Accuracy of Gaussian approach for the performance evaluation of direct-detection receiver with partially polarized noise

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Abstract

We investigate the accuracy of a Gaussian approach (GA) developed to estimate the performance of a direct-detection optical receiver with arbitrary optical and electrical filtering and in presence of partially polarized noise due to polarization dependent loss (PDL). The accuracy is assessed by comparison of the performance estimates obtained from the GA with the estimates obtained from a rigorous method (RM) based on the calculation of the moment generating function of the current at the optical receiver output.

We show that the GA has a good accuracy when considering the variation of: the optical filter bandwidth, extinction ratio, degree of polarization of the noise (*DOP*) and angle between signal and noise polarizations. However, it fails to predict the receiver sensitivity within 2 dB of the RM, when *DOP* is greater than 0.7 and signal and noise polarizations are orthogonal in the Jones space.

Nevertheless, it is shown that the GA provides receiver sensitivity estimates with good accuracy in most cases of long-haul optical communication systems influenced by PDL, where the typical average *DOP* is below 0.15. Due to its simplicity, shorter computation time and good accuracy, the GA is a good tool to assess the performance of such optical systems.

Indexing terms: partially polarized noise, optical receivers, Gaussian approach, sensitivity, polarization dependent loss

I. INTRODUCTION

Recently, some research has been dedicated to the evaluation of the performance of optical receivers with partially polarized noise. Several methods to estimate analytically the direct-detection receiver performance have been proposed [1]-[5]. Basically, two different analytical methods have been proposed: a rigorous method (RM), which is based on the moment generating function (MGF) of the current at the receiver output and has been validated by Monte Carlo simulation [4]; and a simplified approach based on the assumption of a Gaussian distribution of the current with the same mean and variance of the actual probability density function (PDF). This approach is named Gaussian approach (GA) [1]-[3], [5], and its popularity (for receivers with unpolarized noise) is due to its simplicity and speed of bit error probability computation in comparison with rigorous methods. Furthermore, the Gaussian distribution is widely used to evaluate the performance of optical communication systems among other distributions, because it provides sufficiently accurate estimates of the performance with unpolarized noise [6]-[8], although Gaussian and rigorous distributions do not match at all [6]. Additionally, in comparison with experimental results, the GA has also predicted very accurate receiver sensitivities for unpolarized noise [9].

Due to these reasons, the GA has been proposed by several authors to assess the sensitivity of optical receivers in presence of partially polarized noise. A simplified GA was considered in [3] to assess the receiver Q-factor in presence of partially polarized noise, in which the optical and electrical filters have rectangular transfer functions. This problem was solved in [1] where a new formulation was proposed to consider partially polarized noise at the receiver, which takes into account arbitrary optical and electrical filtering, degree of polarization of the noise and angle between signal and noise polarizations. Furthermore, the receiver Q-factor was assessed using a GA and an intersymbol interference (ISI) worst-case approximation and an excellent agreement was found between their Q-factor predictions and experimental results. However, they assume that only the noise is affected by polarization dependent loss (PDL) (that origins partially polarized noise), contrarily to what happens in real systems where signal is also affected by PDL. A generalized GA was then proposed in [5] which takes into account also the effect of PDL on the signal.

Although those two main methods [4], [5] have been proposed by the authors, the accuracy of the GA with partially polarized noise for arbitrary degree of polarization of noise and angle between signal and noise polarizations is still to be reported. In this work, the accuracy of the GA is investigated and discussed for several situations. The investigation is performed by comparing the receiver sensitivity obtained using the RM and the GA. Firstly, the direct-detection receiver model used to develop the RM and GA is described and these two methods are shortly reviewed in section II. Section III presents the GA accuracy studies. Finally, section IV summarizes our main conclusions.

II. RECEIVER MODEL AND METHODS TO ESTIMATE THE PERFORMANCE

As shown in Fig. 1, the receiver consists of an optical filter, a photodetector followed by an electrical filter and a decision circuit. The optical filter is modeled by a lowpass equivalent impulse response $h_{o,l}(t)$ and transfer function $H_{o,l}(f)$. The photodetector is modeled as a square-law detector with responsivity R_s. The electrical filter has impulse response, $h_r(t)$, and models the electronic circuitry of the receiver including the photodetector frequency response.

We consider that the lowpass equivalent signal at the receiver input $\mathbf{s_A}(t)$ is deterministic, has field components along the **x** and **y** directions and arrives completely polarized at the optical receiver input [1], [3], [4]. Notice that the signal $\mathbf{s_A}(t)$ is the information signal after experiencing distortion from the fiber and filtering, amplification along the fiber sections and polarization loss or gain effects. The noise components in the two directions that arrive at the receiver input are correlated due to PDL and, hence, the noise at the optical receiver input $\mathbf{n}_A(t)$ is partially polarized [3]. To describe the partial polarization of the noise at the receiver input, we developed the general equivalent model depicted in Fig. 2, where $s_{e,x}(t)$ and $s_{e,y}(t)$ are equivalent components of the signal electrical field, $\mathbf{s_e}(t)$, along the **x** and **y** directions, respectively, before experiencing PDL. These components are analytically described by

$$\mathbf{s_e}(t) = \sqrt{P_{se}(t)} \cdot e^{j\varphi_{se}(t)} \left[\cos\theta \cdot \mathbf{x} + \sin\theta \cdot \mathbf{y}\right] = s_{e,x}(t) \cdot \mathbf{x} + s_{e,y}(t) \cdot \mathbf{y} \quad (1)$$

where $P_{se}(t)$ is the signal power, $\varphi_{se}(t)$ is the signal phase and θ is the angle that the signal makes with the **x** direction in the Jones space. Consequently, θ defines also the angle that the noise field polarized parallel to the signal makes with the **x** direction [3]. Since signal is assumed to be completely polarized at the optical receiver input, our formulation is only applicable to systems in which polarization-mode dispersion (PMD) is small enough that has a negligible impact on the system performance. The assumption of very small PMD is acceptable, by assuming that the differential group delay between the two noise orthogonal components due to PMD is much smaller than the duration of the optical filter impulse response [4]. Although PMD is considered very small, it is still possible that the noise appears partially polarized at the receiver input due to PDL arising from amplifiers. Examples of such optical communication systems use low-PMD fibers and a large number of inline amplifiers which introduce PDL [1].

