Secure Transmission in Cognitive MIMO Relaying Networks With Outdated Channel State Information

Secure Transmission in Cognitive MIMO Relaying Networks With Outdated Channel State Information

Tao Zhang, *Student Member*, *IEEE*, Yueming Cai, *Senior Member*, *IEEE*, Yuzhen Huang, *Member*, *IEEE*, Trung Q. Duong, *Senior Member*, *IEEE*, and Weiwei Yang, *Member*, *IEEE*

***Abstract*—In this paper, we introduce transmit antenna selection/maximal-ratio combining (TAS/MRC) scheme in dual-hop randomize-and-forward (RaF) cognitive multiple-input multiple-output (MIMO) wiretap networks with outdated channel state information (CSI). In this network, the secondary transmitter adopts TAS scheme to choose the antenna with the maximal received signal-to-noise ratio (SNR), while the secondary receiver and eavesdropper adopt MRC scheme to combine the received signals. To thoroughly assess the secrecy performance achieved by TAS/MRC scheme and the impact of outdated CSI on the secrecy performance, we derive a new closed-form expression for the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks. In order to achieve more insights on the application of TAS/MRC scheme, we further present tractable asymptotic secrecy outage probability at high SNR regimes under two distinct scenarios. From our analysis, several important concluding remarks are obtained as follows: a) The RaF relaying strategy achieves better secrecy performance than that of the decode-and-forward (DF) relaying strategy for dual-hop cognitive MIMO wiretap networks, b) Outdated CSI decreases the secrecy diversity gain of TAS/MRC scheme from $N_{\rm R}\min\left(N_{\rm A},N_{\rm B}\right)$ to $\min\left(N_{\rm R},N_{\rm B}\right)$, c) Although TAS/MRC scheme can not attain full secrecy diversity gain for the considered system with outdated CSI, it still can achieve an extra secrecy coding gain compared with random antenna selection/MRC (RAS/MRC) scheme.**

***Index Terms*—Cognitive radio networks, MIMO, secrecy outage probability, outdated channel state information.**

I. Introduction

COGNITIVE radio, first coined by Mitola, has drawn considerable attention from the research community due to its ability to alleviate spectrum shortage problems. The key idea of cognitive radio is to enable unlicensed users (secondary users) to intelligently share the same spectrum resources with licensed users (primary users) [1]–[3]. Among spectrum sharing cognitive radio networks, taking into account its low complexity of implementation, the underlay scheme has been received much attention. In the underlay scheme, the secondary users (SUs) are allowed to transmit concurrently with the primary users (PUs) in the same spectrum as long as the quality of service of the PUs can be guaranteed [4], [5].

On the other hand, compared with wired transmission, wireless transmission suffers from a more serious eavesdropping due to the inherent openness of the wireless medium [6], [7]. As is well-known, cognitive radio networks can be regarded as a fundamental architecture of intelligent network, which includes a large scale number nodes, a higher transmission rate, and more information exchange. Hence, cognitive radio networks are confronted with a challenge security issue due to the more complex and uncertain transmission environments. Motivated by this, physical layer security technique has emerged as a promising solution to prevent information from being intercepted and to achieve perfect secrecy in cognitive radio networks. The key idea of physical layer security is to differentiate characteristics between the main channel and the eavesdropper's channel, which was first investigated in [8]. Recently, the authors in [9]–[11] have introduced physical layer security into the cognitive radio networks for guaranteeing the secure transmission. Specifically, in [9], the authors proposed three different single-relay selection schemes for the secondary transmission in cognitive radio networks. Later, the authors in [10] extended the analysis in [9] to the more general multi-relay selection scheme. In [11], a new relay selection scheme was proposed to enhance the security of cognitive radio networks, where the first relay was selected to transmit the confidential information and the second relay was selected to transmit the jamming signal to confound the eavesdropper. However, these works only consider the single antenna scenario.

As we known, multi-antenna techniques can effectively improve the transmission rate in cognitive radio networks, and it has become a key enabling technology for future wireless standards, e.g., long term evolution (LTE) and LTE Advanced [12]. Therefore, physical layer security in multi-antenna cognitive wiretap networks has recently attracted tremendous amount of research efforts. For example, as shown in [13], the selection combining (SC) scheme was proposed to enhance the secrecy performance of the cognitive radio networks with secondary receiver being equipped with multiple antennas. Later, the authors in [14] extended the analysis in [13] to the full-duplex scenario, where the full-duplex secondary receiver can simultaneously receive the signal from the secondary source with the selected antenna and transmit jamming signals to the eavesdropper with the other selected antenna. Compared

This work was supported by the Natural Science Foundations of China (No. 61471393, 61501507, 61371122 and 61501512) and the Jiangsu Provincial Natural Science Foundation of China (No. BK20150719 and BK20150718). The work of T. Q. Duong was supported by the U.K. Royal Academy of Engineering Research Fellowship under RF1415\14\22 and by the Newton Institutional Link under Grant ID 172719890.

T. Zhang, Y. Cai and W. Yang are with the College of Communications Engineering, PLA University of Science and Technology, Nanjing 210007, China (e-mail:ztcool@126.com; caiym@vip.sina.com; wwyang1981@163.com).

Y. Huang is with the College of Communications Engineering, PLA University of Science and Technology, Nanjing 21007, China, and also with the School of Information and Communication, Beijing University of Posts and Telecommunications, Beijing 100876, China (email: yzh_huang@sina.com).

T. Q. Duong is with the School of Electronics, Electrical Engineering and Computer Science, Queens University Belfast, Belfast BT7 1NN, U.K (email: trung.q.duong@qub.ac.uk).

with [13] and [14] that investigated secrecy performance for cognitive radio networks using SC scheme, the authors in [15] analyzed the secrecy performance of multiple-input multiple-output (MIMO) cognitive radio networks with transmit antenna selection (TAS) scheme at secondary transmitter and maximal ratio combining (MRC) scheme at secondary receiver. To further exploit the benefit of available multiple antennas, MRC/zeroforcing beamforming (MRC/ZFB) scheme at the relay was proposed to enhance the secrecy performance of the spectrum sharing relaying networks, and an exact closed-form expression for the secrecy outage probability of the considered system was presented [16]. However, perfect channel state informations (CSIs) of the secondary transmission links and the interference links between the PUs and SUs were assumed in the above studies. However, the outdated CSI is often caused by channel variation and the feedback delay between secondary transmitter and secondary receiver, which yields the suboptimal transmission scheme. Therefore, the impact of outdated CSI on the secrecy performance of cognitive radio networks should be considered.

With these in mind, we consider a dual-hop randomize-and-forward (RaF) multi-antenna cognitive radio network, where a secondary transmitter (Alice) communicates with a secondary destination (Bob) with the help of a secondary RaF relay (Relay)[1] in the presence of a primary receiver (PR) and an eavesdropper (Eve). Then, the impact of outdated CSI on the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks with TAS/MRC scheme is analyzed. The main contributions of our work are summarized as follows.

- Based on the proposed analytical model, we first derive the closed-form expression for the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks. The derived analytical expression provides an efficient means to evaluate the impact of key system parameters, i.e, feedback delay, the interference threshold and the number of antennas on the secrecy performance of dual-hop RaF cognitive MIMO wiretap networks. In addition, we find that the RaF relaying strategy achieves better secrecy performance than the DF relaying strategy for dual-hop cognitive MIMO wiretap networks.
- To achieve more insights on the application of TAS/MRC scheme, we present the tractable asymptotic secrecy outage probability for dual-hop RaF cognitive MIMO wiretap networks under two Scenarios. In Scenario I, i.e., the main channel has a good quality while the eavesdropper's channel is severely blocked due to heavy shadowing, the considered system with outdated CSI achieves the secrecy diversity gain of $\min\left(N_{\rm R}, N_{\rm B}\right)$. In Scenario II, i.e., both the main channel and eavesdropper's channel have a good quality, no secrecy diversity gain can be obtained regardless of the outdated CSI.
- Our results demonstrate that the outdated CSI reduces the secrecy diversity order of TAS/MRC scheme from $N_{\rm R}\min\left(N_{\rm A}, N_{\rm B}\right)$ to $\min\left(N_{\rm R}, N_{\rm B}\right)$. In order to show the advantage of TAS/MRC scheme, we provide the secrecy performance analysis of random antenna selection/MRC (RAS/MRC) scheme. Although TAS/MRC scheme cannot attain a full secrecy diversity gain for dual-hop RaF cognitive MIMO wiretap networks with outdated CSI, it can provide more secrecy coding gain compared with RAS/MRC scheme. Specially, when the feedback delay is infinity, TAS/MRC scheme will reduce to RAS/MRC scheme.

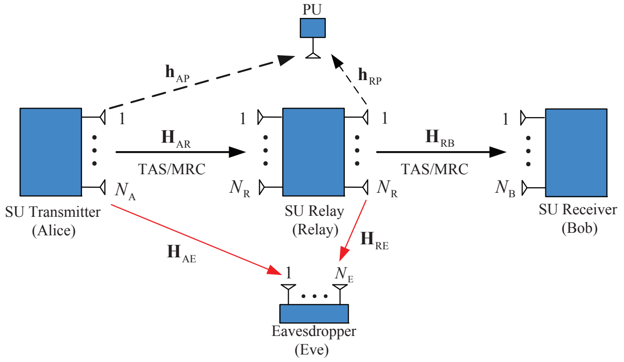

Fig. 1. System model.

The rest of the paper is organized as follows. The system model is introduced in Section II. Section III formulates the problem and presents the analytical expressions of the secrecy outage performance. In Section IV, we provide a high signal-to-noise ratio (SNR) analysis for the secrecy outage probability, and Section V presents the numerical results and discussions. Finally, Section VI concludes the key findings for the paper.

II. System Model

We consider an underlay dual-hop RaF cognitive MIMO wiretap network as shown in Fig. 1, where the PU and SU systems share the same spectral band. The PU system consists of a single antenna primary receiver (PR), where the primary transmitter (PT) is assumed far away from the secondary receiver, thus PT will not interfere the secondary receivers [13]–[15]. The SU system consists of a secondary source (Alice), a secondary RaF relay (Relay), and a secondary destination (Bob), equipped with $N_{\rm A}$, $N_{\rm R}$ and $N_{\rm B}$ antennas, respectively. The eavesdropper (Eve) is equipped with $N_{\rm E}$ antennas and we assume that Eve is a passive eavesdropper such that the instantaneous CSIs of Alice to Eve and Relay to Eve are not available at Alice and Relay. In addition, we assume that there is no direct link between Alice and Bob due to path loss or severe shadowing caused by large obstacles.

In the Alice to Relay link, applying TAS/MRC scheme, the instantaneous SNR at Relay is derived as

$$\gamma_{\rm AR} = \frac{P_S}{\sigma^2}\left\|\mathbf{h}_{\rm AR}^{i^*}\right\|^2, \tag{1}$$

where $P_S = \min\left(\frac{Q}{|h_{1i*}|^2}, P_t\right)$, in which h_{1i*} is the interference channel coefficient of Alice to PR link with zero mean and variance $\lambda_{\rm AP}$, P_t and Q denote the maximum transmit

[1] According to [17]–[20], RaF relaying strategy is widely used for secure transmission, which means that the source and relay use different codebooks to transmit the secret message. Since different codebooks are adopted at the two transmission phases, the eavesdropper cannot combine the received information during the two phases.

power constraint at Alice and the interference temperature constraint at PR, respectively. In addition, $\mathbf{h}_{\mathrm{AR}}^{i^*}$ denotes the $N_{\mathrm{R}} \times 1$ channel vector between the i^*-th transmit antenna at Alice and Relay with zero mean and variance λ_{AR}, σ^2 is the additive white Gaussian noise (AWGN) at Relay. The index of the selected antenna i^* is formulated as

$$i^* = \arg \max_{1 \le i \le N_{\mathrm{A}}} \left\| \mathbf{h}_{\mathrm{AR}}^{i} \right\|^2. \tag{2}$$

Similarly, in the Relay to Bob link, applying TAS/MRC scheme, the instantaneous SNR at Bob is derived as

$$\gamma_{\mathrm{RB}} = \frac{P_R}{\sigma^2} \left\| \mathbf{h}_{\mathrm{RB}}^{j^*} \right\|^2, \tag{3}$$

where $P_R = \min\left(\frac{Q}{|h_{2j*}|^2}, P_t\right)$, in which h_{2j*} is the interference channel coefficient of Relay to PR link with zero mean and variance λ_{RP}, P_t and Q denote the maximum transmit power constraint at Relay and the interference temperature constraint at PR, respectively. In addition, $\mathbf{h}_{\mathrm{RB}}^{j^*}$ denotes the $N_{\mathrm{B}} \times 1$ channel vector between the j^*-th transmit antenna at Relay and Bob with zero mean and variance λ_{RB}, σ^2 is the AWGN at Bob. The index of the selected antenna j^* at Relay is given by

$$j^* = \arg \max_{1 \le j \le N_{\mathrm{R}}} \left\| \mathbf{h}_{\mathrm{RB}}^{j} \right\|^2. \tag{4}$$

Without loss of generality, we assume that MRC scheme is adopted at Eve for improving successful eavesdropping as in [15], [16]. In addition, RaF relaying strategy is used for secure transmission. Thus, the instantaneous SNRs of Alice to Eve link and Relay to Eve link are respective expressed as

$$\gamma_{\mathrm{AE}} = \frac{P_S}{\sigma^2} \|\mathbf{h}_{\mathrm{AE}}\|^2, \tag{5}$$

$$\gamma_{\mathrm{RE}} = \frac{P_R}{\sigma^2} \|\mathbf{h}_{\mathrm{RE}}\|^2, \tag{6}$$

where $\mathbf{h}_{\mathrm{AE}}$ denotes the $N_{\mathrm{E}} \times 1$ channel vector between the i^*-th transmit antenna at Alice and Eve with zero mean and variance λ_{AE}, and $\mathbf{h}_{\mathrm{RE}}$ denotes the $N_{\mathrm{E}} \times 1$ channel vector between the j^*-th transmit antenna at Relay and Eve with zero mean and variance λ_{RE}.

