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Outage Probability of Cognitive Relay Networks over Generalized Fading Channels with Interference Constraints

Petros S. Bithas[a,b,*], George P. Efthymoglou[c], Dimitris S. Kalivas[b]

[a]Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, GR-15236, Penteli, Greece
[b]Department of Electronics, Technological Educational Institute of Piraeus, Thivon 250 & P. Ralli, GR-12244, Egaleo, Greece
[c]Department of Digital Systems, University of Piraeus, Karaoli and Dimitriou 80, Piraeus, Gr-18534, Greece

Abstract

In this paper, we evaluate the outage probability (OP) of a cognitive relay network operating over generalized fading channels, modeled by the generalized-$\mathcal{K}$ and generalized-gamma distributions. In particular, secondary users, based on the underlay approach, cooperate employing decode-and-forward protocol, satisfying in any case an interference constraint on the primary destination users. The derived results include exact expressions as well as approximated ones for high values of the maximum allowed transmitted power. Numerical evaluated results show that the OP of cognitive relay networks is highly related with the fading/shadowing channel conditions as well as interfering constraints, with the latter resulting in higher OP compared to the conventional relaying systems.

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Keywords: Cognitive radio systems, decode-and-forward (DF) relaying, generalized-gamma, generalized-$\mathcal{K}$, outage probability, shadowing.

1. Introduction

Cognitive radio has been considered as an ideal candidate for improving the spectrum utilization and thus increasing the overall system throughput. However, in these networks, interfering effects play a dominant role and thus various approaches have been proposed to protect licensed (primary) users data transmission, namely spectrum underlay, overlay and interweave[1]. As far as the underlay approach is concerned, which is also the subject of this work, the basic idea is that as long as the interference generated by the secondary users does not exceed a predefined threshold at the primary receivers, the secondary transmitters are allowed to transmit[2]. Therefore, based on this approach and in order to extend the coverage of secondary transmission and further enhance the reliability in cognitive radio networks, cooperative relaying techniques have been adopted[3].

The research area of underlay cognitive relay networks has recently gained an increased interest as it is proved by the numerous contributions that exist, for example[3,4,5,6,7,8,9]. More specifically, in[4], the outage probability (OP) of a cognitive relay network, employing secondary transmissions based on the underlay approach, i.e., constrained

* Corresponding author. Tel.: +30-210-810-9182 ; fax: +30-210-613-8343.
E-mail address: pbithas@ieee.org

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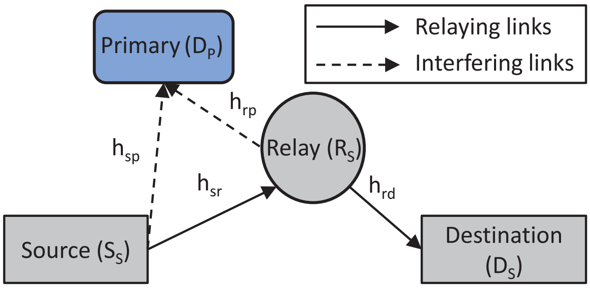

Fig. 1. The mode of operation of the underlay cognitive network under consideration.

generated interference, and supporting a suitable selection criterion was investigated. It was shown that the OP of the cognitive relay network is always higher than that of conventional one due to the interference constraint. In[5], this approach was extended to Nakagami-m fading channels, where the exact OP was derived, while the impact of various key system parameters, such as interference temperature and fading severity, was also investigated. More recently, in[9], the approach of limited maximum transmit power at the secondary source was included in a cooperative diversity scheme for cyclic prefixed single-carrier systems in a spectrum sharing environment with the decode-and-forward (DF) relaying protocol. As a general observation it should be mentioned that the previously published papers, consider only small scale effects despite the fact that the large scale effects (shadowing) become dominant in many land-mobile communication scenarios[10].

