f_1(\widehat{P}_{p,i}, \widehat{P}_{s,i}, \widehat{P}_{z,i}) - f_2(\widehat{P}_{p,i}, \widehat{P}_{s,i}, \widehat{P}_{z,i}) \right]$$

$$- \eta_{\text{SEE}}^* \left[\sum_{i=1}^{I} (\widehat{P}_{s,i} + \widehat{P}_{z,i}) + P_b \right] \leq 0.$$
(A.3)

Combining (A.2) and (A.3), we can observe that the maximum value $f(\eta_{\text{SEE}}^*) = 0$ at the optimal solution $(\widehat{\mathbf{P}}_p^*, \widehat{\mathbf{P}}_s^*, \widehat{\mathbf{P}}_z^*)$. Then, assuming $(\widecheck{\mathbf{P}}_p^*, \widecheck{\mathbf{P}}_s^*, \widecheck{\mathbf{P}}_z^*) \in \Re_1$ and $(\widecheck{\mathbf{P}}_p, \widecheck{\mathbf{P}}_s, \widecheck{\mathbf{P}}_z) \in \Re_1$ are the optimal and feasible solution of problem (16), respectively, as well as $f(\eta_{\text{SEE}}^*) = 0$, that is

$$f(\eta_{\text{SEE}}^{*}) = \max_{\mathbf{P}_{p}, \mathbf{P}_{s}, \mathbf{P}_{z_{i}=1}}^{I} \left[f_{1}(P_{p,i}, P_{s,i}, P_{z,i}) - f_{2}(P_{p,i}, P_{s,i}, P_{z,i}) \right]$$

$$- \eta_{\text{SEE}}^{*} \left[\sum_{i=1}^{I} (P_{s,i} + P_{z,i}) + P_{b} \right]$$

$$= \sum_{i=1}^{I} \left[f_{1}(\widecheck{P}_{p,i}^{*}, \widecheck{P}_{s,i}^{*}, \widecheck{P}_{z,i}^{*}) - f_{2}(\widecheck{P}_{p,i}^{*}, \widecheck{P}_{s,i}^{*}, \widecheck{P}_{z,i}^{*}) \right]$$

$$- \eta_{\text{SEE}}^{*} \left[\sum_{i=1}^{I} (\widecheck{P}_{s,i}^{*} + \widecheck{P}_{z,i}^{*}) + P_{b} \right]$$

$$= 0$$

$$\geq \sum_{i=1}^{I} \left[f_{1}(\widecheck{P}_{p,i}, \widecheck{P}_{s,i}, \widecheck{P}_{z,i}) - f_{2}(\widecheck{P}_{p,i}, \widecheck{P}_{s,i}, \widecheck{P}_{z,i}) \right]$$

$$- \eta_{\text{SEE}}^{*} \left[\sum_{i=1}^{I} (\widecheck{P}_{s,i} + \widecheck{P}_{z,i}) + P_{b} \right]. \tag{A.4}$$

After some operations, we can achieve the following fractional formula

$$\frac{\sum\limits_{i=1}^{I}\left[f_{1}(\widecheck{P}_{p,i},\widecheck{P}_{s,i},\widecheck{P}_{z,i})-f_{2}(\widecheck{P}_{p,i},\widecheck{P}_{s,i},\widecheck{P}_{z,i})\right]}{\sum\limits_{i=1}^{I}\left(\widecheck{P}_{s,i}+\widecheck{P}_{z,i}\right)+P_{b}}$$

$$\leq \eta_{\text{SEE}}^{*}$$

$$=\frac{\sum\limits_{i=1}^{I}\left[f_{1}(\widecheck{P}_{p,i}^{*},\widecheck{P}_{s,i}^{*},\widecheck{P}_{z,i}^{*})-f_{2}(\widecheck{P}_{p,i}^{*},\widecheck{P}_{s,i}^{*},\widecheck{P}_{z,i}^{*})\right]}{\sum\limits_{i=1}^{I}\left(\widecheck{P}_{s,i}^{*}+\widecheck{P}_{z,i}^{*}\right)+P_{b}}.$$
(A.5)

From (A.5), it is easy to find that $(\breve{\mathbf{P}}_p^*, \breve{\mathbf{P}}_s^*, \breve{\mathbf{P}}_z^*)$ is also the optimal solution of (15). Therefore, we can obtain that $(\widehat{\mathbf{P}}_p^*, \widehat{\mathbf{P}}_s^*, \widehat{\mathbf{P}}_z^*)$ is equal to $(\breve{\mathbf{P}}_p^*, \breve{\mathbf{P}}_s^*, \breve{\mathbf{P}}_z^*)$ if and only if $f(\eta_{\mathrm{SEE}}^*) = 0$.

