Optimal Relay Selection for Secure Cooperative Communications with an Adaptive Eavesdropper

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***Abstract*—Optimal relay selection is investigated for secure cooperative communications against an adaptive eavesdropper that can perform eavesdropping if the eavesdropping link has good channel quality or perform jamming otherwise. A number of decode-and-forward relays are available for legitimate communications, among which one relay can be selected to help. For legitimate communications, three cases for availability of the eavesdropping channel information are considered: full channel knowledge, partial channel knowledge, and statistical channel knowledge. An optimal relay selection scheme is proposed for each case. For the first and third cases, exact secrecy outage probability expressions in closed form are derived, and for the second case, an approximate secrecy outage probability is derived, which is tight in the high main-to-eavesdropper ratio regime. Moreover, secrecy diversity order for the proposed relay selection scheme in each case is also derived, which is shown to be a full secrecy diversity. Finally, numerical results are given to verify the theoretical analysis derived in this paper.**

***Index Terms*—Optimal relay selection, physical-layer security, secrecy diversity order, secrecy outage probability.**

I. Introduction

Recently, cooperative transmission by using relays has been considered as a promising method to enhance physical-layer security performance in wireless communication networks against eavesdropping [1], [2], in which the relays can cooperate in three different modes: cooperative beamforming [3]–[7], cooperative jamming [4], [8]–[10], and relay selection (RS) [11]–[14].

In cooperative beamforming mode, all participating relays perform distributed beamforming to forward their received signals to the legitimate receiver. In [3]–[5], decode-and-forward (DF) relays are employed, and the optimal beamforming weight that maximizes the secrecy rate is derived, for the scenarios when there exists one single eavesdropper [3] and multiple eavesdroppers [4], and when the legitimate transmitter also participates in the distributed beamforming [5]. Compared with DF-based cooperative beamforming, it is difficult to derive the optimal beamformer with amplify-and-forward (AF) relays, as an AF relay amplifies signals as well as noise. Thus, sub-optimal beamforming solutions are the major research focus in the literature, for the scenarios with one eavesdropper [3], [6] and with multiple eavesdroppers [3], [7].

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In cooperative jamming mode, when the legitimate transmitter is transmitting, all participating relays transmit interference signals with an aim to confuse the eavesdropper(s). To avoid interfering with the legitimate receiver, the null-space cooperative jamming [8] can be used, which generates interference that is orthogonal to the legitimate signals. The null-space cooperative jamming is simple, and effective, but not optimal in the sense of secrecy rate maximization [15]. For a single-antenna cooperative network, optimal cooperative jamming strategies are derived in [4] with a total relaying power constraint and in [9] with individual relaying power constraints. For a multiple-input-multiple-output (MIMO) relaying network, the work in [10] investigates cooperative jamming for single and multiple data streams transmission, in which the legitimate transmitter or receiver also participates in the cooperative jamming.

In cooperative beamforming mode or cooperative jamming mode, all relays participate in the relaying or jamming. Different from these, the relay selection mode only selects one relay for cooperation. For the scenarios with perfect eavesdropper channel state information (ECSI) and average ECSI, the work in [11] proposes two relay selection schemes that can enhance secrecy rate. The work in [12] gives optimal relay selection schemes for AF and DF systems, by assuming knowledge of perfect ECSI. It is shown that the proposed schemes can achieve full secrecy diversity. For a wireless communication system with an eavesdropper, the work in [13] investigates the tradeoff between security (in terms of intercept probability of the eavesdropper) and reliability (in terms of outage probability of the legitimate receiver). Relay selection is shown to improve the security-reliability tradeoff (SRT). The SRT in cognitive radio networking is studied in [14], where it is shown that more reliable spectrum sensing can improve SRT.

Mixture of cooperative beamforming, cooperative jamming, and/or relay selection has also been investigated recently. Joint relay and jammer selection is investigated in [16], [17]. Several relays are selected, some of which perform information forwarding while others perform jamming of the eavesdropper. The mixture of relay selection and cooperative jamming is considered in [18], as a two-phase cooperation scheme assuming knowledge of global channel state information (CSI). The first phase is for transmission from the source to relays, in which the source also cooperates with the destination to jam the eavesdropper. The second phase is for the selected relay’s forwarding, in which the selected relay also cooperates with the source to jam the eavesdropper.

A mixed relay selection and cooperative jamming scheme is proposed in [19] by assuming knowledge of the distributions of the channels to the eavesdropper. A mixture of cooperative beamforming and cooperative jamming scheme is used in [20] for one-way relaying and in [21] for two-way relaying, in which one relay is selected to perform jamming and all other relays perform distributed beamforming. Moreover, the idea of using a mixture of cooperative beamforming and cooperative jamming schemes is generalized in [15], [22]–[24], in which relays transmit artificial noise to degrade the eavesdropper's reception quality.

We have two observations on the existing research efforts on secure cooperative communications.

- All existing works discussed above consider *passive* eavesdroppers. Actually, an eavesdropper may not work well when the eavesdropping channel (the channel from the legitimate transmitter to the eavesdropper) is not good. In this situation, jamming may be a better choice compared with eavesdropping. In other words, an *adaptive eavesdropper* that can select to perform eavesdropping or jamming based on the eavesdropping channel quality may be more effective to degrade the performance of the legitimate system. Performance analysis of secure cooperative communications against such an adaptive eavesdropper is lacking in the literature.
- In many existing works (see, e.g., [3]–[10], [12], [18], [22]), it is assumed that the ECSI is perfectly known by the legitimate system. However, as indicated in [25], this assumption may not be reasonable for all possible scenarios.

Motivated by the two observations, we focus on relay selection scheme and performance analysis for secure cooperative communications against an adaptive eavesdropper in three different cases of ECSI availability. The main contributions of this paper are summarized as follows:

1) We consider an adaptive eavesdropper that can select to perform eavesdropping or jamming rather than being a passive eavesdropper. In addition, different from existing works (see, e.g., [5], [7], [11], [12], [14]–[16], [22]–[25]) in which the eavesdropper is assumed to be within the wireless coverage of only the relays, we consider that the eavesdropper is located such that it can overhear the wireless signals from both the legitimate transmitter and the relays.
2) For three cases of ECSI availability (full ECSI, partial ECSI, and statistical ECSI), we propose optimal relay selection (ORS) schemes that minimize the secrecy outage probability.
3) We theoretically derive secrecy outage probability expressions in closed form for the proposed ORS schemes in the full and statistical ECSI cases. For the proposed ORS scheme in the partial ECSI case, we derive approximate secrecy outage probability expression, which is a tight approximation in high main-to-eavesdropper ratio regime, as verified by our computer simulation.
4) We analyze secrecy diversity of the three proposed ORS schemes, and theoretically prove that each of the schemes achieves a full secrecy diversity order.

The rest of this paper is organized as follows. Section II describes the considered system model. Section III details the three proposed ORS schemes that minimize secrecy outage probability. Section IV derives the secrecy outage probability expressions for the three ORS schemes, and analyzes the secrecy diversity order. Section V presents simulation results, followed by Section VI that concludes this paper.

II. SYSTEM MODEL

Consider secure communications from a source denoted S to a destination denoted D aided by a number K of DF relays denoted $R_1, R_2, ..., R_K$, as shown in Fig. 1. There is no direct link between S and D. For each transmission from S, one relay is selected to forward its received message to D. There is an adaptive eavesdropper denoted E that can intelligently decide on eavesdropping or jamming. Each node in the system has a single antenna and works in half-duplex mode. All the channels in the system experience independent Rayleigh fading, and channel reciprocity is assumed. Moreover, block fading model is considered, and thus, the instantaneous channel gain (square of channel coefficient magnitude) of any link does not change within one secure transmission (i.e., the source-relay transmission plus the relay-destination transmission), but may change from one secure transmission to the next. Denote f_{Sk}, f_{kD}, f_{SE}, f_{kE}, f_{Ek} ($k \in \{1, 2, ..., K\}$) as the channel gains of links $S-R_k$, R_k-D, $S-E$, R_k-E, and $E-R_k$, respectively.[1] Since the channels follow Rayleigh fading, f_{Sk}, f_{kD}, f_{SE}, f_{kE}, and f_{Ek} are exponentially distributed random variables with mean denoted as Λ_{Sk}, Λ_{kD}, Λ_{SE}, Λ_{kE}, and Λ_{Ek}, respectively. All the K relays are close to each other in a cluster, and thus, we assume $\Lambda_{Sk} = \Lambda_{SR}$, $\Lambda_{kD} = \Lambda_{RD}$, and $\Lambda_{kE} = \Lambda_{Ek} = \Lambda_{RE}$ for $k = 1, \dots, K$. Additive white Gaussian noise with variance σ^2 is assumed at each receiver. Throughout the paper, we use $p_x(\cdot)$ to denote the probability density function of a random variable x.

The communication from the source to the destination has two phases, shown in Fig. 1. In the first phase, the source transmits its message to the relays by using transmit power P_S; in the second phase, one relay, denoted as relay R_{k^*}, is selected to forward its received message to the destination by using transmit power P_R.

The adaptive eavesdropper is placed within the wireless coverage of the source and the relays. Thus, in the first phase, the adaptive eavesdropper can decide to work as an eavesdropper or a jammer, depending on the channel quality of link $S-E$, as follows.

- If f_{SE} (the channel gain of link $S-E$) is above a threshold $\eta_{\rm th}$, the adaptive eavesdropper will eavesdrop the signal from the source. The eavesdropping link is the dashed-dotted line shown in the first-phase plot in Fig. 1. Thus, the received signal-to-noise ratio (SNR) at a relay, say relay R_k, and the adaptive eavesdropper E are expressed as $\frac{P_S f_{Sk}}{\sigma^2}$ and $\frac{P_S f_{SE}}{\sigma^2}$, respectively.
- If f_{SE} is below the threshold $\eta_{\rm th}$, the adaptive eavesdropper will generate artificial interference by using transmit

[1] Note that $f_{kE} = f_{Ek}$ due to channel reciprocity.

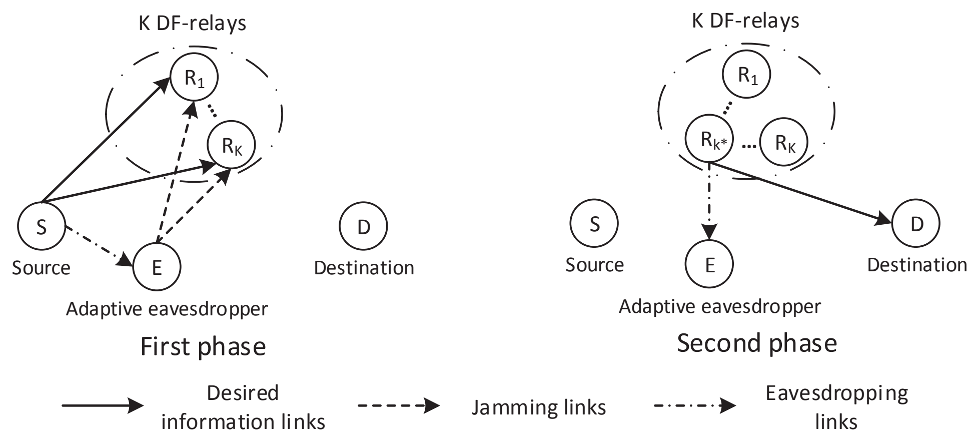


Fig. 1. The considered system with two phases.

power P_J to jam the relays.[2] The jamming links are the dashed line shown in the first-phase plot in Fig. 1. Thus, the received SNR of link $S-R_k$ in the first phase is expressed as $\frac{P_S f_{Sk}}{P_J f_{Ek}+\sigma^2}$.

In the second phase, the adaptive eavesdropper only performs eavesdropping, i.e., eavesdrops the signal from the selected relay. This is because the adaptive eavesdropper is placed between the source and relays, which implies that it is relatively far away to the destination, and thus, the adaptive eavesdropper is unlikely to have a good jamming performance to the destination. Note that, if the adaptive eavesdropper performs eavesdropping in the first phase, it can combine the signals received from the source and the relay R_{k^*} in the two phases by using the maximal ratio combining (MRC) to maximize the overall SNR of the eavesdropping links.

For the legitimate transmission, the performance of DF relaying is limited by the received SNR in both phases. Thus, the capacity of the legitimate transmission with the help of relay R_k is given by

$$C(k)=\begin{cases} C_1(k)\triangleq\frac{1}{2}\log_2\left[1+\min(\gamma_{Sk},\gamma_{kD})\right], \text{if } f_{SE}\geq\eta_{\rm th}, \\ C_2(k)\triangleq\frac{1}{2}\log_2\left[1+\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)\right], \\ \qquad\qquad\qquad\qquad \text{if } f_{SE}<\eta_{\rm th} \end{cases} \tag{1}$$

where $\gamma_{Sk}=\frac{P_S f_{Sk}}{\sigma^2}$, $\gamma_{kD}=\frac{P_R f_{kD}}{\sigma^2}$, and $\gamma_{Ek}=\frac{P_J f_{Ek}}{\sigma^2}$. On the other hand, when relay R_k is selected, the wiretap channel has a capacity expressed as

$$C_{\rm WT}(k)=\begin{cases}\frac{1}{2}\log_2\left(1+\gamma_{SE}+\gamma_{kE}\right), & \text{if } f_{SE}\geq\eta_{\rm th}, \\ \frac{1}{2}\log_2\left(1+\gamma_{kE}\right), & \text{if } f_{SE}<\eta_{\rm th}\end{cases} \tag{2}$$

where $\gamma_{SE}=\frac{P_S f_{SE}}{\sigma^2}$ and $\gamma_{kE}=\frac{P_R f_{kE}}{\sigma^2}$.

Since all channels follow Rayleigh fading, γ_{Sk}, γ_{kD}, γ_{Ek}, γ_{SE}, and γ_{kE} are exponentially distributed random variables with means $\bar{\gamma}_{SR}\triangleq\frac{P_S\Lambda_{SR}}{\sigma^2}$, $\bar{\gamma}_{RD}\triangleq\frac{P_R\Lambda_{RD}}{\sigma^2}$, $\bar{\gamma}_{ER}\triangleq\frac{P_J\Lambda_{RE}}{\sigma^2}$, $\bar{\gamma}_{SE}\triangleq\frac{P_S\Lambda_{SE}}{\sigma^2}$, and $\bar{\gamma}_{RE}\triangleq\frac{P_R\Lambda_{RE}}{\sigma^2}$, respectively.

