# Impact of Primary-User Interference on Multiuser Cognitive Relaying Networks

Diana Pamela Moya Osorio, Edgar Eduardo Benitez Olivo, Mateus Komono Tojeiro, and Luís Vasconcelos Peres

***Abstract*—This paper investigates the impact of primary-user interference on the performance of a cognitive relaying network consisting of a source, an amplify-and-forward relay and multiple destinations. With the aim of exploiting multiuser diversity at the secondary network, two different destination-selection policies are considered, which are based on partial channel state information of the network, accounting for either the direct links or the relaying links. In the setup under investigation, the source's information signal is conveyed to the selected destination by both the direct link and the relaying link, after which a maximal-ratio combining of the signals coming from the source and relay is performed. In addition, we consider that the transmit power of the secondary nodes is constrained by key aspects of underlay spectrum sharing, i.e., the interference temperature at the primary network and the maximum transmit power available at the source and relay. The system performance of the considered destination-selection schemes is analyzed in terms of the outage probability and compared to the optimal criterion. Monte Carlo simulations are provided to verify the attained analytical results.**

***Index Terms*—amplify-and-forward relaying, cooperative diversity, interference, multiuser diversity, underlay spectrum sharing.**

## I. Introduction

### A. Motivation and Background

Current wireless communication networks have experienced an accelerated expansion due to the growing number of connected devices, which imposes an increasing demand for advanced multimedia capabilities. In this context, the design and development of new technologies is of crucial importance for the advent of fifth-generation (5G) wireless networks, which must support such a proliferation of devices, thus requiring a significant increase in the system capacity and bandwidth [1, 2].

On the other hand, the spectrum scarcity has become one of the most critical issues to overcome, so as to make 5G networks a reality. In light of this scenario, part of the research efforts are being focused on the use of higher frequency bands, namely, the millimeter-wave (mm-Wave) radio spectrum, in order to enable ultra broadband applications [3]. In parallel, cognitive radio techniques have stood out as a promising alternative to efficiently exploit the spectrum resources, allowing terminals to be aware of the radio environment and to adapt their transmission settings to establish more reliable communications [4, 5]. Among cognitive radio techniques, the underlay spectrum-sharing approach has proven propitious to alleviate the spectrum-crunch problem by allowing unlicensed users (a.k.a. secondary users) to access a licensed band, allocated to primary users, provided that a certain level of interference on the primary network, referred to as interference temperature, is respected [6, 7].

On the other side, cooperative communications based on relays have drawn attention in the last decade because of the great potential to improve the transmission reliability and coverage extension of a wireless network, as the effect of fading can be counteracted through the use of a new sort of spatial diversity, referred to as cooperative diversity. In this context, two cooperative relaying protocols which govern the relay operation are widely known in the literature: decode-and-forward (DF), whereby the relay decodes and re-encodes the information signal before forwards it, and amplify-and-forward (AF), by which the relay forwards the information signal without hard decoding [8].

In view of the potential to bring both spectrum-usage efficiency and reliability, by leveraging spectrum sharing and cooperative communications together, cognitive relaying networks (CRNs) have received a great deal of attention from the research community and industry [9–11]. For example, in [9], the outage performance of a multiuser multirelay CRN was evaluated, considering underlay spectrum sharing constraints. In [10], the system performance in terms of the outage probability for two incremental DF protocols in CRNs with multiple destinations was investigated. In [11], an outage analysis for proactive DF relaying in underlay multisource multirelay cooperative networks was carried out. However, a common assumption in the aforementioned works, as well as in most of the related literature, is that the impact of the interference coming from the primary users on the secondary network is negligible. Indeed, this can be possible if the primary transmitter is located far enough from the secondary network, so that the interference links from the primary transmitter to the secondary receivers are subject to a severe attenuation due to the path loss and shadowing. On the other hand, because the primary and secondary users share the same frequency band, a mutual interference between them could be inevitable for certain scenarios.

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### B. Related Works

Despite the valuable research endeavors as yet, few studies have examined the effect of the primary-user interference on the secondary-network performance [12–18]. Among them, by considering a conventional secondary network (i.e., without cooperation), in [12], the aggregate interference on a secondary receiver coming from primary and other secondary transmitters is characterized for an underlay cognitive network, for which the spatial randomness of the nodes and a distance-based transmit power control scheme were taken into account by employing an stochastic geometry approach. In [13], the work in [12] was extended by considering massive multiple-input multiplo-output (MIMO) enabled base stations.

On the other hand, considering a cooperative secondary network (i.e., a CRN), in [14], the impact of the primary-user interference and outdated CSI on the outage probability of a three-node CRN with multiple-antenna secondary nodes and DF relaying was examined. In [15], the performance of a generalized order DF relay selection scheme was studied, taking into consideration the primary-user interference over the secondary network. In [16], the effect of the mutual interference between the primary and secondary systems on the outage performance of a cognitive two-way relay network with opportunistic relay selection was analyzed. In [17], the outage performance of a dual-hop multiuser underlay cognitive network in the presence of co-channel interference (CCI) was investigated, considering a DF relay and employing opportunistic scheduling at the destinations, but disregarding the presence of the direct links. In [18], the outage probability and the ergodic capacity were studied for a dual-hop underlay cognitive relaying network, consisting of a source, a DF relay, and a destination, when both primary transmitter interference and the CCI are considered over Nakagami-$m$ fading channels.

### C. Proposal and Contributions

This work aims to contribute to the study of the primary-network interference effect on the performance of underlay cognitive networks. More specifically, in order to exploit the multiuser diversity, the outage performance for two different destination-selection policies in a multiuser cognitive relaying network is analyzed. Motivated by the feedback-overhead efficiency, we consider two destination-selection policies based on partial channel state information (CSI) of the network. A first policy is based on CSI of the direct links (i.e., between the secondary source and each secondary destination), whereas the second policy is based on CSI of the relaying links (i.e., considering each path source-relay-destination). This is in contrast to the optimal selection criterion, which considers the global CSI of the network.