APPENDIX B

PROOF OF THE CONVERGENCE

Assuming that $(\vec{\mathbf{P}}_p^{n+1}, \vec{\mathbf{P}}_s^{n+1}, \vec{\mathbf{P}}_z^{n+1})$ and $(\vec{\mathbf{P}}_p^n, \vec{\mathbf{P}}_s^n, \vec{\mathbf{P}}_z^n)$ are feasible solutions of (22) at iterations n+1 and n, respectively,

and using (19) and (20), we can obtain

$$\begin{split} &f_{2}(\vec{P}_{p,i}^{n+1},\vec{P}_{s,i}^{n+1},\vec{P}_{z,i}^{n+1}) \leq f_{2}(\vec{P}_{p,i}^{n},\vec{P}_{s,i}^{n},\vec{P}_{z,i}^{n}) \\ &+ \frac{b_{i}(\vec{P}_{p,i}^{n+1} - \vec{P}_{p,i}^{n})}{(b_{i}\vec{P}_{p,i}^{n} + \sigma_{c,i}^{2}) \ln 2} + \frac{\text{Tr}\Big[\mathbf{c}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{p,i}^{n+1} - \vec{P}_{p,i}^{n})\Big]}{\ln 2} \\ &+ \frac{\text{Tr}\Big[\mathbf{f}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{s,i}^{n+1} - \vec{P}_{s,i}^{n})\Big]}{\ln 2} + \frac{\text{Tr}\Big[\mathbf{g}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{z,i}^{n+1} - \vec{P}_{z,i}^{n})\Big]}{\ln 2}, \end{split} \tag{B.1}$$

and

$$g_{2}(\vec{P}_{p,i}^{n+1}, \vec{P}_{s,i}^{n+1}, \vec{P}_{z,i}^{n+1}) \leq g_{2}(\vec{P}_{p,i}^{n}, \vec{P}_{s,i}^{n}, \vec{P}_{z,i}^{n})$$

$$+ \frac{d_{i}(\vec{P}_{s,i}^{n+1} - \vec{P}_{s,i}^{n})}{(d_{i}\vec{P}_{s,i}^{n} + \sigma_{p,i}^{2})\ln 2} + \frac{\text{Tr}\Big[\mathbf{c}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{p,i}^{n+1} - \vec{P}_{p,i}^{n})\Big]}{\ln 2}$$

$$+ \frac{\text{Tr}\Big[\mathbf{f}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{s,i}^{n+1} - \vec{P}_{s,i}^{n})\Big]}{\ln 2} + \frac{\text{Tr}\Big[\mathbf{g}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{z,i}^{n+1} - \vec{P}_{z,i}^{n})\Big]}{\ln 2},$$
(B.2)

where $\vec{\Omega}_i^n = \mathbf{c}_i \vec{P}_{p,i}^n + \mathbf{f}_i \vec{P}_{s,i}^n + \mathbf{g}_i \vec{P}_{z,i}^n + \sigma_{e,i}^2 \mathbf{I}_{N_E}$. Substituting feasible solutions of (22) into C1 and C2 of (16), we can obtain

$$f_{1}(\vec{P}_{p,i}^{n+1}, \vec{P}_{s,i}^{n+1}, \vec{P}_{z,i}^{n+1}) - f_{2}(\vec{P}_{p,i}^{n+1}, \vec{P}_{s,i}^{n+1}, \vec{P}_{z,i}^{n+1})$$

$$\geq f_{1}(\vec{P}_{p,i}^{n+1}, \vec{P}_{s,i}^{n+1}, \vec{P}_{z,i}^{n+1}) - f_{2}(\vec{P}_{p,i}^{n}, \vec{P}_{s,i}^{n}, \vec{P}_{z,i}^{n})$$

$$- \frac{\text{Tr}\Big[\mathbf{c}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{p,i}^{n+1} - \vec{P}_{p,i}^{n})\Big]}{\ln 2} - \frac{\text{Tr}\Big[\mathbf{f}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{s,i}^{n+1} - \vec{P}_{s,i}^{n})\Big]}{\ln 2}$$

$$- \frac{\text{Tr}\Big[\mathbf{g}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{z,i}^{n+1} - \vec{P}_{z,i}^{n})\Big]}{\ln 2} - \frac{b_{i}(\vec{P}_{p,i}^{n+1} - \vec{P}_{p,i}^{n})}{(b_{i}\vec{P}_{p,i}^{n} + \sigma_{c,i}^{2})\ln 2} \geq R_{CU}^{\min}, \forall i,$$
(B.3)