Denote the mean value of average channel gains of the legitimate links (links from the source to the relays and from the relays to the destination) as $\Lambda_{\rm M}$, referred to as *average main channel gain*, and denote the mean value of the average channel gains of the links from the source and the relays to the adaptive eavesdropper as $\Lambda_{\rm E}$, referred to as *average eavesdropping channel gain*. Define $\lambda=\frac{\Lambda_{\rm M}}{\Lambda_{\rm E}}$ as the *main-to-eavesdropper ratio (MER)* [12], [26]. Accordingly, the average channel gains of the links can be rewritten as $\Lambda_{SR}=\beta_{SR}\Lambda_{\rm M}$, $\Lambda_{RD}=\beta_{RD}\Lambda_{\rm M}$, $\Lambda_{SE}=\beta_{SE}\Lambda_{\rm E}$, and $\Lambda_{RE}=\beta_{RE}\Lambda_{\rm E}$. Moreover, *the system SNR* is defined as $\gamma=\frac{P_S}{\sigma^2}=\mu\frac{P_R}{\sigma^2}$, with $\mu=P_S/P_R$ being a positive constant.

It is assumed that the legitimate system knows the channel gains from the source to the relays (i.e., $f_{Sk}, k=1,\ldots,K$) and from the relays to the destination (i.e., $f_{kD}, k=1,\ldots,K$), and the adaptive eavesdropper knows the channel gains related to itself (i.e., f_{SE} and f_{kE}, $k=1,\ldots,K$). Similar to existing works that enhance physical-layer security [3]–[12], [15]–[19], [21]–[26], it is assumed that the legitimate system is aware of the presence of the eavesdropper (e.g., by using a detection technique proposed in [27]), as well as a certain level of ECSI. We consider three different cases for availability of ECSI at the legitimate system, as follows.

- *Full ECSI Case:* The legitimate system knows the instantaneous channel gain information of all the eavesdropping links, i.e., f_{SE} and f_{kE}, $k=1,\ldots,K$. This assumption is commonly made in the literature (e.g., see [3]–[5], [7]–[10], [12], [16]–[18], [26]). An example of the case is that the adaptive eavesdropper is a regular user, and the legitimate system can monitor its CSI [28].
- *Partial ECSI Case:* The legitimate system knows the channel gain information of the eavesdropping links from the relays, i.e., f_{kE}, $k=1,\ldots,K$. An example of the case is that the source is a primary user, relays are secondary users that help primary transmissions, and the adaptive eavesdropper is another secondary user that does not help. Due to limited cooperation between the primary system and the non-relay secondary user, the channel gain

[2]For the adaptive eavesdropper, the purpose of the jamming is two-fold. First, when the eavesdropping channel is considered to be not good (i.e., when f_{SE} is below the threshold $\eta_{\rm th}$), jamming can guarantee that the legitimate system's performance can still be degraded by generating interference to the legitimate communication. Second, when the eavesdropping channel is not good, the jamming will force the legitimate system to lower codeword rate (to avoid transmission outage). In other words, the information transmitted by the legitimate system in the current transmission is very limited, and the legitimate system has to use more later time for information transmissions. The eavesdropper then has chances to eavesdrop in the legitimate system's later transmissions when the eavesdropping channel is good.

f_{SE} is unknown.[3]

- *Statistical ECSI Case:* The legitimate system knows mean values of the channel gains of the eavesdropping links. A similar assumption is considered in [16], [17], [29]. An example of the case is that the adaptive eavesdropper is a malicious user to the legitimate system. The statistical ECSI can be obtained by long-term monitoring [17].

III. ORS for Secrecy Outage Probability Minimization

Denote the target secrecy rate of the legitimate transmission as $\mathbf{R}_\mathrm{S}$, and define *secrecy outage* as an event that the achievable secrecy capacity of the legitimate transmission is less than $\mathbf{R}_\mathrm{S}$. In this section, we propose an ORS scheme for each of the three ECSI availability cases, aiming at minimization of the secrecy outage probability (SOP).

A. ORS for Full ECSI Case

In the full ECSI case, since the legitimate system knows the instantaneous channel gain information of all legitimate transmission links and all eavesdropping links, it knows the capacity of the main channel and wiretap channel. Thus, to maximally utilize the main channel capacity, the legitimate system can use the variable-rate strategy for codeword transmission [30], i.e., transmit codewords at a rate $\mathbf{R}_\mathrm{C} = C(k)$ if relay R_k is selected to help. By the variable-rate strategy, the mutual information between the source and the adaptive eavesdropper is given as $\min\big(C(k), C_\mathrm{WT}(k)\big)$ [30]. Therefore, the legitimate system has an achievable secrecy capacity given as

$$C_\mathrm{sec}^\mathrm{F}(k) = [C(k) - C_\mathrm{WT}(k)]^+ = \begin{cases} \left[\frac{1}{2}\log_2\left(\frac{1+\min(\gamma_{Sk},\gamma_{kD})}{1+\gamma_{SE}+\gamma_{kE}}\right)\right]^+, & \text{if } f_{SE} \geq \eta_\mathrm{th}, \\ \left[\frac{1}{2}\log_2\left(\frac{1+\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)}{1+\gamma_{kE}}\right)\right]^+, & \text{if } f_{SE} < \eta_\mathrm{th} \end{cases} \tag{3}$$

where the superscript 'F' means "full ECSI", the subscript "sec" means "secrecy", and $[\cdot]^+ = \max(\cdot, 0)$.

In full ECSI case, minimization of secrecy outage probability in relay selection is equivalent to maximization of the achievable secrecy capacity. Thus, the optimal relay that minimizes the SOP is selected as

$$k^* = \arg\max_{k=1,\ldots,K} C_\mathrm{sec}^\mathrm{F}(k) = \begin{cases} \arg\max\limits_{k=1,\ldots,K} \frac{1+\min(\gamma_{Sk},\gamma_{kD})}{1+\gamma_{SE}+\gamma_{kE}}, & \text{if } f_{SE} \geq \eta_\mathrm{th}, \\ \arg\max\limits_{k=1,\ldots,K} \frac{1+\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)}{1+\gamma_{kE}}, & \text{if } f_{SE} < \eta_\mathrm{th}. \end{cases} \tag{4}$$

B. ORS for Partial ECSI

If relay R_k is selected, the main channel capacity $C(k)$ should take the value of either $C_1(k)$ or $C_2(k)$, as shown in (1). However, in partial ECSI case, since the legitimate system does not have information of f_{SE}, it does not know what value the main channel capacity should take. Note that $C_1(k) > C_2(k)$. Apparently the codeword transmission rate $\mathbf{R}_\mathrm{C}$ should be no more than $C_1(k)$. If $C_2(k) < \mathbf{R}_\mathrm{C} \leq C_1(k)$, then a transmission outage[4] will happen if $f_{SE} < \eta_\mathrm{th}$ (which means that the adaptive eavesdropper works as a jammer in the first phase). Thus, to guarantee there is no transmission outage, a conservative variable-rate $\mathbf{R}_\mathrm{C} = C_2(k)$ is used if relay R_k is selected to help. Thus, the mutual information between the source S and the adaptive eavesdropper E is given as $\min\big(C_2(k), C_\mathrm{WT}(k)\big)$, and the legitimate system has an achievable secrecy capacity given as

$$C_\mathrm{sec}^\mathrm{P}(k) = [C_2(k) - C_\mathrm{WT}(k)]^+ = \begin{cases} \left[\frac{1}{2}\log_2\left(\frac{1+\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)}{1+\gamma_{SE}+\gamma_{kE}}\right)\right]^+, & \text{if } f_{SE} \geq \eta_\mathrm{th}, \\ \left[\frac{1}{2}\log_2\left(\frac{1+\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)}{1+\gamma_{kE}}\right)\right]^+, & \text{if } f_{SE} < \eta_\mathrm{th} \end{cases} \tag{5}$$

where the superscript 'P' means "partial ECSI".

Due to unavailability of f_{SE}, the legitimate system does not know the exact value of the achievable secrecy capacity $C_\mathrm{sec}^\mathrm{P}(k)$. Accordingly, we propose the following ORS scheme: For partial ECSI case, the relay R_{k^*} is selected as

$$k^* = \arg\max_{k=1,\ldots,K} \phi_k \tag{6}$$

in which

$$\phi_k \triangleq 1 + \min\left(\frac{\gamma_{Sk}}{\gamma_{Ek}+1}, \gamma_{kD}\right) - T(1+\gamma_{kE}) \tag{7}$$

with $T \triangleq 2^{2\mathbf{R}_\mathrm{S}}$.

The optimality of the propose ORS scheme is shown in the following theorem.

***Theorem** 1:* In partial ECSI case, the proposed relay selection given in (6) is optimal, i.e., minimizes the SOP.

Proof: The proof is provided in Appendix A. ■

C. ORS for Statistical ECSI

In statistical ECSI case, the legitimate system does not know the instantaneous channel gains of eavesdropping links, and thus, is unable to evaluate $C_2(k)$ or $C(k)$. Therefore, the variable-rate strategy for codeword transmission considered in the full and partial ECSI cases cannot be used.

For any rate in the source S's codeword transmission, a transmission outage will happen if the main channel capacity $C(k)$ is below the code transmission rate. In specific, if source S's codeword transmission rate is $\mathbf{R}_\mathrm{C} > 0$ and relay R_k is selected to help, the transmission outage probability (TOP) conditioned on the channel gain f_{Sk} and f_{kD} is given by

$$P_\mathrm{tran,out}\left(k\middle|f_{Sk}, f_{kD}\right) = \Pr\left(C(k) < \mathbf{R}_\mathrm{C}\middle|f_{Sk}, f_{kD}\right) = \begin{cases} 1, & \text{if } \min(\gamma_{Sk}, \gamma_{kD}) < \gamma_\mathrm{th}, \\ \left[1 - \exp\left(-\frac{\eta_\mathrm{th}}{\Lambda_{SE}}\right)\right] \exp\left(-\frac{\gamma_{Sk}/\gamma_\mathrm{th} - 1}{\bar{\gamma}_{ER}}\right), & \text{if } \min(\gamma_{Sk}, \gamma_{kD}) \geq \gamma_\mathrm{th} \end{cases} \tag{8}$$

where $\Pr(\cdot)$ means probability, and $\gamma_\mathrm{th} = 2^{2\mathbf{R}_\mathrm{C}} - 1$. The derivation is provided in Appendix B.

When a transmission outage happens, the destination D cannot correctly decode its received signal. From (8), it can

[3] Since relays and the adaptive eavesdropper belong to the same secondary system, relays know the channel gain between themselves and the adaptive eavesdropper, and then let the primary system know this information by feedback.

[4] A transmission outage means that the codeword transmission rate is more than the main channel capacity, and thus, the destination is unable to correctly decode the transmitted information.

be seen that transmission outage happens with a nonzero probability. Therefore, to guarantee a certain level of reception quality, here we require that the TOP should be bounded within an acceptable level denoted ε, given as $P_{\text{tran,out}}(k|f_{Sk}, f_{kD}) \le \varepsilon$. From (8), it can be seen that the requirement $P_{\text{tran,out}}(k|f_{Sk}, f_{kD}) \le \varepsilon$ is equivalent to

$$\begin{cases} 2^{2\mathbf{R}_{\text{C}}} - 1 \le \min(\gamma_{Sk}, \gamma_{kD}), \\ \left[1 - \exp\left(-\frac{\eta_{\text{th}}}{\Lambda_{SE}}\right)\right] \exp\left(-\frac{\frac{\gamma_{Sk}}{2^{2\mathbf{R}_{\text{C}}}-1} - 1}{\bar{\gamma}_{ER}}\right) \le \varepsilon \end{cases} \tag{9}$$

which can be further expressed as

$$\begin{cases} 2^{2\mathbf{R}_{\text{C}}} - 1 \le \gamma_{Sk}, \\ 2^{2\mathbf{R}_{\text{C}}} - 1 \le \gamma_{kD}, \\ 2^{2\mathbf{R}_{\text{C}}} - 1 \le \frac{\gamma_{Sk}}{1 + \bar{\gamma}_{ER} \ln\left(\frac{1}{\varepsilon}\left[1 - \exp\left(-\frac{\eta_{\text{th}}}{\Lambda_{SE}}\right)\right]\right)} \end{cases} \tag{10}$$

or in a compact form shown in (11) on top of next page. For notational convenience, we define

$$g(\varepsilon) \triangleq \left(1 + \bar{\gamma}_{ER}\left[\ln\left(\frac{1}{\varepsilon}\left[1 - \exp\left(-\frac{\eta_{\text{th}}}{\Lambda_{SE}}\right)\right]\right)\right]^+\right)^{-1}. \tag{12}$$

Then the inequality (11) is equivalent to $\mathbf{R}_{\text{C}} \le \mathbf{R}_{\text{C}}(k) \triangleq \frac{1}{2}\log_2\left[1 + \min\left(g(\varepsilon)\gamma_{Sk}, \gamma_{kD}\right)\right]$, which means that the TOP of link $S - R_k - D$ will not exceed ε if codeword transmission rate of the source S is not more than $\mathbf{R}_{\text{C}}(k)$. To maximally utilize the capacity of the main channel, we set $\mathbf{R}_{\text{C}} = \mathbf{R}_{\text{C}}(k)$ if relay R_k is selected.

Similar to the full and partial ECSI cases, when relay R_k is selected to help, the mutual information between the source and the adaptive eavesdropper is given as $\min\left(\mathbf{R}_{\text{C}}(k), C_{\text{WT}}(k)\right)$, and thus, the legitimate system has an achievable secrecy capacity expressed as

$$\begin{aligned} C^{\text{S}}_{\text{sec}}(k) &= [\mathbf{R}_{\text{C}}(k) - C_{\text{WT}}(k)]^+ \\ &= \begin{cases} \left[\frac{1}{2}\log_2\left(\frac{1+\min(g(\varepsilon)\gamma_{Sk},\gamma_{kD})}{1+\gamma_{SE}+\gamma_{kE}}\right)\right]^+, & \text{if } f_{SE} \ge \eta_{\text{th}}, \\ \left[\frac{1}{2}\log_2\left(\frac{1+\min(g(\varepsilon)\gamma_{Sk},\gamma_{kD})}{1+\gamma_{kE}}\right)\right]^+, & \text{if } f_{SE} < \eta_{\text{th}} \end{cases} \end{aligned} \tag{13}$$

where superscript 'S' represents "statistical ECSI". Note that the legitimate system does not know the value of $C^{\text{S}}_{\text{sec}}(k)$ due to unavailability of channel gain information f_{SE} and f_{kE}, $k = 1, \ldots, K$.

We propose the following ORS scheme: For statistical ECSI case, the relay R_{k^*} is selected by

$$k^* = \arg\max_{k=1,\ldots,K} \theta_k \tag{14}$$

where $\theta_k = \min(g(\varepsilon)\gamma_{Sk}, \gamma_{kD})$.[5]

The optimality of the proposed ORS scheme is shown in the following theorem.

***Theorem** 2:* In statistical ECSI case, the proposed relay selection scheme in (14) is optimal, i.e., minimizes the SOP while guaranteeing that the TOP is bounded by ε.

