Secure Transmission in Cognitive Radio Networks using Full-duplex Technique with Outdated CSI

Zhihui Shang*, Tao Zhang*, Hao Wu, Xiaoqiang Qiao and Liwei Tao

Abstract
In this paper, we investigate the effects of the outdated channel state information (CSI) on the secrecy performance of an underlay spectrum sharing cognitive radio networks (CRNs) with full-duplex (FD) receivers. Legitimate destination node (Bob) acts as a FD node, transmitting interference signals to a passive eavesdropping node (Eve) while receiving signals. To exploit the benefits of collaborative zero-forcing beamforming and FD technologies, transmit antenna selection-maximal-ratio combining-zero forcing beamforming/maximal-ratio transmission-selection combining-zero forcing beamforming (TAS-MRC-ZFB/MRT-SC-ZFB) scheme is considered at the secondary user transmission link with the outdated CSI and collaborative ZFB is adopted at FD destination node, which tries to improve the transmission efficiency of our considered CRNs. Specifically, in order to evaluate the proposed scheme, the derivation of analytical expression in exact and the high asymptotic closed-form expressions of secrecy outage probability (SOP) are provided of the considered network with and without feedback delay of the CSI. Furthermore, the impact of delay on the second user transmission and interference links of the primary user (PU) node is investigated. The results reveal that outdated CSI of secondary user transmission and collaborative ZFB channels deteriorates the SOP, and the outdated CSI between PU and secondary user (SU) will affect the power margin factors for the secondary transmitter. Furthermore, we also study the effects of different system parameters on the secrecy diversity order and secrecy array gain. The proposed scheme is compared with the existing TAS-MRC/TAS-MRC scheme to verify the improvement of system performance. Finally, Monte Carlo simulations verify the correctness of our theoretical analysis.

Keywords: Cognitive radio network; physical layer security; full-duplex; multiple antennas relay; secrecy outage probability; outdated CSI

1 Introduction
With the increasing demand for wireless communication equipment and services, spectrum resources are increasingly scarce. Cognitive radio networks (CRNs) has attracted the attention of a large number of researchers in the past decade, and it can effectively improve the scarcity and waste of spectrum resources. There are three kinds of CRNs: interweave, underlay and overlay [1]-[4]. In CRNs, unauthorized secondary users (SUs) can directly access the spectrum allocated by the primary users (PUs) in the same frequency bands and spectrum idle, in which they cannot affect the quality of service (QoS) of the PUs. Compared to the above three spectrum sharing method, the SUs CRNs can coexist with the PUs under an underlay scheme, as long as the interference from the SUs is below a specified threshold. The sharing of spectrum resources is more likely to lead to malicious attackers.
In order to solve the above-mentioned problem, the physical layer security (PLS) research under the CRNs has entered people’s vision in recent years, which can strengthen the secure transmission of wireless communications [5]. The introduction of PLS effectively overcomes the vulnerabilities of traditional higher-layer cryptography [6]. Thus, in this work, we will primarily focus on the physical layer secrecy performance of an underlay CRN. In an effort to further improve PLS of wireless transmissions, several techniques were proposed, such as collaborative zero-forcing beamforming (ZFB) [7]-[9], cooperative relays [4], [10]-[11] and full-duplex (FD) techniques [12]-[13]. First, for a CRN, beamforming can be used not only to eliminate the interference from the secondary transmitter to the PU, but also to improve the secrecy performance of the system due to the more concentrated power to the secondary destination. In [9], the authors proposed a zero-forcing jamming scheme to improve the secrecy performance of the wireless network. In [14], the joint optimization of the information and jamming noise beamforming for secrecy rate maximization of the secondary system was analyzed. A zero forcing-based non-iterative algorithm of the iterative algorithm is proposed to study the secure beamforming design for the two-way CRNs [8]. The authors designed and proposed a multiple-input-multi-output (MIMO)-CRNs transmission scheme between the PU and the SU to improve the PLS by using a bi-directional zero-forcing beamformer [15]. In [16], the authors proposed a ZFB technology to secure communications in a two-cell MIMO-NOMA based CRNs, and this method can maximize the total secrecy rate in the lack of conventional transceiver beamforming techniques. Second, the cooperative relay system extends the communication distance and improves the transmission rate through the cooperation between the relay nodes, and has broad application prospects. The author proposed non-energy aware relay selection and energy aware relay selection schemes in CRNs to protect source node transmission from multiple cooperative relays to destination node from leakage to multiple eavesdroppers, which could improve the secrecy performance of system [17]. The authors considered a power allocation method in the cooperative cognitive communication system, which mainly implemented the covert communication problem and improved the secrecy performance of the system [18]. In [19], the authors proposed a new idea of hiding information at PLS to securely transmit confidential cognitive wireless data in a cooperative relay system. Third, the SU base station can use FD technology to receive information from other nodes while transmitting artificial interference signals to prevent eavesdropping by eavesdroppers. The secrecy performance for a new collaboration interference transmission scheme (TAS/MRC/ZFB) for overlay FD operative was analyzed in [20]. In [21], the authors analyzed the secrecy performance for MRC-ZFB/MRT-SC-ZFB scheme with FD receiver underlay CRNs of perfect channel state information (CSI) over Rayleigh fading channels. The effects of perfect CSI on the system performance have been investigated in collaborative zero-forcing beamforming [8], [14-16], cooperative relays network [17-19], and the FD technique [20-21]. Perfect CSI was assumed in these aforementioned works and neglected the impact of channel fading severity on the secrecy performance of the CRNs. In the practical scenario, the perfect CSI is challenging to obtain and the outdated CSI is easy to deteriorate the QoS of the PUs and decrease the secrecy performance of the SUs.
Motivated by this, in our paper, we will analyze the effects of outdated CSI on the secrecy performance of an underlay spectrum sharing CRNs with FD receivers, in which a multi-antenna SU source node (Alice) uses a multi-antenna cooperative relay node (Relay) to send available signals to a multi-antenna legitimate destination node (Bob) for preventing information leakage to an eavesdropper (Eve), while the Eve simultaneously eavesdrops the confidential information from Alice and Relay. The randomize-and-forward (RaF) relay outperforms decode-and-forward (DF) relay in information processing, which has been studied in our previous work [12]. We use the RaF relay forwarding protocol again, which is widely used in the research of CRNs in the past years. In order to improve the transmission quality, the transmit antenna selection-maximal-ratio combining-zero forcing beamforming/maximal-ratio transmission-selection combining-zero forcing beamforming (TAS-MRC-ZFB/MRT-SC-ZFB) scheme with FD receivers is designed in our paper. In the first time-slot (TAS-MRC-ZFB phase), Alice selects the $i$-th best antenna among $N_A$ to send signals to $N_R$ antennas Relay node and Relay adopts MRC scheme to receive the information forwarded from Alice and at the same time, the FD $N_B$ antennas Bob node uses the ZFB scheme to transmit interference signals to reduce the illegal wiretapping of Eve. The FD Bob is designed to direct its beam to the Eve and null the Relay and PU nodes. In the second time-slot (MRT-SC-ZFB phase), Relay node transfers signals to the destination by MRT, the FD Bob selects the $j$-th best antenna among $N_B$ to receive the information from Relay and the remaining $N_B - 1$ antennas also use the ZFB scheme to transmit interference signals to reduce the illegal wiretapping of Eve. The FD Bob is designed to direct its beam to the Eve and null the PU node. Moreover, considered the time delay of feedback, the received CSI at the transmitter (Alice, Relay and Bob) may be outdated, which may in turn deteriorate the performance of TAS-MRC-ZFB/MRT-SC-ZFB scheme. In addition, our paper considers that the design of beamforming for information signals will also be affected by the time delay of feedback. The contributions of our paper are summarized as follows:

- We propose the TAS-MRC-ZFB/MRT-SC-ZFB scheme with outdated CSI. At Bob, due to the feedback delay between Bob and Eve at different time-slots, whose channel coefficient values are used for designing the collaborative transmit ZFB. The beamforming vectors of the information signals are designed at FD Bob node such that they maximize the achievable secrecy performance of the system. We derive an exact expression for the secrecy outage probability (SOP) of the TAS-MRC-ZFB/MRT-SC-ZFB scheme underlay CRNs with outdated CSI and the theory analysis is verified by simulations.

- We derive closed-form analytical expressions for the asymptotic SOPs while assuming outdated CSI of the SU transmission link and the secrecy array gain and the secrecy diversity order are obtained as well as to investigate the impacts of the key system parameters on the secrecy performance of the considered networks, such as the number of antennas at Alice, Relay and Bob, the channel correlation coefficient, the power marginal factor, the PU interference temperature $Q$ and the pre-selected outage probability $P_0$ at Alice and Relay.
• Relative to [10-12] and [21-23], the outdated CSI of CRNs is considered in our work. Moreover, we investigate two different practical diversity combining techniques (TAS-MRC-ZFB and MRT-SC-ZFB) at Relay and Bob as well. Relative to [21], the underlay CRNs with outdated CSI is considered in our work and the relationship for the two different combining schemes is analyzed. The proposed scheme is compared with the existing TAS-MRC/TAS-MRC scheme verify the effectiveness of the proposed scheme in improving system performance. It can be found that the secrecy performance of the considered networks is strongly influenced by the outdated CSI, because the outdated CSI will influence the beamforming design. Besides, the proposed scheme can mitigate the interference effectively with outdated CSI compared to the existing TAS-MRC/TAS-MRC scheme.

