Secure Resource Allocations for Polarization-Enabled Multiple-Access Cooperative Cognitive Radio Networks With Energy Harvesting Capability

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***Abstract*—We address secure communications over energy-harvesting based orthogonal frequency-division multiple-access (OFDMA) cooperative cognitive radio networks, where one primary user (PU) cooperates with several size-limited secondary users (SUs) in terms of both information transmission and energy harvesting. To improve spectrum utilization and ensure that SU transmitters can harvest as much energy as possible, we let the size-limited SUs be equipped with orthogonally dual-polarized antennas (ODPAs). Based on these setting-ups, we propose the polarization-enabled two-phase cooperative framework, where SU transmitters first apply the power splitting technique to harvest energy from radio frequency (RF) signals radiated by the PU, and then use the harvested energy to concurrently transmit their own and the PU's data over the same subcarriers. Under our proposed framework, we develop three secure resource allocation schemes for scenarios when SUs are untrusted users, which implies that each SU may overhear the PU's and the other SUs' confidential information. For these scenarios, which has hardly been studied, we jointly optimize the allocation of relays, subcarriers, power splitting ratios, and powers when SUs adopt the decode-and-forward (DF) strategy or the amplify-and-forward (AF) strategy to relay the PU's information, with the objective to maximize the total secrecy rate of all SUs while guaranteeing the PU's minimum secrecy rate. Finally, we validate and evaluate our proposed cooperative framework and secure resource allocation schemes through numerical analyses.**

***Index Terms*—Energy harvesting, cooperative overlay cognitive radio networks, orthogonally dual-polarized antennas (ODPAs), orthogonal frequency-division multiple-access (OFDMA), secure communication, resource allocation, radio frequency (RF) signals.**

I. INTRODUCTION

ENERGY HARVESTING harvesting based multiple-access cooperative cognitive radio networks (CRNs) [1–3] have attracted considerable attention due to their contributions on improving the wireless network quality-of-service (QoS) [4–12], where secondary users (SUs) can not only cooperate with primary users (PUs) for data transfer, but also harvest energy from PUs' radio frequency (RF) signals. To cooperate in terms of both data transfer and energy harvesting, several cooperation frameworks have been proposed, which can be classified into two- and three-phase categories.

In the time-division multiple-access (TDMA) based three-phase frameworks [1], SUs first harvest energy from PUs' RF signals, and then use the harvested energy to forward PUs' and their own data in the second and third phases, respectively. However, due to three-phase cooperation, system performance and the amount of energy harvested by SUs may not be guaranteed. In two-phase cooperative CRNs, SUs first scavenge energy from PUs' and/or other dedicated energy sources' transmission, and then transmit PUs' and their own signals simultaneously based on techniques, e.g., frequency-division multiple-access (FDMA) and multiple-input multiple-output (MIMO). However, in the FDMA-based frameworks, since both PUs and SUs can only utilize a fraction of spectrum for data transmission [2], they may not have desire to cooperate and then system performance may be degraded largely. Meanwhile, the MIMO-based frameworks [3] may not be suitable for applications with size-limited SUs, e.g., handheld terminals, since the MIMO technology requires strict spacing among antenna elements, e.g., at lease half a wavelength spacing for antenna deployment at SUs, to ensure ideal channel independence [13].

Inspired by [13], we propose a polarization-enabled two-phase cooperative framework for an energy harvesting (EH) based orthogonal frequency-division multiple-access (OFDMA) cooperative CRN, where one PU performs cooperative communication with several EH-based size-limited SUs. We let SUs be equipped with orthogonally dual-polarized antennas (ODPAs). Generally speaking, each ODPA has two co-located and orthogonally dual-polarized antenna elements [14]. Due to the orthogonality of the two antenna elements in the polarization domain, the use of ODPAs does not demand spacing extra requirements for antenna elements [13], which makes ODPAs to be well suitable for devices with strict size limitations. Besides, due to the polarization multiplexing capability provided by ODPAs [14], the size-limited SUs can multiplex and convey the PU's and their own signals over the same subcarriers with the orthogonal polarization. Hence, SUs can first apply the power splitting technique [15, 16] to harvest energy from the PU, and then conduct the PU's and their own data transmissions concurrently with ODPAs. Being able to utilize more spectrum and time for data transmission and energy harvesting, the PU and SUs have more potentials to cooperate, and then system performance can be further improved.

Under our proposed framework, we consider secure resource

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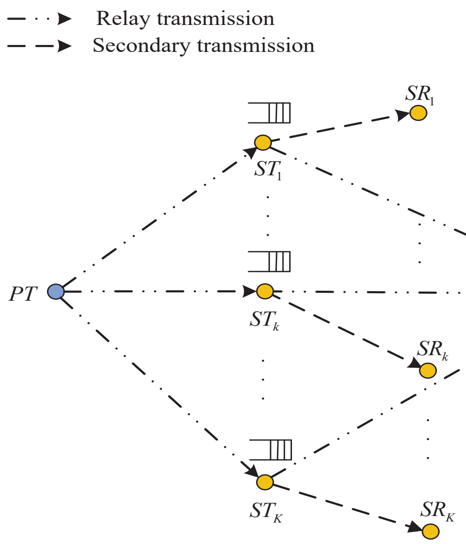

Fig. 1. The system architecture model for our proposed OFDMA-based multiple-access cooperative cognitive radio networks with energy harvesting capability, where ST_k's and SR_k's are equipped with orthogonally dual-polarized antennas.

allocation for the scenarios when SUs are untrusted, which means that each SU may overhear the PU's and the other SUs' information. In the literature, the physical-layer security has been studied in two cases. In one case, all users participating in resource allocation assume that they trust each other, and there exist the external eavesdroppers [17]. This scenario has been widely studied, and many anti-eavesdropping schemes have been proposed based on the techniques of artificial noises, cooperative jamming, etc. While in another case, there is a mutual distrust among network users communicating with each other, and each network user needs to treat some specific users as potential eavesdroppers. Recently, the authors of [18–21] considered secure resource allocation for systems with several untrusted relays or untrusted destinations, where system secrecy performance is guaranteed by designing appropriate resource allocation schemes. The authors of [22, 23] addressed secure communication for non-orthogonal multiple access (NOMA) systems with an untrusted relay or a malicious destination, where system secrecy performance is ensured by letting network nodes transmit information signals and jamming signals simultaneously using the NOMA technique. The authors of [24, 25] considered secure and resilient communication for networks with an untrusted relay or external eavesdropper as well as a hostile jammer, where the jammer can transmit noise-like signals and concurrently wiretap legitimate channels. The authors of [16] and [26, 27] considered the scenarios when the relays and/or destinations are EH-based untrusted users, where several secure transmission schemes are proposed. The authors of [28] proposed an interesting two-way secure communication scheme where two transceivers exchange confidential messages via a wireless-powered untrusted AF relay in the presence of an external jammer. However, in all the above-mentioned works, secure resource allocation of PUs and PUs' cooperative SUs has not been sufficiently considered for EH-based OFDMA CRNs with untrusted cooperative SUs.

Consequently, based on ODPAs and our proposed two-phase cooperative framework, we consider secure communication for

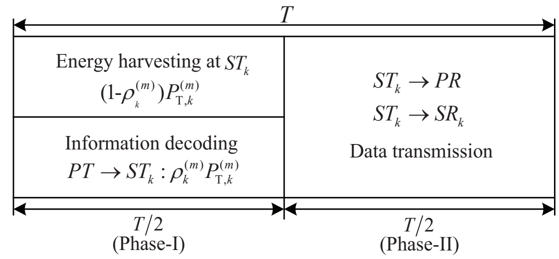

Fig. 2. The cooperative transmission between PT and its cooperative relay ST_k over subcarrier pair (SP) (m,n), where $P_{\mathrm{T},k}^{(m)}$ is the transit power from PT to ST_k over subcarrier m, $\rho_k^{(m)}$ and $1-\rho_k^{(m)}$ are the power splitting ratios of ST_k over subcarrier m.

EH-based OFDMA cooperative CRNs with untrusted and size-limited SUs by jointly optimizing the allocation of relays, subcarriers, power splitting ratios, and powers. Our aim is to guarantee the PU's and all SUs' secure communication, and ensure the energy harvesting of the EH-based SUs. Moreover, three secure resource allocation schemes are proposed for the scenarios when all EH-based SU transmitters adopt the decode-and-forward (DF) strategy or the amplify-and-forward (AF) strategy to forward the PU's information. The performance of our proposed cooperative framework and secure resource allocation schemes are verified through numerical analyses. Based on these numerical analyses, we also observe that both the PU's and SUs' physical-layer security can be enhanced in our proposed cooperative framework.

The rest of this paper is organized as follows. Section II builds up the system model. Section III presents the secure resource allocation for the DF strategy case. Section IV presents the secure resource allocation for the AF strategy case. Section V conducts the numerical analyses. The paper concludes with Section VI.

II. The System Model

Consider a cognitive radio network (CRN) shown in Fig. 1 with one primary user (PU) and K secondary users (SUs), where PT and PR are the PU transmitter and receiver, respectively, and ST_k and SR_k are the kth, $1 \leq k \leq K$, SU transmitter and receiver, respectively. The primary link $PT \rightarrow PR$ is in outage status, and SUs are energy harvesting (EH) based wireless devices [15, 16] with size limitation, e.g., wireless sensors. To improve system performance, we let the size-limited ST_k's and SR_k's be equipped with the orthogonally dual-polarized antennas (ODPAs). Notice that for each ODPA, due to the orthogonality of the two co-located antenna elements in the polarization domain, the ODPA does not have extra spacing requirements for its two antenna elements. Therefore, the ODPAs are suitable for devices with strict size limitations. In addition, to guarantee both PU's and SUs' quality of service (QoS), we propose a polarization-enabled two-phase cooperative framework (PTPCF) for the considered cooperative CRN. The network adopts the orthogonal frequency-division multiple-access (OFDMA) technique to enable multiple SUs' network access, and the network spectrum is divided into N subcarriers. Using Fig. 2, over subcarrier pair (SP) (m,n), $1 \leq m,n \leq N$, we describe PTPCF as follows, where ST_k is a cooperative relay for PT and T is a transmission period.

In Phase-I (first $T/2$), over subcarrier m, PT transmits while ST_k receives. ST_k splits the received radio frequency (RF) signals from PT into two parts with power splitting ratios $\rho_k^{(m)}$ and $1-\rho_k^{(m)}$: one for receiving PT's data and the other for energy harvesting over subcarrier m [15, 16]. In Phase-II (second $T/2$), ST_k utilizes the orthogonal polarization multiplexing capability provided by ODPAs to multiplex and send its own and PT's data over subcarrier n. Using the polarization-related signal processing techniques, e.g., polarization zero-forcing [29], the co-channel interference due to polarization multiplexing can be eliminated, so that system performance can be further improved. For SUs, there exists a tradeoff between the energy-harvesting phase time and the data-transmission phase time, which dictate the amount of harvested energy and data-throughput rate, respectively. Therefore, to achieve a well balanced tradeoff between the energy harvesting time and the data transmission time, it is a common practice to evenly assign the equal duration of $T/2$ for both the energy harvesting and the data transmission phases as widely adopted in [30, 31]. On the other hand, the duration of each phase can be a *variable and unequal*, instead of a *fixed constant* of $T/2$, where the two phases' durations can be dynamically controlled and jointly optimized based on the system status so that entire system performance can be further improved. However, this system performance gain can only be achieved at the extra expenses of system complexity and various wireless resources. In addition, the dynamic control and joint optimization between the two unequal phases durations can often quickly become intractable because dynamic control and joint optimization between the two unequal phases durations often imposes the non-convex structure of the optimization problem and complicated coupling of various control variables. Thus, to avoid this intractability, we adopt the fixed and equal-length two-phases durations scheme. Moreover, we assume that the power splitting ratio $\rho_k^{(m)}$ of ST_k over subcarrier m can only take values from $\boldsymbol{\rho}_k \triangleq \{\rho_{k,1}, \rho_{k,2}, \dots, \rho_{k,I}\}$ with $1 \le k \le K$, since ST_k can only be able to split the received power into two power streams based on a finite discrete set of power splitting ratios instead of a continuous set of power splitting ratios [15].

In addition, due to the utilization of ODPAs, the polarized signals not only experience the spatial channel fading, which captures the effects of multi-path fading, channel path loss, and shadowing, but also experience the polarization fading [13]. The effect of polarization fading can be modeled by the 2×2 channel depolarization matrix as follows:

$$\mathbf{D} = \begin{bmatrix} \mathbf{D}_{\text{HH}} & \mathbf{D}_{\text{HV}} \\ \mathbf{D}_{\text{VH}} & \mathbf{D}_{\text{VV}} \end{bmatrix}, \tag{1}$$

where $\mathbf{D}_{\text{VH}}$, for example, is the polarization-domain channel gain from the horizontally (H) polarized component of a transmitter to the vertically (V) polarized component of a receiver. Ideally, the cross-polar components, i.e., $\mathbf{D}_{\text{VH}}$ and $\mathbf{D}_{\text{HV}}$, should be equal to zero. However, this is actually not the case owing to the imperfect antenna cross-polar isolation and the cross-polar ratio caused by propagation mediums. Moreover, in [32], based on the findings obtained from experimental-measurements results, the authors have observed that the polarization fading characterized by complex correlation coefficient magnitude changes much more slowly than the spatial channel fading characterized by envelope correlation coefficient. Hence, the polarization fading changes much more slowly than the spatial channel fading, and then similar to [13], [29], [33, 34], we also assume that channel depolarization matrices are invariant within T.

III. Secure Resource Allocation for the DF Strategy Case

The PU transmitter and SU transmitters all send confidential signals, and their signals may be overheard by some malicious users, e.g., some malicious SU receivers. In this Section III, we consider the secure resource allocation for the case when SU transmitters adopt the decode-and-forward (DF) strategy to forward data for the PU. In Section IV, we will consider the case when the amplify-and-forward (AF) strategy is utilized by SU transmitters. When ST_k leverages the DF strategy to relay PT's data over subcarrier pair (SP) (m,n), we consider the scenario when all $SR_{k'}$'s, $k' \neq k$, try to eavesdrop on PT's information that is sent by PT over subcarrier m in Phase-I and that is forwarded by ST_k over subcarrier n in Phase-II. Moreover, $SR_{k'}$'s, $k' \neq k$, also try to overhear ST_k's signals over subcarrier n in Phase-II. Please notice that, for cooperation, we assume that SR_k will not overhear PT's signals over the assigned SP (m,n).