Motivated by the preceding, in this paper we extend the analysis presented in these works to generalized fading environments modeled in our case using the generalized-$\mathcal{K}$ ($\mathcal{K}_{\mathcal{G}}$) and generalized-gamma ($\mathcal{G}_{\mathcal{G}}$) distributions[10,11]. Both these fading distributions are very important since they model various fading as well as shadowing conditions, e.g., from worse than Rayleigh to no fading. In particular, we derive novel exact expressions for the OP of an underlay cognitive network employing dual-hop DF relaying for both composite fading environments. In addition, considering higher values of the maximum available transmit power, convenient closed-form asymptotic expressions have been extracted. The rest of the paper is organized as follows. Section II contains the general description of the system and channel model under consideration. In Section III, the OP analysis is performed for both generalized fading models under consideration. Section IV presents some numerical results and Section V includes the concluding remarks.

2. System and Channel Model

We consider a cognitive relay network, where primary users coexist with secondary ones, as shown in Fig. 1. At the first phase, the secondary source (S_S) transmits a signal only to the secondary relay (R_S), since the direct path between S_S and secondary destination (D_S) is considered to be blocked. R_S decodes the received data and at the second phase it forwards it to D_S. In the adopted mode of operation, all secondary transmissions are allowed as long as they do not impose harmful interference at primary destination (D_P). In other words, they could utilize the primary users spectrum only in cases where the generated interference on the D_P remains below an interference threshold I, which represents the maximum tolerable interference level at which the primary user can still maintain reliable communication[4]. In addition, as in[4], it is assumed that R_S and D_S are not subject to any interfering effects coming from the primary source (S_P). Therefore, based on the above assumptions the following transmission power constraints exist for the source and relay, respectively,[5]

$$\begin{aligned} P_s &\le \min\left(\frac{I}{|h_{sp}|^2}, P\right) \\ P_r &\le \min\left(\frac{I}{|h_{rp}|^2}, P\right) \end{aligned} \tag{1}$$

where P is the maximum transmission power constraint, which without loosing the generality, has been considered equal to both links. In addition h_{sp} is the channel gain from S_S to D_P and h_{rp} is the channel gain from R_S to D_P.

The channel state information of h_{sp}, h_{rp} could be available at S_S and R_S by employing pilot signals from a primary receiver[12] or based on channel information estimator (without feedback)[4,13]. In this case the capacity of the secondary user based on a unit bandwidth is given by[14]

$$C = \frac{1}{2}\min\left\{\log_2\left(1 + P_s\frac{|h_{sr}|^2}{N_0}\right), \log_2\left(1 + P_r\frac{|h_{rd}|^2}{N_0}\right)\right\} \tag{2}$$

where h_{sr} is the channel gain from S_S to R_S, h_{rd} is the channel from R_S to D_S and N_0 is the noise power. In this study, two wireless communication scenarios will be investigated as described below.

2.1. Fading scenario A

In this scenario, all links are subject to composite fading, modeled in our case using the $\mathcal{K}_\mathcal{G}$ distribution. Therefore, the power probability density function (PDF) of the channel gains $|h_X|^2$, with $X \in \{sr, rd, sp, rp\}$ is given by[15]

$$f_X(\gamma) = \frac{2\,\Xi_X^{(\beta_X+1)/2}\gamma^{(\beta_X-1)/2}}{\Gamma(m_X)\,\Gamma(k_X)} K_{\alpha_X}\left[2\,(\Xi_X\,\gamma)^{1/2}\right], \quad \gamma \geq 0 \tag{3}$$

with $\alpha_X = k_X - m_X$, $\beta_X = k_X + m_X - 1$, where k_X, m_X are the distribution's shaping parameters, $\Xi_X = (k_X m_X)/\overline{\gamma}_X$, with $\overline{\gamma}_X$ being the distribution's scaling parameter, $\Gamma(\cdot)$ is the Gamma function[16]eq. (8.310/1) and $K_\nu(\cdot)$ is the second kind modified Bessel function of νth order[16]eq. (8.407/1). Since $\mathcal{K}_\mathcal{G}$ is a two parameters distribution, (3) can describe various fading and shadowing models by using different value combinations for k_X and/or m_X[17], e.g., as $k_X \to \infty$, it approximates Nakagami-m distribution or for $m_X = 1$, it coincides with the $\mathcal{K}$-distribution and approximately models Rayleigh-lognormal fading conditions[18]. For integer values of the m_X, the corresponding cumulative distribution function (CDF) of (3) is[19]