2 Methods
The paper is organized as follows. Section 3. presents the system and channel model. Section 4 provides the closed-form expressions for SOP with outdated CSI. Section 5 shows the asymptotic SOP analysis. The results and discussion are presented in Section 6. Finally, conclusions are concluded in Section 7.

3 System and Channel Model

3.1 System Model
We consider an underlay RaF spectrum sharing CRNs with FD receivers as illustrated in Fig. 1. Our designed model consists of a $N_A$ antennas source node (Alice), a $N_R$ antennas RaF relay node (Relay) and a $N_B$ antennas legitimate destination node (Bob), and a PU receiver node and a passive eavesdropper node (Eve) equipped with a single antenna. In our paper, we use the following assumptions: a) the direct link does not exist in our system model due to the long distance between Alice and Bob and the severe shadowing effect. b) Since the secondary user transmission link is far from the PU transmitter, the interference from the PU transmitter is ignored. c) For simplicity, both main and secondary user transmission channels are assumed to be independent and experience quasi-static independent and non-identical Rayleigh fading, and remain unchanged during each time-slot but vary independently from different time-slots. As in [4], the corresponding CSI of Alice to Eve and Relay to Eve are unknown at Alice and Relay, respectively.

The data transmission process is accomplished over two time-slots. In the first time-slot Alice→Relay, Alice selects the $i$-th best antenna among $N_A$ antennas according to the channel conditions between the Alice and Relay. The FD Bob is designed to direct its beam to the Eve and null the Relay and PU nodes. The Bob utilizes the collaborative transmit beamforming to transmit the signal in order to minimize the interference caused to the Relay and PU. The receiver at Relay node employs the TAS-MRC diversity reception. The Relay considered here is RaF relay because RaF relay outperforms DF relay in information processing [12]. In the second time-slot Relay→Bob, Bob selects the $j$-th antenna among $N_B$ to receive the signals from Relay and the remaining $N_B - 1$ antennas transmit beamforming to transmit the signal in order to minimize the interference caused to the PU. The receiver at Bob node employs the MRT-SC diversity reception. To ensure the
QoS for the PU, the transmit power of the Alice and Relay must be kept below a certain threshold so that the interference to the primary user is no greater than the interference temperature $Q$. $h_{MN}$ represents the channel coefficient of any two nodes, for $M, N \in \{A, R, B, E, P\}$, and follows a zero-mean complex Gaussian-random variables (CG-RV) with variance $\lambda_{MN}$, such that $h_{MN} \sim CN(0, \lambda_{MN})$.

3.2 Mathematical Model

In our paper, we define $\tilde{h}_{MN}$ as a delayed version of $h_{MN}$, and the relation can be modeled as $\tilde{h}_{MN}^\tau = \rho_d h_{MN}^\tau + \sqrt{1-\rho_d^2} e_{MN}$, where $MN \in \{A \rightarrow R, R \rightarrow B, B \rightarrow E\}$, and follows a zero-mean complex Gaussian-random variables (CG-RV) with variance $\lambda_{MN}$, such that $h_{MN}^\tau \sim CN(0, \lambda_{MN})$.

3.2.1 In the Alice→Relay link

The TAS-MRC-ZFB scheme is designed at Relay and Bob by using the outdated CSI. The instantaneous CSI for $h_{iAR}$ is available at Relay [26], but $\tilde{h}_{iAR}^\tau$ is different from $h_{iAR}$ due to the outdated CSI. Due to the existence of estimation error, the feedback error model of legitimate channel estimation at Relay can be formulated as [27-29]

$$\tilde{h}_{iAR}^\tau = \rho_1 h_{iAR} + \sqrt{1-\rho_1^2} e_{RR}.$$  

where $h_{iAR}$ denotes the estimated channel, $e_{RR} \sim CN\left(0, \sigma_{RR}^2 \text{I}_{N_R}\right)$ represents the channel estimation error vector, and $\rho_1 \in [0, 1]$ is the correlation coefficient between $h_{iAR}$ and $\tilde{h}_{iAR}^\tau$, which is an $N_R \times 1$ channel link vector between the $i$-th transmit antenna at Alice and Relay with zero mean and variance $\lambda_{AR}$. The index of $i$ is formulated as $i = \arg \max_{1 \leq i \leq N_A} \|h_{iAR}\|^2$. The larger $\rho_1$ yields better channel estimation accuracy, and $\rho_1 = 1$ means that the source obtains the perfect CSI of legitimate channel.

ZFB Collaborative Design at Bob: The FD Bob is designed to direct its beam to the Eve and null the Relay and PU nodes. Due to the feedback delay between Bob and Eve, the CSI of the $h_{BE1}$, whose value is available at Bob and used for designing the collaborative transmit ZFB weight $\tilde{w}_{ZF}$, is assumed to be outdated, and the actual channel is denoted by $\tilde{h}_{BE1}$. $h_{BE1}$ and $h_{BE1}$ denote the $N_B \times 1$ channel between Bob and Eve with zero mean and variance $\lambda_{BE1}$. The designed collaborative beamforming should meet two requirements: (i) it can directly point to the Eve; (ii) simultaneously, it causes no interference to Relay and PU. Therefore,
the beamforming design problem can be mathematically modeled as \[10\]

\[
\begin{align*}
\max_{\mathbf{w}_{ZF}} & \quad \mathbf{h}_{BE_1} \bar{\mathbf{w}}_{ZF} \\
\text{s.t.} & \quad \mathbf{H}_{BZ} \bar{\mathbf{w}}_{ZF} = 0 \\
\quad & \quad \|\bar{\mathbf{w}}_{ZF}\|_F = 1,
\end{align*}
\]

(2)

where \(\|\cdot\|\) is the \(L^2\) norm, and \(\mathbf{H}_{BZ}\) is an \(N_B \times (N_R + 1)\) channel matrix, i.e., \(\mathbf{H}_{BZ} = [\mathbf{H}_{BR}, \mathbf{h}_{BP}]\), where \(\mathbf{H}_{BR}\) and \(\mathbf{h}_{BP}\) are \(N_B \times N_R\), \(N_B \times 1\) channel link matrix and vector between Bob and Relay, Bob and PU, respectively. \(\mathbf{H}_{BZ}\) is the outdated interference channel estimate, which can be gathered by a direct feedback from the Relay and PU with the help of collaboration between two systems or through an indirect feedback by a band manager. The first constraint \(T_1\) is to null the interference to the Relay and PU. The second constraint \(T_2\) normalizes the beamforming weight. Now, using the projection matrix theory, the optimal weight vector \(\mathbf{w}_{ZF}\) can be marked as \([7]\)

\[
\bar{\mathbf{w}}_{ZF} = \frac{T^\dagger \mathbf{h}_{BE_1}}{\|T^\dagger \mathbf{h}_{BE_1}\|},
\]

(3)

where \(T^\dagger = I_{N_B} - \mathbf{H}_{BZ} \left(\mathbf{H}_{BZ}^\dagger \mathbf{H}_{BZ}\right)^{-1} \mathbf{H}_{BZ}\) is the projection idempotent matrix with rank \(N_B - 1\). In solving the signal-to-interference-plus-noise ratio (SINR) below, we can use the idempotent matrix properties to calculate: \(T^\dagger = \left(T^\dagger\right)^2\) and \(\tilde{T}^\dagger = \left(\tilde{T}^\dagger\right)^H\). \(I_{N_B}\) is an \(N_B \times N_B\) identity matrix. The CSI used for ZFB collaborative design is assumed to be outdated compared to the actual CSI used for data transmission. Due to the existence of channel feedback error, the fading coefficient \(\mathbf{h}_{BE_1}\) with estimation error at Bob can be formulated as

\[
\mathbf{h}_{BE_1} = \rho_2 \mathbf{h}_{BE_1} + \sqrt{1 - \rho_2^2} \mathbf{e}_{BE},
\]

(4)

similarly, \(\tilde{\mathbf{h}}_{BE_1}\) and \(\mathbf{h}_{BE_1}\) expression are similar to (1). \(\mathbf{e}_{BE}\) is CG distributed and denotes the error vector, i.e., \(\mathbf{e}_{BE} \sim \mathcal{CN}(0, \sigma^2_{BE} I_{N_B})\). \(\rho_2 \in [0, 1]\) is also the correlation coefficient between \(\tilde{\mathbf{h}}_{BE_1}\) and \(\mathbf{h}_{BE_1}\). \(\rho_2\) is also similar to \(\rho_1\) in (1) which can obtain the perfect CSI of legitimate channel when \(\rho_2 = 1\).

