Cognitive Coded Cooperation in Underlay Spectrum-Sharing Networks under Interference Power Constraints

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***Abstract*—Since the radio frequency spectrum is fast becoming scarce, increasing the spectral utilization is of utmost importance for the sustainable development of wireless communications systems. In an effort to improve the spectral efficiency, cooperative relaying techniques have recently been integrated into spectrum-sharing environments. In this paper, we examine the outage and bit error probabilities of dual-hop cognitive turbo-coded cooperative networks with outdated channel state information (CSI) subject to Rayleigh fading. We assume a spectrum-sharing environment where the transmit power conditions of the underlay network is governed by the combined power constraint of the interference in the primary network and the maximum allowable transmission power at the secondary network. In this network, co-channel interference (CCI) from the primary transmitter on the secondary network is considered and a single relay that maximizes the received signal-to-noise ratio (SNR) is selected among the secondary relays. To efficiently evaluate the key parameters on the system performance, we derive the analytical expressions of the end-to-end outage probability and bit error rate (BER) for the proposed scheme. Assuming binary phase-shift keying (BPSK), we obtain explicit upper bounds on the probability of bit error based on the pairwise error probability (PEP). Furthermore, we present simplified expressions of the outage probability in the high-SNR regime used to quantify the system performance in terms of diversity gain. Finally, simulation results are provided to verify the accuracy of our analytical framework.**

***Index Terms*—Channel state information, coded cooperation, interference temperature limit, relay selection, Turbo codes, underlay spectrum sharing.**

I. Introduction

Recent years have witnessed the growing scarcity of the indispensable electromagnetic spectrum resources. This has resulted from the exponential growth of the number of wireless communications systems and services, which is driving the evolution of wireless networks towards high-speed data networks. However, recent measurements performed by the Spectrum Policy Task Force (SPTF) within the Federal Communications Commission (FCC) have revealed that spectrum scarcity is mainly due to the inefficient and conservative spectrum policies, rather than the physical spectrum shortage [1]. The concept of cognitive radio (CR) [2] has been well exploited as an efficient means to resolve the growing scarcity of the prized radio spectrum in wireless applications. The aforementioned technique allows the unlicensed or secondary users (SUs) to access licensed/primary users' (PUs) spectrum provided the quality of service (QoS) of the latter users is guaranteed.

According to the ways of accessing and/or sharing the licensed users' spectrum, the CR systems are classified into three main paradigms: underlay, overlay and interweave [3]. In the underlay paradigm, the SUs and PUs are allowed to coexist if the interference caused to the PUs is below a pre-selected threshold. In overlay systems, SUs use some PUs information –overheard during PUs transmissions–along with sophisticated signal processing and coding techniques to maintain or improve the performance of PUs. In interweave systems, the SUs can sense the licensed band and access it only when a vacant spectrum band is detected. Among the spectrum-sharing techniques, the underlay scheme is widely used due to its simplicity and promising prospect.

In an effort to extend wireless coverage and improve system performance, cooperative relaying techniques which are being standardized in next generation wireless local area networks and cellular systems [4], can be exploited in spectrum-sharing systems where the transmit power of SUs is strictly limited (see [5]– [15] and the references therein). A recent work in [5] proposed three novel amplify-and-forward (AF) relay selection rules for underlay CR systems under the average interference constraint. In [6], the authors proposed a transmit antenna selection in dual-hop decode-and-forward (DF) underlay CR networks with outdated channel state information (CSI). The end-to-end performance of cooperative AF relaying in spectrum-sharing systems was investigated in [7] and [8]. In [9], the authors extended the analysis to a spectrum-sharing multi-hop AF relaying network. In [10], the exact outage probability of partial AF relay selection in spectrum-sharing cognitive relay networks with imperfect CSI was investigated. Zhong *et al.* [11] studied the impact of outdated CSI on partial relay selection with fixed-gain relays in underlay cognitive networks. In [12], the outage performance of DF cognitive dual-hop systems in Nakagami-*m* fading channels was studied.

While the aforementioned works have greatly improved our understanding on the performance of cognitive relaying techniques in underlay spectrum-sharing systems, they all considered uncoded cooperative relaying protocols. It is well known that coded cooperation [16] with efficient channel coding techniques provides some impressive gains over its non-cooperative counterparts while maintaining the same information rate and transmit power. Many works on conventional coded cooperation have been examined in the existing

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literature (See [17]– [19]). Elfituri *et al.* [17] proposed and investigated a distributed coded cooperative scheme suitable for multiple relays. In [18], a two-level automatic repeat request (ARQ) protocol combined with turbo-coded cooperation was proposed in an effort to guarantee inter-user channel improvement with the aid of the relay-level ARQ. In [19], the authors proposed a dynamic coded cooperation using multiple turbo codes in relay networks where a relay can autonomously determine whether to cooperate or not. To the best of the authors' knowledge, there is no reported work on cognitive coded cooperative relaying systems with the underlay scheme in the existing literature. Moreover, relay selection is seldom used in conventional coded cooperative networks. In [20], the performance of relay and antenna selection in AF coded cooperation using convolutional codes was investigated. Under more practical scenarios, Moualeu *et al.* [21] considered the effects of outdated CSI and studied its impact on the relay selection scheme in conventional coded cooperation. Motivated by these observations, and taking into account the PU's interference on the secondary network also referred to as co-channel interference (CCI), we propose a cognitive turbo-coded cooperation in an underlay CR system. For a practical system and an efficient utilization of the channel resources, relay selection with outdated CSI is considered in the secondary network. Also, CSI of the links between the secondary relays and the primary receiver is delayed which may cause harmful interference on the PU. We derive an expression for the end-to-end outage probability of the proposed scheme under peak interference constraint at the PU's receiver. In addition, we elaborate on the asymptotically high signal-to-noise ratio (SNR) regime to obtain some additional insights into the impact of some key parameters such as the number of relays. Subsequently, we present a bit-error rate (BER) analysis of the underlying system based on pairwise error probability (PEP). It is worth mentioning that the motivation for using coded cooperation instead of repetition coding which is widely investigated in the literature, is due to the fact that the latteris an inefficient code. Unlike repetition coding or uncoded cooperation, coded cooperation splits each codeword into two partitions or sub-codewords (not necessarily of same length). Each sub-codeword is transmitted distributively. Furthermore, coded cooperation in comparison to repetition coding, allows for more bandwidth allocation between the source and the relay due to the structure of the channel coding in use (based on redundancy).

The remainder of this paper is organized as follows. The system model is introduced in Section II. In Section III, we derive analytical expressions for the outage probability of the best relay selection of cognitive turbo-coded cooperation in underlay CR with outdated CSI. Moreover, high-SNR analysis is provided in Section IV. We analyze the upper bounds on the bit error probability in Section V. Numerical results supported by Monte-Carlo simulations for the system under consideration and related discussions are presented in Section VI. Finally, we draw conclusions in Section VII.

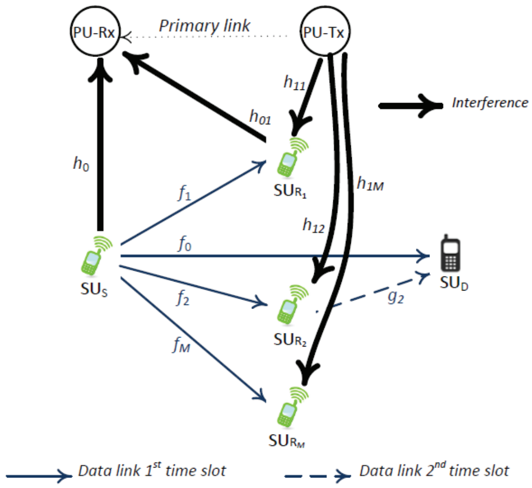

Fig. 1: System model of coded cooperation with relay selection in underlay spectrum sharing environment.

II. System Model

We consider an underlay cognitive cooperative relaying network illustrated in Fig. 1, where the SU and PU systems share the same spectral band in the same geographical area so long as the interference to the PU is below a given threshold. The PU system consists of a PU transmitter (PU-Tx) and a PU receiver (PU-Rx). The SU transmission consists of a secondary source SU_S communicating with a secondary destination SU_D with the help of M secondary relay SU_{R_i} where $i = 1, \ldots, M$. It is assumed that there is a direct link between SU_S and SU_D. All the nodes in cognitive network are equipped with a single antenna and the secondary relays operate in half-duplex mode and are interference-limited [22]– [25]. Additionally, the desired and interfering channels are assumed to be independent and subject to Rayleigh fading and it is noteworthy that the fading coefficients in the secondary system are independent and identically distributed (i.i.d.)[1]. For mathematical tractability and inspired by the scenario investigated in [22] and [23], we consider the case where the relays are corrupted by CCI while the destination is only perturbed by an additive noise. This scenario is applicable in frequency-division relay systems [26] and [27], where the relay and destination nodes undergo different interference patterns. For the destination, this is plausible when the primary transmitter is far enough from its receiver. In such a scenario, the effect of CCI at the destination is negligible compared to the background noise.

The secondary transmission takes place in two time slots. In the first time slot, the secondary source encodes a K-bit message using a rate $R_c = \frac{1}{3}$ turbo encoder and the generated codeword of length N is broadcast to the secondary relays and destination. It is assumed that SU_D listens to the entire codeword, whereas SU_{R_i} only listens to a fraction of the codeword prior to decoding. This scenario is possible when the relays are closer to the source than the destination. Hence, due to their close proximity, the relays need not listen to the

[1]The subscript i representing the relay number can be omitted in the analysis.

entire frame prior to decoding the source message. In [28], the authors show that it is practically possible through some predefined time allocation, for the relays to listen to a fraction of the frame while the destination listens to the entire frame. We consider that the secondary relays only listen to a corrupted version of the systematic bits. The received signals at $\mathrm{SU}_{\mathrm{R}_i}$ and SU_{D} are given respectively by

$$y_{SR_i}(1:K) = \sqrt{P_S} f_i x(1:K) + \sqrt{P_{PU}} h_{1i} b(1:K), \quad (1)$$

$$y_{SD}(1:N) = \sqrt{P_S} f_0 x(1:N) + z_{SD}(1:N), \quad (2)$$

where f_0 and f_i are the channel coefficients between SU_{S} and SU_{D}, and SU_{S} and $\mathrm{SU}_{\mathrm{R}_i}$ respectively, $x(1:N) = \{x(1), \ldots, x(K), x(K+1), \ldots, x(N)\}$ is the binary phase shift keying (BPSK) modulated data symbol, with $x(1:K)$ denoting the systematic bits and $x(K+1:N)$ the parity bits, $b(1:K)$ is the interfering signal from PU_{S}, z_{SD} is the additive white Gaussian noise (AWGN) at SU_{D} with zero mean and variance N_0, and P_S and P_{PU} are the powers at the secondary source and the primary transmitter respectively, and the power at the source is given by

$$P_S = \min\left(\frac{\mathcal{Q}}{|h_0|^2}, \mathcal{P}\right), \quad (3)$$

where $\mathcal{Q}$ denotes the interference temperature limit, $\mathcal{P}$ is the maximum transmit power and h_0 is the channel coefficient between SU_{S} and PU-Rx.

