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Performance analysis of cognitive underlay two-way relay networks with interference and imperfect channel state information

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Abstract

In this paper, we evaluate two-way relay communication systems in cognitive radio environments. The proposed model includes two subsystems: a primary system and a secondary system. The primary system consists of a primary transmitter and a primary receiver while the secondary includes two terminals exchanging their data via an intermediate relay node. Each network node is equipped with a single antenna and operates under a half-duplex mode. The channel state information (CSI) interference from the secondary node to the primary receiver is assumed imperfect. Using analytical methods, this paper derives the interference probability from the secondary system to the primary receiver and an optimal back-off control power coefficient for the secondary transmitter. To evaluate the secondary system quality, an explicit expression for the system outage probability (OP) and its closed form in the high signal-to-noise region (SNR) is presented. Theoretical results are verified using Monte-Carlo simulation.

Keywords: Cognitive radio, Imperfect CSI, Two-way relaying, Underlay approach

1 Introduction

Rapid development of wireless networks coupling with a large number of users and requirements for high-speed wireless services leads to radio frequency spectrum scarcity. Many researchers have enhanced the spectrum efficiency using various methods such as multiplexing and modulation, which are also useful for overcoming fading severity. However, it appears that the current available approaches only enhance a portion of the vast available spectral efficiency rather than potentially being long-term approaches for the next wireless generation systems. Recently, cognitive radio has been proposed as a promising technique to address spectral efficiency problem. It is clear that cognitive radio techniques widen radio spectrum access, where unlicensed users are allowed to operate in the same frequency band allocated to licensed users. Therefore, in the current cognitive radio medium,

there are two main systems: the primary system and the secondary system. To detect spectral opportunities, various spectrum sensing algorithms are presented, where energy detection-based spectrum sensing is an effective and simple detection technique [1–3].

Cognitive radio techniques have not only attracted researchers from academia worldwide but also gaining attention from the industry and governments. As such, these techniques have increasingly become one of the main research areas, and many findings have been published on the topic including the use of (i) multiple input, multiple output (MIMO) technologies [4, 5], (ii) relay selection [6, 7], (iii) multi-hop relaying [8, 9], (iv) physical layer security [10], (v) energy harvesting technologies [11, 12], and (vi) a new system model to analyze system quality [13–15].

In conventional wireless systems, the two-way transmission technique not only enhances spectral efficiency but also allows extended coverage [16]. Therefore, this technique has received considerable researchers' attention in recent years. For this technique, there are two basic signal processing methods being employed at the intermediate

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relay node: AF (amplify and forward) and DF (decode and forward). Most existing studies apply these methods in two-phase two-way or three-phase two-way relay transmission protocols [17]. Furthermore, some studies have evaluated two-way systems in Nakagami- m fading [18] and also in other fading channels [19].

Combining the two-way relay transmission technique with cognitive radio, one significantly increases system spectral efficiency. In [20], Duy et al. analyzed the quality of two-way relay transmission secondary systems in which their model includes three-phase DF relay intermediate nodes. Furthermore, they obtained exact expressions for the system outage probability in Rayleigh fading. For two-way DF relaying systems in cognitive radio environments, Afana et al. derived exact expressions for the system outage probability and bit error rate in a two-way system, consisting of several relay nodes, primary transmitters and primary receivers [21–23] which are important findings for further developments on cognitive relay radio techniques. However, Afana's analytical results are only correct for system models with a large number of relay nodes and a limited number of primary receivers. To overcome this bottleneck, the authors in [24] offered exact expressions for the system outage probability where the numbers of relay nodes and primary receivers are allowed to be arbitrary in Nakagami- m fading. Considering AF two-way relay transmission systems employing massive MIMO, the authors in [25] solved for the optimal beamforming power allocation and optimal coefficients. One of the most important contributions to the literature is presented by Zhang et al. [26], in which the authors evaluated system quality and gave exact expressions for system outage probability when considering interference effects from the primary transmitter to the secondary network nodes. It is noted that the common feature of most current contributions is only to consider two-way systems for perfect channel state information (CSI).

It is also clear that because of continuous random variation of fading channels and channel estimation errors, perfect CSI is practically difficult to acquire. For cognitive radio systems, if the transmitters in the secondary system do not have perfect CSI, these equipments don't effectively and efficiently control their required transmit power, increasing interference to the primary receivers and subsequently affect the primary system operation. Therefore, cognitive radio system quality evaluation under imperfect CSI conditions is necessary as the findings can be used to verify theoretical prediction against practical data. In [27], the authors considered a system model that has two secondary terminals and a number of intermediate relay nodes in cognitive radio environments. Their proposed system is mathematically modeled and solved to obtain optimal beamforming for two cases: perfect CSI and imperfect CSI. However, these

authors did not consider interference effects from the primary transmitters to the secondary system. Considering mutual interference between the primary network and the secondary network, the authors in [28] focused on analyzing the system under imperfect CSI condition. In addition, relay systems' quality is analyzed in cognitive radio environments for imperfect CSI such as [29] evaluated the multi-stage secondary system quality, while [30] studied a cooperative transmission secondary system in Nakagami- m fading.

To the best of our knowledge, the findings on evaluating two-way relay transmission system' quality in cognitive radio environments considering interference from the primary transmitters to the secondary system with imperfect CSI from the secondary network nodes to the primary receivers are not yet available. The contribution of the paper thus are:

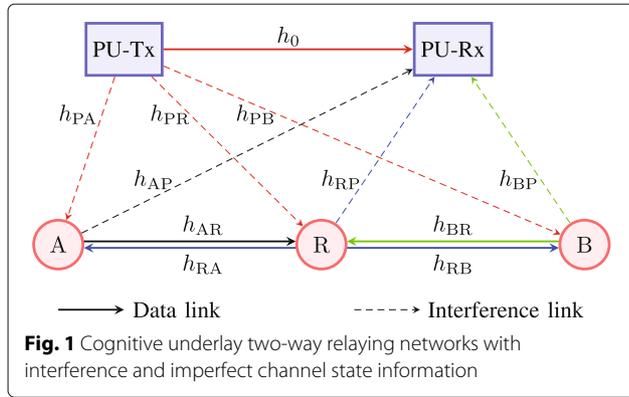
- Deriving the interference probability from the secondary system to primary receivers for imperfect CSI;
- Obtaining power back-off coefficients for secondary network nodes' transmitters to ensure satisfactory interference probability from primary receivers is achieved;
- Deriving an exact expression for the secondary system outage probability;
- Offering an asymptotic outage probability (OP) formula for the secondary system in the high SNR region and determining the system diversity order.