A. Secrecy Rate and Harvested Energy

Suppose that PT cooperates with SU transmitter ST_k over SP (m,n). We let $h_{\text{T},k}^{(m)}$ and $f_{\text{T},k}^{(m)}$ be the spatial channel fading gains of $PT \to ST_k$ and $PT \to SR_k$ on subcarrier m in Phase-I, respectively, while $h_{k,\text{R}}^{(n)}$ and $h_{k,k}^{(n)}$ denote the spatial channel fading gains of $ST_k \to PR$ and $ST_k \to SR_k$ over subcarrier n in Phase-II, respectively. In Phase-I, PT transmits an information signal $s_{\text{T}}^{(m)}$ $\left(E\left[\left|s_{\text{T}}^{(m)}\right|^2\right]=1\right)$ with power $P_{\text{T},k,i}^{(m)}$ to ST_k over subcarrier m. Here, the sub-index i in $P_{\text{T},k,i}^{(m)}$ means that power splitting ratio $\rho_{k,i} \in \boldsymbol{\rho}_k$, $1 \le i \le I$, is used at ST_k. Then, with power splitting ratio $\rho_{k,i}$, the primary signal received at ST_k over subcarrier m, denoted by $\mathbf{r}_{\text{T},k}^{(m)}$, is

$$\mathbf{r}_{\text{T},k}^{(m)} = h_{\text{T},k}^{(m)} \sqrt{\rho_{k,i} P_{\text{T},k,i}^{(m)}} \mathbf{D}_{\text{T},k}^{(m)} \begin{bmatrix} 0 \\ \exp\left\{j\delta_{\text{T}}^{(m)}\right\} \end{bmatrix} s_{\text{T}}^{(m)} + \mathbf{n}_k, \tag{2}$$

where $\mathbf{D}_{\text{T},k}^{(m)}$ is the channel depolarization matrix of link $PT \to ST_k$ over subcarrier m, and the 2-D signal $\mathbf{n}_k$ is the noise at ST_k's ODPA, where the noise power at each polarization branch is σ^2. Also, $\left[0, \exp\left\{j\delta_{\text{T}}^{(m)}\right\}\right]^T$ is PT's polarization state, which implies that PT's antenna is vertically polarized with a phase $\delta_{\text{T}}^{(m)}$ over subcarrier m and $j \triangleq \sqrt{-1}$.

In order to forward PT's signals, ST_k adopts the polarization combining technique [29] to combine the vertical and horizontal components of $\mathbf{r}_{\text{T},k}^{(m)}$ at the energy level. Then, a scalar signal $r_{\text{T},k}^{(m)}$ is yielded, which can be expressed as:

$$r_{\text{T},k}^{(m)} = h_{\text{T},k}^{(m)} \sqrt{\rho_{k,i} P_{\text{T},k,i}^{(m)}} s_{\text{T}}^{(m)} + n_k, \tag{3}$$

where the variance of the combined noise n_k is $2\sigma^2$, since noises at both the vertical and horizontal branches are combined [29]. Hence, if power splitting ratio $\rho_{k,i}$ is used at ST_k, the achievable rate between PT and ST_k over subcarrier m, denoted by $R_{\mathrm{T},k,i}^{(m)}$, can be given as:

$$R_{\mathrm{T},k,i}^{(m)} = C\left(\rho_{k,i} P_{\mathrm{T},k,i}^{(m)} \frac{\Gamma_{\mathrm{T},k}^{(m)}}{2}\right), \tag{4}$$

where $C(x) \triangleq \frac{1}{2}\log_2(1+x)$, and $\Gamma_{\mathrm{T},k}^{(m)} \triangleq \left|h_{\mathrm{T},k}^{(m)}\right|^2/\sigma^2$.

When ST_k cooperates with PT over SP (m,n), similar to Eq. (4), we can write the achievable rate from PT to eavesdropper SR_e, $e \neq k$, over subcarrier m in Phase-I, denoted by $R_{\mathrm{T},e,i}^{(m)}$, as:

$$R_{\mathrm{T},e,i}^{(m)} = C\left(P_{\mathrm{T},k,i}^{(m)} \frac{\Gamma_{\mathrm{T},e}^{(m)}}{2}\right), \tag{5}$$

where $\Gamma_{\mathrm{T},e}^{(m)} \triangleq \left|f_{\mathrm{T},e}^{(m)}\right|^2/\sigma^2$. Besides, notice that we utilize SR_e when referring to an SU receiver as an information eavesdropper.

Since ST_k adopts the DF strategy to forward PT's signals, in Phase-II, ST_k first decodes PT's signal $s_{\mathrm{T}}^{(m)}$ from the above-generated scalar signal $r_{\mathrm{T},k}^{(m)}$. Then, over subcarrier n, ST_k forwards $s_{\mathrm{T}}^{(m)}$ using polarization state $\mathbf{z}_{k,\mathrm{R}}^{(n)}$, and meanwhile transmits its own signal $s_k^{(n)}$ $\left(E\left[\left|s_k^{(n)}\right|^2\right]=1\right)$ using polarization state $\mathbf{z}_{k,k}^{(n)}$. Therefore, with power splitting ratio $\rho_{k,i}$, the transmitted signal at ST_k in Phase-II over subcarrier n can be expressed as:

$$\sqrt{P_{k,\mathrm{R},i}^{(n)}}\mathbf{z}_{k,\mathrm{R}}^{(n)} s_{\mathrm{T}}^{(m)} + \sqrt{P_{k,i}^{(n)}}\mathbf{z}_{k,k}^{(n)} s_k^{(n)}, \tag{6}$$

where $P_{k,\mathrm{R},i}^{(n)}$ and $P_{k,i}^{(n)}$ are the transmit powers from ST_k to PR and SR_k over subcarrier n, respectively. Analyzing Eq. (6), we know that the received signals at PR and SR_k over subcarrier n in Phase-II, denoted by $r_{k,\mathrm{R}}^{(n)}$ and $\mathbf{r}_{k,k}^{(n)}$, respectively, can be expressed as:

$$\begin{cases} r_{k,\mathrm{R}}^{(n)} = \left(\mathbf{U}_{k,\mathrm{R}}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)}\sqrt{P_{k,\mathrm{R},i}^{(n)}}s_{\mathrm{T}}^{(m)} + \mathbf{U}_{k,\mathrm{R}}^{(n)}\mathbf{z}_{k,k}^{(n)}\sqrt{P_{k,i}^{(n)}}s_k^{(n)}\right)_{\mathrm{V}} + n_{\mathrm{R}} & (7) \\ \mathbf{r}_{k,k}^{(n)} = \mathbf{U}_{k,k}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)}\sqrt{P_{k,\mathrm{R},i}^{(n)}}s_{\mathrm{T}}^{(m)} + \mathbf{U}_{k,k}^{(n)}\mathbf{z}_{k,k}^{(n)}\sqrt{P_{k,i}^{(n)}}s_k^{(n)} + \mathbf{n}_k & (8) \end{cases}$$

where $\mathbf{U}_{k,\mathrm{R}}^{(n)} \triangleq \mathbf{D}_{k,\mathrm{R}}^{(n)} h_{k,\mathrm{R}}^{(n)}$ and $\mathbf{U}_{k,k}^{(n)} \triangleq \mathbf{D}_{k,k}^{(n)} h_{k,k}^{(n)}$, and $\mathbf{D}_{k,\mathrm{R}}^{(n)}$ and $\mathbf{D}_{k,k}^{(n)}$ are the channel depolarization matrices of $ST_k \to PR$ and $ST_k \to SR_k$ over subcarrier n, respectively. Moreover, in Eq. (7), $(x)_{\mathrm{V}}$ indicates the extraction of the vertical polarization component in x, because PR can only receive the V-polarized signals. Also, n_{R} is the noise at PR, and the variance is σ^2.

Note that the term $\mathbf{U}_{k,\mathrm{R}}^{(n)}\mathbf{z}_{k,k}^{(n)}\sqrt{P_{k,i}^{(n)}}s_k^{(n)}$ in Eq. (7) is the interference from ST_k to PR. Fortunately, this interference term can be nullified by choosing a suitable $\mathbf{z}_{k,k}^{(n)}$ by ST_k such that $\mathbf{U}_{k,\mathrm{R}}^{(n)}\mathbf{z}_{k,k}^{(n)}\sqrt{P_{k,i}^{(n)}}s_k^{(n)} = [0,0]^T$, when the depolarization matrix $\mathbf{D}_{k,\mathrm{R}}^{(n)}$ is known. This operation is termed the polarization zero-forcing [29]. In addition, to maximize the reception performance at PR, ST_k can set $\mathbf{z}_{k,\mathrm{R}}^{(n)}$ to render $\mathbf{U}_{k,\mathrm{R}}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)} = [0, h_{k,\mathrm{R}}^{(n)}]^T$ (i.e., $\mathbf{D}_{k,\mathrm{R}}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)} = [0,1]^T$) in Eq. (7), so that the signal in Eq. (7) transfers to a pure vertically polarized signal [29]. Then, the received signal at PR in Phase-II can be re-written as:

$$r_{k,\mathrm{R}}^{(n)} = h_{k,\mathrm{R}}^{(n)}\sqrt{P_{k,\mathrm{R},i}^{(n)}}s_{\mathrm{T}}^{(m)} + n_{\mathrm{R}}. \tag{9}$$

Moreover, observing Eq. (8), although SR_k may be able to overhear PT's information from the term $\mathbf{U}_{k,k}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)}\sqrt{P_{k,\mathrm{R},i}^{(n)}}s_{\mathrm{T}}^{(m)}$, for cooperation as stated above and for improving its own reception performance, SR_k chooses to suppress the term $\mathbf{U}_{k,k}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)}\sqrt{P_{k,\mathrm{R},i}^{(n)}}s_{\mathrm{T}}^{(m)}$ and extract its own signal by using the oblique projection polarization filtering technique [13]. Then, SR_k can use the polarization combining technique to convert its received signal into a scalar signal. Therefore, similar to [13] and [29], we can write the achievable rates at PR and SR_k from ST_k over subcarrier n in Phase-II, denoted by $R_{k,\mathrm{R},i}^{(n)}$ and $R_{k,k,i}^{(n)}$, respectively, as:

$$\begin{cases} R_{k,\mathrm{R},i}^{(n)} = C\left(P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,\mathrm{R}}^{(n)}\right), & (10) \\ R_{k,k,i}^{(n)} = C\left(P_{k,i}^{(n)}\frac{\Gamma_{k,k}^{(n)}\sin^2\left(\varphi_k^{(n)}\right)}{2}\right), & (11) \end{cases}$$

where $\Gamma_{k,\mathrm{R}}^{(n)} \triangleq \left|h_{k,\mathrm{R}}^{(n)}\right|^2/\sigma^2$ and $\Gamma_{k,k}^{(n)} \triangleq \left|h_{k,k}^{(n)}\right|^2/\sigma^2$. Besides, $\varphi_k^{(n)}$ in Eq. (11) is the principal angle between the subspaces $\left\langle\boldsymbol{\pi}_{k,\mathrm{R}}^{(n)}\right\rangle$ and $\left\langle\boldsymbol{\pi}_{k,k}^{(n)}\right\rangle$ [32], where $\boldsymbol{\pi}_{k,\mathrm{R}}^{(n)} \triangleq \mathbf{D}_{k,k}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)}$ and $\boldsymbol{\pi}_{k,k}^{(n)} \triangleq \mathbf{D}_{k,k}^{(n)}\mathbf{z}_{k,k}^{(n)}$.

According to Eqs. (4) and (10), we can obtain that when ST_k is selected to relay PT's information over SP (m,n) using the DF strategy and power splitting ratio $\rho_{k,i}$, PT's transmission rate over SP (m,n), denoted by $R_{\mathrm{T},k,i}^{(m,n)}$, can be given by:

$$R_{\mathrm{T},k,i}^{(m,n)} = \min\left\{R_{\mathrm{T},k,i}^{(m)}, R_{k,\mathrm{R},i}^{(n)}\right\}. \tag{12}$$

In addition, similar to Eq. (8), the received signal at each eavesdropper SR_e, $e \neq k$, in Phase-II, denoted by $\mathbf{r}_{k,e}^{(n)}$, can be expressed as:

$$\mathbf{r}_{k,e}^{(n)} = \mathbf{U}_{k,e}^{(n)}\mathbf{z}_{k,\mathrm{R}}^{(n)}\sqrt{P_{k,\mathrm{R},i}^{(n)}}s_{\mathrm{T}}^{(m)} + \mathbf{U}_{k,e}^{(n)}\mathbf{z}_{k,k}^{(n)}\sqrt{P_{k,i}^{(n)}}s_k^{(n)} + \mathbf{n}_e, \tag{13}$$

where $\mathbf{U}_{k,e}^{(n)} \triangleq \mathbf{D}_{k,e}^{(n)} h_{k,e}^{(n)}$, and $\mathbf{D}_{k,e}^{(n)}$ and $h_{k,e}^{(n)}$ are the channel depolarization matrix and the spatial channel fading gain of $ST_k \to SR_e$, $e \neq k$, respectively. Besides, $\mathbf{n}_e$ is the 2-D noise at SR_e's ODPA, and the noise power at each polarization branch of SR_e's ODPA is σ^2.

We assume that each eavesdropper SR_e, $e \neq k$, cannot differentiate and extract PT's and ST_k's signals, which can be guaranteed by preventing SR_e from being aware of the polarization states $\mathbf{z}_{k,\mathrm{R}}^{(n)}$ and $\mathbf{z}_{k,k}^{(n)}$. As such, SR_e cannot extract PT's and ST_k's signals by using the oblique projection polarization filtering technique. Then, similar to Eq. (11), the maximum rates at which SR_e overhears PT's and ST_k's signals in Phase-II, denoted by $R_{\mathrm{T},e,i}^{(n)}$ and $R_{k,e,i}^{(n)}$, respectively, can be written as:

$$\begin{cases} R_{\mathrm{T},e,i}^{(n)} = C\left(\frac{P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,e}^{(n)}}{P_{k,i}^{(n)}\Gamma_{k,e}^{(n)} + 2}\right), & (14) \\ R_{k,e,i}^{(n)} = C\left(\frac{P_{k,i}^{(n)}\Gamma_{k,e}^{(n)}}{P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,e}^{(n)} + 2}\right), & (15) \end{cases}$$

where $\Gamma_{k,e}^{(n)} \triangleq \left|h_{k,e}^{(n)}\right|^2/\sigma^2$. Using Eqs. (14) and (15), we can see that due to the concurrent transmission of both PT's and ST_k's signals at ST_k using ODPAs, SR_e's information eavesdropping rates $R_{\mathrm{T},e,i}^{(n)}$ and $R_{k,e,i}^{(n)}$, $e \neq k$, can be decreased, and then both PT's and ST_k's physical-layer security performance can be enhanced.