All the relays decode the received signals in (1) with the aid of a turbo decoder to estimate the information bits sent by the source. Each relay employs a cyclic redundancy check (CRC) code for error detection and only the reliable relays are selected to form a decoding set denoted by $\mathcal{D}_s$. In the second time slot, the relay with the highest relay-to-destination SNR from $\mathcal{D}_s$ is selected to forward the parity bits to the destination (this scenario is plausible under the assumption that the destination is made aware prior to starting the decoding process. This may be achieved by a low-rate transmission from the selected relay to the destination). The received signal at the destination is given by

$$y_{R_mD}(K+1:N) = \sqrt{P_{R_m}} g_m \hat{x}(K+1:N) + z_{R_mD}(K+1:N), \quad (4)$$

where the vector $\hat{x}(K+1:N)$ is the estimated parity bits, g_m denotes the channel coefficient between the best relay and the destination, z_{R_mD} is the AWGN with zero mean and variance N_0, $P_{R_m} = \min\left(\frac{\mathcal{Q}}{|h_{0m}|^2}, \mathcal{P}\right)$ is the transmit power at $\mathrm{SU}_{\mathrm{R}_m}$, h_{0m} is the channel fading coefficient between $\mathrm{SU}_{\mathrm{R}_m}$ and PU-Rx and m denotes the index for the best relay given by

$$m = \arg\max_{i \in \mathcal{D}_s} \{\hat{\gamma}_{R_iD}\}, \quad (5)$$

where $\hat{\gamma}_{R_iD}$ is the instantaneous SNR used at the time of selection and is given by $\hat{\gamma}_{R_iD} = |\hat{h}_{R_iD}|^2 \bar{\gamma}$ with $\bar{\gamma}$ denoting the average SNR and $\hat{h}_{R_iD}$ is a delayed version of h_{R_iD} used at the transmission instant. Both h_{R_iD} and $\hat{h}_{R_iD}$ are jointly Gaussian random variables (RVs), and their relationship can be modeled according to [29]

$$h_{R_iD} = \rho \hat{h}_{R_iD} + \sqrt{1-\rho^2}\,\omega_i, \quad (6)$$

where ρ is the correlation factor between h_{R_iD} and $\hat{h}_{R_iD}$ and ω_i follows the same distribution as $\hat{h}_{R_iD}$. It is worth mentioning that the interference CSI h_{0m} between the PU-Rx and the best relay can be estimated and fed back directly by PU-Rx or indirectly by a band manager [30] which mediates between PU-Rx and the SU[2]. Due to the feedback delay mentioned above between $\mathrm{SU}_{\mathrm{R}_m}$ and SU_{D}, it is also assumed that the interference channel information at the selection instant and the one at the transmission are not identical. Hence, we have $h_{0m} = \rho_I \hat{h}_{0m} + \sqrt{1-\rho_I^2}\,\eta_m$ where $\hat{h}_{0m}$ is the delayed version of h_{0m}, ρ_I is the correlation factor between h_{0m} and $\hat{h}_{0m}$ and η_m follows the same distribution as $\hat{h}_{0m}$. Due to outdated interference CSI in the $\mathrm{SU}_{\mathrm{R}_m}$–PU-Rx link, the power interference constraints at the relay cannot be met. It follows that, the transmit power at the relay under which the power margin satisfies the predetermined interference outage probability is given by

$$P_{R_m} = \min\left(\frac{\tau\mathcal{Q}}{|h_{0m}|^2}, \mathcal{P}\right), \quad (7)$$

where τ is the power margin factor and can be obtained numerically using the interference outage probability given by [32]

$$\begin{aligned}\mathcal{P}_0 &= \exp\left(\frac{\mathcal{Q}}{\mathcal{P}}\right)\left[1 - Q_1\left(\sqrt{\frac{2\rho_I^2\mathcal{Q}}{(1-\rho_I^2)\mathcal{P}}}, \sqrt{\frac{2\tau\mathcal{Q}}{(1-\rho_I^2)\mathcal{P}}}\right)\right] \\ &- \frac{(1-\tau)}{\sqrt{(1+\tau)^2 - 4\rho_I^2\tau}} Q_1\left(\sqrt{\frac{\mathcal{A}-\mathcal{B}}{2(1-\rho_I^2)\mathcal{P}}}, \sqrt{\frac{\mathcal{A}+\mathcal{B}}{2(1-\rho_I^2)\mathcal{P}}}\right) \\ &+ \frac{1}{2}\left(1 + \frac{(1-\tau)}{\sqrt{(1+\tau)^2 - 4\rho_I^2\tau}}\right)\exp\left(-\frac{(1+\tau)\mathcal{Q}}{(1-\rho_I^2)\mathcal{P}}\right) \\ &\times I_0\left(\frac{2\rho_I\mathcal{Q}\sqrt{\tau}}{(1-\rho_I^2)\mathcal{P}}\right),\end{aligned} \quad (8)$$

where $\mathcal{A} = 2\mathcal{Q}\big((1+\tau)$ and $\mathcal{B} = \sqrt{(1+\tau)^2 - 4\rho_I^2\tau}\big)$, $I_0(\bullet)$ is the zeroth-order modified Bessel function of the first kind defined in [33, Eq. 8.447.1] and $Q_1(\alpha, \beta)$ is first-order Marcum Q-function given by [34]

$$Q_1(\alpha, \beta) = \int_\beta^\infty x \exp\left(-\frac{x^2+\alpha^2}{2}\right) I_0(\alpha x)\mathrm{d}x. \quad (9)$$

III. Outage Performance Analysis

In this section, we analyze the secondary outage performance. For a non-cooperative direct transmission between the source and the destination with instantaneous SNR γ, the instantaneous capacity is given by [35] $\mathcal{C}(\gamma) = \log_2(1+\gamma)$. An outage event occurs when $\mathcal{C}(\gamma)$ falls below a selected threshold rate R_c or equivalently $\gamma < 2^{R_c} - 1$. We assume that the generated codeword is divided into two sub-codewords, which may not beof equal length. We denote by δ the amount of time the relays listen to the source and by $1-\delta$ the fraction of time the destination listens to the relay in the second time

[2]However, several protocols have been proposed in [30], [31] to enable the PUs and SUs to collaborate and exchange information in a way that the interference channel information can be directly fed back from the primary receiver to the secondary network.

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slot. During the first time slot, the destination listens to the entire frame sent by the source with a code rate R_c, whereas the relays only listen to a fraction of the frame sent by the source with a code rate $R_{c_1} = \frac{R_c}{\delta}$. During the second time slot, the best relay transmits with a rate $R_{c_2} = \frac{R_c}{1-\delta}$ to the destination, where $0 < \delta < 1$. It is assumed that $\delta = \frac{K}{N}$ in this work. Using the total probability theorem, the outage probability of the underlying scheme can be rewritten as

$$P_{out} = \mathbb{P}\big\{|\mathcal{D}_s| = \emptyset\big\} + \sum_{|\mathcal{D}_s|=1}^{M} \mathbb{P}\big\{\vartheta = |\mathcal{D}_s|\big\} \times \mathbb{P}\big\{\mathcal{C}(\gamma_{SD}, \gamma_{R_mD}) < R_c\big\}, \quad (10)$$

where $\emptyset$ is the empty set, $|x|$ denotes the cardinality of x, $\mathbb{P}\{x\}$ denotes the probability of x, $\mathbb{P}\big\{|\mathcal{D}_s| = \emptyset\big\}$ and $\mathbb{P}\big\{\vartheta = |\mathcal{D}_s|\big\}$ are given by

$$\mathbb{P}\big\{|\mathcal{D}_s| = \emptyset\big\} = \mathbb{P}\big\{\mathcal{C}(\gamma_{SD}) < R_c\big\}\Big(\mathbb{P}\big\{\mathcal{C}(\gamma_{SR}) < R_c\big\}\Big)^M, \quad (11)$$

$$\mathbb{P}\big\{\vartheta = |\mathcal{D}_s|\big\} = \binom{M}{|\mathcal{D}_s|}\Big(\mathbb{P}\big\{\mathcal{C}(\gamma_{SR}) < R_{c_1}\big\}\Big)^{|\mathcal{D}_s|} \times \Big(1 - \mathbb{P}\big\{\mathcal{C}(\gamma_{SR}) < R_{c_1}\big\}\Big)^{M-|\mathcal{D}_s|}, \quad (12)$$

respectively, with $\mathcal{C}(\gamma_{SD})$, $\mathcal{C}(\gamma_{SR})$ and $\mathcal{C}(\gamma_{SD}, \gamma_{R_mD})$ [3] expressed as

$$\mathcal{C}(\gamma_{SD}) = \log_2\big(1 + \gamma_{SD}\big), \quad (13)$$

$$\mathcal{C}(\gamma_{SR}) = \delta \log_2\big(1 + \gamma_{SR}\big), \quad (14)$$

$$\mathcal{C}(\gamma_{SD}, \gamma_{R_mD}) = \log_2\big(1 + \gamma_{SD}\big) + (1-\delta)\log_2\big(1 + \gamma_{RD}\big). \quad (15)$$

Using (13)–(15) in (11) and (12), the end-to-end outage probability in (10) can be rewritten as

$$P_{out} = F_{\gamma_{SD}^{\text{eff}}}\big(\gamma_{\text{th},1}\big)\Big(F_{\gamma_{SR}^{\text{eff}}}\big(\gamma_{\text{th},2}\big)\Big)^M + \sum_{|\mathcal{D}_s|=1}^{M}\binom{M}{|\mathcal{D}_s|} \times \Big(F_{\gamma_{SR}^{\text{eff}}}\big(\gamma_{\text{th},2}\big)\Big)^{M-|\mathcal{D}_s|}\Big(1 - F_{\gamma_{SR}^{\text{eff}}}\big(\gamma_{\text{th},2}\big)\Big)^{|\mathcal{D}_s|} \times \underbrace{\underbrace{\int_0^{\epsilon}\int_0^{\zeta}}_{\Psi} f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD}) f_{\gamma_{RD}^{\text{eff}}}(\gamma_{RD}) \mathrm{d}\gamma_{RD}\mathrm{d}\gamma_{SD}}_{\mathcal{I}}, \quad (16)$$

where $f_X(x)$ and $F_X(x)$ denote the probability density function (PDF) and the cumulative distribution function (CDF) of the random variable (RV) X, $\gamma_{\text{th},1} = 2^{R_c} - 1$, $\gamma_{\text{th},2} = 2^{R_c/\delta} - 1$, γ_{SD}^{eff}, γ_{SR}^{eff}, and γ_{RD}^{eff} are the SNR of at the SU_D (in the first time slot), signal-to-interference (SIR) at the relay, and SNR at SU_D (in the second time slot) respectively and Ψ corresponds to the region on integration given by

$$\Psi = \Big\{(\gamma_{SD}, \gamma_{RD}) | \gamma_{SD} \geq 0, \gamma_{RD} \geq 0, \big(1 + \gamma_{SD}\big)\Theta < 2^{R_c}\Big\}, \quad (17)$$

with $\Theta = \big(1 + \gamma_{RD}\big)^{1-\delta}$.

Using the constraints in (17) and after some manipulations, it is easy to obtain γ_{SD} and γ_{RD} as follow

$$\gamma_{SD} < \gamma_{\text{th},1} \doteq \epsilon, \quad (18)$$

$$\gamma_{RD} < \frac{2^{R_c\mu}}{\big(1 + \gamma_{SD}\big)^{\mu}} - 1 \doteq \zeta, \quad (19)$$

where $\mu = \frac{1}{1-\delta}$. In what follows, we derive the CDF expressions of X, for $X \in \{\gamma_{SD}^{\text{eff}}, \gamma_{SR}^{\text{eff}}\}$ as well as evaluate the double integral in (16).