From Eq. (2) and Eq. (4), we note that perfect CSI for the Alice to Relay link and Relay to Bob link must be guaranteed for TAS. However, due to the subsequent data transmission and dynamic movements between the nodes, the CSI associated with the selected antenna during the selection of antenna instant may be outdated. We define $\tilde{\mathbf{h}}_{\mathrm{KT}}^{\tau}$ as a delayed version of $\mathbf{h}_{\mathrm{KT}}^{\tau}$, and the relation can be modeled as

$$\tilde{\mathbf{h}}_{\mathrm{KT}}^{\tau} = \rho_d \mathbf{h}_{\mathrm{KT}}^{\tau} + \sqrt{1 - \rho_d^2}\, \mathbf{e}_{\mathrm{KT}}, \tag{7}$$

where $\mathrm{K} \in \{\mathrm{A}, \mathrm{R}\}$, $\mathrm{T} \in \{\mathrm{R}, \mathrm{B}\}$, $\tau \in \{i, j\}$, $d \in \{1, 2\}$, and $\mathbf{e}_{\mathrm{KT}}$ is an $N_{\mathrm{T}} \times 1$ error vector, whose element is complex Gaussian random variable (RV) with zero mean and same variance as $\mathbf{h}_{\mathrm{KT}}^{i}$, and ρ_d is the time correlation coefficient between $\tilde{\mathbf{h}}_{\mathrm{KT}}^{\tau}$ and $\mathbf{h}_{\mathrm{KT}}^{\tau}$ (Specially, $d = 1$ for Alice to Relay link, and $d = 2$ for Relay to Bob link). Using Jake's autocorrelation model [21], [22], we have $\rho_d = J_0\left(2\pi f_d T_d\right)$, where $J_0\left(\cdot\right)$ is the zeroth-order Bessel function of the first kind, f_d is the maximum Doppler frequency, T_d is the delay between the selection instant and the transmission instant.

Thus, due to the feedback delay, the received SNRs at Relay and Bob are respective expressed as

$$\tilde{\gamma}_{\mathrm{AR}} = \frac{P_S}{\sigma^2} \left\| \tilde{\mathbf{h}}_{\mathrm{AR}}^{i^*} \right\|^2, \tag{8}$$

$$\tilde{\gamma}_{\mathrm{RB}} = \frac{P_R}{\sigma^2} \left\| \tilde{\mathbf{h}}_{\mathrm{RB}}^{j^*} \right\|^2. \tag{9}$$

On the other hand, according to the underlay protocol, the interference at PR caused by SU should remain below a predefined interference requirement in order not to degrade the quality of service (QoS) of PU [13]. However, due to the impact of outdated CSI of the interference links between the PUs and SUs, it is difficult to meet the interference requirement at all times. Instead, we take the probabilistic approach as in [5], [23]–[25], where the secondary transmitter adapts its power such that the PUs can maintain a pre-selected outage probability δ_0. Hence, the transmit powers at Alice and Relay are limited to

$$P_S = \min\left(\kappa_1 \frac{Q}{\left|\tilde{h}_{1i*}\right|^2}, P_t\right), \tag{10}$$

$$P_R = \min\left(\kappa_2 \frac{Q}{\left|\tilde{h}_{2j*}\right|^2}, P_t\right), \tag{11}$$

where $\tilde{h}_{1i*}$ is a delayed version of h_{1i*}, $\tilde{h}_{2j*}$ is a delayed version of h_{2j*}. The correlation coefficients between $\tilde{h}_{1i*}$ and h_{1i*}, $\tilde{h}_{2j*}$ and h_{2j*} are expressed as $\rho_3 = J_0\left(2\pi f_3 T_3\right)$, and $\rho_4 = J_0\left(2\pi f_4 T_4\right)$, respectively. In addition, κ_1 and κ_2 denote the power marginal factors at Alice and Relay, respectively. According to [5], [23]–[25], the closed-form expression of κ_1 is not easily derived and it can be numerically derived by solving the following equation.

$$\begin{aligned} \delta_0 = {} & e^{-\frac{Q}{\lambda_{\mathrm{AP}} P_t}} - \frac{t}{r} Q_0\left(\sqrt{\frac{(s-r)\,Q}{2P_t}}, \sqrt{\frac{(s+r)\,Q}{2P_t}}\right) \\ & + \frac{1}{2}\left(1 + \frac{t}{r}\right) e^{-\frac{sQ}{2P_t}} I_0\left(\frac{2\rho_3^2 Q \sqrt{\kappa_1}}{\left(1-\rho_3^2\right)\lambda_{\mathrm{AP}} P_t}\right) \\ & - e^{-\frac{Q}{\lambda_{\mathrm{AP}} P_t}} Q_0\left(\frac{2\rho_3^2 Q}{\left(1-\rho_3^2\right)\lambda_{\mathrm{AP}} P_t}, \frac{2\kappa_1 Q}{\left(1-\rho_3^2\right)\lambda_{\mathrm{AP}} P_t}\right), \end{aligned} \tag{12}$$

where $s = \frac{2}{\lambda_{\mathrm{AP}}}\left(\frac{1+\kappa_1}{1-\rho_3^2}\right)$, $t = \frac{2}{\lambda_{\mathrm{AP}}}\left(\frac{1-\kappa_1}{1-\rho_3^2}\right)$, $r = \sqrt{s^2 - \frac{16\kappa_1\rho_3^2}{\lambda_{\mathrm{AP}}^2\left(1-\rho_3^2\right)}}$ and $Q_0\left(a, b\right)$ is the first-order Marcum Q-function [26], $I_0\left(\cdot\right)$ is the zeroth-order modified Bessel function of the first kind [27, Eq. (8.431.1)]. Similarly, κ_2 can be derived by interchanging $\lambda_{\mathrm{AP}} \to \lambda_{\mathrm{RP}}$ and $\rho_3 \to \rho_4$ in Eq. (12).

To make the following analysis more tractable, we define $\mu = \frac{Q}{P_t}$, $\bar{\gamma}_{\mathrm{B}} = \frac{P_t}{\sigma^2}\lambda_{\mathrm{AR}} = \frac{Q}{\mu\sigma^2}\lambda_{\mathrm{AR}} = \frac{P_t}{\eta\sigma^2}\lambda_{\mathrm{RB}} = \frac{Q}{\mu\eta\sigma^2}\lambda_{\mathrm{RB}}$, and $\bar{\gamma}_{\mathrm{E}} = \frac{P_t}{\sigma^2}\lambda_{\mathrm{AE}} = \frac{Q}{\mu\sigma^2}\lambda_{\mathrm{AE}} = \frac{P_t}{\beta\sigma^2}\lambda_{\mathrm{RE}} = \frac{Q}{\mu\beta\sigma^2}\lambda_{\mathrm{RE}}$.

III. Secrecy Performance Analysis

In this section, we investigate the secrecy outage probability of the dual-hop RaF cognitive MIMO wiretap networks with TAS/MRC scheme. Specifically, we derive closed-form expressions for secrecy outage probability under two cases. Case 1: outdated CSI for the secondary transmission links, and Case 2: perfect CSI for the secondary transmission links. For case 1, to demonstrate the advantage of TAS/MRC scheme with outdated CSI, the analysis for RAS/MRC scheme is also given.

A. Outdated CSI for the secondary transmission links

The secrecy outage probability is defined as the probability that the instantaneous secrecy capacity falls below a predefined threshold R_s. For the RaF protocol, the Alice and Relay transmit independent randomization signal in each hop, and the message is secured if the two hops are both secured [17], [20]. Mathematically, it can be expressed as [20]

$$P_{out}\left(R_s\right) = 1 - \Pr\left\{C_{1s} > R_s\right\} \Pr\left\{C_{2s} > R_s\right\}, \tag{13}$$

where C_{1s} and C_{2s} are the secrecy capacity of the first hop and the second hop, which can be respective expressed as

$$C_{1s} = \log_2 \frac{1+\tilde{\gamma}_{\mathrm{AR}}}{1+\gamma_{\mathrm{AE}}} = \log_2 \frac{1+\min\left(\kappa_1 \frac{Q}{\left|\tilde{h}_{1i*}\right|^2}, P_t\right) \frac{\left\|\tilde{\mathbf{h}}_{\mathrm{AR}}^{i*}\right\|^2}{\sigma^2}}{1+\min\left(\kappa_1 \frac{Q}{\left|\tilde{h}_{1i*}\right|^2}, P_t\right) \frac{\left\|\mathbf{h}_{\mathrm{AE}}\right\|^2}{\sigma^2}}, \tag{14}$$

$$C_{2s} = \log_2 \frac{1+\tilde{\gamma}_{\mathrm{RB}}}{1+\gamma_{\mathrm{RE}}} = \log_2 \frac{1+\min\left(\kappa_2 \frac{Q}{\left|\tilde{h}_{2j*}\right|^2}, P_t\right) \frac{\left\|\tilde{\mathbf{h}}_{\mathrm{RB}}^{j*}\right\|^2}{\sigma^2}}{1+\min\left(\kappa_2 \frac{Q}{\left|\tilde{h}_{2j*}\right|^2}, P_t\right) \frac{\left\|\mathbf{h}_{\mathrm{RE}}\right\|^2}{\sigma^2}}. \tag{15}$$

From (14) and (15), we have

$$\Pr\left\{C_{1s} > R_s\right\} = 1 - \Pr\left\{\tilde{\gamma}_1 \le 2^{R_s}\right\} = 1 - F_{\tilde{\gamma}_1}\left(R_s\right), \tag{16}$$

$$\Pr\left\{C_{2s} > R_s\right\} = 1 - \Pr\left\{\tilde{\gamma}_2 \le 2^{R_s}\right\} = 1 - F_{\tilde{\gamma}_2}\left(R_s\right), \tag{17}$$

where $\tilde{\gamma}_1 = \frac{1+\min\left(\kappa_1 \frac{Q}{\left|\tilde{h}_{1i*}\right|^2}, P_t\right) \frac{\left\|\tilde{\mathbf{h}}_{\mathrm{AR}}^{i*}\right\|^2}{\sigma^2}}{1+\min\left(\kappa_1 \frac{Q}{\left|\tilde{h}_{1i*}\right|^2}, P_t\right) \frac{\left\|\mathbf{h}_{\mathrm{AE}}\right\|^2}{\sigma^2}}$, $\tilde{\gamma}_2 = \frac{1+\min\left(\kappa_2 \frac{Q}{\left|\tilde{h}_{2j*}\right|^2}, P_t\right) \frac{\left\|\tilde{\mathbf{h}}_{\mathrm{RB}}^{j*}\right\|^2}{\sigma^2}}{1+\min\left(\kappa_2 \frac{Q}{\left|\tilde{h}_{2j*}\right|^2}, P_t\right) \frac{\left\|\mathbf{h}_{\mathrm{RE}}\right\|^2}{\sigma^2}}$, $F_{\tilde{\gamma}_1}(\cdot)$ and $F_{\tilde{\gamma}_2}(\cdot)$ are the cumulative distribution functions (CDFs) of $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$, respectively.

Now, taking the detailed derivation of $F_{\tilde{\gamma}_1}(\cdot)$ for example, we first present the CDF of RV $\tilde{X} = \left\|\tilde{\mathbf{h}}_{\mathrm{AR}}^{i*}\right\|^2$, which is given in the following lemma.

Lemma 1. *The CDF of $\tilde{X}$ is given by*

$$F_{\tilde{X}}\left(x\right) = 1 - N_{\mathrm{A}} \sum_{n=0}^{N_{\mathrm{A}}-1} \binom{N_{\mathrm{A}}-1}{n} \frac{\left(-1\right)^n \Phi_1}{\Gamma\left(N_{\mathrm{R}}\right)} \sum_{k=0}^{\varphi_1} \binom{\varphi_1}{k}$$
$$\times \sum_{m=0}^{N_{\mathrm{R}}+k-1} \frac{\Gamma\left(N_{\mathrm{R}}+\varphi_1\right) \rho_1^k \left(1-\rho_1\right)^{\varphi_1-k} x^m e^{-\frac{1+n}{\lambda_{\mathrm{AR}}\zeta_1}x}}{\Gamma\left(m+1\right)\left(1+n\right)^{N_{\mathrm{R}}+k-m} \zeta_1^{m+\varphi_1} \left(\lambda_{\mathrm{AR}}\right)^m}, \tag{18}$$

where $\zeta_1 = 1 + n\left(1-\rho_1\right)$ and $\Phi_1 = \sum_{n_1=0}^{n} \sum_{n_2=0}^{n_1} \cdots \sum_{n_{N_{\mathrm{R}}-1}}^{n_{N_{\mathrm{R}}-2}} \frac{n!}{n_{N_{\mathrm{R}}-1}!} \prod_{i=1}^{N_{\mathrm{R}}-1} \frac{\left(i!\right)^{n_{i+1}-n_i}}{\left(n_{i+1}-n_i\right)!}$ with $\varphi_1 = \sum_{q=1}^{N_{\mathrm{R}}-1} n_q$, $n_0 = n$ and $n_{N_{\mathrm{R}}} = 0$.