Due to the feedback delay, the corresponding signal-to-noise ratio (SNR) and SINR at Relay and Eve can be expressed as

\[
\gamma_{AR} = \frac{P_S}{\sigma_R^2} \max_{i \in N_A} \frac{\|\mathbf{h}_{AR}^i\|^2}{\|\mathbf{h}_{AR}^i\|^2},
\]

(5)

and

\[
\gamma_{AE} = \frac{P_S |\mathbf{h}_{AE}|^2}{P_B \|\mathbf{h}_{BE_1} \bar{\mathbf{w}}_{ZF}\|^2 + \sigma_E^2},
\]

(6)
where \( P_S \) is the transmit power of Alice and it is limited by the PU interference temperature \( Q \) and \( P_t \) is maximum transmit power via \( P_S = \min \left( P_t, \frac{Q}{|h_{AP}|^2} \kappa_1 \right) \),

\( \tilde{h}_{AP} \) is delayed channel coefficients of \( h_{AP} \), \( \kappa_1 \) represents the power marginal factor at Alice. \( P_{R1} \) is the transmit power of Bob. \( \sigma_E^2 \) and \( \sigma_E^2 \) are the additive white Gaussian noise (AWGN) at Relay and Eve respectively. \( h_{AE} \) is channel coefficients between Alice and Eve with zero mean and variance \( \lambda_{AE} \).

3.2.2 In the Relay→Bob link

The MRT-SC-ZFB scheme is designed at Bob by using the outdated CSI. The instantaneous CSI for \( h_{RB} \) available at Bob. Similarly to (1), \( \tilde{h}_{RB}^j \) is the delay version of \( h_{RB} \) and \( \tilde{h}_{RB}^j \) can be presented as

\[
\tilde{h}_{RB}^j = \rho_3 h_{RB}^j + \sqrt{1-\rho_3^2} e_{RB},
\]

where the expression of \( h_{RB}^j \) is similar to (1) and \( h_{RB}^j \) is the channel coefficient between the Relay node and \( j \)-th antenna of the Bob node, \( e_{RB} \sim CN \left( 0, \sigma_E^2 \mathbf{1}_{N_B} \right) \) represents the channel estimation error vector, and \( \rho_3 \in [0, 1] \) is also the correlation coefficient between \( \tilde{h}_{RB}^j \) and \( h_{RB}^j \), which is an \( N_B \times 1 \) channel link vector between the Relay and the \( j \)-th transmit antenna at Bob with zero mean and variance \( \lambda_{RB} \).

The index of \( j \) is formulated as \( j = \arg \max_{1 \leq j \leq N_B} \| h_{RB}^j \|^2 \). The larger \( \rho_3 = 1 \) yields better channel estimation accuracy, \( \rho_3 = 1 \) means that the Relay also obtains the perfect CSI of legitimate channel, which is similar to (1).

ZFB Collaborative Design at Bob: The FD Bob is designed to direct its beam to the Eve and null the PU nodes. Due to the feedback delay between Bob and Eve, the CSI of the \( h_{BE2} \), whose value is available at Bob and used for designing the collaborative transmit ZFB weight \( \tilde{w}_{ZF2} \), is assumed to be outdated, which is similar to (4). Therefore, the beamforming design problem can be mathematically modeled as

\[
\max_{\tilde{w}_{ZF2}} \| \tilde{h}_{BE2} \tilde{w}_{ZF2} \|\]

s.t. \( T_3 : \| \tilde{h}_{BP} \tilde{w}_{ZF2} \| = 0 \)

\( T_4 : \| \tilde{w}_{ZF2} \|_F = 1 \),

where \( \tilde{h}_{BE2} \) and \( \tilde{h}_{BP} \) denote the \((N_B - 1) \times 1 \) channel between Bob and Eve, Bob and PU, respectively. The third constraint \( T_3 \) is to null the interference to the PU. The fourth constraint \( T_4 \) normalizes the beamforming weight. Similarly, the optimal weight vector \( \tilde{w}_{ZF2} \) can be marked as \( \tilde{w}_{ZF2} = \tilde{T}^{\diamond} \tilde{h}_{BE2} \), where

\[
\tilde{T}^{\diamond} = \mathbf{I}_{N_B - 1} - \tilde{h}_{BP} \left( \tilde{h}_{BP}^\dagger \right)^{-1} \tilde{h}_{BP}^\dagger
\]

is the projection idempotent matrix with rank \( N_B - 2 \). \( \mathbf{I}_{N_B - 1} \) is an \((N_B - 1) \times (N_B - 1)\) identity matrix. The CSI used for ZFB collaborative design is also assumed to be outdated compared to the actual CSI used for data transmission. Based on the existence of channel feedback error, the fading coefficient \( \tilde{h}_{BE2} \) with estimation error at Bob can be formulated as \( \tilde{h}_{BE2} = \rho_4 h_{BE2} + \sqrt{1-\rho_4^2} e_{BE2} \). Similarly, \( \tilde{h}_{BE2} \), \( h_{BE2} \), \( e_{BE} \) and \( \rho_4 \) expression are similar to (1).
Due to the feedback delay, the corresponding SNR and SINR at Bob and Eve can be expressed as

$$\gamma_{RB} = \frac{P_R \max_{j \in N_R} \| h_{RB}^j \|^2}{\sigma_B^2},$$  

(9)

and

$$\gamma_{RE} = \frac{P_R \| h_{RE} \|^2}{P_{B2} \| h_{BE2} \|^2 + \sigma_E^2},$$  

(10)

where $P_R$ is the transmit power of Relay, and it is also limited by the PU interference temperature $Q$ and $P_t$ is maximum transmit power via $P_R = \min (P_t, \frac{Q}{\| h_{RP} \|^2} \kappa_2)$, $h_{RP}$ is delayed channel coefficients of $h_{RP}$, $\| h_{RP} \|^2$ and $\| h_{RE} \|^2$ are exponentially distributed with rate parameter 2, i.e., $\| h_{RP} \|^2$ and $\| h_{RE} \|^2 \sim \text{exp}(2) [30, \text{Eq. (24)}]$. $\kappa_2$ represents the power marginal factor at Relay. $\sigma_B^2$ is the AWGN at Bob. $P_{B2}$ is the transmit power of the Bob. $h_{BE2}$ is an $(N_B - 1) \times 1$ channel link vector between Bob and Eve with zero mean and variance $\lambda_{BE2}$.

Due to the impact of outdated CSI of the interference links between the main links and Secondary user transmission links, it is difficult to meet the interference requirement at all times. In addition, we can use the probabilistic approach as in [4] and [31], where the Alice and Relay adapt their power such that the PUs can maintain a pre-selected outage probability $P_0$. From [4, 31], the closed expression of $\kappa_1$ cannot be obtained, but it can be obtained by $P_0$. Where

$$P_0 = \exp \left( - \frac{Q}{\lambda_{AP} \rho_5} \right) \left[ 1 - Q_0 \left( \frac{2 \rho_2 Q}{(1 - \rho_5) \lambda_{AP} P_5}, \frac{2 \rho_1 Q}{(1 - \rho_5) \lambda_{AP} P_5} \right) \right] + \frac{1}{2} \left( 1 + \frac{1}{\gamma} \right) \exp \left( - \frac{Q}{\lambda_{AP} \rho_5} \right) I_0 \left( \frac{2 \rho_2 Q}{(1 - \rho_5) \lambda_{AP} P_5} \right) - \frac{1}{2} Q_0 \left( \frac{\sqrt{2 \pi \gamma}}{2 \rho_5}, \sqrt{\frac{(\gamma + \rho_5^2)}{2 \rho_5}} \right),$$  

(11)

where $r = \sqrt{s^2 - \frac{16 \rho_1 \rho_5^2}{\lambda_{AP} (1 - \rho_5^2)}}$, $t = \left( \frac{1 - \rho_1}{1 - \rho_5} \right) \frac{2}{\lambda_{AP}}$, $s = \left( 1 + \kappa_1 \frac{2}{1 - \rho_5} \right) \frac{2}{\lambda_{AP}}$, and $I_0 (\cdot)$ is the zeroth-order modified Bessel function of the first kind [32, Eq. (8.431.1)], $Q_0 (a, b)$ is the generalized Marcum function [33]. In addition, $\kappa_2$ can be obtained as $\lambda_{AP} \to \lambda_{RP}$, $\kappa_1 \to \kappa_2$ and $\rho_5 \to \rho_6$ in (10).

Owing to the RaF strategy at Relay, the achievable secrecy rate of an underlay RaF spectrum sharing CRNs with FD receivers is given by $C_{S} = [C_{B} - C_{E}]^+ [12]$, where $C_{B} = \log_2 (1 + \gamma_{B})$ and $C_{E} = \log_2 (1 + \gamma_{E})$ are the capacities for main channel and the eavesdropping channel, respectively. $\gamma = \{ 1, 2 \}$ represents the first time-slot and the second time-slot, respectively. $\Phi \in \{ \text{TAS} - \text{MRC} - \text{ZFB}, \text{MRT} - \text{SC} - \text{ZFB} \}$ represents different scheme of the two different time-slots. In the following section, we will focus on analyzing the key secrecy performance of an underlay RaF spectrum sharing CRNs with the TAS-MRC-ZFB/MRT-SC-ZFB scheme, by adopting the condition and average approach.
for mathematical derivation, i.e., the Cumulative Distribution Function (CDF) of $\gamma_{B\pi}$ and Probability Density Function (PDF) of $\gamma_{E\pi}$ at different time-slots.