The paper is organized as follows: Section 2 outlines the proposed system model. The outage probability for the secondary system is studied in Section 3 while Section 4 presents simulation results. Section 5 concludes the main findings of this paper and gives possible future work.

2 System model

Figure 1 shows the system model which includes network nodes of the primary network and the secondary network. The primary network consists of a primary transmitter PU-Tx and a primary receiver PU-Rx while the secondary network consists of two terminals A and B exchanging data via the intermediate relay node R. It is assumed that each network node is equipped with a single antenna and operates in the half-duplex mode.

The channel coefficient from node X to node Y is denoted as h_{XY} , where $X, Y \in \{A, B, R, P\}$. The interference channel from the secondary nodes to the primary receiver (PU-Rx) is h_{XP} , and the interference channel from the primary transmitter (PU-Tx) to secondary nodes is h_{PX} with $X \in \{A, B, R\}$. It is assumed that all channels experience flat independent Rayleigh fading. Therefore, the channel



gain from node X to node Y, $|h_{XY}|^2$, is an exponential-distributed random variable having the cumulative distribution function (CDF) and probability density function (PDF) given as

$$F_{|h_{XY}|^2}(z) = 1 - e^{-\frac{z}{\lambda_{XY}}}, \quad (1)$$

$$f_{|h_{XY}|^2}(z) = \frac{1}{\lambda_{XY}} e^{-\frac{z}{\lambda_{XY}}}, \quad (2)$$

where $\lambda_{XY} = \mathbb{E}\{|h_{XY}|^2\}$ with $\mathbb{E}\{\cdot\}$ being expectation operator.

The two-way relay transmission process between node A and node B occurs in three phases, and relay node R processes its received signals using DF relaying. In the first phase, node A transmits its signals to node R. Then, node B transmits its signals to node R in the second phase. Finally, the relay decodes and encodes its received signals from node A and node B before broadcasting these signals to the two terminals in the third phase.

Since the secondary system operates at the primary system frequency band, the transmit power of the secondary network nodes has to be adjusted to ensure that interference \tilde{I}_p to the receiver PU-Rx is kept under a threshold. Thus, if the secondary nodes fully possess the interference CSI at the primary receiver, the best transmit power of the secondary nodes can be defined as

$$P_X = \frac{\tilde{I}_p}{|h_{XP}|^2}, \quad X \in \{A, B, R\}. \quad (3)$$

However, in practice, perfect CSI of the interference links from secondary transmitters to the primary receiver is not available at the corresponding secondary transmitters because of channel estimation errors or time-varying impairments, is possibly caused by the combination of channel estimation error, mobility, feedback delay, and limited feedback. Therefore, interference channel coefficients from the secondary node X to the primary receiver Y are often estimated as \hat{h}_{XP} , which are different from

the exact channel coefficients, mathematically described as [31]

$$\hat{h}_{XP} = \rho h_{XP} + \sqrt{1 - \rho^2} \xi_{XP}, \quad (4)$$

where ξ_{XP} is a complex symmetric zero-mean Gaussian random variable with the variance λ_{XP} , and ρ is a correlation coefficient between the real channel and the estimated channel. This correlation coefficient can be determined using a pilot symbol modulated parameter (PSAM) [32]. For Rayleigh fading channels, the joint PDF of $|\hat{h}_{XP}|^2$ and $|h_{XP}|^2$ is defined as [31]

$$f_{|h_{XP}|^2, |\hat{h}_{XP}|^2}(x, y) = \frac{e^{-\frac{x+y}{(1-\rho^2)\lambda_{XP}}}}{(1-\rho^2)\lambda_{XP}^2} I_0\left(\frac{2\rho\sqrt{xy}}{(1-\rho^2)\lambda_{XP}}\right), \quad (5)$$

where $I_0(x) = \frac{1}{\pi} \int_0^\pi e^{x \cos \theta} d\theta$ is the zeroth-order modified Bessel function of the first kind.

From (5), we obtain the PDF of $|\hat{h}_{XP}|^2$ as [33]

$$\begin{aligned} f_{|\hat{h}_{XP}|^2}(y) &= \int_0^\infty \frac{e^{-\frac{x+y}{(1-\rho^2)\lambda_{XP}}}}{(1-\rho^2)\lambda_{XP}^2} I_0\left(\frac{2\rho\sqrt{xy}}{(1-\rho^2)\lambda_{XP}}\right) dx \\ &= \frac{1}{\lambda_{XP}} e^{-\frac{y}{\lambda_{XP}}}. \end{aligned} \quad (6)$$

As a result, the best transmit power of the secondary network nodes for imperfect CSI can be defined as

$$P_X = \frac{\tilde{I}_p}{|\hat{h}_{XP}|^2}, \quad X \in \{A, B, R\}. \quad (7)$$

In the first phase, the received signal at node R from node A can be written as

$$y_{AR} = \sqrt{\frac{\tilde{I}_p}{|\hat{h}_{AP}|^2}} h_{AR} x_A + \sqrt{P_{PU-Tx}} h_{PR} x_P + n_R^1, \quad (8)$$

where x_X is the transmit symbol of node X with $\mathbb{E}\{|x_X|^2\} = 1$; $n_R^k \sim \mathcal{N}(0, N_0)$ is additive white Gaussian noise (AWGN) at phase k with zero mean and variance of N_0 . In addition, x_P and P_{PU-Tx} are the transmit symbol and the transmit power of the primary transmitter PU-Tx, respectively, with $\mathbb{E}\{|x_P|^2\} = 1$. Similarly, we can write the received signal at node R from node B in the second phase as

$$y_{BR} = \sqrt{\frac{\tilde{I}_p}{|\hat{h}_{BP}|^2}} h_{BR} x_B + \sqrt{P_{PU-Tx}} h_{PR} x_P + n_R^2. \quad (9)$$