In Fig. 2, $n_{e,x}(t)$ and $n_{e,y}(t)$ are equivalent components of the noise, $\mathbf{n_e}(t)$, along the **x** and **y** directions, respectively, before experiencing PDL. These components are uncorrelated fictitious sources of additive white Gaussian noise with zero mean and power spectral density S_{ASE}. The accumulated noise that arrives at the receiver input has two components: the component parallel to the signal, which has a much larger influence on the system performance, since it affects the variance of the signal-amplified spontaneous emission (ASE) beat noise [3], [10]; and the orthogonal (to the signal) noise component, which influences only the ASE-ASE beat noise [3], [10] and usually has a smaller impact on the receiver performance. **K** is a Jones matrix which characterises PDL that signal and noise (both parallel and orthogonal components) experience along transmission through the optical communication system. It causes coupling between the unpolarized noise components at its input, and origins partially polarized noise at its output. **K** is defined as [4]

$$\mathbf{K} = \begin{bmatrix} \sqrt{1-\alpha_{PDL}} & 0 \\ 0 & \sqrt{1+\alpha_{PDL}} \end{bmatrix} \quad (2)$$

with α_{PDL} defined as one half of the normalized attenuation difference between the two principal axes of PDL [3]. The degree of polarization, *DOP*, is the ratio between the intensity of the polarized part of the noise and the total intensity of the noise and satisfies $0 \leq DOP \leq 1$, where $DOP = 0$ holds for completely unpolarized noise and $DOP = 1$ holds for completely polarized noise. For the considered matrix **K** definition, *DOP* is equal to α_{PDL} [4].[1] As PDL is a stochastic phenomenon [3], the *DOP* also fluctuates randomly. Typical average *DOP* of 0.15 can be found in long-haul communication systems [1], [2].

By using the unit vectors $\mathbf{s_s}$ and $\mathbf{s_p}$ to define the polarization directions of the signal and noise in the Stokes space, respectively [1], the angle on the Poincaré sphere between signal and noise polarizations is given by

$$\mathbf{s_s} \bullet \mathbf{s_p} = \frac{\alpha_{PDL} - \cos 2\theta}{1 - \alpha_{PDL}\cos 2\theta} \quad (3)$$

where $\mathbf{s_s} \bullet \mathbf{s_p}$ defines the standard inner product between vectors $\mathbf{s_s}$ and $\mathbf{s_p}$. When signal and noise polarizations are antiparallel on the Poincaré sphere, i. e., $\mathbf{s_s} \bullet \mathbf{s_p} = -1$, signal and noise

[1] In the remainder of the paper, *DOP* and α_{PDL} are referred indistinguishably.

polarizations are orthogonal in the Jones space [1]. Expression (3) shows that this is equivalent to set θ = 0. When signal and noise polarizations are parallel on the Poincaré sphere, i. e., $\mathbf{s_s} \bullet \mathbf{s_p} = 1$, noise and signal polarizations are parallel in the Jones space [1], and this corresponds to set $\theta = \pi/2$.

The current at the decision circuit input is given by

$$i_d(t) = \left\{ R_s \left| \left[\mathbf{K} \cdot \mathbf{s_e}(t) + \mathbf{K} \cdot \mathbf{n_e}(t) \right] * h_{o,l}(t) \right|^2 \right\} * h_r(t) \tag{4}$$

where the symbol * stands for convolution. The assumption that the ASE noise at the optical receiver input $\mathbf{n}_A(t)$ is partially polarized due to PDL implies that this noise is originated in erbium-doped fiber amplifiers (EDFAs) in the link or by an optical pre-amplifier, and PDL is due to isolators inside the EDFAs. Hence, shot noise and noise due to the receiver electric circuit are neglected in expression (4), since ASE noise is the dominant source of noise at the receiver [1].

In the following, we present a brief description of the rigorous method and the GA. Details of the RM derivation can be found elsewhere [4]. The RM was obtained by expanding the signal $\mathbf{s_e}(t)$ and the noise $\mathbf{n_e}(t)$ in Fourier series and by passing those signals through matrix **K.** Then, the MGF of the current can be obtained through an extensive matricial development, similarly to the derivation presented in [11], and the bit error probability is estimated numerically using the saddlepoint approximation.

The GA was derived in [5], by considering the equivalent model of Fig. 2 and the formulation presented in [8] adapted to consider partially polarized noise. The GA is based on the Gaussian distribution of the output current in presence of partially polarized noise with mean and variance given, respectively, by

$$m(t) = m_{un}(t) \left[\frac{1 - \alpha_{PDL}^2}{1 - \alpha_{PDL} \left(\mathbf{s_s} \bullet \mathbf{s_p} \right)} \right] + m_{ASE} \tag{5}$$

$$\sigma^2(t) = \sigma^2_{ASE-ASE-un} \cdot \left(1+\alpha^2_{PDL}\right) + \sigma^2_{s-ASE-un}(t)\left[1 - 2\alpha_{PDL}\frac{\alpha_{PDL} - \left(\mathbf{s_s} \bullet \mathbf{s_p}\right)}{1-\alpha_{PDL}\left(\mathbf{s_s} \bullet \mathbf{s_p}\right)} + \alpha^2_{PDL}\right] \tag{6}$$

where $m_{un}(t)$, $\sigma^2_{ASE-ASE-un}$ and $\sigma^2_{s-ASE-un}(t)$ are, respectively, the signal mean, the ASE-ASE beat noise variance and the signal-ASE beat noise variance of unpolarized noise given by [8]

$$m_{un}(t) = R_s \int_{-\infty}^{+\infty} \left|s_A(\tau) * h_{o,l}(\tau)\right|^2 \cdot h_r(t-\tau)\ d\tau \tag{7}$$

$$\sigma^2_{ASE-ASE-un} = 2R_s^2 S^2_{ASE} \cdot \int_{-\infty}^{+\infty} \left|H_r(f)\right|^2 \left[\left|H_{o,l}(f)\right|^2 * \left|H_{o,l}(-f)\right|^2\right] df \tag{8}$$

$$\sigma^2_{s-ASE-un}(t) = 2R_s^2 S_{ASE} \int_{-\infty}^{+\infty} \left|\left\{\left[s_A(\tau) * h_{o,l}(\tau)\right] \cdot h_r(t-\tau)\right\} * h_{o,l}(\tau)\right|^2 d\tau \tag{9}$$

and m_{ASE} is the ASE noise current mean [8]. For $\alpha_{PDL} = 0$, expressions (5) and (6) degenerate into the mean and variance expressions given by (7)-(9) and proposed in [8], obtained for unpolarized noise. From equation (6), the variance of ASE-ASE beat noise is only affected by the *DOP* and not by the angle between signal and noise polarizations. As shown in [3], both parallel and orthogonal noise components affect this beat noise variance. The angle between signal and noise polarizations affects only the signal-ASE beat noise variance (since it characterizes the fraction of the noise component that beats with the signal, i. e., the parallel noise component [3]) and the signal mean: for $\mathbf{s_s}\bullet\mathbf{s_p} = -1$ (orthogonal polarizations), the signal-ASE beat noise power and signal mean are reduced, ASE-ASE beat noise can become the dominant noise source after detection and receiver performance becomes degraded; for $\mathbf{s_s}\bullet\mathbf{s_p} = 1$ (parallel polarizations), both signal-ASE beat noise power and signal power are enhanced, and hence, the receiver performance should remain practically unchanged. So, it is preferable that signal and noise polarizations are parallel to ensure that performance is not degraded by partially polarized noise.