Proof: The proof can be found in [5]. ■

Then, we focus on deriving the CDF of $\tilde{\gamma}_1$ in the following key theorem.

Theorem 1. *The CDF of $\tilde{\gamma}_1$ is formulated as*

$$F_{\tilde{\gamma}_1}\left(R_s\right) = 1 - N_{\mathrm{A}} \sum_{n=0}^{N_{\mathrm{A}}-1} \binom{N_{\mathrm{A}}-1}{n} \frac{\left(-1\right)^n \Phi_1}{\Gamma\left(N_{\mathrm{R}}\right)} \sum_{k=0}^{\varphi_1} \binom{\varphi_1}{k}$$
$$\times \sum_{m=0}^{N_{\mathrm{R}}+k-1} \frac{\Gamma\left(N_{\mathrm{R}}+\varphi_1\right) \rho_1^k \left(1-\rho_1\right)^{\varphi_1-k}}{\Gamma\left(m+1\right)\left(1+n\right)^{N_{\mathrm{R}}+k-m} \zeta_1^{m+\varphi_1} \left(N_{\mathrm{E}}-1\right)!}$$
$$\times \sum_{i=0}^{m} \binom{m}{i} \left(2^{R_s}-1\right)^{m-i} \left(2^{R_s}\right)^i \left(i+N_{\mathrm{E}}-1\right)!$$
$$\times \left\{ \frac{e^{-\frac{1+n}{\bar{\gamma}_{\mathrm{B}}\zeta_1}\left(2^{R_s}-1\right)} \left(1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}\right)}{\left(\bar{\gamma}_{\mathrm{B}}\right)^m \left(\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}}} \left[\frac{\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}\zeta_1}{\bar{\gamma}_{\mathrm{B}}\zeta_1+\left(1+n\right)2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right]^{i+N_{\mathrm{E}}} \right.$$
$$+ \frac{\left(\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\lambda_{\mathrm{AP}}\right)^{m-i+1}}{\left(\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right)^m \left(\kappa_1\mu\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}} \lambda_{\mathrm{AP}}} \left[\frac{\kappa_1\mu\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}\zeta_1}{\bar{\gamma}_{\mathrm{B}}\zeta_1+\left(1+n\right)2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right]^{i+N_{\mathrm{E}}}$$
$$\left. \times \frac{\Gamma\left(m-i+1, \frac{\left(1+n\right)\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}{\zeta_1\lambda_{\mathrm{AP}}\bar{\gamma}_{\mathrm{B}}}\right)}{\left[\left(1+n\right)\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right]^{m-i+1}} \right\}. \tag{19}$$

Proof: See Appendix A. ■

By interchanging the parameters in Eq. (19), i.e., $N_{\mathrm{A}} \to N_{\mathrm{R}}$, $N_{\mathrm{R}} \to N_{\mathrm{B}}$, $\lambda_{\mathrm{AR}} \to \lambda_{\mathrm{RB}}$, $\lambda_{\mathrm{AE}} \to \lambda_{\mathrm{RE}}$, $\lambda_{\mathrm{AP}} \to \lambda_{\mathrm{RP}}$, $\rho_1 \to \rho_2$, $\rho_3 \to \rho_4$, and $\kappa_1 \to \kappa_2$, we can obtain the CDF of $\tilde{\gamma}_2$. Then, substituting the CDFs of $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ into Eq. (13) and performing some mathematical manipulations, the closed-form expression for the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks is derived.

Note that, when the secondary transmitters have no CSI of the main channel, RAS/MRC can be regarded as an efficient way to secure transmission. Thus, by following the proof in **Appendix A**, the CDF of $\tilde{\gamma}_1$ with RAS/MRC scheme is given by

$$F_{\tilde{\gamma}_1}\left(R_s\right) = 1 - \sum_{m=0}^{N_{\mathrm{R}}-1} \frac{1}{m!\left(N_{\mathrm{E}}-1\right)!} \sum_{i=0}^{m} \binom{m}{i} \left(2^{R_s}-1\right)^{m-i} \left(2^{R_s}\right)^i$$
$$\times \left(i+N_{\mathrm{E}}-1\right)! \left\{ \frac{e^{-\frac{2^{R_s}-1}{\bar{\gamma}_{\mathrm{B}}}} \left(1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}\right)}{\left(\bar{\gamma}_{\mathrm{B}}\right)^m \left(\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}}} \left(\frac{\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}}{\bar{\gamma}_{\mathrm{B}}+2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right)^{i+N_{\mathrm{E}}} \right.$$
$$+ \frac{\left(\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\lambda_{\mathrm{AP}}\right)^{m-i+1}}{\left(\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right)^m \left(\kappa_1\mu\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}} \lambda_{\mathrm{AP}}} \left(\frac{\kappa_1\mu\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}}{\bar{\gamma}_{\mathrm{B}}+2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right)^{i+N_{\mathrm{E}}}$$
$$\left. \times \frac{\Gamma\left(m-i+1, \frac{\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}{\bar{\gamma}_{\mathrm{B}}\lambda_{\mathrm{AP}}}\right)}{\left[\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right]^{m-i+1}} \right\}. \tag{20}$$

By interchanging the parameters in Eq. (20), i.e., $N_{\mathrm{R}} \to N_{\mathrm{B}}$, $\lambda_{\mathrm{AR}} \to \lambda_{\mathrm{RB}}$, $\lambda_{\mathrm{AE}} \to \lambda_{\mathrm{RE}}$, $\lambda_{\mathrm{AP}} \to \lambda_{\mathrm{RP}}$, $\rho_3 \to \rho_4$, and $\kappa_1 \rightarrow \kappa_2$, the CDF of $\tilde{\gamma}_2$ in RAS/MRC scheme can be easily derived. Then, substituting the CDFs of $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ into (13) and performing some mathematical manipulations, the closed-form expression for the secrecy outage probability of the considered system with RAS/MRC scheme is obtained.

B. Perfect CSI for the secondary transmission links

When the CSIs about the secondary transmission links are perfect, the outage probability is mathematically expressed as

$$\begin{aligned} P_{out}\left(R_s\right) &= 1-\Pr\left\{C_{1s} > R_s\right\}\Pr\left\{C_{2s} > R_s\right\} \\ &= F_{\gamma_1}\left(R_s\right)+F_{\gamma_2}\left(R_s\right)-F_{\gamma_1}\left(R_s\right)F_{\gamma_2}\left(R_s\right), \end{aligned} \tag{21}$$

where $\gamma_1 = \frac{1+\min\left(\kappa_1\frac{Q}{\left|\tilde{h}_{1i*}\right|^2},P_t\right)\frac{\left\|\mathbf{h}_{\mathrm{AR}}^{i^*}\right\|^2}{\sigma^2}}{1+\min\left(\kappa_1\frac{Q}{\left|\tilde{h}_{1i*}\right|^2},P_t\right)\frac{\left\|\mathbf{h}_{\mathrm{AE}}\right\|^2}{\sigma^2}}$, $\gamma_2 = \frac{1+\min\left(\kappa_2\frac{Q}{\left|\tilde{h}_{2j*}\right|^2},P_t\right)\frac{\left\|\mathbf{h}_{\mathrm{RB}}^{j^*}\right\|^2}{\sigma^2}}{1+\min\left(\kappa_2\frac{Q}{\left|\tilde{h}_{2j*}\right|^2},P_t\right)\frac{\left\|\mathbf{h}_{\mathrm{RE}}\right\|^2}{\sigma^2}}$, $F_{\gamma_1}\left(\cdot\right)$ and $F_{\gamma_2}\left(\cdot\right)$ are the CDFs of γ_1 and γ_2, respectively.

Similar to the analysis in Section A, we first present the CDF of $X = \left\|\mathbf{h}_{\mathrm{AR}}^{i^*}\right\|^2$ in the following lemma.

Lemma 2. *The CDF of X is given by*

$$\begin{aligned} F_X\left(x\right) &= \sum_{p=0}^{N_{\mathrm{A}}}\binom{N_{\mathrm{A}}}{p}(-1)^p e^{-\frac{x}{\lambda_{\mathrm{AR}}}} \\ &\times\prod_{u=1}^{N_{\mathrm{R}}-1}\left[\sum_{i_u=0}^{i_{u-1}}\binom{i_{u-1}}{i_u}\left(\frac{1}{u!}\right)^{i_u-i_{u+1}}\right]\left(\frac{x}{\lambda_{\mathrm{AR}}}\right)^{\theta}, \end{aligned} \tag{22}$$

where $\theta = \sum_{u=1}^{N_{\mathrm{R}}-1} i_u$, $i_0 = p$, and $i_{N_{\mathrm{R}}} = 0$.

Proof: The proof can be found in [15]. ■

Then, we focus on deriving the CDF of γ_1 in the following theorem.

Theorem 2. *The CDF of γ_1 can be expressed as*

$$\begin{aligned} F_{\gamma_1}\left(R_s\right) &= \sum_{p=0}^{N_{\mathrm{A}}}\binom{N_{\mathrm{A}}}{p}(-1)^p\prod_{u=1}^{N_{\mathrm{R}}-1}\left[\sum_{i_u=0}^{i_{u-1}}\binom{i_{u-1}}{i_u}\left(\frac{1}{u!}\right)^{i_u-i_{u+1}}\right] \\ &\times\sum_{i=0}^{\theta}\binom{\theta}{i}\left(2^{R_s}-1\right)^{\theta-i}\left(2^{R_s}\right)^i\frac{(i+N_{\mathrm{E}}-1)!}{(N_{\mathrm{E}}-1)!} \\ &\times\left\{\frac{e^{-\frac{2^{R_s}-1}{\bar{\gamma}_{\mathrm{B}}}}\left(1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}\right)}{\left(\bar{\gamma}_{\mathrm{B}}\right)^{\theta}\left(\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}}}\left(\frac{\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}}{\bar{\gamma}_{\mathrm{B}}+2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right)^{i+N_{\mathrm{E}}}+\left(\frac{\kappa_1\mu\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}}{\bar{\gamma}_{\mathrm{B}}+\bar{\gamma}_{\mathrm{E}}2^{R_s}}\right)^{i+N_{\mathrm{E}}}\right. \\ &\times\left.\frac{\left(\lambda_{\mathrm{AP}}\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right)^{\theta-i+1}\Gamma\left(\theta-i+1,\frac{\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}{\lambda_{\mathrm{AP}}\bar{\gamma}_{\mathrm{B}}}\right)}{\left(\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right)^{\theta}\left(\kappa_1\mu\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}}\lambda_{\mathrm{AP}}\left[\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right]^{\theta-i+1}}\right\}. \end{aligned} \tag{23}$$

Proof: Following similar procedure as in the proof of Theorem 1, the above result can be easily obtained. ■

By interchanging the parameters in Eq. (23), i.e., $N_{\mathrm{A}} \rightarrow N_{\mathrm{R}}$, $N_{\mathrm{R}} \rightarrow N_{\mathrm{B}}$, $\lambda_{\mathrm{AR}} \rightarrow \lambda_{\mathrm{RB}}$, $\lambda_{\mathrm{AE}} \rightarrow \lambda_{\mathrm{RE}}$, $\lambda_{\mathrm{AP}} \rightarrow \lambda_{\mathrm{RP}}$, $\rho_3 \rightarrow \rho_4$, and $\kappa_1 \rightarrow \kappa_2$, we can obtain the CDF of γ_2. Then, substituting the CDFs of γ_1 and γ_2 into (21) yields the closed-form expression for the secrecy outage probability of the considered system with perfect CSI for the secondary transmission links.

IV. High SNR Analysis

The derived closed-form expressions in **Theorem 1** and **Theorem 2** provide an efficient means to evaluate the secrecy performance of the considered system. However, the derived expressions are too complicated to extract any insight on the impact of key system parameters on the secrecy performance of the considered system, i.e, feedback delay, the number of antennas and the interference threshold. Thus, in this section, we turn our attention to analyze the asymptotic secrecy outage probability in high SNR regimes under two distinct scenarios: 1) $\bar{\gamma}_{\mathrm{B}} \rightarrow \infty$ and fixed $\bar{\gamma}_{\mathrm{E}}$, that is a scenario where the main channel has a good quality while the eavesdropper's channel is severely blocked due to heavy shadowing. 2) $\bar{\gamma}_{\mathrm{B}} \rightarrow \infty$ and $\bar{\gamma}_{\mathrm{E}} \rightarrow \infty$, that is a scenario where both the main channel and eavesdropper's channel have a good quality.

A. Scenario I: $\bar{\gamma}_{\mathrm{B}} \rightarrow \infty$ and fixed $\bar{\gamma}_{\mathrm{E}}$

In order to characterize the effect of outdated CSI on the secrecy diversity gain and secrecy coding gain of the system under this scenario, we analyze the asymptotic secrecy outage probability under two cases. Case 1: outdated CSIs for the secondary transmission links ($\rho_1 \neq 1, \rho_2 \neq 1$), and Case 2: perfect CSIs for the secondary transmission links ($\rho_1 = \rho_2 = 1$). Then, we have the following two corollaries.