$$F_X(\gamma) = 1 - 2\frac{(\Xi_X\gamma)^{\frac{k_X}{2}}}{\Gamma(k_X)}\sum_{q=0}^{m_X-1}\frac{(\Xi_X\gamma)^{\frac{q}{2}}}{q!}K_{k_X-q}\left(\sqrt{\Xi_X\gamma}\right). \tag{4}$$

2.2. Fading scenario B

For the second case, all links are subject to generalized fading, modeled in our case using the $\mathcal{G}_\mathcal{G}$ distribution. Therefore, the PDF of the channel gain $|h_X|^2$ is given by[20]

$$f_X(\gamma) = \frac{b_X\,\gamma^{m_X b_X/2-1}}{2\,\Gamma(m_X)\,(\tau_X\,\overline{\gamma}_X)^{m_X\,b_X/2}}\exp\left[-\left(\frac{\gamma}{\tau_X\,\overline{\gamma}_X}\right)^{b_X/2}\right] \tag{5}$$

where $b_X > 0$ and $m_X \geq 1/2$ are the distribution's shaping parameters related to the fading severity and $\tau_X = \Gamma(m_X)/\Gamma(m_X + 2/b_X)$. For different values of m_X and b_X, (3) simplifies to several important distributions used in fading channel modeling, e.g., Rayleigh, Nakagami-m and Weibull[20]. Its corresponding CDF can be expressed as

$$F_X(\gamma) = 1 - \frac{\Gamma\left[m_X, (\gamma/(\tau_X\overline{\gamma}_X))^{b_X/2}\right]}{\Gamma(m_X)} \tag{6}$$

where $\Gamma(\cdot,\cdot)$ is the upper incomplete Gamma function[16]eq. (8.350/2).

3. Outage Probability Analysis

In this section the OP of the cognitive relay network under consideration for both fading channel models will be analyzed. The OP is defined as the probability that the instantaneous output signal to noise ratio (SNR) falls below a predetermined threshold γ_{th} and is given by[5]

$$P_{\text{out}} = \Pr\left\{\min\left(\underbrace{P_s\frac{|h_{sr}|^2}{N_0}}_{Z_s}, \underbrace{P_r\frac{|h_{rd}|^2}{N_0}}_{Z_r}\right) < \gamma_{\text{th}}\right\} = F_{Z_s}(\gamma_{\text{th}}) + F_{Z_r}(\gamma_{\text{th}}) - F_{Z_s}(\gamma_{\text{th}})F_{Z_r}(\gamma_{\text{th}}). \tag{7}$$

In (7), the definition of two new random variables (RV)s Z_s, Z_r is provided. It has been proved that the CDF of Z_s is given by[15]

$$F_{Z_s}(\gamma_{\text{th}}) = F_{\text{sr}}\left(\frac{\gamma_{\text{th}}N_0}{P}\right)F_{\text{sp}}\left(\frac{I}{P}\right) + \underbrace{\int_{I/P}^{\infty} f_{\text{sp}}(x)F_{\text{sr}}\left(\frac{\gamma_{\text{th}}N_0 x}{I}\right)dx}_{\mathcal{I}}. \tag{8}$$

It is noted that $F_{Z_r}(\gamma_{\text{th}})$ can be evaluated by substituting in (8) sr, sp with rd, rp, respectively. Next, integral $\mathcal{I}$ will be evaluated for both scenarios under consideration.