All eavesdroppers SR_e's, $e \neq k$, adopt the selective combining approach to deal with PT's signals that are overheard in Phase-I and Phase-II over SP (m,n). Then, using Eqs. (5), (12), and (14), we can express the secrecy rate of PT over SP (m,n), denoted by $SR_{\mathrm{T},k,i}^{(m,n)}$, as:

$$\begin{aligned} SR_{\mathrm{T},k,i}^{(m,n)} &= \left[R_{\mathrm{T},k,i}^{(m,n)} - \max_{e\neq k}\left\{R_{\mathrm{T},e,i}^{(m,n)}\right\}\right]^{+} \\ &= \Big[\min\left\{R_{\mathrm{T},k,i}^{(m)}, R_{k,\mathrm{R},i}^{(n)}\right\} \\ &\qquad - \max_{e\neq k}\left\{\max\left\{R_{\mathrm{T},e,i}^{(m)}, R_{\mathrm{T},e,i}^{(n)}\right\}\right\}\Big]^{+}, \end{aligned} \tag{16}$$

where $[x]^{+} \triangleq \max\{x, 0\}$, $R_{\mathrm{T},k,i}^{(m,n)}$ (see Eq. (12)) is PT's transmission rate when cooperating with ST_k over SP (m,n), and $R_{\mathrm{T},e,i}^{(m,n)} \triangleq \max\left\{R_{\mathrm{T},e,i}^{(m)}, R_{\mathrm{T},e,i}^{(n)}\right\}$ is SR_e's maximum rate to overhear PT's information signals. Furthermore, over SP (m,n), the secrecy rate $SR_{\mathrm{T},k,i}^{(m,n)}$ quantifies the maximum achievable rate at which PT can reliably send its confidential messages to PR while all eavesdroppers are unable to decode the received messages [17].

Similarly, using Eqs. (11) and (15), when power splitting ratio $\rho_{k,i}$ is utilized, we can write the secrecy rate of ST_k over subcarrier n in Phase-II, denoted by $SR_{k,i}^{(n)}$, as:

$$SR_{k,i}^{(n)} = \left[R_{k,k,i}^{(n)} - \max_{e\neq k}\left\{R_{k,e,i}^{(n)}\right\}\right]^{+}. \tag{17}$$

Moreover, for SP (m,n), the harvested energy of each SU transmitter ST_k over subcarrier m in Phase-I, denoted by $Q_k^{(m,n)}$, can be given by:

$$\begin{aligned} Q_k^{(m,n)} &= \frac{T}{2}\eta_k\left(1-\sum_{i=1}^{I}\rho_{k,i}w_{k,i}^{(m,n)}\right) \\ &\quad\times\left(\sum_{k'=1}^{K}\sum_{i=1}^{I}w_{k',i}^{(m,n)}P_{\mathrm{T},k',i}^{(m)}\right)\left|h_{\mathrm{T},k}^{(m)}\right|^2, \end{aligned} \tag{18}$$

where $0<\eta_k<1$ is ST_k's energy conversion efficiency. Besides, $w_{k,i}^{(m,n)} \in \{0,1\}$, where $w_{k,i}^{(m,n)}=1$ implies that ST_k is selected to cooperate with PT over SP (m,n) with $\rho_{k,i}$; $w_{k,i}^{(m,n)}=0$ otherwise. Similarly, we can explain $w_{k',i}^{(m,n)}$.

B. Optimization Problem Formulation

While the ODPAs are the key techniques applied in both [13] and our this paper for cooperative CRNs, the designing goals, implementation architectures, and assumptions are very different between these two papers. Using ODPAs, the authors of [13] had proposed a two-phase cooperative framework for cooperative CRNs consisting of one PU and two trusted cooperative SUs, with the objective to maximize the system throughputs. Unlike [13], in this paper we aim at optimizing the secure communication for OFDMA-based cooperative CRNs while taking into account multiple untrusted and EH-based SUs which have not been considered in [13]. Towards that end, we aim at guaranteeing the PU's and all SUs' secure communications and enabling each SU to have the energy harvesting capability. Consequently, we need to propose and develop our architectures and schemes to jointly optimize the allocation of relays, subcarriers, power splitting ratios, and powers, which are different implementation architectures as compared with those in [13]. We formulate the secure resource allocation problem as follows:

$$\max_{\mathcal{W},\,\mathcal{P}}\left\{\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)}SR_{k,i}^{(n)}\right\} \tag{19}$$

s.t.

$$\begin{aligned} &C1: \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)}SR_{\mathrm{T},k,i}^{(m,n)} \geq R_{\mathrm{T}}^{\min}, \\ &C2: \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)}\left(P_{k,\mathrm{R},i}^{(n)}+P_{k,i}^{(n)}\right)\frac{T}{2}+P_k^{\mathrm{c}}T \\ &\qquad\qquad \leq \sum_{m=1}^{N}\sum_{n=1}^{N}Q_k^{(m,n)}+B_k^{\mathrm{o}}, \forall k, \\ &C3: \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)}P_{\mathrm{T},k,i}^{(m)} \leq P_{\mathrm{T}}^{\max}, \\ &C4: \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)}\left(P_{k,\mathrm{R},i}^{(n)}+P_{k,i}^{(n)}\right) \leq P_k^{\max}, \forall k, \\ &C5: \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)} \leq 1, \forall m, \\ &C6: \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)} \leq 1, \forall n, \\ &C7: \sum_{i=1}^{I}w_{k,i}^{(m,n)} \leq 1, \forall m,n,k, \\ &C8:\; w_{k,i}^{(m,n)} \in \{0,1\}, \forall k, \forall m, \forall n, \forall i, \end{aligned}$$

where $\mathcal{W} \triangleq \left\{w_{k,i}^{(m,n)} \in \{0,1\}, \forall k,i,m,n\right\}$, $\mathcal{P} \triangleq \Big\{0 \leq P_{\mathrm{T},k,i}^{(m)} \leq P_{\mathrm{T}}^{\max}, 0 \leq P_{k,\mathrm{R},i}^{(n)}, P_{k,i}^{(n)} \leq P_k^{\max}, \forall k,i,m,n\Big\}$. Besides, P_k^{c} is ST_k's constant circuit power consumption, and B_k^{o} is ST_k's initial energy. $C1$ is the QoS guarantee, i.e., the minimum secrecy rate requirement, of PT. $C2$ states that the total consumed energy of ST_k cannot exceed the sum of its initial energy B_k^{o} and its harvested energy. $C3-C4$ are the total transmit power constraints for PT and ST_k, respectively, where $P_{\mathrm{T}}^{\max}$ and $P_k^{\max}$ are the maximum transmit powers of PT and ST_k, respectively. $C5-C8$ guarantee that each subcarrier can be at most used one time in each transmission phase, and at most one power splitting ratio can be utilized by ST_k over SP (m,n).

C. Dual Problem Formulation

The problem given in Eq. (19) is a non-convex mixed integer and nonlinear programming problem. Using the Lagrangian dual method, we can derive its asymptotically optimal solution [35]. The harvested energy $Q_k^{(m,n)}$ (see Eq. (18)) not only relates to ST_k's transmit powers $P_{\mathrm{T},k,i}^{(m)}$'s, $\forall i$, but also relates to other $ST_{k'}$'s transmit powers $P_{\mathrm{T},k',i}^{(m)}$'s, $\forall k' \neq k, \forall i$. Therefore, to decompose the problem specified by Eq. (19) into some subproblems, we first introduce the following variables. Define $\mathcal{D}$ as the set of all possible user cooperation policies $\mathcal{W}$'s satisfying $C5-C8$. In addition, define $\mathcal{P}_{\mathcal{S}}(\mathcal{W})$ as the set of all possible power allocations $\mathcal{P}$'s for the given user cooperation policy $\mathcal{W}$, where $P_{\mathrm{T},k,i}^{(m)}$, $P_{k,\mathrm{R},i}^{(n)}$, $P_{k,i}^{(n)}$, $SR_{\mathrm{T},k,i}^{(m,n)}$, $SR_{k,i}^{(n)} \geq 0$

for $w_{k,i}^{(m,n)} = 1$, and $P_{\mathrm{T},k,i}^{(m)} = P_{k,\mathrm{R},i}^{(n)} = P_{k,i}^{(n)} = SR_{\mathrm{T},k,i}^{(m,n)} = SR_{k,i}^{(n)} = 0$ for $w_{k,i}^{(m,n)} = 0$. Then, based on the definition of the above variables, i.e., $\mathcal{D}$ and $\mathcal{P}_{\mathcal{S}}(\mathcal{W})$, we can write the Lagrange dual function of the primal problem given in Eq. (19) as follows:

$$g(\boldsymbol{\phi}) \triangleq \max_{\substack{\mathcal{W}\in\mathcal{D} \\ \mathcal{P}\in\mathcal{P}_{\mathcal{S}}(\mathcal{W})}} \left\{\mathcal{L}(\mathcal{W},\mathcal{P},\boldsymbol{\phi})\right\}, \tag{20}$$

where the Lagrangian $\mathcal{L}(\mathcal{W},\mathcal{P},\boldsymbol{\phi})$ is given by:

$$\begin{aligned}
&\mathcal{L}(\mathcal{W},\mathcal{P},\boldsymbol{\phi}) \\
&= \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I} SR_{k,i}^{(n)} + \sum_{k=1}^{K}\chi_k\Bigg(\sum_{m=1}^{N}\sum_{n=1}^{N} Q_k^{(m,n)} \\
&\quad + B_k^{\mathrm{o}} - P_k^{\mathrm{c}}T - \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}\left(P_{k,\mathrm{R},i}^{(n)} + P_{k,i}^{(n)}\right)\frac{T}{2}\Bigg) \\
&\quad + \sum_{k=1}^{K}\beta_k\left(P_k^{\max} - \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}\left(P_{k,\mathrm{R},i}^{(n)} + P_{k,i}^{(n)}\right)\right) \\
&\quad + \mu\left(P_{\mathrm{T}}^{\max} - \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I} P_{\mathrm{T},k,i}^{(m)}\right) \\
&\quad + \lambda\left(\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I} SR_{\mathrm{T},k,i}^{(m,n)} - R_{\mathrm{T}}^{\min}\right),
\end{aligned} \tag{21}$$

where $\boldsymbol{\phi} \triangleq [\lambda, \mu, \chi_k, \beta_k]^T, \forall k$, is the Lagrange multiplier vector, and due to the introduction of $\mathcal{D}$ and $\mathcal{P}_{\mathcal{S}}(\mathcal{W})$, we can omit $w_{k,i}^{(m,n)}$'s in this equation. Then, the dual problem for the primal problem in Eq. (19) is:

$$\min_{\boldsymbol{\phi}\succeq 0} \quad \{g(\boldsymbol{\phi})\}. \tag{22}$$

We can derive the solution of the primal problem given in Eq. (19) by solving its dual problem specified by Eq. (22). For the dual problem given in Eq. (22), we can use an iterative approach to solve it. In each iteration, we first calculate the optimal solution $\{\mathcal{W}(\boldsymbol{\phi}), \mathcal{P}(\boldsymbol{\phi})\}$ to the optimization problem specified by Eq. (20) for given $\boldsymbol{\phi}$. Then, the obtained solution of Eq. (20) is used for updating $\boldsymbol{\phi}$ by using the following subgradient method [36]

$$\boldsymbol{\phi}(l+1) = [\boldsymbol{\phi}(l) - \epsilon(l)\, d(\boldsymbol{\phi}(l))]^{+}, \tag{23}$$

where $d(\boldsymbol{\phi})$ is the subgradient of $g(\boldsymbol{\phi})$ at $\boldsymbol{\phi}$ with $d(\boldsymbol{\phi}) = \nabla_{\boldsymbol{\phi}}\mathcal{L}(\mathcal{W}(\boldsymbol{\phi}), \mathcal{P}(\boldsymbol{\phi}), \boldsymbol{\phi})$. The convergence of $\boldsymbol{\phi}$ can be guaranteed by the diminishing step size, e.g., $\epsilon(l) = 1/l$, $l \in \{1, 2, \cdots\}$ [36]. Once $\boldsymbol{\phi}$ converges to the optimal solution $\boldsymbol{\phi}^{\dagger}$, we can obtain the dual-problem-domain optimal solution $\{\mathcal{W}^{\dagger}, \mathcal{P}^{\dagger}\}$ by solving the dual problem given in Eq. (22), where $(\cdot)^{\dagger}$ denotes the optimal solution of one function $(\cdot)$. The solution $\{\mathcal{W}^{\dagger}, \mathcal{P}^{\dagger}\}$ is asymptotically optimal due to the vanishing duality gap when the subcarrier number N is sufficiently large [35]. Hence, we can use it as the primal-problem-domain optimal solution to the primal problem given in Eq. (19).