Therefore, the signal power to noise and interference ratio of the received signal at R in the first and second phases can be given, respectively, by

$$\gamma_{AR} = \frac{\tilde{I}_p |h_{AR}|^2}{|\hat{h}_{AP}|^2 (N_0 + P_{PU-Tx} |h_{PR}|^2)} \quad (10)$$

and

$$\gamma_{BR} = \frac{\tilde{I}_p |h_{BR}|^2}{|\hat{h}_{BP}|^2 (N_0 + P_{PU-Tx} |h_{PR}|^2)}. \quad (11)$$

In the third phase, relay node R adjusts its transmit power to keep interference at the primary receiver input under a threshold \tilde{I}_p . The received signal at terminal X with $X \in \{A, B\}$ in the third phase is given as

$$y_{RX} = \sqrt{\frac{\tilde{I}_p}{|\hat{h}_{XP}|^2}} h_{RX} x_R + \sqrt{P_{PU-Tx}} h_{PX} x_P + n_X, \quad (12)$$

where $n_X \sim \mathcal{N}(0, N_0)$ is AWGN at the receiver input of terminal node X, and x_R is the transmit symbol of relay node R with $\mathbb{E}\{|x_R|^2\} = 1$.

Thus, the simultaneous signal power to interference ratio at the two terminals A and B can be given by

$$\gamma_{RA} = \frac{\tilde{I}_p |h_{RA}|^2}{|\hat{h}_{RP}|^2 (N_0 + P_{PU-Tx} |h_{PA}|^2)} \quad (13)$$

and

$$\gamma_{RB} = \frac{\tilde{I}_p |h_{RB}|^2}{|\hat{h}_{RP}|^2 (N_0 + P_{PU-Tx} |h_{PB}|^2)}. \quad (14)$$

3 Performance analysis

In this section, we study the performance of primary and secondary networks. For the primary networks, we consider the interference probability. For the secondary networks, we derive the system outage probability and its asymptotic expression at high SNR regime.

3.1 Primary networks: interference probability analysis

The interference probability is defined as the probability that the interference from secondary transmitters received at the primary transmitters is greater than the interference threshold, I_p . Considering three communications phases for the secondary networks, we may write the primary interference probability using the theorem of total probability as follows:

$$\begin{aligned} P_I &= \Pr(P_A |h_{AP}|^2 > \tilde{I}_p) \\ &+ \Pr(P_A |h_{AP}|^2 \leq \tilde{I}_p) \Pr(P_B |h_{BP}|^2 > \tilde{I}_p) \\ &+ \Pr(P_A |h_{AP}|^2 \leq \tilde{I}_p) \Pr(P_B |h_{BP}|^2 \leq \tilde{I}_p) \\ &\times \Pr(P_R |h_{RP}|^2 > \tilde{I}_p). \end{aligned} \quad (15)$$

Using the result in [29], we straightforwardly arrive at

$$P_I = 0.875, \quad (16)$$

where $\Pr\left(\frac{|h_{XP}|^2}{|\hat{h}_{XP}|^2} > 1\right) = \frac{1}{2}$ is for Rayleigh fading channels.

To reduce P_I , we adopt the back-off technique, i.e., reducing the secondary transmit power to obtain acceptable interference. Denoting δ_X with $0 \leq \delta_X \leq 1$ as the back-off power control coefficient of node X, the transmit power of node X can be rewritten as

$$\bar{P}_X = \delta_X P_X = \frac{\delta_X \tilde{I}_p}{|\hat{h}_{XP}|^2}. \quad (17)$$

Applying Lemma 1 in [29], after tedious manipulations, we finally obtain the closed-form expression for the interference probability as

$$\begin{aligned} P_I &= \frac{1 + \varphi_A}{2} + \frac{1 + \varphi_B}{2} \frac{1 - \varphi_A}{2} + \frac{1 + \varphi_R}{2} \frac{1 - \varphi_A}{2} \frac{1 - \varphi_B}{2} \\ &= 1 - \left(\frac{1 - \varphi_A}{2}\right) \left(\frac{1 - \varphi_B}{2}\right) \left(\frac{1 - \varphi_R}{2}\right), \end{aligned} \quad (18)$$

where $\varphi_X = \frac{\delta_X - 1}{\sqrt{(\delta_X + 1)^2 - 4\rho^2 \delta_X}}$ with $X \in \{A, B, R\}$.

Applying the arithmetic-geometric inequality ([34], Eq. (11.116)) for three positive numbers $\frac{1 - \varphi_A}{2}$, $\frac{1 - \varphi_B}{2}$, and $\frac{1 - \varphi_R}{2}$ in (18), we have

$$\left(\frac{1 - \varphi_A}{2}\right) \left(\frac{1 - \varphi_B}{2}\right) \left(\frac{1 - \varphi_R}{2}\right) \leq \left(\frac{\frac{1 - \varphi_A}{2} + \frac{1 - \varphi_B}{2} + \frac{1 - \varphi_R}{2}}{3}\right)^3. \quad (19)$$

From (19), it appears that the interference probability can achieve its minimum if and only if $\delta_A = \delta_B = \delta_R = \delta$, where $\varphi = \frac{\delta - 1}{\sqrt{(\delta + 1)^2 - 4\rho^2 \delta}}$.

The minimum of P_I may be given as

$$P_I = 1 - \left(\frac{1 - \varphi}{2}\right)^3, \quad (20)$$

for an equi-correlation coefficient ρ in all interference channels.

