Underlay Cognitive Proactive DF Relay Networks With Multiple Primary Transmitters and Receivers

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Abstract—The performance of underlay cognitive relay networks with multiple primary users and multiple proactive decode-and-forward relays is investigated. Particularly, both interference power constraints at multiple primary receivers and multiple primary transmitters’ interference at secondary transmission nodes are taken into account. Considering correlations among the received signal-to-interference-plus-noise ratios, exact closed-form expressions for the outage probabilities of secondary users are derived for the cases with or without a direct secondary link over Rayleigh fading channels. A novel method is proposed to analyze the outage probability for cognitive proactive decode-and-forward relay networks in the presence of a direct secondary link. Simulation results show that the diversity gain is zero in the presence of multiple primary transmitters’ interference, but the outage floor in the high SNR can be significantly decreased by an increase of the number of relays or by exploiting a direct secondary link.

I. INTRODUCTION

The dilemma between spectrum scarcity and underutilization motivates the emergence of cognitive radio [1], [2]. In cognitive radio networks, the unlicensed users (secondary users, SUs) always access the licensed spectrum via interweave, overlay, and underlay modes [3]. For underlay cognitive radio networks, the SUs are allowed to coexist with the licensed user (primary user, PU) provided that the interference limits at the PU receiver are satisfied. To compensate the performance loss caused by the constraints of SU’s transmission powers, cooperative relay techniques are incorporated into the transmission of underlay cognitive radio networks when there exist multiple potential users. Cognitive relay networks are receiving great interest from both academic and industrial sectors owing to their potential to alleviate the spectrum scarcity problem.

There have been active studies on underlay cognitive relay networks. In [4], with both maximum transmit power and peak interference power constraints, outage analysis was conducted for underlay cognitive radio networks with multiple incremental relays over Rayleigh fading channels, where the interference from the PU is omitted. Considering the same scenario as in [4], the Nth best relay selection for underlay cognitive relay network was investigated in [5]. The authors in [6] analyzed the performance of the SU under interference power constraints with PU’s interference. Exact outage probability and diversity gain for the SU were studied for single decode-and-forward (DF) relaying in [7] and multiple DF relaying in [8] accounting for a direct secondary link.

Note that the aforementioned works only consider interference power constraints at a single PU receiver or interference from a single PU transmitter. This scenario may not be the case in future cognitive networks, where the primary system could be a cellular network with more than one PU [9]. Accordingly, the authors in [10]-[12] investigated the end-to-end performance of cognitive relay networks under spectrum sharing constraints for multiple PU receivers. Further, in [13] and [14], the impact of multiple primary transmitters and receivers on the outage performance of underlay cognitive relay networks was evaluated, where only a single proactive DF relay is deployed and the direct secondary link is neglected. However, in practical wireless scenarios, there always exist multiple available relays which can significantly increase the system performance and the direct secondary link has great impact on SUs. To the best of the authors’ knowledge, there is no literature studying outage probability for cognitive radio networks equipped with multiple proactive DF relays, especially for the case with a direct secondary link.

In this paper, we extend previous works by accounting for both interference power constraints at multiple PU receivers and interference from multiple PU transmitters with multiple available proactive DF relays. By considering the correlation among the received signal-to-interference-plus-noise ratios (SINRs) caused by multiple PUs’ interference, exact outage probabilities for underlay cognitive relay networks are derived for the cases with and without a direct secondary link over Rayleigh fading channels. In particular, a novel and simple method that enables solving for the outage performance of the SU with a direct secondary link is revealed. Furthermore, our results show that: (1) in the presence of primary transmitters’ interference, diversity gain cannot be obtained and there exist outage floors in high signal-to-noise ratio (SNR) regimes, (2) exploiting a direct secondary link or increasing the number of relays are effective ways to mitigate the performance degradation caused by the presence of multiple PUs, (3) the interference caused by the PU transmitters has great impact on the SU, which cannot be ignored. The remainder of this paper is organized as follows. Section II describes the underlay
cognitive radio model with multiple primary transmitters and multiple primary receivers. In Section III, exact closed-form expressions for the outage probabilities for the cases with and without direct secondary link are provided. Simulation results and discussions are given in Section IV. Finally, Section V concludes this paper.