D. Optimizing Primal Variables for Given Lagrange Multipliers

According to the above discussion, we know that getting the optimal solution $\{\mathcal{W}(\boldsymbol{\phi}), \mathcal{P}(\boldsymbol{\phi})\}$ to the optimization problem specified by Eq. (20) for given $\boldsymbol{\phi}$ is a key step to solve the dual problem given in Eq. (22). We will present the detailed derivation of $\{\mathcal{W}(\boldsymbol{\phi}), \mathcal{P}(\boldsymbol{\phi})\}$. Before that, let us re-write $g(\boldsymbol{\phi})$ defined in Eq. (20) as follows:

$$\begin{aligned}
g(\boldsymbol{\phi}) = &\max_{\substack{\mathcal{W}\in\mathcal{D} \\ \mathcal{P}\in\mathcal{P}_{\mathcal{S}}(\mathcal{W})}} \left\{\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}\mathcal{L}_{k,i}^{(m,n)}\right\} - \lambda R_{\mathrm{T}}^{\min} \\
&+ \mu P_{\mathrm{T}}^{\max} + \sum_{k=1}^{K}\chi_k\left(B_k^{\mathrm{o}} - P_k^{\mathrm{c}}T\right) + \sum_{k=1}^{K}\beta_k P_k^{\max},
\end{aligned} \tag{24}$$

where $\mathcal{L}_{k,i}^{(m,n)}$ is given by:

$$\begin{aligned}
\mathcal{L}_{k,i}^{(m,n)} &= SR_{k,i}^{(n)} + \lambda SR_{\mathrm{T},k,i}^{(m,n)} - \mu P_{\mathrm{T},k,i}^{(m)} \\
&\quad - \left(\frac{T\chi_k}{2} + \beta_k\right)\left(P_{k,\mathrm{R},i}^{(n)} + P_{k,i}^{(n)}\right) \\
&\quad + \frac{T}{2}\chi_k\eta_k\left(1-\rho_{k,i}\right)P_{\mathrm{T},k,i}^{(m)}\left|h_{\mathrm{T},k}^{(m)}\right|^2 \\
&\quad + \sum_{k'\neq k}\frac{T}{2}\chi_{k'}\eta_{k'}P_{\mathrm{T},k,i}^{(m)}\left|h_{\mathrm{T},k'}^{(m)}\right|^2,
\end{aligned} \tag{25}$$

where the second and third rows are related to the energy $Q_k^{(m,n)}$ and $Q_{k'}^{(m,n)}$'s harvested by ST_k and $ST_{k'}$'s, $k' \neq k$, over SP (m,n), respectively, when $w_{k,i}^{(m,n)} = 1$.

Observing Eqs. (24) and (25), we know that the definitions of $\mathcal{D}$ and $\mathcal{P}_{\mathcal{S}}(\mathcal{W})$ enable us to present $\mathcal{L}(\mathcal{W},\mathcal{P},\boldsymbol{\phi})$ in Eq. (20) in a simple form, which makes the problem given in Eq. (20) easily tractable mathematically by considering $\mathcal{L}_{k,i}^{(m,n)}$'s. In $\mathcal{L}_{k,i}^{(m,n)}$, different from Eq. (18), the harvested energy of each SU transmitter over SP (m,n) can be expressed in a simple expression (see the second and third rows in Eq. (25)), which is only related to ST_k's power $P_{\mathrm{T},k,i}^{(m)}$. This enlightens us to solve the problem given in Eq. (20) based on $\mathcal{L}_{k,i}^{(m,n)}$'s by the following two steps.

1) Power Allocation Policy: Suppose that ST_k cooperates with PT over SP (m,n) with power splitting ratio $\rho_{k,i}$, i.e., $w_{k,i}^{(m,n)} = 1$. Then, for given $\boldsymbol{\phi}$, PT can determine the power allocation over assignment unit (k,i,m,n) by solving the following subproblem:

$$\max_{\left\{P_{\mathrm{T},k,i}^{(m)},\, P_{k,\mathrm{R},i}^{(n)},\, P_{k,i}^{(n)}\right\}} \left\{\mathcal{L}_{k,i}^{(m,n)}\right\}, \tag{26}$$

where $0 \leq P_{\mathrm{T},k,i}^{(m)} \leq P_{\mathrm{T}}^{\max}$ and $0 \leq P_{k,\mathrm{R},i}^{(n)}, P_{k,i}^{(n)} \leq P_k^{\max}$. To solve the optimization problem specified by Eq. (26), we first give the following lemmas and theorems to simplify the expressions of the secrecy rates $SR_{\mathrm{T},k,i}^{(m,n)}$'s and $SR_{k,i}^{(n)}$'s.

Lemma 1: The secrecy rate $SR_{\mathrm{T},k,i}^{(m,n)}$ given in Eq. (16) and the secrecy rate $SR_{k,i}^{(n)}$ given in Eq. (17) can be re-written as:

$$\begin{cases}
SR_{\mathrm{T},k,i}^{(m,n)} = \Big[\min\left\{R_{\mathrm{T},k,i}^{(m)}, R_{k,\mathrm{R},i}^{(n)}\right\} \\
\qquad\qquad - \max\left\{ER_{\mathrm{T},k,i}^{(m)}, ER_{\mathrm{T},k,i}^{(n)}\right\}\Big]^{+}, & (27) \\
SR_{k,i}^{(n)} = \left[R_{k,k,i}^{(n)} - ER_{\mathrm{S},k,i}^{(n)}\right]^{+}, & (28)
\end{cases}$$

respectively, where

$$\begin{cases} ER_{\text{T},k,i}^{(m)} \triangleq \max_{e \neq k} \left\{ R_{\text{T},e,i}^{(m)} \right\} = C\left(P_{\text{T},k,i}^{(m)} \max_{e \neq k} \left\{ \frac{\Gamma_{\text{T},e}^{(m)}}{2} \right\} \right) & (29) \\ ER_{\text{T},k,i}^{(n)} \triangleq \max_{e \neq k} \left\{ R_{\text{T},e,i}^{(n)} \right\} = C\left(\frac{P_{k,\text{R},i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}}{P_{k,i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} + 2} \right) & (30) \\ ER_{\text{S},k,i}^{(n)} \triangleq \max_{e \neq k} \left\{ R_{k,e,i}^{(n)} \right\} = C\left(\frac{P_{k,i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}}{P_{k,\text{R},i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} + 2} \right) & (31) \end{cases}$$

and $ER_{\text{T},k,i}^{(m)}$ and $ER_{\text{T},k,i}^{(n)}$ are the maximum eavesdropping rates at which information eavesdroppers, i.e., SR_e's, $e \neq k$, overhear the PU's information over subcarriers m and n, respectively, when ST_k is selected to cooperative with PT over SP (m, n). Similarly, $ER_{\text{S},k,i}^{(n)}$ is the maximum eavesdropping rate at which SR_e's, $e \neq k$, overhear ST_k's information over subcarrier n.

Proof: Observing Eq. (16), we can re-write PT's secrecy rate $SR_{\text{T},k,i}^{(m,n)}$ as follows:

$$SR_{\text{T},k,i}^{(m,n)} = \Big[\min \left\{ R_{\text{T},k,i}^{(m)}, R_{k,\text{R},i}^{(n)} \right\} - \max \left\{ \max_{e \neq k} \left\{ R_{\text{T},e,i}^{(m)} \right\}, \max_{e \neq k} \left\{ R_{\text{T},e,i}^{(n)} \right\} \right\} \Big]^+. \quad (32)$$

Besides, it can be verified that, when $P_{\text{T},k,i}^{(m)} \geq 0$, $P_{k,\text{R},i}^{(n)} \geq 0$, and $P_{k,i}^{(n)} \geq 0$, $R_{\text{T},e,i}^{(m)}$ and $R_{\text{T},e,i}^{(n)}$ given in Eqs. (5) and (14) are monotonically increasing functions of $\Gamma_{\text{T},e}^{(m)}$ and $\Gamma_{k,e}^{(n)}$, respectively. Together with Eq. (32), we can derive Eq. (27). Similarly, we can derive Eq. (28) from Eq. (17). ■

Theorem 1: The secrecy rate $SR_{\text{T},k,i}^{(m,n)}$ given in Eq. (27) and the secrecy rate $SR_{k,i}^{(n)}$ given in Eq. (28) can be further re-written as:

$$SR_{\text{T},k,i}^{(m,n)} = \frac{1}{2} \left[\log_2 \left(\frac{1 + P_{k,\text{R},i}^{(n)} \Gamma_{k,\text{R}}^{(n)}}{1 + \frac{P_{k,\text{R},i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}}{P_{k,i}^{(n)}(\boldsymbol{\phi}) \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} + 2}} \right) \right]^+, \quad (33)$$

and

$$SR_{k,i}^{(n)} = \frac{1}{2} \left[\log_2 \left(\frac{1 + P_{k,i}^{(n)}(\boldsymbol{\phi}) \frac{\Gamma_{k,k}^{(n)} \sin^2\left(\varphi_k^{(n)}\right)}{2}}{1 + \frac{P_{k,i}^{(n)}(\boldsymbol{\phi}) \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}}{P_{k,\text{R},i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} + 2}} \right) \right]^+, \quad (34)$$

respectively, where the optimal $P_{k,i}^{(n)}(\boldsymbol{\phi})$ for given $\boldsymbol{\phi}$ is

$$P_{k,i}^{(n)}(\boldsymbol{\phi}) = \left[\frac{\rho_{k,i} \Gamma_{\text{T},k}^{(m)}}{\Gamma_{k,\text{R}}^{(n)} \max_{e \neq k} \left\{ \Gamma_{\text{T},e}^{(m)} \right\}} - \frac{2}{\max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}} \right]_0^{P_k^{\max}}, \quad (35)$$

where $[x]_a^b \triangleq \min\{b, \max\{x, a\}\}$ is the projection function of x with $a < b$.

Proof: Observing Eq. (27), we can further re-write PT's secrecy rate $SR_{\text{T},k,i}^{(m,n)}$ as follows:

$$SR_{\text{T},k,i}^{(m,n)} = \Big[\min \left\{ R_{\text{T},k,i}^{(m)}, R_{k,\text{R},i}^{(n)} \right\} + \min \left\{ -ER_{\text{T},k,i}^{(m)}, -ER_{\text{T},k,i}^{(n)} \right\} \Big]^+. \quad (36)$$

Following the procedure similar to that as described in [2], we can show that $\min\left\{ R_{\text{T},k,i}^{(m)}, R_{k,\text{R},i}^{(n)} \right\}$ and $\min\left\{ -ER_{\text{T},k,i}^{(m)}, -ER_{\text{T},k,i}^{(n)} \right\}$ in Eq. (36) can be maximized, respectively, and thus $SR_{\text{T},k,i}^{(m,n)}$ given in Eq. (36) can be maximized, if and only if $R_{\text{T},k,i}^{(m)} = R_{k,\text{R},i}^{(n)}$ and $ER_{\text{T},k,i}^{(m)} = ER_{\text{T},k,i}^{(n)}$ hold. Then, we can simplify $SR_{\text{T},k,i}^{(m,n)}$ as:

$$SR_{\text{T},k,i}^{(m,n)} = \left[R_{k,\text{R},i}^{(n)} - ER_{\text{T},k,i}^{(n)} \right]^+. \quad (37)$$

Moreover, using $R_{\text{T},k,i}^{(m)} = R_{k,\text{R},i}^{(n)}$ and $ER_{\text{T},k,i}^{(m)} = ER_{\text{T},k,i}^{(n)}$, we can also derive

$$\begin{cases} P_{\text{T},k,i}^{(m)} = \frac{2 P_{k,\text{R},i}^{(n)} \Gamma_{k,\text{R}}^{(n)}}{\rho_{k,i} \Gamma_{\text{T},k}^{(m)}}, & (38) \\ P_{\text{T},k,i}^{(m)} \max_{e \neq k} \left\{ \frac{\Gamma_{\text{T},e}^{(m)}}{2} \right\} = \frac{P_{k,\text{R},i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}}{P_{k,i}^{(n)} \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} + 2}, & (39) \end{cases}$$

respectively. Plugging Eq. (38) into Eq. (39), for given $\boldsymbol{\phi}$, we can obtain the optimal $P_{k,i}^{(n)}(\boldsymbol{\phi})$ that is given in Eq. (35). Then, plugging $P_{k,i}^{(n)}(\boldsymbol{\phi})$ and the expressions of $R_{k,\text{R},i}^{(n)}$ (see Eq. (10)) and $ER_{\text{T},k,i}^{(n)}$ (see Eq. (30)) into Eq. (37), we can re-write the secrecy rate $SR_{\text{T},k,i}^{(m,n)}$ as Eq. (33). Similarly, we can re-write ST_k's secrecy rate $SR_{k,i}^{(n)}$ given in Eq. (28) as Eq. (34), by plugging $P_{k,i}^{(n)}(\boldsymbol{\phi})$ and the expressions of $R_{k,k,i}^{(n)}$ (see Eq. (11)) and $ER_{\text{S},k,i}^{(n)}$ (see Eq. (31)) into Eq. (28). ■

Theorem 2: The secrecy rate $SR_{\text{T},k,i}^{(m,n)}$ given in Eq. (33) and the secrecy rate $SR_{k,i}^{(n)}$ given in Eq. (34) are both positive and concave in $P_{k,\text{R},i}^{(n)}$ under the following conditions:

$$\begin{cases} P_{k,i}^{(n)}(\boldsymbol{\phi}) > \frac{1}{\Gamma_{k,\text{R}}^{(n)}} - \frac{2}{\max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}}, & (40) \\ P_{k,\text{R},i}^{(n)} > P_k^{\text{th}} \triangleq \frac{2}{\Gamma_{k,k}^{(n)} \sin^2\left(\varphi_k^{(n)}\right)} - \frac{2}{\max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\}}. & (41) \end{cases}$$

Proof: Let the secrecy rates $SR_{\text{T},k,i}^{(m,n)} > 0$ and $SR_{k,i}^{(n)} > 0$. Since $\log_2(x) > 0$ if and only if $x > 1$, we can easily derive Eqs. (40) and (41) by letting $\left(1 + P_{k,\text{R},i}^{(n)} \Gamma_{k,\text{R}}^{(n)}\right) \Big/ \left(1 + P_{k,\text{R},i}^{(n)} \zeta_{k,1}\right) > 1$ and $\left(1 + \left(P_{k,i}^{(n)}(\boldsymbol{\phi}) \Gamma_{k,k}^{(n)} \sin^2\left(\varphi_k^{(n)}\right)\right)/2\right) \Big/ \left(1 + \zeta_{k,2}/P_{k,\text{R},i}^{(n)}\right) > 1$ in Eqs. (33) and (34), respectively, where the parameters $\zeta_{k,1} \triangleq \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} \Big/ \left(P_{k,i}^{(n)}(\boldsymbol{\phi}) \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} + 2 \right)$ and $\zeta_{k,2} \triangleq P_{k,i}^{(n)}(\boldsymbol{\phi}) \max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} \Big/ \left(\max_{e \neq k} \left\{ \Gamma_{k,e}^{(n)} \right\} + 2 \right)$. Moreover, when $SR_{\text{T},k,i}^{(m,n)} > 0$ and $SR_{k,i}^{(n)} > 0$, i.e., Eqs. (40) and