Although the back-off power control technique is useful in obtaining satisfactory P_I , it also degrades the secondary network performance. Thus, it is necessary to calculate the back-off power control peak coefficient for a given P_I . Using the analysis method as in [29], we can find the back-off power control peak coefficient as follows:

$$\delta_{\max} = \frac{1 + \kappa^2 - 2\kappa^2 \rho^2 - 2\sqrt{\kappa^2 - \kappa^2 \rho^2 - \kappa^4 \rho^2 + \kappa^4 \rho^2}}{1 - \kappa^2}, \quad (21)$$

where $\kappa = 2\sqrt[3]{1 - P_I} - 1$.

3.2 Secondary two-way relaying networks

In this section, the performance of cognitive underlay two-way relaying networks over Rayleigh fading channels is studied starting with the instantaneous SNRs at the

receiving nodes using the back-off coefficient. In particular, we obtain the SNR at R in the first and second phase, respectively, as follows:

$$\gamma'_{AR} = \delta_A \gamma_{AR}, \tag{22}$$

and

$$\gamma'_{BR} = \delta_B \gamma_{BR}. \tag{23}$$

For the third phase, we have the SNRs at A and B, respectively, as

$$\gamma'_{RA} = \delta_R \gamma_{RA}, \tag{24}$$

and

$$\gamma'_{RB} = \delta_R \gamma_{RB}. \tag{25}$$

For two-way DF relaying, the secondary system outage probability can be written as

$$OP = 1 - Pr(\gamma'_{AR} > \gamma_{th}, \gamma'_{BR} > \gamma_{th}, \gamma_e > \gamma_{th}), \tag{26}$$

where γ_e is defined as

$$\gamma_e = \min\{\gamma'_{RA}, \gamma'_{RB}\} \tag{27}$$

and γ_{th} is the given SNR threshold.

Assuming that γ'_{AR} , γ'_{BR} , and γ_e are independent of each other, we may write

$$\begin{aligned} OP &= 1 - Pr(\gamma'_{AR} > \gamma_{th}) Pr(\gamma'_{BR} > \gamma_{th}) Pr(\gamma_e > \gamma_{th}) \\ &= 1 - [1 - F_{\gamma'_{AR}}(\gamma_{th})][1 - F_{\gamma'_{BR}}(\gamma_{th})] \\ &\quad \times [1 - F_{\gamma_e}(\gamma_{th})], \end{aligned} \tag{28}$$

where $F_Z(z)$ is the CDF of Z .

In order to derive the exact expression of the system outage probability, we consider the following Lemma.

Lemma 1 *Let X and Y are exponentially distributed random variables with means λ_X and λ_Y , respectively, and Z is a random variable defined as $Z = \frac{X}{PY+1}$, where $P > 0$, $P \in \mathbb{R}$. The CDF of Z can be given as*

$$F_Z(z) = 1 - \frac{\lambda_X}{Pz\lambda_Y + \lambda_X} e^{-\frac{z}{\lambda_X}}. \tag{29}$$

Proof We have

$$\begin{aligned} F_Z(z) &= Pr\left(\frac{X}{PY+1} < z\right) \\ &= \int_0^\infty Pr(X < z + Pzy) f_Y(y) dy \\ &= 1 - \int_0^\infty e^{-\frac{z+Pzy}{\lambda_X}} \frac{1}{\lambda_Y} e^{-\frac{y}{\lambda_Y}} dy \\ &= 1 - \frac{1}{\lambda_Y} e^{-\frac{z}{\lambda_X}} \int_0^\infty e^{-\left(\frac{Pz}{\lambda_X} + \frac{1}{\lambda_Y}\right)y} dy. \end{aligned} \tag{30}$$

Applying ([34], eq. (3.310¹¹)), we obtain the CDF of Z as (29). \square

Then, the exact closed-form expression for the system OP is stated in Theorem 1.

Theorem 1 *For a given ρ , the closed-form expression for the system outage probability over Rayleigh fading channels is*

$$\begin{aligned} OP &= 1 - \frac{\delta_A I_p \lambda_{AR}}{\gamma_{th} P \lambda_{PR} \lambda_{AP}} e^{m_1 k_1} Ei(-m_1 k_1) \\ &\quad \times \frac{\delta_B I_p \lambda_{BR}}{\gamma_{th} P \lambda_{PR} \lambda_{BP}} e^{m_2 k_2} Ei(-m_2 k_2) \frac{\psi}{\lambda_{RP} (x_2 - x_1)} \\ &\quad \times \left[-e^{x_1 \left(\phi + \frac{1}{\lambda_{RP}}\right)} Ei\left(-x_1 \left(\phi + \frac{1}{\lambda_{RP}}\right)\right) \right. \\ &\quad \left. + e^{x_2 \left(\phi + \frac{1}{\lambda_{RP}}\right)} Ei\left(-x_2 \left(\phi + \frac{1}{\lambda_{RP}}\right)\right) \right], \end{aligned} \tag{31}$$

where $Ei(\cdot)$ is the exponential integral [27, Eq. (8.211)],

$$\begin{aligned} m_1 &= \frac{\delta_A I_p \lambda_{AR}}{\gamma_{th} P \lambda_{PR}}, m_2 = \frac{\delta_B I_p \lambda_{BR}}{\gamma_{th} P \lambda_{PR}}, k_1 = \frac{\gamma_{th}}{\delta_A I_p \lambda_{AR}} + \frac{1}{\lambda_{AP}}, k_2 = \\ &= \frac{\gamma_{th}}{\delta_B I_p \lambda_{BR}} + \frac{1}{\lambda_{BP}}, x_1 = \frac{\delta_R I_p \lambda_{RA}}{\gamma_{th} P \lambda_{PA}}, x_2 = \frac{\delta_R I_p \lambda_{RB}}{\gamma_{th} P \lambda_{PB}}, \phi = \frac{\gamma_{th}}{\delta_R I_p \lambda_{RA}} + \\ &= \frac{\gamma_{th}}{\delta_R I_p \lambda_{RB}}, \text{ and } \psi = \frac{\delta_R^2 I_p^2 \lambda_{RA} \lambda_{RB}}{\gamma_{th}^2 P^2 \lambda_{PA} \lambda_{PB}}. \end{aligned}$$

Proof From (26), we can see that the explicit expression for the system outage probability in (28) can be defined after determining the CDF of γ'_{AR} , γ'_{BR} , and γ_e .