A. CDF of γ_{SD}^{eff}

Using (2) and (3), the SNR at SU_D can be written as

$$\gamma_{SD}^{\text{eff}} = \min\left(\frac{\mathcal{Q}}{|h_0|^2}, \mathcal{P}\right)\frac{|f_0|^2}{N_0}. \quad (20)$$

Consequently, the CDF γ_{SD}^{eff} is given by

$$F_{\gamma_{SD}^{\text{eff}}}(\gamma_{\text{th},1}) = \mathbb{P}\left\{\frac{\mathcal{Q}|f_0|^2}{|h_0|^2 N_0} < \gamma_{\text{th},1}, \frac{\mathcal{Q}}{|h_0|^2} < \mathcal{P}\right\} + \mathbb{P}\left\{\frac{\mathcal{P}|f_0|^2}{N_0} < \gamma_{\text{th},1}, \frac{\mathcal{Q}}{|h_0|^2} > \mathcal{P}\right\}. \quad (21)$$

We denote the first and second parts of the summation in (21) by Λ_1 and Λ_2 respectively. Using the properties of probability theory in [36], Λ_1 can be rewritten as

$$\Lambda_1 = \int_{\frac{\mathcal{Q}}{\mathcal{P}}}^{\infty} f_{|h_0|^2}(x) F_{|f_0|^2}\left(\frac{\gamma_{\text{th},1} N_0 x}{\mathcal{Q}}\right)\mathrm{d}x. \quad (22)$$

where $f_{|h_0|^2}(x) = \frac{N_0}{\mathcal{Q}}\exp\big(-\frac{xN_0}{\mathcal{Q}}\big)$ (it is assumed that h_0 follows a Rayleigh distribution, and hence $|h_0|^2$ is exponentially distributed of mean $\frac{\mathcal{Q}}{N_0}$). Therefore, to derive Λ_1, we substitute the expression of the CDF of $|f_0^2|$ given in the form of $F_{|f_0|^2}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{SD}}\right)$ in (22). After some manipulations, Λ_1 is given by

$$\Lambda_1 = \exp\left(-\frac{N_0}{\mathcal{P}}\right)\left(1 - \left(1 + \frac{\gamma_{\text{th},1}}{\bar{\gamma}_{SD}}\right)^{-1}\exp\left(-\frac{N_0\gamma_{\text{th},1}}{\bar{\gamma}_{SD}\mathcal{P}}\right)\right), \quad (23)$$

where $\bar{\gamma}_{SD} = \mathbb{E}\langle\gamma_{SD}\rangle$ with $\mathbb{E}\langle\bullet\rangle$ denoting the expecting operator.

To evaluate Λ_2, we use the fact that $|f_0|^2$ and $|h_0|^2$ are independent. Thus, Λ_2 is given by

$$\Lambda_2 = \mathbb{P}\left\{|f_0|^2 < \frac{\gamma_{\text{th},1}N_0}{\mathcal{P}}\right\}\mathbb{P}\left\{|h_0|^2 < \frac{\mathcal{Q}}{\mathcal{P}}\right\} = \left(1 - \exp\left(-\frac{\gamma_{\text{th},1}N_0}{\bar{\gamma}_{SD}\mathcal{P}}\right)\right)\left(1 - \exp\left(-\frac{N_0}{\mathcal{P}}\right)\right). \quad (24)$$

[3]The expression in (15) cannot be reduced to $\mathcal{C}(\gamma_{SD}, \gamma_{R_mD}) = \log_2\big(1 + \gamma_{SD} + \gamma_{RD}\big)$ because the transmission rates for the direct link and the link between the best relay and the destination are not equal. This emanates from the fact that in the first time slot, the destination listens to the entire codeword whereas in the second time slot, only the parity bits are forwarded by the relay to the destination.

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After combining (23) and (24) in (21), it is easy to obtain the CDF of γ_{SD}^{eff}. In what follows, using $\frac{\partial F_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD})}{\partial \gamma_{SD}}$, the PDF of γ_{SD}^{eff} is given by

$$f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD}) = \exp\left(-\frac{N_0}{\mathcal{P}}\right)\exp\left(-\frac{N_0\gamma_{SD}}{\mathcal{P}\bar{\gamma}_{SD}}\right)\left[\frac{1}{\bar{\gamma}_{SD}} \times\left(1+\frac{\gamma_{SD}}{\bar{\gamma}_{SD}}\right)^{-2} + \frac{N_0}{\bar{\gamma}_{SD}\mathcal{P}}\left(1+\frac{\gamma_{SD}}{\bar{\gamma}_{SD}}\right)^{-1}\right] + \frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}\left(1-\exp\left(-\frac{N_0}{\mathcal{P}}\right)\right)\exp\left(-\frac{N_0\gamma_{SD}}{\mathcal{P}\bar{\gamma}_{SD}}\right). \tag{25}$$

B. CDF of γ_{SR}^{eff}

As mentioned above, the relays listen to a fraction of the frame prior to decoding. In this scenario, it is assumed that the primary transmitter imposes CCI at the secondary relays due to its proximity but not at the secondary destination. To this end, using (1), the received SIR at the ith relay is given by [4]

$$\gamma_{SR_i}^{\text{eff}} = \min\left(\frac{\mathcal{Q}}{|h_0|^2},\mathcal{P}\right)\frac{|f_i|^2}{P_{PU}|h_{1i}|^2}. \tag{26}$$

Lemma 1: The CDF of $\gamma_{SR_i}^{\text{eff}}$, i.e., $F_{\gamma_{SR_i}^{\text{eff}}}(\gamma_{SR})$ is given by

$$F_{\gamma_{SR_i}^{\text{eff}}}(\gamma_{\text{th},2}) = \exp\left(-\frac{N_0}{\mathcal{P}}\right) - \frac{\bar{\gamma}_{SR_i}}{\gamma_{\text{th},2}\bar{\gamma}_I^2}\exp\left(\frac{\bar{\gamma}_{SR_i}}{\gamma_{\text{th},2}\bar{\gamma}_I^2}\right) \times\Gamma\left(0,\frac{\bar{\gamma}_{SR_i}}{\gamma_{\text{th},2}\bar{\gamma}_I^2}\left(1+\frac{N_0\gamma_{\text{th},2}\bar{\gamma}_I^2}{\mathcal{P}\bar{\gamma}_{SR_i}}\right)\right) + \left(1-\left(1+\frac{N_0\gamma_{\text{th},2}\bar{\gamma}_I^2}{\mathcal{P}\bar{\gamma}_{SR_i}}\right)^{-1}\right)\left(1-\exp\left(-\frac{N_0}{\mathcal{P}}\right)\right), \tag{27}$$

where $\bar{\gamma}_I = \frac{P_{PU}}{N_0}$ and $\Gamma(a,x)$ is the incomplete Gamma function [33, Eq. 8.350.2].

Proof: See appendix A. ■

C. Derivation of $\mathcal{I}$

In (16), the double integral $\mathcal{I}$ is not easy to evaluate. In the sequel, we evaluate the expression of $\mathcal{I}$. First, we rewrite $\mathcal{I}$ as

$$\mathcal{I} = \int_0^{\epsilon} f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD})F_{\gamma_{R_mD}^{\text{eff}}}(\zeta)\mathrm{d}\gamma_{SD}, \tag{28}$$

where ζ is a function of γ_{SD}. In what follows, we derive the CDF of $\gamma_{R_mD}^{\text{eff}}$. The received SNR at the destination in the second time slot can be obtained with the aid of (4) as

$$\gamma_{R_mD}^{\text{eff}} = \min\left\{\frac{\tau\mathcal{Q}}{|h_{0m}|^2},\mathcal{P}\right\}\frac{|g_m|^2}{N_0}. \tag{29}$$

[4]It should be noted that although the index i representing the relay number is included in this section, it is dropped in the subsequent outage analysis, due to the i.i.d. assumption.

From (29), the CDF of $\gamma_{R_mD}^{\text{eff}}$, i.e., $F_{\gamma_{R_mD}^{\text{eff}}}(x)$ is given by

$$F_{\gamma_{R_mD}^{\text{eff}}}(x) = \underbrace{\mathbb{P}\left\{\frac{\tau\mathcal{Q}|g_m|^2}{|h_{0m}|^2N_0} < x, \frac{\tau\mathcal{Q}}{|h_{0m}|^2} < \mathcal{P}\right\}}_{\mathcal{I}_1} + \underbrace{\mathbb{P}\left\{\frac{\mathcal{P}|g_m|^2}{N_0} < x, \frac{\tau\mathcal{Q}}{|h_{0m}|^2} > \mathcal{P}\right\}}_{\mathcal{I}_2}. \tag{30}$$

The term $\mathcal{I}_1$ which can be rewritten as

$$\mathcal{I}_1 = \int_{\frac{\tau\mathcal{Q}}{\mathcal{P}}}^{\infty} f_{|h_{0m}|^2}(y)F_{|g_m|^2}\left(\frac{N_0xy}{\tau\mathcal{Q}}\right)\mathrm{d}y, \tag{31}$$

where $F_{|g_m|^2}\left(\frac{N_0xy}{\tau\mathcal{Q}}\right)$ is given by [37]

$$F_{|g_m|^2}\left(\frac{N_0xy}{\tau\mathcal{Q}}\right) = 1-\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1}e^{-\frac{N_0xy}{\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}}. \tag{32}$$

Substituting (32) in (31) and after some manipulations, $\mathcal{I}_1$ can be expressed as

$$\mathcal{I}_1 = \exp\left(-\frac{\tau N_0}{\mathcal{P}}\right)\left[1-\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1} \times\left(1+\frac{N_0x}{\tau\mathcal{Q}\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)^{-1}e^{-\frac{N_0x}{\mathcal{P}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}}\right]. \tag{33}$$

Since $|g_m|^2$ and $|h_{0m}|^2$ are independent, with the aid of (32) and after some manipulations, $\mathcal{I}_2$ is given by

$$\mathcal{I}_2 = \left(1-\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1}e^{-\frac{N_0x}{\mathcal{P}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}}\right) \times\left(1-\exp\left(-\frac{\tau N_0}{\mathcal{P}}\right)\right). \tag{34}$$

By combining (33) and (34) in (28), and after some manipulations, it is easy to obtain $\mathcal{I}$ which is given by

$$\mathcal{I} = \exp\left(-\frac{\tau N_0}{\mathcal{P}}\right)\left[F_{\gamma_{SD}^{\text{eff}}}(\gamma_{\text{th},1}) - \sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1} \times\underbrace{\int_0^{\gamma_{\text{th},1}} f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD})\left(1+\frac{\zeta}{\tau\mathcal{Q}\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)^{-1} \times\exp\left(-\frac{N_0\zeta}{\mathcal{P}\bar{\gamma}_{RD}}\right)\mathrm{d}\gamma_{SD}}_{\mathcal{K}_1}\right] + \left(1-\exp\left(-\frac{\tau N_0}{\mathcal{P}}\right)\right) \times\left[F_{\gamma_{SD}^{\text{eff}}}(\gamma_{\text{th},1}) - \sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1} \times\underbrace{\int_0^{\gamma_{\text{th},1}} f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD})\exp\left(-\frac{N_0\zeta}{\mathcal{P}\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)\mathrm{d}\gamma_{SD}}_{\mathcal{K}_2}\right]. \tag{35}$$

However, the expression in (35) is in integral form which cannot be evaluated straightforwardly as shown by $\mathcal{K}_1$ and $\mathcal{K}_2$. The terms $\mathcal{K}_1$ and $\mathcal{K}_2$ are evaluated, and (35) can further be expressed as seen on top of the next page, where ${}_2F_1\left(w,x;y;z\right)$ is the Gauss Hypergeometric function defined in [33, Eq. 9.111]. Substituting (23), (24), (27) and (36) in (16) yields the expression of the end-to-end outage probability of the underlying scheme.

Proof: See appendix B. ■

IV. Asymptotic Analysis

The expression of the end-to-end outage probability derived after substituting (23), (24), (27) and (36) in (16) is complex to analyze and it does not provide useful insights into the system performance. To this end, we examine the asymptotic behavior of the outage probability at high SNR when $\bar{\gamma}_{SD} = \bar{\gamma}_{SR} = \bar{\gamma}_{RD} = \bar{\gamma} \to \infty$ to determine the diversity order achieved by the system. It is noteworthy that similar to [6], we assume that the primary receiver is able to tolerate high amount of interference. In addition, we assume without loss of generality that $\rho_1 = \rho_2 = \rho$ and $\bar{\gamma}_{\mathcal{Q}} = \bar{\gamma}_{\mathcal{P}} = \bar{\gamma}$, where $\bar{\gamma}_{\mathcal{Q}} = \frac{\mathcal{Q}}{N_0}$ and $\bar{\gamma}_{\mathcal{P}} = \frac{\mathcal{P}}{N_0}$. At high SNR, the expression in (16) can be approximated by

$$P_{out} \approx \int_0^{\epsilon} f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD}) F_{\gamma_{R_mD}^{\text{eff}}}(\zeta) \mathrm{d}\gamma_{SD}, \tag{37}$$

where ϵ and ζ are defined in (18) and (19) respectively. In the sequel, we derive an approximation for the expressions $f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD})$ and $F_{\gamma_{R_mD}^{\text{eff}}}(\zeta)$.