Proof: The proof is presented in Appendix C. ∎

[5]From (12), it can be seen that the proposed ORS scheme needs to know the value of the term $[1-\exp(-\eta_{\text{th}}/\Lambda_{SE})]$, which is exactly equal to $\Pr(f_{SE} < \eta_{\text{th}})$, i.e., the probability that the eavesdropper jams the legitimate link in the first phase. The probability $\Pr(f_{SE} < \eta_{\text{th}})$ can be estimated by the legitimate system's long-term observation of the jamming behavior of the eavesdropper.

IV. Analysis of the Proposed ORS Schemes

In this section, we derive the SOP of the three proposed ORS schemes in their corresponding cases of ECSI availability. Furthermore, to gain more insights, the secrecy diversity of the three ORS schemes is also analyzed.

A. SOP Analysis

1) SOP of ORS for full ECSI case: Recall that a secrecy outage means that the achievable secrecy capacity is below the target secrecy rate $\mathbf{R}_{\text{S}}$. We have the following lemma for the SOP of the proposed ORS in the full ECSI case.

***Lemma** 1:* SOP of the proposed ORS in the full ECSI case is given in closed form shown in (15) on top of next page, with $\text{erfc}(x) \triangleq 1 - \frac{2}{\sqrt{\pi}}\int_0^x \exp(-t^2)\text{d}t$ being the complementary error function, and $a(\cdot)$, b and $c(\cdot)$ defined as

$$\begin{cases} a(z) = \left(\frac{1}{\bar{\gamma}_{SR}} + \frac{1}{\bar{\gamma}_{RD}}\right)(z + T - 1), \\ b = \frac{\bar{\gamma}_{SR}}{4T\bar{\gamma}_{RE}\bar{\gamma}_{ER}}, \\ c(z) = 1 + \frac{\bar{\gamma}_{RE}T}{\bar{\gamma}_{SR}} + \frac{\bar{\gamma}_{RE}T}{\bar{\gamma}_{RD}} + \frac{\bar{\gamma}_{ER}(z+T-1)}{\bar{\gamma}_{SR}}. \end{cases} \tag{16}$$

Proof: According to the definition of secrecy outage, the SOP of the proposed ORS in (4) for the full ECSI case can be written as

$$\begin{aligned} &P^{\text{F}}_{\text{sec,out}} \\ &= \Pr\left(C^{\text{F}}_{\text{sec}}(k^*) < \mathbf{R}_{\text{S}}\right) \\ &= \Pr\left(\max_{k=1,\ldots,K} C^{\text{F}}_{\text{sec}}(k) < \mathbf{R}_{\text{S}}\right) \\ &= \Pr\left(\max_{k=1,\ldots,K} C^{\text{F}}_{\text{sec}}(k) < \mathbf{R}_{\text{S}}, f_{SE} \ge \eta_{\text{th}}\right) \\ &\quad + \Pr\left(\max_{k=1,\ldots,K} C^{\text{F}}_{\text{sec}}(k) < \mathbf{R}_{\text{S}}, f_{SE} < \eta_{\text{th}}\right) \\ &= \Pr\left(\max_{k=1,\ldots,K}\left[\frac{1}{2}\log_2\left(\frac{1+\min(\gamma_{Sk},\gamma_{kD})}{1+\gamma_{SE}+\gamma_{kE}}\right)\right]^+ < \mathbf{R}_{\text{S}}, f_{SE} \ge \eta_{\text{th}}\right) \\ &\quad + \Pr\Bigg(\max_{k=1,\ldots,K}\left[\frac{1}{2}\log_2\left(\frac{1+\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)}{1+\gamma_{kE}}\right)\right]^+ < \mathbf{R}_{\text{S}}, \\ &\qquad\qquad f_{SE} < \eta_{\text{th}}\Bigg) \\ &= \underbrace{\Pr\left(\max_{k=1,\ldots,K} \frac{1+\min(\gamma_{Sk},\gamma_{kD})}{1+\gamma_{SE}+\gamma_{kE}} < T, f_{SE} \ge \eta_{\text{th}}\right)}_{\kappa_1} \\ &\quad + \underbrace{\Pr\left(\max_{k=1,\ldots,K} \frac{1+\min\left(\frac{\gamma_{Sk}}{\gamma_{Ek}+1},\gamma_{kD}\right)}{1+\gamma_{kE}} < T, f_{SE} < \eta_{\text{th}}\right)}_{\kappa_2} \end{aligned} \tag{17}$$

where the first equality is from the SOP definition, the second equality is from (4), the third equality is from Total Probability Theorem, the fourth equality is from (3), and the last equality is from some math manipulations and $T = 2^{2\mathbf{R}_S}$. Here f_{SE}, γ_{kE}, γ_{Ek}, γ_{Sk}, and γ_{kD} are exponentially distributed. The term κ_1 can be expressed as (18) on top of next page, where step (i) uses the Binomial Theorem [31, p.10]. The term κ_2 can be calculated as (19) on top of next page, where the second equality uses the fact that γ_{Sk} and γ_{kD} are exponentially distributed, and the last equality uses [32, eq. (3.322.2)]. Here

$$2^{2\mathbf{R}_{\mathrm{C}}}-1\leq\ \min\left(\left(1+\bar{\gamma}_{ER}\left[\ln\left(\frac{1}{\varepsilon}\left[1-\exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right)\right]\right)\right]^{+}\right)^{-1}\gamma_{Sk},\gamma_{kD}\right)\tag{11}$$

$$\begin{aligned}P_{\mathrm{sec,out}}^{\mathrm{F}}&=\sum\nolimits_{m=0}^{K}\binom{K}{m}(-1)^{m}\frac{\exp\left[-\left(\frac{m}{\bar{\gamma}_{SR}}+\frac{m}{\bar{\gamma}_{RD}}\right)(T-1)-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\left(1+\frac{mT\bar{\gamma}_{SE}}{\bar{\gamma}_{SR}}+\frac{mT\gamma_{\bar{S}E}}{\bar{\gamma}_{RD}}\right)\right]}{\left[1+\frac{T\bar{\gamma}_{RE}}{\bar{\gamma}_{SR}}+\frac{T\bar{\gamma}_{RE}}{\bar{\gamma}_{RD}}\right]^{m}\left[1+\frac{mT\bar{\gamma}_{SE}}{\bar{\gamma}_{SR}}+\frac{mT\bar{\gamma}_{SE}}{\bar{\gamma}_{RD}}\right]}\\&\quad+\left[1-\exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right)\right]\left(1-\exp\left[-a(0)\right]\sqrt{\pi b}\exp\left(b[c(0)]^{2}\right)\mathrm{erfc}\left(\sqrt{b}c(0)\right)\right)^{K}\end{aligned}\tag{15}$$

$$\begin{aligned}\kappa_{1}&=\int_{\eta_{\mathrm{th}}}^{\infty}p_{f_{SE}}(x)\prod_{k=1}^{K}\int_{0}^{\infty}\Pr\left(\min\left(\gamma_{Sk},\gamma_{kD}\right)<T-1+\frac{TP_{S}x}{\sigma^{2}}+Ty_{k}\right)p_{\gamma_{kE}}(y_{k})\mathrm{d}y_{k}\mathrm{d}x\\&=\int_{\eta_{\mathrm{th}}}^{\infty}p_{f_{SE}}(x)\prod_{k=1}^{K}\int_{0}^{\infty}\left[1-\Pr\left(\gamma_{Sk}>T-1+\frac{TP_{S}x}{\sigma^{2}}+Ty_{k}\right)\Pr\left(\gamma_{kD}>T-1+\frac{TP_{S}x}{\sigma^{2}}+Ty_{k}\right)\right]p_{\gamma_{kE}}(y_{k})\mathrm{d}y_{k}\mathrm{d}x\\&=\int_{\eta_{\mathrm{th}}}^{\infty}\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\prod_{k=1}^{K}\int_{0}^{\infty}\left(1-\exp\left[-\left(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}\right)\left(T-1+\frac{TP_{S}x}{\sigma^{2}}+Ty_{k}\right)\right]\right)\frac{1}{\bar{\gamma}_{RE}}\exp\left(-\frac{y_{k}}{\bar{\gamma}_{RE}}\right)\mathrm{d}y_{k}\mathrm{d}x\\&=\int_{\eta_{\mathrm{th}}}^{\infty}\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\left(1-\frac{\frac{1}{\bar{\gamma}_{RE}}\exp\left[-\left(\frac{1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}\right)\left(T-1+\frac{TP_{S}x}{\sigma^{2}}\right)\right]}{\frac{1}{\bar{\gamma}_{RE}}+\frac{T}{\bar{\gamma}_{SR}}+\frac{T}{\bar{\gamma}_{RD}}}\right)^{K}\mathrm{d}x\\&\overset{\text{(i)}}{=}\sum_{m=0}^{K}\binom{K}{m}\frac{(-1)^{m}}{\Lambda_{SE}}\left[1+T\left(\frac{\bar{\gamma}_{RE}}{\bar{\gamma}_{SR}}+\frac{\bar{\gamma}_{RE}}{\bar{\gamma}_{RD}}\right)\right]^{-m}\exp\left[-\left(\frac{m}{\bar{\gamma}_{SR}}+\frac{m}{\bar{\gamma}_{RD}}\right)(T-1)\right]\int_{\eta_{\mathrm{th}}}^{\infty}\exp\left[-x\left(\frac{1}{\Lambda_{SE}}+\frac{mTP_{S}}{\bar{\gamma}_{SR}\sigma^{2}}+\frac{mTP_{S}}{\bar{\gamma}_{RD}\sigma^{2}}\right)\right]\mathrm{d}x\\&=\sum_{m=0}^{K}\binom{K}{m}(-1)^{m}\frac{\exp\left[-\left(\frac{m}{\bar{\gamma}_{SR}}+\frac{m}{\bar{\gamma}_{RD}}\right)(T-1)-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\left(1+\frac{mT\bar{\gamma}_{SE}}{\bar{\gamma}_{SR}}+\frac{mT\gamma_{\bar{S}E}}{\bar{\gamma}_{RD}}\right)\right]}{\left[1+\frac{T\bar{\gamma}_{RE}}{\bar{\gamma}_{SR}}+\frac{T\bar{\gamma}_{RE}}{\bar{\gamma}_{RD}}\right]^{m}\left[1+\frac{mT\bar{\gamma}_{SE}}{\bar{\gamma}_{SR}}+\frac{mT\bar{\gamma}_{SE}}{\bar{\gamma}_{RD}}\right]}\end{aligned}\tag{18}$$

$$\begin{aligned}\kappa_{2}&=\Pr\left(f_{SE}<\eta_{\mathrm{th}}\right)\prod_{k=1}^{K}\int_{0}^{\infty}\Pr\left(\min\left(\frac{\gamma_{Sk}}{P_{J}x/\sigma^{2}+1},\gamma_{kD}\right)<T-1+\frac{TP_{R}x}{\sigma^{2}}\right)p_{f_{kE}}(x)\mathrm{d}x\\&=\left[1-\exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right)\right]\left\{\int_{0}^{\infty}\left(1-\exp\left[-\left(\frac{P_{J}x/\sigma^{2}+1}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}\right)\left(T-1+\frac{TP_{R}x}{\sigma^{2}}\right)\right]\right)\frac{1}{\Lambda_{RE}}\exp\left(-\frac{x}{\Lambda_{RE}}\right)\mathrm{d}x\right\}^{K}\\&=\left[1-\exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right)\right]\left\{1-\frac{1}{\Lambda_{RE}}\exp\left[-\left(\frac{T-1}{\bar{\gamma}_{SR}}+\frac{T-1}{\bar{\gamma}_{RD}}\right)\right]\right.\\&\qquad\left.\times\int_{0}^{\infty}\exp\left(-\left[\frac{TP_{J}P_{R}}{\bar{\gamma}_{SR}(\sigma^{2})^{2}}x^{2}+\left(\frac{1}{\Lambda_{RE}}+\frac{P_{J}(T-1)+P_{R}T}{\bar{\gamma}_{SR}\sigma^{2}}+\frac{P_{R}T}{\bar{\gamma}_{RD}\sigma^{2}}\right)x\right]\right)\mathrm{d}x\right\}^{K}\\&=\left[1-\exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right)\right]\left(1-\exp\left[-a(0)\right]\sqrt{\pi b}\exp\left(b[c(0)]^{2}\right)\mathrm{erfc}\left(\sqrt{b}c(0)\right)\right)^{K}\end{aligned}\tag{19}$$

$\mathrm{erfc}(x)\triangleq 1-\frac{2}{\sqrt{\pi}}\int_{0}^{x}\exp(-t^{2})\mathrm{d}t$ is the complementary error function, and $a(\cdot)$, b and $c(\cdot)$ are defined in (16).

By substituting (18) and (19) into (17), the SOP expression can be obtained in closed form in (15). This completes the proof. ■

2) SOP of ORS for partial ECSI: The following lemma gives an expression for the SOP of the proposed ORS scheme for the partial ECSI case.