In our setup, the primary network is composed by one transmitter communicating with one receiver, while the secondary network is composed by one source communicating with one out of multiple destinations via both the direct link and an AF relay. A maximal-ratio combining (MRC) of the signals coming from the source and relay is performed at the selected destination. Also, following an underlay spectrum-sharing approach, we consider that the transmit power of the secondary nodes is constrained by two key system parameters: the maximum-available transmit power at the source and relay and the interference temperature imposed by the primary receiver.

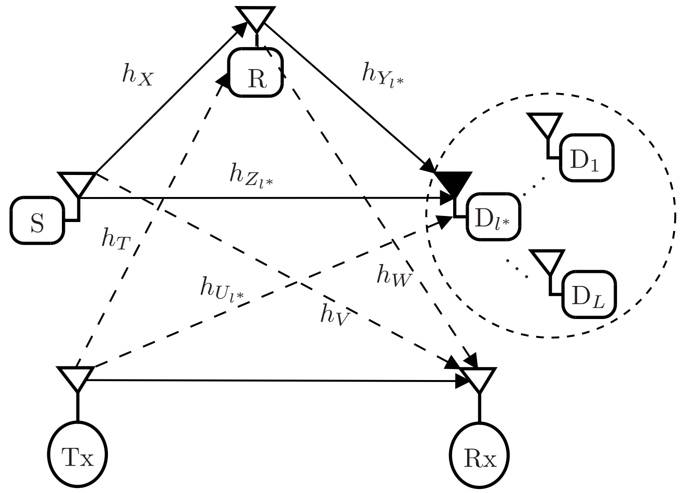


Fig. 1. System model of a cognitive relaying network, which operates under the presence of a primary-user pair. (data links: solid lines; interference links: dashed lines).

Our contribution in this paper is summarized as follows[1]:

- As in related studies, an exact treatment proves intractable, as the involved probabilities are extremely intricate. Instead, herein we derive single-fold integral-form approximations for the outage probability of the considered destination-selection schemes. Importantly, these approximations prove very tight to the exact outage probability under both destination-selection policies.
- We compare the performance of the considered selection policies to that of the optimal counterpart, also under the effect of primary-user interference.

The remainder of this paper is organized as follows. Section II introduces the system model. Section III describes the destination-selection policies, while the outage probability of both schemes is investigated in Section IV, by performing an approximation-based analysis. Section V illustrates some numerical results that validate the foregoing analysis. Finally, the main conclusions are drawn in Section VI.

*Notation:* Throughout this paper, $f_X(\cdot)$ and $F_X(\cdot)$ denote the probability density function (PDF) and cumulative distribution function (CDF) of a random variable $X$, respectively, $E[\cdot]$ is the expectation operator, and $\Pr[\cdot]$ stands for probability.

## II. SYSTEM MODEL

Consider the underlay CRN setting shown in Fig. 1, which consists of one source (S), one AF relay (R) and $L$ destinations ($\mathrm{D}_l$), with $l\in\{1, ..., L\}$, operating in the presence of a primary transmitter (Tx) and a primary receiver (Rx). All

[1]Preliminary results of this work were accepted for presentation in SBrT'17 [19]. Therein, the outage performance for four different destination-selection criteria in multiuser CRNs is assessed by exhaustive Monte Carlo Simulations, including the optimal selection scheme. The currently presented work extends the performance evaluation in [19], by performing a mathematical analysis of the outage probability for two of those destination-selection schemes.

terminals are considered to be single-antenna devices, which operate in half-duplex mode and in time division multiple access (TDMA). The channel coefficients corresponding to the data links S→R (first hop), R→$\mathrm{D}_l$ ($l$th second-hop), and S→$\mathrm{D}_l$ ($l$th direct link) are denoted by $h_X$, $h_{Y_l}$, and $h_{Z_l}$, respectively; and the channel coefficients corresponding to the interfering links S→Rx, R→Rx, Tx→R, and Tx→$\mathrm{D}_l$ are denoted by $h_V$, $h_W$, $h_T$, and $h_{U_l}$. All the links are assumed to undergo block Rayleigh fading and additive white Gaussian noise. Thus, the channel coefficients $h_A$, with $A\in\{X,Y_l,Z_l,V,W,T,U_l\}$, can be modeled as independent circularly-symmetric complex Gaussian random variables of zero mean and variance $\Omega_A$, that is, $\mathcal{CN}(0,\Omega_A)$, where $\Omega_A=E[|h_A|^2]$. Correspondingly, the channel gains $g_A = |h_A|^2$, with $A\in\{X,Y_l,Z_l,V,W,T,U_l\}$, are exponentially distributed with mean value $\Omega_A$. Moreover, the channel coefficients are supposed to remain constant during the transmission of a data block, but vary independently through consecutive blocks. Considering this, the instantaneous received signal-to-noise ratios (SNRs) for the links S→R, R→$\mathrm{D}_l$, S→$\mathrm{D}_l$, S→Rx, R→Rx, Tx→R and Tx→$\mathrm{D}_l$ are respectively given by $X=g_X P_{\mathrm{S}}/N_0$, $Y_l=g_{Y_l}P_{\mathrm{R}}/N_0$, $Z_l=g_{Z_l}P_{\mathrm{S}}/N_0$, $V=g_V P_{\mathrm{S}}/N_0$, $W=g_W P_{\mathrm{R}}/N_0$, $T=g_T P_{\mathrm{Tx}}/N_0$, and $U_l=g_{U_l}P_{\mathrm{Tx}}/N_0$, where $P_{\mathrm{S}}$, $P_{\mathrm{R}}$, and $P_{\mathrm{Tx}}$ are the transmit powers at S, R, and Tx. Note that the transmit power at the primary transmitter, $P_{\mathrm{Tx}}$, is modeled as a constant, while the transmit powers at the secondary source and relay, $P_S$ and $P_R$, are characterized so as to satisfy underlay spectrum-sharing constraints, namely, the maximum interference tolerated at the primary receiver and the maximum transmit power available at the secondary nodes, that is

$$P_{\mathrm{S}}=\min\left\{\frac{I}{g_V},\, P\right\}, \tag{1}$$

$$P_{\mathrm{R}}=\min\left\{\frac{I}{g_W}, P\right\} \tag{2}$$

Under these assumptions, by considering the $l$th relaying link, the received signals at R and $\mathrm{D}_l$ at time $t$ are given, respectively, by