II. SYSTEM MODEL

Consider an overlay cognitive radio network as shown in Fig. 1, where the primary network consists of $N$ PU transmitters $\{v_1, v_2, \ldots, v_N\}$ and $M$ PU receivers $\{v_1, v_2, \ldots, v_M\}$ [15], while in the secondary network, SU source $s$ sends messages toward destination $d$ via a direct link or with the aid of one best relay selected from the candidate relay set $\mathcal{R} = \{r_1, r_2, \ldots, r_K\}$. The dash and solid lines denote the transmission from the primary transmitter $u$ and secondary source $s$, respectively. The dash dot line denotes the transmission from the relay $r_k$. In the relay transmission, a two time slot proactive DF relay protocol is deployed by utilizing the aid of one best relay selected from the candidate relay set $\mathcal{R} = \{r_1, r_2, \ldots, r_K\}$. The dash and solid lines denote the transmission from the primary transmitter $u$ and secondary source $s$, respectively. The dash dot line denotes the transmission from the relay $r_k$. In the relay transmission, a two time slot proactive DF relay protocol is deployed by utilizing the method of distributed timers [15]. The noise terms at receivers are modeled as zero-mean Gaussian random variables with common variance, $N_0$. The instantaneous channel gain between node $i$ and node $j$, denoted as $g_{ij} = |h_{ij}|^2$, follows an exponential distribution with mean $\sigma^2_{ij}$. For simplicity of analysis, let $\sigma^2_{sv} = \sigma^2_{uv}$, $\sigma^2_{sr} = \sigma^2_{ur}$, $\sigma^2_{ur,v} = \sigma^2_{ur}$, $\sigma^2_{uv,d} = \sigma^2_{rd}$, and $\sigma^2_{rv} = \sigma^2_{rv}$, $\forall 1 \leq n \leq N$, $1 \leq i \leq M$, and $1 \leq j \leq K$. Additionally, all PU transmitters transmit with equal and fixed power, $P_u$. The SU adaptively adjusts the transmission powers of secondary nodes to ensure maximum interference power $I$ at the PU receivers. To avoid interfering with the PUs’ communications, the allowed maximum transmission powers of SU source $s$ and the relay $r_k$ are limited by [10], [11] $P_s = I/X_1$ and $P_{rk} = I/X_{2k}$ with $X_1 = \max_{1 \leq m \leq M} (g_{sv,m})$ and $X_{2k} = \max_{1 \leq m \leq M} (g_{rv,m})$.

III. OUTAGE PERFORMANCE

A. Without Direct Secondary Link

In cognitive relay networks, the direct link between SU source and destination may not be available due to a variety of reasons, such as the presence of shadowing, deep fading, and so on. In this case, only the relay with largest end-to-end SINR is selected as the best relay to decode and forward the source message. According to the proactive DF relay protocol, the end-to-end SINR $\gamma_{end}$ is given by

$$\gamma_{end} = \max_{r_k \in \mathcal{R}} (\min (\delta_{sr_k}, \delta_{rv,d}))$$

(1)

where $\delta_{sr_k}$ and $\delta_{rv,d}$ respectively represent the received SINR at the relay $r_k$ and SU destination $d$, which are given by

$$\delta_{sr_k} = \frac{P_g g_{sr_k}}{\sum_{n=1}^{N} P_u g_{un,r_k} + N_0} = \frac{\gamma_{g_{sr_k}}}{X_1 (\gamma_{Y_{1k}} + 1)}$$

(2)

$$\delta_{rv,d} = \frac{P_g g_{rv,d}}{\sum_{n=1}^{N} P_u g_{un,d} + N_0} = \frac{\gamma_{g_{rv,d}}}{X_{2k} (\gamma_{Y_{2}} + 1)}$$

(3)

where $\gamma = \frac{I}{N_0}$ and $\gamma_l = \frac{P_A}{N_0}$ denote the SNR and interference-to-noise ratio (INR), $Y_{1k} = \sum_{n=1}^{N} g_{un,r_k}$ and $Y_{2} = \sum_{n=1}^{N} g_{un,d}$ are the interference at the relay $r_k$ and secondary destination $d$ from primary transmitters.

