

# On the Performance of Semiconductor Optical Amplifier-Assisted Outdoor Optical Wireless Links

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**Abstract**—We present an analytical framework for estimating the benefits that arise from the utilization of semiconductor optical amplifiers at the receiver of fade impaired outdoor optical wireless systems. We first investigate the impact of fading on both the signal optical power and the amplified spontaneous emission, and derive analytical relations that accurately associate the system bit-error-rate with the channel state. We then utilize the analytical relations to assess the performance of the amplified system under moderate-to-strong ( $\gamma - \gamma$ ) fading in terms of first and second order signal statistics. Our results show that the receiver sensitivity improvement, which is imparted by the amplification process, can drastically reduce the average bit-error-rate, link outage probability and average fade duration, provided that the link length remains within certain limits that are determined by the turbulence intensity scenario under consideration.

**Index Terms**—Bit-error-rate (BER), outage probability, level crossing rate (LCR), average fade duration (AFD), gamma-gamma fading, outdoor optical wireless, semiconductor optical amplifier (SOA).

## I. INTRODUCTION

OPTICAL wireless (OW) technology has drawn considerable attention as a means of implementing reliable high-capacity outdoor systems that may not be implemented by conventional fiber optics [1]. Hero experiments involve intersatellite or satellites-to-earth links that have demonstrated the potential of OW system utilization in extreme application scenarios [2], culminating in the recent moon-to-earth OW communication [3]. Outdoor OW are equally important in down-to-earth systems that are used to interconnect buildings or business networks in urban environments at very high capacities that are comparable with fiber-based solutions [4]–[6]. The widespread application of outdoor OW, however, is hindered by atmospheric effects that induce a severe penalty on the link budget. Fog, snow, rain and air pollution account for a relatively static loss in the OW channel that needs to be compensated by amplification, coding and/or diversity [7]–[9], while the existence of variable temperature air pockets in the transmission path imparts a time-varying loss that is generally described as fading. Fading is also typically tackled by providing an

adequate link margin, while a number of techniques have been proposed with a goal of reducing the impact of fading and minimizing the margin that is required. Beam focusing [10], aperture averaging [11]–[13], spatial and temporal diversity [12], [14]–[21], coding [21]–[25], relaying [26]–[28] and amplification [28]–[31] are candidate techniques that have been proposed to effectively minimize the impact of fading and contribute to more reliable outdoor OW links.

Within the context of fade mitigation, we recently studied the performance of a semiconductor optical amplifier (SOA) assisted OW system in the presence of moderate-to-strong fading [32]. Based on a technique that was experimentally investigated earlier [30], we provided an analytical framework for assessing key metrics of the SOA-assisted system operation, including the outage probability and average fade duration, and demonstrated that the SOA can provide a very significant level of 2R regeneration. We also concluded, however, that optimal regeneration requires optical powers of the same order of magnitude with the SOA saturation power (a few dBm). Even though this could be the case in a relay, which will restore and retransmit the OW signal, typical optical receivers exhibit sensitivities of approximately 30 dB lower than the SOA saturation power, and the proposed technique does not provide a regenerative benefit at the link endpoint.

The deployment of the SOA at the OW receiver, however, also provides a substantial sensitivity improvement due to amplification [33], [34]. In this mode of operation the SOA does not alter the OW signal statistics and fading is still evident on the received signal, since the SOA input power is several orders of magnitude smaller than its saturation power and very limited regeneration is achieved. Rather, it is the signal beating with the SOA noise on the receiver photodiode that generates a dominant (signal-spontaneous) electrical noise component and enables the error-free receiver operation as long as the fading is not strong enough to attenuate the received power to levels comparable with those of the SOA noise. Consequently, even though the SOA is not capable of acting as a regenerator, it will provide a sizable sensitivity improvement and reduce the fade margin that is required at the receiver. In a similar fashion, the sensitivity improvement will translate into a significant boost in the system performance in terms of its first and second order statistics, provided that the fade margin is kept unaltered in the SOA-assisted system.