A. Approximation of the PDF $f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD})$

At high SNR, the expression of (25) can be reduced to

$$f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD}) \approx \frac{1}{\bar{\gamma}}\left(1+\frac{\gamma_{SD}}{\bar{\gamma}}\right)^{-2} \exp\left(-\frac{1}{\bar{\gamma}} - \frac{\gamma_{SD}}{\bar{\gamma}^2}\right). \tag{38}$$

With the aid of the Taylor series expansion and using the following approximations $\exp\left(-\frac{1}{x}\right) \approx 1-\frac{1}{x}$, for $x \to \infty$, the PDF of γ_{SD}^{eff} can be approximated by

$$f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD}) = \frac{1}{\bar{\gamma}}. \tag{39}$$

B. Approximation of the CDF $F_{\gamma_{R_mD}^{\text{eff}}}(x)$

Using (29) and (30), the CDF of $\gamma_{R_mD}^{\text{eff}}$ is given by

$$F_{\gamma_{R_mD}^{\text{eff}}}(x) = \mathbb{P}\left\{ \min\left(\frac{\tau\bar{\gamma}}{|h_0|^2}, \bar{\gamma}\right)|g_m|^2 < x \right\}. \tag{40}$$

At high SNR, i.e., $\bar{\gamma} \to \infty$, the following approximation is valid $\min\left(\frac{\tau\bar{\gamma}}{|h_0|^2}, \bar{\gamma}\right) \approx \bar{\gamma}$. Using this approximation, the CDF of $\gamma_{R_mD}^{\text{eff}}$ can be approximated by

$$F_{\gamma_{R_mD}^{\text{eff}}}(x) \approx \mathbb{P}\left(|g_m|^2 < \frac{x}{\bar{\gamma}}\right) = F_{|g_m|^2}\left(\frac{x}{\bar{\gamma}}\right). \tag{41}$$

From (32), the PDF $f_{|g_m|^2}(x)$ can be easily be given by

$$f_{|g_m|^2}(x) = \sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}\frac{(-1)^{j-1}}{\bar{\gamma}(1-\rho+\frac{\rho}{j})} e^{-\frac{x}{\bar{\gamma}\left(1-\rho+\frac{\rho}{j}\right)}}. \tag{42}$$

It is worthy to note that the expression in (42) can be maximized when $|\mathcal{D}_s| = M$. In what follows, we derive the CDF $F_{\gamma_{R_mD}^{\text{eff}}}(x)$ for both outdated and perfect CSI.

Outdated CSI ($0 \leq \rho < 1$): With the aid of $\frac{\partial F_X(x)}{\partial x}$ and the approximation $\exp\left(-\frac{1}{x}\right) \approx 1-\frac{1}{x}$ for $x \to \infty$, $F_{\gamma_{R_mD}^{\text{eff}}}(x)$ can be expressed as

$$F_{\gamma_{R_mD}^{\text{eff}}}(x) \approx \underbrace{\sum_{j=1}^{M}\binom{M}{j}\frac{(-1)^{j-1}}{1-\rho+\frac{\rho}{j}}}_{\mathcal{A}}\frac{x}{\bar{\gamma}}. \tag{43}$$

Substituting (38) and (43) in (37), and after some manipulations, the outage probability at high SNR is given by

$$P_{out} \overset{\bar{\gamma}\to\infty}{\approx} \bar{\gamma}^{-2}\underbrace{\mathcal{A}\int_0^{\epsilon}\left(\frac{2^{R_c\mu}}{(1+\gamma_{SD})^{\mu}}-1\right)\mathrm{d}\gamma_{SD}}_{G_{c_1}}, \tag{44}$$

where G_{c_1} is a constant value and can easily be evaluated as

$$G_{c_1} = \left(\frac{\mu 2^{R_c} - 2^{R_c\mu}}{1-\mu}+1\right)\sum_{j=1}^{M}\binom{M}{j}\frac{(-1)^{j-1}}{1-\rho+\frac{\rho}{j}}. \tag{45}$$

It can be seen from (44) that the achievable diversity gain for this case is two regardless of the number of relays M. This can be explained as follows: when the correlation factor is outdated, i.e., $\rho \neq 1$, the probability that the worst relay is chosen is non-zero and the selected relay contributes with a $\frac{1}{\bar{\gamma}}$ term to the outage probability. Since the strict definition of the diversity order is referred to infinitely high SNRs, it should be noted that as the SNR grows, the effect of selecting the worst relay is emphasized. Therefore, the term $\frac{1}{\bar{\gamma}}$ becomes the most dominant one in the outage probability expression. In addition, since the direct link is considered in this work and is independent of other indirect paths leading to the destination, the term $\frac{1}{\bar{\gamma}}$ also dominates. Due to the independency of both paths, i.e., direct and selected indirect paths, it can be noted that the term $\frac{1}{\bar{\gamma}^2}$ becomes in the asymptotic regime the dominant term of the end-to-end outage probability.

Ideal CSI ($\rho = 1$): After substituting $\rho = 1$ in (42), performing some manipulations and observing the identity $(1+x)^y = \sum_{k=0}^{y}\binom{k}{y}x^y$, it is easy to obtain the CDF of $\gamma_{R_mD}^{\text{eff}}$

$$F_{\gamma_{R_mD}^{\text{eff}}}(x) \approx x^M\bar{\gamma}^{-M}. \tag{46}$$

Combining (38) and (46) in (37), the outage probability can be approximated by

$$P_{out} \overset{\bar{\gamma}\to\infty}{\approx} \frac{1}{\bar{\gamma}^{M+1}}\underbrace{\int_0^{\epsilon}\left(\frac{2^{R_c\mu}}{(1+\gamma_{SD})}-1\right)^M\mathrm{d}\gamma_{SD}}_{G_{c_2}}, \tag{47}$$

where G_{c_2} is a constant value which can be obtained numerically and the expression in (47) shows that full diversity of the order $M+1$ is achieved.

Moreover, it can easily be noticed that the correlation ρ_I (or the CSI of the SU_{R_m}–PU-Rx link) has no effect whatsoever

$$\begin{aligned}
\mathcal{I} &= \exp\left(-\frac{\tau N_0}{\mathcal{P}}\right)\Bigg[F_{\gamma_{SD}^{\text{eff}}}(\gamma_{\text{th},1}) - \sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1}\Bigg\{\exp\left(\frac{N_0}{\mathcal{P}\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)\Bigg(\exp\left(-\frac{N_0}{\mathcal{P}}\right)\sum_{k=0}^{\infty}\sum_{l=0}^{\infty}\sum_{m=0}^{\infty}\sum_{n=0}^{m}\binom{m}{n} \\
&\times \left(\frac{N_0}{\mathcal{P}}\right)^{m}\frac{(-1)^{k+l-m}(k+1)}{\tau^{l}m!\bar{\gamma}_{SD}^{k+n+1}}\left(\frac{2^{R_c\mu}}{\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)^{m+l-n}\frac{\gamma_{\text{th},1}^{n+k+1}}{n+k+1}\,{}_2F_1\Big(\mu(l+m-n,n+k+1,n+k+2,-\gamma_{\text{th},1})\Big) \\
&\times \left(1-\frac{1}{\tau\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)^{-l-1} + \exp\left(-\frac{N_0}{\mathcal{P}}\right)\sum_{k=0}^{\infty}\sum_{l=0}^{\infty}\sum_{m=0}^{\infty}\sum_{n=0}^{m}\binom{m}{n}\left(\frac{N_0}{\mathcal{P}}\right)^{m+1}\left(\frac{2^{R_c\mu}}{\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)^{l+m-n} \\
&\times \frac{(-1)^{k+l+m}}{\tau^{l}m!\bar{\gamma}_{SD}^{k+n+1}}\left(1-\frac{1}{\tau\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)^{-l-1}\frac{\gamma_{\text{th},1}^{n+k+1}}{n+k+1}\,{}_2F_1\Big(\mu(l+m-n),n+k+1,n+k+2;-\gamma_{\text{th},1}\Big) \\
&+ \left(1-\exp\left(-\frac{N_0}{\mathcal{P}}\right)\right)\sum_{k=0}^{\infty}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\binom{l}{m}\left(\frac{N_0}{\mathcal{P}}\right)^{l+1}\frac{(-1)^{k+l}}{\tau^{l}l!}\left(\frac{2^{R_c\mu}}{\bar{\gamma}_{RD}}(1-\rho+\frac{\rho}{j})\right)^{k+l-m}\left(1-\frac{1}{\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)^{-k-1} \\
&\times \frac{\gamma_{\text{th},1}^{m+1}}{m+1}\,{}_2F_1\Big(\mu(k+l-m),m+1,m+2,-\gamma_{\text{th},1}\Big)\Bigg)\Bigg\}\Bigg] + \left(1-\exp\left(-\frac{\tau N_0}{\mathcal{P}}\right)\right)\Bigg[F_{\gamma_{SD}^{\text{eff}}}(\gamma_{\text{th},1}) - \sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1} \\
&\times \Bigg\{\exp\left(\frac{N_0}{\bar{\gamma}_{RD}(1-\rho+\frac{\rho}{j})}\right)\Bigg(\exp\left(-\frac{N_0}{\mathcal{P}}\right)\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\sum_{v=0}^{n}\binom{n}{v}\left(\frac{N_0}{\mathcal{P}}\right)^{n}\frac{(-1)^{m+n}(m+1)}{n!\bar{\gamma}_{SD}^{m+v+1}\bar{\gamma}_{RD}^{n-v}}\left(\frac{2^{R_c\mu}}{1-\rho+\frac{\rho}{j}}\right)^{n-v}\frac{\gamma_{\text{th},1}^{m+v+1}}{m+v+1} \\
&\times {}_2F_1\Big(\mu(n-v),m+v+1,m+v+2;-\gamma_{\text{th},1}\Big) + \exp\left(-\frac{N_0}{\mathcal{P}}\right)\sum_{k=0}^{\infty}\sum_{n=0}^{\infty}\sum_{v=0}^{\infty}\binom{n}{v}\left(\frac{N_0}{\mathcal{P}}\right)^{v+1}\frac{(-1)^{k+n}}{n!\bar{\gamma}_{SD}^{k+v+1}\bar{\gamma}_{RD}^{n-v}}\left(\frac{2^{R_c\mu}}{1-\rho+\frac{\rho}{j}}\right)^{n-v} \\
&\times \frac{\gamma_{\text{th},1}^{m+v+1}}{m+v+1}\,{}_2F_1\Big(\mu(n-v),m+v+1,m+v+2;-\gamma_{\text{th},1}\Big) + \left(1-\exp\left(-\frac{N_0}{\mathcal{P}}\right)\right)\sum_{n=0}^{\infty}\sum_{v=0}^{n}\binom{n}{v}\left(\frac{N_0}{\mathcal{P}}\right)^{n+1}\frac{(-1)^{n}}{n!\bar{\gamma}_{SD}^{v+1}\bar{\gamma}_{RD}^{n-v}} \\
&\times \left(\frac{2^{R_c\mu}}{1-\rho+\frac{\rho}{j}}\right)^{n-v}\frac{\gamma_{\text{th},1}^{v+1}}{v+1}\,{}_2F_1\Big(\mu(n-v),v+1,v+2;-\gamma_{\text{th},1}\Big)\Bigg)\Bigg\}\Bigg].
\end{aligned} \tag{36}$$

on the diversity order of the system. This is because, as shown above, the power margin factor τ which is a function of ρ_I from (8), does not feature in the approximation of the CDF $F_{\gamma_{R_mD}^{\text{eff}}}$ due to the fact that, at high SNR, the term $\bar{\gamma}$ is the dominant one in the expression $\min\left(\frac{\tau\bar{\gamma}}{|h_0|^2},\bar{\gamma}\right)$. This leads to the outage probability being approximated by (43) and (46) which depend on the CSI of the secondary link between the relay and destination nodes. Hence, whether the CSI of the link between the SU_{R_m} and PU-Rx is outdated or perfect is pointless from the diversity analysis point of view.