The outage probability is defined as the probability that the end-to-end SINR falls below the predetermined outage threshold [7], mathematically

$$P_{out} = \Pr (\gamma_{end} < \gamma_{th})$$

(4)

where, with $R$ denoting the transmission rate, $\gamma_{th} = 2^{2R} - 1$ is the predetermined outage threshold. Note that, due to the interference from $N$ PU transmitters and interference power constraints at $M$ PU receivers, the received SINR at the relay $r_k$ and at the SU destination $d$ are correlated for different relays. Thus, conditioned on the common terms $X_1$ and $Y_2$, the outage probability of the SU is written as

$$P_{out} = \int_0^{\infty} \int_0^{\infty} \Pr (\gamma_{end} < \gamma_{th} | x_1, y_2) \times f_{X_1}(x_1) f_{Y_2}(y_2) dx_1 dy_2$$

(5)

in which $f_{X_1}(x_1)$ and $f_{Y_2}(y_2)$ respectively represent the probability density function (PDF) of $X_1$ and $Y_2$. Further, the cumulative distribution function (CDF) of $X_1$ is $F_{X_1}(x_1) = \left(1 - \exp \left(-\frac{x_1}{\sigma^2_{sv}} \right) \right)^M$. Then, by employing the binomial theorem and taking the derivative of $F_{X_1}(x_1)$ with respect to $x_1$, the PDF of $X_1$ is obtained as

$$f_{X_1}(x_1) = \sum_{m=1}^{M} \binom{M}{m} \left(-\frac{x_1}{\sigma^2_{sv}} \right)^m \exp \left(-\frac{m_1 x_1}{\sigma^2_{sv}} \right)$$

(6)

where $C_{M}^{m}$ is the binomial coefficient. $Y_2$ quantifies the interference from multiple PU transmitters at the SU destination $d$, and has PDF

$$f_{Y_2}(y_2) = \frac{y_2^{N-1}}{\Gamma(N)} \left(\frac{\sigma^2_{sv}}{\sigma^2_{uv,d}} \right)^N \exp \left(-\frac{y_2}{\sigma^2_{uv,d}} \right).$$

(7)

Using the laws of probability theory, the conditional outage probability $\Pr (\gamma_{end} < \gamma_{th} | x_1, y_2)$ in (5) is written as

$$\Pr (\gamma_{end} < \gamma_{th} | x_1, y_2) = [1 - \Pr (\delta_{sr_k} > \gamma_{th} | x_1) \Pr (\delta_{rv,d} > \gamma_{th} | y_2)]^K.$$
According to the binomial theorem, (8) can be further expanded as

\[ Pr(\gamma_{end} < \gamma_{th} \mid x_1, y_2) = \sum_{k=0}^{K} C_K^k (-1)^k \left( Pr(\delta_{sr_k} > \gamma_{th} \mid x_1) \right)^k \]

(9)

and

\[ \Omega_2 = \int_0^\infty \left[ Pr(\delta_{rd} > \gamma_{th} \mid y_2) \right]^k f_{y_2}(y_2) \, dy_2 \]

\[ = \frac{(M!)^k (A_3)^k \sigma_d^2}{\prod_{m=1}^{M-1} (1 + m A_3)^k} \Phi_2(N, k, \cdots, \frac{1}{1 + MA_3}, \frac{\sigma_d^2}{\sigma_{sr}^2}) \]

(15)

where \( A_1 = \frac{\gamma_{sr}^2 m_2}{\gamma_{sr}^2 \gamma_{th}}, \ A_2 = \frac{1}{\gamma_{sr}^2 \gamma_{th}}, \ A_3 = \frac{\gamma_{sr}^2 \gamma_{th}}{\gamma_{sr}^2 \gamma_{th}} \), \( \xi(n, a) = x^{n-1} e^{-a} \Gamma(-n + 1, x) \), \( \Gamma(\cdot, \cdot) \) denotes the upper incomplete gamma function [16], and \( \Phi_2(a, b_1, \cdots, b_k; z) \).