***Lemma** 2:* SOP of the proposed ORS scheme for the partial ECSI case can be expressed as

$$\begin{aligned}P_{\mathrm{sec,out}}^{\mathrm{P}}=\chi+&\left(1-\exp\left[-a(0)\right]\sqrt{\pi b}\exp\left(b[c(0)]^{2}\right)\right.\\&\left.\times\,\mathrm{erfc}\left(\sqrt{b}c(0)\right)\right)^{K}\left[1-\exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right)\right]\end{aligned}\tag{20}$$

where $a(z)$, b and $c(z)$ have been defined in (16), and χ represents the following integral

$$\begin{aligned}\chi\triangleq\int_{\eta_{\mathrm{th}}}^{\infty}&\left(1-\exp\left[-a\left(\frac{TP_{S}x}{\sigma^{2}}\right)\right]\sqrt{\pi b}\exp\left(b\left[c\left(\frac{TP_{S}x}{\sigma^{2}}\right)\right]^{2}\right)\right.\\&\left.\times\,\mathrm{erfc}\left(\sqrt{b}c\left(\frac{TP_{S}x}{\sigma^{2}}\right)\right)\right)^{K}\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\mathrm{d}x.\end{aligned}\tag{21}$$

Proof: According to the achievable secrecy capacity expression of link $S{-}R_k{-}D$ shown in (5) and the relay selection rule given in (6), the SOP of the ORS for the partial ECSI case can be expressed as

$$\begin{aligned}P^{\rm P}_{\rm sec,out}=&\Pr\left(C^{\rm P}_{\rm sec}(k^*)<\mathbf{R}_{\rm S}\right)\\=&\Pr\left(\frac{1+\min\left(\frac{\gamma_{Sk^*}}{\gamma_{Ek^*}+1},\gamma_{k^*D}\right)}{1+\gamma_{SE}+\gamma_{k^*E}}<T, f_{SE}\geq\eta_{\rm th}\right)\\&+\Pr\left(\frac{1+\min\left(\frac{\gamma_{Sk^*}}{\gamma_{Ek^*}+1},\gamma_{k^*D}\right)}{1+\gamma_{k^*E}}<T, f_{SE}<\eta_{\rm th}\right)\\=&\Pr\left(\max_{k=1,\dots,K}\phi_k<T\gamma_{SE}, f_{SE}\geq\eta_{\rm th}\right)\\&+\Pr\left(\max_{k=1,\dots,K}\phi_k<0, f_{SE}<\eta_{\rm th}\right).\end{aligned}\tag{22}$$

Since ϕ_k is independent from the channel gain f_{SE} and $\gamma_{SE}=P_s f_{SE}/\sigma^2$, (22) can be further expressed as

$$\begin{aligned}P^{\rm P}_{\rm sec,out}=&\int_{\eta_{\rm th}}^{\infty}\prod_{k=1}^{K}\Pr\left(\phi_k<\tfrac{TP_Sx}{\sigma^2}\right)p_{f_{SE}}(x){\rm d}x\\&+\prod_{k=1}^{K}\Pr\left(\phi_k<0\right)\Pr\left(f_{SE}<\eta_{\rm th}\right).\end{aligned}\tag{23}$$

Next we focus on computing the probability $\Pr(\phi_k<z)$, $z\in(0,\infty)$. Since $\phi_k=1+\min\left(\frac{\gamma_{Sk}}{\gamma_{Ek}+1},\gamma_{kD}\right)-T\left(1+\gamma_{kE}\right)$, the probability $\Pr(\phi_k<z)$ can be calculated as

$$\begin{aligned}&\Pr\left(\phi_k<z\right)\\&=\Pr\left(1+\min\left(\tfrac{\gamma_{Sk}}{\gamma_{Ek}+1},\gamma_{kD}\right)-T\left(1+\gamma_{kE}\right)<z\right)\\&=\int_0^{\infty}\Pr\Big(\min\left(\tfrac{\gamma_{Sk}}{P_Jx/\sigma^2+1},\gamma_{kD}\right)<z-1+T\left(1+\tfrac{P_Rx}{\sigma^2}\right)\Big)\\&\qquad\times p_{f_{kE}}(x){\rm d}x\\&=\int_0^{\infty}\Big[1-\Pr\left(\tfrac{\gamma_{Sk}}{P_Jx/\sigma^2+1}>z-1+T\left(1+\tfrac{P_Rx}{\sigma^2}\right)\right)\\&\quad\times\Pr\left(\gamma_{kD}>z-1+T\left(1+\tfrac{P_Rx}{\sigma^2}\right)\right)\Big]p_{f_{kE}}(x){\rm d}x\\&=\int_0^{\infty}\Big(1-\exp\Big[-\Big(\tfrac{P_Jx/\sigma^2+1}{\bar\gamma_{SR}}+\tfrac{1}{\bar\gamma_{RD}}\Big)\Big(z-1+T+\tfrac{TP_Rx}{\sigma^2}\Big)\Big]\Big)\\&\qquad\times\tfrac{1}{\Lambda_{RE}}\exp\left(-\tfrac{x}{\Lambda_{RE}}\right){\rm d}x\\&=1-\tfrac{1}{\Lambda_{RE}}\exp\left[-\left(\tfrac{1}{\bar\gamma_{SR}}+\tfrac{1}{\bar\gamma_{RD}}\right)(z+T-1)\right]\\&\quad\times\int_0^{\infty}\exp\Big[-\tfrac{TP_JP_R}{\bar\gamma_{SR}(\sigma^2)^2}x^2\\&\qquad-\tfrac{1}{\Lambda_{RE}}\left(1+\tfrac{T\bar\gamma_{RE}}{\bar\gamma_{SR}}+\tfrac{T\bar\gamma_{RE}}{\bar\gamma_{RD}}+\tfrac{\bar\gamma_{ER}(z+T-1)}{\bar\gamma_{SR}}\right)x\Big]{\rm d}x\\&=1-\exp\left[-a(z)\right]\sqrt{\pi b}\exp\left(b[c(z)]^2\right){\rm erfc}\left(\sqrt{b}c(z)\right)\end{aligned}\tag{24}$$

where the fourth equality uses the fact that γ_{Sk} γ_{kD}, and f_{kE} are exponentially distributed, the last equality uses [32, eq. (3.322.2)], and $a(z)$, b and $c(z)$ have been defined in (16). Applying (24) with $z=\frac{TP_Sx}{\sigma^2}$ and $z=0$ in (23) and using $p_{f_{SE}}(x)=\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)$, we have the SOP expression given in (20) for the proposed ORS in the partial ECSI case.

This completes the proof. ■

However, in the SOP expression given in (20), it is difficult to solve the integral in (21), due to the presence of the term ${\rm erfc}\Big(\sqrt{b}c\left(\frac{TP_Sx}{\sigma^2}\right)\Big)$. Thus, we consider a high MER approximation for $P^{\rm P}_{\rm sec,out}$ instead of an exact expression. According to [32, eq. (8.254)], when x is sufficiently large, the complementary error function ${\rm erfc}(x)$ can be asymptotically expressed as

$${\rm erfc}(x)\simeq\frac{\exp(-x^2)}{\sqrt{\pi}x}\sum_{i=0}^{l}(-1)^i\frac{(2i-1)!!}{(2x^2)^i}\tag{25}$$

where l is any positive integer, and $(\cdot)!!$ means double factorial. Thus, $\exp(x^2){\rm erfc}(x)$ can be asymptotically expressed as

$$\exp(x^2){\rm erfc}(x)\simeq\frac{1}{\sqrt{\pi}x}\sum_{i=0}^{l}(-1)^i\frac{(2i-1)!!}{(2x^2)^i}.\tag{26}$$

Since $b\cdot c(TP_Sx/\sigma^2)\rightarrow\infty$ holds for MER $\lambda\rightarrow\infty$, with the help of (26) with $l=1$, the term $\exp\Big(b\left[c\left(\frac{TP_Sx}{\sigma^2}\right)\right]^2\Big){\rm erfc}\Big(\sqrt{b}c\left(\frac{TP_Sx}{\sigma^2}\right)\Big)$ in (21) can be asymptotically expressed as

$$\begin{aligned}&\exp\Big(b\left[c\left(\tfrac{TP_Sx}{\sigma^2}\right)\right]^2\Big){\rm erfc}\Big(\sqrt{b}c\left(\tfrac{TP_Sx}{\sigma^2}\right)\Big)\\&\overset{\lambda\to\infty}{\simeq}\frac{1}{\sqrt{\pi b}c(\frac{TP_Sx}{\sigma^2})}\left(1-\frac{1}{2b[c(\frac{TP_Sx}{\sigma^2})]^2}\right).\end{aligned}\tag{27}$$

Thus, by applying (27) into (21), the term χ can be asymptotically expressed as

$$\begin{aligned}\chi\simeq&\int_{\eta_{\rm th}}^{\infty}\left(1-\frac{\exp\left[-a\left(\frac{TP_Sx}{\sigma^2}\right)\right]}{c\left(\frac{TP_Sx}{\sigma^2}\right)}\left(1-\frac{1}{2b\left[c\left(\frac{TP_Sx}{\sigma^2}\right)\right]^2}\right)\right)^K\\&\times\tfrac{1}{\Lambda_{SE}}\exp\left(-\tfrac{x}{\Lambda_{SE}}\right){\rm d}x\\\overset{\rm (ii)}{=}&\int_{\eta_{\rm th}}^{\infty}\sum_{m=0}^{K}\binom{K}{m}\sum_{n=0}^{m}\binom{m}{n}(-1)^{m+n}\\&\times\frac{\exp\left[-ma\left(\frac{TP_Sx}{\sigma^2}\right)-\frac{x}{\Lambda_{SE}}\right]}{2^nb^n\left[c\left(\frac{TP_Sx}{\sigma^2}\right)\right]^{m+2n}\Lambda_{SE}}{\rm d}x\\\overset{\rm (iii)}{=}&\sum_{m=0}^{K}\binom{K}{m}\sum_{n=0}^{m}\binom{m}{n}(-1)^{m+n}\frac{\exp[-ma(0)]}{2^nb^ne^{m+2n}\Lambda_{SE}}\\&\times\underbrace{\int_{\eta_{\rm th}}^{\infty}\frac{\exp\left[-\left(md+\frac{1}{\Lambda_{SE}}\right)x\right]}{\left(x+\frac{c(0)}{e}\right)^{m+2n}}{\rm d}x}_{\mathcal{I}(m,n)}\end{aligned}\tag{28}$$

where step (ii) uses Binomial Theorem [31, p.10] twice and step (iii) uses the following equivalent form of $a\left(\frac{TP_Sx}{\sigma^2}\right)$ and $c\left(\frac{TP_Sx}{\sigma^2}\right)$, based on (16), as

$$a\left(\tfrac{TP_Sx}{\sigma^2}\right)=\underbrace{\left(\tfrac{1}{\bar\gamma_{SR}}+\tfrac{1}{\bar\gamma_{RD}}\right)(T-1)}_{=a(0)}+\underbrace{\left[\left(\tfrac{1}{\bar\gamma_{SR}}+\tfrac{1}{\bar\gamma_{RD}}\right)\tfrac{TP_S}{\sigma^2}\right]}_{=d}x,\tag{29}$$

$$c\left(\tfrac{TP_Sx}{\sigma^2}\right)=\underbrace{1+\tfrac{T\bar\gamma_{RE}}{\bar\gamma_{SR}}+\tfrac{T\bar\gamma_{RE}}{\bar\gamma_{RD}}+\tfrac{\bar\gamma_{ER}}{\bar\gamma_{SR}}(T-1)}_{=c(0)}+\underbrace{\left[\tfrac{\bar\gamma_{ER}TP_S}{\bar\gamma_{SR}\sigma^2}\right]}_{=e}x.\tag{30}$$

Then, with the help of [32, eqs. (3.352.2), (3.353.1)], the term $\mathcal{I}(m,n)$ in (28) is obtained as (31) on top of next page, where ${\rm Ei}(x)\triangleq\int_{-\infty}^{x}\frac{\exp(t)}{t}{\rm d}t$ is the exponential integral function. Substituting (28) into (20), the high MER approximate ex-

$$\mathcal{I}(m,n)=\begin{cases}\Lambda_{SE}\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right), & \text{if } m=0,n=0,\\ \exp\left[\frac{c(0)}{e}\left(d+\frac{1}{\Lambda_{SE}}\right)\right]{\rm Ei}\left[-\left(\eta_{\rm th}+\frac{c(0)}{e}\right)\left(d+\frac{1}{\Lambda_{SE}}\right)\right], & \text{if } m=1,n=0,\\ \exp\left[-\eta_{\rm th}\left(md+\frac{1}{\Lambda_{SE}}\right)\right]\sum_{i=1}^{m+2n-1}\frac{(i-1)![-(md+\frac{1}{\Lambda_{SE}})]^{m+2n-i-1}}{(m+2n-1)!(\eta_{\rm th}+\frac{c(0)}{e})^{i}} & \\ \quad-\frac{[-(md+\frac{1}{\Lambda_{SE}})]^{m+2n-1}}{(m+2n-1)!}\exp\left[\frac{c(0)}{e}\left(md+\frac{1}{\Lambda_{SE}}\right)\right]{\rm Ei}\left(-\left(\eta_{\rm th}+\frac{c(0)}{e}\right)\left(md+\frac{1}{\Lambda_{SE}}\right)\right), & \text{else}\end{cases} \tag{31}$$

pression for $P^{\rm P}_{\rm sec,out}$ is derived as

$$\begin{aligned}&P^{\rm P}_{\rm sec,out}\\ &\simeq\sum_{m=0}^{K}\binom{K}{m}\sum_{n=0}^{m}\binom{m}{n}(-1)^{m+n}\frac{\exp[-ma(0)]}{2^n b^n e^{m+2n}\Lambda_{SE}}\mathcal{I}(m,n)\\ &\quad+\Big(1-\exp\left[-a(0)\right]\sqrt{\pi b}\exp\left(b[c(0)]^2\right){\rm erfc}\big(\sqrt{b}c(0)\big)\Big)^K\\ &\qquad\times\left[1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right].\end{aligned} \tag{32}$$

3) SOP of ORS for statistical ECSI: For the proposed ORS for the statistical ECSI case, we have the following lemma for the SOP expression.

***Lemma** 3:* SOP of the proposed ORS in the statistical ECSI case is given in closed form as

$$\begin{aligned}P^{\rm S}_{\rm sec,out}=&\sum_{m=0}^{K}\left\{\binom{K}{m}(-1)^m\frac{\exp[-m(T-1)\mathcal{B}(\varepsilon)]}{1+mT\bar{\gamma}_{RE}\mathcal{B}(\varepsilon)}\right.\\ &\left.\times\left(\frac{\exp\left[-\frac{\eta_{\rm th}}{\Lambda_{SE}}\left(1+mT\bar{\gamma}_{SE}\mathcal{B}(\varepsilon)\right)\right]}{1+mT\bar{\gamma}_{SE}\mathcal{B}(\varepsilon)}+\left[1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\right)\right\}\end{aligned} \tag{33}$$

with $\mathcal{B}(\varepsilon)$ defined as

$$\begin{aligned}\mathcal{B}(\varepsilon)&\triangleq\frac{1}{g(\varepsilon)\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}\\ &=\frac{1+\frac{P_J\Lambda_{RE}}{\sigma^2}\left[\ln\left(\frac{1}{\varepsilon}\left[1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\right)\right]^{+}}{\bar{\gamma}_{SR}}+\frac{1}{\bar{\gamma}_{RD}}.\end{aligned} \tag{34}$$

Proof: The SOP of the proposed ORS for the statistical ECSI case can be derived from (13) and (14), as

$$\begin{aligned}P^{\rm S}_{\rm sec,out}&=\Pr\left(C^{\rm S}_{\rm sec}(k^*)<\mathbf{R}_{\rm S}\right)\\ &=\textstyle\sum_{i=1}^{K}\Pr(k^*=i)\Pr(C^{\rm S}_{\rm sec}(i)<\mathbf{R}_{\rm S})\end{aligned} \tag{35}$$

where $\Pr(k^*=i)=1/K$ is the probability that relay R_i is selected by the relay selection rule in (14), and the probability $\Pr(C^{\rm S}_{\rm sec}(i)<\mathbf{R}_{\rm S})$ can be expressed based on (13) as

$$\begin{aligned}&\Pr(C^{\rm S}_{\rm sec}(i)<\mathbf{R}_{\rm S})\\ &=\underbrace{\Pr\left(\frac{1+\max_{k=1,\dots,K}\min(g(\varepsilon)\gamma_{Sk},\gamma_{kD})}{1+\gamma_{SE}+\gamma_{iE}}<T,f_{SE}\ge\eta_{\rm th}\right)}_{\rho_1}\\ &+\underbrace{\Pr\left(\frac{1+\max_{k=1,\dots,K}\min(g(\varepsilon)\gamma_{Sk},\gamma_{kD})}{1+\gamma_{iE}}<T,f_{SE}<\eta_{\rm th}\right)}_{\rho_2}.\end{aligned} \tag{36}$$