3.1. Fading scenario A

Substituting (3) and (4) in $\mathcal{I}$ of (8), integrals of the following form appear

$$\begin{aligned} \mathcal{I}_1 &= \int_{I/P}^{\infty} x^{\frac{k_{sp}+m_{sp}}{2}-1} K_{\alpha_{sp}}\left[2\left(\Xi_{sp}x\right)^{1/2}\right]dx \\ \mathcal{I}_2 &= \int_{I/P}^{\infty} x^{\frac{k_{sp}+m_{sp}+k_{sr}+q}{2}-1} K_{\alpha_{sp}}\left[2\left(\Xi_{sp}x\right)^{1/2}\right] K_{k_{sr}-q}\left[2\left(\frac{\Xi_{sr}\gamma_{\text{th}}N_0 x}{I}\right)^{1/2}\right]dx. \end{aligned} \tag{9}$$

Integral $\mathcal{I}_1$ can be evaluated in closed form by making a change of variables of the form $y = x^{1/2}$, changing the integration limits and employing[16]eq. (6.561/16) as well as[21]eq. (03.04.21.0007.01), to yield

$$\begin{aligned} \mathcal{I}_1 =& \frac{\Gamma(k_{sp})\Gamma(m_{sp})}{2\Xi_{sp}^{\frac{k_{sp}+m_{sp}}{2}}} + \frac{\pi\csc\left[\pi\left(k_{sp}-m_{sp}\right)\right]}{2\Xi_{sp}^{\frac{k_{sp}+m_{sp}}{2}}}\left[\left(\frac{I\Xi_{sp}}{P}\right)^{k_{sp}}\Gamma(k_{sp})\,{}_P\tilde{F}_Q\left(k_{sp}; 1+k_{sp}, 1+k_{sp}-m_{sp}; \frac{I\Xi_{sp}}{P}\right)\right. \\ & \left. -\Gamma(m_{sp})\left(\frac{I\Xi_{sp}}{P}\right)^{m_{sp}}\,{}_P\tilde{F}_Q\left(m_{sp}; 1+m_{sp}, 1-k_{sp}+m_{sp}; \frac{I\Xi_{sp}}{P}\right)\right] \end{aligned} \tag{10}$$

where ${}_P\tilde{F}_Q(\cdot)$ is the regularized generalized hypergeometric function[21]eq. (07.32.02.0001.01). Obtaining a closed-form expression for $\mathcal{I}_2$ seems to be impossible. An alternative approach is to employ the infinite series representation for Bessel $K_v(z)$ function, i.e., $K_v(z) = \frac{\pi\csc(\pi v)}{2}\left(\sum_{i=0}^{\infty}\frac{(z/2)^{2i-v}}{\Gamma(i-v+1)i!} - \sum_{i=0}^{\infty}\frac{(z/2)^{2i+v}}{\Gamma(i+v+1)i!}\right)$[21]eq. (03.04.06.0002.01). Substituting this infinite series expression in $\mathcal{I}_2$, integrals of the same form as $\mathcal{I}_1$ appear, which can be solved by following a similar approach as the one for deriving (10). Therefore, based on these solutions the final expression for $\mathcal{I}$ is given by

$$\begin{aligned} \mathcal{I} =& 1 + \frac{\pi\csc[\pi(k_{sp}-m_{sp})]}{\Gamma(m_{sp})\Gamma(k_{sp})}\left[\left(\frac{I\Xi_{sp}}{P}\right)^{k_{sp}}\Gamma(k_{sp})\,{}_P\tilde{F}_Q\left(k_{sp}; 1+k_{sp}, 1+k_{sp}-m_{sp}; \frac{I\Xi_{sp}}{P}\right)\right. \\ & \left. -{}_P\tilde{F}_Q\left(m_{sp}; 1+m_{sp}, 1-k_{sp}+m_{sp}; \frac{I\Xi_{sp}}{P}\right)\Gamma(m_{sp})\left(\frac{I\Xi_{sp}}{P}\right)^{m_{sp}}\right] - \frac{\pi\csc[\pi(k_{sp}-m_{sp})]}{\Gamma(m_{sp})\Gamma(k_{sp})\Gamma(k_{sr})}\sum_{q=0}^{m_{sr}-1}\frac{\left[\mathcal{F}\left(k_{sp}, m_{sp}\right) - \mathcal{F}\left(m_{sp}, k_{sp}\right)\right]}{q!} \end{aligned} \tag{11}$$