$$y_{\mathrm{R}}(t)=\sqrt{P_{\mathrm{S}}}h_X s_{\mathrm{S}}(t)+\sqrt{P_{\mathrm{Tx}}}h_T s_{\mathrm{Tx}}(t)+n_{\mathrm{R}}(t), \tag{3}$$

$$y_{\mathrm{D}_l}(t)=\sqrt{P_{\mathrm{R}}}h_{Y_l}s_{\mathrm{R}}(t)+\sqrt{P_{\mathrm{Tx}}}h_{U_l}s_{\mathrm{Tx}}(t)+n_{\mathrm{D}_l}(t), \tag{4}$$

where $s_{\mathrm{S}}(t)$, $s_{\mathrm{R}}(t)$, and $s_{\mathrm{Tx}}(t)$ are the transmit signals at S, R, and Tx, respectively, with normalized mean power $E\{|s_{\mathrm{S}}(t)|^2\}=E\{|s_{\mathrm{R}}(t)|^2\}=E\{|s_{\mathrm{Tx}}(t)|^2\}=1$; and $n_{\mathrm{R}}(t)$ and $n_{\mathrm{D}_l}(t)$ are the AWGN components at $R$ and $\mathrm{D}_l$ with mean power $N_0$. In addition, by considering the AF relaying protocol, we have that $s_{\mathrm{R}}(t)=\beta y_{\mathrm{R}}(t)$, where $\beta$ is the amplification factor, given by

$$\beta=\frac{1}{\sqrt{g_X P_{\mathrm{S}}+g_T P_{\mathrm{Tx}}+N_0}}. \tag{5}$$

Therefore, from (4), the received signal at $\mathrm{D}_l$ can be rewritten as

$$\begin{aligned}y_{\mathrm{D}_l}(t)&=\sqrt{P_{\mathrm{S}}P_{\mathrm{R}}}h_X h_{Y_l}\beta s_{\mathrm{S}}(t)+\sqrt{P_{\mathrm{R}}P_{\mathrm{Tx}}}h_{Y_l}h_T\beta s_{\mathrm{Tx}}(t)\\&\quad+\sqrt{P_{\mathrm{R}}}h_{Y_l}\beta n_{\mathrm{R}}(t)+\sqrt{P_{\mathrm{Tx}}}h_{U_l}s_{\mathrm{Tx}}(t)+n_{\mathrm{D}_l}(t).\end{aligned} \tag{6}$$

Thus, the end-to-end instantaneous received SINR at $\mathrm{D}_l$, via the relaying link, can be expressed as

$$\begin{aligned}\Theta_l&=\frac{g_X P_{\mathrm{S}}g_{Y_l}P_{\mathrm{R}}\beta^2}{g_{Y_l}P_{\mathrm{R}}g_T P_{\mathrm{Tx}}\beta^2+g_{U_l}P_{\mathrm{Tx}}+\left(g_{Y_l}P_{\mathrm{R}}\beta^2+1\right)N_0}\\&\overset{(a)}{=}\frac{XY_l}{X\left(U_l+1\right)+Y_l\left(T+1\right)+\left(T+1\right)\left(U_l+1\right)}\\&=\frac{\frac{X}{T+1}\frac{Y_l}{U_l+1}}{\frac{X}{T+1}+\frac{Y_l}{U_l+1}+1}\\&\overset{(b)}{=}\frac{AB_l}{A+B_l+1},\end{aligned} \tag{7}$$

where the step $(a)$ results from replacing $\beta$ as given in (5), dividing the numerator and denominator by $N_0^2$, and performing some mathematical manipulations. The step $(b)$ results from defining $A\triangleq\frac{X}{T+1}$ and $B_l\triangleq\frac{Y_l}{U_l+1}$ as the received SINRs at the first hop (S→R) and the $l$th second hop (R→$\mathrm{D}_l$), respectively. Similarly, we can define $C_l\triangleq\frac{Z_l}{U_l+1}$ as the received SINR at the direct link (S→$\mathrm{D}_l$).

Now, let $\bar{\gamma}_{P_{\mathrm{Tx}}}=P_{\mathrm{Tx}}/N_0$ denote the transmit SNR at the primary transmitter (Tx), $\bar{\gamma}_P=P/N_0$ denote the maximum transmit SNR at the secondary source and relay (S and R), and $\bar{\gamma}_I=I/N_0$ denote the maximum interference-to-noise ratio tolerated at the primary receiver (Rx). Therefore, from (1) and (2), the instantaneous received SNRs $X$ and $Y_l$ can be written, respectively, as

$$X=\min\left\{\frac{\bar{\gamma}_I}{g_V},\bar{\gamma}_P\right\}g_X=\begin{cases}\bar{\gamma}_I\frac{g_X}{g_V}, & g_V>\frac{\bar{\gamma}_I}{\bar{\gamma}_P}\\ \bar{\gamma}_P g_X, & g_V\le\frac{\bar{\gamma}_I}{\bar{\gamma}_P},\end{cases} \tag{8}$$

$$Y_l=\min\left\{\frac{\bar{\gamma}_I}{g_W},\bar{\gamma}_P\right\}g_{Y_l}=\begin{cases}\bar{\gamma}_I\frac{g_{Y_l}}{g_W}, & g_W>\frac{\bar{\gamma}_I}{\bar{\gamma}_P}\\ \bar{\gamma}_P g_{Y_l}, & g_W\le\frac{\bar{\gamma}_I}{\bar{\gamma}_P}.\end{cases} \tag{9}$$

## III. Destination Selection Policies

In the proposed system, the signals coming from S and R are assumed to be combined at $\mathrm{D}_l$, with $l\in\{1,...,L\}$, by using a MRC technique. Additionally, it is considered that only one of the $L$ destinations is selected to participate in the communication process. Therefore, in order to prioritize the feedback efficiency, the system performance is evaluated for the following two destination-selection policies based on partial CSI:

1) **Direct Link-Based Policy (DL)**: this policy selects the destination $\mathrm{D}_{l^*}$ that maximizes the received SINR at the direct link, that is
$$l^*=\arg\max_l\{C_l\}. \tag{10}$$
2) **Max-Min-Based Policy (MM)**: this policy selects the destination $\mathrm{D}_{l^*}$ that maximizes the minimum between the received SINRs at the two-hops of the relaying link, that is
$$l^*=\arg\max_l\{\min\{A,B_l\}\}. \tag{11}$$

For these policies, the system performance is evaluated in terms of the outage probability in the following section.