After obtaining the mean and variance given by expressions (5) and (6), and by assuming a Gaussian distribution for the current at the decision circuit input, the error probability associated with each bit is computed at the sampling instant and the bit error probability is obtained by averaging the error probability over all bits of the sequence and by optimizing numerically the threshold level, by following the reasoning described in [8].

Instead of using the GA, simpler methods to assess the receiver performance with partially polarized noise can be proposed by considering approximations for expressions (5) and (6) in order to obtain the receiver Q-factor or optical signal-to-noise ratio, similarly to what is done in [1], [3], [12]. For example, the GA degenerates in the receiver Q-factor presented in [1], if expressions (5) and (6) are obtained for the worst-case of ISI and by neglecting the effect of PDL on the signal.

III. ACCURACY OF THE GAUSSIAN APPROACH

To study the GA accuracy, we consider that the optical receiver has an erbium-doped fibre amplifier as preamplifier with gain G = 30 dB and spontaneous emission noise factor n_{sp} = 2. We assume a back-to-back configuration and that the PDL is due to the isolators inside the EDFA. The PIN photodetector responsivity is R_s = 1 A/W. The optical filter is a Gaussian filter with -3 dB bandwidth $2B$ and the electrical filter is a 2nd order Butterworth filter with -3 dB bandwidth of $0.65B$, where B is the bit rate of 40 Gbit/s. Chirpless intensity-modulated signals with rectangular pulse shape and variable extinction ratio r are considered at the optical receiver input. The extinction ratio is defined as the ratio between the stationary levels of the optical power of a bit '1' and the optical power of a bit '0'. The parameters μ and η defined in [11] for the RM are continuously optimized until the receiver bit error probability stabilizes. The parameter μ defines the size of the matrix that characterizes the noise filtering by the receiver and it is related with the duration of the total impulse response of the receiver [11]. The parameter η defines the range of frequencies that should be considered after the optical filter in order to retain the frequency components of the signal spectrum relevant to the computation of the bit error probability [11]. The receiver sensitivity is obtained for the bit error probability of 10^{-12}.

The GA accuracy is studied by varying α_{PDL} (*DOP*) and θ, which, by combination with the α_{PDL} variation, changes $\mathbf{s_s} \bullet \mathbf{s_p}$ accordingly with expression (3).

Fig. 3 shows the sensitivity obtained using the RM minus the sensitivity obtained using the GA as a function of $\mathbf{s_s} \bullet \mathbf{s_p}$ and *DOP*. Fig. 3 a) and b) correspond to r = 10 and $r = \infty$, respectively. The sensitivities obtained using the RM, for unpolarized noise (*DOP* = 0), for r = 10 and $r = \infty$ are, respectively, −28.3 dBm and −31.7 dBm. For *DOP* = 0.9 and $\mathbf{s_s} \bullet \mathbf{s_p} = -1$, the sensitivities obtained using the RM for r = 10 and $r = \infty$ are, respectively, −22 dBm and −24 dBm. Fig. 3 shows that the GA provides very accurate predictions of the sensitivity for a very wide range of combinations of $\mathbf{s_s} \bullet \mathbf{s_p}$ and *DOP*. Only for angles corresponding to nearly $\mathbf{s_s} \bullet \mathbf{s_p} = -1$ and a very high *DOP*, the GA gives very significant errors (above 2 dB). This can be explained by the strong reduction of signal and signal-ASE beat noise powers when $\mathbf{s_s} \bullet \mathbf{s_p} \approx -1$. With such a strong reduction, the ASE-ASE beat noise starts to have an important impact on the receiver performance. As previously reported in [6], [8], the GA accuracy weakens under these conditions.

Furthermore, Fig. 3 also shows that the GA can predict both pessimistic and optimistic estimates, and that this pessimism/optimism is very dependent on the extinction ratio, as reported in [13]. So, it would be of great interest to study the impact of extinction ratio on the GA accuracy, in presence of partially polarized noise.

Fig. 4 shows the sensitivity obtained using the RM minus the sensitivity obtained using the GA as a function of the extinction ratio, *r* and *DOP*. Fig. 4 a) and b) correspond to, respectively, $\mathbf{s_s} \bullet \mathbf{s_p} = 1$ and $\mathbf{s_s} \bullet \mathbf{s_p} = -1$. Fig. 4 shows two distinct behaviors depending on the angle between signal and noise polarizations. For $\mathbf{s_s} \bullet \mathbf{s_p} = 1$, the GA accuracy is very good, but is slightly diminished with the increase of extinction ratio. The increase of extinction ratio increases the ratio between the ASE-ASE beat noise power and the signal-ASE beat noise power in the zeroes of the bit sequence, which slightly reduces the accuracy of the GA. For $\mathbf{s_s} \bullet \mathbf{s_p} = -1$, the increase of DOP reduces significantly the signal and signal-ASE beat noise powers and ASE-ASE beat noise becomes dominant. For $DOP > 0.3$ and $r > 100$, the GA accuracy, which depends on this dominance, is almost independent of the extinction ratio. For smaller *DOP*, the increase of the extinction ratio reduces slightly the GA accuracy, since it enhances the ASE-ASE beat noise dominance.

Figs. 3 and 4 show that, for *DOP* below 0.4, the GA error is always below 1dB. Let us consider 1dB as a reference limit for acceptable GA estimates discrepancy. This implies a maximum acceptable *DOP* of 0.4. Furthermore, let us require that the *DOP* exceeds 0.4 with a small probability of 0.1% to ensure that the GA leads to reasonable estimates almost over all time. Because the ratio between the highest and lowest gains along the principal axes of PDL follows a Maxwellian distribution [14], the average *DOP* is 0.167, for the probability of 0.1% of the *DOP* being above 0.4.[2] This means that, for systems with average *DOP* do not exceeding 0.167, the GA gives reasonably accurate sensitivity estimates (with discrepancy below 1dB) in more than 99.9% of the cases. As in long haul optical communication systems

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[2] As shown in [12], [15], the *DOP* follows also a Maxwellian distribution as long as the total PDL of the link is kept below 2 dB.