Corollary 1. *When the CSIs for the secondary transmission links are outdated, the asymptotic outage probability of dual-hop RaF cognitive MIMO wiretap networks when $\bar{\gamma}_{\mathrm{B}} \rightarrow \infty$ and fixed $\bar{\gamma}_{\mathrm{E}}$ is given by*

$$P_{out}\left(R_s\right) \approx \Delta_{\mathrm{A}}\bar{\gamma}_{\mathrm{B}}^{-\min\left(N_{\mathrm{R}},N_{\mathrm{B}}\right)}, \tag{24}$$

where Δ_{A} is given by

$$\Delta_{\mathrm{A}} = \begin{cases} \Delta_1, & N_{\mathrm{R}} < N_{\mathrm{B}} \\ \Delta_1+\Delta_2, & N_{\mathrm{R}} = N_{\mathrm{B}} \\ \Delta_2, & N_{\mathrm{R}} > N_{\mathrm{B}} \end{cases} \tag{25}$$

with Δ_1 and Δ_2 being expressed as

$$\begin{aligned} \Delta_1 &= N_{\mathrm{A}}\sum_{n=0}^{N_{\mathrm{A}}-1}\binom{N_{\mathrm{A}}-1}{n}\frac{(-1)^n\Phi_1}{\Gamma\left(N_{\mathrm{R}}\right)}\frac{\Gamma\left(N_{\mathrm{R}}+\varphi_1\right)\left(1-\rho_1\right)^{\varphi_1}}{\Gamma\left(N_{\mathrm{R}}+1\right)\zeta_1^{N_{\mathrm{R}}+\varphi_1}} \\ &\times\sum_{i=0}^{N_{\mathrm{R}}}\binom{N_{\mathrm{R}}}{i}\left(2^{R_s}-1\right)^{N_{\mathrm{R}}-i}\left(2^{R_s}\right)^i(i+N_{\mathrm{E}}-1)!(\bar{\gamma}_{\mathrm{E}})^i \\ &\times\left[\frac{1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}}{(N_{\mathrm{E}}-1)!}+\frac{\left(\lambda_{\mathrm{AP}}\right)^{N_R}\Gamma\left(N_{\mathrm{R}}+1,\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}\right)}{\left(\kappa_1\mu\right)^{N_R}\left(N_{\mathrm{E}}-1\right)!}\right], \end{aligned} \tag{26}$$

$$\Delta_2 = N_{\mathrm{R}} \sum_{n=0}^{N_{\mathrm{R}}-1} \binom{N_{\mathrm{R}}-1}{n} \frac{(-1)^n \Phi_2}{\Gamma(N_{\mathrm{B}})} \frac{\Gamma(N_{\mathrm{B}}+\varphi_2)(1-\rho_2)^{\varphi_2}}{\Gamma(N_{\mathrm{B}}+1)\zeta_2^{N_{\mathrm{B}}+\varphi_2}}$$
$$\times \sum_{i=0}^{N_{\mathrm{B}}} \binom{N_{\mathrm{B}}}{i} \left(2^{R_s}-1\right)^{N_{\mathrm{B}}-i} \left(2^{R_s}\right)^i (i+N_{\mathrm{E}}-1)!(\beta\bar{\gamma}_{\mathrm{E}})^i$$
$$\times \left[\frac{1-\mathrm{e}^{-\frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}}}{(\eta)^{N_{\mathrm{B}}}(N_{\mathrm{E}}-1)!} + \frac{(\lambda_{\mathrm{RP}})^{N_{\mathrm{B}}}\Gamma\left(N_{\mathrm{B}}+1, \frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}\right)}{(\kappa_2\mu\eta)^{N_{\mathrm{B}}}(N_{\mathrm{E}}-1)!}\right]. \quad (27)$$

Proof: See Appendix B. ■

Corollary 2. *When the CSIs for the secondary transmission links are perfectly known, the asymptotic outage probability of dual-hop RaF cognitive MIMO wiretap networks when $\bar{\gamma}_{\mathrm{B}} \to \infty$ and fixed $\bar{\gamma}_{\mathrm{E}}$ is given by*

$$P_{out}(R_s) \approx \Delta_{\mathrm{B}} \bar{\gamma}_{\mathrm{B}}^{-N_{\mathrm{R}}\min(N_{\mathrm{A}},N_{\mathrm{B}})}, \quad (28)$$

where Δ_{B} is given by

$$\Delta_{\mathrm{B}} = \begin{cases} \Delta_3, & N_{\mathrm{A}} < N_{\mathrm{B}} \\ \Delta_3 + \Delta_4, & N_{\mathrm{A}} = N_{\mathrm{B}} \\ \Delta_4, & N_{\mathrm{A}} > N_{\mathrm{B}} \end{cases} \quad (29)$$

with Δ_3 and Δ_4 being expressed as

$$\Delta_3 = \frac{1}{(N_{\mathrm{R}}!)^{N_{\mathrm{A}}}} \sum_{i=0}^{N_{\mathrm{A}}N_{\mathrm{R}}} \binom{N_{\mathrm{A}}N_{\mathrm{R}}}{i} \left(2^{R_s}-1\right)^{N_{\mathrm{A}}N_{\mathrm{R}}-i}$$
$$\times \left(2^{R_s}\right)^i (i+N_{\mathrm{E}}-1)!(\bar{\gamma}_{\mathrm{E}})^i$$
$$\times \left[\frac{1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}}{(N_{\mathrm{E}}-1)!} + \frac{(\lambda_{\mathrm{AP}})^{N_{\mathrm{A}}N_{\mathrm{R}}}\Gamma\left(N_{\mathrm{A}}N_{\mathrm{R}}+1, \frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}\right)}{(\kappa_1\mu)^{N_{\mathrm{A}}N_{\mathrm{R}}}(N_{\mathrm{E}}-1)!}\right], \quad (30)$$

$$\Delta_4 = \frac{1}{(N_{\mathrm{B}}!)^{N_{\mathrm{R}}}} \sum_{i=0}^{N_{\mathrm{R}}N_{\mathrm{B}}} \binom{N_{\mathrm{R}}N_{\mathrm{B}}}{i} \left(2^{R_s}-1\right)^{N_{\mathrm{R}}N_{\mathrm{B}}-i}$$
$$\times \left(2^{R_s}\right)^i (i+N_{\mathrm{E}}-1)!(\beta\bar{\gamma}_{\mathrm{E}})^i$$
$$\times \left[\frac{1-\mathrm{e}^{-\frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}}}{\eta^{N_{\mathrm{R}}N_{\mathrm{B}}}(N_{\mathrm{E}}-1)!} + \frac{(\lambda_{\mathrm{RP}})^{N_{\mathrm{R}}N_{\mathrm{B}}}\Gamma\left(N_{\mathrm{R}}N_{\mathrm{B}}+1, \frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}\right)}{(\kappa_2\mu\eta)^{N_{\mathrm{R}}N_{\mathrm{B}}}(N_{\mathrm{E}}-1)!}\right]. \quad (31)$$

Proof: See Appendix C. ■

Remark 1: From **Corollary 1** and **Corollary 2**, we find that the considered two cases achieve different secrecy diversity gains, i.e., $\min(N_{\mathrm{R}}, N_{\mathrm{B}})$ and $N_{\mathrm{R}}\min(N_{\mathrm{A}}, N_{\mathrm{B}})$. The result demonstrates that the outdated CSI has a significantly impact on the achievable secrecy diversity gain of the system and it will reduce the secrecy diversity gain from $N_{\mathrm{R}}\min(N_{\mathrm{A}}, N_{\mathrm{B}})$ to $\min(N_{\mathrm{R}}, N_{\mathrm{B}})$ for Scenario I. In addition, the parameters of the number of antennas, the eavesdropper's channel and the interference temperature constraint of the primary networks will affect the secrecy performance through the secrecy coding gain, i.e.,

$$G_1 = (\Delta_{\mathrm{A}})^{-\frac{1}{\min(N_{\mathrm{R}},N_{\mathrm{B}})}}, \quad (32)$$

$$G_2 = (\Delta_{\mathrm{B}})^{-\frac{1}{N_{\mathrm{R}}\min(N_{\mathrm{A}},N_{\mathrm{B}})}}. \quad (33)$$

B. Scenario II: $\bar{\gamma}_{\mathrm{B}} \to \infty$ and $\bar{\gamma}_{\mathrm{E}} \to \infty$

Now, we focus on analyzing the approximated secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks under Scenario II.

Corollary 3. *When the CSIs for the secondary transmission links are outdated, the asymptotic outage probability of dual-hop RaF cognitive MIMO wiretap networks when $\bar{\gamma}_{\mathrm{B}} \to \infty$ and $\bar{\gamma}_{\mathrm{E}} \to \infty$ is given by*

$$P_{out}(R_s) \approx F_{\tilde{\gamma}_1}(R_s) + F_{\tilde{\gamma}_2}(R_s) - F_{\tilde{\gamma}_1}(R_s) F_{\tilde{\gamma}_2}(R_s), \quad (34)$$

where $F_{\tilde{\gamma}_1}(R_s)$ and $F_{\tilde{\gamma}_2}(R_s)$ are respective expressed as

$$F_{\tilde{\gamma}_1}(R_s) \approx 1 - N_{\mathrm{A}} \sum_{n=0}^{N_{\mathrm{A}}-1} \binom{N_{\mathrm{A}}-1}{n} \frac{(-1)^n \Phi_1}{\Gamma(N_{\mathrm{R}})} \sum_{k=0}^{\varphi_1} \binom{\varphi_1}{k}$$
$$\times \sum_{m=0}^{N_{\mathrm{R}}+k-1} \frac{\Gamma(N_{\mathrm{R}}+\varphi_1)\rho_1^k(1-\rho_1)^{\varphi_1-k}}{\Gamma(m+1)(1+n)^{N_{\mathrm{R}}+k-m}\zeta_1^{m+\varphi_1}}$$
$$\times \frac{\left(2^{R_s}\right)^m (m+N_{\mathrm{E}}-1)!}{(N_{\mathrm{E}}-1)!(\bar{\gamma}_{\mathrm{B}})^m(\bar{\gamma}_{\mathrm{E}})^{N_{\mathrm{E}}}} \left[\frac{\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}\zeta_1}{\bar{\gamma}_{\mathrm{B}}\zeta_1 + (1+n)2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right]^{m+N_{\mathrm{E}}}$$
$$\times \left[1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}} + \frac{\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\Gamma\left(1, \frac{(1+n)\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}{\zeta_1\lambda_{\mathrm{AP}}\bar{\gamma}_{\mathrm{B}}}\right)}{(1+n)\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}\right], \quad (35)$$

and

$$F_{\tilde{\gamma}_2}(R_s) \approx 1 - N_{\mathrm{R}} \sum_{n=0}^{N_{\mathrm{R}}-1} \binom{N_{\mathrm{R}}-1}{n} \frac{(-1)^n \Phi_2}{\Gamma(N_{\mathrm{B}})} \sum_{k=0}^{\varphi_2} \binom{\varphi_2}{k}$$
$$\times \sum_{m=0}^{N_{\mathrm{B}}+k-1} \frac{\Gamma(N_{\mathrm{B}}+\varphi_2)\rho_2^k(1-\rho_2)^{\varphi_2-k}}{\Gamma(m+1)(1+n)^{N_{\mathrm{B}}+k-m}\zeta_1^{m+\varphi_2}}$$
$$\times \frac{\left(2^{R_s}\right)^m (m+N_{\mathrm{E}}-1)!}{(N_{\mathrm{E}}-1)!(\eta\bar{\gamma}_{\mathrm{B}})^m(\beta\bar{\gamma}_{\mathrm{E}})^{N_{\mathrm{E}}}} \left[\frac{\beta\bar{\gamma}_{\mathrm{E}}\eta\bar{\gamma}_{\mathrm{B}}\zeta_2}{\eta\bar{\gamma}_{\mathrm{B}}\zeta_2 + (1+n)2^{R_s}\beta\bar{\gamma}_{\mathrm{E}}}\right]^{m+N_{\mathrm{E}}}$$
$$\times \left[1-\mathrm{e}^{-\frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}} + \frac{\zeta_2\kappa_2\mu\eta\bar{\gamma}_{\mathrm{B}}\Gamma\left(1, \frac{(1+n)\left(2^{R_s}-1\right)\lambda_{\mathrm{RP}}+\zeta_2\kappa_2\mu\eta\bar{\gamma}_{\mathrm{B}}}{\zeta_2\lambda_{\mathrm{RP}}\eta\bar{\gamma}_{\mathrm{B}}}\right)}{(1+n)\left(2^{R_s}-1\right)\lambda_{\mathrm{RP}}+\zeta_2\kappa_2\mu\eta\bar{\gamma}_{\mathrm{B}}}\right]. \quad (36)$$