## IV. Outage Probability

By definition, the system is in outage when the received SINR at the selected destination, $\gamma_{\text{MRC}}$, is below a certain threshold $\tau$. In this case, by considering a half-duplex mode operation, it is defined that $\tau \triangleq 2^{2\mathcal{R}} - 1$, where $\mathcal{R}$ is the target spectral efficiency in bits/s/Hz. Hence, the outage probability can be expressed as

$$\begin{aligned} P_{\text{OUT}} &= \Pr\left(\gamma_{\text{MRC}} < \tau\right) \\ &= \Pr\left(\Theta_{l^*} + C_{l^*} < \tau\right). \end{aligned} \tag{12}$$

For both destination-selection policies, the outage probability can be derived as described in Propositions 1 and 2, respectively, to be presented later on. Before proceeding, we present the following lemma, which will be useful in the proof of these propositions.

*Lemma* 1. The CDF and PDF for the instantaneous received SINR at the $l$th destination via the corresponding direct link, $C_l$, are respectively given by Eqs. (13) and (14), shown at the top of the next page, where $\text{Ei}(\cdot)$ stands for the exponential integral function [20, Eq. (8.211.1)].

*Proof.* The proof is provided in Appendix A. ■

Correspondingly, from *Lemma* 1, we can obtain the CDF and PDF for random variables $A$ and $B_l$, by substituting $\Omega_{Z_l}$ and $\Omega_{U_l}$ by $\Omega_X$ and $\Omega_T$ in (13) and (14), respectively, for the case of $A$, and $\Omega_V$ and $\Omega_{Z_l}$ by $\Omega_W$ and $\Omega_{Y_l}$, respectively, for the case of $B_l$.

Now, with the results of *Lemma* 1 as our primary tool, we can formulate the following propositions on the outage probability for the proposed destination-selection policies.

*Proposition* 1. An approximate integral-form expression for the outage probability of a multiuser cognitive relaying network under primary-user interference, which employs a DL-based destination-selection scheme, is given by

$$P_{\text{OUT}}^{\text{DL}} \approx L \int_0^{\tau} F_{\Phi_l}\left(\tau - c_l\right) F_{C_l}\left(c_l\right)^{L-1} f_{C_l}\left(c_l\right) dc_l, \tag{15}$$

where $\Phi_l \triangleq \min\{A, B_l\}$, and the PDF and CDF of $C_l$ are obtained as in *Lemma* 1.

*Proof.* The proof is provided in Appendix B. ■

*Proposition* 2. An approximate integral-form expression for the outage probability of a multiuser cognitive relaying network under primary-user interference, which employs the MM-based destination-selection scheme, is given by

$$\begin{aligned} P_{\text{OUT}}^{\text{M-M}} \approx & \int_0^{\tau} \Big[\left(1 - F_A\left(\tau - c_l\right)\right) F_{B_l}\left(\tau - c_l\right)^L \\ & + F_A\left(\tau - c_l\right)\left(1 - F_{B_l}\left(\tau - c_l\right)\right)\Big] f_{C_l}\left(c_l\right) dc_l, \\ & + \int_0^{\tau} \int_0^{\tau - c_l} F_A\left(b_l\right) f_B\left(b_l\right) f_{C_l}\left(c_l\right) db_l dc_l \\ & + \int_0^{\tau} \int_0^{\tau - c_l} F_B\left(a\right)^L f_A\left(a\right) f_{C_l}\left(c_l\right) da dc_l, \end{aligned} \tag{16}$$

where the PDFs and CDFs of $A$, $B_l$, and $C_l$ are obtained as in *Lemma* 1.

*Proof.* The proof is provided in Appendix C. ■

## V. Numerical Results and Discussions

In this section, the approximate outage expressions derived in Section IV are evaluated, considering some illustrative cases. For this purpose, let us consider a two-dimensional network topology, as illustrated in Fig. 2, where the secondary source and relay are located at $(0, 0)$ and $(0.5, 0)$, respectively. The secondary destinations are clustered and collocated at $(0, 1)$, and the primary users Tx and Rx are located at (0, 1) and (1, 1), respectively. Without loss of generality, the average channel gain for the links between any pair of nodes is assumed to be determined by the path loss, i.e., $\Omega_A = d_A^{-\alpha}$, with $A \in \{X, Y_l, Z_l, V, W, T, U_l\}$, where $d_A$ is the distance between the corresponding nodes and $\alpha$ is the path loss exponent. In the following examples, the path loss exponent is set as $\alpha = 4$ and the target spectral efficiency is set as $\mathcal{R} = 1$.

Fig. 3 illustrates the outage probability versus the transmit SNR $\bar{\gamma}_P$, considering the two destination-selection policies described in Section III, for a different number of secondary destinations $L = 1, 3, 5, 7$. We corroborate our analytical formulas via Monte Carlo simulations. It can be observed from Fig. 3 that our approximate expressions in (15) and (16) prove very tight, especially for $L > 1$. For comparison, the outage probability of the optimal destination-selection criterion, which considers global CSI of the network, is also shown. As expected, the optimal scheme achieves the best performance. Additionally, note that the DL-based policy, which maximizes the received SINR at the direct links, $C_l$, achieves a nearly-optimal performance. Thus, for the considered scenario, this policy proves more advantageous than the optimal criterion, as only partial knowledge of the CSI is required, thereby alleviating drastically the feedback overhead of the network. On the other hand, noted that the outage performance for the MM-based policy remains almost the same, as the number of secondary destinations increases. In addition, note from the slopes of the curves at high SNR that, for the DL-based criterion, the diversity order increases as $L$ increases; while for the MM-based counterpart, the diversity order does not improve. This is because the multiuser diversity for the former criterion is exploited from the direct links, thus not being compromised by the channel condition of any other link. Conversely, for the MM-based criterion, the multiuser diversity of the second hops is bottlenecked by the channel condition of the first hop, which is common to all destinations.