where

$$\mathcal{F}(x,y)=\sum_{i=0}^{\infty}\frac{\Xi_{sp}^{i+y}/i!}{\Gamma(i-x+y+1)}\left[\frac{\Gamma(i+k_{sr}+y)\Gamma(i+y+q)}{(\Xi_{sr}N_0\gamma_{\text{th}}/I)^{i+y}}-{}_PF_Q\left(i+k_{sr}+y;1+i+k_{sr}+y,1+k_{sr}-q;\frac{\Xi_{sr}N_0\gamma_{\text{th}}}{P}\right)\left(\frac{I}{P}\right)^{i+y}\right.$$
$$\left.\times\left(\frac{\Xi_{sr}N_0\gamma_{\text{th}}}{P}\right)^{k_{sr}}\frac{\Gamma(q-k_{sr})}{i+k_{sr}+y}-\left(\frac{\Xi_{sr}N_0\gamma_{\text{th}}}{P}\right)^{q}\left(\frac{I}{P}\right)^{i+y}\frac{\Gamma(k_{sr}-q)}{i+y+q}{}_PF_Q\left(i+q+y;1-k_{sr}+q,1+i+y+q;\frac{\Xi_{sr}N_0\gamma_{\text{th}}}{P}\right)\right] \quad (12)$$

with ${}_PF_Q(\cdot)$ being the generalized hypergeometric function[16]eq. (9.14).

3.1.1. Asymptotic analysis

In order to better understand the impact of the interference temperature constraint on the OP, similar to[5], we will present an asymptotic analysis. In particular, we consider the case of higher values of P. Following such an approach and using[21]eq. (07.22.06.0003.01), the hypergeometric function simplifies to ${}_PF_Q\,(a_1;b_1,b_2;z)\to 1$, for $(z\to 0)$. Therefore, based on this simplification using the definitions of the Gauss hypergeometric function as well as the generalized hypergeometric function,[16]eqs. (9.100) and (9.14), respectively, and after some mathematical manipulations, (11) simplifies to the following closed-form expression

$$\mathcal{I}\simeq 1-\frac{1}{m_{sp}}\left(\frac{\Xi_{sp}I}{P}\right)^{m_{sp}}\frac{\Gamma(k_{sp}-m_{sp})}{\Gamma(m_{sp})\Gamma(k_{sp})}-\frac{1}{k_{sp}}\left(\frac{\Xi_{sp}I}{P}\right)^{k_{sp}}\frac{\Gamma(m_{sp}-k_{sp})}{\Gamma(m_{sp})\Gamma(k_{sp})}$$
$$-\frac{\pi\csc\left[\pi\left(k_{sp}-m_{sp}\right)\right]}{\Gamma(k_{sr})\Gamma(m_{sp})\Gamma(k_{sp})}\sum_{q=0}^{m_{sr}-1}\frac{1}{q!}\left[\mathcal{Q}\left(k_{sp},m_{sp}\right)-\mathcal{Q}\left(m_{sp},k_{sp}\right)\right] \quad (13)$$

where

$$\mathcal{Q}(x,y)=\left(\frac{\Xi_{sp}I}{\Xi_{sr}N_0\gamma_{\text{th}}}\right)^{y}\frac{\Gamma(k_{sr}+y)\Gamma(y+q)}{\Gamma(y-x+1)}{}_2F_1\left(k_{sr}+y,y+q;y-x+1;\frac{\Xi_{sp}I}{\Xi_{sr}N_0\gamma_{\text{th}}}\right)$$
$$-\left(\frac{\Xi_{sr}N_0\gamma_{\text{th}}}{P}\right)^{k_{sr}}\left(\frac{\Xi_{sp}I}{P}\right)^{y}\frac{\Gamma(k_{sr}+y)\Gamma(q-k_{sr})}{\Gamma(k_{sr}+y+1)\Gamma(y-x+1)}-\left(\frac{\Xi_{sr}N_0\gamma_{\text{th}}}{P}\right)^{q}\left(\frac{\Xi_{sp}I}{P}\right)^{y}\frac{\Gamma(y+q)\Gamma(k_{sr}-q)}{\Gamma(y+q+1)\Gamma(y-x+1)}. \quad (14)$$