B. With Direct Secondary Link

When the direct secondary link is available, the SU source broadcasts the message to the SU destination in the first time slot and the relay with largest end-to-end SINR. Then, in the following, second time slot, the best relay forwards the source messages to the SU destination. Finally, the SU destination combines the signals received from the direct link and the best relay using maximum ratio combining (MRC). In this case, the received SINR \( \gamma_{end}^{direct} \) is given by

\[ \gamma_{end}^{direct} = \max_{r_k \in K} \left( \min(\delta_{sr_k}, \delta_{sd} + \delta_{rd}) \right) \]

(16)

where \( \delta_{sd} = \frac{\gamma_{sd}^2}{\gamma_{sd}^2 (\gamma_{sr}^2 + \gamma_{rd})^2} \) denotes the SINR at the SU destination received via the direct secondary link.

According to the relay selection and considering the dependence among the received SINRs, the outage probability for the proactive DF relay protocol with a direct link is given by

\[ P_{out}^{direct} = \frac{M! \sigma_{rad}^2 M}{\prod_{m=1}^{M} (a^2 \gamma_{th} (\gamma_{th} + 1) + m \gamma_{rad}^2)} \]

(12)

Incorporating (9), (10), and (11) into (5) and employing some mathematical manipulations, an exact closed-form expression for the outage probability of the SU can be given by

\[ P_{out} = \sum_{k=0}^{K} C_K^k (-1)^k \Omega_1 \Omega_2 \]

(13)

where,

\[ \Omega_1 = \int_0^\infty \left[ \frac{\gamma_{sr}}{\gamma_{sr} + 1} \right]^k f_{\gamma_{sr}}(\gamma_{sr}) \, d\gamma_{sr} \]

\[ = \sum_{m=1}^{M} C_M^{m_1} (-1)^{m_1 + 1} A_1 \xi(k N, A_1 + k A_2) \]

(14)
can be rewritten as

\[
\Pr \left( \gamma_{\text{end}} < \gamma_{\text{th}} | x_1, y_2, z \right) = \left( \Pr \left( \delta_{sr} < \gamma_{\text{th}} | x_1 \right) \right)^K \Pr \left( \delta_{sd} < \gamma_{\text{th}} | x_1 \right) \tag{19}
\]

\[
+ \sum_{k=1}^{K} C_K^k \left( \Pr \left( \delta_{sd} + \delta_{r,d} < \gamma_{\text{th}} | x_1, y_2, z \right) \right)^k \times \left( \Pr \left( \delta_{sr} > \gamma_{\text{th}} | x_1 \right) \right)^{K-k}.
\]

Then incorporating (19) into (17) yields \( P_{\text{out}} = J_1 + J_2 \), where, after mathematical manipulations, \( J_1 \) is given by

\[
J_1 = \sum_{k=0}^{K} \frac{C_K^{k_1}}{(-1)^{k_1}} \int_0^\infty \int_0^\infty \int_0^{\gamma_{\text{th}}(\gamma_{\text{th}}+1)} \Pr(\delta_{sr} > \gamma_{\text{th}} | x_1) f_X(x_1) dX_1
\]

and \( J_2 \) is given by

\[
J_2 = \sum_{k=1}^{K-k} \sum_{k_1=0}^{k} \frac{C_K^{k_1}}{(-1)^{k_1}} \int_0^\infty \int_0^\infty \int_0^{\gamma_{\text{th}}(\gamma_{\text{th}}+1)} \Pr(\delta_{sr} > \gamma_{\text{th}} | x_1) f_X(x_1) dX_1
\]

by considering the limits of the integration variables. Similar to the calculation of \( \Pr(\delta_{sr} > \gamma_{\text{th}} | x_1) \), \( \Pr(\delta_{sd} < \gamma_{\text{th}} | x_1) \) in (20) is shown to be

\[
\Pr(\delta_{sd} < \gamma_{\text{th}} | x_1) = 1 - \exp \left( \frac{-\gamma_{\text{th}} x_1}{\gamma_{\text{sd}}} \right) \frac{(\gamma_{\text{sd}})^2}{(\gamma_{\text{sd}}^2 + \gamma_{\text{sd}} x_1 \gamma_{\text{sr}} x_1 \gamma_{\text{sd}}^2)^2}.
\]