(30 spans), the average *DOP* does not exceed typically 0.15 [1], [2], we can consider that the GA provides good performance estimates in these optical communication systems.

Consider now the case of *DOP* = 0.4, $\mathbf{s_s} \bullet \mathbf{s_p} = -1$ and $r = \infty$, which is a stringent situation for the GA accuracy, since its error is near 1dB, for the optical filter bandwidth of 2*B* [see Fig. 3 b)]. We are interested in investigating the GA accuracy, when the optical filter bandwidth is varied from 2*B*. Fig. 5 shows the sensitivity obtained using the RM and the sensitivity obtained using the GA as a function of the Gaussian optical filter −3dB bandwidth normalized to the bit rate. Fig. 5 shows that the GA error has an abrupt decrease for smaller bandwidths[3] (in comparison with the bandwidth of 2*B*), reaches a maximum on the optimum optical filter bandwidth, and decreases slowly for higher bandwidths. This dependence of the GA error on the optical filter bandwidth has been observed also in [8], for unpolarized noise. Notice that the GA error increases less than 0.1dB (for the optimum bandwidth) in comparison with the case of the bandwidth of 2*B*. Furthermore, the sensitivity behavior predicted by the GA is very similar to the behavior predicted by RM. So, we can consider that the optical filter bandwidth variation is not so significant for the GA accuracy as the *DOP* variation.

Similar conclusions to those obtained from Fig. 3-5 for the Gaussian optical filter have been also found using Fabry-Perot optical filters.

One important factor to decide for the GA is the computation time, which is extremely dependent on the efficiency of the algorithm utilized. For sequence lengths of 2^8, the computation time that the GA takes to obtain the bit error probability is less than one second, while the RM takes about 164 seconds. For sequence lengths of 2^{12}, the GA computation time

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[3] For these smaller bandwidths, the ISI is the dominant mechanism of performance degradation and, it is known that the GA becomes more accurate with the ISI increase [6], [8].

is about 20 seconds, while the computation time using the RM requires about 8800 seconds.[4] So, although, the GA can lead to errors above 1 dB for particular situations of the optical communication system, the GA is advantageous (due to its fastness) over the RM for extensive optimization, for example, of a large set of parameters of the optical communication system. Furthermore, the GA error can be reduced when the GA is used in combination with the RM for system optimization. For example, the RM can be used to obtain the sensitivity for null PDL (as a reference), and then the GA applied to assess the impact of PDL on the receiver sensitivity, since the sensitivity dependence on the PDL predicted by the GA is very similar to that one predicted by the RM. Obviously, the GA fastness is also advantageous over Monte Carlo simulation, since the estimation of very low bit error probability is almost unfeasible using Monte Carlo simulation.

IV. CONCLUSIONS

We have investigated the accuracy of the Gaussian approach (which is widely used to estimate the performance in direct-detection receivers with unpolarized noise due to its simplicity and shorter computation time) in receivers with partially polarized noise and arbitrary optical filtering.

We have shown that the GA can give significant errors (above 2 dB), especially in systems with high *DOP* and orthogonal signal and noise polarizations in the Jones space, i. e., $\mathbf{s_s} \bullet \mathbf{s_p} = -1$. This is mainly due to the enhancement of the ASE-ASE beat noise power over the signal and signal-ASE beat noise powers which, as previously reported by other authors

[4] These computation times were obtained using Matlab 7.0 on a computer with 3GHz dual-core processor and 2GB of RAM memory.

[6], reduces the accuracy of the GA. However, when we move away from $\mathbf{s_s} \bullet \mathbf{s_p} = -1$, the GA accuracy increases and gives very accurate results as *DOP* decreases and $\mathbf{s_s} \bullet \mathbf{s_p}$ approaches 1.

We have also studied the variation of the GA accuracy with the extinction ratio. For $\mathbf{s_s} \bullet \mathbf{s_p} = 1$, the enhancement of the extinction ratio just reduces slightly the GA accuracy; however, for $\mathbf{s_s} \bullet \mathbf{s_p} = -1$, the GA accuracy is practically independent of the extinction ratio and is much more dependent on the *DOP*.

We have shown that the GA is usually a good tool to estimate the direct-detection receiver performance in presence of partially polarized noise. The GA allows the system engineer to obtain the receiver sensitivity and to assess the tolerance of the receiver to PDL much more quickly than the RM, it is much simpler to implement and predicts reasonably accurate sensitivity estimates in almost all cases. Furthermore, the results presented in [1], which compare the *Q*-factor obtained theoretically with experimental results for receivers with partially polarized noise, indicate that the GA sensitivity estimates should be very close to sensitivity estimates obtained experimentally.

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Figure captions

Figure 1. Optical receiver scheme.

Figure 2. Scheme of the general equivalent model of partially polarized noise at the optical receiver.

Figure 3. Differences [in dB] between the sensitivity obtained through the RM and the sensitivity obtained through the GA as a function of *DOP* and $\mathbf{s_s} \bullet \mathbf{s_p}$. a) $r = 10$, b) $r = \infty$.

Figure 4. Differences [in dB] between the sensitivity obtained through the RM and the sensitivity obtained through the GA as a function of *DOP* and *r*. a) Parallel signal and noise polarizations in the Jones space, $\mathbf{s_s} \bullet \mathbf{s_p} = 1$, b) Orthogonal signal and noise polarizations in the Jones space, $\mathbf{s_s} \bullet \mathbf{s_p} = -1$.

Figure 5. Sensitivity [dBm] obtained through the RM (solid line) and the sensitivity obtained through the GA (solid-marked line) as a function of the Gaussian optical filter −3dB bandwidth normalized to the bit rate, for $DOP = 0.4$, $\mathbf{s_s} \bullet \mathbf{s_p} = -1$ and $r = \infty$.