To our knowledge, a full analysis of the beneficial impact of the sensitivity improvement due to amplification has only

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been performed for first order statistics in the weak (log-normal) turbulence regime [31], while no related work has been recorded for medium-to-strong ( $\gamma - \gamma$ ) turbulence or second order statistics. In this work, we assess the beneficial impact of the SOA on the receiver performance by analytically associating the optical noise components that arise from the amplification process with the  $\gamma - \gamma$  channel state. This approach enables the accurate calculation of the electrical noise variances, and consequently the system bit-error-rate (BER), in any given channel state; as a result, key first and second order metrics can be calculated in a straightforward fashion by treating the BER as a random variable that directly correlates with the  $\gamma - \gamma$  channel.

The rest of this paper is organized as follows: In Section II we present the mathematical model that describes the BER performance of the system in the presence of  $\gamma - \gamma$  fading. The mathematical model makes no assumptions on the signal and noise contributions, both electrical and optical, that affect the system so as to accurately calculate its performance. In Section III we analytically evaluate the SOA-assisted system performance in terms of average BER and outage probability. The evaluation is carried out for both channel state aware (optimum) and non-aware (sub-optimum) receivers, after further optimizing their performance by taking into account the impact of channel fading on the instantaneous system BER. The first order results demonstrate that, even in this turbulence regime, optical amplification compensates for the required fade margin and increases the system availability by one or two additional “9”s, depending on the link length. Section IV discusses the second order statistics performance of the system and its main contribution is the analytical derivation of the level crossing rate (LCR) and the average fade duration (AFD) at the presence of the SOA. Our results show that the expected duration of fades is decreased by to at least 75% of its original value without the SOA, thus verifying the superior performance of the SOA-assisted system. We also demonstrate in this section that the second order statistics can be calculated in a straightforward fashion from the improved sensitivity, which makes this work readily applicable to all turbulence regimes irrespective of their strength. Finally, Section V discusses future studies that can base upon this work and concludes the paper.

## II. PRELIMINARIES AND NOISE MODEL

As it has been extensively described [32], the SOA-based fade mitigation technique utilizes a SOA to partially alleviate the impact of fades on the OW signal. Following the analysis found therein, the transmitted optical signal experiences time-varying power fluctuations due to fading, and these fluctuations occur at timescales significantly greater than the bit period. This corresponds to a slow modulation of the amplitude of thousands of successive optical pulses, which gradually diminish in power while the channel enters a fade state. Due to the slow modulation process the pulses profiles are not distorted and each pulse can be in principle restored independently by signal processing regeneration techniques, including SOA-based 2R regenerators.

Even though signal restoration is particularly appealing, especially in intermediate relays, a more typical role for SOAs in

OW systems would be to simply provide a static gain that compensates for link losses or provides the required fade margin. An interesting and potentially useful aspect of utilizing the SOA in this fashion stems from the observation that the amplifier modifies the noise properties of the system and a dominant electrical noise component emerges from the beating between the optical signal and the amplified spontaneous emission on the receiver photodiode. This leads to an extended sensitivity improvement at the receiver that adds to the available link budget, providing a direct benefit from using the amplifier. An in-depth treatment of the amplified system, however, requires the development of an analytical model that takes into account the impact of fading both on the signal power and the electrical noise variances. This association enables the calculation of the system BER in any given channel state and its treatment as a random variable, which also allows the derivation of first and second order statistics for the optical signal in terms of the BER rather than absolute or normalized power levels.

The main goal of this section is to derive analytical equations for the amplified system BER as a random variable whose value is determined by the channel state. We assume that the OW system utilizes return-to-zero (RZ) on/off optical pulses, which experience slowly varying power fluctuations, due to fading, and that the optical power  $P_{in}$  of each received pulse at the input of SOA is a random variable, following the preceding discussion. In the context of the current work  $P_{in}$  obeys  $\gamma - \gamma$  statistics with a probability density function (pdf) [13], [35]

$$f_{P_{in}}(z) = \frac{2(m_y m_x)^{\frac{m_y+m_x}{2}} z^{\frac{m_y+m_x}{2}-1}}{\Gamma(m_x) \Gamma(m_y) \frac{\bar{P}_{in}^{\frac{m_y+m_x}{2}}}{P_{in}^{\frac{m_y+m_x}{2}}}} \times K_{m_y-m_x} \left( 2 \sqrt{m_y m_x \frac{z}{\bar{P}_{in}}} \right), \quad (1)$$

where  $\bar{P}_{in}$  is the average SOA input optical power, while  $\Gamma(\cdot)$  and  $K_\nu(\cdot)$  denote the Gamma and second kind modified Bessel functions, respectively. Moreover,  $m_x$  and  $m_y$  are two  $\gamma - \gamma$  distribution parameters related to the effective numbers of large- and small-scale scatterers in the OW link.