Fig. 4 shows the outage probability versus the normalized distance between the secondary source and relay. For clarity, only the cases $L = 3$ and $7$ are presented. Observe that, for any relay position, the best performance is always attained by the optimal destination-selection criterion, as expected. Also note that, when the relay is close to the source, the DL-based policy provides the worst performance among the three considered criteria. In addition, the performance gap among the considered policies increases, as $L$ increases. This is because, for this relay position, the first hop presents a good channel condition in average, whereas the second hops and the direct links present weaker channel conditions. Thus, multiuser

$$F_{C_l}(c_l) = e^{-\frac{\bar{\gamma}_I}{\bar{\gamma}_P \Omega_V}} + \frac{\bar{\gamma}_I \Omega_{Z_l} e^{\frac{\bar{\gamma}_I \Omega_{Z_l} + c_l \Omega_V}{\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_V}} \operatorname{Ei}\left[-\frac{(c_l \Omega_V + \bar{\gamma}_I \Omega_{Z_l})(\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} + \bar{\gamma}_P \Omega_{Z_l})}{\bar{\gamma}_P \bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_V \Omega_{Z_l}}\right]}{\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_V} + \frac{\left(1 - e^{-\frac{\bar{\gamma}_I}{\bar{\gamma}_P}\Omega_V}\right)}{\bar{\gamma}_P \Omega_{Z_l} + \bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l}} \left[\bar{\gamma}_P \Omega_{Z_l}\left(1 - e^{-\frac{c_l}{\bar{\gamma}_P \Omega_{Z_l}}}\right) + \bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l}\right] \tag{13}$$

$$f_{C_l}(c_l) = \frac{-1}{\bar{\gamma}_{P_{Tx}} c_l^3 \Omega_{U_l}^2 \Omega_V^2} \Bigg[ \frac{\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_V e^{-\frac{\bar{\gamma}_I \Omega_{Z_l} + c_l \Omega_V}{\bar{\gamma}_P \Omega_{Z_l} \Omega_V}}}{(c_l \Omega_V + \bar{\gamma}_I \Omega_{Z_l})(\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} + \bar{\gamma}_P \Omega_{Z_l})^2} \Big[ e^{\frac{\bar{\gamma}_I}{\bar{\gamma}_P \Omega_V}} \bar{\gamma}_{P_{Tx}} c_l^2 \Omega_{U_l} \Omega_V (c_l \Omega_V + \bar{\gamma}_I \Omega_{Z_l})(\bar{\gamma}_P \Omega_{Z_l} + \bar{\gamma}_{P_{Tx}} \Omega_{U_l}(c_l + \bar{\gamma}_P \Omega_{Z_l})) - \bar{\gamma}_I^2 \bar{\gamma}_P^2 \Omega_{Z_l}^4 - \bar{\gamma}_P \bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_{Z_l} \left(c_l^2 \Omega_V^2 + \bar{\gamma}_I^2 \Omega_{Z_l}^2\right) - \bar{\gamma}_{P_{Tx}}^2 c_l^2 \Omega_{U_l}^2 \Omega_V \left(c_l^2 \Omega_V + \bar{\gamma}_P c_l \Omega_V \Omega_{Z_l} + \bar{\gamma}_I \bar{\gamma}_P \Omega_{Z_l}^2\right) \Big] - e^{\frac{\bar{\gamma}_I \Omega_{Z_l} + c_l \Omega_V}{\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_V}} \bar{\gamma}_I \Omega_{Z_l} \left(\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_V + \bar{\gamma}_I \Omega_{Z_l}\right) \operatorname{Ei}\left[-\frac{(c_l \Omega_V + \bar{\gamma}_I \Omega_{Z_l})(\bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} + \bar{\gamma}_P \Omega_{Z_l})}{\bar{\gamma}_P \bar{\gamma}_{P_{Tx}} c_l \Omega_{U_l} \Omega_V \Omega_{Z_l}}\right] \Bigg] \tag{14}$$

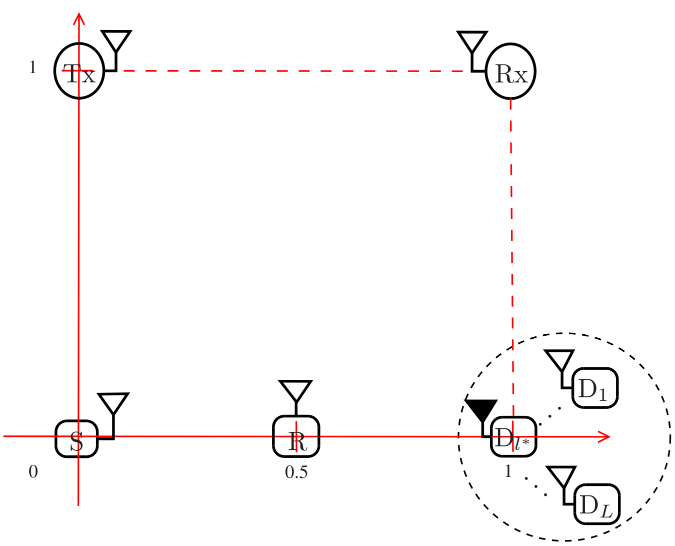


Fig. 2. Network topology.