V. Upper Bounds on the Bit Error Rate

In this section, we analyze the performance of the underlying scheme in terms of the average BER. We assume binary phase shift keying (BPSK) modulation.

A. Average Pairwise Error Probability

The conditional pairwise error probability for a coded system is defined as the probability that for a transmitted codeword $\mathbf{x} = \{x_1, x_2, \ldots, x_N\}$, its corresponding but erroneous codeword $\hat{\mathbf{x}} = \{\hat{x}_1, \hat{x}_2, \ldots, \hat{x}_N\}$ will be received. This can be mathematically given by [38]

$$P(\mathbf{x} \to \hat{\mathbf{x}}|\gamma) = Q_2\left(\sqrt{2\sum_{i\in\iota}\gamma(i)}\right), \tag{48}$$

where $Q_2(x)$ denotes the Gaussian Q-function, γ is the instantaneous received SNR for code bit i and ι denotes the set of all code bits for which $\mathbf{x} \neq \hat{\mathbf{x}}$. It is worth mentioning that an error event occurs when $\hat{\mathbf{x}}$ is selected over $\mathbf{x}$. Moreover, without loss of generality and for the purpose of error rate analysis, we restrict ourselves to a chosen all-zero transmitted codeword. As such, conditional PEP is not a function of both $\mathbf{x}$ and $\hat{\mathbf{x}}$ but rather on the Hamming distance denoted by d based on the error event. Using (48), the end-to-end conditional PEP can be expressed as

$$\begin{aligned}
P(d|\gamma_{SD},\gamma_{SR},\gamma_{R_mD}) &= Q_2\left(\sqrt{2d\gamma_{SD}}\right)\left(Q_2\left(\sqrt{2d_1\gamma_{SR}}\right)\right)^{M} \\
&+ \sum_{|\mathcal{D}_s|=1}^{M}\times\left(Q_2\left(\sqrt{2d_1\gamma_{SR}}\right)\right)^{|D_s|}\left(1-Q_2\left(\sqrt{2d_1\gamma_{SR}}\right)\right)^{\mathcal{C}} \\
&\times\binom{M}{|\mathcal{D}_s|}Q_2\left(\sqrt{2d\gamma_{SD}+2d_2\gamma_{RD}}\right),
\end{aligned} \tag{49}$$

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where $\mathcal{C} = M - |\mathcal{D}_s|$, $d = d_1 + d_2$, with d_1 and d_2 representing the Hamming weights in the source-to-relay and relay-to-destination links respectively.

The unconditional PEP can be obtained from (49) and can be written as shown on top of the next page.

In order to evaluate the unconditional PEP in (50), we need to first find a tractable form of the Gaussian Q-function, as well as the PDFs of γ_{SR}^{eff} and $\gamma_{R_m D}^{\text{eff}}$. In the sequel, we present the aforementioned expressions. With the aid of the alternative representation of the Gaussian Q-function [39] and a simple and accurate approximate expression of the complementary error function [40], the Gaussian Q-function can be easily expressed as

$$Q_2(x) = \frac{1}{12}\exp\left(-\frac{x^2}{2}\right) + \frac{1}{4}\exp\left(-\frac{2}{3}x^2\right). \tag{51}$$

From (27), using $f_{\gamma_{SR}^{\text{eff}}}(x) = \frac{\partial F_{\gamma_{SR}^{\text{eff}}}(x)}{\partial x}$ and after some algebraic manipulations, the PDF of γ_{SR}^{eff} is given by

$$\begin{aligned} f_{\gamma_{SR}^{\text{eff}}}(y) = \frac{N_0}{\mathcal{P}\bar{\gamma}_I^4}\Bigg(&\bar{\gamma}_I^2\exp\left(-\frac{N_0}{\mathcal{P}}\right)\left[\frac{N_0\bar{\gamma}_I^4(e^{-\frac{N_0}{\mathcal{P}}}-1)}{(\bar{\gamma}_{SR}N_0+\bar{\gamma}_I^2\mathcal{P}y)^2}\right. \\ &\left.-\frac{\bar{\gamma}_{SR}\mathcal{P}}{y^2\left(\bar{\gamma}_{SR}\mathcal{P}+N_0\bar{\gamma}_I^2 y\right)}\right] + \frac{(\bar{\gamma}_{SR}+\bar{\gamma}_I^2 y)}{y^3} \\ &\times\exp\left(\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2 y}\right)\Gamma\left(0, \frac{N_0}{\mathcal{P}}+\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2 y}\right)\Bigg). \end{aligned} \tag{52}$$

In what follows, we present the PDF of $\gamma_{R_m D}^{\text{eff}}$ using the same method as (52). Hence, the PDF of $\gamma_{R_m D}^{\text{eff}}$ is given by

$$\begin{aligned} f_{\gamma_{R_m D}^{\text{eff}}}(z) = &\exp\left(-\frac{\tau N_0}{\mathcal{P}}\right)\Bigg\{\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1} \\ &\times\frac{e^{-\frac{N_0 z}{\mathcal{P}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}}}{\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)\left(1+\frac{N_0 z}{\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}\right)} \\ \times&\left[\frac{N_0}{\tau\mathcal{Q}}\left(1+\frac{N_0 z}{\tau\mathcal{Q}\left(1-\rho+\frac{\rho}{j}\right)}\right)^{-1}+\frac{N_0}{\mathcal{P}}\right]\Bigg\}+\left(1-e^{-\frac{\tau N_0}{\mathcal{P}}}\right) \\ &\times\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1}\left(\frac{N_0 e^{-\frac{N_0 z}{\mathcal{P}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}}}{\mathcal{P}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}\right). \end{aligned} \tag{53}$$

After substituting (25) and (51) in (50), the term $\mathcal{J}_1$ can be evaluated with the aid of [33, Eq. 3.353.3], [33, Eq. 3.352.4] and $\text{Ei}(-a) = \Gamma(0, a)$ (where $\text{Ei}(-a)$ is the exponential integral given by $\text{Ei}(-a) = -\int_a^\infty e^{-t}t^{-1}dt$). After some algebraic manipulations, $\mathcal{J}_1$ is given by

$$\begin{aligned} \mathcal{J}_1 = &\frac{1}{12}e^{-\frac{N_0}{\mathcal{P}}}\Bigg\{1-\left(\frac{N_0}{\mathcal{P}}+d\bar{\gamma}_{SD}\right)e^{\left(\frac{N_0}{\mathcal{P}}+d\bar{\gamma}_{SD}\right)} \\ &\times\Gamma\left(0, \frac{N_0}{\mathcal{P}}+d\bar{\gamma}_{SD}\right)+e^{\left(1+\frac{\bar{\gamma}_{SD}\mathcal{P}d}{N_0}\right)}\Gamma\left(0, 1+\frac{\bar{\gamma}_{SD}\mathcal{P}d}{N_0}\right)\Bigg\} \\ &+\frac{1}{12}\left(\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}\right)\left(1-e^{\left(-\frac{N_0}{\mathcal{P}}\right)}\right)\left(\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}+d\right)^{-1}+\frac{1}{4}e^{-\frac{N_0}{\mathcal{P}}} \\ &\times\Bigg\{1-\left(\frac{N_0}{\mathcal{P}}+\frac{4}{3}d\bar{\gamma}_{SD}\right)e^{\left(\frac{N_0}{\mathcal{P}}+\frac{4}{3}d\bar{\gamma}_{SD}\right)}\Gamma\left(0, \frac{N_0}{\mathcal{P}}+\frac{4}{3}d\bar{\gamma}_{SD}\right) \\ &+e^{\left(1+\frac{4\bar{\gamma}_{SD}\mathcal{P}d}{3N_0}\right)}\Gamma\left(0, 1+\frac{4\bar{\gamma}_{SD}\mathcal{P}d}{3N_0}\right)\Bigg\}+\frac{1}{4}\left(\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}\right) \\ &\times\left(1-e^{-\frac{N_0}{\mathcal{P}}}\right)\left(\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}+\frac{4}{3}d\right)^{-1}. \end{aligned} \tag{54}$$

Moreover, in order to evaluate $\mathcal{J}_2$, we substitute (52) and (51) in (50) and using [33, Eq. 3.353.3] and [33, Eq. 3.382.4], the term $\mathcal{J}_2$ in (50) can be expressed as shown in the next page.

Using the method to derive (54), the term $\mathcal{J}_3$ can be evaluated and is given in the next page. After substituting (54)–(56) in (50), we obtain the expression for the average PEP for the underlying coded system in underlay spectrum sensing.

B. Bit Error Rate

In the sequel, the BER performance of the underlying scheme is evaluated. The expression of the upper bounds on the average BER is given by [41]

$$P_b \leq \frac{1}{K}\sum_{d=d_f}^{\infty} a(d)P(d), \tag{57}$$

where $a(d)$ is the number of error events with Hamming weight d, d_f is the free Hamming distance. The number of error events $a(d)$ can be obtained using the transfer bound technique in [42] and can be expressed as

$$a(d) = \underbrace{\sum_{i=1}^{K}\sum_{d_1=1}^{K}\sum_{d_2=1}^{K}}_{d=i+d_1+d_2}\frac{i}{K}\binom{K}{i}p(d_1|i)p(d_2|i), \tag{58}$$

where $p(d_j|i) = t(K, i, d_j)/\binom{K}{i}$ ($j = \{1, 2\}$), $t(K, i, d_j)$ can be obtained recursively from the transfer function of the underlying turbo code $T(J, I, D) = \sum_{j\geq 0}\sum_{i\geq 0}\sum_{d\geq 0} J^j I^j D^d t(j, i, d)$, $J^j I^j D^d$ is a monomial with j equal to 1, i and d are input and output and can take the values 0 and 1.