The term ρ_1 can be calculated as follows

$$\begin{aligned}\rho_1=&\int_{\eta_{\rm th}}^{\infty}\int_0^{\infty}\prod_{k=1}^{K}\Big(1-\Pr\left(g(\varepsilon)\gamma_{Sk}>T-1+\tfrac{TP_Sx}{\sigma^2}+Ty\right)\\ &\times\Pr\big(\gamma_{kD}>T-1+\tfrac{TP_Sx}{\sigma^2}+Ty\big)\Big)p_{\gamma_{iE}}(y)p_{f_{SE}}(x){\rm d}y{\rm d}x\\ =&\int_{\eta_{\rm th}}^{\infty}\int_0^{\infty}\sum_{m=0}^{K}\binom{K}{m}(-1)^m\exp\Big[-m\mathcal{B}(\varepsilon)\\ &\times\left(T-1+\tfrac{TP_Sx}{\sigma^2}+Ty\right)\Big]\frac{\exp\left(-\frac{x}{\Lambda_{SE}}-\frac{y}{\bar{\gamma}_{RE}}\right)}{\Lambda_{SE}\bar{\gamma}_{RE}}{\rm d}y{\rm d}x\\ =&\frac{1}{\Lambda_{SE}\bar{\gamma}_{RE}}\sum_{m=0}^{K}\left[\binom{K}{m}(-1)^m\exp\left[-m(T-1)\mathcal{B}(\varepsilon)\right]\right.\\ &\times\int_{\eta_{\rm th}}^{\infty}\exp\left[-\tfrac{x}{\Lambda_{SE}}\left(1+mT\bar{\gamma}_{SE}\mathcal{B}(\varepsilon)\right)\right]{\rm d}x\\ &\left.\times\int_0^{\infty}\exp\left[-\tfrac{y}{\bar{\gamma}_{RE}}\left(1+mT\bar{\gamma}_{RE}\mathcal{B}(\varepsilon)\right)\right]{\rm d}y\right]\\ =&\sum_{m=0}^{K}\binom{K}{m}\frac{\exp\left[-m(T-1)\mathcal{B}(\varepsilon)-\frac{\eta_{\rm th}}{\Lambda_{SE}}\left(1+mT\bar{\gamma}_{SE}\mathcal{B}(\varepsilon)\right)\right]}{(-1)^m[1+mT\bar{\gamma}_{SE}\mathcal{B}(\varepsilon)][1+mT\bar{\gamma}_{RE}\mathcal{B}(\varepsilon)]}\end{aligned} \tag{37}$$

where the second equality uses the fact that γ_{Sk}, γ_{kD}, γ_{iE}, and f_{SE} are exponentially distributed, and the term $\mathcal{B}(\varepsilon)$ is defined in (34).

The term ρ_2 is obtained as

$$\begin{aligned}\rho_2=&\Pr(f_{SE}<\eta_{\rm th})\int_0^{\infty}\prod_{k=1}^{K}\Big(1-\Pr\left(g(\varepsilon)\gamma_{Sk}>T-1+Tx\right)\\ &\times\Pr\left(\gamma_{kD}>T-1+Tx\right)\Big)p_{\gamma_{iE}}(x){\rm d}x\\ =&\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\sum_{m=0}^{K}\binom{K}{m}(-1)^m\exp\left[-m(T-1)\mathcal{B}(\varepsilon)\right]\\ &\times\tfrac{1}{\bar{\gamma}_{RE}}\int_0^{\infty}\exp\left[-\tfrac{x}{\bar{\gamma}_{RE}}\left(1+mT\bar{\gamma}_{RE}\mathcal{B}(\varepsilon)\right)\right]{\rm d}x\\ =&\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\sum_{m=0}^{K}\binom{K}{m}(-1)^m\frac{\exp[-m(T-1)\mathcal{B}(\varepsilon)]}{1+mT\bar{\gamma}_{RE}\mathcal{B}(\varepsilon)}.\end{aligned} \tag{38}$$

By substituting (37) and (38) in (36), a closed-form expression for $\Pr(C^{\rm S}_{\rm sec}(i)<\mathbf{R}_{\rm S})$ is obtained, based on which the SOP $P^{\rm S}_{\rm sec,out}$ can be derived in closed form given in (33).

This completes the proof. ∎

Recall that the TOP is set to be ε in the statistical ECSI case. If we view the SOP expression in (33) as a function of ε, it is interesting to investigate the trend of SOP when ε varies. We have the following observations.

From the first equalities of (37) and (38), it is seen that both ρ_1 and ρ_2 monotonically decrease with $g(\varepsilon)$. On the other hand, it is seen from (12) that $g(\varepsilon)$ monotonically increases with ε for $\varepsilon \leq 1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)$ and is fixed to 1 for $\varepsilon > 1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)$. Therefore, if $\varepsilon \leq 1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)$, the secrecy outage probability $P_{\rm sec,out}^{\rm S}$ monotonically decreases with ε. This observation is intuitive, because a larger ε expects to lead to higher transmission rate, which results in a smaller SOP. However, if ε further increases from $1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)$, the three constraints on codeword transmission rate in (10) can be simplified to the first two constraints, i.e., the codeword transmission rate is determined on γ_{Sk} and γ_{kD}, and is independent of ε. This means that the SOP keeps unchanged if ε further increases from $1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)$. This phenomenon is called *SOP saturation*.

It is interesting that the starting value of ε for the SOP saturation, i.e., $1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)$, is also the probability that the adaptive eavesdropper selects to perform jamming. The insight behind this observation is as follows. Recall that the codeword transmission rate $\mathbf{R}_{\rm C}$ is selected based on the three constraints in (10). When the adaptive eavesdropper performs eavesdropping, the first two constraints can guarantee that there is no TOP. In other words, the TOP of the system is always not more than the probability that the adaptive eavesdropper performs jamming. Therefore, if the TOP requirement ε is more than the probability that the adaptive eavesdropper performs jamming, the TOP requirement can be relaxed.

B. Secrecy Diversity Analysis

Traditional diversity order is defined as $G_d \triangleq -\lim_{\gamma\to\infty}\frac{\log P_{\rm out}(\gamma)}{\log\gamma}$, where $P_{\rm out}$ is the transmission outage probability and γ is the system SNR [33]. Based on this, an intuitive definition for secrecy diversity order is $G_d \triangleq -\lim_{\gamma\to\infty}\frac{\log P_{\rm sec,out}(\gamma)}{\log\gamma}$. However, it is indicated in [26] that, when there exists eavesdropping, the SOP cannot achieve zero when $\gamma\to\infty$, because a larger system SNR γ increases the main channel capacity as well as the eavesdropping channel capacity. It is also shown in [26] that, when the legitimate transmit power goes to infinity, an *SOP floor* is achieved, which gives the best possible secrecy outage performance that the legitimate system can achieve. Thus, it is proposed in [26] to use the SOP floor to define the secrecy diversity order. Similar to this definition, the secrecy diversity order of our considered system is defined as $G_d \triangleq -\lim_{\lambda\to\infty}\frac{\log \underline{P}_{\rm sec,out}(\lambda)}{\log\lambda}$, where $\underline{P}_{\rm sec,out}(\lambda) \triangleq \lim_{\gamma\to\infty} P_{\rm sec,out}(\lambda,\gamma)$ is the SOP floor in high system SNR regime.

The following lemma, which is part of Proposition 1 in [12], will be used in our secrecy diversity analysis.

***Lemma** 4:* For two independent and exponentially distributed random variables X and Y with mean Λ_x and Λ_y, respectively, when $\frac{\Lambda_x}{\Lambda_y}\to 0$, the equation $\exp(-\frac{x}{\Lambda_y}) = 1-\frac{x}{\Lambda_y}$ holds.

Proof: The proof of Lemma 4 is given in [12, Appendix A]. ■

1) Secrecy Diversity Analysis of ORS for full ECSI: From (17) we know that, when system SNR $\gamma\to\infty$, κ_1 can be asymptotically expressed as

$$\begin{aligned}\kappa_1 &\overset{\gamma\to\infty}{\simeq} \underline{\kappa}_1\\ &= \int_{\eta_{\rm th}}^{\infty}\left(\prod_{k=1}^{K}\int_0^{\infty}\Pr\Big(\min(\mu f_{Sk}, f_{kD}) < T(\mu x + y_k)\Big)\right.\\ &\qquad \left.\times\, p_{f_{kE}}(y_k)\mathrm{d}y_k\right)p_{f_{SE}}(x)\mathrm{d}x\\ &= \int_{\eta_{\rm th}}^{\infty}\left[\prod_{k=1}^{K}\int_0^{\infty}\left(1-\exp\left[-\left(\frac{T(\mu x+y_k)}{\mu\Lambda_{SR}}+\frac{T(\mu x+y_k)}{\Lambda_{RD}}\right)\right]\right)\right.\\ &\qquad \left.\times\,\frac{1}{\Lambda_{RE}}\exp\left(-\frac{y_k}{\Lambda_{RE}}\right)\mathrm{d}y_k\right]\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\mathrm{d}x \qquad (39)\end{aligned}$$

in which the last equality uses the fact that f_{Sk}, f_{kD}, f_{kE}, and f_{SE} are exponentially distributed. In the above expression, x represents exponentially distributed random variable with mean Λ_{SE}. When MER $\lambda\to\infty$, we have $\Lambda_{SE}/\Lambda_{SR} = (\beta_{SE}/\beta_{SR})\times(1/\lambda)\to 0$. Thus, from Lemma 4, we have $\exp(-\frac{Tx}{\Lambda_{SR}}) = 1-\frac{Tx}{\Lambda_{SR}}$. Similarly, we also have $\exp(-\frac{Ty_k}{\mu\Lambda_{SR}}) = 1-\frac{Ty_k}{\mu\Lambda_{SR}}$, $\exp(-\frac{T\mu x}{\Lambda_{RD}}) = 1-\frac{T\mu x}{\Lambda_{RD}}$, and $\exp(-\frac{Ty_k}{\Lambda_{RD}}) = 1-\frac{Ty_k}{\Lambda_{RD}}$. Therefore, when MER goes to infinity, after ignoring the high-order infinitesimals, we have the following equation

$$1-\exp\left[-\left(\frac{T(\mu x+y_k)}{\mu\Lambda_{SR}}+\frac{T(\mu x+y_k)}{\Lambda_{RD}}\right)\right] = \frac{T(\mu x+y_k)}{\mu\Lambda_{SR}}+\frac{T(\mu x+y_k)}{\Lambda_{RD}}. \qquad (40)$$

Then, substituting (40) into (39), the high MER expression for $\underline{\kappa}_1$ is obtained as

$$\begin{aligned}\underline{\kappa}_1 &\overset{\lambda\to\infty}{\simeq} \int_{\eta_{\rm th}}^{\infty}\prod_{k=1}^{K}\left[\frac{Tx}{\Lambda_{SR}}+\frac{T\mu x}{\Lambda_{RD}}+\int_0^{\infty}\left(\frac{Ty_k}{\mu\Lambda_{SR}}+\frac{Ty_k}{\Lambda_{RD}}\right)\frac{1}{\Lambda_{RE}}\right.\\ &\qquad \left.\times\exp\left(-\frac{y_k}{\Lambda_{RE}}\right)\mathrm{d}y_k\right]\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\mathrm{d}x\\ &\overset{\rm (iv)}{=}\int_{\eta_{\rm th}}^{\infty}\left(\frac{Tx}{\Lambda_{SR}}+\frac{T\mu x}{\Lambda_{RD}}+\frac{T\Lambda_{RE}}{\mu\Lambda_{SR}}+\frac{T\Lambda_{RE}}{\Lambda_{RD}}\right)^K\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\mathrm{d}x\\ &=\int_{\eta_{\rm th}}^{\infty}\sum_{m=0}^{K}\binom{K}{m}\left[\left(\frac{T\Lambda_{RE}}{\mu\Lambda_{SR}}+\frac{T\Lambda_{RE}}{\Lambda_{RD}}\right)^{K-m}\left(\frac{T}{\Lambda_{SR}}+\frac{T\mu}{\Lambda_{RD}}\right)^m\right.\\ &\qquad \left.\times\frac{x^m}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\right]\mathrm{d}x\\ &\overset{\rm (v)}{=}\sum_{m=0}^{K}\binom{K}{m}\left[\left(\frac{T\Lambda_{RE}}{\mu\Lambda_{SR}}+\frac{T\Lambda_{RE}}{\Lambda_{RD}}\right)^{K-m}\left(\frac{T\Lambda_{SE}}{\Lambda_{SR}}+\frac{T\mu\Lambda_{SE}}{\Lambda_{RD}}\right)^m\right.\\ &\qquad \left.\times\,\Gamma\left(m+1,\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\\ &=\lambda^{-K}\sum_{m=0}^{K}\binom{K}{m}\left[\left(\frac{T\beta_{RE}}{\mu\beta_{SR}}+\frac{T\beta_{RE}}{\beta_{RD}}\right)^{K-m}\right.\\ &\qquad \left.\times\left(\frac{T\beta_{SE}}{\beta_{SR}}+\frac{T\mu\beta_{SE}}{\beta_{RD}}\right)^m\Gamma\left(m+1,\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right] \qquad (41)\end{aligned}$$

where steps (iv) and (v) use [32, eq. (3.351.3)] and [32, eq. (3.351.2)], respectively, and $\Gamma(\alpha,z) \triangleq \int_z^{\infty}\exp(-t)t^{\alpha-1}\mathrm{d}t$ is the upper incomplete Gamma function [32, eq. 8.350.2]. From (41), it is known $\underline{\kappa}_1 \overset{\lambda\to\infty}{\propto} \lambda^{-K}$.