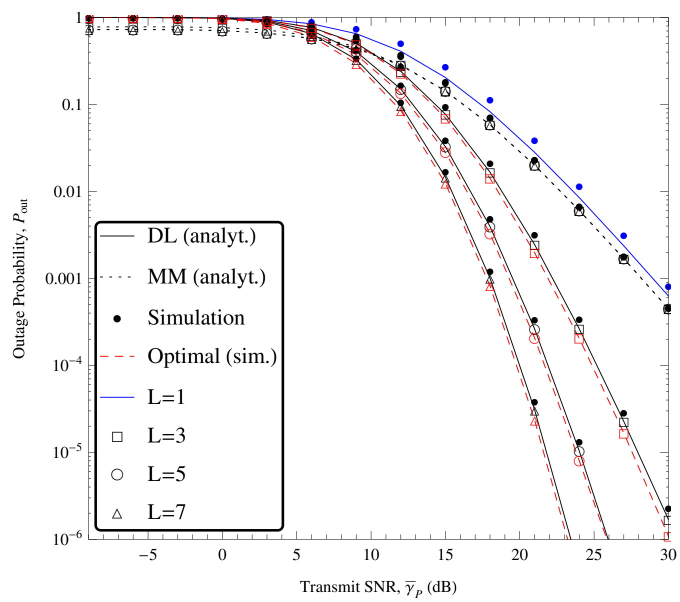


Fig. 3. Outage propability vs. transmit SNR $\bar{\gamma}_P$ for $L = 1, 3, 5$ and 7, with $\bar{\gamma}_{P_{\mathrm{Tx}}} = 20$ dB, $\bar{\gamma}_I = 50$ dB, and $d_X/d_{Z_l}$=0.5.

diversity can be efficiently exploited. On the other hand, as the relay moves closer to the destinations, observe that the outage performance of the DL-based criterion approaches that of the optimal policy, whereas the performance of the MM-based criterion worsens. This is due to the fact that, in average, all the second hops and direct links exhibit good channel conditions, while the first hop is weaker. Under this condition, the MM-based criterion is governed by the channel state of the first hop, which is the bottleneck, thus it is not possible to take full advantage of multiuser diversity. Additionally, it can be observed that the best relay position is closer to the source for both the optimal and MM-based criteria, whereas it is midway between the source and relay for the DL-based criterion.

To complement the previous results, the outage probability versus the transmit SNR $\bar{\gamma}_P$, for both destination-selection policies, is illustrated in Fig. 5, by considering $L = 3$. For comparison purposes, three relative positions of R were contrasted, namely $d_X/d_{Z_l} = 0.1$, 0.5, 0.9. It can be observed that the MM-based policy presents the worst performance for the positions of R closest to D. Also, the diversity order is lower than that attained by the DL-based and optimal policies. For those positions, the DL-based policy presents the same diversity order and an excellent approximation to the optimal policy. Furthermore, for the normalized distance $d_X/d_{Z_l} = 0.1$ (i.e., when R is close to S), the MM-based policy attains the same diversity order of that corresponding to the DL-based policy with a slightly performance improvement. However, for that position, the optimal policy presents an increased diversity order with respect to the two analyzed policies, thus the outage performance is superior. This behavior can be explained by perceiving that for the positions of R closest to S, the first-

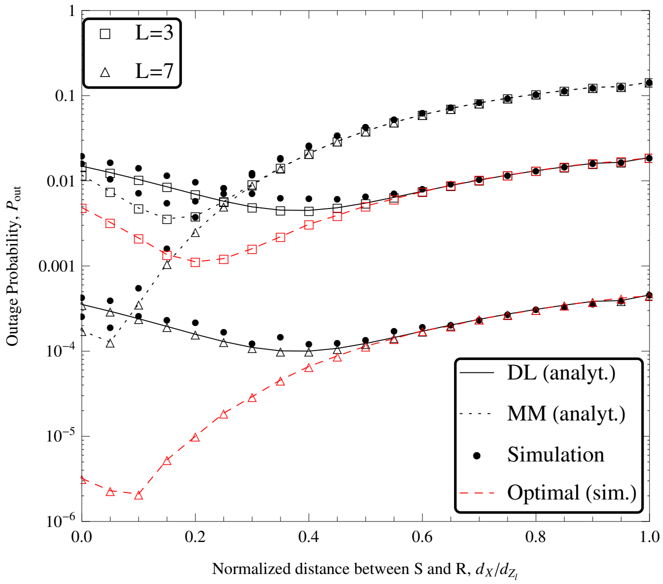


Fig. 4. Outage probability vs. normalized distance between secondary source and relay for $L = 3$ and 7, with $\bar{\gamma}_{P_{\mathrm{Tx}}} = 20$ dB, $\bar{\gamma}_I = 50$ dB and $\bar{\gamma}_P = 20$ dB.

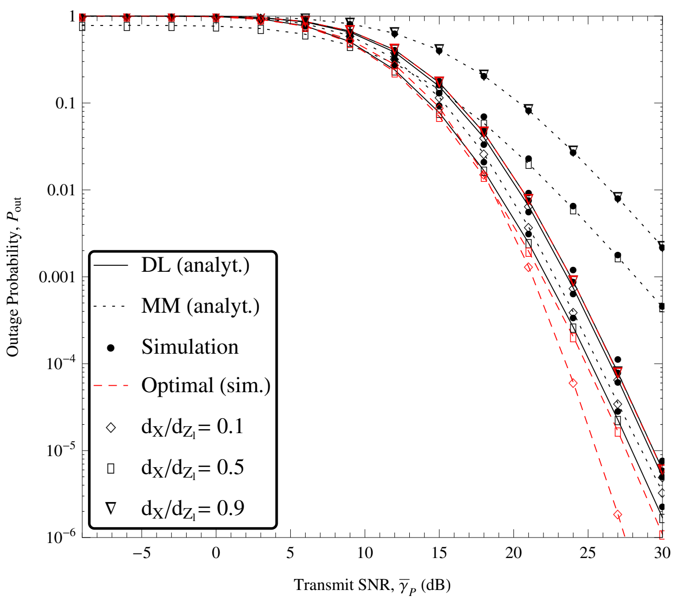


Fig. 5. Outage probability vs. transmit SNR $\bar{\gamma}_P$ for different normalized distances between S and R, $d_X/d_{W_l}$=0.1, 0.5, 0.9, with $L = 3$, $\bar{\gamma}_{P_{\mathrm{Tx}}}$=20 dB and $\bar{\gamma}_I$ = 50 dB.

hop relaying link is strong, thus strengthening the second hop with multiuser diversity leads to performance gains and to a greater diversity order, as the first hop does not represent a bottleneck. Otherwise, for the positions of R nearest to D, the first hop represents a bottleneck, thus impeding the MM-based policy from attaining diversity gains. Moreover, we can also notice that the other policies do not attain full diversity.