Using the expression of the average PEP (obtained by substituting (54)–(56) in (50) but omitted here due to space limitation) in (57), the resulting average BER yields very loose bounds. In an effort to circumvent this drawback, a technique called the limit-before-average method [43] is used

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$$P(d)=\underbrace{\left(\int_0^{\infty}Q_2\left(\sqrt{2dw}\right)f_{\gamma_{SD}^{\text{eff}}}(w)\mathrm{d}w\right)}_{\mathcal{J}_1}\underbrace{\left(\int_0^{\infty}Q_2\left(\sqrt{2dy}\right)f_{\gamma_{SR}^{\text{eff}}}(y)\mathrm{d}y\right)^{M}}_{\mathcal{J}_2}+\sum_{|\mathcal{D}_s|=1}^{M}\left(\int_0^{\infty}Q_2\left(\sqrt{2dy}\right)f_{\gamma_{SR}^{\text{eff}}}(y)\mathrm{d}y\right)^{|\mathcal{D}_s|}$$
$$\times\binom{M}{|\mathcal{D}_s|}\left(1-\int_0^{\infty}Q_2\left(\sqrt{2dy}\right)f_{\gamma_{SR}^{\text{eff}}}(y)\mathrm{d}y\right)^{M-|\mathcal{D}_s|}\underbrace{\int_0^{\infty}\int_0^{\infty}Q_2\left(\sqrt{2dw+2d_2z}\right)f_{\gamma_{SD}^{\text{eff}}}(w)f_{\gamma_{R_mD}^{\text{eff}}}(z)\mathrm{d}w\mathrm{d}z}_{\mathcal{J}_3}. \quad (50)$$

$$\mathcal{J}_2=\frac{1}{12}\Bigg\{\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2}e^{-\frac{N_0}{\mathcal{P}}}\left[\frac{N_0\bar{\gamma}_I^2}{\mathcal{P}}\left(e^{\frac{N_0}{\mathcal{P}}}-1\right)\left(\frac{\mathcal{P}}{N_0\bar{\gamma}_{SR}}-\frac{d_1}{\bar{\gamma}_I^2}e^{\frac{N_0\bar{\gamma}_{SR}d_1}{\mathcal{P}\bar{\gamma}_I^2}}\right)\Gamma\left(0,\frac{N_0\bar{\gamma}_{SR}d_1}{\mathcal{P}\bar{\gamma}_I^2}\right)-\bar{\gamma}_{SR}\int_0^{\infty}\frac{\mathcal{P}e^{-d_1y}}{y^2\left(\bar{\gamma}_{SR}\mathcal{P}+N_0\bar{\gamma}_I^2y\right)}\mathrm{d}y\right]$$
$$+\frac{\bar{\gamma}_{SR}^2}{\bar{\gamma}_I^4}\int_0^{\infty}y^{-3}e^{\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}-d_1y}\Gamma\left(0,\frac{N_0}{\mathcal{P}}+\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}\right)\mathrm{d}y\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2}\int_0^{\infty}y^{-2}e^{\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}-d_1y}\Gamma\left(0,\frac{N_0}{\mathcal{P}}+\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}\right)\mathrm{d}y\Bigg\}+\frac{1}{4}\Bigg\{\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2}e^{-\frac{N_0}{\mathcal{P}}}$$
$$\times\left[\frac{N_0\bar{\gamma}_I^2}{\mathcal{P}}\left(e^{\frac{N_0}{\mathcal{P}}}-1\right)\left(\frac{\mathcal{P}}{N_0\bar{\gamma}_{SR}}-\frac{4d_1}{3\bar{\gamma}_I^2}e^{\frac{4N_0\bar{\gamma}_{SR}d_1}{3\mathcal{P}\bar{\gamma}_I^2}}\right)\Gamma\left(0,\frac{4N_0\bar{\gamma}_{SR}d_1}{3\mathcal{P}\bar{\gamma}_I^2}\right)\bar{\gamma}_{SR}\int_0^{\infty}\frac{\mathcal{P}e^{-\frac{4}{3}d_1y}}{y^2\left(\bar{\gamma}_{SR}\mathcal{P}+N_0\bar{\gamma}_I^2y\right)}\mathrm{d}y\right]$$
$$+\frac{\bar{\gamma}_{SR}^2}{\bar{\gamma}_I^4}\int_0^{\infty}y^{-3}e^{\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}-\frac{4}{3}d_1y}\Gamma\left(0,\frac{N_0}{\mathcal{P}}+\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}\right)\mathrm{d}y+\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2}\int_0^{\infty}y^{-2}e^{\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}-\frac{4}{3}d_1y}\Gamma\left(0,\frac{N_0}{\mathcal{P}}+\frac{\bar{\gamma}_{SR}}{\bar{\gamma}_I^2y}\right)\mathrm{d}y\Bigg\}. \quad (55)$$

$$\mathcal{J}_3=\frac{1}{144}\Bigg\{e^{-\frac{\tau N_0}{\mathcal{P}}}\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1}\frac{N_0}{N_0+\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}\left(d+\frac{N_0}{\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}\right)^{-1}$$
$$\times\left(1+\left(1+\frac{N_0}{\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{2}\right)}\right)^{-2}\right)+\left(1-e^{-\frac{\tau N_0}{\mathcal{P}}}\right)\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}\frac{(-1)^{j-1}N_0}{\tau\mathcal{Q}\left(1-\rho+\frac{\rho}{j}\right)}\left(\frac{N_0}{\tau\mathcal{Q}\left(1-\rho+\frac{\rho}{j}\right)}+d\right)^{-1}\Bigg\}$$
$$\times\left\{e^{-\frac{N_0}{\mathcal{P}}}\left[1-\left(\frac{N_0}{\mathcal{P}}+d\bar{\gamma}_{SD}\right)e^{\left(\frac{N_0}{\mathcal{P}}+d\bar{\gamma}_{SD}\right)}\Gamma\left(0,\frac{N_0}{\mathcal{P}}+d\bar{\gamma}_{SD}\right)+e^{\left(1+\frac{\bar{\gamma}_{SD}\mathcal{P}d}{N_0}\right)}\Gamma\left(0,1+\frac{\bar{\gamma}_{SD}\mathcal{P}d}{N_0}\right)\right]+\left(\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}+d\right)^{-1}\right.$$
$$\left.\times\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}\left(1-e^{\left(-\frac{N_0}{\mathcal{P}}\right)}\right)\right\}+\frac{1}{16}\Bigg\{e^{-\frac{\tau N_0}{\mathcal{P}}}\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}(-1)^{j-1}\frac{N_0}{N_0+\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}\left(\frac{4}{3}d+\frac{N_0}{\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}\right)^{-1}$$
$$\times\left(1+\left(1+\frac{N_0}{\tau\mathcal{Q}\bar{\gamma}_{RD}\left(1-\rho+\frac{\rho}{j}\right)}\right)^{-2}\right)+\left(1-e^{-\frac{\tau N_0}{\mathcal{P}}}\right)\sum_{j=1}^{|\mathcal{D}_s|}\binom{|\mathcal{D}_s|}{j}\frac{(-1)^{j-1}N_0}{\tau\mathcal{Q}\left(1-\rho+\frac{\rho}{j}\right)}\left(\frac{N_0}{\tau\mathcal{Q}\left(1-\rho+\frac{\rho}{j}\right)}+\frac{4}{3}d\right)^{-1}\Bigg\}$$
$$\times\left\{e^{-\frac{N_0}{\mathcal{P}}}\left[1-\left(\frac{N_0}{\mathcal{P}}+\frac{4}{3}d\bar{\gamma}_{SD}\right)e^{\left(\frac{N_0}{\mathcal{P}}+\frac{4}{3}d\bar{\gamma}_{SD}\right)}\Gamma\left(0,\frac{N_0}{\mathcal{P}}+\frac{4}{3}d\bar{\gamma}_{SD}\right)+e^{\left(1+\frac{4\bar{\gamma}_{SD}\mathcal{P}d}{3N_0}\right)}\Gamma\left(0,1+\frac{4\bar{\gamma}_{SD}\mathcal{P}d}{3N_0}\right)\right]\right.$$
$$\left.+\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}\left(1-e^{\left(-\frac{N_0}{\mathcal{P}}\right)}\right)\left(\frac{N_0}{\mathcal{P}\bar{\gamma}_{SD}}+\frac{4}{3}d\right)^{-1}\right\}. \quad (56)$$

to provide tight bounds. Therefore, the average BER can be upper bounded by

$$P_b=\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\min\left(\frac{1}{2},\frac{1}{K}\sum_{d=d_f}^{\infty}a(d)P(d|w,y,z)\right)\mathrm{d}w\mathrm{d}y\mathrm{d}z, \quad (59)$$

where $P(d|w,y,z)$ is the conditional PEP defined in (49). Due to the min function which cannot be interchanged with the summation in (59), it is not easy to derive the bit error probability in a closed form. For this reason, the analytical BER can be solved numerically.

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VI. Numerical Results

In this section, we present some numerical results in order to validate the analytical framework proposed in this work as well as highlight the outage and BER performances of the underlying scheme. In our simulations, unless otherwise specified, we use the following parameters without loss of generality: $\bar{\gamma}_{SD} = \bar{\gamma}_{SR} = \bar{\gamma}_{RD} = \bar{\gamma}$, $R_c = \frac{1}{3}$, $M = 5$ and the interference outage probability $\mathcal{P}_o = 0.1$.

Fig. 2 shows the performance comparison of the simulated and analytical outage probability of the underlying scheme. It is evident that the simulated outage probability corroborates the analytical results presented in this work. Moreover, the achievable diversity is dependent on the nature of the desired CSI only, i.e., when $\rho = 1$, full diversity of the order $M+1$ is obtained regardless of the nature of the interference CSI ρ_I (outdated or perfect), whereas the diversity gain is reduced to two for outdated CSI $\rho \neq 1$, in this case $\rho = 0$ and $\rho = 0.707$. As noted in Section IV-B and as can be seen in Fig. 2, the nature of the interfering CSI does not have any impact on the diversity gain of the system.

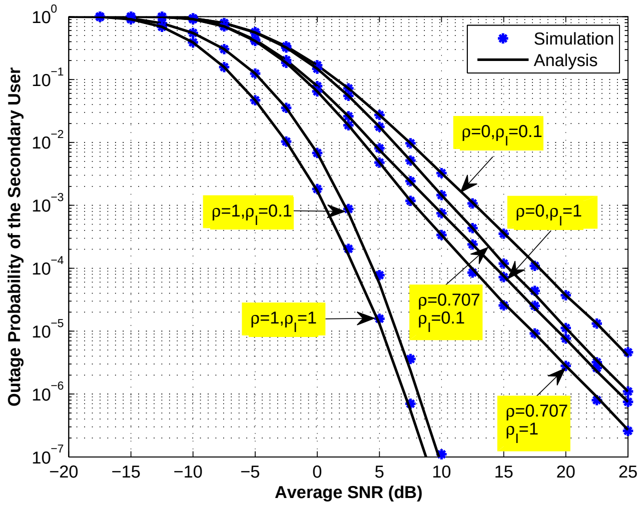

Fig. 2: Outage performance of relay selection in coded cooperation in underlay spectrum sharing system with outdated CSI and CCI $\bar{\gamma}_I = 0$dB.

Fig. 3 depicts an outage performance comparison of the coded versus the uncoded in underlay spectrum-sharing systems with outdated CSI and CCI. In all cases, we assume that the CSI of the primary system is outdated and we set $\rho_I = 0.1$; however, the CSI of the secondary network is assumed to be outdated ($\rho = 0.707$) and perfect ($\rho = 1$). It can be observed that the coded system outperforms the uncoded one by about 5dB in the case of outdated CSI (in the secondary network) and 3.5dB for perfect CSI. This explains our motivation for investigating the coded cooperative in underlay spectrum-sharing systems.

In Fig. 4, the outage probability is shown versus γ_{th} of the relay selection in coded cooperation underlay spectrum-sharing system with outdated CSI. It can be observed that both the Monte-Carlo simulations and analytical expressions

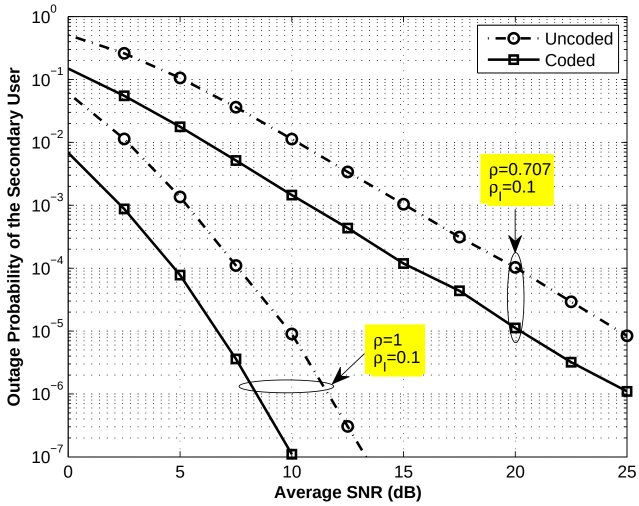

Fig. 3: Outage performance comparison of coded versus uncoded cooperation in underlay spectrum-sharing systems with outdated CSI and CCI $\bar{\gamma}_I = 0$dB.

are in good agreement. Moreover, it is noted that the outage probability with perfect desired CSI outperforms the one with outdated with both perfect and outdated interference CSI ρ_I. In addition, it can be observed that for all cases, i.e., combinations of outdated/perfect desired and outdated/ideal interfering CSI, the outage performance of the underlying scheme deteriorates approaching one for high values of γ_{th}, whereas the performance improves for low values of γ_{th}. This is because for high values of γ_{th}, the probability of an outage event occurring increases due to the high rate. On the other hand, in the case of low rate, the outage event tends to occur less frequently; therefore the probability of such an event decreases as a function of the target rate which also decreases.