By letting $\gamma\to\infty$, the floor of κ_2 is obtained as (42) on top of next page, where step (vi) comes from the fact that f_{Sk}, f_{kD}, f_{SE}, and f_{kE} follow exponential distributions,

$$
\begin{aligned}
\kappa_2 &\overset{\gamma\to\infty}{\simeq} \underline{\kappa}_2 = \prod_{k=1}^{K}\left[\int_0^\infty \Pr\left(\min\left(\tfrac{\mu f_{Sk}}{P_J x/\sigma^2+1}, f_{kD}\right) < Tx\right) p_{f_{kE}}(x)\mathrm{d}x\right]\Pr\left(f_{SE}<\eta_{\rm th}\right)\\
&\overset{\rm (vi)}{=} \prod_{k=1}^{K}\left(1-\int_0^\infty \tfrac{1}{\Lambda_{RE}}\exp\left[-\tfrac{TP_J/\sigma^2}{\mu\Lambda_{SR}}x^2-\left(\tfrac{1}{\Lambda_{RE}}+\tfrac{T}{\mu\Lambda_{SR}}+\tfrac{T}{\Lambda_{RD}}\right)x\right]\mathrm{d}x\right)\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\\
&\overset{\rm (vii)}{=} \left(1-\sqrt{\tfrac{\pi\mu\beta_{SR}\lambda}{4T\beta_{RE}\bar{\gamma}_{ER}}}\exp\left[\tfrac{\mu\beta_{SR}\lambda}{4T\beta_{RE}\bar{\gamma}_{ER}}\left(1+\tfrac{\beta_{RE}T}{\mu\beta_{SR}\lambda}+\tfrac{\beta_{RE}T}{\beta_{RD}\lambda}\right)^2\right]\right.\\
&\quad\left.\times\mathrm{erfc}\left[\sqrt{\tfrac{\mu\beta_{SR}\lambda}{4T\beta_{RE}\bar{\gamma}_{ER}}}\left(1+\tfrac{\beta_{RE}T}{\mu\beta_{SR}\lambda}+\tfrac{\beta_{RE}T}{\beta_{RD}\lambda}\right)\right]\right)^K\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]
\end{aligned}\qquad (42)
$$

and step (vii) uses [32, eq. (3.322.2)]. Furthermore, letting MER λ go to infinity and using the asymptotic expression of $\mathrm{erfc}(x)$ given in (25) with $l=1$ into (42), we have $\underline{\kappa}_2 \overset{\lambda\to\infty}{\simeq} [1-\exp(-\frac{\eta_{\rm th}}{\Lambda_{SE}})]\left(\frac{2T\bar{\gamma}_{ER}\beta_{RE}}{\mu\beta_{SR}\lambda}\right)^K \propto \lambda^{-K}$. Thus, we have $\underline{P}^{\rm F}_{\rm sec,out} = \underline{\kappa}_1+\underline{\kappa}_2 \overset{\lambda\to\infty}{\propto} \lambda^{-K}$, which indicates that the secrecy diversity order of the proposed ORS for the full ECSI case is K, which is a full secrecy diversity.

2) Secrecy Diversity Analysis of ORS for the Partial ECSI Case: It is known from (7) that, if $\gamma\to\infty$, we have $\phi_k \simeq \phi_k' \triangleq \min(\frac{\gamma_{Sk}}{\gamma_{Ek}+1},\gamma_{kD}) - T\gamma_{kE}$. Then, according to (23), the floor of SOP $P^{\rm P}_{\rm sec,out}$ can be expressed as

$$
\begin{aligned}
P^{\rm P}_{\rm sec,out} &\overset{\gamma\to\infty}{\simeq} \underline{P}^{\rm P}_{\rm sec,out}\\
&= \int_{\eta_{\rm th}}^{\infty}\prod_{k=1}^{K}\Pr\left(\phi_k'<\tfrac{TP_Sx}{\sigma^2}\right)p_{f_{SE}}(x)\mathrm{d}x\\
&\quad+\prod_{k=1}^{K}\Pr\left(\phi_k'<0\right)\Pr\left(f_{SE}<\eta_{\rm th}\right).
\end{aligned}\qquad (43)
$$

Similar to the derivations in (24), the terms $\Pr(\phi_k' < \frac{TP_Sx}{\sigma^2})$ and $\Pr(\phi_k'<0)$ are expressed as

$$
\begin{aligned}
&\Pr(\phi_k'<\tfrac{TP_Sx}{\sigma^2})\\
&=1-\exp\left(-\tfrac{Tx}{\Lambda_{SR}}-\tfrac{T\mu x}{\Lambda_{RD}}\right)\sqrt{\tfrac{\pi\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\\
&\quad\times\exp\left[\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}\left(1+\tfrac{T\beta_{RE}}{\mu\beta_{SR}\lambda}+\tfrac{T\beta_{RE}}{\beta_{RD}\lambda}+\tfrac{TP_J\beta_{RE}x}{\sigma^2\beta_{SR}\lambda}\right)^2\right]\\
&\quad\times\mathrm{erfc}\left[\sqrt{\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\left(1+\tfrac{T\beta_{RE}}{\mu\beta_{SR}\lambda}+\tfrac{T\beta_{RE}}{\beta_{RD}\lambda}+\tfrac{TP_J\beta_{RE}x}{\sigma^2\beta_{SR}\lambda}\right)\right]\\
&\overset{\lambda\to\infty}{\simeq} 1-\exp\left(-\tfrac{Tx}{\Lambda_{SR}}-\tfrac{T\mu x}{\Lambda_{RD}}\right)\sqrt{\tfrac{\pi\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\exp\left(\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}\right)\\
&\quad\times\mathrm{erfc}\left(\sqrt{\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\right),
\end{aligned}\qquad (44)
$$

$$
\begin{aligned}
&\Pr(\phi_k'<0)\\
&=1-\sqrt{\tfrac{\pi\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\exp\left[\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}\left(1+\tfrac{T\beta_{RE}}{\mu\beta_{SR}\lambda}+\tfrac{T\beta_{RE}}{\beta_{RD}\lambda}\right)^2\right]\\
&\quad\times\mathrm{erfc}\left[\sqrt{\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\left(1+\tfrac{T\beta_{RE}}{\mu\beta_{SR}\lambda}+\tfrac{T\beta_{RE}}{\beta_{RD}\lambda}\right)\right]\\
&\overset{\lambda\to\infty}{\simeq} 1-\sqrt{\tfrac{\pi\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\exp\left(\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}\right)\mathrm{erfc}\left(\sqrt{\tfrac{\mu\beta_{SR}\lambda}{4T\bar{\gamma}_{ER}\beta_{RE}}}\right).
\end{aligned}\qquad (45)
$$

By subsequently using the asymptotic expression of $\mathrm{erfc}(x)$ in (25) with $l=1$ to (44) and (45), we have

$$
\begin{aligned}
\Pr(\phi_k'<\tfrac{TP_Sx}{\sigma^2}) &\overset{\lambda\to\infty}{\simeq} 1-\exp\left(-\tfrac{Tx}{\Lambda_{SR}}-\tfrac{T\mu x}{\Lambda_{RD}}\right)\left(1-\tfrac{2T\bar{\gamma}_{ER}\beta_{RE}}{\mu\beta_{SR}\lambda}\right)\\
&\overset{\lambda\to\infty}{\simeq} 1-\exp\left(-\tfrac{Tx}{\Lambda_{SR}}-\tfrac{T\mu x}{\Lambda_{RD}}\right),
\end{aligned}\qquad (46)
$$

$$
\Pr(\phi_k'<0) \overset{\lambda\to\infty}{\simeq} 1-\left(1-\tfrac{2T\bar{\gamma}_{ER}\beta_{RE}}{\mu\beta_{SR}\lambda}\right) = \tfrac{2T\bar{\gamma}_{ER}\beta_{RE}}{\mu\beta_{SR}\lambda}. \qquad (47)
$$

Using (46) and (47) in (43) and then computing the integral leads to the high MER expression for $\underline{P}^{\rm P}_{\rm sec,out}$ given as

$$
\begin{aligned}
&\underline{P}^{\rm P}_{\rm sec,out}\\
&\overset{\lambda\to\infty}{\simeq}\int_{\eta_{\rm th}}^{\infty}\left[1-\exp\left(-\tfrac{Tx}{\Lambda_{SR}}-\tfrac{T\mu x}{\Lambda_{RD}}\right)\right]^K\tfrac{1}{\Lambda_{SE}}\exp\left(-\tfrac{x}{\Lambda_{SE}}\right)\mathrm{d}x\\
&\quad+\left(\tfrac{2T\bar{\gamma}_{ER}\beta_{RE}}{\mu\beta_{SR}\lambda}\right)^K\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\\
&\overset{\rm (viii)}{=}\tfrac{1}{\Lambda_{SE}}\left(\tfrac{T}{\Lambda_{SR}}+\tfrac{T\mu}{\Lambda_{RD}}\right)^K\int_{\eta_{\rm th}}^{\infty}x^K\exp\left(-\tfrac{x}{\Lambda_{SE}}\right)\mathrm{d}x\\
&\quad+\left(\tfrac{2T\bar{\gamma}_{ER}\beta_{RE}}{\mu\beta_{SR}\lambda}\right)^K\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\\
&\overset{\rm (ix)}{=}\left(\left(\tfrac{T\beta_{SE}}{\beta_{SR}}+\tfrac{T\mu\beta_{SE}}{\beta_{RD}}\right)^K\Gamma\left(K+1,\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right.\\
&\quad\left.+\left(\tfrac{2T\bar{\gamma}_{ER}\beta_{RE}}{\mu\beta_{SR}}\right)^K\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\right)\lambda^{-K}\\
&\propto\lambda^{-K}
\end{aligned}\qquad (48)
$$

in which the fact $1-\exp\left(-\frac{Tx}{\Lambda_{SR}}-\frac{T\mu x}{\Lambda_{RD}}\right)=\left(\frac{T}{\Lambda_{SR}}+\frac{T\mu}{\Lambda_{RD}}\right)x$ obtained from Lemma 4 is used in step (viii), and the expression of the upper incomplete Gamma function (given below equation (41)) is used in step (ix). Expression (48) means that, the same as the full ECSI case, the proposed ORS for the partial ECSI case also achieves a full secrecy diversity. Thus, availability of the channel gain f_{SE} does not affect the secrecy diversity order.

3) Secrecy Diversity Analysis of ORS for the Statistical ECSI Case: According to (36), in high system SNR, the terms

ρ_1 and ρ_2 can be rewritten as

$$\begin{aligned}\rho_1 &\overset{\gamma\to\infty}{\simeq} \underline{\rho}_1\\ &= \int_{\eta_{\rm th}}^{\infty}\int_0^{\infty}\prod_{k=1}^{K}\Pr\Big(\min\left(g(\varepsilon)\mu f_{Sk}, f_{kD}\right)<T\mu x+Ty\Big)\\ &\quad\times p_{f_{SE}}(x)p_{f_{iE}}(y)\mathrm{d}y\mathrm{d}x\\ &\overset{\text{(x)}}{=} \int_{\eta_{\rm th}}^{\infty}\int_0^{\infty}\left\{1-\exp\left[-\left(\tfrac{T(\mu x+y)}{g(\varepsilon)\mu\Lambda_{SR}}+\tfrac{T(\mu x+y)}{\Lambda_{RD}}\right)\right]\right\}^K\\ &\quad\times\tfrac{1}{\Lambda_{SE}\Lambda_{RE}}\exp\left(-\tfrac{x}{\Lambda_{SE}}-\tfrac{y}{\Lambda_{RE}}\right)\mathrm{d}y\mathrm{d}x, \qquad (49)\end{aligned}$$

$$\begin{aligned}\rho_2 &\overset{\gamma\to\infty}{\simeq} \underline{\rho}_2\\ &= \Pr(f_{SE}<\eta_{\rm th})\int_0^{\infty}\prod_{k=1}^{K}\Pr\Big(\min\left(g(\varepsilon)\mu f_{Sk}, f_{kD}\right)<Ty\Big)\\ &\quad\times p_{f_{iE}}(y)\mathrm{d}y\\ &\overset{\text{(xi)}}{=} \left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\int_0^{\infty}\tfrac{1}{\Lambda_{RE}}\exp\left(-\tfrac{y}{\Lambda_{RE}}\right)\\ &\quad\times\left\{1-\exp\left[-\left(\tfrac{Ty}{g(\varepsilon)\mu\Lambda_{SR}}+\tfrac{Ty}{\Lambda_{RD}}\right)\right]\right\}^K\mathrm{d}y \qquad (50)\end{aligned}$$

in which step (x) and (xi) use the fact that f_{Sk}, f_{kD}, f_{SE}, and f_{iE} are exponentially distributed. Then, letting $\lambda\to\infty$ and using Lemma 4 in the term $\exp[\cdot]$ inside the brackets $\{\cdot\}$, we have

$$\begin{aligned}\underline{\rho}_1 &\overset{\lambda\to\infty}{\simeq} \frac{\left(\frac{T}{g(\varepsilon)\mu\Lambda_{SR}}+\frac{T}{\Lambda_{RD}}\right)^K}{\Lambda_{SE}\Lambda_{RE}}\int_{\eta_{\rm th}}^{\infty}\int_0^{\infty}(\mu x+y)^K\\ &\quad\times\exp\left(-\tfrac{x}{\Lambda_{SE}}-\tfrac{y}{\Lambda_{RE}}\right)\mathrm{d}y\mathrm{d}x\\ &= \frac{\left(\frac{T}{g(\varepsilon)\mu\Lambda_{SR}}+\frac{T}{\Lambda_{RD}}\right)^K}{\Lambda_{SE}\Lambda_{RE}}\sum_{m=0}^{K}\binom{K}{m}\mu^m\int_{\eta_{\rm th}}^{\infty}x^m\\ &\quad\times\exp\left(-\tfrac{x}{\Lambda_{SE}}\right)\mathrm{d}x\int_0^{\infty}y^{K-m}\exp\left(-\tfrac{y}{\Lambda_{RE}}\right)\mathrm{d}y\\ &= \lambda^{-K}\sum_{m=0}^{K}\binom{K}{m}\mu^m\left(\tfrac{T}{g(\varepsilon)\mu\beta_{SR}}+\tfrac{T}{\beta_{RD}}\right)^K\beta_{SE}^m\beta_{RE}^{K-m}\\ &\quad\times\Gamma(m+1,\tfrac{\eta_{\rm th}}{\Lambda_{SE}})\Gamma(K-m+1),\end{aligned}$$

$$\begin{aligned}\underline{\rho}_2 &\overset{\lambda\to\infty}{\simeq} \left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\frac{\left(\frac{T}{g(\varepsilon)\mu\Lambda_{SR}}+\frac{T}{\Lambda_{RD}}\right)^K}{\Lambda_{RE}}\\ &\quad\times\int_0^{\infty}y^K\exp\left(-\tfrac{y}{\Lambda_{RE}}\right)\mathrm{d}y\\ &=\lambda^{-K}\left[1-\exp\left(-\tfrac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\left(\tfrac{T\beta_{RE}}{g(\varepsilon)\mu\beta_{SR}}+\tfrac{T\beta_{RE}}{\beta_{RD}}\right)^K\Gamma(K+1)\end{aligned}$$

where $\Gamma(n)\triangleq\int_0^{\infty}\exp(-t)t^{n-1}\mathrm{d}t$ is the Gamma function [32, eq. (8.310.1)]. Obviously, we have $\underline{P}_{\rm sec,out}^{\rm S}=\underline{\rho}_1+\underline{\rho}_2\overset{\lambda\to\infty}{\propto}\lambda^{-K}$, which means that the proposed ORS for statistical ECSI case also achieves a full secrecy diversity. This result reveals that, by introducing an acceptable level of TOP, the proposed ORS for the statistical ECSI case has the same secrecy diversity as those of the full and partial ECSI cases.