Fig. 6 illustrates the outage probability versus the transmit SNR $\bar{\gamma}_P$, by setting the number of destinations to $L = 3$ and the normalized distance between source and relay to $d_X/d_{Z_l}$=0.5. In this figure, we consider only the DL-based

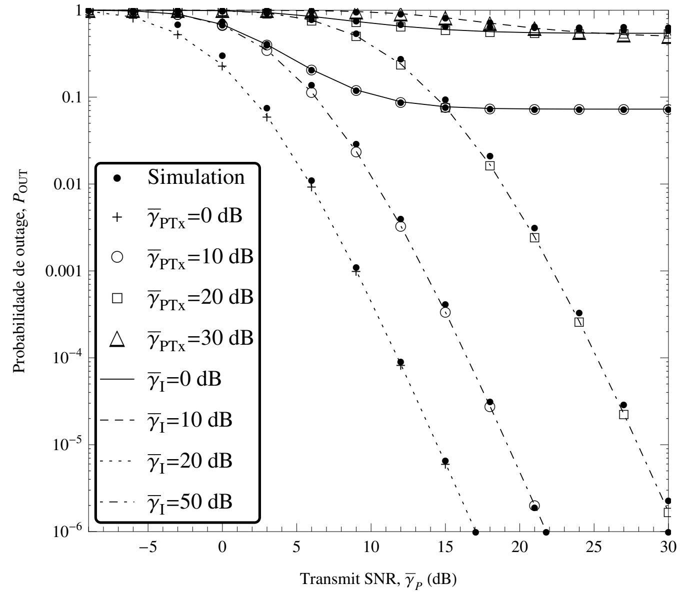


Fig. 6. Outage probability vs. transmit SNR $\bar{\gamma}_P$ for different values of $\bar{\gamma}_I$ and $\bar{\gamma}_{P_{\mathrm{Tx}}}$, with $L = 3$.

selection policy, as the results for the MM-based policy present the same behavior. Simulations were performed for different configurations of $\bar{\gamma}_{P_{\mathrm{Tx}}}$ and $\bar{\gamma}_I$. It can be observed that performance floors are inflicted by the interference temperature $\bar{\gamma}_I$. Thus, up to $\bar{\gamma}_I = 10$ dB, the secondary network performance is highly impaired by the constraints imposed by the primary network. On the other hand, a variation on $\bar{\gamma}_{P_{\mathrm{Tx}}}$ does not determine the emergence of performance floors. However, an increase on $\bar{\gamma}_{P_{\mathrm{Tx}}}$ can lead to important performance losses for the secondary network, as can be observed in the curves for $\bar{\gamma}_I = 0$ dB and $\bar{\gamma}_I = 50$ dB. This concern can be critical for various scenarios leveraging cognitive radio, as those based on sensors and unmanned aerial vehicles (UAVs), where the secondary nodes can be very close to the primary transmitters. In those cases, the underlay spectrum sharing strategy could not be the best option for cognitive relaying networks. Therefore, the consideration of the interference from the primary network over the secondary network is of crucial importance for practical design criteria of spectrum-sharing networks when the underlay paradigm is taken into account.

## VI. Conclusion

In this paper, the outage performance of a multiuser cognitive relaying network under the impact of the primary-network interference was investigated by considering two destination-selection policies based on partial CSI: one taking into account the direct links and one considering the dual-hop relaying links between the source and destinations. Integral-form expressions for the outage probability of the considered destination-selection policies were derived. It was noticed that the DL-based destination selection criterion is an excellent approximation to the optimal criterion which considers global CSI, while being more efficient in terms of the required feedback overhead, especially for the relay positions beyond midpoint between the source and the collocated destinations.

On the other hand, for positions close to the source, the MM-based policy presents a better performance. However, for these positions, both policies present performances losses when compared with the optimal policy. Finally, it was found that the interference temperature imposed by the primary receiver is responsible for system performance floors, while the interference coming from the primary network over the secondary network can cause significant performance losses in the cognitive network, which can be critical in practical underlay spectrum sharing networks.

## APPENDIX A
## PROOF OF LEMMA 1

The CDF of the received SINR $C_l$ can be formulated as

$$\begin{aligned} F_{\gamma_{C_l}}(c_l) &= \Pr\left(\gamma_{C_l} < c_l | g_V\right) \\ &= \Pr\left(\frac{Z_l}{U_l+1} < c_l | g_V\right) \\ &= \int_0^\infty \Pr\left(Z_l < c_l(u_l+1)|g_V\right) f_{U_l}(u_l)\, du_l \\ &= I_1 + I_2, \end{aligned} \tag{17}$$

where, by considering (8), the terms $I_1$ and $I_2$ can be expressed as

$$I_1 = \int_{\bar{\gamma}_I/\bar{\gamma}_P}^{\infty} \int_0^\infty F_{g_{Z_l}}\left[\tfrac{c_l v(u_l+1)}{\gamma_I}\right] f_{U_l}(u_l)\, f_V(v)\, du_l dv \tag{18}$$

$$I_2 = \int_0^{\bar{\gamma}_I/\bar{\gamma}_P} \int_0^\infty F_{g_{Z_l}}\left[\tfrac{c_l (u_l+1)}{\gamma_P}\right] f_{U_l}(u_l)\, f_{g_V}(v)\, du_l dv. \tag{19}$$

Then, by solving exponential-function integrals and considering [20, eq. (3.352-2)], the CDF of $C_l$ can be obtained as in (13), and by applying the derivative to that expression, the PDF of $C_l$ can be obtained as in (14).