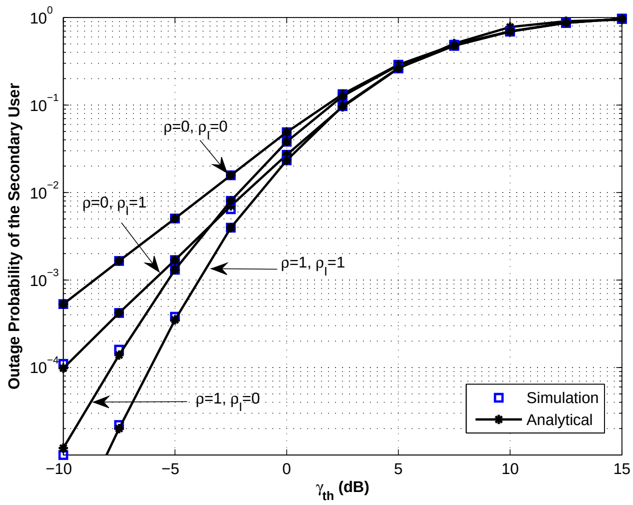

Fig. 4: Outage probability versus γ_{th} of relay selection in coded cooperation in underlay spectrum sharing system with outdated CSI: $M = 3$, $\bar{\gamma}_I = 0$dB and system SNR=10dB.

The cooperation level δ is a function of the tradeoff parameter f and can be expressed as $\delta = \frac{K+f(N-K)}{N}$, where $f \in [0,1]$. As $f \rightarrow 0$, the listening time of the relay nodes decreases, i.e., the relays belonging to the set $\mathcal{D}_s$ may potentially spend more time in the retransmission of the parity bits to the destination, whereas for $f \rightarrow 1$ (which has no practical meaning), the relays dedicate all the time to listening with no transmission. In Fig. 5, we study the effect of the tradeoff parameter f on the outage probability for various average SNRs. It can be seen that as f approaches one ($f \rightarrow 1$), there is less time for retransmission by the potential best relay (hence there is less cooperation), and the outage performance becomes worse. On the other hand, for $f \rightarrow 0$, there is a little more cooperation time than when $f \rightarrow 1$ which leads to a better outage probability (with respect to the outage probability when $f \rightarrow 1$). We can also note that the optimum tradeoff parameter f that leads to minimum outage probability is a function of both the correlation coefficient ρ and the average SNR. As the average SNR increases, the quality of the overall system improves as well. In such a scenario, the optimum tradeoff parameter f can be seen to converge to a value which allows for data transmission by both the source and relay nodes. For e.g., when an average SNR=15dB, the optimum tradeoff parameter which we denote f_{opt} is equal to $f_{opt} \approx 0.7$, whereas for SNR=25dB, $f_{opt} \approx 0.5$. This can be explained by noting that at high average SNR, the outage probability improves certainly due to a better listening time (more cooperation).

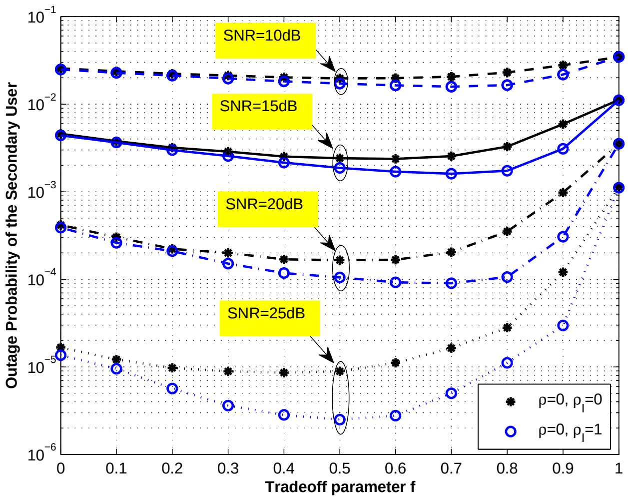

Fig. 5: Outage performance versus tradeoff parameter f for various average link SNRs, outdated desired CSI and $\bar{\gamma}_I = 20$dB.

Fig. 6 shows the outage probability versus the correlation factor ρ for various average SNR. It is to be noted that for small values of ρ, for e.g. $\rho \in [0, 0.6]$, the corresponding outage probability is almost invariant. This can be explained by the fact that for low correlation factor as given above, the outage probability slowly improves. However, for $\rho \rightarrow 1$ there is noticeable change in the outage performance which confirms that for CSI close to the ideal case, the outage probability improves.

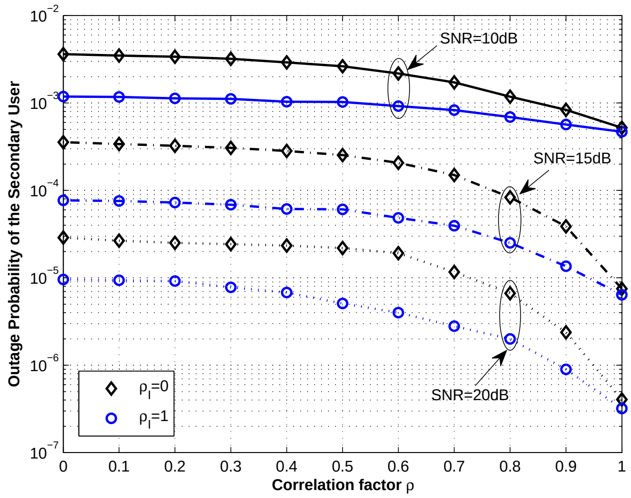

Fig. 6: Outage probability versus correlation factor ρ for various average link SNRs, outdated desired CSI and $\bar{\gamma}_I = 5$dB.

In Fig. 7, the outage probability versus the number of relays M for various average SNRs and outdated desired CSI ($\rho = 0$) is shown. It is evident that as the number of relays increases, the outage performance improves. However, as can be seen in all three scenarios (all average SNRs) the outage performance reaches saturation as the number of relays increases which is tantamount to no performance improvement. For example for SNR= 20dB, the outage probability performance when $M = 11$ is the same as the one when $M = 15$ for both outdated and perfect interference CSI ($\rho_I = 0$ and $\rho_I = 1$). Hence, it can be noted that as the average SNR increases for outdated desired CSI $\rho = 0$, increasing the number of relays in the secondary networks does not improve the secondary outage performance. Intuitively, this can be explained by noting that the same diversity of order two is obtained for $\rho = 0$ regardless of the number of relays, but some coding gain is obtained depending the number relays present in the network. This coding gain then becomes negligible as the number of relay increases as depicted in Fig. 7. Furthermore, it is also observed that, as the number of relays increases, the performance gap for the same desired CSI (in this case $\rho = 0$) between $\rho_I = 0$ and $\rho_I = 1$ widens.

Fig. 8 shows a performance comparison between the simulated BER and union bounds on the BER of the underlying scheme for outdated primary-secondary interfering CSI $\rho_I = 0.1$ and various secondary CSI ρ (outdated and ideal scenarios). It can be observed that the simulated BER results corroborate the analytical framework presented in this work. The bounds on the BER are seen to be tight over the entire SNR regime. We also note that full diversity is achieved for ideal CSI $\rho = 1$, whereas diversity is reduced to two for outdated CSI $\rho \neq 1$.

In Fig. 9, we provide the BER performance for outdated secondary CSI and various values of ρ_I and $\bar{\gamma}_I$. First, we

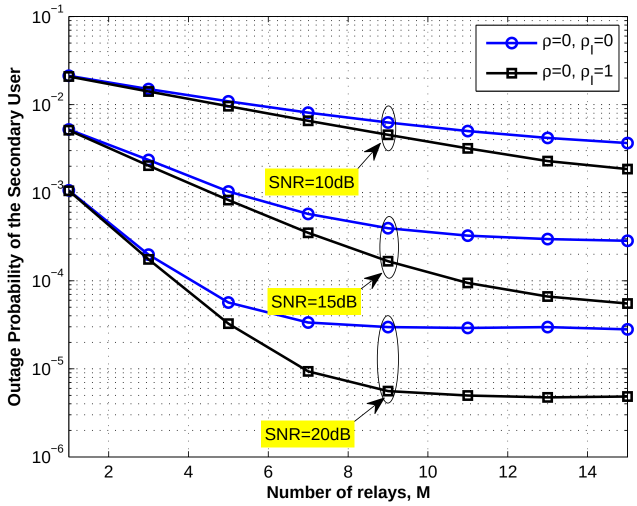

Fig. 7: Exact outage probability versus number of relay M for various average link SNRs and $\bar{\gamma}_I = 10$dB.

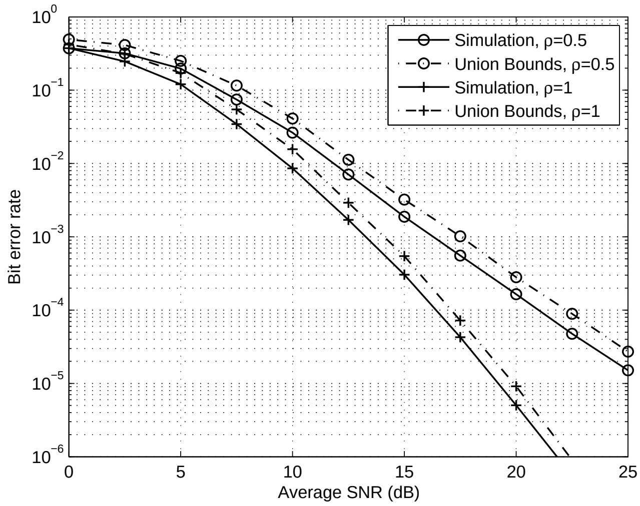

Fig. 8: BER performance comparison of simulated versus union bounds for outdated and ideal secondary CSI, $\bar{\gamma}_I = 10$dB.

note that the BER performance for the case when $\rho_I = 1$ outperforms the one with outdated secondary-primary CSI $\rho_I \neq 1$. Second, it can be observed that as the instantaneous interference-to-noise ratio (INR) $\bar{\gamma}_I$ increases, the performance gap between $\rho_I = 0.1$ and perfect secondary-primary CSI $\rho_I = 1$ decreases for any fixed secondary CSI (in this case, we set $\rho = 0$). We have noted that the performance gap decreases further for increasing $\bar{\gamma}_I$ but have omitted other cases (other values of $\bar{\gamma}_I$) for better clarity in Fig. 9. It can be implied that when the interference on the SU from the PU increases, the effect of the interfering CSI on the underlying system reduces.

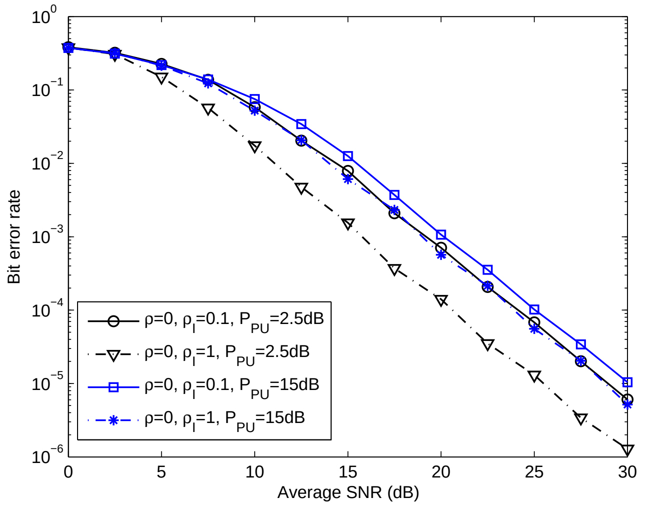

Fig. 9: BER performance of the proposed scheme for outdated secondary CSI and outdated/ideal secondary-primary.