The optical pulses traverse the SOA and, depending on the channel state, partially saturate it. For a RZ line coded system, the power transfer function that relates the output and input powers per optical pulse is given by [36], [37]

$$P_{out}(z) = P_{sat} \log_{10} \left[ 1 + G \left( \exp \left( \frac{z}{P_{sat}} \right) - 1 \right) \right], \quad (2)$$

where  $G$  is the SOA small-signal gain,  $P_{sat}$  is the rate-dependent saturation parameter of the SOA

$$P_{sat} = \frac{U_{sat}}{T_b}, \quad (3)$$

$U_{sat}$  is the SOA saturation energy and  $T_b$  is the bit duration. Apart from providing a certain degree of gain to the incoming signal, the SOA also generates a significant amplified-spontaneous-emission (ASE) optical noise component with a power density

$$P_n = n_{sp} h \frac{c}{\lambda}. \quad (4)$$

TABLE I  
SYSTEM PARAMETERS

Parameter	Symbol	Value
Refractive index structure	$C_n^2$	$4.58 \times 10^{-13} \text{ m}^{-2/3}$
Receiver aperture diameter	$D$	10 mm
Link length	$L$	250, 500, 1000 m
Wavelength	$\lambda$	1550 nm
Line Rate	$T_b^{-1}$	10 Gb/s
SOA small-signal gain	$G$	20 or 30 dB
Saturation parameter	$P_{sat}$	1 mW
Population inversion factor	$n_{sp}$	4.0
Photodiode responsivity	$R$	1.25 A/W
Receiver temperature	$T$	300° K
Resistor load	$R_L$	100 $\Omega$
Electrical noise figure	$F_n$	3 dB
Electrical bandwidth	$B_e$	7 GHz
Optical bandwidth	$B_o$	50 GHz

In the last equation,  $c$  is the vacuum light speed,  $h$  is the Planck constant,  $n_{sp}$  is the population inversion factor and  $\lambda$  denotes the wavelength. The ASE noise beats with the received signal on the receiver photo-diode, and a number of electrical noise components manifest at the input of the electronic receiver. The noise components are described by the following noise variances that mathematically describe the thermal, shot, signal-spontaneous beating and spontaneous-spontaneous beating contributions as

$$\sigma_{th}^2 = \frac{4 k_B T F_n B_e}{R_L}, \quad (5a)$$

$$\sigma_{shot}^2(z) = 2 q R (P_{out}(z) + (G - 1) P_n B_o) B_e, \quad (5b)$$

$$\sigma_{sig-sp}^2(z) = 4 R^2 P_{out}(z) (G - 1) P_n B_e, \quad (5c)$$

and

$$\sigma_{sp-sp}^2 = R^2 ((G - 1) P_n)^2 (2 B_o - B_e) B_e, \quad (5d)$$

respectively. In (5),  $B_e$  and  $B_o$  are the electrical and optical bandwidths, respectively,  $R$  is the photodiode responsivity,  $T$  is the receiver temperature,  $k_B$  denotes the Boltzmann constant,  $F_n$  is the electric noise figure and  $R_L$  is the resistor load. All these parameters are summarized in Table I. In all the above expressions, the SOA small signal gain is used to calculate the noise variances despite the fact that the gain is compressed due to saturation effects, as it is clearly predicted by (2). It is noted here that this approximation does not affect the key contributions of this work. In fact, the noise powers, that are predicted by (5), are higher than those that would be calculated after taking into consideration the gain saturation and, as a result, this work can serve as the *worst-case scenario*.

### III. FIRST ORDER STATISTICS

In the current section we discuss the improvement that is achieved by introducing the SOA at the OW system receiver in terms of first order statistics. By utilizing the mathematical framework that we developed in the previous section, we assess the average BER of a SOA-assisted system and demonstrate that the SOA provides a link margin that can fully compensate for any practically considered fade margin. We further explore this result by calculating the outage probability of OW systems

with and without SOAs and show that an excess power margin is observed even after compensating the fade margin. In principle, this excess margin can be exploited to mitigate additional static or varying loss effects.