We first consider the CDF of γ'_{AR} . Using the conditional probability, we can write the CDF of γ'_{AR} as

$$F_{\gamma'_{AR}}(\gamma_{th}) = \int_0^\infty F_{\gamma'_{AR}||h_{AP}|^2}(\gamma_{th}|x) f_{|h_{AP}|^2}(x) dx \tag{32}$$

where $F_{\gamma'_{AR}||h_{AP}|^2}(\gamma_{th}|x)$ is the CDF of γ'_{AR} conditioned on $|h_{AP}|^2$ and $f_{|h_{AP}|^2}(x)$ is the PDF of $|h_{AP}|^2$.

Recalling (10) and (22), we can write

$$F_{\gamma'_{AR}||h_{AP}|^2}(\gamma_{th}|x) = Pr\left(\frac{|h_{AR}|^2}{1 + P|h_{PR}|^2} < \frac{x\gamma_{th}}{\delta_A I_p}\right), \tag{33}$$

where $I_p = \tilde{I}_p/N_0$ and $P = P_{PU-Tx}/N_0$.

Applying the result of Lemma 1, where X, Y , and z correspond $|h_{AR}|^2, |h_{PR}|^2$, and $\frac{x\gamma_{th}}{\delta_A I_p}$, respectively, we have

$$\begin{aligned} F_{\gamma'_{AR}||\hat{h}_{AP}|^2}(\gamma_{th}|x) &= 1 - \frac{\delta_A I_p \lambda_{AR}}{\gamma_{th} P \lambda_{PR}} \left(x + \frac{\delta_A I_p \lambda_{AR}}{\gamma_{th} P \lambda_{PR}}\right) \\ &\quad \times e^{-\frac{x\gamma_{th}}{\delta_A I_p \lambda_{AR}}}. \end{aligned} \tag{34}$$

Substituting (34) and (2) into (35), we have

$$F_{\gamma'_{AR}}(\gamma_{th}) = 1 - \int_0^\infty \frac{\delta_A I_P \lambda_{AR}}{\gamma_{th} P \lambda_{PR} \lambda_{AP} \left(x + \frac{\delta_A I_P \lambda_{AR}}{\gamma_{th} P \lambda_{PR}}\right)} \times e^{-\left(\frac{\gamma_{th}}{\delta_A I_P \lambda_{AR}} + \frac{1}{\lambda_{AP}}\right)x} dx. \quad (35)$$

Using ([34], Eq. (3.352.4)), we obtain

$$F_{\gamma'_{AR}}(\gamma_{th}) = 1 + \frac{\delta_A I_P \lambda_{AR}}{\gamma_{th} P \lambda_{PR} \lambda_{AP}} e^{m_1 k_1} \text{Ei}(-m_1 k_1), \quad (36)$$

where $m_1 = \frac{\delta_A I_P \lambda_{AR}}{\gamma_{th} P \lambda_{PR}}$ and $k_1 = \frac{\gamma_{th}}{\delta_A I_P \lambda_{AR}} + \frac{1}{\lambda_{AP}}$.

Here, we note that γ'_{AR} and γ'_{BR} take the same form. Similarly, the CDF of γ'_{BR} can be given by

$$F_{\gamma'_{BR}}(\gamma_{th}) = 1 + \frac{\delta_B I_P \lambda_{BR}}{\gamma_{th} P \lambda_{PR} \lambda_{BP}} e^{m_2 k_2} \text{Ei}(-m_2 k_2), \quad (37)$$

where $m_2 = \frac{\delta_B I_P \lambda_{BR}}{\gamma_{th} P \lambda_{PR}}$ and $k_2 = \frac{\gamma_{th}}{\delta_B I_P \lambda_{BR}} + \frac{1}{\lambda_{BP}}$.

We are now in a position to derive the CDF of $F_{\gamma_e}(\gamma_{th})$. Making use the fact that γ_{RA} and γ_{RB} are correlated due to the common random variable $|\hat{h}_{RP}|^2$, we can write the CDF of $F_{\gamma_e}(\gamma_{th})$ as

$$F_{\gamma_e} = \int_0^\infty F_{\gamma_e || h_{RP}|^2}(\gamma_{th} | x) f_{|h_{RP}|^2}(x) dx, \quad (38)$$

where $F_{\gamma_e || \hat{h}_{RP}|^2}(\gamma_{th} | x)$ denotes the CDF of γ_e conditioned on $|\hat{h}_{RP}|^2$ given by

$$\begin{aligned} & F_{\gamma_e || \hat{h}_{RP}|^2}(\gamma_{th} | x) \\ &= \Pr \left[\min \left(\frac{\delta_R I_P |h_{RA}|^2}{x(1+P|h_{PA}|^2)}, \frac{\delta_R I_P |h_{RB}|^2}{x(1+P|h_{PB}|^2)} \right) < \gamma_{th} \right] \\ &= 1 - \Pr \left(\frac{|h_{RA}|^2}{1+P|h_{PA}|^2} > \frac{x\gamma_{th}}{\delta_R I_P} \right) \\ &\quad \times \Pr \left(\frac{|h_{RB}|^2}{1+P|h_{PB}|^2} > \frac{x\gamma_{th}}{\delta_R I_P} \right). \end{aligned} \quad (39)$$

Applying Lemma 1 for the second term in (39), where X, Y , and z correspond $|h_{RA}|^2, |h_{PA}|^2$, and $\frac{x\gamma_{th}}{\delta_R I_P}$, respectively, we have

$$\Pr \left(\frac{|h_{RA}|^2}{1+P|h_{PA}|^2} > \frac{x\gamma_{th}}{\delta_R I_P} \right) = \frac{\delta_R I_P \lambda_{RA}}{\gamma_{th} P \lambda_{PA} (x + x_1)} \times e^{-\frac{\gamma_{th} x}{\delta_R I_P \lambda_{RA}}}, \quad (40)$$

where $x_1 = \frac{\delta_R I_P \lambda_{RA}}{\gamma_{th} P \lambda_{PA}}$. Similarly, we have

$$\Pr \left(\frac{|h_{RB}|^2}{1+P|h_{PB}|^2} > \frac{x\gamma_{th}}{\delta_R I_P} \right) = \frac{\delta_R I_P \lambda_{RB}}{\gamma_{th} P \lambda_{PB} (x + x_2)} \times e^{-\frac{\gamma_{th} x}{\delta_R I_P \lambda_{RB}}}, \quad (41)$$

where $x_2 = \frac{\delta_R I_P \lambda_{RB}}{\gamma_{th} P \lambda_{PB}}$.