(41) holding, the second derivatives of $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ with respect to $P_{k,\mathrm{R},i}^{(n)}$ can be given by:

$$\begin{cases} \frac{\partial^2 SR_{\mathrm{T},k,i}^{(m,n)}}{\partial\left(P_{k,\mathrm{R},i}^{(n)}\right)^2} = \frac{1}{\log 2}\frac{\left(\zeta_{k,1}-\Gamma_{k,\mathrm{R}}^{(n)}\right)}{\left(1+\Gamma_{k,\mathrm{R}}^{(n)}P_{k,\mathrm{R},i}^{(n)}\right)^2\left(1+\zeta_{k,1}P_{k,\mathrm{R},i}^{(n)}\right)^2} \\ \qquad\qquad \times\left(2\Gamma_{k,\mathrm{R}}^{(n)}\zeta_{k,1}P_{k,\mathrm{R},i}^{(n)}+\zeta_{k,1}+\Gamma_{k,\mathrm{R}}^{(n)}\right), & (42) \\ \frac{\partial^2 SR_{k,i}^{(n)}}{\partial\left(P_{k,\mathrm{R},i}^{(n)}\right)^2} = -\frac{1}{2\log 2}\frac{\zeta_{k,2}\left(2P_{k,\mathrm{R},i}^{(n)}+\zeta_{k,2}\right)}{\left(\zeta_{k,2}+P_{k,\mathrm{R},i}^{(n)}\right)^2\left(P_{k,\mathrm{R},i}^{(n)}\right)^2}. & (43) \end{cases}$$

It's easy to verify that $\zeta_{k,2} \geq 0$ and $0 \leq \zeta_{k,1} < \Gamma_{k,\mathrm{R}}^{(n)}$ when Eq. (40) holds. Hence, we can obtain that $\partial^2 SR_{\mathrm{T},k,i}^{(m,n)} \Big/ \partial\left(P_{k,\mathrm{R},i}^{(n)}\right)^2 \leq 0$ and $\partial^2 SR_{k,i}^{(n)} \Big/ \partial\left(P_{k,\mathrm{R},i}^{(n)}\right)^2 \leq 0$, and then $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ are both concave in terms of $P_{k,\mathrm{R},i}^{(n)}$. ■

Notice that PT and ST_k will not cooperate with each other if $SR_{\mathrm{T},k,i}^{(m,n)} = 0$ and/or $SR_{k,i}^{(n)} = 0$, since secure communication cannot be guaranteed in such cases [17]. Hence, we must solve the optimization problem specified by Eq. (26) under the conditions given in Eqs. (40) and (41). Besides, plugging Eq. (38) and $P_{k,i}^{(n)}(\boldsymbol{\phi})$ determined by Eq. (35) into the problem specified by Eq. (26), we can transform the problem given in Eq. (26) into a one-dimensional convex optimization problem with respect to $P_{k,\mathrm{R},i}^{(n)}$. To get the optimal $P_{k,\mathrm{R},i}^{(n)}(\boldsymbol{\phi})$ for given $\boldsymbol{\phi}$, we can use the following gradient method [36] to solve the problem given in Eq. (26).

$$P_{k,\mathrm{R},i}^{(n)}(q+1) = \left[P_{k,\mathrm{R},i}^{(n)}(q) + \xi(q)\frac{\partial \mathcal{L}_{k,i}^{(m,n)}}{\partial P_{k,\mathrm{R},i}^{(n)}}\left(P_{k,\mathrm{R},i}^{(n)}(q)\right)\right]_{P_k^{\min}}^{P_k^{\max}}$$

where $\xi(q) = \frac{1}{q}, q \in \{1, 2, \cdots\}$, is the step size, $P_k^{\max}$ is the maximum transmit power of ST_k, and $P_k^{\min} = \max\left\{0, P_k^{\mathrm{th}}\right\}$, where P_k^{th} is given in Eq. (41). For given $\boldsymbol{\phi}$, after calculating the optimal $P_{k,\mathrm{R},i}^{(n)}(\boldsymbol{\phi})$, we can calculate the optimal $P_{\mathrm{T},k,i}^{(m)}(\boldsymbol{\phi})$ by using Eq. (38).

2) User Cooperation Policy: After solving the problem in Eq. (26), for given $\boldsymbol{\phi}$, we can determine the optimal $\mathcal{P}(\boldsymbol{\phi})$, and then to determine the optimal user cooperation policy $\mathcal{W}(\boldsymbol{\phi}) \in \mathcal{D}$. Suppose that (m,n) is a valid subcarrier pair, i.e., SP (m,n) is used by PT to cooperate with some SU. Then, it is obvious from Eq. (24) that SP (m,n) should be assigned to the SU and power splitting pair (k,i), when the following selection criterion is satisfied:

$$w_{k,i}^{(m,n)} = \begin{cases} 1, & \text{if } (k,i) = \underset{(c,d)}{\operatorname{argmax}} \left\{\mathcal{L}_{c,d}^{(m,n)}\right\}, \\ 0, & \text{otherwise.} \end{cases} \tag{44}$$

Here, we can use the binary-search-tree method, whose complexity is $O(\log_2(KI))$ [37], to search for the (k,i) satisfying Eq. (44), where K is the number of SUs, and I is the number of power splitting ratios in the power splitting ratio set $\boldsymbol{\rho}_k \triangleq \{\rho_{k,1}, \cdots, \rho_{k,I}\}$. Using Eq. (44), we can see that each ST_k can only be allocated one power splitting ratio over its assigned SP (m,n).

TABLE I
RA-PSC: DISTRIBUTED RESOURCE ALLOCATION ALGORITHM FOR POLARIZATION BASED SECURE COMMUNICATION IN CRNS

Initialization: PT initializes $\{\lambda, \mu\}$. Each ST_k initializes $\{\beta_k, \chi_k\}$ and broadcasts them to PT.
Repeat
1. Based on given $\boldsymbol{\phi} = [\lambda, \mu, \chi_k, \beta_k]^T, \forall k$, for each (k,i,m,n), PT first computes $P_{k,i}^{(n)}(\boldsymbol{\phi})$ by using Eq. (35). If $P_{k,i}^{(n)}(\boldsymbol{\phi})$ satisfies Eq. (40), PT calculates $P_{\mathrm{T},k,i}^{(m)}(\boldsymbol{\phi})$ and $P_{k,\mathrm{R},i}^{(n)}(\boldsymbol{\phi})$ by solving the problem given in Eq. (26). Then, PT computes $\mathcal{L}_{k,i}^{(m,n)}$ by utilizing Eq. (25) and meanwhile delivers $P_{\mathrm{T},k,i}^{(m)}(\boldsymbol{\phi})$, $P_{k,\mathrm{R},i}^{(n)}(\boldsymbol{\phi})$, $P_{k,i}^{(n)}(\boldsymbol{\phi})$, and $\mathcal{L}_{k,i}^{(m,n)}$ to the associated ST_k.
2. PT determines the optimal SU and power splitting pair (k,i) for each SP (m,n) according to Eq. (44). Based on the obtained results, PT selects the optimal subcarrier pairs by the Hopcroft-Karp method. Then, which $w_{k,i}^{(m,n)}$'s should be equal to 1, i.e., the optimal $\mathcal{W}(\boldsymbol{\phi})$ for given $(\boldsymbol{\phi})$, can be determined.
3. PT updates $\{\lambda, \mu\}$ and each ST_k updates $\{\beta_k, \chi_k\}$ by using Eq. (23). Then, each ST_k communicates $\{\beta_k, \chi_k\}$ to PT.

Until Maximal iteration number reaches.

It remains to determine the optimal subcarrier pairs. To each valid SP (m,n), we first calculate the value of $\mathcal{L}_{k,i}^{(m,n)}$ for the optimal (k,i) satisfying Eq. (44), and denote this value as $L(m,n)$. Then, we define a $N \times N$ matrix $\mathbf{L} \triangleq [L(m,n)]$, where N is the number of subcarriers. To guarantee $\mathcal{W}(\boldsymbol{\phi}) \in \mathcal{D}$ and maximize $g(\boldsymbol{\phi})$ given in Eq. (24), we should pick exactly one element in each row and each column of matrix $\mathbf{L}$ such that the sum of $L(m,n)$'s is as large as possible. This can be efficiently solved by the Hopcroft-Karp method, whose complexity is $O(N^{2.5})$ [38].

Our proposed resource allocation algorithm RA-PSC is summarized in Table I. For each SP (m,n), since PT only needs to solve the problem in Eq. (26) for ST_k's whose powers $P_{k,i}^{(n)}(\boldsymbol{\phi})$'s satisfy Eq. (40), PT needs to solve at most $K \times I \times N^2$ subproblems given in Eq. (26). Then, the complexity of *Power Allocation* step is at most $O\left(MKIN^2\right)$, where M is the maximum iteration number of the gradient method solving the problem in Eq. (26). Together with the analysis for *User Cooperation* step, we can know that the total complexity of RA-PSC for given $\boldsymbol{\phi}$ is at most $O\left(MKIN^2 + N^{2.5}\right)$, which grows polynomially with the subcarrier number N.

E. The DF Strategy Case with Jamming Signals

Observing Eq. (5), we can deduce that when PT cooperates with ST_k over SP (m,n), the rate $R_{\mathrm{T},e,i}^{(m)}$ from PT to eavesdropper $SR_e, e \neq k$, in Phase-I may be very high if the channel between PT and $SR_e, e \neq k$, is in a good state. To decrease $R_{\mathrm{T},e,i}^{(m)}$ at SR_e, $e \neq k$, PR can send jamming signals over subcarrier m in Phase-I. Then, similar to Eq. (14), we can express $R_{\mathrm{T},e,i}^{(m)}$ at SR_e, $e \neq k$, as:

$$R_{\mathrm{T},e,i}^{(m)} = C\left(\frac{P_{\mathrm{T},k,i}^{(m)}\Gamma_{\mathrm{T},e}^{(m)}}{P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},e}^{(m)} + 2}\right), \tag{45}$$

where $P_{\mathrm{R},k,i}^{(m)}$ is PR's transmit power over subcarrier m when $w_{k,i}^{(m,n)} = 1$, and $\Gamma_{\mathrm{R},e}^{(m)} \triangleq \left|f_{\mathrm{R},e}^{(m)}\right|^2/\sigma^2$, where $f_{\mathrm{R},e}^{(m)}$ is the spatial channel fading gain of $PR \rightarrow SR_e, e \neq k$. Compared with Eq. (5), it can be seen that $R_{\mathrm{T},e,i}^{(m)}$ in Eq. (45) can be decreased.

Besides, the jamming signals generated by PR are pseudo-random signals [17], which can be perfectly known at ST_k, but not at SR_e's, $e \neq k$.[1]

Moreover, inspired by [16] and [17], we can treat the jamming signals sent by PR also as energy signals for ST_k, since the jamming signals are perfectly known at ST_k. Then, ST_k only harvests energy from the received jamming signals, but does not forward them. Consequently, we can still express ST_k's secrecy rate $SR_{k,i}^{(n)}$ as Eq. (28). Also, following the procedure similar to that as described in the proof of Lemma 1, we can still write PT's secrecy rate $SR_{\mathrm{T},k,i}^{(m,n)}$ over SP (m,n) as Eq. (27), with replacing $ER_{\mathrm{T},k,i}^{(m)}$ in Eq. (27) by

$$ER_{\mathrm{T},k,i}^{(m)} = \max_{e\neq k}\left\{R_{\mathrm{T},e,i}^{(m)}\right\} \approx C\left(\frac{P_{\mathrm{T},k,i}^{(m)}}{P_{\mathrm{R},k,i}^{(m)}}\max_{e\neq k}\left\{\frac{\Gamma_{\mathrm{T},e}^{(m)}}{\Gamma_{\mathrm{R},e}^{(m)}}\right\}\right), \tag{46}$$

where we assume that the interference $P_{\mathrm{R},k,i}^{(m)}\left|f_{\mathrm{R},e}^{(m)}\right|^2$ from PR to SR_e, $e \neq k$, is much larger than the variance, i.e., $2\sigma^2$, of the noise at SR_e, $e \neq k$; then $P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},e}^{(m)} \gg 2$ holds in Eq. (45) and thus Eq. (46) can be easily derived.

Similar to Eq. (18), for SP (m,n), the harvested energy $Q_k^{(m,n)}$ at each ST_k over subcarrier m can be written as:

$$Q_k^{(m,n)} = \underbrace{\frac{T\eta_k\left(1-\sum_{i=1}^{I}\rho_{k,i}w_{k,i}^{(m,n)}\right)}{2}\left(\sum_{k'=1}^{K}\sum_{i=1}^{I}w_{k',i}^{(m,n)}P_{\mathrm{T},k',i}^{(m)}\right)\left|h_{\mathrm{T},k}^{(m)}\right|^2}_{\text{energy harvested from } PT\text{'s transmission over subcarrier } m} + \underbrace{\frac{T\eta_k}{2}\left(\sum_{k'=1}^{K}\sum_{i=1}^{I}w_{k',i}^{(m,n)}P_{\mathrm{R},k',i}^{(m)}\right)\left|h_{\mathrm{R},k}^{(m)}\right|^2}_{\text{energy harvested from } PR\text{'s transmission over subcarrier } m}, \tag{47}$$

where $h_{\mathrm{R},k}^{(m)}$ is the spatial channel fading gain from PR to ST_k over subcarrier m.

Observing Eqs. (46) and (47), we can know that the transmission of jamming signals by PR can not only increase PT's secrecy rate, but also increase the harvested energy of SU transmitters. In this case, we can formulate the secure resource allocation problem as follows:

$$\max_{\mathcal{W},\widetilde{\mathcal{P}}}\left\{\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)}SR_{k,i}^{(n)}\right\} \tag{48}$$

$$\text{s.t.}\quad C1-C8,$$

$$C9: \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{i=1}^{I}w_{k,i}^{(m,n)}P_{\mathrm{R},k,i}^{(m)} \leq P_{\mathrm{R}}^{\max}.$$

Here, $\widetilde{\mathcal{P}} \triangleq \left\{0 \leq P_{\mathrm{T},k,i}^{(m)} \leq P_{\mathrm{T}}^{\max}, 0 \leq P_{\mathrm{R},k,i}^{(m)} \leq P_{\mathrm{R}}^{\max}, 0 \leq P_{k,\mathrm{R},i}^{(n)}, P_{k,i}^{(n)} \leq P_k^{\max}, \forall k, \forall i, \forall m, \forall n\right\}$, where $P_{\mathrm{R}}^{\max}$ is PR's maximum transmit power.