#### A. Average Bit-Error-Rate Analysis

Given (2) and (5), it is possible to estimate the signal and noise electrical powers when the on “1” and off “0” symbols are transmitted on the optical link as

$$I_1(z) = R P_{out}(z), \quad (6a)$$

$$\sigma_1^2(z) = \sigma_{th}^2 + \sigma_{shot}^2(z) + \sigma_{sig-sp}^2(z) + \sigma_{sp-sp}^2, \quad (6b)$$

and

$$I_0 = 0, \quad (7a)$$

$$\sigma_0^2 = \sigma_{th}^2 + \sigma_{shot}^2(0) + \sigma_{sp-sp}^2, \quad (7b)$$

respectively. Then, the BER performance of the system is evaluated by

$$BER(z) = \frac{1}{4} \operatorname{erfc} \left( \frac{I_1(z) - I_{th}}{\sigma_1(z) \sqrt{2}} \right) + \frac{1}{4} \operatorname{erfc} \left( \frac{I_{th}}{\sigma_0 \sqrt{2}} \right), \quad (8)$$

where  $I_{th}$  is the decision threshold of the electronic receiver, and the average BER can be calculated from (8) after integrating over all possible channel states to obtain

$$\overline{BER} = \int_0^\infty BER(z) f_{P_{in}}(z) dz. \quad (9)$$

One key challenge here is to determine the decision threshold  $I_{th}$  at the receiver so as to achieve optimal average BER performance. We will investigate the system operation assuming that the receiver is both non-aware and aware of the channel state:

1) *Reception Without CSI*: If the receiver can not acquire information about the channel state (non-CSI receiver) and the decision threshold has to be a-priori set during the link establishment, then optimal operation is achieved for a maximum-likelihood threshold that is calculated after differentiating (9) with respect to  $I_{th}$  to finally obtain

$$\int_0^\infty \frac{\exp \left( -\frac{(I_1(z) - I_{th})^2}{2\sigma_1^2(z)} \right)}{\sigma_1(z)} f_{P_{in}}(z) dz = \frac{\exp \left( -\frac{I_{th}^2}{2\sigma_0^2} \right)}{\sigma_0}. \quad (10)$$

2) *Reception With CSI*: If the receiver is capable of monitoring the channel state, then a symbol-by-symbol decision threshold can set for each respective channel state. In this case the threshold for any given state can be approximated by [38]

$$I_{th}(z) = \frac{\sigma_0 I_1(z)}{\sigma_0 + \sigma_1(z)}, \quad (11)$$

and (9) simplifies to

$$\overline{BER} = \frac{1}{2} \int_0^\infty \operatorname{erfc} \left( \frac{Q(z)}{\sqrt{2}} \right) f_{P_{in}}(z) dz, \quad (12)$$

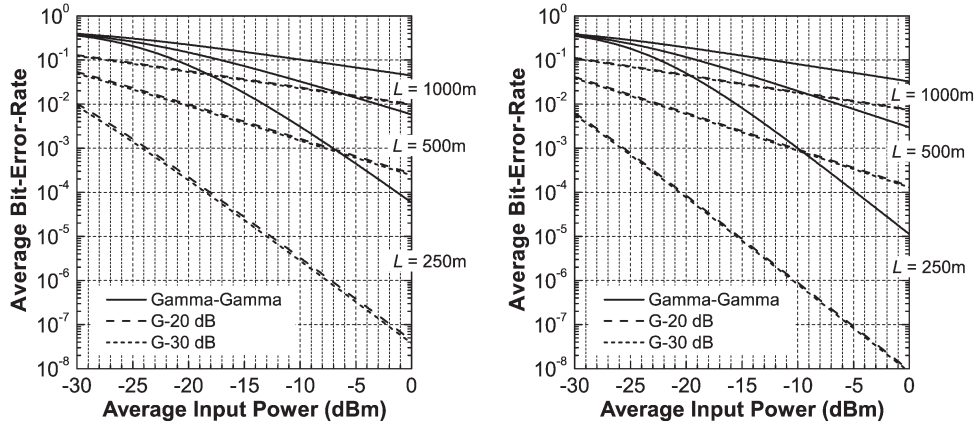


Fig. 1. Average bit-error-rate versus the average input power for a non-CSI (left) and a CSI (right) receiver.