Substituting (10) and (22) into (20), \( J_1 \) can be obtained as

\[
J_1 = \sum_{k_1=0}^{K} \sum_{m=1}^{M} A_1 \xi \left( k_1 N - 1, k_1 A_2 + A_1 \right)
\]

\[
- \frac{m_1}{\sigma_{sv}^2} \Phi_2 \left( 1, k_1 N, N; 2; \frac{m_1}{\sigma_{sv}^2 A_1}, \frac{1}{\sigma_{sv}^2 A_4} \right),
\]

\[
\left[ \frac{k_1 \gamma_{\text{th}}}{\gamma_{\text{sd}}^2 + \gamma_{\text{th}} \gamma_{\text{sr}} \gamma_{\text{sd}}^2} + \frac{m_1}{\gamma_{\text{sd}}^2 + \gamma_{\text{sd}}^2} \right] \frac{C_K^{k_1}}{(-1)^{k_1}} \gamma_{\text{sd}}^2 \theta_{\text{sd}}^2
\]

where \( A_4 = \frac{\gamma_{\text{sd}}^2}{\gamma_{\text{sd}}^2 + \gamma_{\text{sr}} \gamma_{\text{sd}}^2} \). Note that calculating the conditional probability \( \Pr(\delta_{r,d} < \gamma_{\text{th}} - \delta_{sd} | x_1, y_2, z) \) can be substituted using (10) and (22) into (21) and changing the order of integration, \( J_2 \) can be obtained as

\[
J_2 = \sum_{k=1}^{K} \sum_{k_1=0}^{K-k} \frac{C_K^{k_1}}{(-1)^{k_1}} \left( \Theta_1 - \Theta_2 \right)
\]

in which, using (6), (7), (10), and (26), \( \Theta_1 \) is directly calculated as shown in (29) at the top of the next page, and \( \Theta_2 \) is written as

\[
\Theta_2 = \int_0^\infty \int_0^\infty \int_0^\infty \int_0^{\gamma_{\text{th}}(\gamma_{\text{th}}+1)} \Pr(\delta_{sr} > \gamma_{\text{th}} | x_1) \frac{x_1}{\gamma_{\text{sd}}^2} \Phi_2 \left( 1, k_1 N, N; 2; \frac{m_1}{\gamma_{\text{sd}}^2 A_1}, \frac{1}{\gamma_{\text{sd}}^2 A_4} \right)
\]

\[
\times \exp \left( \frac{-x_1 \gamma_{\text{th}} \gamma(\gamma_{\text{th}}+1)}{\gamma_{\text{sd}}^2} \right) \exp \left( \frac{x_1^2}{\gamma_{\text{sd}}^2} \right) f_X(x_1) f_Y(y_2) f_v(v) \ dX_1 \ dY_2 \ dv.
\]

After some appropriate substitutions and tedious but necessary mathematical manipulations, a closed-form expression for (30) can be obtained shown in (31) at the top of the next page. Finally, combining the expressions for \( J_1 \) and \( J_2 \) yields a closed-form expression for the outage probability of the SU with direct link and multiple PUs’ interference.

IV. EXAMPLES

This section presents some application examples and simulation results to affirm the analytical results. The parameters used in the examples are set as: \( \sigma_{sr}^2 = \sigma_{sd}^2 = \sigma_{rv}^2 = 1 \), \( \sigma_{sd}^2 = \sigma_{sr}^2 = 20 \), and \( R = 1 \) bit/s/HZ. As 

\[
\text{Defining } V = \max_{r_i \in \mathbb{C}} \left( g_{r,d}/X_{2i} \right), (24) \text{ can be rewritten as }
\]

\[
(\Pr(\delta_{r,d} < \gamma_{\text{th}} - \delta_{sd} | x_1, y_2, z)) \tag{25}
\]

\[
= \Pr \left( \frac{\gamma}{\gamma_{Y_2} + 1} \max_{r_i \in \mathbb{C}} \left( g_{r,d}/X_{2i} \right) < \gamma_{\text{th}} - \delta_{sd} | x_1, y_2, z \right).
\]