3.2. Fading scenario B

Substituting (5) and (6) in $\mathcal{I}$ of (8), and using the infinite series representation for the upper incomplete gamma function[16]eq. (8.354/2), i.e., $\Gamma(a,z)=\Gamma(a)-z^a\sum_{i=0}^{\infty}\frac{(-z)^i}{(a+i)i!}$, integrals of the following form appear

$$\mathcal{I}_3=\int_{I/P}^{\infty}x^t\exp\left[-\left(\frac{x}{\tau_{sp}\overline{\gamma}_{sp}}\right)^{b_{sp}/2}\right]dx \quad (15)$$

where $t=\frac{m_{sp}b_{sp}}{2}-1$ or $t=\frac{m_{sp}b_{sp}+ib_{sr}+m_{sr}b_{sr}}{2}-1$. These integrals can be solved by making a change of variables of the form $y=x^{b_{sp}/2}$ and employing[16]eq. (3.351/2). Based on this solution and after some mathematical manipulations yields the following exact expression for $\mathcal{I}$ of (8)

$$\mathcal{I}=\frac{1}{\Gamma(m_{sp})}\Gamma\left[m_{sp},\left(\frac{I/P}{\tau_{sp}\overline{\gamma}_{sp}}\right)^{b_{sp}/2}\right]\left[1-\Gamma(m_{sr})\right]$$
$$+\frac{1}{\Gamma(m_{sp})}\left(\frac{\tau_{sp}\overline{\gamma}_{sp}N_0\gamma_{\text{th}}}{\tau_{sr}\overline{\gamma}_{sr}I}\right)^{\frac{m_{sp}b_{sp}}{2}}\sum_{i=0}^{\infty}\left(\frac{\tau_{sp}\overline{\gamma}_{sp}N_0\gamma_{\text{th}}}{\tau_{sr}\overline{\gamma}_{sr}I}\right)^{\frac{ib_{sp}}{2}}\frac{(-1)^i}{(m_{sr}+i)i!}\Gamma\left[m_{sp}+\frac{ib_{sr}}{b_{sp}}+\frac{m_{sr}b_{sr}}{b_{sp}},\left(\frac{I/P}{\tau_{sp}\overline{\gamma}_{sp}}\right)^{\frac{b_{sp}}{2}}\right]. \quad (16)$$

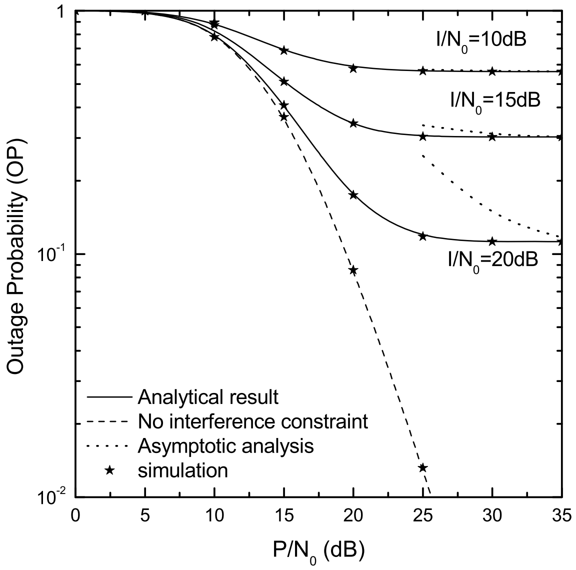

Fig. 2. $\mathcal{K}_{\mathcal{G}}$ fading: Outage probability as a function of P/N_0 for various values of the interference constraints.