and

$$g_{1}(\vec{P}_{p,i}^{n+1}, \vec{P}_{s,i}^{n+1}, \vec{P}_{z,i}^{n+1}) - g_{2}(\vec{P}_{p,i}^{n+1}, \vec{P}_{s,i}^{n+1}, \vec{P}_{z,i}^{n+1})$$

$$\geq g_{1}(\vec{P}_{p,i}^{n+1}, \vec{P}_{s,i}^{n+1}, \vec{P}_{z,i}^{n+1}) - g_{2}(\vec{P}_{p,i}^{n}, \vec{P}_{s,i}^{n}, \vec{P}_{z,i}^{n})$$

$$- \frac{\text{Tr}\Big[\mathbf{c}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{p,i}^{n+1} - \vec{P}_{p,i}^{n})\Big] - \frac{\text{Tr}\Big[\mathbf{f}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{s,i}^{n+1} - \vec{P}_{s,i}^{n})\Big]}{\ln 2}$$

$$- \frac{\text{Tr}\Big[\mathbf{g}_{i}(\vec{\Omega}_{i}^{n})^{-1}(\vec{P}_{z,i}^{n+1} - \vec{P}_{z,i}^{n})\Big]}{\ln 2} - \frac{d_{i}(\vec{P}_{s,i}^{n+1} - \vec{P}_{s,i}^{n})}{(d_{i}\vec{P}_{s,i}^{n} + \sigma_{p,i}^{2})\ln 2} \geq R_{PU}^{\min}, \forall i.$$
(B.4)

From (B.3) and (B.4), we can observe that the feasible solutions of (22) are also suitable for (16).

According to (19), we also obtain

$$\begin{split} &f_{2}(\bar{P}_{p,i}^{n+1},\bar{P}_{s,i}^{n+1},\bar{P}_{z,i}^{n+1}) \leq f_{2}(\bar{P}_{p,i}^{n},\bar{P}_{s,i}^{n},\bar{P}_{z,i}^{n}) \\ &+ \frac{b_{i}(\bar{P}_{p,i}^{n+1} - \bar{P}_{p,i}^{n})}{(b_{i}\bar{P}_{p,i}^{n} + \sigma_{c,i}^{2})\ln 2} + \frac{\text{Tr}\Big[\mathbf{c}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{p,i}^{n+1} - \bar{P}_{p,i}^{n})\Big]}{\ln 2} \\ &+ \frac{\text{Tr}\Big[\mathbf{f}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{s,i}^{n+1} - \bar{P}_{s,i}^{n})\Big]}{\ln 2} + \frac{\text{Tr}\Big[\mathbf{g}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{z,i}^{n+1} - \bar{P}_{z,i}^{n})\Big]}{\ln 2}. \end{split}$$
(B.5)

Then, following the iterative procedure in (22), we arrive at

$$\begin{split} &\sum_{i=1}^{I} \left\{ f_{1}(\bar{P}_{p,i}^{n+1}, \bar{P}_{s,i}^{n+1}, \bar{P}_{z,i}^{n+1}) - f_{2}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) \right. \\ &- \frac{b_{i}(\bar{P}_{p,i}^{n+1} - \bar{P}_{p,i}^{n})}{(b_{i}\bar{P}_{p,i}^{n} + \sigma_{c,i}^{2})ln2} - \frac{\text{Tr}\Big[\mathbf{c}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{p,i}^{n+1} - \bar{P}_{p,i}^{n})\Big]}{\ln 2} \\ &- \frac{\text{Tr}\Big[\mathbf{f}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{s,i}^{n+1} - \bar{P}_{s,i}^{n})\Big]}{\ln 2} - \frac{\text{Tr}\Big[\mathbf{g}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{z,i}^{n+1} - \bar{P}_{z,i}^{n})\Big]}{\ln 2} \\ &- \eta_{\text{SEE}}\left[\sum_{i=1}^{I} (\bar{P}_{s,i}^{n+1} + \bar{P}_{z,i}^{n+1}) + P_{b}\right] \\ &= \max_{\mathbf{P}_{p},\mathbf{P}_{s},\mathbf{P}_{z}} \sum_{i=1}^{I} \left\{ f_{1}\left(P_{p,i},P_{s,i},P_{z,i}\right) - f_{2}(\bar{P}_{p,i}^{n},\bar{P}_{s,i}^{n},\bar{P}_{z,i}^{n}) \right. \\ &- \frac{b_{i}(P_{p,i} - \bar{P}_{p,i}^{n})}{(b_{i}\bar{P}_{p,i}^{n} + \sigma_{c,i}^{2})\ln 2} - \frac{\text{Tr}\Big[\mathbf{c}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(P_{p,i} - \bar{P}_{p,i}^{n})\Big]}{\ln 2} \\ &- \frac{\text{Tr}\Big[\mathbf{f}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(P_{s,i} - \bar{P}_{s,i}^{n})\Big]}{\ln 2} - \frac{\text{Tr}\Big[\mathbf{g}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(P_{z,i} - \bar{P}_{z,i}^{n})\Big]}{\ln 2} \\ &\geq \sum_{i=1}^{I} \Big[f_{1}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) - f_{2}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n})\Big] \\ &- \eta_{\text{SEE}}\Big[\sum_{i=1}^{I} (\bar{P}_{s,i}^{n} + \bar{P}_{s,i}^{n}) + P_{b}\Big]. \end{aligned} \tag{B.6}$$