## APPENDIX B
## PROOF OF PROPOSITION 1

For the DL-based destination selection policy, the outage probability in (12) can be rewritten as

$$\begin{aligned} P_{\text{OUT}}^{\text{DL}} &= \Pr\left(\Theta_{l^*} + C_{l^*} < \tau\right) \\ &\overset{(a)}{=} \sum_{l=1}^{L} \Pr\left(\frac{AB_l}{A+B_l+1} + C_l < \tau | l = l^*\right) \Pr\left(l = l^*\right) \\ &\overset{(b)}{>} \sum_{l=1}^{L} \Pr\left(\min\{A, B_l\} + C_l < \tau\right) \Pr\left(C_l > \max_{\substack{i=1,\ldots,L \\ i\neq l}} \{C_i\}\right) \\ &= L \int_0^\tau \Pr\left(\min\{A, B_l\} < \tau - c_l\right) F_{C_l}(c_l)^{L-1} f_{C_l}(c_l)\, dc_l, \end{aligned} \tag{20}$$

where the step $(a)$ is obtained by applying the Total Probability Theorem [21], and $(b)$ is obtained by using the well known approximation of $\Theta_l$ by its upper-bound $\Phi_l = \min\{A, B_l\}$, which has proved to render a tight approximation [22]. Also,

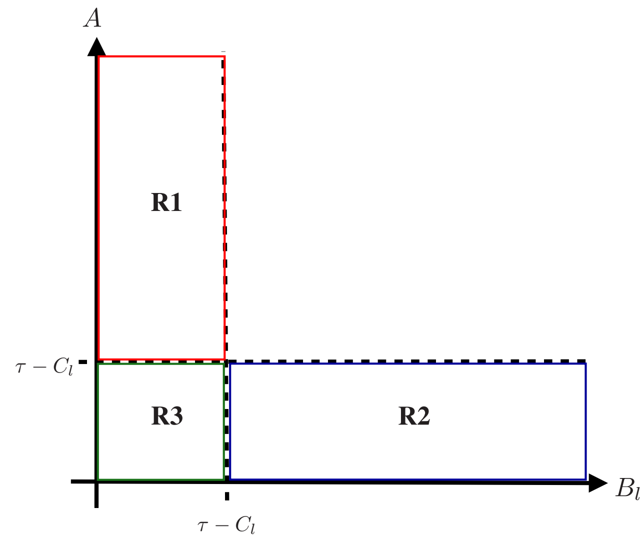


Fig. 7. Regions for the random variables $A$ and $B_l$

as $A$ and $B_l$ are independent random variables, then the CDF of $\Phi_l$ can be expressed as

$$F_{\Phi_l}(\phi_l) = F_A(\phi_l) + F_{B_l}(\phi_l) - F_A(\phi_l) F_{B_l}(\phi_l). \tag{21}$$

By substituting (21) in (20), we arrive to the expression in (15).

## APPENDIX C
## PROOF OF PROPOSITION 2

Under the same considerations of Appendix B, from (12), the outage probability for the MM destination-selection policy can be rewritten as

$$\begin{aligned} P_{\text{OUT}}^{\text{M-M}} > &\sum_{l=1}^{L} \Pr\left(\min\{A, B_l\} + C_l < \tau\right) \\ &\times \Pr\left(\min\{A, B_l\} > \max_{\substack{i=1,\ldots,L \\ i\neq l}} \{\min\{A, B_i\}\}\right). \end{aligned} \tag{22}$$

The expression above can be analyzed by considering the regions for random variables $A$ and $B_l$ as depicted in Fig. 7, that is: 1) $A > \tau - C_l$ and $B < \tau - C_l$, 2) $A < \tau - C_l$ and $B > \tau - C_l$, and 3) $A < \tau - C_l$ and $B < \tau - C_l$. For the first region, we have that $B_l$ is always lower than $A$, thus the destination selection is dominated by $B_l$, and the expression in (22) for this region can be rewritten as

$$\begin{aligned} P_{\text{OUT}}^{\text{R1}} &= \sum_{l=1}^{L} \Pr(A > \tau - C_l, B < \tau - C_l) \Pr\left(B_l > \max_{\substack{i=1,\ldots,L \\ i\neq l}} \{B_i\}\right) \\ &= L \int_0^\tau \left(1 - F_A(\tau - c_l)\right) \int_0^{\tau - c_l} F_{B_l}(b_l)^{L-1} f_{B_l}(b_l)\, f_{C_l}(c_l)\, d_l dc_l \\ &= \int_0^\tau \left(1 - F_A(\tau - c_l)\right) F_{B_l}(\tau - c_l)^L f_{C_l}(c_l)\, dc_l. \end{aligned} \tag{23}$$

By following the same rationale, in the second region, the destination selection is dominated by $A$. In this case, as all destinations present the same first-hop link, the probability of selection of each one of them is equal to $1/L$, thus, for this region, (22) can be rewritten as

$$\begin{aligned} P_{\text{OUT}}^{\text{R2}} &= \sum_{l=1}^{L} \Pr(A<\tau-C_l, B>\tau-C_l)\,\frac{1}{L} \\ &= \int_{0}^{\tau} F_A(\tau-c_l)\left(1-F_{B_l}(\tau-c_l)\right) f_{C_l}(c_l)\,dc_l. \end{aligned} \tag{24}$$

For the third region, we split the region into two subregions, a)$A < B_l$ and b)$B_l < A$. For the first subregion, we have the same condition of region 2, thus all destinations have the same probability of selection and (22) for this case can be rewritten as

$$\begin{aligned} P_{\text{OUT}}^{\text{R3a}} &= \sum_{l=1}^{L} \Pr(A<\tau-C_l, B<\tau-C_l, A<B_l)\,\frac{1}{L} \\ &= \int_0^{\tau}\int_0^{\tau-c_l} F_A(b_l)\, f_B(b_l)\, f_{C_l}(c_l)\,db_l dc_l. \end{aligned} \tag{25}$$

For the second subregion, we have the same condition of region 1, thus (22) for this case can be rewritten as

$$\begin{aligned} P_{\text{OUT}}^{\text{R3b}} &= \sum_{l=1}^{L} \Pr(A>\tau-C_l, B<\tau-C_l, B_l<A) \\ &\quad \times \Pr\left(B_l > \max_{\substack{i=1,\dots,L\\ i\neq l}} \{B_i\}\right) \\ &= \int_0^{\tau}\int_0^{\tau-c_l} F_B(a)^L\, f_A(a)\, f_{C_l}(c_l)\,da dc_l. \end{aligned} \tag{26}$$

Finally, by summing up (23) to (26), we arrive to the expression in (16).

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