VII. Conclusion

The effect of outdated CSI on relay selection turbo-coded cooperative in an underlay spectrum-sharing system subject to Rayleigh fading was investigated. We derived an analytical expression of the exact end-to-end outage probability as well as its asymptotic expression at high SNR. It was noted that the analytical outage probability expression of the coded scheme in an underlay spectrum-sharing systems studied in this work was not straightforward and less informative regarding the impact of some system parameters such as the number of relays. The diversity gain on the outage performance was found to be dependent on the nature of the desired CSI regardless of the interference CSI. Finally, we derived some expressions for the upper bounds on the average BER of the proposed scheme using the pairwise error probability. Results showed that the analytical BER yielded tight bounds over the entire SNR regime.

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Appendix A
Derivation of *Lemma 1*

Using (26), the CDF $F_{\gamma_{SR_i}^{\text{eff}}}(\gamma_{\text{th},2})$ can be rewritten as

$$F_{\gamma_{SR_i}^{\text{eff}}}(\gamma_{\text{th},2}) = \underbrace{\mathbb{P}\left\{\frac{\mathcal{Q}|f_i|^2}{|h_0|^2 P_{PU}|h_{1i}|^2} < \gamma_{\text{th},2}, \frac{\mathcal{Q}}{|h_0|^2} < \mathcal{P}\right\}}_{\mathcal{B}_1} + \underbrace{\mathbb{P}\left\{\frac{\mathcal{P}|f_i|^2}{P_{PU}|h_{1i}|^2} < \gamma_{\text{th},2}, \frac{\mathcal{Q}}{|h_0|^2} > \mathcal{P}\right\}}_{\mathcal{B}_2}. \quad (60)$$

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We first use the properties of probability theory [36] and $\mathcal{B}_1$ can be rewritten as

$$\mathcal{B}_1 = \int_{\frac{\mathcal{Q}}{\mathcal{P}}}^{\infty} f_{|h_0|^2}(y) F_U\left(\frac{\gamma_{\text{th},2} P_{PU} y}{\mathcal{Q}}\right) \mathrm{d}y, \quad (61)$$

where $U = \frac{X}{Y}$ with X and Y denoting $|f_i|^2$ and $|h_{1i}|^2$ respectively. In what follows, we derive the CDF $F_U(x)$ in (61). The CDF $F_U\left(\frac{\gamma_{\text{th},2} P_{PU} y}{\mathcal{Q}}\right)$ can be rewritten as

$$F_U\left(\frac{\gamma_{\text{th},2} P_{PU} y}{\mathcal{Q}}\right) = \int_0^{\infty} f_{|h_{1i}|^2}(x) F_{|f_i|^2}\left(\frac{\gamma_{\text{th},2} P_{PU} x y}{\mathcal{Q}}\right). \quad (62)$$

Using $F_{|f_i|^2}(x) = 1 - \exp\left(-\frac{x}{\bar{\gamma}_{SR_i}}\right)$ in (62) and after some algebraic manipulations, (62) can be expressed as

$$F_U\left(\frac{\gamma_{\text{th},2} P_{PU} y}{\mathcal{Q}}\right) = 1 - \left(1 + \frac{\gamma_{\text{th},2} \bar{\gamma}_I P_{PU}}{\mathcal{Q} \bar{\gamma}_{SR_i}} y\right)^{-1}. \quad (63)$$

After substituting (63) in (61) and with the aid of [33, Eq. 3.382.4] and [33, Eq. 3.382.5], and after some manipulations, a closed-form expression of $\mathcal{B}_1$ is given by

$$\mathcal{B}_1 = \exp\left(-\frac{N_0}{\mathcal{P}}\right) - \frac{N_0 \bar{\gamma}_{SR_i}}{\gamma_{\text{th},2} \bar{\gamma}_I P_{PU}} \exp\left(\frac{N_0 \bar{\gamma}_{SR_i}}{\gamma_{\text{th},2} \bar{\gamma}_I P_{PU}}\right) \times \Gamma\left(0, \frac{N_0 \bar{\gamma}_{SR_i}}{\gamma_{\text{th},2} \bar{\gamma}_{SR_i} P_{PU}} \left(1 + \frac{\gamma_{\text{th},2} \bar{\gamma}_I P_{PU}}{\mathcal{P} \bar{\gamma}_{SR_i}}\right)\right). \quad (64)$$

Due to the fact that U and $|h_0|^2$ are independent, $\mathcal{B}_2$ can further be written as

$$\mathcal{B}_2 = \mathbb{P}\left\{U < \frac{P_{PU} \gamma_{\text{th},2}}{\mathcal{P}}\right\} \mathbb{P}\left\{|h_0|^2 < \frac{\mathcal{Q}}{\mathcal{P}}\right\} = F_U\left(\frac{\gamma_{\text{th},2} P_{PU}}{\mathcal{P}}\right) F_{|h_0|^2}\left(\frac{\mathcal{Q}}{\mathcal{P}}\right). \quad (65)$$

Using (63) and through some manipulations, we can easily obtain a closed-form expression for $\mathcal{B}_2$ given by

$$\mathcal{B}_2 = \left(1 - \left(1 + \frac{\gamma_{\text{th},2} \bar{\gamma}_I P_{PU}}{\mathcal{P} \bar{\gamma}_{SR_i}}\right)^{-1}\right) \left(1 - \exp\left(-\frac{N_0}{\mathcal{P}}\right)\right). \quad (66)$$

Combining (64) and (66) completes the proof.

Appendix B
Derivation of $\mathcal{I}$

The expression in (35) is in integral form due to $\mathcal{K}_1$ and $\mathcal{K}_2$. In order to find $\mathcal{I}$ in a non-integral form, we evaluate the integral expressions of $\mathcal{K}_1$ and $\mathcal{K}_2$. In what follows, we first evaluate the expression of $\mathcal{K}_1$. From (35), $\mathcal{K}_1$ is given by

$$\mathcal{K}_1 = \int_0^{\gamma_{\text{th},1}} f_{\gamma_{SD}^{\text{eff}}}(\gamma_{SD}) \left(1 + \frac{\zeta}{\tau \bar{\gamma}_{RD}(1 - \rho + \frac{\rho}{j})}\right)^{-1} \mathrm{d}\gamma_{SD}. \quad (67)$$

Using (25) and (19) and after many manipulations, $\mathcal{K}_1$ can further be expressed as

$$\mathcal{K}_1 = \exp\left(\frac{N_0}{\mathcal{P} \bar{\gamma}_{RD}(1 - \rho + \frac{\rho}{j})}\right) \left(\mathcal{A}_1 + \mathcal{A}_2 + \mathcal{A}_3\right), \quad (68)$$

where

$$\mathcal{A}_1 = \frac{1}{\bar{\gamma}_{SD}} \exp\left(-\frac{N_0}{\mathcal{P}}\right) \int_0^{\epsilon} \left(1 + \frac{\gamma_{SD}}{\bar{\gamma}_{SD}}\right)^{-2} \times \Bigg(1 - \underbrace{\frac{1}{\tau \bar{\gamma}_{RD}(1 - \rho + \frac{\rho}{j})}}_{\mathcal{C}_1} + \underbrace{\frac{2^{R_c \mu}}{\tau \bar{\gamma}_{RD}(1 - \rho + \frac{\rho}{j})}}_{\mathcal{C}_2} \frac{1}{(1 + \gamma_{SD})^{\mu}}\Bigg)^{-1} \times \exp\Bigg(-\frac{N_0 \gamma_{SD}}{\mathcal{P} \bar{\gamma}_{SD}} - \underbrace{\frac{2^{R_c \mu} N_0}{\mathcal{P} \bar{\gamma}_{RD}(1 - \rho + \frac{\rho}{j})}}_{\mathcal{C}_3} \frac{1}{(1 + \gamma_{SD})^{\mu}}\Bigg) \mathrm{d}\gamma_{SD}, \quad (69)$$

$$\mathcal{A}_2 = \frac{N_0}{\mathcal{P} \bar{\gamma}_{SD}} \exp\left(-\frac{N_0}{\mathcal{P}}\right) \int_0^{\epsilon} \left(1 + \frac{\gamma_{SD}}{\bar{\gamma}_{SD}}\right)^{-1} \times \left(\mathcal{C}_1 + \frac{\mathcal{C}_2}{(1 + \gamma_{SD})^{\mu}}\right)^{-1} \exp\left(-\frac{N_0 \gamma_{SD}}{\mathcal{P} \bar{\gamma}_{SD}} \frac{\mathcal{C}_3}{(1 + \gamma_{SD})^{\mu}}\right) \mathrm{d}\gamma_{SD}, \quad (70)$$

$$\mathcal{A}_3 = \frac{N_0}{\mathcal{P} \bar{\gamma}_{SD}} \left(1 - \exp\left(-\frac{N_0}{\mathcal{P}}\right)\right) \int_0^{\epsilon} \left(\mathcal{C}_1 + \frac{\mathcal{C}_2}{(1 + \gamma_{Sd})^{\mu}}\right)^{-1} \times \exp\left(-\frac{N_0 \gamma_{SD}}{\mathcal{P} \bar{\gamma}_{SD}} - \frac{\mathcal{C}_3}{(1 + \gamma_{SD})^{\mu}}\right) \mathrm{d}\gamma_{SD}. \quad (71)$$

We first evaluate the expression of $\mathcal{A}_1$ in (69). Using $(1 + x)^{-n} = \sum_{k=0}^{\infty} \binom{n+k-1}{k} (-1)^k x^k$, $\exp(-x) = \sum_{m=0}^{\infty} \frac{(-1)^m}{m!} x^m$, the binomial expansion $(a + b)^n = \sum_{k=0}^{n} \binom{n}{k} a^k b^{n-k}$ and after many algebraic manipulations and with the aid of [33, Eq. 3.194.1], $\mathcal{A}_1$ can further be reduced to

$$\mathcal{A}_1 = \exp\left(-\frac{N_0}{\mathcal{P}}\right) \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \sum_{n=0}^{m} \binom{m}{n} \left(\frac{N_0}{\mathcal{P}}\right)^m \times \frac{(-1)^{k+l-m}(k+1)}{\tau^l m! \bar{\gamma}_{SD}^{k+n+1}} \left(\frac{2^{R_c \mu}}{\bar{\gamma}_{RD}(1 - \rho + \frac{\rho}{j})}\right)^{m+l-n} \times \frac{\gamma_{\text{th},1}^{n+k+1}}{n+k+1} \left(1 - \frac{1}{\tau \bar{\gamma}_{RD}(1 - \rho + \frac{\rho}{j})}\right)^{-l-1} \times {}_2F_1\Big(\mu(l + m - n, n + k + 1, n + k + 2, -\gamma_{\text{th},1}\Big). \quad (72)$$

The expressions $\mathcal{A}_2$ and $\mathcal{A}_3$ can be evaluated in a similar fashion and the resulting expressions are substituted in (68) to obtain $\mathcal{K}_1$. Additionally, $\mathcal{K}_2$ can be obtained as shown above for $\mathcal{K}_1$ and the evaluation of both $\mathcal{K}_1$ and $\mathcal{K}_2$ in (35) complete the proof.

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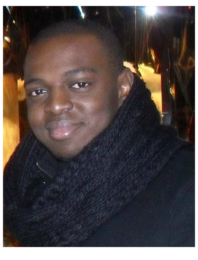

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