3.2.1. Asymptotic analysis

For higher values of $\overline{\gamma}_{sr}$ and P, the upper incomplete Gamma function of the CDF expression in (6), simplifies as follows $\Gamma(a,z) = \Gamma(a) - \frac{z^a}{a}$, for $(z \to 0)$[21]eq. (06.06.06.0004.01). Based on this expression and following a similar approach for deriving (16), the following closed-form expression has been obtained

$$\mathcal{I} \simeq \frac{1-\Gamma(m_{sr})}{\Gamma(m_{sp})}\left(\Gamma(m_{sp}) - \left(\frac{I}{\tau_{sp}\overline{\gamma}_{sp}P}\right)^{\frac{m_{sp}b_{sp}}{2}}\frac{1}{m_{sp}}\right) + \frac{1}{\Gamma(m_{sp})m_{sr}}\left(\frac{\tau_{sp}\overline{\gamma}_{sp}N_0\gamma_{\text{th}}}{\tau_{sr}\overline{\gamma}_{sr}I}\right)^{\frac{m_{sr}b_{sr}}{2}}\left[\Gamma\left(m_{sp}+\frac{m_{sr}b_{sr}}{b_{sp}}\right) - \left(\frac{I}{\tau_{sp}\overline{\gamma}_{sp}P}\right)^{\left(m_{sp}+\frac{m_{sr}b_{sr}}{b_{sp}}\right)\frac{b_{sp}}{2}}\frac{1}{m_{sp}+\frac{m_{sr}b_{sr}}{b_{sp}}}\right]. \quad (17)$$

4. Numerical Results

In this section, using the previously derived expressions for the instantaneous output SNR, the OP of the underlay dual-hop DF relay scheme will be studied. In Fig. 2, considering $\mathcal{K}_{\mathcal{G}}$ fading/shadowing environment and assuming $k_{sp} = 0.9, m_{sp} = 0.6, \overline{\gamma}_{sp} = 0\text{dB}$, $k_{sr} = 2.9, m_{sr} = 2$, $\overline{\gamma}_{sr} = 0\text{dB}$, $\gamma_{\text{th}} = 10\text{dB}$, the OP is plotted as a function of the ratio P/N_0 for various values of I/N_0. In the same figure, for comparison purposes, the asymptotic OP, obtained using (13) as well as the corresponding performance of the system under consideration without interference temperature constraint, are also plotted. In this figure, it is shown that the performance improves as P/N_0 increases, with however a decreased rate for higher values of P/N_0. In addition, as I/N_0 increases, i.e., the interference temperature constraint becomes loose, the performance also improves, whilst the performance of the system without constraints is always better, as expected. It is interesting to note that the curves, based on the asymptotic expression given in (13), are quite close to the exact ones, especially for higher values of the P/N_0. In Fig. 3, for the same composite fading environment and in order to better understand the impact of the fading/shadowing parameters to the system performance, the OP is plotted as a function of P/N_0 for various values of the secondary transmission channel parameters as well as under different interference temperature constraints. In particular, we have assumed three communication scenarios, with severe, i.e., $(k_{sr} = k_{rd} = 1.5;\ m_{sr} = m_{rd} = 1)$, moderate, i.e., $(k_{sr} = k_{rd} = 2.5; m_{sr} = m_{rd} = 2)$ and light, i.e., $(k_{sr} = k_{rd} = 3.5; m_{sr} = m_{rd} = 3)$ fading/shadowing conditions. For all scenarios we have also assumed $(k_{sp} = k_{rp} = 0.6; m_{sp} = m_{rp} = 0.5)$. As previously, it is depicted that the performance improves as P/N_0 and/or I/N_0 increase. An