In the time-slots of two independent transmissions, in order to facilitate analysis, we define $\mu = \frac{Q}{P_t}, \frac{\lambda_{AR}}{\lambda_{AR}} = \zeta, \frac{\lambda_{AE}}{\lambda_{AE}} = \eta, \frac{\lambda_{BE1}}{\lambda_{BE1}} = \varepsilon, \frac{P_t}{\mu} \lambda_{AR} = \frac{Q}{\mu} \lambda_{AR} = \frac{P_t}{\mu} \lambda_{RB} = \frac{Q}{\mu} \lambda_{RB}, \gamma_E = \frac{P_t}{\mu} \lambda_{AE} = \frac{Q}{\mu} \lambda_{AE} = \frac{P_t}{\mu} \lambda_{RE} = \frac{Q}{\mu} \lambda_{RE}, \gamma_{BE1} = \frac{P_t}{\mu} \lambda_{BE1} = \frac{P_t}{\mu} \lambda_{BE2}$.

4 Secrecy Outage Probability Analysis

In this section, we analyze the SOP of an underlay RaF spectrum sharing CRNs with outdated CSI. Specifically, we derive closed-form expressions for SOP under TAS-MRC-ZFB/MRT-SC-ZFB scheme. In our considered system, we give a pre-determined threshold $R_S$, if $C_S \geq R_S$, the perfect secrecy is guaranteed. Otherwise, if $C_S < R_S$, then the information-theoretic security will be compromised. For the RaF spectrum sharing CRNs system, the SOP can be simplified to [34]

$$P_{out}(R_S) = \Pr(C_{S\pi} \leq R_S) = \int_0^\infty \mathcal{F}_{\gamma_{E\pi}}(2^{R_S}(1 + y) - 1)f_{\gamma_{E\pi}}(y) dy, (12)$$

and

$$P_{out}(R_S) = 1 - \Pr\{C_{S1}^{TAS-MRC-ZFB} > R_S\} \times \Pr\{C_{S2}^{MRT-SC-ZFB} > R_S\}. (13)$$

The secrecy capacity of $C_{S1}^{TAS-MRC-ZFB}$ and $C_{S2}^{MRT-SC-ZFB}$ can be obtained respectively as

$$C_{S1}^{TAS-MRC-ZFB} = \log_2 \frac{1 + \gamma_{AR}}{1 + \gamma_{AE}}$$

$$= \log_2 \frac{1 + \min\left(P_t, \frac{Q}{|h_{AR}|^2 \kappa_1}\right) \frac{\max\{\|h_{AR}^i\|^2\}}{\sigma_R^2}}{1 + \min\left(P_t, \frac{Q}{|h_{AR}|^2 \kappa_1}\right) \frac{\|h_{AR}^i\|^2}{\sigma_R^2} + \frac{\sigma_R^2}{P_t |h_{AR}^i|^2}}, (14)$$

and

$$C_{S2}^{MRT-SC-ZFB} = \log_2 \frac{1 + \gamma_{RB}}{1 + \gamma_{RE}}$$

$$= \log_2 \frac{1 + \min\left(P_t, \frac{Q}{|h_{RB}|^2 \kappa_2}\right) \frac{\max\{\|h_{RB}^i\|^2\}}{\sigma_R^2}}{1 + \min\left(P_t, \frac{Q}{|h_{RB}|^2 \kappa_2}\right) \frac{\|h_{RB}^i\|^2}{\sigma_R^2} + \frac{\sigma_R^2}{P_t |h_{RB}^i|^2}}, (15)$$

Using formula (14) and (15), we have

$$\Pr\{C_{S1}^\Phi > R_S\} = 1 - \Pr\{\gamma_1^\Phi \leq 2^{R_S}\} = 1 - F_{\gamma_1^\Phi}(R_S),$$

$$\Pr\{C_{S2}^\Phi > R_S\} = 1 - \Pr\{\gamma_2^\Phi \leq 2^{R_S}\} = 1 - F_{\gamma_2^\Phi}(R_S),$$

(16)

(17)
where $\gamma_1^\Phi = 1 + \min \left( P_1, \frac{Q}{P_2\lambda A P_{\text{Rand}}} \right) \frac{\max \left( \| \tilde{B}_{n R} \| \right)}{\tilde{r}_R}$ and $\gamma_2^\Phi = 1 + \min \left( P_1, \frac{Q}{P_2\lambda A P_{\text{Rand}}} \right) \frac{\max \left( \| \tilde{B}_{n R} \| \right)}{\tilde{r}_R}$, $F_{\gamma_1^\Phi} (R_S)$ and $F_{\gamma_2^\Phi} (R_S)$ are the CDF of $\gamma_1^\Phi$ and $\gamma_2^\Phi$, respectively.

Using (13), the SOP is given by

$$P_{out} (R_S) = F_{\gamma_1^TAS-MRC-ZFB} (R_S) + F_{\gamma_2^TAS-MRC-ZFB} (R_S)$$

$$- F_{\gamma_1^TAS-MRC-ZFB} (R_S) F_{\gamma_2^TAS-MRC-ZFB} (R_S).$$

Next, we present a comprehensive investigation on each hop $F_{\gamma_1^\Phi} (R_S)$ in TASS-MRC-ZFB/MRT-SC-ZFB scheme with outdated CSI.

4.1 TAS-MRC-ZFB Scheme

In the first time-slot, according to (5) and [4, 35], the conditional CDF of $\gamma_{B1}^{TAS-MRC-ZFB}$ with outdated CSI is given by

$$F_{\gamma_{B1}^{TAS-MRC-ZFB}} (x|G) = 1 - N_A \sum_{i=0}^{N_A - 1} \left( \frac{N_A - 1}{i} \right) \frac{\phi_i}{\Gamma(N_R)} \sum_{k=0}^{\phi_i} \left( \frac{1}{\Gamma(k+1)N_R} \right) \sum_{m=0}^{N_R-1} \frac{\tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}}{\sum_{j=0}^{N_R-k+1} \tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}},$$

\[ (19) \]

where $\tau_1 = 1 + i (1 - \rho_1)$, $\Theta_{N_R-1} = \sum_{n_1=0}^{N_R-1} \cdots \sum_{n_{N_R-1}=0}^{N_R-1} \frac{1}{(n_1\cdots n_{N_R-1})}$, $\phi_1 = \frac{N_R-1}{n_1}$.

Similarly, from (6), the conditional PDF of $\gamma_{E1}^{TAS-MRC-ZFB}$ may be derived as following Lemma 1.

**Lemma 1**: The conditional PDF of $\gamma_{E1}^{TAS-MRC-ZFB}$ can be given by

$$f_{\gamma_{E1}^{TAS-MRC-ZFB}} (y|G) = \sum_{n=0}^{N_B-N_R-2} \left( \frac{N_B-N_R-2}{n} \right) \frac{\phi_i}{\Gamma(N_R)} \sum_{k=0}^{\phi_i} \left( \frac{1}{\Gamma(k+1)N_R} \right) \sum_{m=0}^{N_R-1} \frac{\tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}}{\sum_{j=0}^{N_R-k+1} \tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}},$$

\[ (20) \]

**Proof of Lemma 1**: See Appendix A.

Then, upon substituting (19) and (20) into (12), and by $\Psi (\alpha, \gamma; z) = \frac{1}{\Gamma (\alpha)} \int_0^\infty \frac{e^{-x} \gamma^\alpha (1 + t) ^{-\alpha - 1} dt}{\Gamma (\gamma)}$, we can obtain the conditional CDF of $\gamma_1^{TAS-MRC-ZFB}$ as

$$F_{\gamma_1^{TAS-MRC-ZFB}} (R_S|G) = 1 - N_A \sum_{i=0}^{N_A - 1} \left( \frac{N_A - 1}{i} \right) \frac{\phi_i}{\Gamma(N_R)} \sum_{k=0}^{\phi_i} \left( \frac{1}{\Gamma(k+1)N_R} \right) \sum_{m=0}^{N_R-1} \frac{\tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}}{\sum_{j=0}^{N_R-k+1} \tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}},$$

\[ (21) \]

$$\times (1 - \rho_2^n) \times \Psi (q + 1, q + n - 2 + N_R - N_B, \frac{\tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}}{\sum_{j=0}^{N_R-k+1} \tau_{\gamma_1^\Phi} (N_R+\phi_i) \rho_i^{N_R-1-k} \gamma^{N_R-k+1}},$$

\[ (21) \]

$$\times (N_R - N_R - 1 - n) \left( \frac{P_2 \lambda A R_{\gamma_1^\Phi}}{P_2 \lambda A R_{\gamma_1^\Phi}} \right)^q \Gamma (q + 1).$$
Then, the PDF of random variable $\gamma$ given by (4) can be derived as $f_G(g) = \frac{1}{2\pi g} \exp \left(-\frac{1}{2g}\right)$, by substituting $f_G(g)$ into $F_{\gamma_{\text{TAS-MRC-ZFB}}} (R_S) = \int_0^\infty F_{\gamma_{\text{TAS-MRC-ZFB}}} (R_S) f_G (g) \, dg$, after mathematical conversion, we can get

$$
F_{\gamma_{\text{TAS-MRC-ZFB}}} (R_S) = \int_0^{\frac{1}{\gamma}} \left[ 1 - N_A \sum_{i=0}^{N_A-1} \left( \frac{N_A - i}{\Gamma(N,R_i)} \right) \sum_{k=0}^{\phi_i} \phi_i \sum_{m=0}^{N_R - k - 1} \left( \frac{(1 + \rho_2 n)^m}{\gamma R_S} \right) \right] \, dg 
$$

(22)

As a result, the CDF of $\gamma_{\text{TAS-MRC-ZFB}}$ can be given by the following Theorem.