Proof: See Appendix D. ■

Corollary 4. *When the CSIs for the secondary transmission links are perfect, the asymptotic outage probability of dual-hop RaF cognitive MIMO wiretap networks when $\bar{\gamma}_{\mathrm{B}} \to \infty$ and $\bar{\gamma}_{\mathrm{E}} \to \infty$ is given by*

$$P_{out}(R_s) \approx F_{\gamma_1}(R_s) + F_{\gamma_2}(R_s) - F_{\gamma_1}(R_s) F_{\gamma_2}(R_s), \quad (37)$$

where $F_{\gamma_1}(R_s)$ and $F_{\gamma_2}(R_s)$ are respective expressed as

$$F_{\gamma_1}(R_s) \approx \sum_{p=0}^{N_{\mathrm{A}}} \binom{N_{\mathrm{A}}}{p} (-1)^p \prod_{u=1}^{N_{\mathrm{R}}-1} \left[\sum_{i_u=0}^{i_{u-1}} \binom{i_{u-1}}{i_u} \left(\frac{1}{u!}\right)^{i_u-i_{u+1}}\right]$$
$$\times \frac{\left(2^{R_s}\right)^\theta (\theta+N_{\mathrm{E}}-1)!}{(\bar{\gamma}_{\mathrm{B}})^\theta(\bar{\gamma}_{\mathrm{E}})^{N_{\mathrm{E}}}(N_{\mathrm{E}}-1)!} \left(\frac{\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}}{\bar{\gamma}_{\mathrm{B}}+\bar{\gamma}_{\mathrm{E}}2^{R_s}}\right)^{\theta+N_{\mathrm{E}}}$$

$$\times\left[1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}+\frac{\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\Gamma\left(1,\frac{\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}{\lambda_{\mathrm{AP}}\bar{\gamma}_{\mathrm{B}}}\right)}{\left[\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\right]}\right], \tag{38}$$

and

$$F_{\gamma_2}(R_s)\approx\sum_{p=0}^{N_{\mathrm{R}}}\binom{N_{\mathrm{R}}}{p}(-1)^p\prod_{u=1}^{N_{\mathrm{B}}-1}\left[\sum_{i_u=0}^{i_{u-1}}\binom{i_{u-1}}{i_u}\left(\frac{1}{u!}\right)^{i_u-i_{u+1}}\right]$$
$$\times\frac{\left(2^{R_s}\right)^{\theta}(\theta+N_{\mathrm{E}}-1)!}{(\eta\bar{\gamma}_{\mathrm{B}})^{\theta}(\beta\bar{\gamma}_{\mathrm{E}})^{N_{\mathrm{E}}}(N_{\mathrm{E}}-1)!}\left(\frac{\beta\bar{\gamma}_{\mathrm{E}}\eta\bar{\gamma}_{\mathrm{B}}}{\eta\bar{\gamma}_{\mathrm{B}}+\beta\bar{\gamma}_{\mathrm{E}}2^{R_s}}\right)^{\theta+N_{\mathrm{E}}}$$
$$\times\left[1-\mathrm{e}^{-\frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}}+\frac{\kappa_2\mu\eta\bar{\gamma}_{\mathrm{B}}\Gamma\left(1,\frac{\left(2^{R_s}-1\right)\lambda_{\mathrm{RP}}+\kappa_2\mu\eta\bar{\gamma}_{\mathrm{B}}}{\lambda_{\mathrm{RP}}\eta\bar{\gamma}_{\mathrm{B}}}\right)}{\left[\left(2^{R_s}-1\right)\lambda_{\mathrm{RP}}+\kappa_2\mu\eta\bar{\gamma}_{\mathrm{B}}\right]}\right]. \tag{39}$$

Proof: Following a similar procedure as in the proof of Corollary 3, the above result can be easily obtained after some simple mathematical manipulations. ■

Remark 2: From **Corollary 3** and **Corollary 4**, we find that the two cases exhibit the secrecy outage floor when $\bar{\gamma}_{\mathrm{B}}\to\infty$ and $\bar{\gamma}_{\mathrm{E}}\to\infty$, which indicates that no secrecy diversity gain can be obtained. That is to say, the outdated CSI affects the secrecy performance by degrading the secrecy coding gain for Scenario II.

V. Numerical Results

In this section, representative numerical results are provided to evaluate the impacts of the number of antennas, outdated CSIs for the secondary transmission links, and outdated CSIs for the interference links between PUs and SUs on the secrecy outage performance of the secondary system. Unless otherwise stated, the following parameters are set, i.e., the SNR is $\frac{P_t}{\sigma^2}$, the secrecy rate is $R_s=1$, the noise variance is $\sigma^2=1$, and the average powers of all channel links are set to one. As shown in these figures, the Monte Carlo simulation results are in exact agreement with the analytical ones, which corroborates the accuracy of the analytical expressions.

Figs. 2 and 3 illustrate the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks with TAS/MRC scheme. From both figures, we find that the secrecy outage probability of RaF relaying strategy is lower than that of DF relaying strategy and the secrecy outage performance can be improved by adopting more antennas at Relay and decreasing the feedback delay for both RaF and DF relaying strategies. In addition, the secrecy outage probability of the considered system using RaF relaying strategy becomes saturated due to the fixed interference temperature constraint, which verifies the analytical results shown in Eq. (34) and Eq. (37). However, the secrecy outage probability of the considered system using DF relaying strategy is not always decreasing with the increasing of the SNR. This is intuitive since the instantaneous SNR gap between the main channel and the eavesdropper's channel is mainly determined by interference threshold Q at high SNR, and the instantaneous SNR gap will become small with the increasing of the SNR.

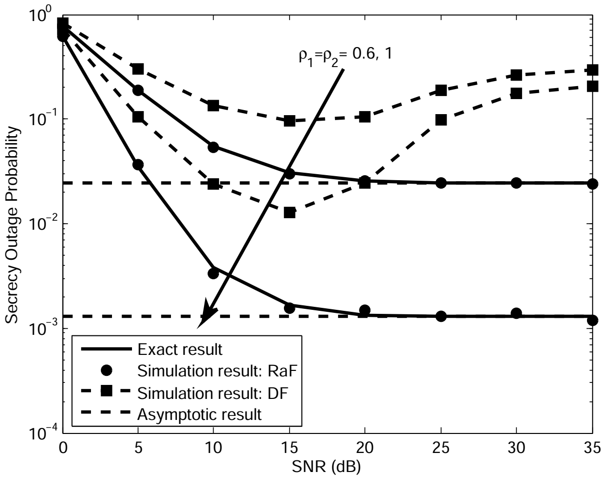

Fig. 2. Secrecy outage probability for TAS/MRC scheme: $\rho_3=1$, $\rho_4=1$, $N_{\mathrm{A}}=2$, $N_{\mathrm{R}}=4$, $N_{\mathrm{B}}=2$, $N_{\mathrm{E}}=2$, and $Q=20$dB.

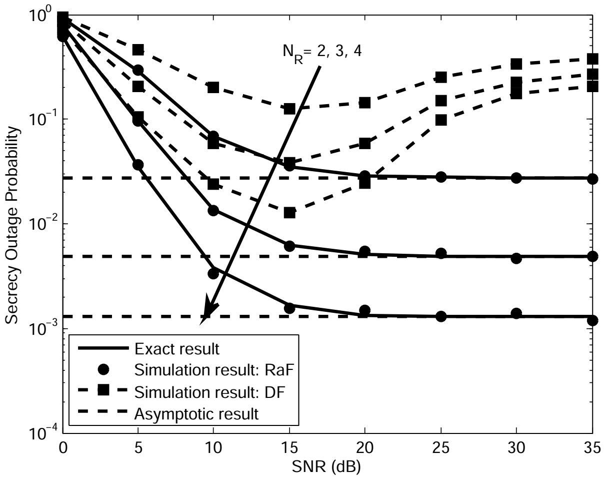

Fig. 3. Secrecy outage probability for TAS/MRC scheme: $\rho_1=\rho_2=1$, $\rho_3=\rho_4=1$, $N_{\mathrm{A}}=2$, $N_{\mathrm{B}}=2$, $N_{\mathrm{E}}=2$, and $Q=20$dB.

Fig. 4 plots the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks under different N_{A} with perfect and outdated CSI, respectively. As shown in the figure, when N_{A} increases from 1 to 3, the outage probability decreases for both cases. As can be observed, when $N_{\mathrm{A}}=1,2$, and 3, the achievable secrecy diversity gains are always 2 in the outdated CSI case, which confirms the analytical findings of **Corollary 1** that when the feedback exists, N_{A} will not affect the secrecy diversity gain of the system, as indicated in Eq. (24). Moreover, we see that the left two sets of curves associated with perfect CSI achieve the same secrecy diversity gain of 4, which confirms the analytical findings of **Corollary 2** that when the CSI is perfect, the full diversity order of $N_{\mathrm{R}}\min(N_{\mathrm{A}},N_{\mathrm{B}})$ can be achieved, as indicated in Eq. (28).

Fig. 5 shows the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks under different N_{R} with perfect and outdated CSI, respectively. As can be observed, when $N_{\mathrm{R}}=1,2$, and 3, the achievable secrecy diversity gains are 1, 2, and 2 in the outdated CSI case, which become 2, 4, and 6 in the perfect CSI case. In other words, when the CSI is outdated, the secrecy diversity gain improves with the increase of N_{R}, while keeps constant when $N_{\mathrm{R}}<N_{\mathrm{B}}$, as indicated in

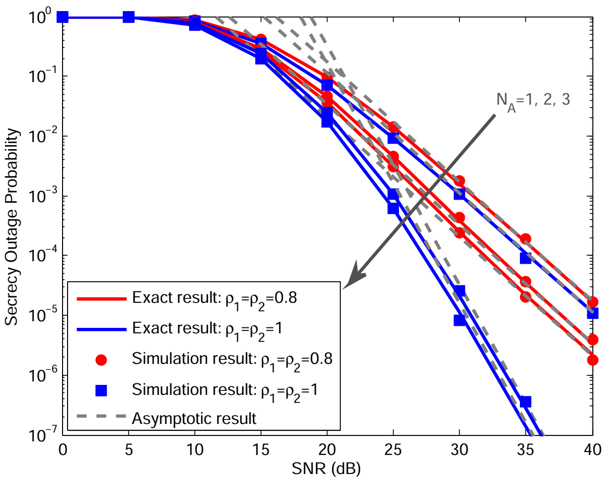

Fig. 4. Exact and asymptotic secrecy outage probabilities for TAS/MRC scheme: $\rho_3 = 1$, $\rho_4 = 1$, $N_{\rm R} = 2$, $N_{\rm B} = 2$, $N_{\rm E} = 2$, and $\bar{\gamma}_{\rm E} = 10$dB.

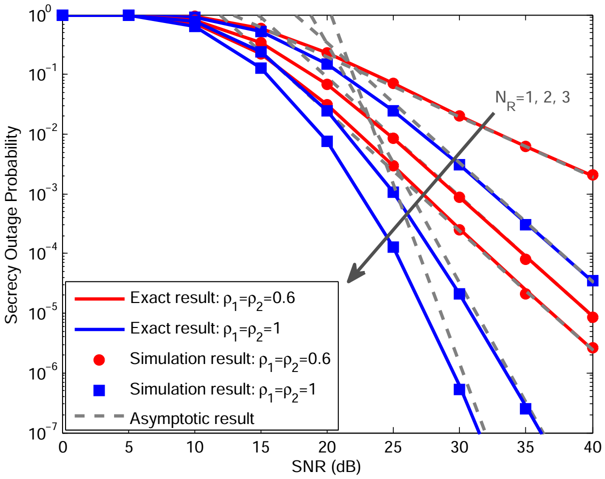

Fig. 5. Exact and asymptotic secrecy outage probabilities for TAS/MRC scheme: $\rho_3 = 1$, $\rho_4 = 1$, $N_{\rm A} = 2$, $N_{\rm B} = 2$, $N_{\rm E} = 2$, and $\bar{\gamma}_{\rm E} = 10$dB.

Eq. (24). However, when it comes to the perfect CSI case, the secrecy diversity gain increases linearly with $N_{\rm R}$, as indicated in Eq. (28).

Fig. 6 provides the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks under different $N_{\rm E}$ with perfect and outdated CSI, respectively. As can be observed, when $N_{\rm E} = 1, 3$, and 5, the achievable secrecy diversity gains are always 2 for outdated CSI case and 4 for perfect CSI case. The results demonstrate that the eavesdropper does not affect the secrecy diversity gain, and it will deteriorate the secrecy outage performance by degrading the secrecy coding gain, as indicated in Eq. (32) and Eq. (33).

Fig. 7 compares the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks for different relaying strategy and different interference outage constraints, respectively. As observed from the figure, the secrecy performance of RaF relaying strategy is better than that of DF relaying strategy. This is intuitive since the eavesdropper can not combine the eavesdropping information with RaF relaying strategy. In addition, for RaF relaying strategy, the secrecy outage probability of the system with $\delta_0 = 10\%$ is strictly smaller than that with $\delta_0 = 1\%$, which explains the fact

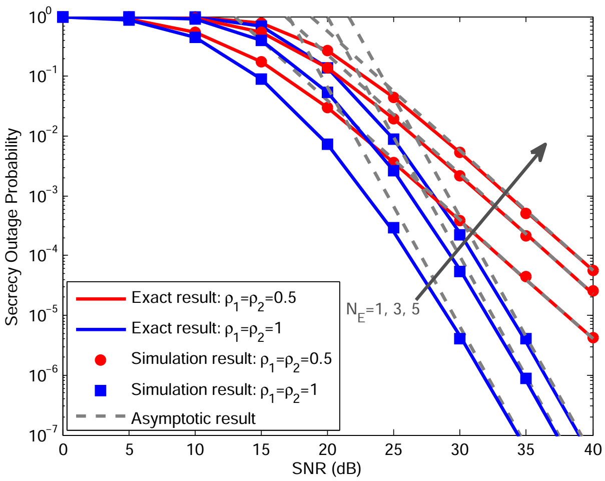

Fig. 6. Exact and asymptotic secrecy outage probabilities for TAS/MRC scheme: $\rho_3 = 1$, $\rho_4 = 1$, $N_{\rm A} = 2$, $N_{\rm R} = 2$, $N_{\rm B} = 2$, and $\bar{\gamma}_{\rm E} = 10$dB.