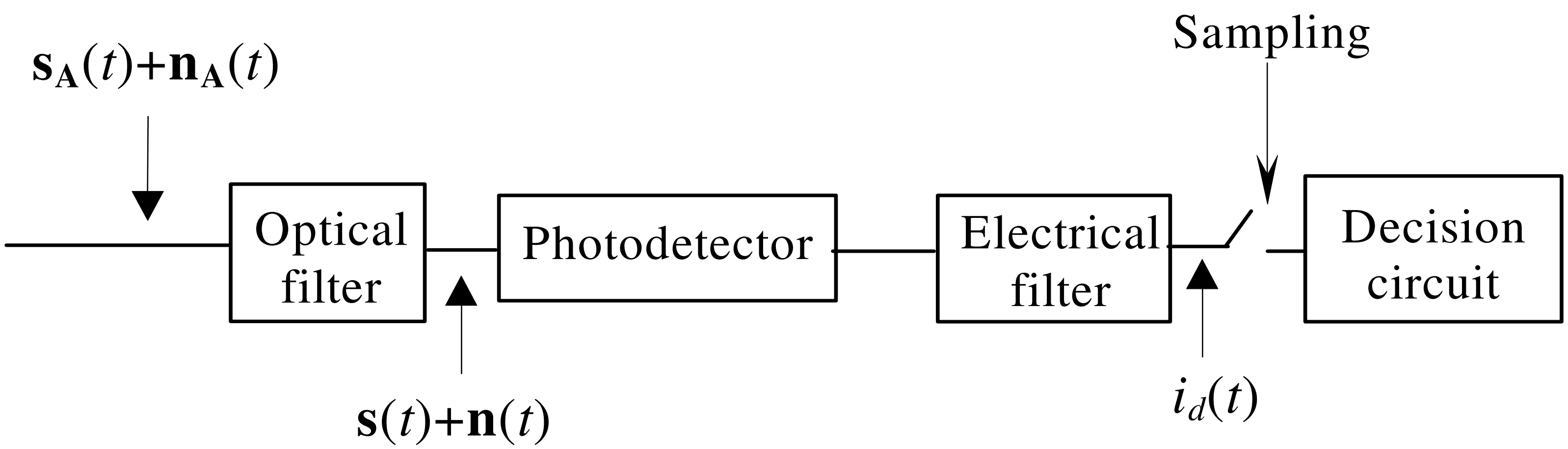

Sampling
$\mathbf{s_A}(t)+\mathbf{n_A}(t)$
Optical filter
Photodetector
Electrical filter
Decision circuit
$\mathbf{s}(t)+\mathbf{n}(t)$
$i_d(t)$

Figure 1

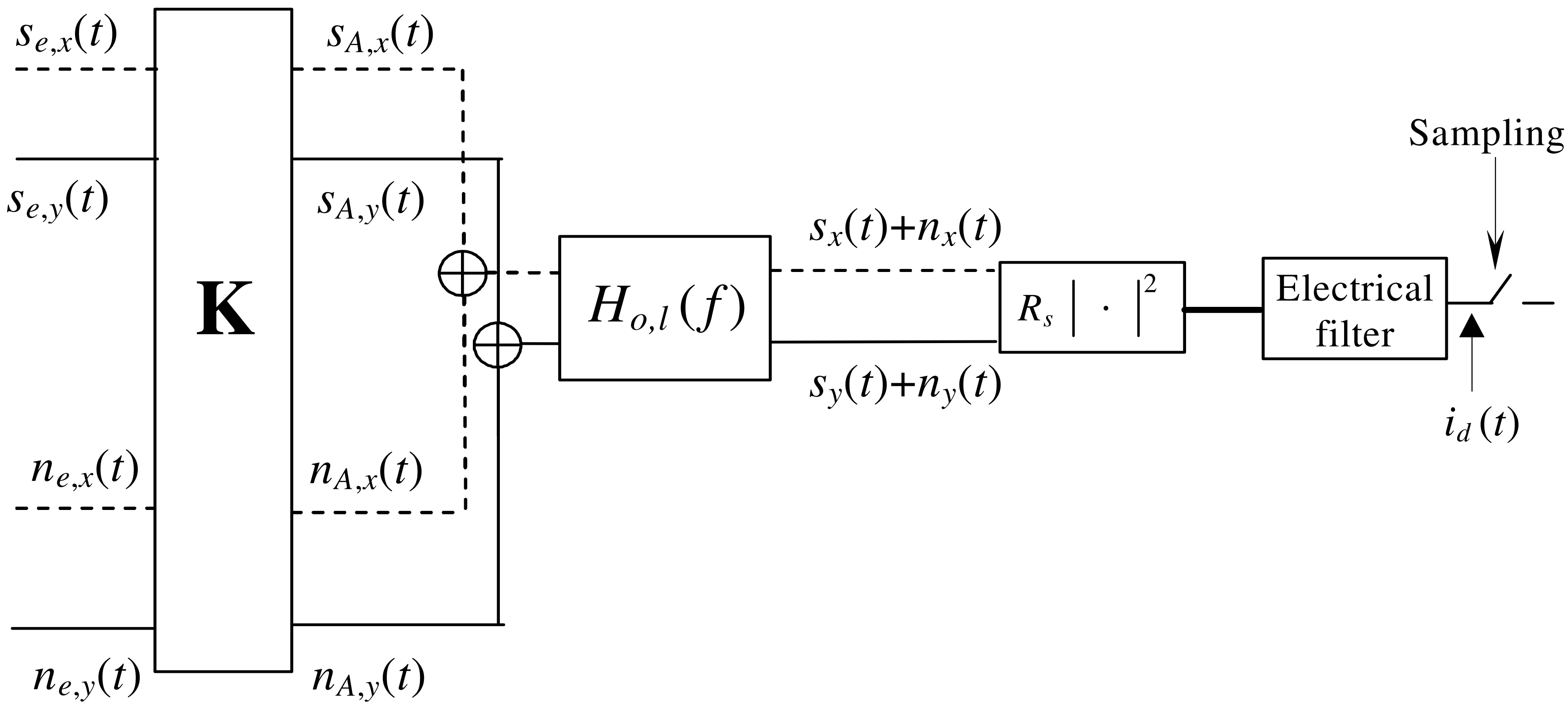

$s_{e,x}(t)$
$s_{e,y}(t)$
$n_{e,x}(t)$
$n_{e,y}(t)$
K
$s_{A,x}(t)$
$s_{A,y}(t)$
$n_{A,x}(t)$
$n_{A,y}(t)$
$H_{o,l}(f)$
$s_x(t)+n_x(t)$
$s_y(t)+n_y(t)$
$R_s\,|\cdot|^2$
Electrical filter
Sampling
$i_d(t)$