TABLE II  
GAMMA-GAMMA PARAMETERS

$L$ (m)	$m_x$	$m_y$	$\sigma_{\gamma-\gamma}$	$b_x$	$b_y$
250	5.93	1.99	0.87	18.19	30.14
500	4.20	0.83	1.31	11.56	42.83
1000	5.54	0.39	1.79	3.93	48.46

with

$$Q(z) = \frac{I_1(z)}{\sigma_0 + \sigma_1(z)}. \tag{13}$$

Eq. (9) and (12) are plotted against the average received optical power  $\bar{P}_{in}$  in Fig. 1 for two SOAs with small signal gains of 20 and 30 dB. The OW link distances are limited to 250, 500 and 1000 m due to the strong turbulence conditions that are anticipated by the system parameters of Tables I and II. In fact, the results for longer length links (not shown for clarity) exhibit very poor BER performance, and a similar study for lengths over 1000 m would require more benign fading parameters or the replacement of the  $\gamma - \gamma$  with a negative-exponential distribution so as to describe intense fading more accurately. For the links under consideration, the results demonstrate a 17 dB power margin improvement when the SOA is deployed in the non-CSI system irrespective of the link length. The margin improvement is decreased by approximately 1 dB in the CSI system, since the receiver is partially capable of self-adjusting to link fades, still the SOA contributes the main part to fade mitigation. Clearly, the SOA provides a significant benefit to the link budget, and will either (a) allow for higher link availability whenever the rest of the static (rain/snow/fog) and time varying losses (building sway) are accounted for, as we demonstrate in the next section, or (b) allow for the power budget redistribution to compensate for effects other than fading in systems that are transmission power limited, for example due to eye-safety considerations.

**B. Outage Probability Analysis**

An outage occurs whenever the BER of the OW system exceeds a certain level that is determined by the system error

detection and correction capabilities. For a given BER target  $BER_0$  the outage probability is given by

$$\Pr\{BER(z) > BER_0\}, \tag{14}$$

still this calculation requires the knowledge of the BER pdf, which can be challenging to derive. Alternatively, the outage probability can be calculated in a straight-forward fashion from (1) as

$$\Pr\{z \leq P_s\} = \int_0^{P_s} f_{P_{in}}(z) dz, \tag{15}$$

where  $P_s$  is the receiver sensitivity that achieves the required BER level  $BER_0$ . Following the presented mathematical analysis, the receiver sensitivity is obtained after solving

$$BER(P_s) = BER_0, \tag{16a}$$

or equivalently

$$\frac{1}{4} \operatorname{erfc}\left(\frac{I_1(P_s) - I_{th}}{\sigma_1(P_s) \sqrt{2}}\right) + \frac{1}{4} \operatorname{erfc}\left(\frac{I_{th}}{\sigma_0 \sqrt{2}}\right) = BER_0. \tag{16b}$$

The optimal decision threshold is calculated by

$$I_{th}(P_s) = \frac{\sigma_0 I_1(P_s)}{\sigma_0 + \sigma_1(P_s)} \tag{16c}$$

for both CSI and non-CSI receivers. This can be justified from the fact that the non-CSI receiver will be a-priori optimized for the required BER threshold, following (16b) and (16c). The CSI receiver, on the other hand, will dynamically adapt to the same decision threshold when the input optical power equals the receiver sensitivity, and as a result both receivers exhibit identical sensitivities for any given BER target level.