**Theorem 1:** The CDF of $\gamma_{\text{TAS-MRC-ZFB}}$ is formulated as

$$
F_{\gamma_{\text{TAS-MRC-ZFB}}} (R_S) = 1 - N_A \sum_{i=0}^{N_A-1} \left( \frac{N_A - i}{\Gamma(N,R_i)} \right) \sum_{k=0}^{\phi_i} \phi_i \sum_{m=0}^{N_R - k - 1} \left( \frac{(1 + \rho_2 n)^m}{\gamma R_S} \right) \right] \, dg 
$$

(23)

where $\int_0^\infty e^{-x}e^{-\mu x} \, dx = \mu^{-1}\Gamma (\nu, \mu)$ [32, Eqs. (3.381.3), (8.350.2)] is the incomplete upper gamma function.

### 4.2 MRT-SC-ZFB Scheme

In the second time-slot, according to (9) and [4], the conditional CDF of $\gamma_{\text{MRT-SC-ZFB}}$ with outdated CSI is given by

$$
F_{\gamma_{\text{MRT-SC-ZFB}}} (x|G_1) = 1 - N_B \sum_{i=0}^{N_B-1} \left( \frac{N_B - i}{\Gamma(N,R_i)} \right) \sum_{k=0}^{\phi_i} \phi_i \sum_{m=0}^{N_R - k - 1} \left( \frac{(1 + \rho_2 n)^m}{\gamma R_S} \right) \right] \, dg 
$$

(24)
in addition, \( \{ \tau_2, \Theta_{N_R,2}, \phi_2 \} \) can be obtained as \( \tau_1 \to \tau_2, \Theta_{N_R,1} \to \Theta_{N_R,2} \) and \( \phi_1 \to \phi_2 \) in (19).

Similarly, the conditional PDF of \( \gamma_{E_2}^{MRT-SC-ZFB} \) with outdated CSI is in the following **Lemma 2**.

**Lemma 2**: The conditional PDF of \( \gamma_{E_2}^{MRT-SC-ZFB} \) with outdated CSI can be given by

\[
\begin{align*}
\frac{f_{\gamma_{E_2}^{MRT-SC-ZFB}}(g|G_1)}{(R_S|G_1)} &= 1 - N_B \sum_{i=0}^{N_B-1} \left( \frac{N_B - 1}{i} \right) \frac{(-1)^i \Theta_{N_R,2}}{\Gamma(N_R)} \sum_{k=0}^{\phi_2} \frac{\phi_2}{k} \sum_{m=0}^{\phi_2} \frac{\phi_2}{N_B + k - 1} \\
&\times \exp \left( -\frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \right) \frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \sum_{q=0}^{m-1} \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \exp \left( -\left( 1 + \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \right) \right) \\
&\times \left( 1 - \phi_2 \right) + \left( 1 - \phi_2 \right) \left( \frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \right) \sum_{q=0}^{m-1} \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \exp \left( -\left( 1 + \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \right) \right) \\
&\times \left( 1 - \phi_2 \right) + \left( 1 - \phi_2 \right) \left( \frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \right) \sum_{q=0}^{m-1} \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \exp \left( -\left( 1 + \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \right) \right).
\end{align*}
\]

**Proof of Lemma 2**: The proof process is similar to (20) and will not be described here.

Then, upon substituting (24) and (25) into (12), we can obtain the conditional CDF of \( \gamma_{E_2}^{MRT-SC-ZFB} \) as

\[
\begin{align*}
F_{\gamma_{E_2}^{MRT-SC-ZFB}}(R_S|G_1) &= 1 - N_B \sum_{i=0}^{N_B-1} \left( \frac{N_B - 1}{i} \right) \frac{(-1)^i \Theta_{N_R,2}}{\Gamma(N_R)} \sum_{k=0}^{\phi_2} \frac{\phi_2}{k} \sum_{m=0}^{\phi_2} \frac{\phi_2}{N_B + k - 1} \\
&\times \exp \left( -\frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \right) \frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \sum_{q=0}^{m-1} \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \exp \left( -\left( 1 + \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \right) \right) \\
&\times \left( 1 - \phi_2 \right) + \left( 1 - \phi_2 \right) \left( \frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \right) \sum_{q=0}^{m-1} \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \exp \left( -\left( 1 + \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \right) \right) \\
&\times \left( 1 - \phi_2 \right) + \left( 1 - \phi_2 \right) \left( \frac{\gamma_{E_2}^{MRT}}{\gamma_{E_2}^{MRT}} \right) \sum_{q=0}^{m-1} \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \exp \left( -\left( 1 + \left( 2^R - 1 \right) \gamma_{E_2}^{MRT} \right) \right).
\end{align*}
\]

Similarly, the PDF of random variable \( G_1 = \frac{1}{\lambda_{B_E}} \) under outdated CSI can be derived as \( f_{G_1}(g) = \frac{\lambda_{B_E}}{\lambda_{B_E}} \exp \left( -\frac{\lambda_{B_E}}{\lambda_{B_E}} g \right) \) by substituting \( f_{G_1}(g) \) into

\[
F_{\gamma_{E_2}^{MRT-SC-ZFB}}(R_S) = \int_0^{\infty} F_{\gamma_{E_2}^{MRT-SC-ZFB}}(R_S|G_1) f_{G_1}(g) \, dg,
\]

after mathematical conversion, we can get

\[
\begin{align*}
F_{\gamma_{E_2}^{MRT-SC-ZFB}}(R_S) &= \int_0^{\infty} F_{\gamma_{E_2}^{MRT-SC-ZFB}}(R_S|G_1) f_{G_1}(g) \, dg - \int_0^{\infty} F_{\gamma_{E_2}^{MRT-SC-ZFB}}(R_S|G_1) f_{G_1}(g) \, dg \\
&= \int_0^{\infty} f_{\gamma_{E_2}^{MRT-SC-ZFB}}(g|G_1) \, dg
\end{align*}
\]

(27)
As a result, the CDF of $\gamma_2^{MRT-SC-ZFB}$ can be given by the following **Theorem 2**.

**Theorem 2**: The CDF of $\gamma_2^{MRT-SC-ZFB}$ is formulated as

\[
F_{\gamma_2^{MRT-SC-ZFB}} = 1 - \sum_{b=0}^{N_B-1} \sum_{k=0}^{\infty} \frac{\gamma_2^{N_B+k-1}}{\Gamma(N_B+B+1)} \sum_{q=0}^{m} \left( \begin{array}{c} m \\ q \end{array} \right) \left( 2^{B}-1 \right)^{m-q} \left( \frac{w_R}{w_B} \right)^{q} \times \\
\Gamma(q+1) \sum_{n=0}^{N_B-3-n} \left( \begin{array}{c} N_B-3-n \\ n \end{array} \right) (\rho_4)^{2(N_B-3-n)} (1-\rho_4)^n \\
\times \frac{1}{\gamma_B^{2q}} \Psi \left( \begin{array}{c} q+1, q+n+4 - N_B, 1(i+2)2^{B}Q \end{array} \right) + (N_B-2-n) \times \\
\exp \left( \frac{(1+i)(2^{B}-1)R_{RP}+2^B\zeta_B^2\gamma_B^2}{\gamma_B^{2q}} \right) \left( \begin{array}{c} m-q+1 \\ q \end{array} \right) \frac{(1+i)(2^{B}-1)R_{RP}+2^B\zeta_B^2\gamma_B^2}{\gamma_B^{2q}} \right). \tag{28}
\]

To this end, by substituting (23) and (28) into (18), we can easily obtain the final SOP of proposed scheme.

## 5 Asymptotic SOP Analysis

In the above section, we have derived an exact closed-form expression of the SOP and the complexity of the SOP expression limits the effective judgment of our proposed scheme on the system performance. Therefore, in order to further verify the effect of system parameters on the performance of our proposed scheme, we will consider two special scenarios, that is $\{\gamma_B \to \infty, \text{fixed } \gamma_E\}$ and $\{\gamma_B \to \infty, \gamma_E \to \infty\}$. 1) $\gamma_B \to \infty$ and fixed $\gamma_E$, that is a scenario where Relay and Bob located close to Alice and Relay, i.e., the main transmission channel is better than the wiretap channel. 2) $\gamma_B \to \infty$ and $\gamma_E \to \infty$, that is a scenario where the main and wiretap channels have superior SNR, i.e., Relay, Bob and Eve are located close to Alice and Relay, respectively.