Substituting (B.5) into (B.6), we can further have

$$\sum_{i=1}^{I} \left[f_{1}(\bar{P}_{p,i}^{n+1}, \bar{P}_{s,i}^{n+1}, \bar{P}_{z,i}^{n+1}) - f_{2}(\bar{P}_{p,i}^{n+1}, \bar{P}_{s,i}^{n+1}, \bar{P}_{z,i}^{n+1}) \right] \\
- \eta_{\text{SEE}} \left[\sum_{i=1}^{I} (\bar{P}_{s,i}^{n+1} + \bar{P}_{z,i}^{n+1}) + P_{b} \right] \\
\geq \sum_{i=1}^{I} \left\{ f_{1}(\bar{P}_{p,i}^{n+1}, \bar{P}_{s,i}^{n+1}, \bar{P}_{z,i}^{n+1}) - f_{2}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) \right. \\
- \frac{b_{i}(\bar{P}_{p,i}^{n+1} - \bar{P}_{p,i}^{n})}{(b_{i}\bar{P}_{p,i}^{n} + \sigma_{c,i}^{2}) \ln 2} - \frac{\text{Tr} \left[\mathbf{c}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{p,i}^{n+1} - \bar{P}_{p,i}^{n}) \right]}{\ln 2} \\
- \frac{\text{Tr} \left[\mathbf{f}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{s,i}^{n+1} - \bar{P}_{s,i}^{n}) \right]}{\ln 2} - \frac{\text{Tr} \left[\mathbf{g}_{i}(\bar{\mathbf{\Omega}}_{i}^{n})^{-1}(\bar{P}_{z,i}^{n+1} - \bar{P}_{z,i}^{n}) \right]}{\ln 2} \right\} \\
- \eta_{\text{SEE}} \left[\sum_{i=1}^{I} (\bar{P}_{s,i}^{n+1} + \bar{P}_{z,i}^{n+1}) + P_{b} \right] \\
\geq \sum_{i=1}^{I} \left[f_{1}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) - f_{2}(\bar{P}_{p,i}^{n}, \bar{P}_{s,i}^{n}, \bar{P}_{z,i}^{n}) \right] \\
- \eta_{\text{SEE}} \left[\sum_{i=1}^{I} (\bar{P}_{s,i}^{n} + \bar{P}_{z,i}^{n}) + P_{b} \right]. \tag{B.7}$$

From (B.7), we can observe that the proposed iterative procedure is monotonically non-decreasing with the increasing of iterative numbers. In addition, by employing the transmit power constraints of PBS and CBS, i.e., $\sum_{i}^{I} P_{p,i} \leq P_{\mathrm{PBS}}^{\mathrm{total}}$ and

 $\sum_{i=1}^{I} (P_{s,i} + P_{z,i}) \leq P_{\text{CBS}}^{\text{total}}$, the upper bound of the objective function can be given by

$$\begin{split} &\sum_{i=1}^{I} \left[f_{1}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) - f_{2}\left(P_{p,i}, P_{s,i}, P_{z,i}\right) \right] \\ &- \eta_{\text{SEE}} \Bigg[\sum_{i=1}^{I} \left(P_{s,i} + P_{z,i}\right) + P_{b} \Bigg] \leq \sum_{i=1}^{I} \left[\log_{2}(1 + \frac{e_{i}P_{s,i}}{b_{i}P_{p,i} + \sigma_{c,i}^{2}}) \right] \\ &\leq \frac{\max(e_{i})P_{\text{CBS}}^{\text{total}}}{\Delta f N_{0} \ln 2}. \end{split} \tag{B.8}$$

Combining (B.7) and (B.8), we can guarantee that the iterative procedure in (22) will converge to an ε -optimal solution of (16) after sufficient iterations.

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