For later use, we give the CDF and PDF of \( V \). By referring to (12), \( F_V(v) \) is given by

\[
F_V(v) = \left[ 1 - \Pr \left( \frac{g_{r,d}}{X_{2i}} > v \right) \right]^k
\]

\[
= \left[ 1 - \left( \sum_{m=0}^{M} C_M^{m_2} \frac{(-1)^{m_2} \sigma_{rv}^2 \sigma_{sd}^2}{\sigma_{rv}^2 + m_2 \sigma_{rd}^2} \right)^k \right] \times \left[ \prod_{m=1}^{M} \left( \frac{\sigma_{rv}^2 + m_2 \sigma_{rd}^2}{} \right)^{k_2} \right] \times \frac{C_k^{2}}{(-1)^{k} \sigma_{rv}^2 \sigma_{sd}^2}.
\]

Incorporating (25) into (21) and changing the order of integration, \( J_2 \) can be obtained as

\[
J_2 = \sum_{k=1}^{K} \sum_{k_1=0}^{K-k} \frac{C_K^{k_1}}{(-1)^{k_1}} \left( \Theta_1 - \Theta_2 \right)
\]

where \( \Theta_1 \) is directly calculated as shown in (29) at the top of the next page, and \( \Theta_2 \) is written as

\[
\Theta_2 = \int_0^\infty \int_0^\infty \int_0^\infty \int_0^{\gamma_{\text{th}}(\gamma_{\text{th}}+1)} \Pr(\delta_{sr} > \gamma_{\text{th}} | x_1) \frac{x_1}{\gamma_{\text{sd}}^2} \Phi_2 \left( 1, k_1 N, N; 2; \frac{m_1}{\gamma_{\text{sd}}^2 A_1}, \frac{1}{\gamma_{\text{sd}}^2 A_4} \right)
\]

\[
\times \exp \left( \frac{-x_1 \gamma_{\text{th}} \gamma(\gamma_{\text{th}}+1)}{\gamma_{\text{sd}}^2} \right) \exp \left( \frac{x_1^2}{\gamma_{\text{sd}}^2} \right) f_X(x_1) f_Y(y_2) f_v(v) \ dX_1 \ dY_2 \ dv.
\]
\[
\begin{align*}
\Theta_1 &= \left[ \int_0^\infty f_X(x_1) \left( \Pr(\delta_{srk} > \gamma_{th} | x_1) \right)^{k+k_1} dx_1 \right] \left[ \int_0^\infty f_{Y_2}(y_2) F_Y \left( \frac{\gamma_{th}(\gamma_{ty}+1)}{\gamma} \right) dy_2 \right] \\
&= \sum_{m_1=0}^{M} \sum_{k_2=0}^{k} \frac{C_k^2 C_{M}^{m_1} A_1 \xi((k+k_1) N, (k+k_1) A_2 + A_1)}{(-1)^{k_2+m_1+1}} (M!)^{-k_2} (\sigma_{ad}^2)^{\gamma} \prod_{m=1}^{M} (A_3 + m)^{k_2} \\
&\times \Phi_2 \left( N, k_2, \ldots, k_2; N + 1; \gamma_{th} \right) \\
\Theta_2 &= \sum_{l_1=0}^{N-1} \sum_{m_1=0}^{M} \sum_{k_2=0}^{k} \sum_{m_2=1}^{M} \sum_{m_3=0}^{M} C_{M}^{m_1} C_{k}^{2} C_{M}^{m_2} C_{l_1}^{m_3} k_2 \sigma_{rv}^2 \Gamma(m_3) \\
&\times \exp \left( \frac{1}{\gamma_{th}} \right) \Phi_2 \left( 1, (k+k_1) N - l_1; 2; \frac{m_1}{\sigma_{sv}^2 A_1} + \frac{1}{\sigma_{sv}^2 A_4}; \frac{m_2}{\sigma_{sv}^2 A_2} + \frac{1}{\sigma_{sv}^2 A_3} + (k+k_1) \gamma_{th} \right) \\
&\times \Phi_2 \left( m_3, 2, k_2 - 1, \cdots, k_2 - 1; m_3 + 1; \frac{\sigma_{rv}^2}{m_2 \sigma_{rd}^2} + \frac{\sigma_{rv}^2}{m_3 \sigma_{rd}^2} + \cdots + \frac{\sigma_{rv}^2}{M \sigma_{rd}^2}; \gamma_{th} \right) 
\end{align*}
\] (29)