### 5.1 Scenario 1: $\gamma_B \to \infty$ and fixed $\gamma_E$

In order to verify the effect of outdated CSI on the system’s secrecy diversity gain and secrecy coding gain, we analyze a special case of asymptotic SOP ($\rho_1 \neq 1, \rho_2 \neq 1, \rho_3 \neq 1, \rho_4 \neq 1$).

**Corollary 1**: When the CSIs for second user transmission link and collaborative beamforming link are outdated, the asymptotic expression for SOP of an underlay RaF spectrum sharing CRNs with FD receivers under $\gamma_B \to \infty$ and fixed $\gamma_E$ is approximated as

\[
P_{out}^{TAS-MRC-ZFB/MRT-SC-ZFB} (R_B) \approx (\Delta_1 + \Delta_2) \gamma_B^{-N_B}, \tag{29}
\]
where
\[
\Delta_1 = N_A \sum_{i=0}^{N_A-1} \left( \binom{N_A-1}{i} \left( -1 \right)^i \frac{\Gamma(\nu + \phi (1-\rho_1)}{\Gamma(\nu)\Gamma(\nu + \phi(1-\rho_1))} \sum_{q=0}^{N_R} \left( \frac{N_R}{q} \right)^2 R_{2q} \right) \times (2^{N_R-1} N_A - N_R - 2) \sum_{n=0}^{N_R-2} \left( \frac{N_B - N_R - 2}{n} \right) (\rho_2)_{2(N_R - N_R - 2 - n)} (1 - \rho_2)^{n} \left( \frac{N_R}{\tau_{BE}} \right)^{q} \times \Gamma(q+1) \left[ \frac{1}{\tau_{BE}} \Psi \left( q + 1, n + q + 3 + N_R - N_B, \frac{1}{\tau_{BE}} \right) + (N_R - N_R - 1 - n) \times \Psi \left( q + 1, n + q + 2 + N_R - N_B, \frac{1}{\tau_{BE}} \right) \right] \left[ \left( 1 - \exp \left( -\frac{\lambda_m}{\lambda_{AP}} \right) \right) + \left( \frac{\lambda_{AP}}{\lambda_{AP}} \right)^{N_R} \right] \times \left( N_R + 1, \frac{\tau_{BE}}{\lambda_{AP}} \right) \right] ,
\]
and
\[
\Delta_2 = N_B \sum_{i=0}^{N_B-1} \left( \binom{N_B-1}{i} \left( -1 \right)^i \frac{\Gamma(\nu + \phi (1-\rho_1)}}{\Gamma(\nu)\Gamma(\nu + \phi(1-\rho_1))} \sum_{j=0}^{N_R} \left( \frac{N_R}{j} \right)^2 R_{j} \right) \times (2^{N_B-1} N_B - N_B - 3) \sum_{n=0}^{N_B-3} \left( \frac{N_B - 3}{n} \right) (\rho_2)_{2(N_B - 3 - n)} (1 - \rho_2)^{n} \left( \frac{N_B}{\tau_{BE}} \right)^{1} \Psi \left( j + 1, j + 4 + n - N_B, \frac{1}{\tau_{BE}} \right) + (N_R - 2 - n) \Psi \left( j + 1, j + 3 + n - N_B, \frac{1}{\tau_{BE}} \right) \right] \times \left[ \left( 1 - \exp \left( -\frac{\lambda_m}{\lambda_{AP}} \right) \right) + \left( \frac{\lambda_{AP}}{\lambda_{AP}} \right)^{N_R} \Gamma \left( N_R + 1, \frac{\tau_{BE}}{\lambda_{AP}} \right) \right] .
\]

Proof of Corollary 1: See Appendix B.

Remark 1: From Corollary 1, the secrecy diversity gain of our proposed scheme is \( N_R \) and secrecy diversity order \( N_R \) is independent of the parameters like \( \rho_1 \), \( \rho_2 \), \( \rho_3 \), \( \rho_4 \), \( \rho_5 \), etc. \( N_R \) is the secrecy diversity order that determines the slope of the asymptotic SOP curve. In addition, the secrecy performance of our proposed scheme affects the communication quality of the wiretap channel and main channel through coding gain, i.e., \( G = \Delta^{-1/N_R} \). Therefore, it is not difficult to find that the more \( N_R \), the better the system performance. From the above results, we can find that secrecy diversity gain improves with increasing the number of \( N_R \) antennas.

5.2 Scenario II: \( \tau_{BE} \rightarrow \infty \) and \( \tau_{BE} \rightarrow \infty \)

Now, the approximated SOP expression for our proposed scheme under outdated CSI can be analyzed in the following Corollary 2.

Corollary 2: When the CSIs of our considered system is outdated (secondary transmission links and collaborative ZFB link Bob \( \rightarrow \) Eve), the asymptotic SOP of an underlay RaF spectrum sharing CRNs with outdated CSI under \( \tau_{BE} \rightarrow \infty \) and \( \tau_{BE} \rightarrow \infty \) is given by
\[
F_{\text{out}}^{\text{TAS-MRC-ZFB/MRT-SC-ZFB}} (R_S) \approx 1 - \left( 1 - F_{\text{TAS-MRC-ZFB}} (R_S) \right) \left( 1 - F_{\text{MRT-SC-ZFB}} (R_S) \right).
\]

By using (23) and (28), we can easily obtain
\[
F_{\text{TAS-MRT-ZFB}} (R_S) \approx 1 - N_A \sum_{i=0}^{N_A-1} \left( \binom{N_A-1}{i} \left( -1 \right)^i \frac{\Gamma(\nu + \phi (1-\rho_1)}}{\Gamma(\nu)\Gamma(\nu + \phi(1-\rho_1))} \sum_{k=0}^{\rho_1} \left( \frac{1}{k} \right)^{N_R+k-1} m \sum_{m=0}^{N_R+k-1} \sum_{n=0}^{N_R+k-1} \left( \frac{N_B - N_R - 2}{n} \right) (1 - \rho_2)^{n} \left( \frac{N_R}{\tau_{BE}} \right)^{1} \Psi \left( m + 1, m + n + 3 + N_R - N_B, \frac{1}{\tau_{BE}} \right) \right] \times \left[ \left( 1 - \exp \left( -\frac{\lambda_m}{\lambda_{AP}} \right) \right) + \Gamma \left( 1, \frac{\tau_{BE}}{\lambda_{AP}} \right) \right] \left( N_R + 1, \frac{\tau_{BE}}{\lambda_{AP}} \right) .
\]
designed beamforming can mitigate the interference effectively with outdated CSI. The considered scheme of our paper validates that our Eve node, so the ZFB design maximizes the transmission of directional interference. ZFB/MRT-SC-ZFB scheme, the FD destination node knows the perfect CSI of the ρ fixed values. When the SOP curves for any value of (ρ, ρ) → ∞ the number of time correlation coefficient (ρ, ρ) = (2, 2, 5) and P₀ = 20%. (b) The SOP versus system mean SNR with different correlation coefficient (ρ₀, ρ₀) and Q when τ₁ = τ₂ = 10dB, (N₁, N₁) = (2, 4) and P₀ = 20%.

Further, substituting (33) and (34) into (32), we can easily obtain the final result under Scenario II.

Remark 2: We can observe from Corollary 2 that the proposed scheme with τ → ∞ and τ → ∞ achieve the secrecy outage floor under outdated CSI and we cannot get the secrecy diversity gain. Therefore, the secrecy performance of our considered system would be affected by the security coding gain for Scenario II.

6 Results and Discussion

This section deals in providing the numerical results to examine the secrecy performance of an underlay RaF spectrum sharing CRNs with outdated CSI. Our interest is in examining the effects of the number of (N₁, N₁, N₁), (ρ₁, ρ₂, ρ₃, ρ₄) and (ρ₁, ρ₃). We set σ² = σ² = σ² = 1, R₄ = 2bit/s/Hz, ζ = η = ε = 1 and P₄ = P₄. d₄ represents the distance from M to N, in which d₄ = 1. We set λ₄ = λ₄ = 2, all others channel links variance are 1. The transmission signal-to-noise ratio is defined as SNR. Moreover, we clearly found that the analytical curves are completely in conformity with the Monte Carlo simulations’ results in order to verify the analytical derivations. The proposed scheme is compared with the existing TAS-MRC/TAS-MRC scheme to verify the improvement of system performance [4]. Furthermore, the SOP aggravates due to the outdated CSI.

Fig. 2 presents the SOP versus SNR for the two different combining schemes with outdated CSI. From both figures, we find that the SOP decreases with increasing the number of time correlation coefficient (ρ₁, ρ₂, ρ₃) and Q. It is also observed that the SOP curves for any value of (ρ₁, ρ₂, ρ₃), (ρ₃, ρ₄, ρ₅) and Q tend to different fixed values. When ρ₁ = ρ₂ = ρ₅ = 1 and ρ₃ = ρ₄ = ρ₆ = 1 are better than that of ρ₁ = ρ₂ = ρ₅ = 0.5 and ρ₃ = ρ₄ = ρ₆ = 0.5. This is because when time correlation coefficient increases, the CSI of CRNs is close to the perfect. In the TAS-MRC-ZFB/MRT-SC-ZFB scheme, the FD destination node knows the perfect CSI of the Eve node, so the ZFB design maximizes the transmission of directional interference signals to the Eve node.
Finally, we can easily conclude that TAS-MRC-ZFB/MRT-SC-ZFB scheme achieves better secrecy performance than TAS-MRC/TAS-MRC with outdated CSI.