The problem specified by Eq. (48) can also be solved by using the Lagrangian dual method. Following the procedure similar to that as described for the problem in Eq. (19), for given Lagrange multiplier vector $\widetilde{\boldsymbol{\phi}} \triangleq [\lambda, \mu, \tau, \chi_k, \beta_k]^T$, $\forall k$, we can determine the power allocation over assignment unit (k,i,m,n) when $w_{k,i}^{(m,n)} = 1$ by solving the following optimization problem:

$$\max_{\left\{P_{\mathrm{T},k,i}^{(m)}, P_{\mathrm{R},k,i}^{(m)}, P_{k,\mathrm{R},i}^{(n)}, P_{k,i}^{(n)}\right\}}\left\{\mathcal{L}_{k,i}^{(m,n)}\right\}, \tag{49}$$

where $0 \leq P_{\mathrm{T},k,i}^{(m)} \leq P_{\mathrm{T}}^{\max}$, $0 \leq P_{\mathrm{R},k,i}^{(m)} \leq P_{\mathrm{R}}^{\max}$, $0 \leq P_{k,\mathrm{R},i}^{(n)}, P_{k,i}^{(n)} \leq P_k^{\max}$, and

$$\begin{aligned}\mathcal{L}_{k,i}^{(m,n)} = {} & SR_{k,i}^{(n)} + \lambda SR_{\mathrm{T},k,i}^{(m,n)} - \mu P_{\mathrm{T},k,i}^{(m)} \\ & - \left(\frac{T\chi_k}{2} + \beta_k\right)\left(P_{k,\mathrm{R},i}^{(n)} + P_{k,i}^{(n)}\right) - \tau P_{\mathrm{R},k,i}^{(m)} \\ & + \frac{T}{2}\chi_k\eta_k\left(\left(1-\rho_{k,i}\right)P_{\mathrm{T},k,i}^{(m)}\left|h_{\mathrm{T},k}^{(m)}\right|^2 + P_{\mathrm{R},k,i}^{(m)}\left|h_{\mathrm{R},k}^{(m)}\right|^2\right) \\ & + \sum_{k'\neq k}\frac{T}{2}\chi_{k'}\eta_{k'}\left(P_{\mathrm{T},k,i}^{(m)}\left|h_{\mathrm{T},k'}^{(m)}\right|^2 + P_{\mathrm{R},k,i}^{(m)}\left|h_{\mathrm{R},k'}^{(m)}\right|^2\right),\end{aligned} \tag{50}$$

where λ, χ_k, μ, β_k, and τ in $\widetilde{\boldsymbol{\phi}}$ are Lagrange multipliers of $C1-C4$ and $C9$, respectively.[2]

Unlike the problem given in Eq. (26), due to the existence of variable $P_{\mathrm{R},k,i}^{(m)}$ in the problem specified by Eq. (49), we cannot directly convert $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ in Eq. (50) into concave functions. Consequently, to solve the non-convex problem in Eq. (49), we need to approximate $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ as concave functions. Before that, using the similar methods as those in Theorem 1 and Theorem 2, we first re-write $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ given in Eqs. (27) and (28) as:

$$SR_{\mathrm{T},k,i}^{(m,n)} = R_{k,\mathrm{R},i}^{(n)} - ER_{\mathrm{T},k,i}^{(n)}, \tag{51}$$

$$SR_{k,i}^{(n)} = R_{k,k,i}^{(n)} - ER_{\mathrm{S},k,i}^{(n)}, \tag{52}$$

respectively, under the conditions given in Eq. (41) and the following inequality:

$$P_{k,i}^{(n)} > \frac{1}{\Gamma_{k,\mathrm{R}}^{(n)}} - \frac{2}{\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}}. \tag{53}$$

Following the procedure similar to that as described in the proof of Theorem 2, it is easy to prove that $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ are positive under the conditions given in Eqs. (41) and (53). Then, plugging $R_{k,\mathrm{R},i}^{(n)}$ and $ER_{\mathrm{T},k,i}^{(n)}$ in Eqs. (10) and (30), respectively, into Eq. (51), and $R_{k,k,i}^{(n)}$ and $ER_{\mathrm{S},k,i}^{(n)}$ in Eqs. (11) and (31), respectively, into Eq. (52), we can obtain that

$$\begin{aligned}SR_{\mathrm{T},k,i}^{(m,n)} = {} & C\left(P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,\mathrm{R}}^{(n)}\right) + C\left(P_{k,i}^{(n)}\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\} + 1\right) \\ & - C\left(\left(P_{k,\mathrm{R},i}^{(n)} + P_{k,i}^{(n)}\right)\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\} + 1\right),\end{aligned} \tag{54}$$

[1]This can be implemented by using a short secret key as seed information for generating the jamming signal sequences similar to those discussed in [17], [34].

[2]Although this paper is an extended version of our previous work in [34], unlike [34], to further improve system performance, we employ PR to transmit jamming signals, instead of letting PT split its power for information signal and energy signal transmissions, respectively. Hence, the optimization problem given in Eq. (48) is different from the resource allocation problem in [34]. Moreover, unlike [34], we will transform the non-convex optimization problem given in Eq. (48) into a convex optimization problem instead of directly solving it by using the subgradient method [36] as what was done in [34].

and

$$SR_{k,i}^{(n)} = C\left(P_{k,i}^{(n)} \frac{\Gamma_{k,k}^{(n)} \sin^2\left(\varphi_k^{(n)}\right)}{2}\right) + C\left(P_{k,\mathrm{R},i}^{(n)} \max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}+1\right) - C\left(\left(P_{k,\mathrm{R},i}^{(n)} + P_{k,i}^{(n)}\right)\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}+1\right). \quad (55)$$

Let

$$\begin{cases} g_{1,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) \triangleq C\left(P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,\mathrm{R}}^{(n)}\right) + C\left(P_{k,i}^{(n)}\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}+1\right), \\ g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) \triangleq C\left(\left(P_{k,\mathrm{R},i}^{(n)} + P_{k,i}^{(n)}\right)\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}+1\right), \\ g_{3,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) \triangleq C\left(P_{k,\mathrm{R},i}^{(n)}\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}+1\right) \\ \qquad\qquad + C\left(P_{k,i}^{(n)}\frac{\Gamma_{k,k}^{(n)}\sin^2\left(\varphi_k^{(n)}\right)}{2}\right). \end{cases}$$

Then, $SR_{\mathrm{T},k,i}^{(m,n)} = g_{1,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) - g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}\right)$ and $SR_{k,i}^{(n)} = g_{3,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) - g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}\right)$. Since the function $C(x) \triangleq \frac{1}{2}\log_2(1+x)$ is concave, all $g_{\iota,k}^{(n)}\left(\widetilde{\mathcal{P}}\right)$'s, $\iota \in \{1,2,3\}$, are concave functions with respect to $\widetilde{\mathcal{P}}$. Hence, both $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ are the difference of two concave functions (D.C.), that is, both $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ are D.C. functions [39]. Moreover, since $g_{2,k}^{(n)}$ is differential, around any fixed point $\widetilde{\mathcal{P}}_0$, we can approximate it by its first order Taylor expansion:

$$g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) \approx g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}_0\right) + \nabla g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}_0\right)\left(\widetilde{\mathcal{P}} - \widetilde{\mathcal{P}}_0\right). \quad (56)$$

Consequently, around $\widetilde{\mathcal{P}}_0$, we can approximate $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ as follows:

$$\begin{cases} SR_{\mathrm{T},k,i}^{(m,n)} \approx g_{1,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) - \left(g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}_0\right) + \nabla g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}_0\right)\left(\widetilde{\mathcal{P}} - \widetilde{\mathcal{P}}_0\right)\right), \\ SR_{k,i}^{(n)} \approx g_{3,k}^{(n)}\left(\widetilde{\mathcal{P}}\right) - \left(g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}_0\right) + \nabla g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}_0\right)\left(\widetilde{\mathcal{P}} - \widetilde{\mathcal{P}}_0\right)\right). \end{cases}$$

As such, around $\widetilde{\mathcal{P}}_0$, $SR_{\mathrm{T},k,i}^{(m,n)}$ given in Eq. (54) and $SR_{k,i}^{(n)}$ given in Eq. (55) can be approximated as concave functions with respect to $\widetilde{\mathcal{P}}$. Hence, around $\widetilde{\mathcal{P}}_0$, $\mathcal{L}_{k,i}^{(m,n)}$ given in Eq. (50) can be approximated as a concave function with respect to $\widetilde{\mathcal{P}}$, and then the problem given in Eq. (49) becomes a convex optimization problem of $\widetilde{\mathcal{P}}$. Hence, similar to the problem given in Eq. (26), we can efficiently solve the problem in Eq. (49) around $\widetilde{\mathcal{P}}_0$ by using the gradient method [36]. Notice that similar to the problem in Eq. (26), we can also obtain Eq. (38) and the following equation:

$$P_{\mathrm{R},k,i}^{(m)} = \frac{2\Gamma_{k,\mathrm{R}}^{(n)}\left(P_{k,i}^{(n)}\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}+2\right)\max_{e\neq k}\left\{\frac{\Gamma_{\mathrm{T},e}^{(m)}}{\Gamma_{\mathrm{R},e}^{(m)}}\right\}}{\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\}\rho_{k,i}\Gamma_{\mathrm{T},k}^{(m)}}, \quad (57)$$

when solving the optimization problem given in Eq. (49).

Based on the above discussion, we can utilize a D.C. iteration method [39] to solve the problem given in Eq. (49). Let $\widetilde{\mathcal{P}}_0(\kappa)$ denote the fixed point chosen at the κth iteration of the D.C. iteration method. Around $\widetilde{\mathcal{P}}_0(\kappa)$, we approximate $SR_{\mathrm{T},k,i}^{(m,n)}$ and $SR_{k,i}^{(n)}$ as concave functions with respect to $\widetilde{\mathcal{P}}$, and solve the problem specified by Eq. (49) to derive $\widetilde{\mathcal{P}}_0(\kappa+1)$. Similarly, based on $\widetilde{\mathcal{P}}_0(\kappa+1)$, we can derive $\widetilde{\mathcal{P}}_0(\kappa+2)$. The process repeats until $\left\{\widetilde{\mathcal{P}}_0(\kappa)\right\}$ converges. Then, for given $\widetilde{\boldsymbol{\phi}}$, we can obtain the power allocation $\widetilde{\mathcal{P}}\left(\widetilde{\boldsymbol{\phi}}\right)$, which is very close to the power allocation obtained by the global search method to be shown in Section V. We summarize the procedures to solve the problem given in Eq. (49) in Table II. Once $\widetilde{\mathcal{P}}\left(\widetilde{\boldsymbol{\phi}}\right)$ is obtained, we can determine the user cooperation policy $\mathcal{W}\left(\widetilde{\boldsymbol{\phi}}\right)$ for given $\widetilde{\boldsymbol{\phi}}$ by using the method in RA-PSC.

TABLE II
THE D.C. OPTIMIZATION BASED ITERATION ALGORITHM FOR DERIVING THE POWER ALLOCATION $\widetilde{\mathcal{P}}\left(\widetilde{\boldsymbol{\phi}}\right)$.

1.**Initialization**: Give an initial point $\widetilde{\mathcal{P}}_0(0)$, and calculate derivatives $\nabla g_{\iota,k}^{(n)}\left(\widetilde{\mathcal{P}}_0(0)\right)$, $\iota \in \{1,2,3\}$. Besides, set the tolerance ς to be a very small value, and let $\kappa = 0$.
2. **Repeat**
3. Solve the optimization problem in Eq. (49) to derive $\widetilde{\mathcal{P}}_0(\kappa+1)$ by
4. linearizing functions $g_{\iota,k}^{(n)}\left(\widetilde{\mathcal{P}}\right)$, $\iota \in \{1,2,3\}$, at the point $\widetilde{\mathcal{P}}_0(\kappa)$.
5. Set $\kappa = \kappa + 1$.
6. Calculate $\nabla g_{\iota,k}^{(n)}\left(\widetilde{\mathcal{P}}_0(\kappa)\right)$, $\iota \in \{1,2,3\}$.
7. **Until** $\left|\mathcal{L}_{k,i}^{(m,n)}\left(\widetilde{\mathcal{P}}_0(\kappa), \widetilde{\boldsymbol{\phi}}\right) - \mathcal{L}_{k,i}^{(m,n)}\left(\widetilde{\mathcal{P}}_0(\kappa-1), \widetilde{\boldsymbol{\phi}}\right)\right| \leq \varsigma$.

When PR is employed to transmit jamming signals in the DF strategy case, we name our proposed resource allocation scheme RA-PSC-DF-PRJ. Similar to RA-PSC, the complexity of RA-PSC-DF-PRJ is also mainly due to power allocation. For each SP (m,n), the complexity to determine powers, e.g., $P_{\mathrm{T},k,i}^{(m)}$'s, is $O(JMKIN^2)$, where J is the maximum iteration number of the D.C. iteration algorithm in Table II, and M is the maximum iteration number of the gradient method solving the problem in Eq. (49) for given $\widetilde{\mathcal{P}}_0(\kappa)$ in Table II. Then, the total complexity of RA-PSC-DF-PRJ for given $\widetilde{\boldsymbol{\phi}}$ is $O\left(JMKIN^2 + N^{2.5}\right)$.

IV. SECURE RESOURCE ALLOCATION FOR THE AF STRATEGY CASE

We consider the secure resource allocation when SU transmitters adopt the AF strategy to relay information for PT. Different from the DF strategy case, we consider the scenario when not only all SU receivers but also ST_k may try to eavesdrop on PT's information when relaying information for PT over SP (m,n). While the other SU transmitters $ST_{k'}, k' \neq k$, only harvest energy over SP (m,n) to increase the amount of harvested energy and then to increase their transmission rates. Moreover, similar to Section III-E, to maintain the confidentiality of PT's information, we assume that PR also sends jamming signals in Phase-I, while simultaneously avoiding the jamming signals being known by all SU transmitters and receivers.