Figure 2

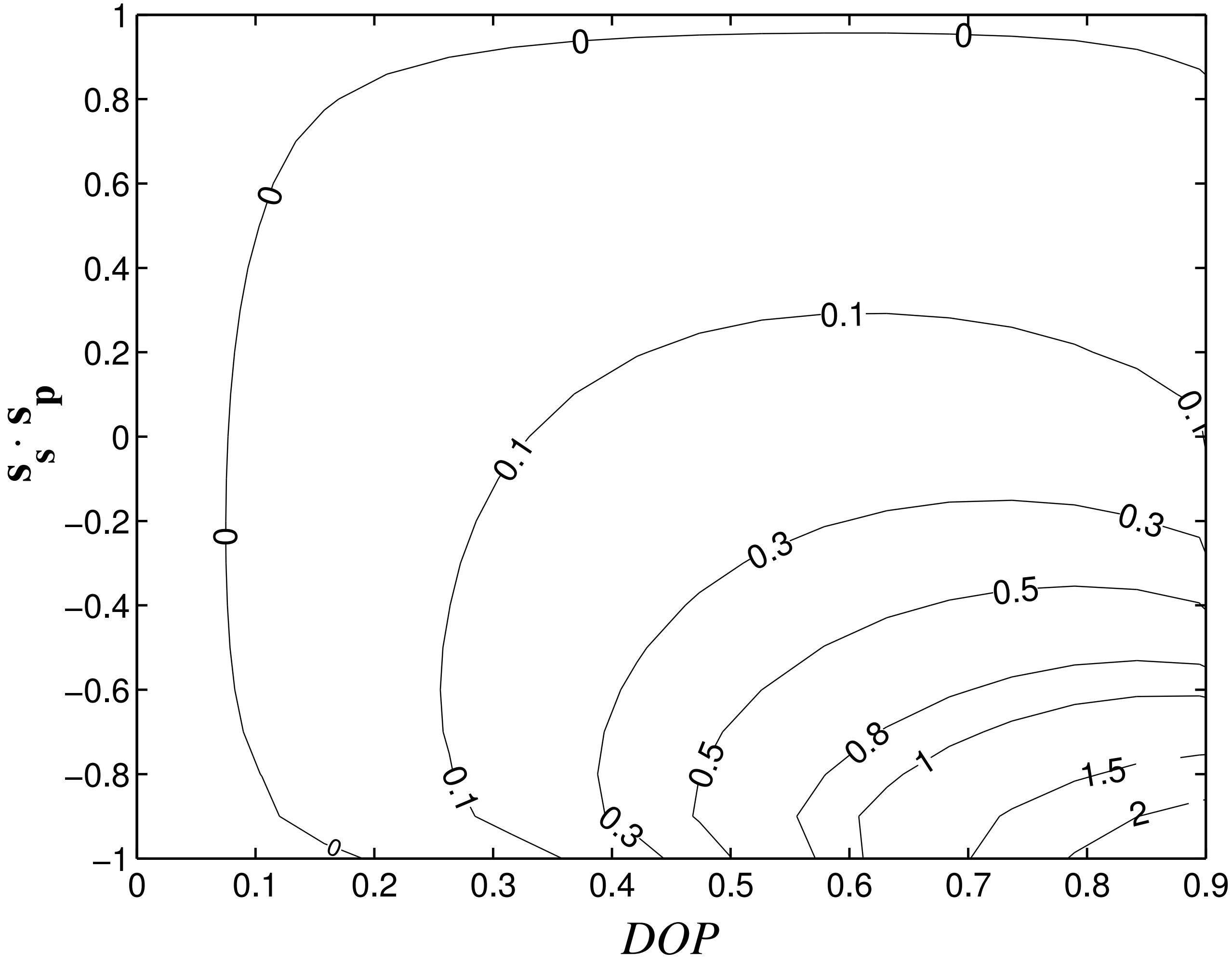

1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
DOP
s · s
s p
0
0.1
0.3
0.5
0.8
1
1.5
2

Figure 3 a)