Fig. 3 and 4 present the SOP versus average SNR for TAS-MRC-ZFB/MRT-SC-ZFB scheme under different $(N_A, N_R, N_B, \rho_1, \rho_2, \rho_3, \rho_4)$, $(\rho_5, \rho_6)$ and $(\rho_5, \rho_6, N_R, Q)$ when $P_0 = 5\%$ and $P_1 = P_2 = P_3 = P_4 = 0.5$ and $Q = 20dB$.

Fig. 4 The SOP versus system mean SNR for different number $N_R, Q$ and $(\rho_5, \rho_6)$ when $\tau_{BE1} = \tau_{BE2} = 20dB$, $(N_A, N_B) = (2, 5)$, $P_0 = 5\%$ and $\rho_1 = \rho_2 = \rho_3 = \rho_4 = 0.5$ and 1.

Fig. 5 presents the effects of the power margin factors $\kappa_1$ and $\kappa_2$ versus SNR under various the pre-selected outage probability of PU ($P_0$) and time correlation coefficients $\rho_5$ and $\rho_6$. In Fig. 5, it shows that the power margin factors $\kappa_1$ and $\kappa_2$ decline with the increase of SNR. It also shows that in the low SNR regime, the power margin factors $\kappa_1 = 1$ and $\kappa_2 = 1$ because of the interference to the PU is less than the pre-selected outage probability value of PU. In addition, when $\rho_5, \rho_6$ and $P_0$ is fixed, $\kappa_2$ is better than $\kappa_1$ at a certain SNR, this is because the average value of the PU link in $\kappa_2$ is 2, i.e., $\lambda_{RP} = 2$. Besides, it is also observed from this
Figure 5 The power marginal factors $\kappa_1$ and $\kappa_2$ versus system mean SNR under the different $\rho_5$, $\rho_6$ and $P_0$.

Figure 6 Exact and asymptotic SOP versus system mean SNR for different number $(N_R, N_B)$ and $(\rho_1, \rho_2, \rho_3, \rho_4)$ under Scenario I when $\rho_5 = \rho_6 = 1$, $N_A = 2$, $\tau_{BE1} = \tau_{BE2} = 10dB$ and $P_0 = 10\%$.

Figure, the smaller the pre-selected outage probability value ($P_0$) and the correlation coefficients $\rho_5$ and $\rho_6$, the better the QoS for PU.

Fig. 6 and 7 plot the SOP versus average SNR for TAS-MRC-ZFB/MRT-SC-ZFB scheme under two different Scenarios. In Fig. 6, as indicated in (29) with outdated CSI. As depicted in this figure, it shows that the SOP decreases with increasing the number of $(N_R, N_B)$, and increases the transmit power at Alice and Relay, the system performance becomes better. In addition, it can be found that some of the asymptotic curves are parallel, this is because they have the same secrecy diversity gain $N_R$. However, $N_A$ and $N_B$ will not affect the secrecy diversity gain of the considered system. It follows that the higher time correlation coefficient $(\rho_1, \rho_2, \rho_3, \rho_4)$, the more obvious the improvement of the secrecy performance of our considered system under Scenario I. In Fig. 7, as illustrated, the results show that the SOP decreases with increasing the number of time correlation coefficient $(\rho_1, \rho_2, \rho_3, \rho_4)$ and $(N_R, N_B)$. It is also observed from Fig. 7 that the SOP curves for any value of $(N_A, N_R, N_B)$ and $(\rho_1, \rho_2, \rho_3, \rho_4)$ tend to different fixed values. When $\rho_1 = \rho_2 = \rho_3 = \rho_4 = 1$, the SOP is minimum and diversity order achieves the maximum value $N_R$ and this situation is a perfect CSI, but the actual physical scenario is difficult to achieve. In addition, the SOP of the system tends to the secrecy outage floor, which validates the theoretical analysis conclusion of Corollary 2.

When $N_A$ and $N_B$ are fixed and $\rho_1 = \rho_2 = \rho_3 = \rho_4 = 1$, with the increment of $N_R$, the secrecy performance becomes worse, this is because the number of antennas transmitting interference signals to Eve at Bob is reduced. Finally, the SOP curves for our proposed scheme match well with the simulation results, indicating the correctness of (32).

Fig. 8 presents the SOP versus time correlation coefficient $\rho_1$ and $\rho_3$ for TAS-MRC-ZFB/MRT-SC-ZFB scheme with outdated CSI. As shown in Fig. 8, the SOP decreases with increasing the number of time correlation coefficient $\rho_2$, thus the secrecy performance of $\rho_2 = 1$ is better than that of $\rho_2 = 0.2$ and $0.5$. When maximizing $\rho_2$ ($\rho_2 = 1$), the FD destination node knows the perfect CSI of the Eve node, so the ZFB design maximizes the transmission of directional interference signals to the Eve node. We also observe that the SOP decreases when the correlation coefficient $\rho_1$ and $\rho_3$ are increased. This is because when $\rho_1$ and $\rho_3$ increases, the CSI of CRNs is close to the perfect. Therefore when $\rho_1 = \rho_3 = 1$, the system performance is the best.
7 Conclusion and Future Work

We analyzed an underlay RaF spectrum sharing CRNs with FD receivers and studied the effects of outdated CSI on cooperative relay node with TAS-MRC-ZFB/MRT-SC-ZFB scheme. We derived the closed-form expressions for the exact and the high SNR regime asymptotic under two different scenarios and analyzed the effects of the time delay on the secrecy performance of our considered system. We also investigated the impact of key parameters \((\rho_1, \rho_2, \rho_3, \rho_4), (\rho_5, \rho_6), (N_A, N_R, N_B), P_0\) and \(Q\) on the system secrecy performance with a passive eavesdropper under outdated CSI and the secrecy diversity gain of TAS-MRC-ZFB/MRT-SC-ZFB scheme with outdated CSI is \(N_R\). Our results have shown that outdated CSI has a negative impact on ZFB coding and secrecy performance. We found that the proposed scheme outperform better performance than the existing TAS-MRC/TAS-MRC scheme. The analysis performed in this paper will be of great use in designing the practical spectrum sharing CRNs systems that are subject to channel estimation errors.

For future works, we will consider a more challenging scenario such that CRNs of FD mode can further introduce different key technologies, including NOMA, mmWave small cells, D2D communications, mobile edge computing, etc., which can offer a number advantages of improved spectral efficiency, relaxed channel feedback and low transmission latency.

List of Abbreviations

channel state information (CSI); cognitive radio networks (CRNs); full-duplex (FD); transmit antenna selection-maximal-ratio combining-zero forcing beamforming/maximal-ratio transmission-selection combining-zero forcing beamforming (TAS-MRC-ZFB/MRT-SC-ZFB); secrecy outage probability (SOP); primary user (PU); secondary users (SUs); primary users (PUs); quality of service (QoS); physical layer security (PLS); multiple-input-multi-output (MIMO); randomize-and-forward (RaF); decode-and-forward (DF); secrecy outage probability (SOP); complex Gaussian-random variables (CG-RV); additive white Gaussian noise (AWGN); signal-to-interference-plus-noise ratio (SINR); signal-to-noise ratio (SNR); Cumulative Distribution Function (CDF); Probability Density Function (PDF).

Declarations

7.1 Availability of data and materials
Not applicable.

7.2 Competing interests
The authors declare that they have no competing interests.
7.3 Funding
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7.4 Authors' contributions
Z. Shang is the main writer of this paper, Z. Shang and T. Zhang conceived the model, T. Zhang, H. Wu, X. Qiao and L. Tao provided some suggestions and revised the paper. All authors read and approved the final manuscript.

Appendix A
We define $z_1 = P_{B1}[h_{B1}^1|^2]/\sigma^2$, the PDF of $f_{Z_1}(z_1)$ can be expressed as \[ f_{Z_1}(z_1) = \sum_{n=0}^{N_B-N_R-2} \frac{(\rho_2)^{2(N_B-N_R-2-n)}(1-\rho_2)^n}{\sigma^2} \cdot \frac{(\rho_2)^{(2(N_B-N_R-2-n))(1-\rho_2)^n}}{(N_B-N_R-2-n)!} \exp\left(-\frac{\sigma^2}{\bar{P}_{B1}(\lambda BE)}\right). \] (35)

We can define $\gamma_E^{TAS-MRC-ZFB}$ as
\[ \gamma_E^{TAS-MRC-ZFB} = \frac{P_{B1}|h_{B1}^1|^2}{\bar{P}_{B1}|h_{B1}^1|^2 + \sigma^2} = \frac{X_E}{z_1 + 1}, \] (36)

Then, the conditional CDF of $\gamma_E^{TAS-MRC-ZFB}$ can be derived as
\[ F_{\gamma_E^{TAS-MRC-ZFB}}(y|G) = 1 - \sum_{n=0}^{N_B-N_R-2} \left( \frac{N_B-N_R-2}{n} \right)(1-\rho_2)^n \times \frac{(\rho_2)^{(2(N_B-N_R-2-n))(1-\rho_2)^n}}{(N_B-N_R-2-n)!} \exp\left(-\frac{\sigma^2}{\gamma_E^{TAS-MRC-ZFB}}\right). \] (37)

Finally, the $f_{\gamma_E^{TAS-MRC-ZFB}}(y)$ in Lemma 1 can be obtained by taking derivative in (37).