V. Performance Evaluation

We use computer simulation to verify our theoretical results and evaluate our proposed ORS schemes. In our simulation, we set $P_S=P_R$, and thus, $\mu=1$. Noise power is $\sigma^2=1$, and thus, the system SNR is given as $\gamma=P_S=P_R$. The threshold of the adaptive eavesdropper for eavesdropping and jamming is $\eta_{\rm th}=\Lambda_{SE}$, i.e., the adaptive eavesdropper performs eavesdropping in the first phase if the channel gain of link $S-E$ is better than its average value, or performs jamming otherwise. We consider that the average main channel gain and average eavesdropping channel gain are $\Lambda_{\rm M}=1$ and $\Lambda_{\rm E}=1/\lambda$, respectively. We set $\beta_{SR}=\beta_{RD}=\beta_{SE}=\beta_{RE}=1$. Thus, links $S-R_k$, R_k-D, $S-E$ and R_k-E have average channel gains given as $\Lambda_{SR}=1,\Lambda_{RD}=1$, $\Lambda_{SE}=\frac{1}{\lambda}$, and $\Lambda_{RE}=\frac{1}{\lambda}$, respectively.

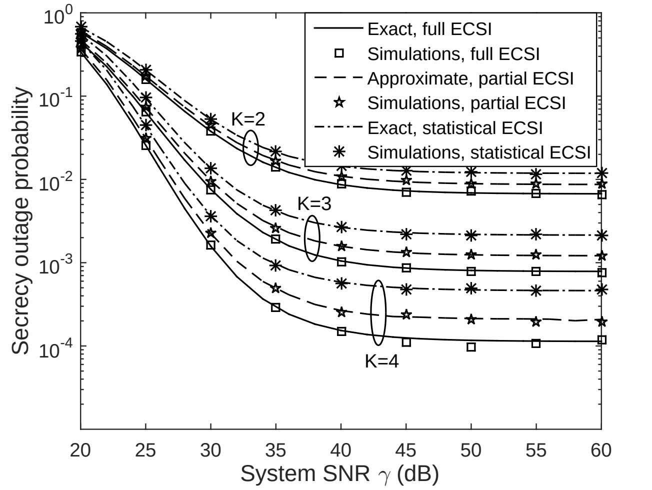


Fig. 2. SOP of the proposed ORS schemes ($\lambda=35$dB, $P_J=30$dB, $\mathbf{R}_{\rm S}=3$bps/Hz, $\varepsilon=0.1$ [for the statistical ECSI case]).

For the three proposed ORS schemes, Fig. 2 shows the derived SOP and simulated SOP when the number of relays K is 2, 3, or 4. It can be seen that the simulation results match our theoretical analysis, which verifies our closed-form SOP expressions for full and statistical ECSI cases, as well as the tightness of our SOP approximation for the partial ECSI case. For each K value, the SOP in full ECSI case is the lowest, while the SOP in the statistical ECSI case is the highest. When the number of relays increases from 2 to 4, the SOP of the proposed schemes become much lower because all proposed schemes achieve a full secrecy diversity. As the system SNR γ increases beyond 50dB, the SOP of each scheme converges, which is actually the SOP floor discussed in Section IV-B.

Next we evaluate the secrecy diversity. Fig. 3 shows the SOP of the proposed ORS schemes versus MER. To demonstrate the secrecy diversity, the SOP floors obtained by letting $\gamma=\infty$ and the benchmark curve $1.9\times10^5\times\lambda^{-2}$ are also plotted in this figure. As MER increases, the SOP of each ORS scheme decreases due to the secrecy diversity. It is seen that, when $\gamma=40$dB, the SOP of each ORS scheme is very close to its SOP floor. Further, comparing the SOP floors and the benchmark curve, it is observed that the magnitude of the slope of SOP floors are 2 in high MER regime ($\lambda=30\sim35$dB), which is equal to the number of relays. This is consistent with our analysis in Section IV-B that a full secrecy diversity order can

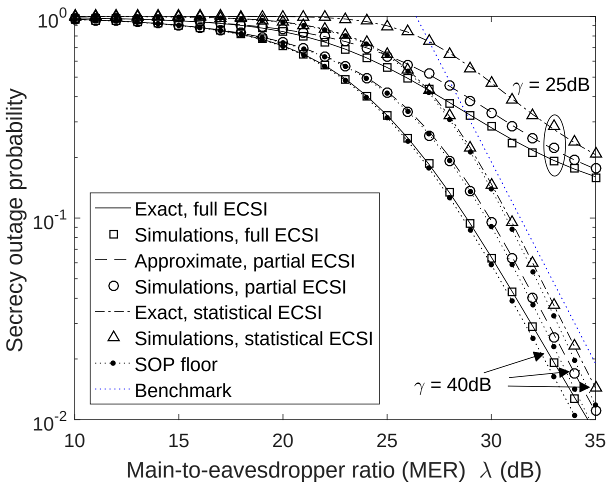


Fig. 3. SOP of the proposed ORS schemes with system SNR $\gamma = 25$dB and $\gamma = 40$dB, where $K = 2$, $P_J = 30$dB, $\mathbf{R}_\mathrm{S} = 3$bps/Hz, and $\varepsilon = 0.1$ (for the statistical ECSI case). To verify the secrecy diversity, the SOP floor of each ORS scheme and the benchmark curve $1.9 \times 10^5 \times \lambda^{-2}$ are also plotted in this figure.

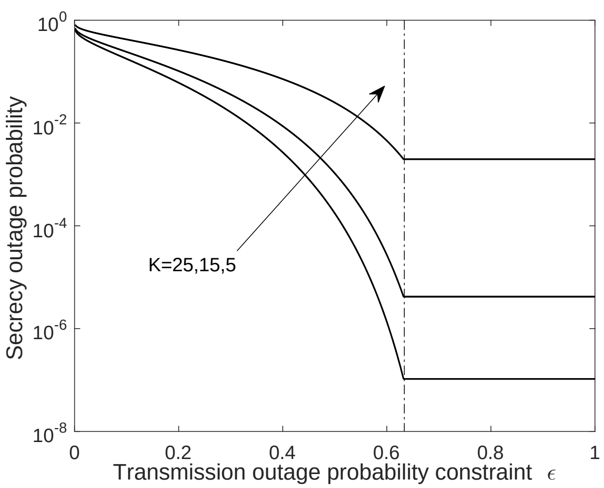


Fig. 4. The SOP-TOP tradeoff of the proposed ORS scheme for the statistical ECSI case with $K = 5, 15, 25$, where $\gamma = 30$dB, $\lambda = 25$dB, $P_J = 35$dB, and $\mathbf{R}_\mathrm{S} = 2$bps/Hz.

be achieved by the proposed ORS schemes.[6]

Based on (33), Fig. 4 shows the SOP versus TOP constraint ε in the proposed ORS scheme for the statistical ECSI case with $K = 5$, $K = 15$ and $K = 25$. It can be seen that when $\varepsilon \leq 1 - \exp\left(-\frac{\eta_\mathrm{th}}{\Lambda_{SE}}\right) \approx 0.6321$, the SOP curves decrease when ε increases, because a higher ε means relaxation of the TOP constraint. When $\varepsilon > 0.6321$, the SOP keeps unchanged when ε increases, which is the SOP saturation discussed in Section IV-A3.

It is desired to compare the performance of our proposed ORS schemes with other schemes in the literature. Since there is no existing scheme in the literature that considers an adaptive eavesdropper, here we compare with five relay selection schemes in the literature: the first two schemes are for scenarios with instantaneous ECSI, and the other schemes are for a scenario without any ECSI, as follows. Scheme-1: the P-DFbORS scheme proposed in [12], where the relay is selected as $k^* = \arg \max\limits_{k=1,\ldots,K} \frac{1+\min(\gamma_{Sk},\gamma_{kD})}{1+\gamma_{kE}}$. Scheme-2: the relay selection scheme proposed in [11], where the relay is selected as $k^* = \arg \max\limits_{k=1,\ldots,K} \frac{\gamma_{kD}}{\gamma_{kE}}$. Scheme-3: the conventional relay selection proposed in [34], where the relay is selected as $k^* = \arg \max\limits_{k=1,\ldots,K} \min(w\gamma_{Sk}, (1-w)\gamma_{kD})$, in which $w \in (0, 1)$ and $1-w$ are the weight factors for the source-relay hop and relay-destination hop, respectively. In our simulation, we consider $w = 0.5$. Scheme-4: the SS-RD scheme proposed in [35], where the relay is selected as $k^* = \arg\max_{k=1,\ldots,K} \gamma_{kD}$. Scheme-5: the SS-SR scheme also proposed in [35], where the relay is selected as $k^* = \arg\max_{k=1,\ldots,K} \gamma_{Sk}$. Moreover, we also provide the simulated SOP of round-robin relay selection as a benchmark for comparison.

Fig. 5 shows the SOP of proposed ORS schemes as well as Scheme-1∼Scheme-5 and round-robin scheme in full ECSI, partial ECSI and statistical ECSI cases. Since Scheme-1 and Scheme-2 require information of channel gains $f_{kE}, k = 1, \ldots, K$, which is not available in the statistical ECSI case, Scheme-1 and Scheme-2 are simulated only in the full and partial ECSI cases. It is shown that, for each ECSI availability case, the proposed ORS scheme outperforms other schemes. In full and partial ECSI cases, as the MER increases, the SOP of the proposed schemes decrease faster than those of other schemes, which means that the proposed schemes achieve a higher secrecy diversity order than other schemes under attacks from an adaptive eavesdropper. In statistical ECSI case, the proposed scheme and Scheme-3 have higher secrecy diversity order than other schemes.

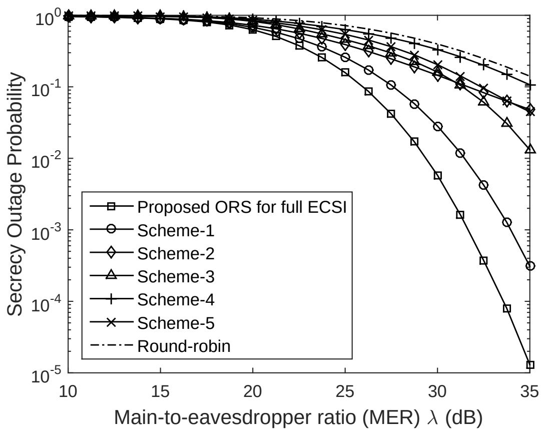
VI. Conclusion

In this paper, we have studied the relay selection in a secure cooperative network with an adaptive eavesdropper. For full, partial, and statistical ECSI cases, we have proposed ORS schemes that minimize the SOP of legitimate communications. To evaluate the secrecy performance of the proposed schemes, we have derived closed-form SOP expressions for our proposed ORS schemes in full and statistical ECSI cases, and approximate SOP expression under high MER for our proposed ORS scheme in the partial ECSI case. We have also analyzed the secrecy diversity order of the proposed ORS schemes, and shown that the schemes all achieve a full secrecy diversity order. Simulation results have validated our theoretical analysis of the proposed ORS schemes, and shown the advantages of our proposed ORS schemes over existing relay selection schemes that consider only passive eavesdroppers or do not consider any eavesdropper.

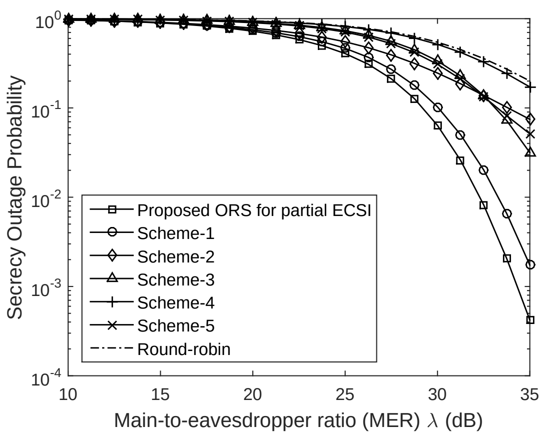
Appendix A
Proof of Theorem 1

A secrecy outage happens when the secrecy capacity of the legitimate system given in (5) is less than the target secrecy rate $\mathbf{R}_\mathrm{S}$. If relay R_k is selected to help, conditioned on the channel gains f_{Sk}, f_{kD} and f_{kE} (which are known in partial

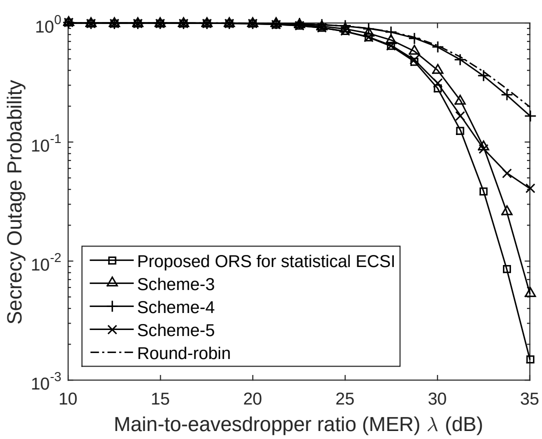
[6]Note that when $\gamma = 25$dB, the magnitude of the slope of the SOP curves are less than 2 in high MER regime. This is because the secrecy diversity is defined based on the SOP floor that is achieved when $\gamma \to \infty$.



(a) Full ECSI case



(b) Partial ECSI case



(c) statistical ECSI case

Fig. 5. SOP in different ECSI availability cases with $\gamma = 40$dB, $P_J = 40$dB, $K = 6$ and $\mathbf{R}_\mathrm{S} = 3$bps/Hz. For the statistical ECSI case, the TOP constraint is $\varepsilon = 0.2$.