Substituting (40), (41), and (39) into (38), we obtain

$$\begin{aligned} F_{\gamma_e}(\gamma_{th}) &= 1 - \psi \int_0^\infty \frac{1}{(x + x_1)(x + x_2)} e^{-\phi x} f_{|\hat{h}_{RP}|^2}(x) dx \\ &= 1 - \frac{\psi}{\lambda_{RP}(x_2 - x_1)} \int_0^\infty \frac{1}{(x + x_1)} e^{-\left(\phi + \frac{1}{\lambda_{RP}}\right)x} dx \\ &\quad + \frac{\psi}{\lambda_{RP}(x_2 - x_1)} \int_0^\infty \frac{1}{(x + x_2)} e^{-\left(\phi + \frac{1}{\lambda_{RP}}\right)x} dx, \end{aligned} \quad (42)$$

where $\phi = \frac{\gamma_{th}}{\delta_R I_P \lambda_{RA}} + \frac{\gamma_{th}}{\delta_R I_P \lambda_{RB}}$ and $\psi = \frac{\delta_R^2 I_P^2 \lambda_{RA} \lambda_{RB}}{\gamma_{th}^2 P^2 \lambda_{PA} \lambda_{PB}}$.

Applying ([34], Eq. (3.352.4)), one has

$$\begin{aligned} F_{\gamma_e}(\gamma_{th}) &= 1 + \frac{\psi}{\lambda_{RP}(x_2 - x_1)} e^{x_1 \left(\phi + \frac{1}{\lambda_{RP}}\right)} \\ &\quad \times \text{Ei} \left[-x_1 \left(\phi + \frac{1}{\lambda_{RP}} \right) \right] \\ &\quad - \frac{\psi}{\lambda_{RP}(x_2 - x_1)} e^{x_2 \left(\phi + \frac{1}{\lambda_{RP}}\right)} \\ &\quad \times \text{Ei} \left[-x_2 \left(\phi + \frac{1}{\lambda_{RP}} \right) \right]. \end{aligned} \quad (43)$$

Substituting (36), (37), and (43) into (28), we obtain an exact expression for the secondary system outage probability, when the interference CSI to the primary receiver is imperfect as in (31). □

3.2.1 Asymptotic system outage probability at high SNR regime

By using $1 - e^{-x} \approx x$, the approximate CDF expression for $\gamma'_{AR}, \gamma'_{BR}$, and γ_e over the high SNR region can be calculated, so that the corresponding asymptotic system outage probability can be found.

Theorem 2 *Over Rayleigh fading channels, the asymptotic system outage probability at high SNR regime is of the form as (44).*

$$\begin{aligned} \text{OP}^{I_P \rightarrow +\infty} &\approx 1 - \left(1 - \frac{\gamma_{th} \lambda_{AP}}{\delta_A I_P \lambda_{AR}} (1 + P \lambda_{PR}) \right) \left(1 - \frac{\gamma_{th} \lambda_{BP}}{\delta_A I_P \lambda_{BR}} (1 + P \lambda_{PR}) \right) \\ &\quad \times \left(1 - \frac{\gamma_{th} (1 + P \lambda_{PA}) \lambda_{RP}}{\delta_R I_P \lambda_{RA}} - \frac{\gamma_{th} (1 + P \lambda_{PB}) \lambda_{RP}}{\delta_R I_P \lambda_{RB}} \right). \end{aligned} \quad (44)$$

Proof We start the proof from the definition of $F_{\gamma'_{AR}}(\gamma_{th})$ as

$$\begin{aligned}
 F_{\gamma'_{AR}}(\gamma_{th}) &= \Pr\left(\frac{\delta_A I_P |h_{AR}|^2}{|\hat{h}_{AP}|^2 (1 + P|h_{PR}|^2)} < \gamma_{th}\right) \\
 &= \int_0^\infty \int_0^\infty \Pr\left(|h_{AR}|^2 < \frac{x\gamma_{th}(1 + P\gamma)}{\delta_A I_P}\right) \\
 &\quad \times f_{|\hat{h}_{AP}|^2}(x) f_{|h_{PR}|^2}(y) dx dy. \tag{45}
 \end{aligned}$$

Based on the exponential approximate property, we are able to find the approximate CDF for γ'_{AR} as

$$\begin{aligned}
 F_{\gamma'_{AR}}(\gamma_{th}) \stackrel{I_p \rightarrow +\infty}{\approx} &\int_0^\infty \int_0^\infty \frac{x\gamma_{th}(1 + P\gamma)}{\delta_A I_P \lambda_{AR}} \\
 &\times \frac{1}{\lambda_{AP}} e^{-\frac{x}{\lambda_{AP}}} \frac{1}{\lambda_{PR}} e^{-\frac{y}{\lambda_{PR}}} dx dy. \tag{46}
 \end{aligned}$$

Using ([34], Eq. (3.351.3)) for the inner integral of (46), we have

$$\begin{aligned}
 F_{\gamma'_{AR}}(\gamma_{th}) \stackrel{I_p \rightarrow +\infty}{\approx} &\frac{\gamma_{th} \lambda_{AP}}{\delta_A I_P \lambda_{AR}} \int_0^\infty (1 + P\gamma) \frac{1}{\lambda_{PR}} e^{-\frac{y}{\lambda_{PR}}} dy \\
 &= \frac{\gamma_{th} \lambda_{AP}}{\delta_A I_P \lambda_{AR}} (1 + P\lambda_{PR}). \tag{47}
 \end{aligned}$$