Appendix B
In the first time-slot, using (19), when $\gamma_B \to \infty$, the $F_{\gamma_E^{TAS-MRC-ZFB}}(x|G)$ can be approximated as
\[ F_{\gamma_E^{TAS-MRC-ZFB}}(x|G) \approx N_A \sum_{i=0}^{N_A-1} \left( \frac{N_A - 1}{i} \right)(1-\rho_2)^n \exp\left(-\frac{\sigma^2}{\bar{P}_{S\lambda AE}}\right). \] (38)

Thus, by substituting (38) and (20) into (12), the asymptotic conditional CDF of $\gamma_E^{TAS-MRC-ZFB}$ is given by
\[ F_{\gamma_E^{TAS-MRC-ZFB}}(R_S|G) = N_A \sum_{i=0}^{N_A-1} \left( \frac{N_A - 1}{i} \right)(1-\rho_2)^n \exp\left(-\frac{\sigma^2}{\bar{P}_{S\lambda AE}}\right). \] (39)
Based on $F_{\mathcal{T}_{\text{AS-MRC-ZFB}}} (R_S) = \int_0^\infty F_{\mathcal{T}_{\text{AS-MRC-ZFB}}} (R_S | G) f_G (g) \, dg$, after mathematical conversion, we can get

$$
F_{\mathcal{T}_{\text{AS-MRC-ZFB}}} (R_S) = \left( \frac{1}{\tau_B} \right)^{N_B} \frac{N_R}{N_A} \sum_{i=0}^{N_A-1} \left( \frac{N_A - 1}{i} \right) \frac{(-1)^i \Theta N_R, 2 \Gamma (N_R + \phi_1)}{\Gamma (N_R) \Gamma (N_R + 1)} 
\times \frac{(1 - \rho_1) \beta_1}{\tau_1^{N_R + \phi_1}} \sum_{q=0}^{N_R \phi_1} \left( \frac{N_R}{q} \right) (2^{R_S - 1})^{N_R - q} 2^{R_S} \sum_{n=0}^{N_R - 2} \left( \frac{N_R - N_R - 2}{n} \right) 
\times (\rho_2)^2 (N_R - N_R - 2) (1 - \rho_2) \sum_{n=0}^{N_R - 2} \left( \frac{N_R - N_R - 2}{n} \right) 
\times \left( \frac{1}{\tau_{BE}} \right) \Gamma (q + 1) \left( 1 - \exp \left( -\frac{\kappa_1 \mu}{\lambda_{AP}} \right) \right) + \left( \frac{N_R}{\tau_{BE}} \right) \Gamma (N_R + 1, \frac{\kappa_1 \mu}{\lambda_{AP}}) .
$$

Similarly, in the second time-slot, using (24), when $\tau_B \to \infty$, the $F_{\mathcal{T}_{\text{MRT-SC-ZFB}}} (x | G_1)$ can be approximated as

$$
F_{\mathcal{T}_{\text{MRT-SC-ZFB}}} (x | G_1) \approx N_B \sum_{i=0}^{N_B-1} \left( \frac{N_B - 1}{i} \right) \frac{(-1)^i \Theta N_R, 2 \Gamma (N_R + \phi_2)}{\Gamma (N_R) \Gamma (N_R + 1)} 
\times \frac{\Gamma (N_R + \phi_2) (1 - \rho_3) \beta_2}{\tau_2^{N_R + \phi_2}} \frac{\sigma_R^2}{P_R \lambda_{RR}} \frac{N_R}{\Gamma (N_R + 1)}.
$$

Similarly, by substituting (41) and (25) into (12), the asymptotic conditional CDF of $\gamma_{\mathcal{T}_{\text{MRT-SC-ZFB}}}$ is given by

$$
F_{\mathcal{T}_{\text{MRT-SC-ZFB}}} (R_S | G_1) = N_B \sum_{j=0}^{N_R} \left( \frac{N_R}{j} \right) \frac{(-1)^j \Theta N_R, 2 \Gamma (N_R + \phi_2)}{\Gamma (N_R) \Gamma (N_R + 1)} 
\times \frac{\tau_2^{N_R + \phi_2}}{P_R \lambda_{RR}} \frac{\sigma_R^2}{N_B} \frac{N_B}{\Gamma (N_R + 1)} 
\times \frac{N_B - 3}{n} (\rho_4)^2 (N_B - 3) \left[ \frac{1}{\varepsilon_{BE}} \right] \psi \left( j + 1, j + 4 + n - N_B, \frac{1}{\varepsilon_{BE}} \right) 
\times \left( 1 - \rho_2 \right)^n .
$$

Based on $F_{\mathcal{T}_{\text{MRT-SC-ZFB}}} (R_S) = \int_0^\infty F_{\mathcal{T}_{\text{MRT-SC-ZFB}}} (R_S | G_1) f_{G_1} (g) \, dg$, after mathematical conversion, we can get

$$
F_{\mathcal{T}_{\text{MRT-SC-ZFB}}} (R_S) = \left( \frac{1}{\tau_B} \right)^{N_B} \frac{N_R}{N_A} \sum_{i=0}^{N_A-1} \left( \frac{N_A - 1}{i} \right) \frac{(-1)^i \Theta N_R, 2 \Gamma (N_R + \phi_2)}{\Gamma (N_R) \Gamma (N_R + 1)} 
\times \frac{(1 - \rho_1) \beta_1}{\tau_1^{N_R + \phi_1}} \sum_{q=0}^{N_R \phi_1} \left( \frac{N_R}{q} \right) (2^{R_S - 1})^{N_R - q} 2^{R_S} \sum_{n=0}^{N_R - 2} \left( \frac{N_R - N_R - 2}{n} \right) 
\times (\rho_2)^2 (N_R - N_R - 2) (1 - \rho_2) \sum_{n=0}^{N_R - 2} \left( \frac{N_R - N_R - 2}{n} \right) 
\times \left( \frac{1}{\tau_{BE}} \right) \Gamma (q + 1) \left( 1 - \exp \left( -\frac{\kappa_2 \mu}{\lambda_{RP}} \right) \right) + \left( \frac{N_R}{\tau_{BE}} \right) \Gamma (N_R + 1, \frac{\kappa_2 \mu}{\lambda_{RP}}) .
$$

Now, using (40) and (43), we obtain (30), (31) and (29).
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Figures

Figure 1 System model.

Figure 2 (a) T2a; (b) T2b.

Figure 3 The SOP versus system mean SNR for different correlation coefficient ($\rho_1, \rho_2, \rho_3, \rho_4$), ($\rho_5, \rho_6$) and ($N_R, N_B$) when $N_A = 2$, $\tau_{BE1} = \tau_{BE2} = 10dB$, $P_0 = 10\%$ and $Q = 20dB$.

Figure 4 The SOP versus system mean SNR for different number $N_B$, $Q$ and ($\rho_5, \rho_6$) when $\tau_{BE1} = \tau_{BE2} = 20dB$, ($N_A, N_B$) = (2, 5), $P_0 = 5\%$ and $\rho_1 = \rho_2 = \rho_3 = \rho_4 = 0.5$ and 1.

Figure 5 The power marginal factors $\kappa_1$ and $\kappa_2$ versus system mean SNR under the different $\rho_5$, $\rho_6$ and $P_0$.

Figure 6 Exact and asymptotic SOP versus system mean SNR for different number ($N_R, N_B$) and ($\rho_1, \rho_2, \rho_3, \rho_4$) under Scenario I when $\rho_5 = \rho_6 = 1$, $N_A = 2$, $\tau_{BE1} = \tau_{BE2} = 10dB$ and $P_0 = 10\%$.

Figure 7 Exact and asymptotic SOP versus system mean SNR for different number ($N_R, N_B$) and ($\rho_1, \rho_2, \rho_3, \rho_4$) under Scenario II when $\tau_{BE1} = \tau_{BE2} = 10dB$, $\tau_B/\tau_E = 1dB$, $N_A = 2$, $\rho_5 = \rho_6 = 1$ and $P_0 = 5\%$.

Figure 8 The SOP versus $\rho_1$ and $\rho_3$ with different correlation coefficient $\rho_2$ and $\rho_4$ when $\tau_{BE1} = \tau_{BE2} = 10dB$, ($N_A, N_R, N_B$) = (2, 2, 4), $\rho_5 = \rho_6 = 1$, $P_0 = 5\%$ and $P_1 = Q = 20dB$.

Additional Files
This is as a reference to check the layout of the article as the authors intended.