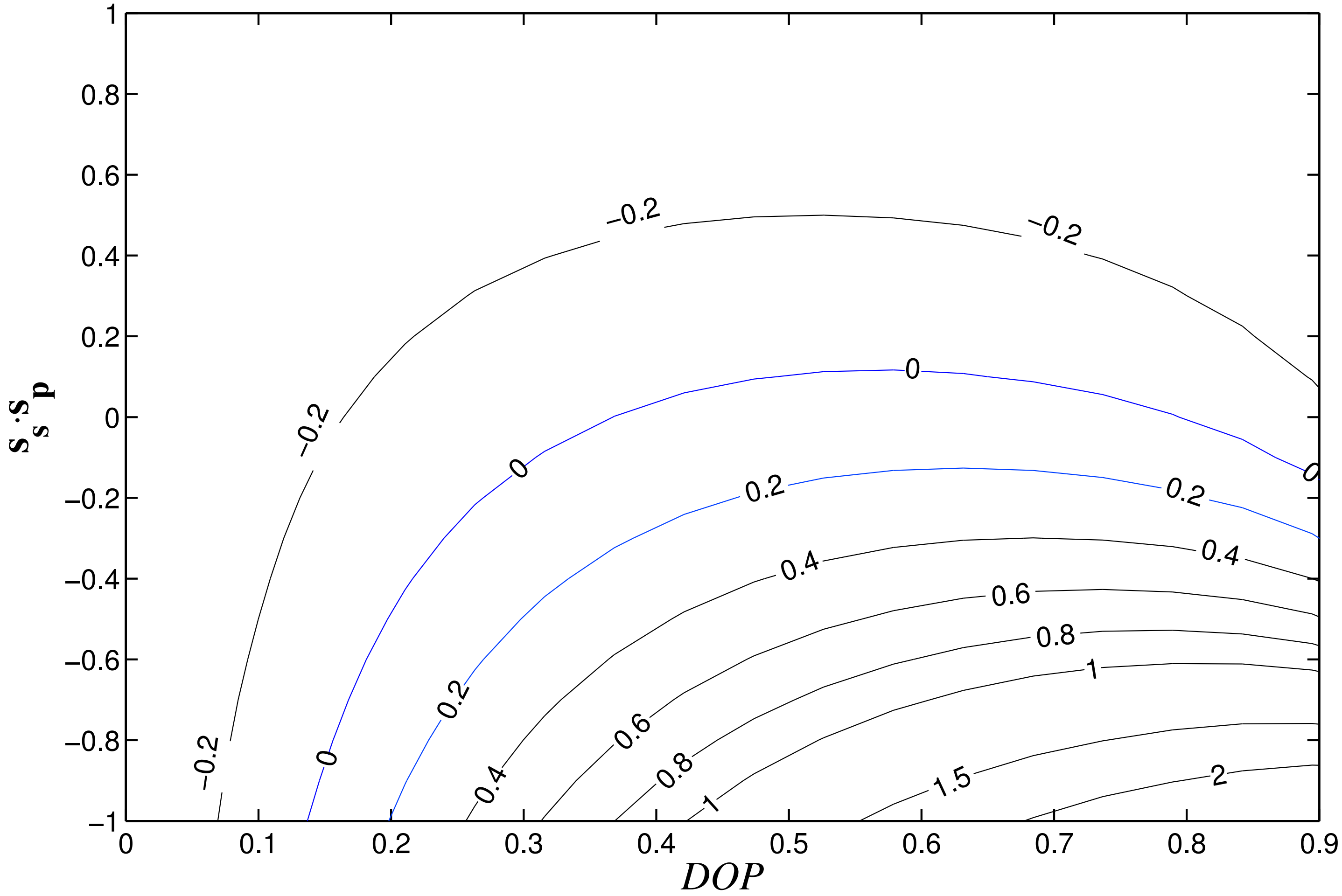

1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
DOP
−0.2
0
0.2
0.4
0.6
0.8
1
1.5
2

Figure 3 b)

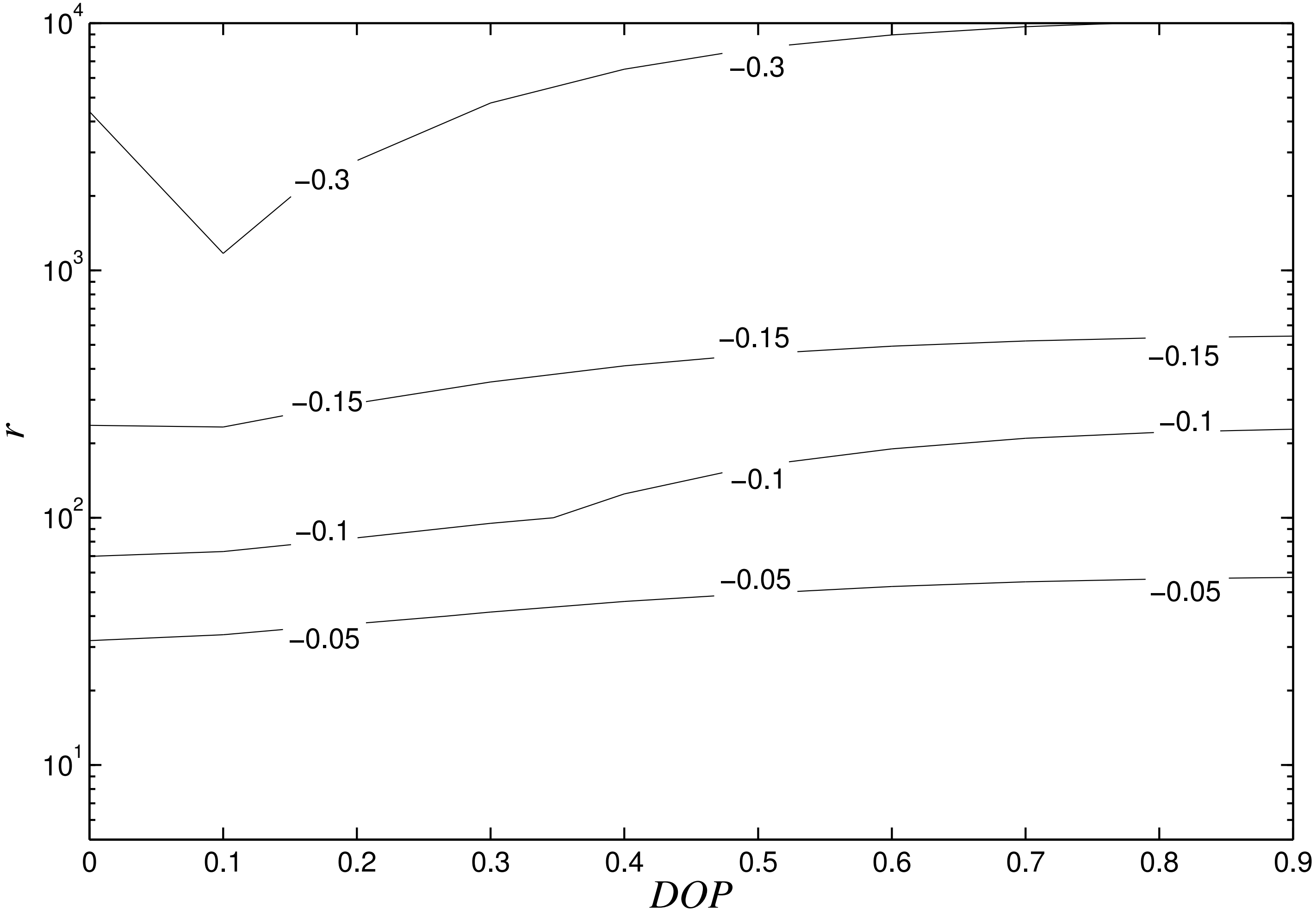
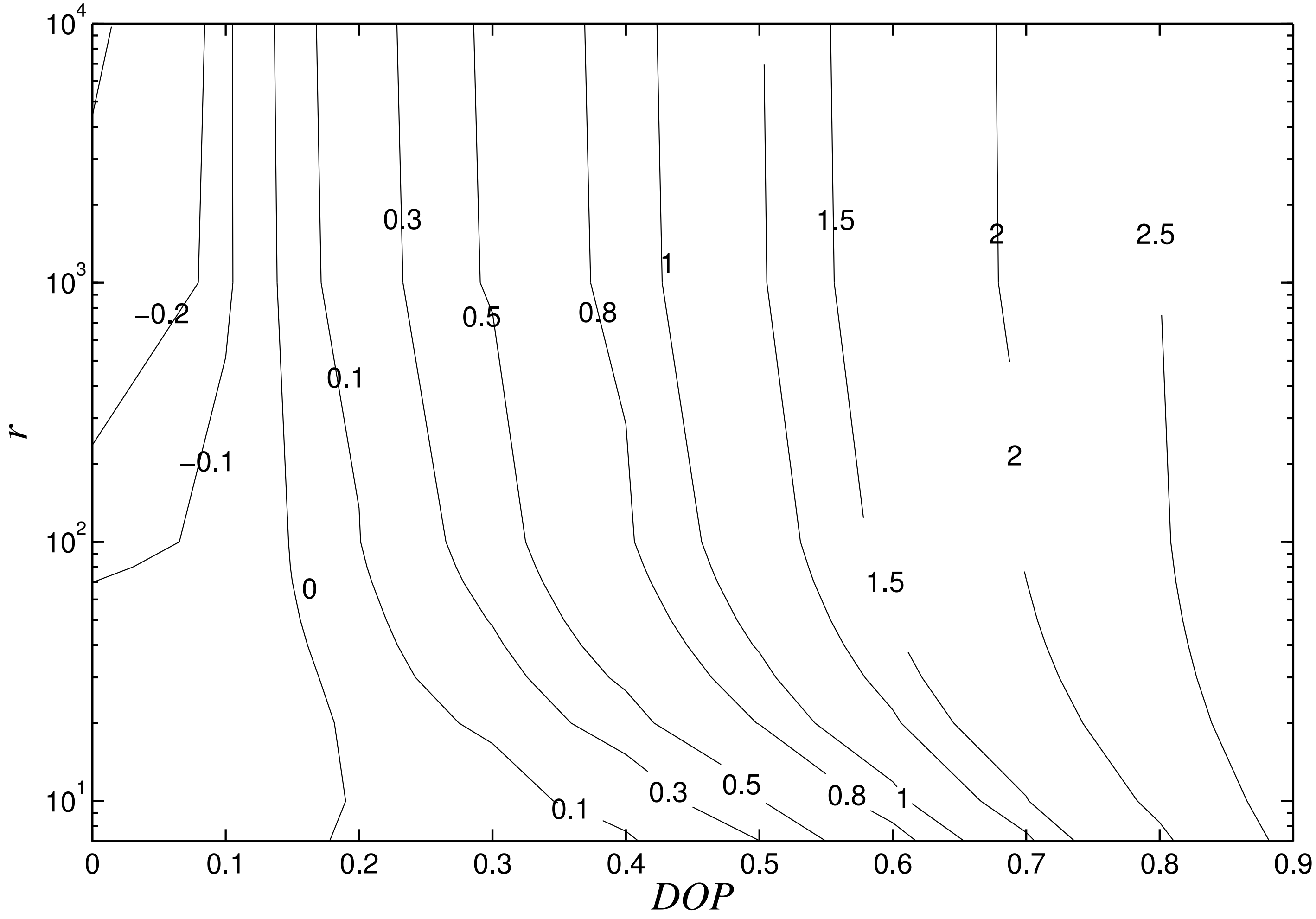