Suppose that ST_k cooperates with PT over SP (m,n). Then, similar to the analysis for the DF strategy case, we can still express the secrecy rate $SR_{k,i}^{(n)}$ of ST_k over subcarrier n as Eq. (28), while the secrecy rate $SR_{\mathrm{T},k,i}^{(m,n)}$ of PT over SP (m,n)

can be written as:[3]

$$SR_{\mathrm{T},k,i}^{(m,n)} = \left[R_{\mathrm{T},k,i}^{(m,n)} - \max\left\{R_{\mathrm{T},k,i}^{(m)}, \max_{1\le e\le K}\left\{R_{\mathrm{T},e,i}^{(m)}\right\}, \max_{e\neq k}\left\{R_{\mathrm{T},e,i}^{(n)}\right\}\right\}\right]^{+}. \quad (58)$$

where

$$\begin{cases} R_{\mathrm{T},k,i}^{(m,n)} = C\left(\dfrac{\rho_{k,i}P_{\mathrm{T},k,i}^{(m)}\Gamma_{\mathrm{T},k}^{(m)}P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,\mathrm{R}}^{(n)}}{2P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,\mathrm{R}}^{(n)}+\psi_{k,i}^{(m)}}\right), & (59)\\ R_{\mathrm{T},k,i}^{(m)} = C\left(\dfrac{\rho_{k,i}P_{\mathrm{T},k,i}^{(m)}\Gamma_{\mathrm{T},k}^{(m)}}{\rho_{k,i}P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},k}^{(m)}+2}\right), & (60)\\ R_{\mathrm{T},e,i}^{(m)} = C\left(\dfrac{P_{\mathrm{T},k,i}^{(m)}\Gamma_{\mathrm{T},e}^{(m)}}{P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},e}^{(m)}+2}\right), \quad 1\le e\le K, & (61)\\ R_{\mathrm{T},e,i}^{(n)} = C\left(\dfrac{\rho_{k,i}P_{\mathrm{T},k,i}^{(m)}\Gamma_{\mathrm{T},k}^{(m)}P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,e}^{(n)}}{\vartheta_{k,e,i}^{(m,n)}}\right), \quad e\neq k, & (62)\end{cases}$$

where $\Gamma_{\mathrm{R},k}^{(m)} \triangleq \left|h_{\mathrm{R},k}^{(m)}\right|^2/\sigma^2$, $h_{\mathrm{R},k}^{(m)}$ is the spatial channel fading gain of $PR \to ST_k$ on subcarrier m, $\psi_{k,i}^{(m)} \triangleq 2 + \rho_{k,i}P_{\mathrm{T},k,i}^{(m)}\Gamma_{\mathrm{T},k}^{(m)} + \rho_{k,i}P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},k}^{(m)}$, and $\vartheta_{k,e,i}^{(m,n)} \triangleq 2P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,e}^{(n)} + \left(2+\Gamma_{k,e}^{(n)}P_{k,i}^{(n)}\right)\psi_{k,i}^{(m)} + \rho_{k,i}P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},k}^{(m)}P_{k,\mathrm{R},i}^{(n)}\Gamma_{k,e}^{(n)}$. Moreover, $R_{\mathrm{T},k,i}^{(m,n)}$ is the transmission rate from PT to PR over SP (m,n) via ST_k's data forwarding, $R_{\mathrm{T},k,i}^{(m)}$ and $R_{\mathrm{T},e,i}^{(m)}$ are the eavesdropping rates at which ST_k and SR_e, $1\le e\le K$, overhear PT's information over subcarrier m in Phase-I, respectively, and $R_{\mathrm{T},e,i}^{(n)}$ is the eavesdropping rate at which SR_e, $e\neq k$, overhears PT's information over subcarrier n in Phase-II. Please notice that similar to the DF strategy case, in Eq. (62), we assume that SR_k chooses to eliminate PT's signal and extract its own signal from the received signal in Phase-II, so as to maximize its own reception performance.

In Phase-I, since each ST_k cannot distinguish between the RF signals sent by PT and PR, it harvests energy from both PT and PR with a certain power spitting ratio as that discussed in [16]. Then, the harvested energy $Q_k^{(m,n)}$ of each ST_k over SP (m,n) can be expressed as:

$$Q_k^{(m,n)} = \frac{T\eta_k\left(1-\sum_{i=1}^{I}\rho_{k,i}w_{k,i}^{(m,n)}\right)}{2}\left[\sum_{k'=1}^{K}\sum_{i=1}^{I}w_{k',i}^{(m,n)}P_{\mathrm{T},k',i}^{(m)}\left|h_{\mathrm{T},k}^{(m)}\right|^2 + \sum_{k'=1}^{K}\sum_{i=1}^{I}w_{k',i}^{(m,n)}P_{\mathrm{R},k',i}^{(m)}\left|h_{\mathrm{R},k}^{(m)}\right|^2\right]. \quad (63)$$

Similar to the DF strategy case in Section III-E, we can still formulate the secure resource allocation problem for the AF strategy case as the problem given in Eq. (48).[4] Hence, by using the Lagrangian dual method, we can still determine the power allocation over (k,i,m,n) for given Lagrange multiplier vector $\widetilde{\boldsymbol{\phi}} \triangleq [\lambda,\mu,\tau,\chi_k,\beta_k]^T, \forall k$, by solving the problem in Eq. (49). However, since PT's secrecy rate $SR_{\mathrm{T},k,i}^{(m,n)}$ and ST_k's harvested energy $Q_k^{(m,n)}$ over SP (m,n) are different from those in Section III-E, we write $\mathcal{L}_{k,i}^{(m,n)}$ in the problem given in Eq. (49) as:

$$\begin{aligned}\mathcal{L}_{k,i}^{(m,n)} = {} & SR_{k,i}^{(n)} + \lambda SR_{\mathrm{T},k,i}^{(m,n)} - \mu P_{\mathrm{T},k,i}^{(m)} \\ & - \left(\frac{T\chi_k}{2}+\beta_k\right)\left(P_{k,\mathrm{R},i}^{(n)}+P_{k,i}^{(n)}\right) - \tau P_{\mathrm{R},k,i}^{(m)} \\ & + \frac{T}{2}\chi_k\eta_k\left(1-\rho_{k,i}\right)\left(P_{\mathrm{T},k,i}^{(m)}\left|h_{\mathrm{T},k}^{(m)}\right|^2 + P_{\mathrm{R},k,i}^{(m)}\left|h_{\mathrm{R},k}^{(m)}\right|^2\right) \\ & + \sum_{k'\neq k}\frac{T}{2}\chi_{k'}\eta_{k'}\left(P_{\mathrm{T},k,i}^{(m)}\left|h_{\mathrm{T},k'}^{(m)}\right|^2 + P_{\mathrm{R},k,i}^{(m)}\left|h_{\mathrm{R},k'}^{(m)}\right|^2\right). \quad (64)\end{aligned}$$

For the AF strategy case, to solve the optimization problem given in Eq. (49), we first re-write PT's secrecy rate $SR_{\mathrm{T},k,i}^{(m,n)}$ given in Eq. (58) as follows:

$$SR_{\mathrm{T},k,i}^{(m,n)} = \left[R_{\mathrm{T},k,i}^{(m,n)} - \max\left\{R_{\mathrm{T},k,i}^{(m)}, ER_{\mathrm{T},k,i}^{(m)}, ER_{\mathrm{T},k,i}^{(n)}\right\}\right]^{+}, \quad (65)$$

where

$$\begin{cases} ER_{\mathrm{T},k,i}^{(m)} \triangleq \max_{1\le e\le K}\left\{R_{\mathrm{T},e,i}^{(m)}\right\} \approx C\left(\dfrac{P_{\mathrm{T},k,i}^{(m)}}{P_{\mathrm{R},k,i}^{(m)}}\max_{1\le e\le K}\left\{\dfrac{\Gamma_{\mathrm{T},e}^{(m)}}{\Gamma_{\mathrm{R},e}^{(m)}}\right\}\right) & (66)\\ ER_{\mathrm{T},k,i}^{(n)} \triangleq \max_{e\neq k}\left\{R_{\mathrm{T},e,i}^{(n)}\right\} = C\left(\dfrac{\rho_{k,i}P_{\mathrm{T},k,i}^{(m)}\Gamma_{\mathrm{T},k}^{(m)}P_{k,\mathrm{R},i}^{(n)}}{\max_{e\neq k}\left\{\frac{\vartheta_{k,e,i}^{(m,n)}}{\Gamma_{k,e}^{(n)}}\right\}}\right) & (67)\end{cases}$$

where similar to Eq. (46), we still assume that the interference $P_{\mathrm{R},k,i}^{(m)}\left|f_{\mathrm{R},e}^{(m)}\right|^2$ from PR to SR_e is much larger than the variance, i.e., $2\sigma^2$, of the noise at SR_e, i.e., $P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},e}^{(m)} \gg 2$; then Eq. (66) can be directly derived from Eq. (61). Besides, $\max_{e\neq k}\left\{\vartheta_{k,e,i}^{(m,n)}\Big/\Gamma_{k,e}^{(n)}\right\} = 2P_{k,\mathrm{R},i}^{(n)} + \rho_{k,i}P_{\mathrm{R},k,i}^{(m)}\Gamma_{\mathrm{R},k}^{(m)}P_{k,\mathrm{R},i}^{(n)} + \left(2\Big/\max_{e\neq k}\left\{\Gamma_{k,e}^{(n)}\right\} + P_{k,i}^{(n)}\right)\psi_{k,i}^{(m)}$ in Eq. (67), where Eq. (67) is derived from Eq. (62).

Then, in Eq. (65), letting $t_{k,i}^{(m,n)} \triangleq \max\left\{R_{\mathrm{T},k,i}^{(m)}, ER_{\mathrm{T},k,i}^{(m)}, ER_{\mathrm{T},k,i}^{(n)}\right\}$ and re-writing $SR_{\mathrm{T},k,i}^{(m,n)}$ as $SR_{\mathrm{T},k,i}^{(m,n)} = R_{\mathrm{T},k,i}^{(m,n)} - t_{k,i}^{(m,n)}$, for the AF strategy case, we can re-write the optimization problem specified by Eq. (49) as:

$$\begin{aligned} & \max_{\left\{P_{\mathrm{T},k,i}^{(m)},P_{\mathrm{R},k,i}^{(m)},P_{k,\mathrm{R},i}^{(n)},P_{k,i}^{(n)}\right\}} \left\{\mathcal{L}_{k,i}^{(m,n)}\right\} \quad (68)\\ & \text{s.t. } SR_{\mathrm{T},k,i}^{(m,n)}, SR_{k,i}^{(n)} > 0, \\ & \qquad R_{\mathrm{T},k,i}^{(m)}, ER_{\mathrm{T},k,i}^{(m)}, ER_{\mathrm{T},k,i}^{(n)} \le t_{k,i}^{(m,n)},\end{aligned}$$

[3]Due to lack of space, we omit the detailed derivations (see [40] for more details).

[4]Notice that in this paper, we extend our work in [40], where there exist only one untrusted SU transmitter and several untrusted SU receivers, to the scenario where there exist multiple untrusted SU transmitter-receiver pairs. Hence, the formulated optimization problem in this paper is not exactly the same as that in [40]. Besides, for the AF strategy case, unlike [40], we will also transform the optimization problem given in Eq. (48) into a convex optimization problem instead of directly solving it using the subgradient method [36] as what was done in [40].

where $0 \leq P_{\mathrm{T},k,i}^{(m)} \leq P_{\mathrm{T}}^{\max}$, $0 \leq P_{\mathrm{R},k,i}^{(m)} \leq P_{\mathrm{R}}^{\max}$, and $0 \leq P_{k,\mathrm{R},i}^{(n)}, P_{k,i}^{(n)} \leq P_{k}^{\max}$. For given $\widetilde{\phi}$, we can solve the problem specified by Eq. (68) by using the block coordinate descent (BCD) method [41]. First, we solve the problem given in Eq. (68) to obtain $P_{\mathrm{T},k,i}^{(m)}$ and $P_{\mathrm{R},k,i}^{(m)}$ for given $P_{k,\mathrm{R},i}^{(n)}$ and $P_{k,i}^{(n)}$. For given $P_{k,\mathrm{R},i}^{(n)}$ and $P_{k,i}^{(n)}$, $SR_{\mathrm{T},k,i}^{(m,n)}$, $SR_{k,i}^{(n)}$, $R_{\mathrm{T},k,i}^{(m)}$, $ER_{\mathrm{T},k,i}^{(m)}$, and $ER_{\mathrm{T},k,i}^{(n)}$ can all be written as D.C. functions. Therefore, we can use the similar method as that in Section III-E to transform the problem specified by Eq. (68) into a convex optimization problem, which can be easily solved. Second, using the similar method as above, we solve the problem given in Eq. (68) to obtain $P_{k,\mathrm{R},i}^{(n)}$ and $P_{k,i}^{(n)}$ for given $P_{\mathrm{T},k,i}^{(m)}$ and $P_{\mathrm{R},k,i}^{(m)}$. For given $\widetilde{\phi}$, repeat the above procedures until $\left\{P_{\mathrm{T},k,i}^{(m)}, P_{\mathrm{R},k,i}^{(m)}, P_{k,\mathrm{R},i}^{(n)}, P_{k,i}^{(n)}\right\}$ converge. Then, we can obtain the power allocation $\widetilde{\mathcal{P}}\left(\widetilde{\phi}\right)$ for given $\widetilde{\phi}$. Once $\widetilde{\mathcal{P}}\left(\widetilde{\phi}\right)$ is obtained, we can determine the user cooperation policy $\mathcal{W}\left(\widetilde{\phi}\right)$ by using the method in RA-PSC. Here, for the AF strategy case, we name our proposed resource allocation scheme RA-PSC-AF-PRJ. Similar to RA-PSC-DF-PRJ, the complexity of RA-PSC-AF-PRJ for given $\widetilde{\phi}$ is $O\left(GJMKIN^2 + N^{2.5}\right)$, where G is the maximum iteration number of the BCD method, and J and M are the same as those explained in Section III-E.

V. Performance Evaluations

Suppose that the small-scale fading between PT and ST_k's follows Rician fading with Rician factor equal to 6 dB, since Rician fading is more appropriate to incorporate the effect of line-of-sight (LOS) component in RF-based EH systems [42]. Besides, we set the large-scale fading as path loss attenuation with path loss exponent equal to 3. The PU and all SUs are located in a circular area with a radius of $r = 20$ m. Moreover, unless otherwise specified, we let $K = 6$, $N = 32$, $P_{\mathrm{T}}^{\max} = 0.4$ W, $P_{\mathrm{R}}^{\max} = P_{k}^{\max} = 0.2$ W, $R_{\mathrm{T}}^{\min} = 4$ Mbps, $T = 1$, $\eta_k = 0.5$, and $B_k^{\mathrm{o}} = 13$ dBm. Meanwhile, the bandwidth of each OFDMA subcarrier is equal to 0.156 MHZ.