ECSI case), the conditional SOP is given as

$$\begin{aligned}
&P_{\mathrm{sec,out}}\left(k\middle|f_{Sk}, f_{kD}, f_{kE}\right) \\
&= \Pr\left(C_{\mathrm{sec}}^{\mathrm{P}}(k) < \mathbf{R}_\mathrm{S}\middle| f_{Sk}, f_{kD}, f_{kE}\right) \\
&= \Pr\left(\frac{1+\min(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD})}{1+\gamma_{SE}+\gamma_{kE}} < T, f_{SE} \geq \eta_{\mathrm{th}}\middle| f_{Sk}, f_{kD}, f_{kE}\right) \\
&\quad + \Pr\left(\frac{1+\min(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD})}{1+\gamma_{kE}} < T, f_{SE} < \eta_{\mathrm{th}}\middle| f_{Sk}, f_{kD}, f_{kE}\right) \\
&= \underbrace{\Pr\left(\phi_k < \frac{TP_S f_{SE}}{\sigma^2}, f_{SE} \geq \eta_{\mathrm{th}}\middle| f_{Sk}, f_{kD}, f_{kE}\right)}_{\xi_{k,1}} \\
&\quad + \underbrace{\Pr\left(\phi_k < 0, f_{SE} < \eta_{\mathrm{th}}\middle| f_{Sk}, f_{kD}, f_{kE}\right)}_{\xi_{k,2}}
\end{aligned} \tag{51}$$

in which the last two equalities come from (5) and definition of ϕ_k in (7), respectively. Here $\Pr(\cdot)$ means probability of an event. Since ϕ_k given in (7) is only related to the channel gains f_{Sk}, f_{kD}, and f_{kE} (noting that $f_{Ek} = f_{kE}$ due to channel reciprocity) that are known in partial ECSI case, ϕ_k is also known for each k. Thus, term $\xi_{k,1}$ can be expressed as

$$\begin{aligned}
\xi_{k,1} &= \Pr\left(f_{SE} \geq \max\left(\eta_{\mathrm{th}}, \frac{\phi_k\sigma^2}{TP_S}\right)\right) \\
&= \int_{\max\left(\eta_{\mathrm{th}}, \frac{\phi_k\sigma^2}{TP_S}\right)}^{\infty} p_{f_{SE}}(x)\mathrm{d}x \\
&= \begin{cases} \exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right), & \text{if } \phi_k < \frac{\eta_{\mathrm{th}}P_S T}{\sigma^2}, \\ \exp\left(-\frac{\phi_k}{T\bar{\gamma}_{SE}}\right), & \text{if } \phi_k \geq \frac{\eta_{\mathrm{th}}P_S T}{\sigma^2} \end{cases}
\end{aligned} \tag{52}$$

in which $p_{f_{SE}}(\cdot)$ is the probability density function of f_{SE} (recalling that f_{SE} is an exponentially distributed random variable with mean Λ_{SE}). Similarly, the term $\xi_{k,2}$ is obtained as

$$\xi_{k,2} = \begin{cases} 1 - \exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right), & \text{if } \phi_k < 0, \\ 0, & \text{if } \phi_k \geq 0. \end{cases} \tag{53}$$

Substituting (52) and (53) into (51), the conditional SOP is derived as

$$\begin{aligned}
&P_{\mathrm{sec,out}}\left(k\middle|f_{Sk}, f_{kD}, f_{kE}\right) \\
&= \begin{cases} 1, & \text{if } \phi_k < 0, \\ \exp\left(-\frac{\eta_{\mathrm{th}}}{\Lambda_{SE}}\right), & \text{if } 0 \leq \phi_k < \frac{\eta_{\mathrm{th}}P_S T}{\sigma^2}, \\ \exp\left(-\frac{\phi_k}{T\bar{\gamma}_{SE}}\right), & \text{if } \phi_k \geq \frac{\eta_{\mathrm{th}}P_S T}{\sigma^2}. \end{cases}
\end{aligned} \tag{54}$$

From (54), the conditional SOP is a non-increasing function of ϕ_k. Thus, for ORS that minimizes the SOP, it is optimal to select relay $k^* = \arg\max_{k=1,\dots,K} \phi_k$. This completes the proof.

Appendix B
Derivation of (8)

From (1), the conditional TOP on link $S-R_k-D$ can be written as

$$\begin{aligned} & P_{\text{tran,out}}\left(k\middle|f_{Sk},f_{kD}\right) \\ &= \underbrace{\Pr\left(C_1(k)<\mathbf{R}_\text{C}, f_{SE}\geq\eta_\text{th}\middle|f_{Sk},f_{kD}\right)}_{\zeta_{k,1}} \\ &\quad + \underbrace{\Pr\left(C_2(k)<\mathbf{R}_\text{C}, f_{SE}<\eta_\text{th}\middle|f_{Sk},f_{kD}\right)}_{\zeta_{k,2}}. \end{aligned} \tag{55}$$

Recall that f_{SE} is an exponentially distributed random variable with mean Λ_{SE}. The term $\zeta_{k,1}$ can be further computed as

$$\begin{aligned} \zeta_{k,1} &= \Pr\left(\min(\gamma_{Sk},\gamma_{kD})<\gamma_\text{th}, f_{SE}\geq\eta_\text{th}\middle|f_{Sk},f_{kD}\right) \\ &= \begin{cases} \exp\left(-\frac{\eta_\text{th}}{\Lambda_{SE}}\right), \text{ if } \min\left(\gamma_{Sk},\gamma_{kD}\right)<\gamma_\text{th}, \\ 0, \qquad \text{if } \min\left(\gamma_{Sk},\gamma_{kD}\right)\geq\gamma_\text{th}. \end{cases} \end{aligned} \tag{56}$$

Using the Total Probability Theorem, the term $\zeta_{k,2}$ can be expressed as in (57) on top of next page, in which the last equality uses the fact that f_{SE} and γ_{Ek} are exponentially distributed with mean Λ_{SE} and $\bar{\gamma}_{ER}$, respectively.

Replacing (56) and (57) in (55), the conditional TOP can be given as in (8).

Appendix C
Proof of Theorem 2

In statistical ECSI case, if relay R_k is selected to help, the codeword transmission rate of the legitimate system is set up at $\mathbf{R}_\text{C}=\mathbf{R}_\text{C}(k)$, which guarantees that the TOP of link $S-R_k-D$ is bounded by ε. Therefore, the optimal relay selection should select the relay that leads to minimal SOP conditioned on the channel gains f_{Sk} and f_{kD}, i.e., $k^*=\arg\min_{k=1,\ldots,K} P_{\text{sec,out}}(k|f_{Sk},f_{kD})$.

If relay R_k is selected to help, the conditional SOP of link $S-R_k-D$ can be expressed as

$$\begin{aligned} & P_{\text{sec,out}}(k|f_{Sk},f_{kD}) = \Pr(C_\text{sec}^\text{S}(k)<\mathbf{R}_\text{S}|f_{Sk},f_{kD}) \\ &= \Pr\left(\tfrac{1+\theta_k}{1+\gamma_{SE}+\gamma_{kE}}<T, f_{SE}\geq\eta_\text{th}\middle| f_{Sk},f_{kD}\right) \\ &\quad + \Pr\left(\tfrac{1+\theta_k}{1+\gamma_{kE}}<T, f_{SE}<\eta_\text{th}\middle| f_{Sk},f_{kD}\right) \\ &= \underbrace{\Pr\left(\gamma_{SE}+\gamma_{kE}>\tfrac{1}{T}\left(\theta_k-T+1\right), f_{SE}\geq\eta_\text{th}\middle| f_{Sk},f_{kD}\right)}_{\psi_{k,1}} \\ &\quad + \underbrace{\Pr\left(\gamma_{kE}>\tfrac{1}{T}\left(\theta_k-T+1\right), f_{SE}<\eta_\text{th}\middle| f_{Sk},f_{kD}\right)}_{\psi_{k,2}} \end{aligned} \tag{58}$$

in which the second equality comes from (13).

Recall that $\gamma_{SE}=P_S f_{SE}/\sigma^2$, $\gamma_{kE}=P_R f_{kE}/\sigma^2$, and f_{SE} and f_{kE} are exponentially distributed with mean Λ_{SE} and Λ_{RE}, respectively. For the term $\psi_{k,1}$, we have

$$\begin{aligned} \psi_{k,1} &= \int_{\eta_\text{th}}^{\infty} \Pr\left(f_{kE}>\tfrac{\sigma^2}{TP_R}(\theta_k-T+1)-\tfrac{P_S x}{P_R}\middle| f_{Sk},f_{kD}\right) \\ &\qquad \times p_{f_{SE}}(x)\mathrm{d}x \\ &= \begin{cases} \int_{\eta_\text{th}}^{\infty} p_{f_{SE}}(x)\mathrm{d}x = \exp\left(-\frac{\eta_\text{th}}{\Lambda_{SE}}\right), \\ \qquad\qquad \text{if } 0<\theta_k\leq\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1, \\ A(\theta_k), \qquad \text{if } \theta_k>\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1 \end{cases} \end{aligned} \tag{59}$$

where $A(\theta_k)$ can be expressed as in (60) on top of next page. The term $\psi_{k,2}$ can be obtained as

$$\psi_{k,2} = \begin{cases} 1-\exp\left(-\frac{\eta_\text{th}}{\Lambda_{SE}}\right), \text{ if } 0<\theta_k\leq T-1, \\ \left(1-\exp\left(-\frac{\eta_\text{th}}{\Lambda_{SE}}\right)\right)\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}\right), \text{ if } \theta_k>T-1. \end{cases} \tag{61}$$

Substituting (59) and (61) into (58), the conditional SOP is obtained as

$$\begin{aligned} & P_{\text{sec,out}}(k|f_{Sk},f_{kD}) \\ &= \begin{cases} 1, \text{ if } 0<\theta_k\leq T-1, \\ \exp(-\frac{\eta_\text{th}}{\Lambda_{SE}})+\left(1-\exp\left(-\frac{\eta_\text{th}}{\Lambda_{SE}}\right)\right)\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}\right), \\ \qquad \text{if } T-1<\theta_k\leq\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1, \\ A(\theta_k)+\left(1-\exp\left(-\frac{\eta_\text{th}}{\Lambda_{SE}}\right)\right) \\ \qquad \times\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}\right), \text{ if } \theta_k>\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1. \end{cases} \end{aligned} \tag{62}$$

Considering $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ in (62) as a function of θ_k, it can be easily seen from (62) that the function is continuous at $\theta_k=T-1$. Further, based on the first equality in (60), we have $\lim_{\theta_k\to\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1} A(\theta_k)=\int_{\eta_\text{th}}^{\infty} p_{f_{SE}}(x)\mathrm{d}x=\exp\left(-\frac{\eta_\text{th}}{\Lambda_{SE}}\right)$, based on which we can see that $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ in (62) is continuous at $\theta_k=\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1$. Thus, it can be concluded that $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ is a continuous function of θ_k.

From (62), we have the following observations for SOP $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ when θ_k increases starting from 0:

- When $0<\theta_k\leq T-1$, the SOP $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ keeps unchanged.
- When $T-1<\theta_k\leq\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1$, the SOP $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ monotonically decreases with θ_k.
- When $\theta_k>\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1$, the expression of $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ has a term $A(\theta_k)$ as shown in (62). From the second equality in (60), the first order derivative of $A(\theta_k)$ is obtained as

$$\begin{aligned} \frac{\mathrm{d}A(\theta_k)}{\mathrm{d}\theta_k} &= -\frac{1}{T\bar{\gamma}_{RE}\Lambda_{SE}}\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}\right) \\ &\quad \times\int_{\eta_\text{th}}^{\frac{\sigma^2}{TP_S}(\theta_k-T+1)}\exp\left(-x\nu\right)\mathrm{d}x \\ &<0 \end{aligned} \tag{63}$$

which means $A(\theta_k)$ monotonically decreases with θ_k, and accordingly, $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ also monotonically decreases with θ_k for $\theta_k>\frac{TP_S\eta_\text{th}}{\sigma^2}+T-1$.

Overall, $P_{\text{sec,out}}(k|f_{Sk},f_{kD})$ is a continuous and non-increasing function of θ_k. Thus, to minimize the SOP, the relay R_{k^*} should be selected as $k^*=\arg\max_{k=1,\ldots,K}\theta_k$, which is exactly the relay selected by the proposed ORS scheme in (14).

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$$\begin{aligned}\zeta_{k,2}=&\Pr\left(\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)<\gamma_{\rm th},\min\left(\gamma_{Sk},\gamma_{kD}\right)<\gamma_{\rm th},f_{SE}<\eta_{\rm th}\Big|\,f_{Sk},f_{kD}\right)\\ &+\Pr\left(\min\left(\frac{\gamma_{Sk}}{1+\gamma_{Ek}},\gamma_{kD}\right)<\gamma_{\rm th},\min\left(\gamma_{Sk},\gamma_{kD}\right)\geq\gamma_{\rm th},f_{SE}<\eta_{\rm th}\Big|\,f_{Sk},f_{kD}\right)\\ =&\Pr\left(\min\left(\gamma_{Sk},\gamma_{kD}\right)<\gamma_{\rm th},f_{SE}<\eta_{\rm th}|\,f_{Sk},f_{kD}\right)+\Pr\left(\gamma_{Ek}>\frac{\gamma_{Sk}}{\gamma_{\rm th}}-1,\min\left(\gamma_{Sk},\gamma_{kD}\right)\geq\gamma_{\rm th},f_{SE}<\eta_{\rm th}\Big|\,f_{Sk},f_{kD}\right)\\ =&\begin{cases}1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right), & \text{if }\ \min(\gamma_{Sk},\gamma_{kD})<\gamma_{\rm th},\\ \left[1-\exp\left(-\frac{\eta_{\rm th}}{\Lambda_{SE}}\right)\right]\exp\left(-\frac{\gamma_{Sk}/\gamma_{\rm th}-1}{\bar{\gamma}_{ER}}\right), & \text{if }\ \min(\gamma_{Sk},\gamma_{kD})\geq\gamma_{\rm th}.\end{cases}\end{aligned}\tag{57}$$

$$\begin{aligned}A(\theta_k)=&\int_{\eta_{\rm th}}^{\frac{\sigma^2}{TP_S}(\theta_k-T+1)}\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}+\frac{P_S x}{P_R\Lambda_{RE}}\right)p_{f_{SE}}(x)\mathrm{d}x+\int_{\frac{\sigma^2}{TP_S}(\theta_k-T+1)}^{\infty}p_{f_{SE}}(x)\mathrm{d}x\\ =&\frac{1}{\Lambda_{SE}}\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}\right)\int_{\eta_{\rm th}}^{\frac{\sigma^2}{TP_S}(\theta_k-T+1)}\exp\left(-x\underbrace{\left(\frac{1}{\Lambda_{SE}}-\frac{P_S}{P_R\Lambda_{RE}}\right)}_{\nu}\right)\mathrm{d}x+\int_{\frac{\sigma^2}{TP_S}(\theta_k-T+1)}^{\infty}\frac{1}{\Lambda_{SE}}\exp\left(-\frac{x}{\Lambda_{SE}}\right)\mathrm{d}x\\ =&\begin{cases}\frac{1}{\Lambda_{SE}}\exp\Big(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}\Big)\Big(\frac{\sigma^2}{TP_S}(\theta_k-T+1)-\eta_{\rm th}\Big)+\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{SE}}\right), & \text{if }\nu=0,\\ \frac{1}{\nu\Lambda_{SE}}\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{RE}}\right)\Big(\exp(-\nu\eta_{\rm th})-\exp\Big(-\frac{\sigma^2\nu}{TP_S}(\theta_k-T+1)\Big)\Big)+\exp\left(-\frac{\theta_k-T+1}{T\bar{\gamma}_{SE}}\right), & \text{if }\nu\neq 0.\end{cases}\end{aligned}\tag{60}$$

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