10^4
10^3
10^2
10^1
r
−0.3
−0.3
−0.15
−0.15
−0.15
−0.1
−0.1
−0.1
−0.05
−0.05
−0.05
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
DOP

Figure 4 a)



10^4
10^3
10^2
10^1
r
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
DOP
−0.2
−0.1
0
0.1
0.3
0.5
0.8
1
1.5
2
2.5

Figure 4 b)

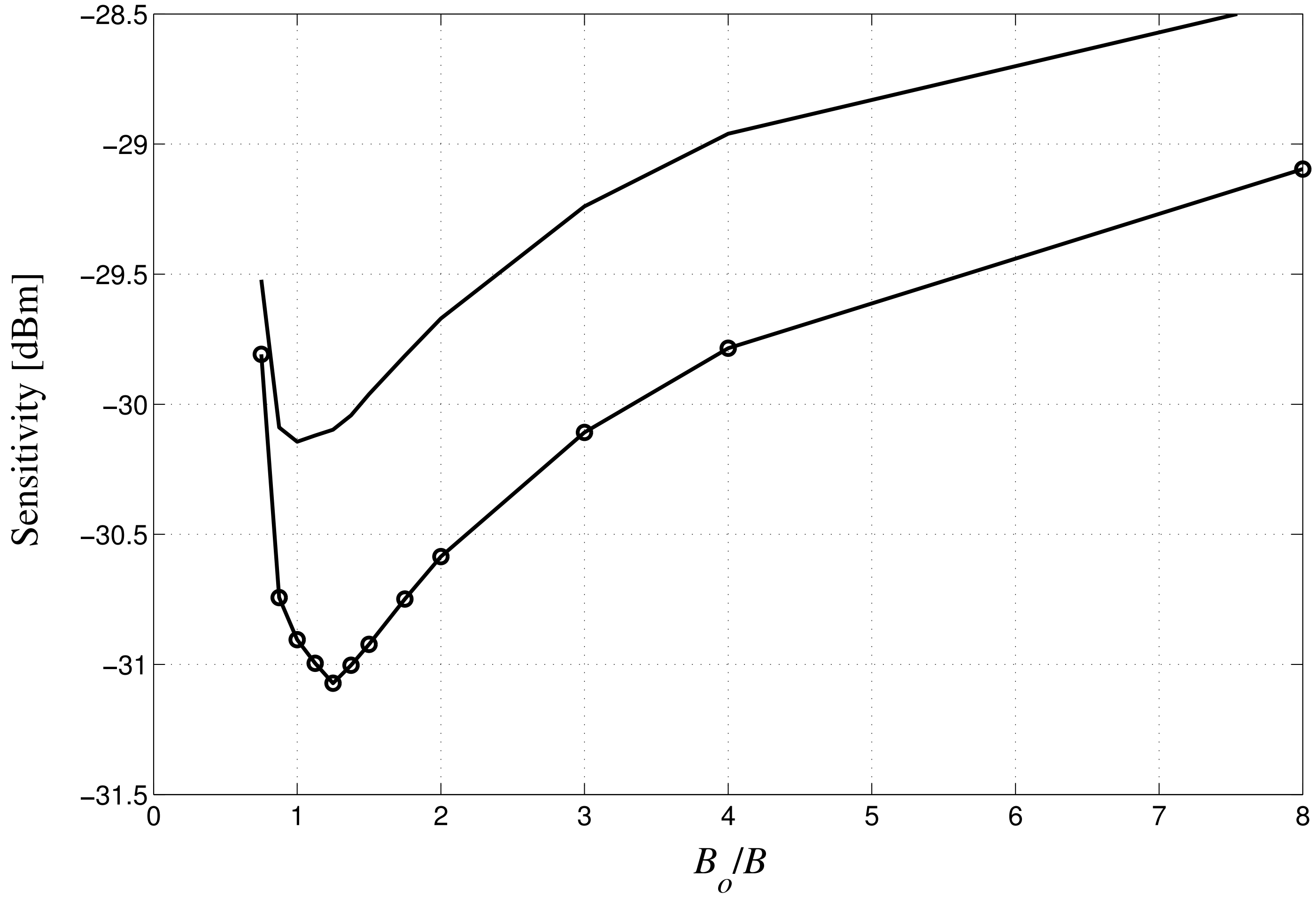


Figure 5