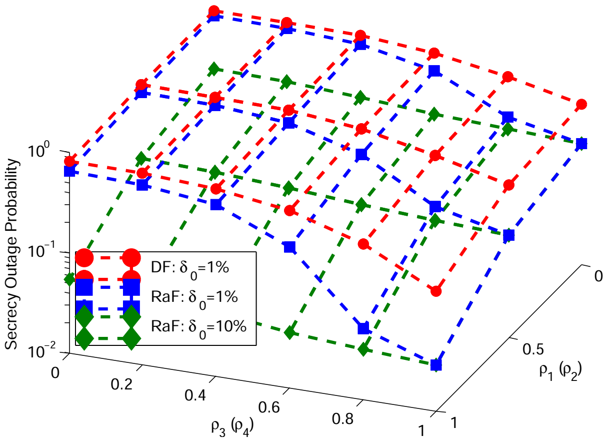

Fig. 7. Secrecy outage probabilities with different correlation coefficients $\rho_1(\rho_2)$ and $\rho_3(\rho_4)$: $N_{\rm A} = 2$, $N_{\rm R} = 2$, $N_{\rm B} = 2$, $N_{\rm E} = 2$, and $P_t = Q =$ 20 dB.

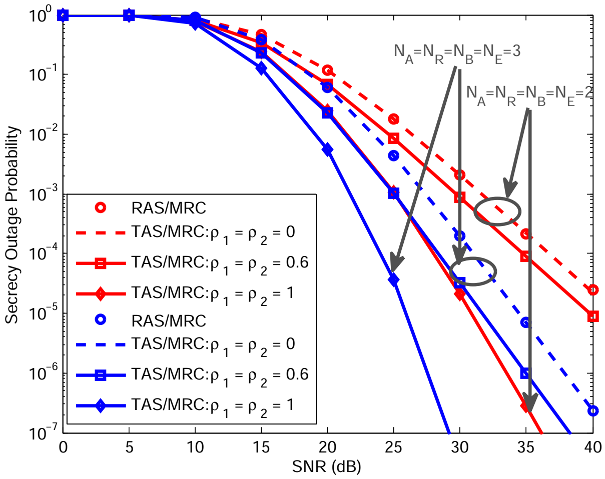

Fig. 8. Performance comparison between RAS/MRC and TAS/MRC when $\rho_3 = \rho_4 = 1$ and $\bar{\gamma}_{\rm E} = 10$dB.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2016.2608966, IEEE Access

that allowing a less stringent interference outage constraint could significantly improve the secrecy outage performance of the secondary transmission. Moreover, we observe that the performance gain depends on $\rho_1\left(\rho_2\right)$, the larger $\rho_1\left(\rho_2\right)$, the higher the gain. Finally, we can see that, at the low correlation regime, i.e., $\rho_3\left(\rho_4\right) < 0.4$, the performance gap between different interference outage constraints is large, in contrast, at the high correlation, i.e., $\rho_3\left(\rho_4\right) > 0.8$, the performance gap is very small. This is intuitive since the interference outage constraint will not affect the secondary transmission when the CSI of the interference link from secondary transmitter to PR is perfect.

Fig. 8 provides the performance comparison between TAS/MRC scheme and RAS/MRC scheme. As shown in the figure, TAS/MRC scheme always achieves better secrecy outage performance than RAS/MRC scheme for both $N_{\rm A} = N_{\rm R} = N_{\rm B} = N_{\rm E} = 2$ and $N_{\rm A} = N_{\rm R} = N_{\rm B} = N_{\rm E} = 3$. When the CSI is perfect, i.e., $\rho_1 = \rho_2 = 1$, TAS/MRC scheme attains more secrecy diversity gain and secrecy coding gain than RAS/MRC. When the CSI is outdated, i.e., $\rho_1 = \rho_2 = 0.6$, although TAS/MRC scheme can not attain more secrecy diversity gain, it may still worthwhile to choose TAS/MRC scheme over RAS/MRC scheme for it can provide more secrecy coding gain. Specially, when the feedback delay is infinity, i.e., $\rho_1 = \rho_2 = 0$, TAS/MRC scheme reduces to RAS/MRC scheme.

VI. Conclusions

In this paper, we introduced TAS/MRC scheme in dual-hop RaF cognitive MIMO wiretap networks with outdated CSI. In our analysis, the secondary transmitter adopted TAS scheme to choose the antenna that maximizes the received SNR to transmit information, while the secondary receiver and eavesdropper adopted MRC scheme to combine the received signals. We derived new closed-form expression for the secrecy outage probability of dual-hop RaF cognitive MIMO wiretap networks. Further, tractable asymptotic secrecy outage probabilities at high SNR regime were analyzed under two distinct scenarios. From the analysis, we observed that the outdated CSI reduced the secrecy diversity gain of TAS/MRC scheme from $N_{\rm R}\min\left(N_{\rm A}, N_{\rm B}\right)$ to $\min\left(N_{\rm R}, N_{\rm B}\right)$. Finally, our results demonstrate that although TAS/MRC scheme could not attain more secrecy diversity gain for the considered system with outdated CSI compared with RAS/MRC scheme, it could provide more secrecy coding gain.

Appendix A
Proof of Theorem 1

For the derivation of the CDF of $\tilde{\gamma}_1$, we first define $\tilde{X} = \left\|\tilde{\mathbf{h}}_{\rm AR}^{i^*}\right\|^2$, $Y = \left\|\mathbf{h}_{\rm AE}\right\|^2$, $Z = \left|\tilde{h}_{1i*}\right|^2$ in $\tilde{\gamma}_1$, and then we have

$$F_{\tilde{\gamma}_1}\left(R_s\right) = \underbrace{\Pr\left\{\frac{1+P_t\frac{\tilde{X}}{\sigma^2}}{1+P_t\frac{Y}{\sigma^2}} \le 2^{R_s}, P_t \le \kappa_1\frac{Q}{Z}\right\}}_{\Xi_1}$$
$$+\underbrace{\Pr\left\{\frac{1+\kappa_1\frac{Q}{Z}\frac{\tilde{X}}{\sigma^2}}{1+\kappa_1\frac{Q}{Z}\frac{Y}{\sigma^2}} \le 2^{R_s}, \kappa_1\frac{Q}{Z} \le P_t\right\}}_{\Xi_2}. \tag{40}$$

Firstly, we focus on deriving the first summand Ξ_1 in (40) and we have

$$\Xi_1 = F_Z\left(\kappa_1\frac{Q}{Z}\right)\int_0^\infty F_{\tilde{X}}\left(\left(2^{R_s}-1\right)\frac{\sigma^2}{P_t}+2^{R_s}y\right)f_Y\left(y\right)dy. \tag{41}$$

Substituting the probability density function (PDF) of Y and the CDFs of $\tilde{X}$ and Z into (41) and performing some mathematical manipulations, the closed-form expression for Ξ_1 can be derived with the help of [27] as

$$\Xi_1 = \left(1-{\rm e}^{-\frac{\kappa_1\mu}{\lambda_{\rm AP}}}\right)\left\{1-N_{\rm A}\sum_{n=0}^{N_{\rm A}-1}\binom{N_{\rm A}-1}{n}\frac{\left(-1\right)^n\Phi_1}{\Gamma\left(N_{\rm R}\right)}\right.$$
$$\times\sum_{k=0}^{\varphi_1}\binom{\varphi_1}{k}\sum_{m=0}^{N_{\rm R}+k-1}\frac{\Gamma\left(N_{\rm R}+\varphi_1\right)\rho_1^k\left(1-\rho_1\right)^{\varphi_1-k}}{\Gamma\left(m+1\right)\left(1+n\right)^{N_{\rm R}+k-m}\zeta_1^{m+\varphi_1}}$$
$$\times\frac{e^{-\frac{1+n}{\bar{\gamma}_{\rm B}\zeta_1}\left(2^{R_s}-1\right)}}{\left(\bar{\gamma}_{\rm B}\right)^m\left(\bar{\gamma}_{\rm E}\right)^{N_E}\left(N_{\rm E}-1\right)!}\sum_{i=0}^{m}\binom{m}{i}\left(2^{R_s}-1\right)^{m-i}\left(2^{R_s}\right)^i$$
$$\left.\times\left(i+N_{\rm E}-1\right)!\left(\frac{\bar{\gamma}_{\rm E}\bar{\gamma}_{\rm B}\zeta_1}{\bar{\gamma}_{\rm B}\zeta_1+\left(1+n\right)2^{R_s}\bar{\gamma}_{\rm E}}\right)^{i+N_{\rm E}}\right\}. \tag{42}$$

Then, we focus on deriving the second summand Ξ_2 in (40). Observing that RV Z depends on RVs $\tilde{X}$ and Z, thus, Ξ_2 can be derived by solving the following double integral as

$$\Xi_2 = \int_{\frac{\kappa_1 Q}{P_t}}^\infty\underbrace{\int_0^\infty F_{\tilde{X}}\left(\left(2^{R_s}-1\right)\frac{z\sigma^2}{\kappa_1 Q}+2^{R_s}y\right)f_Y\left(y\right)dy}_{\Xi_3}f_Z\left(z\right)dz. \tag{43}$$

Substituting the CDF of $\tilde{X}$ and the PDF of Y into (43) and performing some simple mathematical manipulations, the inner integral Ξ_3 can be derived with the help of [27] as

$$\Xi_3 = 1-N_{\rm A}\sum_{n=0}^{N_{\rm A}-1}\binom{N_{\rm A}-1}{n}\frac{\left(-1\right)^n\Phi_1}{\Gamma\left(N_{\rm R}\right)}$$
$$\times\sum_{k=0}^{\varphi_1}\binom{\varphi_1}{k}\sum_{m=0}^{N_{\rm R}+k-1}\frac{\Gamma\left(N_{\rm R}+\varphi_1\right)\rho_1^k\left(1-\rho_1\right)^{\varphi_1-k}}{\Gamma\left(m+1\right)\left(1+n\right)^{N_{\rm R}+k-m}\zeta_1^{m+\varphi_1}}$$
$$\times\frac{e^{-\frac{1+n}{\kappa_1\mu\bar{\gamma}_{\rm B}\zeta_1}\left(2^{R_s}-1\right)z}}{\left(\kappa_1\mu\bar{\gamma}_{\rm B}\right)^m\left(\kappa_1\mu\bar{\gamma}_{\rm E}\right)^{N_{\rm E}}\left(N_{\rm E}-1\right)!}\sum_{i=0}^{m}\binom{m}{i}\left(\left(2^{R_s}-1\right)z\right)^{m-i}$$
$$\times\left(2^{R_s}\right)^i\left(i+N_{\rm E}-1\right)!\left[\frac{\kappa_1\mu\bar{\gamma}_{\rm E}\bar{\gamma}_{\rm B}\zeta_1}{\bar{\gamma}_{\rm B}\zeta_1+\left(1+n\right)2^{R_s}\bar{\gamma}_{\rm E}}\right]^{i+N_{\rm E}}. \tag{44}$$

Then, inserting (44) and the PDF of Z into (43) and performing some simple mathematical manipulations, we obtain the closed-form expression for Ξ_2 with the help of [27] as

$$\Xi_2 = \exp\left(-\frac{\kappa_1\mu}{\lambda_{\rm AP}}\right)-N_{\rm A}\sum_{n=0}^{N_{\rm A}-1}\binom{N_{\rm A}-1}{n}\frac{\left(-1\right)^n\Phi_1}{\Gamma\left(N_{\rm R}\right)}\sum_{k=0}^{\varphi_1}\binom{\varphi_1}{k}$$
$$\times\sum_{m=0}^{N_{\rm R}+k-1}\frac{\Gamma\left(N_{\rm R}+\varphi_1\right)\rho_1^k\left(1-\rho_1\right)^{\varphi_1-k}\sum_{i=0}^{m}\binom{m}{i}\left(2^{R_s}\right)^i}{\Gamma\left(m+1\right)\left(1+n\right)^{N_{\rm R}+k-m}\zeta_1^{m+\varphi_1}\left(\kappa_1\mu\bar{\gamma}_{\rm B}\right)^m}$$
$$\times\frac{\left(2^{R_s}-1\right)^{m-i}\left(i+N_{\rm E}-1\right)!}{\left(\kappa_1\mu\bar{\gamma}_{\rm E}\right)^{N_{\rm E}}\left(N_{\rm E}-1\right)!\lambda_{\rm AP}}\left[\frac{\kappa_1\mu\bar{\gamma}_{\rm E}\bar{\gamma}_{\rm B}\zeta_1}{\bar{\gamma}_{\rm B}\zeta_1+\left(1+n\right)2^{R_s}\bar{\gamma}_{\rm E}}\right]^{i+N_{\rm E}}$$

$$\times\frac{\left(\kappa_1\mu\bar{\gamma}_{\rm B}\zeta_1\lambda_{\rm AP}\right)^{m-i+1}\Gamma\left(m-i+1,\frac{(1+n)\left(2^{R_s}-1\right)\lambda_{\rm AP}+\zeta_1\kappa_1\mu\bar{\gamma}_{\rm B}}{\zeta_1\bar{\gamma}_{\rm B}\lambda_{\rm AP}}\right)}{\left[(1+n)\left(2^{R_s}-1\right)\lambda_{\rm AP}+\zeta_1\kappa_1\mu\bar{\gamma}_{\rm B}\right]^{m-i+1}}. \tag{45}$$

Finally, substituting (42) and (45) into (40), the CDF of $\tilde{\gamma}_1$ with the outdated CSIs for the secondary transmission links in (19) is derived.