Utilizing similar analytical steps, we find the approximate CDF expression for γ'_{BR} as

$$F_{\gamma'_{BR}}(\gamma_{th}) \stackrel{I_p \rightarrow +\infty}{\approx} \frac{\gamma_{th} \lambda_{BP}}{\delta_B I_P \lambda_{BR}} (1 + P\lambda_{PR}), \tag{48}$$

For the approximate CDF expression for γ_e , from (39), we have

$$\begin{aligned}
 F_{\gamma_e|\hat{h}_{AP}|^2}(\gamma_{th}, x) &= 1 - \left[1 - \underbrace{\Pr\left(\frac{|h_{RA}|^2}{1 + P|h_{PA}|^2} < \frac{x\gamma_{th}}{\delta_R I_P}\right)}_{I_1} \right] \\
 &\quad \times \left[1 - \underbrace{\Pr\left(\frac{|h_{RB}|^2}{1 + P|h_{PB}|^2} < \frac{x\gamma_{th}}{\delta_R I_P}\right)}_{I_2} \right]. \tag{49}
 \end{aligned}$$

We first calculate I_1 as follows:

$$\begin{aligned}
 I_1 &= \Pr\left(\frac{|h_{RA}|^2}{1 + P|h_{PA}|^2} < \frac{x\gamma_{th}}{\delta_R I_P}\right) \\
 &= \int_0^\infty \Pr\left(|h_{RA}|^2 < \frac{(1 + P\gamma)x\gamma_{th}}{\delta_R I_P}\right) f_{|h_{PA}|^2}(\gamma) d\gamma \\
 &\stackrel{I_p \rightarrow +\infty}{\approx} \int_0^\infty \frac{(1 + P\gamma)x\gamma_{th}}{\delta_R I_P \lambda_{RA}} \frac{1}{\lambda_{PA}} e^{-\frac{\gamma}{\lambda_{PA}}} d\gamma \\
 &= \frac{\gamma_{th}(1 + P\lambda_{PA})}{\delta_R I_P \lambda_{RA}} x. \tag{50}
 \end{aligned}$$

Similarly, we have I_2 given by

$$\begin{aligned}
 I_2 &= \Pr\left(\frac{|h_{RB}|^2}{1 + P|h_{PB}|^2} < \frac{x\gamma_{th}}{\delta_R I_P}\right) \\
 &\approx \frac{\gamma_{th}(1 + P\lambda_{PB})}{\delta_R I_P \lambda_{RB}} x. \tag{51}
 \end{aligned}$$

Substituting I_1 in (50) and I_2 in (51) into (49), we can define the approximate CDF expression for γ_e as

$$\begin{aligned}
 F_{\gamma_e}(\gamma_{th}) &= \int_0^\infty \left(\frac{\gamma_{th}(1 + P\lambda_{PA})}{\delta_R I_P \lambda_{RA}} x + \frac{\gamma_{th}(1 + P\lambda_{PB})}{\delta_R I_P \lambda_{RB}} x \right) f_{|h_{RP}|^2}(x) dx \\
 &\quad - \int_0^\infty \left(\frac{\gamma_{th}(1 + P\lambda_{PA})}{\delta_R I_P \lambda_{RA}} \frac{\gamma_{th}(1 + P\lambda_{PB})}{\delta_R I_P \lambda_{RB}} x^2 \right) f_{|h_{RP}|^2}(x) dx. \tag{52}
 \end{aligned}$$

With the help of ([34], Eq. (3.351.3)), we derive the closed-form CDF expression for γ_e in the high SNR region as

$$F_{\gamma_e}(\gamma_{th}) \stackrel{I_p \rightarrow +\infty}{\approx} \left(\frac{\gamma_{th}(1 + P\lambda_{PA})}{\delta_R I_P \lambda_{RA}} + \frac{\gamma_{th}(1 + P\lambda_{PB})}{\delta_R I_P \lambda_{RB}} \right) \lambda_{RP}. \tag{53}$$

Substituting (47), (48), and (53) into (28), we obtain the approximate expression for the system outage probability in the high SNR region as in (44).

From (44), for $I_p \rightarrow +\infty$, we have

$$\text{OP} \stackrel{I_p \rightarrow +\infty}{\sim} \frac{1}{I_P} M, \tag{54}$$

where

$$\begin{aligned}
 M &= \frac{\gamma_{th} \lambda_{AP}}{\delta_A \lambda_{AR}} (1 + P\lambda_{PR}) + \frac{\gamma_{th} \lambda_{BP}}{\delta_B \lambda_{BR}} (1 + P\lambda_{PR}) \\
 &\quad + \frac{\gamma_{th}(1 + P\lambda_{PA}) \lambda_{RP}}{\delta_R \lambda_{RA}} + \frac{\gamma_{th}(1 + P\lambda_{PB}) \lambda_{RP}}{\delta_R \lambda_{RB}}. \tag{55}
 \end{aligned}$$