Observe the outage probability tends to be stable in the high SNR regime (the SNR \(\gamma\) is larger than 20 dB), namely, there exist outage floors in the high SNR regime, which indicates the system diversity order is zero in the presence of multiple primary transmitters. Expectedly, the presence of multiple primary transmitters’ interference badly degrades the performance of the SU, and the outage performance improves with the decrease of the number of primary transmitters. For example, when \(\gamma = 20\) dB, \(N = 5\) results in outage \(1.08 \times 10^{-2}\) while \(N = 1\) results in outage \(1.10 \times 10^{-5}\) with a direct secondary link. Moreover, it can be seen that the performance of the secondary system with a direct secondary link outperforms that without the direct secondary link. As such, exploiting a direct secondary link can be considered as an efficient way to decrease the outage floor. For example, when \(N = 1\), the presence of the direct secondary link improves performance as much as 2 dB (or 58.5% in transmitter power) when the target outage probability is \(10^{-3}\).

The outage probability of the SU for the cases with and without a direct secondary link is illustrated in Fig. 3 versus SNR \(\gamma\) for several numbers of primary receivers \(M = \{1, 5, 8\}\). Similar to Fig. 2, the outage floor phenomenon occurs in the high SNR regime and exploiting a direct secondary link effectively boosts the performance of the secondary systems. As expected, the greater the number of primary receivers, the lower the secondary outage probability. This is due to the reason that the transmission powers of the secondary nodes must comply with more constraints with the increase of the number of primary receivers, and thus the end-to-end SINR is decreased. For example, when \(\gamma = 20\) dB, \(M = 5\) results in outage \(9.84 \times 10^{-4}\) while \(M = 1\) results in outage \(9.22 \times 10^{-5}\) both with a direct secondary link.

Fig. 4 shows the outage probability of the SU for the cases with and without a direct secondary link versus SNR \(\gamma\) for several numbers of relays \(K = \{1, 4, 7\}\). It is shown that, with an increase of the number of relays, the SU’s outage performance improves, but the slopes of the outage probability for both the cases with and without a direct secondary link is zero in the
high SNR regime. In other words, diversity gain cannot be obtained when there exist multiple primary transmitters, but increasing the number of relays can significantly decrease the outage floor. This is explainable since MRC is not optimal in the presence of non-Gaussian interference. For example, when $\gamma = 20$ dB, $K = 4$ results in outage $6.52 \times 10^{-3}$ while $K = 7$ results in outage $3.92 \times 10^{-4}$ without a direct link. Hence, the performance loss caused by multiple PUs can be compensated by increasing the number of available relays.

Fig. 5 plots the outage probability of the SU versus SNR gamma $\gamma$ for the cases with and without a direct secondary link for $\rho = \{1, 10, 25\}$. Obviously, the outage probability of the SU is decreased with an increase of $\rho$ since the larger $\rho$ means that the transmission powers of the secondary nodes are larger than those of the PU transmitters and the end-to-end SINR is improved. For example, when $\gamma = 20$ dB, for the case with a direct secondary link, the outage probability for $\rho = 1$ is $0.231$, yet the outage probability for $\rho = 1$ is $1.76 \times 10^{-3}$.

V. CONCLUSION

In this paper, by considering multiple PU transmitters and multiple PU receivers, the outage probabilities for underlay cognitive multiple relay networks with or without a direct secondary link were investigated. Particularly, a novel and simple method was proposed to obtain a closed-form expression for the outage probability of proactive DF relaying with a direct secondary link. It was shown that diversity gain cannot be obtained in the presence of multiple transmitters’ interference.

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