Appendix B
Proof of Corollary 1

When the CSIs for the secondary transmission links are outdated, the CDF of $\tilde{X}$ simplifies to

$$F_{\tilde{X}}(x)\overset{x\to0}{\approx}N_{\rm A}\sum_{n=0}^{N_{\rm A}-1}\binom{N_{\rm A}-1}{n}\frac{(-1)^n\Phi_1}{\Gamma(N_{\rm R})}\times\frac{\Gamma(N_{\rm R}+\varphi_1)(1-\rho_1)^{\varphi_1}}{\Gamma(N_{\rm R}+1)\zeta_1^{N_{\rm R}+\varphi_1}}\left(\frac{x}{\lambda_{\rm AR}}\right)^{N_{\rm R}}. \tag{46}$$

Based to the derivation of (42), substituting (46) and the CDF of $\tilde{X}$ and the PDF of Y into (41), the asymptotic expression of Ξ_1 can be derived as

$$\Xi_1\approx\left(1-{\rm e}^{-\frac{\kappa_1\mu}{\lambda_{\rm AP}}}\right)N_{\rm A}\sum_{n=0}^{N_{\rm A}-1}\binom{N_{\rm A}-1}{n}\times\frac{(-1)^n\Phi_1}{\Gamma(N_{\rm R})}\frac{\Gamma(N_{\rm R}+\varphi_1)(1-\rho_1)^{\varphi_1}}{\Gamma(N_{\rm R}+1)\zeta_1^{N_{\rm R}+\varphi_1}}\times\frac{\sum_{i=0}^{N_{\rm R}}\binom{N_{\rm R}}{i}\left(2^{R_s}-1\right)^{N_{\rm R}-i}\left(2^{R_s}\right)^i(i+N_{\rm E}-1)!(\bar{\gamma}_{\rm E})^i}{(\bar{\gamma}_{\rm B})^{N_{\rm R}}(N_{\rm E}-1)!}. \tag{47}$$

Similarly, we derive the asymptotic expression of Ξ_2 as

$$\Xi_2\approx N_{\rm A}\sum_{n=0}^{N_{\rm A}-1}\binom{N_{\rm A}-1}{n}\frac{(-1)^n\Phi_1}{\Gamma(N_{\rm R})}\frac{\Gamma(N_{\rm R}+\varphi_1)(1-\rho_1)^{\varphi_1}}{\Gamma(N_{\rm R}+1)\zeta_1^{N_{\rm R}+\varphi_1}}\times\sum_{i=0}^{N_{\rm R}}\binom{N_{\rm R}}{i}\left(2^{R_s}-1\right)^{N_{\rm R}-i}\left(2^{R_s}\right)^i(i+N_{\rm E}-1)!\times\frac{(\bar{\gamma}_{\rm E})^i(\lambda_{\rm AP})^{N_{\rm R}}\Gamma\left(N_{\rm R}+1,\frac{\kappa_1\mu}{\lambda_{\rm AP}}\right)}{(\kappa_1\mu\bar{\gamma}_{\rm B})^{N_{\rm R}}(N_{\rm E}-1)!}. \tag{48}$$

To this end, pulling (47) and (48) together, the asymptotic CDF of $\tilde{\gamma}_1$ with the outdated CSIs for the secondary transmission links is given by

$$F_{\tilde{\gamma}_1}(R_s)\approx N_{\rm A}\sum_{n=0}^{N_{\rm A}-1}\binom{N_{\rm A}-1}{n}\frac{(-1)^n\Phi_1}{\Gamma(N_{\rm R})}\frac{\Gamma(N_{\rm R}+\varphi_1)(1-\rho_1)^{\varphi_1}}{\Gamma(N_{\rm R}+1)\zeta_1^{N_{\rm R}+\varphi_1}}\times\sum_{i=0}^{N_{\rm R}}\binom{N_{\rm R}}{i}\left(2^{R_s}-1\right)^{N_{\rm R}-i}\left(2^{R_s}\right)^i(i+N_{\rm E}-1)!(\bar{\gamma}_{\rm E})^i\times\left\{\frac{1-{\rm e}^{-\frac{\kappa_1\mu}{\lambda_{\rm AP}}}}{(\bar{\gamma}_{\rm B})^{N_{\rm R}}(N_{\rm E}-1)!}+\frac{(\lambda_{\rm AP})^{N_{\rm R}}\Gamma\left(N_{\rm R}+1,\frac{\kappa_1\mu}{\lambda_{\rm AP}}\right)}{(\kappa_1\mu\bar{\gamma}_{\rm B})^{N_{\rm R}}(N_{\rm E}-1)!}\right\}. \tag{49}$$

By interchanging the parameters in Eq. (49), the asymptotic CDF of $\tilde{\gamma}_2$ with the outdated CSIs for the secondary transmission links can be easily derived as

$$F_{\tilde{\gamma}_2}(R_s)\approx N_{\rm R}\sum_{n=0}^{N_{\rm R}-1}\binom{N_{\rm R}-1}{n}\frac{(-1)^n\Phi_2}{\Gamma(N_{\rm B})}\frac{\Gamma(N_{\rm B}+\varphi_2)(1-\rho_2)^{\varphi_2}}{\Gamma(N_{\rm B}+1)\zeta_2^{N_{\rm B}+\varphi_2}}\times\sum_{i=0}^{N_{\rm B}}\binom{N_{\rm B}}{i}\left(2^{R_s}-1\right)^{N_{\rm B}-i}\left(2^{R_s}\right)^i(i+N_{\rm E}-1)!(\beta\bar{\gamma}_{\rm E})^i\times\left\{\frac{1-{\rm e}^{-\frac{\kappa_2\mu}{\lambda_{\rm RP}}}}{(\eta\bar{\gamma}_{\rm B})^{N_{\rm B}}(N_{\rm E}-1)!}+\frac{(\lambda_{\rm RP})^{N_{\rm B}}\Gamma\left(N_{\rm B}+1,\frac{\kappa_2\mu}{\lambda_{\rm RP}}\right)}{(\kappa_2\mu\eta\bar{\gamma}_{\rm B})^{N_{\rm B}}(N_{\rm E}-1)!}\right\}. \tag{50}$$

Finally, substituting (49) and (50) into (13), the asymptotic secrecy outage probability of the considered system with the outdated CSIs for the secondary transmission links is derived.

Appendix C
Proof of Corollary 2

When the CSIs for the secondary transmission links are perfect, the CDF of X simplifies to

$$F_X(x)\overset{x\to0}{\approx}\frac{1}{(N_{\rm R}!)^{N_{\rm A}}}\left(\frac{x}{\lambda_{\rm AR}}\right)^{N_{\rm A}N_{\rm R}}. \tag{51}$$

With the help of Appendix B, we respective derive the asymptotic expressions of Ξ_1 and Ξ_2 as

$$\Xi_1\approx\frac{1-{\rm e}^{-\frac{\kappa_1\mu}{\lambda_{\rm AP}}}}{(N_{\rm R}!)^{N_{\rm A}}}\sum_{i=0}^{N_{\rm A}N_{\rm R}}\binom{N_{\rm A}N_{\rm R}}{i}\left(2^{R_s}-1\right)^{N_{\rm A}N_{\rm R}-i}\times\frac{\left(2^{R_s}\right)^i(i+N_{\rm E}-1)!(\bar{\gamma}_{\rm E})^i}{(\bar{\gamma}_{\rm B})^{N_{\rm A}N_{\rm R}}(N_{\rm E}-1)!}, \tag{52}$$

and

$$\Xi_2\approx\sum_{i=0}^{N_{\rm A}N_{\rm R}}\binom{N_{\rm A}N_{\rm R}}{i}\left(2^{R_s}-1\right)^{N_{\rm A}N_{\rm R}-i}(i+N_{\rm E}-1)!\times\left(2^{R_s}\right)^i\frac{(\bar{\gamma}_{\rm E})^i(\lambda_{\rm AP})^{N_{\rm A}N_{\rm R}}\Gamma\left(N_{\rm A}N_{\rm R}+1,\frac{\kappa_1\mu}{\lambda_{\rm AP}}\right)}{(N_{\rm R}!)^{N_{\rm A}}(\kappa_1\mu\bar{\gamma}_{\rm B})^{N_{\rm A}N_{\rm R}}(N_{\rm E}-1)!}. \tag{53}$$

Then, pulling (52) and (53) together, the asymptotic CDF of γ_1 with the perfect CSIs for the secondary transmission links is given by

$$F_{\gamma_1}(R_s)\approx\frac{1}{(N_{\rm R}!)^{N_{\rm A}}}\sum_{i=0}^{N_{\rm A}N_{\rm R}}\binom{N_{\rm A}N_{\rm R}}{i}\left(2^{R_s}-1\right)^{N_{\rm A}N_{\rm R}-i}\times\left(2^{R_s}\right)^i(i+N_{\rm E}-1)!(\bar{\gamma}_{\rm E})^i\frac{1}{(\bar{\gamma}_{\rm B})^{N_{\rm A}N_{\rm R}}(N_{\rm E}-1)!}\times\left[1-{\rm e}^{-\frac{\kappa_1\mu}{\lambda_{\rm AP}}}+\left(\frac{\lambda_{\rm AP}}{\kappa_1\mu}\right)^{N_{\rm A}N_{\rm R}}\Gamma\left(N_{\rm A}N_{\rm R}+1,\frac{\kappa_1\mu}{\lambda_{\rm AP}}\right)\right]. \tag{54}$$

By interchanging the parameters in Eq. (54), the asymptotic CDF of γ_2 with the perfect CSIs for the secondary transmission links can be easily derived as

$$\begin{aligned}
F_{\gamma_2}\left(R_s\right) \approx & \frac{1}{\left(N_{\mathrm{B}}!\right)^{N_{\mathrm{R}}}} \sum_{i=0}^{N_{\mathrm{R}}N_{\mathrm{B}}} \binom{N_{\mathrm{R}}N_{\mathrm{B}}}{i} \left(2^{R_s}-1\right)^{N_{\mathrm{R}}N_{\mathrm{B}}-i} \\
& \times \left(2^{R_s}\right)^{i} \left(i+N_{\mathrm{E}}-1\right)! (\beta\bar{\gamma}_{\mathrm{E}})^{i} \frac{1}{\left(\eta\bar{\gamma}_{\mathrm{B}}\right)^{N_{\mathrm{R}}N_{\mathrm{B}}} \left(N_{\mathrm{E}}-1\right)!} \\
& \times \left[1-\mathrm{e}^{-\frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}}+\left(\frac{\lambda_{\mathrm{RP}}}{\kappa_2\mu}\right)^{N_{\mathrm{R}}N_{\mathrm{B}}} \Gamma\left(N_{\mathrm{R}}N_{\mathrm{B}}+1, \frac{\kappa_2\mu}{\lambda_{\mathrm{RP}}}\right)\right]. \qquad (55)
\end{aligned}$$

To this end, substituting (54) and (55) into (21), the asymptotic secrecy outage probability of the considered system with the perfect CSIs for the secondary transmission links can be derived.