□

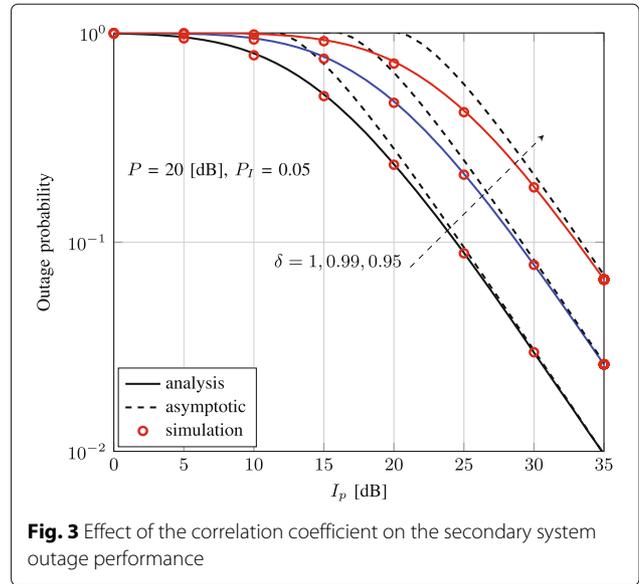
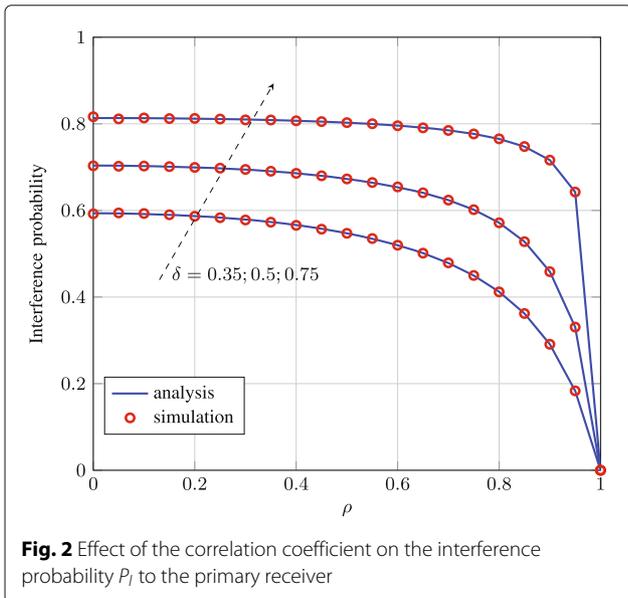
Therefore, it can be seen that over the high SNR region, the system outage probability is proportional to $\frac{1}{I_p}$. It can be shown that over the high SNR region, the system diversity is one.

4 Numerical results and discussion

In this section, the analytical results are verified using Monte-Carlo simulation. It is assumed that the system network nodes lie on a plane coordinate system Oxy , and the distance between node A and node B is normalized to 1. Therefore, for simulation purposes, the two secondary terminals are placed at $A[0; 0]$, $B[1; 0]$, $PU-Tx[0; 1]$, and $PU-Rx[1; 1]$, respectively, and the relay node is located at $R[0,5; 0]$. d_{MN} is the physical distance between two network nodes M and N, where $M, N \in \{A, B, R, PU - Rx, PU - Tx\}$. For free-space path loss transmission, we have $\lambda_{MN} = d_{MN}^{-\eta}$, where η is a path loss exponent, $2 \leq \eta \leq 6$. For simulation purposes, the following are also used: $\eta = 3$, $\gamma_{th} = 1.25$, $\delta_A = \delta_B = \delta_R = \delta_{max}$, and $P = 20$ dB.

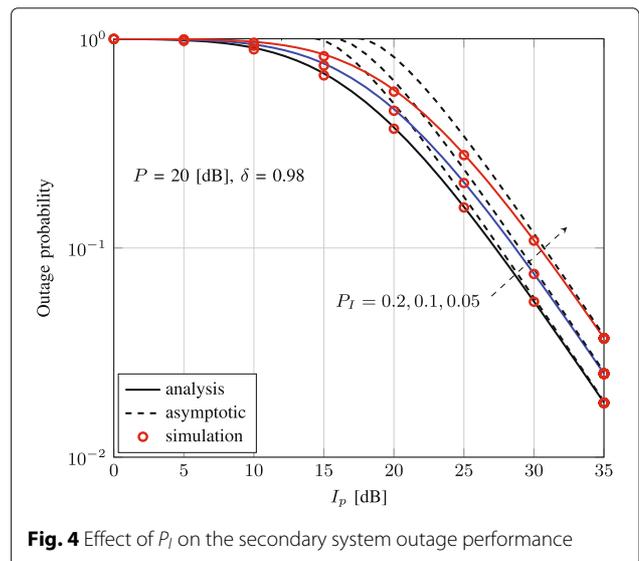
Figure 2 shows the secondary system interference probability to the primary receiver (P_I) as a function of ρ for three cases: $\delta = 0.35$, $\delta = 0.5$, and $\delta = 0.75$. It can be seen that our theoretical prediction and the simulation results are consistent, verifying our analyses. Furthermore, P_I is an inverse function of ρ , and there appears a singularity for $\rho \rightarrow 1^1$.

In Fig. 3, the secondary system outage probability for (i) when the correlation coefficient ρ is varied and (ii) $P_I = 0.05$, $P = 20$ [dB] is presented, from which our analytical results are consistent with the simulation results, verifying our derivation approach. Furthermore, the severity of the correlation coefficient ρ to the secondary system quality



is revealed when the secondary transmitters adjust their power following the back-off power δ_{max} .

Figure 4 presents the secondary system outage probability when the interference channel to the primary receiver is imperfect with a correlation coefficient $\rho = 0.98$ for $P = 20$ dB. The system is also simulated for $P_I = 0.2$, $P_I = 0.1$, and $P_I = 0.05$. It can be seen from Fig. 4 that reducing the interference probability degrades the secondary system quality. This is because the decrease in the interference probability P_I leads to the decrease of the back-off factor. Therefore, the secondary network nodes' transmit power decreases, hence increasing the secondary system outage probability.



5 Conclusion

This paper studies the DF two-way relay transmission system in cognitive radio environments. Furthermore, our proposed model considers the primary transmitter interference to the secondary system and evaluates the system quality when the interference CSI from the secondary transmitters to the primary receiver is imperfect. This paper has derived the interference probability to the primary receiver, the maximum back-off power factor which is used to keep interference under a threshold level. For the secondary system, an exact expression for the system outage probability and its asymptotic expression for the high SNR region have been obtained. These new findings have been verified using the Monte-Carlo simulation results. Further studies on two-way relay systems with imperfect CSI at the primary transmitters will be reported in a separate publication.

Endnote

¹ ρ can be assumed less than 1 to avoid the singularity.

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Authors' contributions

HVT and VNQB proposed the system model, derived the system performance, and performed the simulation and manuscript writing. KNL contributed in the manuscript preparation and manuscript revision. All authors read and approved the final manuscript.

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