Eq. (15) is plotted in Fig. 2 for BER targets of  $10^{-3}$  and  $10^{-6}$ , which correspond to receiver sensitivities of  $-21.2$  and  $-19.4$  dBm, respectively, for the parameter values of Table I. The presented results show that the SOA-assisted system provides a link margin that corresponds to the sensitivity improvement that is brought about by the amplification process,

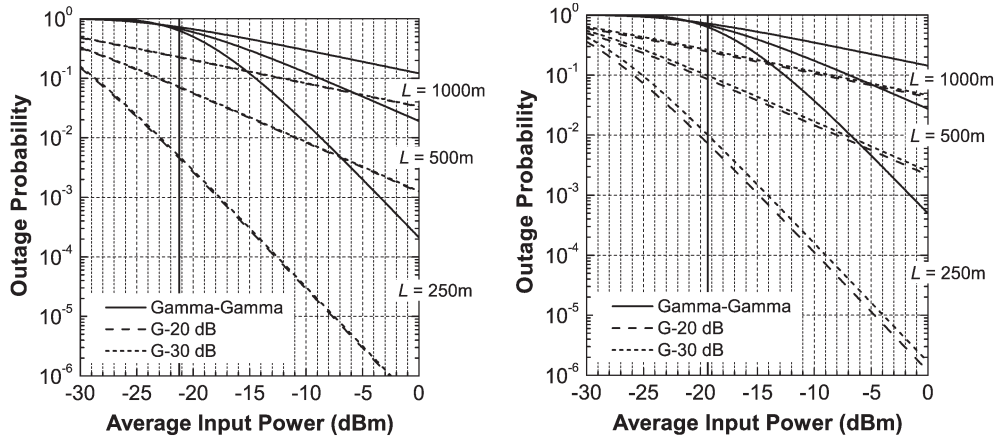


Fig. 2. Outage probability versus the average input power for  $BER_0 = 10^{-3}$  (left) and  $BER_0 = 10^{-6}$  (right). The solid vertical line corresponds to the receiver sensitivity without the SOA.

irrespective of the link length. The sensitivity improvement itself is approximately equal to 14.3 dB for the BER target of  $10^{-3}$  and 12.5–13.8 dB for the BER target of  $10^{-6}$ , depending on the SOA gain. This observation verifies the validity of the results and can also be used as a design rule for determining the power budget any given system availability. For example, if a 250 m link is required to operate with 99.99% availability then a fade margin of 12 dB must be supplied for a BER target of  $10^{-3}$ —the deployment of the SOA will compensate for the fade margin and will also provide a limited excess margin that allows for lowering the transmission power or partially mitigate the impact of additional static or time-varying losses. If the BER target is lowered to  $10^{-6}$  then the required fade margin increases by 1 dB and the SOA is simply compensating for it.

It is also of importance to notice that the SOA has a very significant effect on the link availability for fixed received powers. Considering the same 99.99% availability 250 m original link without the SOA, the results show that the SOA deployment increases the link availability to over 99.9999% for both BER targets. A similar, although less pronounced behavior, is also observed for longer link lengths of and the results show that the SOA can provide one additional “9” to the 500 m link. Fading in longer links, however, can not be compensated to a significant level by the SOA alone due to the strongly fluctuating behavior of the  $\gamma - \gamma$  channel. In this regime, a combination of mitigation techniques will be required or even the segmentation of the link by intermediate relays that are also utilizing SOAs in a regenerative mode as we have previously proposed [32].

#### IV. SECOND ORDER STATISTICS

The goal of this section is to evaluate the performance of the SOA-assisted system in terms of the second order statistics and mainly the level crossing rate and the average fade duration. In contrast with existing works that discuss the second order properties of the system in terms of power thresholds, we focus on the actual BER properties of the SOA-assisted system and derive the LCR and AFD for a target BER level  $BER_0$ . To this

end, we first evaluate the system LCR and then utilize the AFD definition to obtain analytical results for the AFD, as well.

The LCR is calculated from the joint pdf of the optical signal power  $z$  and its time derivative  $\dot{z}$ . For a  $\gamma - \gamma$  channel the joint pdf is given by [39]

$$f_{v,\dot{v}}(y, w) = \frac{1}{\sqrt{8\pi}} \frac{m_x^{m_x} m_y^{m_y} y^{m_y - \frac{3}{2}}}{\Gamma(m_x) \Gamma(m_y)} \int_0^\infty \frac{x^{m_x - m_y - \frac{1}{2}}}{\sqrt{b_x^2 y + b_y^2 x^2}} \times \exp \left[ -m_x x - \frac{m_y y}{x} - \frac{w^2 x}{8y (b_x^2 y + b_y^2 x^2)} \right] dx, \quad (17)$$