Fig. 3 depicts the convergence performance of our proposed secure resource allocation schemes. As can be observed from Fig. 3(a), RA-PSC can converge to a satisfactory solution within merely around 20 iterations. The scheme RA-PSC-DF-PRJ, which is based on the D.C. optimization, has a relatively poor convergence performance, due to the first-order Taylor approximation of $g_{2,k}^{(n)}\left(\widetilde{\mathcal{P}}\right)$'s in Eq. (56). However, RA-PSC-DF-PRJ can still satisfactorily converge to the targeted optimal solution within around 40 iterations. Moreover, for RA-PSC, Fig. 3(b) depicts the total secrecy rate of all SUs versus the subcarrier number N, where the total secrecy rate of all SUs corresponding to the primal-problem-domain solution of the problem in Eq. (19) is also presented. It can be seen that the difference between the dual-problem-domain secrecy rate and the primal-problem-domain secrecy rate approaches to zero even when N takes small values. In addition, for RA-PSC-DF-PRJ, Fig. 3(c) shows the total secrecy rate of all SUs versus PT's minimum secrecy rate requirement $R_{\mathrm{T}}^{\min}$. For comparison purposes, we also show the total secrecy rate of all SUs determined by the global search method. For simplicity, we

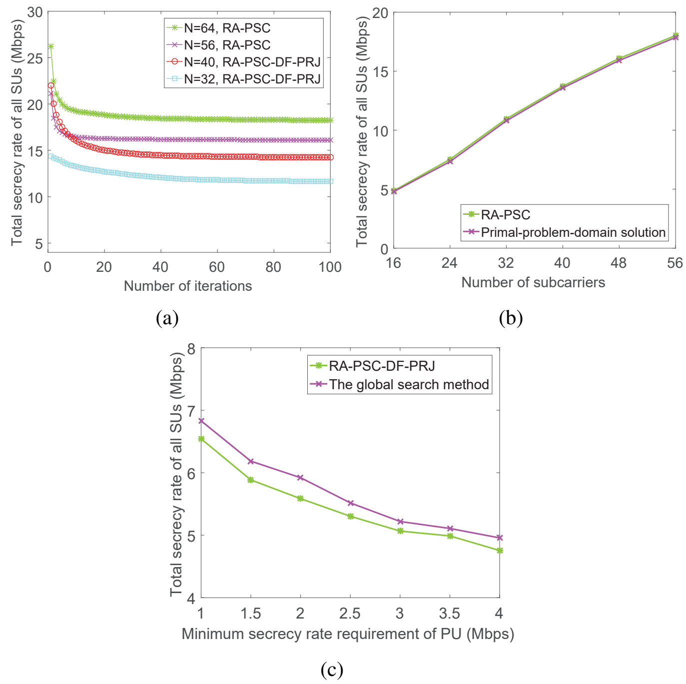

Fig. 3. Convergence performance of our proposed secure resource allocation schemes. (a) Convergence of RA-PSC and RA-PSC-DF-PRJ for different numbers of subcarriers; (b) Total secrecy rate of all SUs versus number of subcarriers; (c) Total secrecy rate of all SUs versus minimum secrecy rate requirement of PU.

take $N = 16$. Analyzing Fig. 3(c), we can observe that the total secrecy rate of all SUs obtained by RA-PSC-DF-PRJ is within about 90% of that obtained by the global search method. All the results in Fig. 3 confirm that our proposed D.C. optimization schemes have well satisfied convergence and approximation performances.

In Figs. 4-5, for EH-based cooperative CRNs, we evaluate the performance of our proposed framework PTPCF by comparing it with other cooperative frameworks. The first one is the TDMA-based three-phase cooperative framework (TTPCF) [1]. The second one is a FDMA-based two-phase cooperative framework (FTPCF), which is similar to the framework in [2]. In FTPCF, SU transmitters scavenge energy from PT's transmission in the first phase, and then use the harvested energy to forward PT's and their own data over different subcarriers.

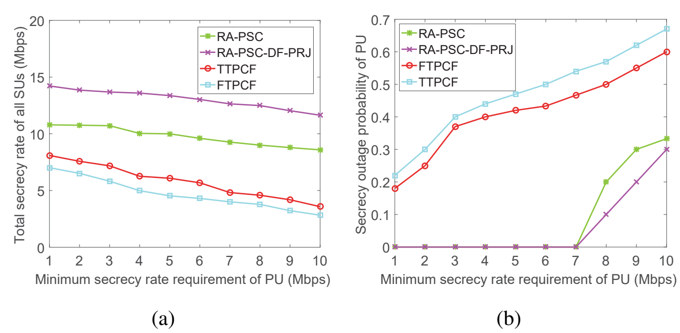

Fig. 4. Total secrecy rate of all SUs and secrecy outage probability of PU versus minimum secrecy rate requirement of PU. (a) Total secrecy rate of all SUs; (b) Secrecy outage probability of PU.

Fig. 4 depicts the total secrecy rate of all SUs and the secrecy outage probability of the PU versus the PU's minimum secrecy rate requirement, i.e., $R_{\mathrm{T}}^{\min}$, where the secrecy outage probability of the PU is the probability that the PU's secrecy rate is less than $R_{\mathrm{T}}^{\min}$. Analyzing Fig. 4, we can see that for PTPCF, system performance obtained by RA-PSC is worse than that obtained by RA-PSC-DF-PRJ. The reason for this is that in RA-PSC-DF-PRJ, when jamming signals are transmitted by PR, ST_k's can scavenge more energy while the eavesdropping rates at which SU receivers overhear PT's information in Phase-I can also be decreased. Moreover, analyzing Fig. 4, we can also see that compared with TTPCF and FTPCF, PTPCF can achieve much better system performance regardless whether PR transmits jamming signals or not. This is because by utilizing ODPAs at each ST_k in PTPCF, ST_k can concurrently transmit PT's and its own data concurrently by leveraging the polarization multiplexing capability provided through ODPAs, while the co-channel interference due to polarization multiplexing can be eliminated by using techniques, e.g., polarization zero-forcing. On one hand, this ensures that ST_k can have more time for energy harvesting while both PT and ST_k can utilize more spectrum and time for data transmission. On the other hand, as shown in Eqs. (14) and (15), this can decrease the eavesdropping rate at each eavesdropper $SR_e, e \neq k$, since without knowing ST_k's polarization states $\mathbf{z}_{k,\mathrm{R}}^{(n)}$ and $\mathbf{z}_{k,k}^{(n)}$ (see Eq. (13)), $SR_e, e \neq k$, cannot distinguish between PT's and ST_k's signals. However, PT and each ST_k in TTPCF and FTPCF can only utilize a relatively small part of transmission periods or subcarriers for data transmission and energy harvesting. Besides, since PT's and ST_k's signals are transmitted over different time periods or subcarriers, the eavesdropping rate at each SR_e, $e \neq k$, may be very high in TTPCF and FTPCF.

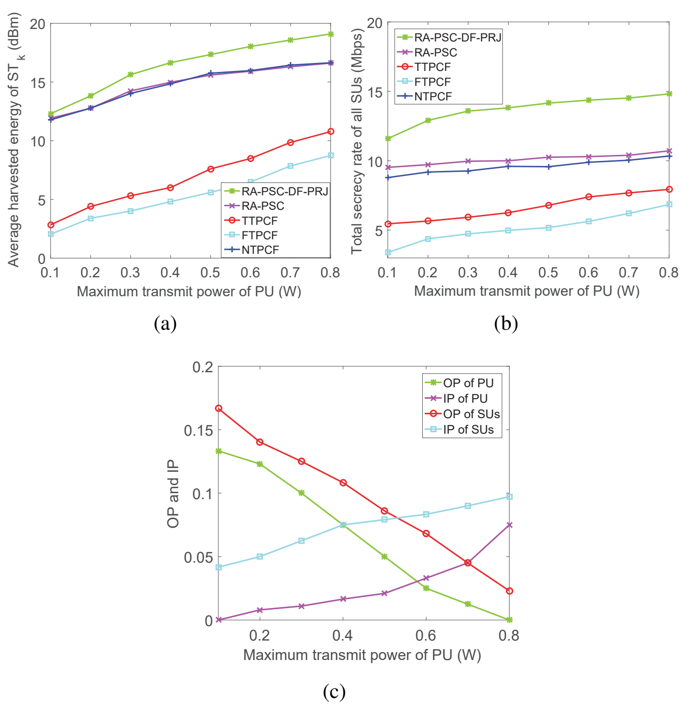

Fig. 5. Total secrecy rate of all SUs, average harvested energy of ST_k, and OP & IP versus PT's maximum transmit power. (a) Total secrecy rate of all SUs; (b) Average harvested energy of ST_k; (c) OP and IP.

Figs. 5 (a)-(b) show the total secrecy rate of all SUs and the average harvested energy of each ST_k versus PT's maximum transmit power $P_{\mathrm{T}}^{\max}$. For comparison purposes, in addition to TTPCF and FTPCF, we also consider a non-orthogonal multiple-access (NOMA) [43] based two-phase cooperative framework (NTPCF). In NTPCF, ST_k's first harvest energy from PT, and then use the state-of-the-art technique, i.e., NOMA, to concurrently transmit their own and the PU's data. Analyzing Fig. 5(b), we can also see that the average harvested energy of each ST_k in TTPCF and FTPCF is much lower than that harvested in PTPCF. Besides, unlike PTPCF, the total secrecy rate of all SUs in TTPCF and FTPCF cannot be improved observably even when the average harvested energy of each ST_k increases. This is because unlike PTPCF, without extra interference at each eavesdropper SR_e, the channel state from PT's cooperator $ST_k, k \neq e$, to the strongest eavesdropper may be better than that from ST_k to SR_k in TTPCF and FTPCF. Then, the secrecy rate of ST_k cannot be positive. Moreover, Figs. 5(a)-(b) show that PTPCF can achieve a slightly better system performance than NTPCF, when no jamming signals are considered, i.e., in the case of the scheme RA-PSC. This is because in NTPCF, the PU and SU receivers can only partially remove the co-channel interference by using NOMA, while in PTPCF the PU and SU receivers can totally eliminate the co-channel interference by using the other techniques, e.g., polarization zero-forcing. Besides, since the PU and SU receivers can only partially eliminate the co-channel interference in NTPCF, while eavesdroppers SR_e's, $e \neq k$, cannot totally eliminate the interference from ST_k's (see Eqs. (14) and (15)) in PTPCF, the computation complexity of the resource allocation scheme based on NTPCF is similar to that of our proposed schemes. Furthermore, due to channel estimation errors, the outage probability (OP) and the intercept probability (IP) may not be zero. Taking ST_k for example, the OP is the probability that the channel capacity between ST_k and SR_k is less than ST_k's actual transmission rate, while the IP is the probability that SR_e's, $e \neq k$, eavesdropping rate is larger than ST_k's actual transmission rate [44]. In Fig. 5 (c), we show the OP and IP versus $P_{\mathrm{T}}^{\max}$. We can see that as $P_{\mathrm{T}}^{\max}$ increases, the OP related to system reliability [44] decreases while the IP related to system security [45] increases. Thus, there is a tradeoff between security and reliability.

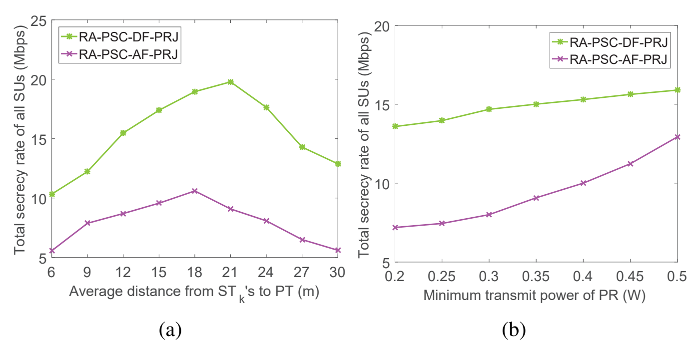

Fig. 6. Total secrecy rate of all SUs versus average distance from ST_k's to PT and PR's maximum transmit power $P_{\mathrm{R}}^{\max}$. (a) Total secrecy rate of all SUs versus the average distance from ST_k's to PT; (b) Total secrecy rate of all SUs versus $P_{\mathrm{R}}^{\max}$.

Fig. 6 depicts the total secrecy rate of all SUs versus the average distance from ST_k's to PT, denoted by d_{PS}, and PR's maximum transmit power $P_{\text{R}}^{\max}$. Analyzing Fig. 6(a), we can see that the total secrecy rate of all SUs first increases and then decreases as d_{PS} increases. This is because ST_k's can harvest more energy from PR, when d_{PS} increases and the average distance from ST_k's to PR decreases. However, as d_{PS} goes beyond certain values, the achievable transmission rate from PT to ST_k's may decrease sharply and the interference from PR to ST_k's may be very high. Moreover, from Fig. 6(b), it can be seen that the total secrecy rate of all SUs increases as $P_{\text{R}}^{\max}$ increases. In addition, analyzing Figs. 6(a)-(b), we can observe that system performance obtained by RA-PSC-AF-PRJ for the AF strategy case is worse than that obtained by RA-PSC-DF-PRJ for the DF strategy case. This is because for the AF strategy case, on one hand, not only SU receivers but also SU transmitters try to overhear the PU's confidential signals. On the other hand, to maintain the confidentiality of PT's information, PR avoids its jamming signals being known by SU transmitters. Consequently, for the AF strategy case, the interference at SU transmitters increases (see Eq. (60)).

VI. Conclusions

We addressed secure communication for polarization-enabled EH-based cooperative CRNs with one PU and several SUs. Assuming that SUs are equipped with ODPAs, we proposed a polarization-enabled two-phase cooperative framework, where SU transmitters first harvest energy from the PU's RF signals, and then use the harvested energy to concurrently transmit the PU's and their own data on the same subcarriers. Under the assumption that SUs are untrusted, we jointly optimized the allocation of relays, subcarriers, power splitting ratios, and powers, so as to maximize the total secrecy rate of all SUs while guaranteeing the PU's minimum secrecy rate requirement. Although our proposed optimization problems are non-convex, we still developed three efficient secure resource allocation schemes. Finally, we validated and evaluated our proposed cooperative framework and resource allocation schemes through numerical analyses.

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