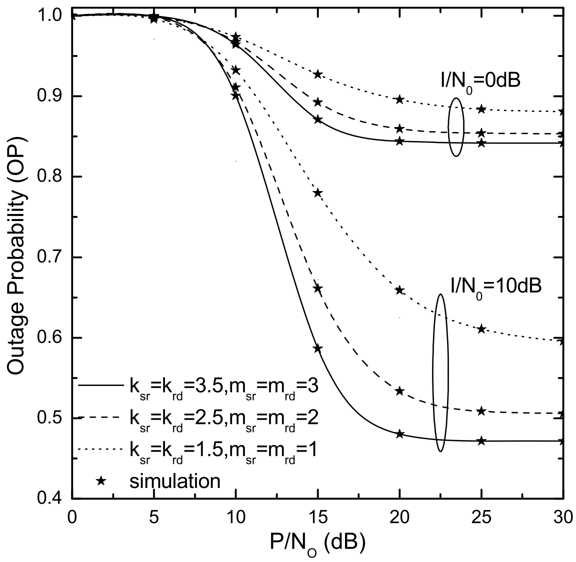

Fig. 3. $\mathcal{K}_{\mathcal{G}}$ fading: Outage probability as a function of P/N_0 for different fading/shadowing environments.

interesting observation is that the performance gap among the three channel conditions under consideration increases for higher values of I/N_0.

Finally, in Fig. 4, considering $\mathcal{G}_{\mathcal{G}}$ fading channels the OP is plotted as a function of the P/N_0 for various values of the average input SNR for both secondary wireless links. In this figure we have assumed, $m_{sp} = m_{rp} = 3, b_{sp} = b_{rp} = 1.5, \overline{\gamma}_{sp} = \overline{\gamma}_{rp} = 10$dB, $m_{sr} = m_{rd} = 2, b_{sr} = b_{rd} = 1, I = 15$dB, $\gamma_{\text{th}} = 10$dB. In addition, in the same figure, the corresponding curves, based on the asymptotic expression for the OP derived in (17), are also included. In this figure, it is depicted that the OP improves as P/N_0 and/or $\overline{\gamma}_X$, with $X \in \{sr, rd\}$, increase. It is interesting to note that even for moderate values of $\overline{\gamma}_X$, the OP plots based on the approximated expression are quite close to the ones obtained using the exact, which however becomes almost equal for higher values of the P/N_0 and/or $\overline{\gamma}_X$. For comparison purposes, computer simulation performance results are also included in all figures, verifying the validity of the proposed theoretical approach.

5. Conclusions

In this paper, the OP of a cognitive relaying network, which is based on the underlay approach, operating over generalized fading channels, modeled by the $\mathcal{K}_{\mathcal{G}}$ and $\mathcal{G}_{\mathcal{G}}$ distributions, is investigated. Exact as well as approximated expressions of the OP have been derived, for both communication scenarios. Various numerical evaluated results with parameters of interest the fading/shadowing severity, the interference constraint and the maximum allowed transmission power have been presented. In all cases, it was shown that the performance decreases as the interference constraint becomes tighter or fading/shadowing conditions worsen.

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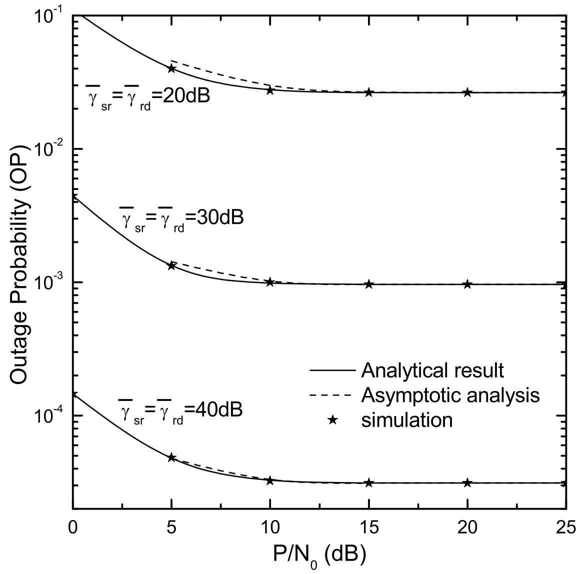

Fig. 4. $\mathcal{G}_\mathcal{G}$ fading: Outage probability as a function of P/N_0 for various values of the $\overline{\gamma}_X$, with $X \in \{sr, rd\}$.

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