Appendix D
Proof of Corollary 3

Similar to (40), the CDF of $\tilde{\gamma}_1$ with the outdated CSIs for the secondary transmission links can be expressed as

$$\begin{aligned}
F_{\tilde{\gamma}_1}\left(R_s\right) = & \underbrace{\Pr\left\{\frac{1+P_t\frac{\tilde{X}}{\sigma^2}}{1+P_t\frac{Y}{\sigma^2}} \leq 2^{R_s}, P_t \leq \kappa_1\frac{Q}{Z}\right\}}_{\Xi_4} \\
& + \underbrace{\Pr\left\{\frac{1+\kappa_1\frac{Q}{Z}\frac{\tilde{X}}{\sigma^2}}{1+\kappa_1\frac{Q}{Z}\frac{Y}{\sigma^2}} \leq 2^{R_s}, \kappa_1\frac{Q}{Z} \leq P_t\right\}}_{\Xi_5}. \qquad (56)
\end{aligned}$$

When $\bar{\gamma}_{\mathrm{B}} \to \infty$ and $\bar{\gamma}_{\mathrm{E}} \to \infty$, Ξ_4 and Ξ_5 can be derived, after performing some simple algebraic manipulations, as

$$\begin{aligned}
\Xi_4 = & \left(1-\mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}\right)\left\{1-N_{\mathrm{A}}\sum_{n=0}^{N_{\mathrm{A}}-1}\binom{N_{\mathrm{A}}-1}{n}\frac{(-1)^n\Phi_1}{\Gamma\left(N_{\mathrm{R}}\right)}\right. \\
& \times \sum_{k=0}^{\varphi_1}\binom{\varphi_1}{k}\sum_{m=0}^{N_{\mathrm{R}}+k-1}\frac{\Gamma\left(N_{\mathrm{R}}+\varphi_1\right)\rho_1^k(1-\rho_1)^{\varphi_1-k}}{\Gamma\left(m+1\right)\left(1+n\right)^{N_{\mathrm{R}}+k-m}\zeta_1^{m+\varphi_1}} \\
& \left.\times\frac{\left(2^{R_s}\right)^m\left(m+N_{\mathrm{E}}-1\right)!}{\left(\bar{\gamma}_{\mathrm{B}}\right)^m\left(\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}}\left(N_{\mathrm{E}}-1\right)!}\left[\frac{\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}\zeta_1}{\bar{\gamma}_{\mathrm{B}}\zeta_1+\left(1+n\right)2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right]^{m+N_{\mathrm{E}}}\right\}, \qquad (57)
\end{aligned}$$

and

$$\begin{aligned}
\Xi_5 = & \mathrm{e}^{-\frac{\kappa_1\mu}{\lambda_{\mathrm{AP}}}}-N_{\mathrm{A}}\sum_{n=0}^{N_{\mathrm{A}}-1}\binom{N_{\mathrm{A}}-1}{n}\frac{(-1)^n\Phi_1}{\Gamma\left(N_{\mathrm{R}}\right)} \\
& \times \sum_{k=0}^{\varphi_1}\binom{\varphi_1}{k}\sum_{m=0}^{N_{\mathrm{R}}+k-1}\frac{\Gamma\left(N_{\mathrm{R}}+\varphi_1\right)\rho_1^k(1-\rho_1)^{\varphi_1-k}}{\Gamma\left(m+1\right)\left(1+n\right)^{N_{\mathrm{R}}+k-m}\zeta_1^{m+\varphi_1}} \\
& \times\frac{\left(2^{R_s}\right)^m\left(m+N_{\mathrm{E}}-1\right)!}{\left(\bar{\gamma}_{\mathrm{B}}\right)^m\left(\bar{\gamma}_{\mathrm{E}}\right)^{N_{\mathrm{E}}}\left(N_{\mathrm{E}}-1\right)!}\left[\frac{\bar{\gamma}_{\mathrm{E}}\bar{\gamma}_{\mathrm{B}}\zeta_1}{\bar{\gamma}_{\mathrm{B}}\zeta_1+\left(1+n\right)2^{R_s}\bar{\gamma}_{\mathrm{E}}}\right]^{m+N_{\mathrm{E}}} \\
& \times\frac{\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}\Gamma\left(1,\frac{(1+n)\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}{\zeta_1\lambda_{\mathrm{AP}}\bar{\gamma}_{\mathrm{B}}}\right)}{\left(1+n\right)\left(2^{R_s}-1\right)\lambda_{\mathrm{AP}}+\zeta_1\kappa_1\mu\bar{\gamma}_{\mathrm{B}}}. \qquad (58)
\end{aligned}$$

To this end, substituting (57) and (58) into (56), we obtain the asymptotic CDF of $\tilde{\gamma}_1$. By interchanging the parameters in Eq. (56), the asymptotic CDF of $\tilde{\gamma}_2$ of the considered system can be easily derived. Finally, pulling the asymptotic CDFs of $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ together, the asymptotic secrecy outage probability of the considered system can be derived.

References

[1] J. Mitola, “Cognitive radio: An integrated agent architecture for software defined radio,” *Ph. D. dissertation,* Royal Inst. Technol. (KTH), Stockholm, Sweden, Dec. 2000.

[2] J. Lee, H. Wang, J. G. Andrews, and D. Hong, “Outage probability of cognitive relay networks with interference constraints,” *IEEE Trans. Wireless Commun.,* vol. 10, no. 2, pp. 390-395, Feb. 2011.

[3] Y. Deng, M. Elkashlan, N. Yang, P. L. Yeoh, and R. K. Mallik, “Impact of primary network on secondary network with generalized selection combining,” *IEEE Trans. Veh. Technol.,* vol. 64, no. 7, pp. 3280-3285, Jul. 2015.

[4] B. Zhong, Z. Zhang, X. Zhang, J. Wang, and K. Long, “Partial relay selection with fixed-gain relays and outdated CSI in underlay cognitive networks”, *IEEE Trans. Veh. Technol.,* vol. 62, no. 9, pp. 4696-4701, Nov. 2013.

[5] Y. Huang, F. S. Al-Qahtani, C. Zhong, Q. Wu, J. Wang, and H. M. Alnuweiri, “Cognitive MIMO relaying networks with primary user’s interference and outdated channel state information,” *IEEE Trans. Commun.*, vol. 62, no. 12, pp. 4241-4254, Dec. 2014.

[6] H. M. Wang, F. Liu, and M. Yang. “Joint cooperative beamforming, jamming and power allocation to secure AF relay systems”, *IEEE Trans. Veh. Technol.,* vol. 64, no. 10, pp. 4893-4898, Oct. 2015.

[7] L. J. Rodriguez, N. H. Tran, T. Q. Duong, T. Le-Ngoc, M. Elkashlan, and S. Shetty, “Physical layer security in wireless cooperative relay networks: state of the art and beyond,” *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 32-39, Mar. 2015.

[8] A. D. Wyner, “The wire-tap channel,” *Bell Syst. Tech. J.,* vol. 54, no. 8, pp.1355-1367, Oct. 1975.

[9] T. Q. Duong, T. T. Duy, M. Elkashlan, N. H. Tran, and O. A. Dobre, “Secured cooperative cognitive radio networks with relay selection,” *in Proc. of IEEE Globecom,* 2014, Austin, US, pp. 3074-3079.

[10] Y. Zou, B. Champagne, W.-P. Zhu, and L. Hanzo, “Relay-selection improves the security-reliability trade-off in cognitive radio Systems,” *IEEE Trans. Commun.,* vol. 63, no. 1, pp. 215-228, Jan. 2015.

[11] Y. Liu, L. Wang, T. T. Duy, M. Elkashlan, and T. Q. Duong, “Relay selection for security enhancement in cognitive relay networks, ” *IEEE Commun. Lett.,* vol. 4, no. 1, pp. 46-49, Feb. 2015.

[12] N. B. Mehta, S. Kashyap, and A. F. Molisch, “Antenna selection in LTE: From motivation to specification,” *IEEE Commun. Mag.*, vol. 50,no. 10, pp. 144-150, Oct. 2012.

[13] M. Elkashlan, L. Wang, T. Q. Duong, G. K. Karagiannidis, and A. Nallanathan, “On the security of cognitive radio networks,” *IEEE Trans. Veh. Technol.*, vol. 64, no. 8, pp. 3790-3795, Aug. 2015.

[14] T. Zhang, Y. Cai, Y. Huang, C. Zhong, W. Yang, and G. K. Karagiannidis, “Secure transmission in cognitive wiretap networks,” *in Proc. of IEEE VTC-Spring* 2016, Nanjing, China.

[15] H. Zhao, Y. Tan, G. Pan, Y. Chen, and N. Yang, “Secrecy outage on transmit antenna selection/maximal ratio combining in MIMO cognitive radio networks,” *IEEE Trans. Veh. Technol.* to appear, 2016, DOI10.1109/TVT.2016.2529704.

[16] T. Zhang, Y. Huang, Y. Cai, and W. Yang, “Secure transmission in spectrum sharing relaying networks with multiple antennas,” *IEEE Commun. Lett.,* vol. 20, no. 4, pp. 824-827, Apr. 2016.

[17] O. O. Koyluoglu, C. E. Koksal, and H. El Gamal, “On secrecy capacity scaling in wireless networks,” *IEEE Trans. Inf. Theory,* vol. 58, no. 5, pp. 3000-3015, May 2012.

[18] C. Cai, Y. Cai, W. Yang, and W. Yang, “Secure connectivity using randomize-and-forward strategy in cooperative wireless networks,” *IEEE Commun. Lett.,* vol. 17, no. 7, pp. 1340-1343, Jul. 2013.

[19] C. Cai, Y. Cai, X. Zhou, W. Yang, and W. Yang, “When does relay transmission give a more secure connection in wireless ad hoc networks,” *IEEE Trans. Inf. Forensics Security,* vol. 9, no. 4, pp. 624-632, Apr. 2014.

[20] J. Mo, M. Tao, and Y. Liu, “Relay placement for physical layer security: A secure connection perspective,” *IEEE Commun. Lett.,* vol. 16, no. 6, pp. 878-881, Jun. 2012.

[21] Y. Ma, D. Zhang, A. Leith, and Z. Wang, “Error performance of transmit beamforming with delayed and limited feedback,” *IEEE Trans. Wireless Commun.,* vol. 8, no. 3, pp. 1164-1170, Mar. 2009.

[22] Y. Huang, F. S. Al-Qahtani, T. Q. Duong, and J. Wang, “Secure transmission in MIMO wiretap channels using general-order transmit antenna selection with outdated CSI,” *IEEE Trans. Commun.*, vol. 63, no.8, pp. 2959-2971, Aug. 2015.

[23] H. A. Suraweera, P. J. Smith, and M. Shafi, “Capacity limits and performance analysis of cognitive radio with imperfect channel knowledge,” *IEEE Trans Veh. Technol.,* vol. 59, no. 4, pp. 1811-1822, May 2010.

[24] H. Kim, H. Wang, S. Lim, and D. Hong, "On the impact of outdated channel information on the capacity of secondary user in spectrum sharing environments," *IEEE Trans. Wireless Commun.,* vol. 11, no. 1, pp. 284-295, Jan. 2012.

[25] Q. Wu, Y. Huang, J. Wang, and Y. Cheng, "Effective capacity of cognitive radio systems with GSC diversity under imperfect channel knowledge," *IEEE Commun. Lett.,* vol. 16, no. 11, pp. 1792-1795, Nov. 2012.

[26] A. H. Nuttall, "Some integrals involving the Q-function," Naval Underwater Syst. Cent., New London, CT, USA, Tech. Rep. 4297, Apr. 1971.

[27] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 7th ed. San Diego, CA: Academic, 2007.

Tao Zhang (S'13) received his B.S. degree in Communication Engineering from the College of Communications Engineering, PLA University of Science and Technology, Nanjing, China, in 2011. He is currently pursuing for the Ph.D. degree in Communications and Information Systems at the College of Communications Engineering, PLA University of Science and Technology, Nanjing, China. His current research interest includes cooperative communications, wireless sensor networks, physical layer security, and cognitive radio systems.

Yueming Cai (M'05-SM'12) received his B.S. degree in Physics from Xiamen University, Xiamen, China in 1982, the M.S. degree in Micro-electronics Engineering and the Ph.D. degree in Communications and Information Systems both from Southeast University, Nanjing, China in 1988 and 1996, respectively. His current research interests include MIMO systems, OFDM systems, signal processing in communications, cooperative communications and wireless sensor networks.

Yuzhen Huang (S'12-M'16) received his B.S. degree in Communications Engineering, and Ph.D. degree in Communications and Information Systems from College of Communications Engineering, PLA University of Science and Technology, in 2008 and 2013 respectively. He has been with College of Communications Engineering, PLA University of Science and Technology since 2013, and currently as an Assistant Professor. Since 2016, he has been a Post-Doctoral Research Associate with the School of Information and Communication, Beijing University of Posts and Telecommunications, Beijing. His research interests focus on channel coding, MIMO communications systems, cooperative communications, physical layer security, and cognitive radio systems. He currently serves as an Associate Editor of KSII Transactions on Internet and Information Systems. He and his coauthors have been awarded a Best Paper Award at the WCSP 2013. He received an IEEE Communications Letters exemplary reviewer certificate for 2014.

Trung Q. Duong (S'05-M'12-SM'13) received his Ph.D. degree in Telecommunications Systems from Blekinge Institute of Technology (BTH), Sweden in 2012. Since 2013, he has joined Queen's University Belfast, UK as a Lecturer (Assistant Professor). His current research interests include physical layer security, energy-harvesting communications, cognitive relay networks. He is the author or co-author of 190 technical papers published in scientific journals and presented at international conferences.

Dr. Duong currently serves as an Editor for the IEEE Transactions on Communications, IEEE Communications Letters, IET Communications, Wiley Transactions on Emerging Telecommunications Technologies, and Electronics Letters. He has also served as the Guest Editor of the special issue on some major journals including IEEE Journal in Selected Areas on Communications, IET Communications, IEEE Wireless Communications Magazine, IEEE Communications Magazine, EURASIP Journal on Wireless Communications and Networking, EURASIP Journal on Advances Signal Processing. He was awarded the Best Paper Award at the IEEE Vehicular Technology Conference (VTC-Spring) in 2013, IEEE International Conference on Communications (ICC) 2014. He is the recipient of prestigious Royal Academy of Engineering Research Fellowship (2015-2020).

Weiwei Yang (S'08-M'12) received his B.S., M.S., and Ph.D. degrees from College of Communications Engineering, PLA University of Science and Technology, Nanjing, China, in 2003, 2006, and 2011, respectively. His research interests include orthogonal frequency domain multiplexing systems, signal processing in communications, cooperative communications, wireless sensor networks and network security.