where  $v$  corresponds to the normalized power

$$v = \frac{z}{\bar{P}_{in}}. \quad (18)$$

The calculation of the LCR for a specific BER level, however, requires the derivation of the joint pdf between the BER random variable  $b$  and its time derivative. To this end, we utilize (8) to associate  $b$  with  $v$  as

$$b = BER(v \bar{P}_{in}) \Rightarrow v = \frac{T(b)}{\bar{P}_{in}}, \quad (19)$$

where  $T(\cdot)$  denotes the inverse BER function. The joint pdf for the BER is calculated using the following change of variables

$$v = \frac{T(b)}{\bar{P}_{in}}, \quad (20a)$$

$$\dot{v} = \frac{T'(b)}{\bar{P}_{in}} \dot{b} \quad (20b)$$

and after combining (17) and (20) we find that

$$f_{b,\dot{b}}(y, w) = \left( \frac{T'(y)}{\bar{P}_{in}} \right)^2 f_{v,\dot{v}} \left( \frac{T(y)}{\bar{P}_{in}}, w \frac{T'(y)}{\bar{P}_{in}} \right). \quad (21)$$



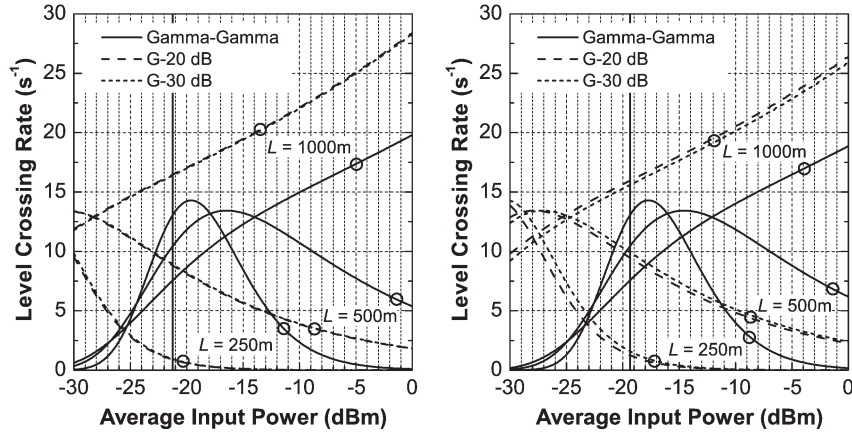


Fig. 3. Average fade duration versus the average input power for  $BER_0 = 10^{-3}$ (left) and  $BER_0 = 10^{-6}$  (right). The solid vertical line corresponds to the receiver sensitivity without the SOA.

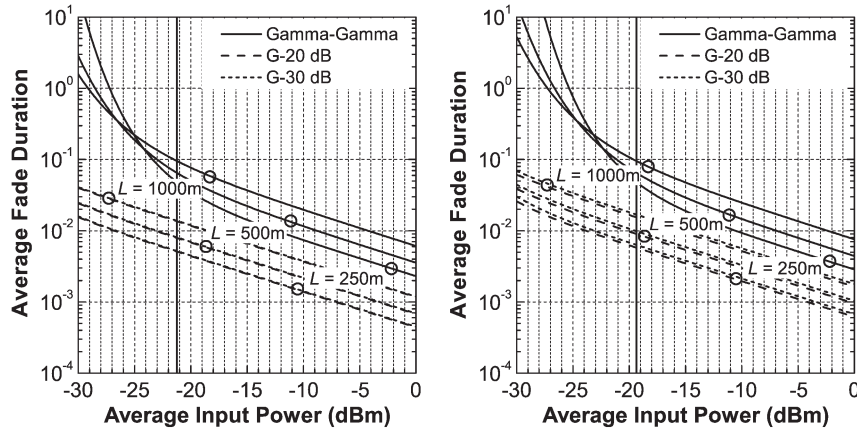


Fig. 4. Average fade duration versus the average input power for  $BER_0 = 10^{-3}$  (left) and  $BER_0 = 10^{-6}$  (right). The solid vertical line corresponds to the receiver sensitivity without the SOA.

From its definition, the LCR is finally calculated by

$$\begin{aligned}
 LCR &= \int_0^\infty f_{b,i}(BER_0, w) w dw \\
 &= \left( \frac{T'(BER_0)}{\bar{P}_{in}} \right)^2 \\
 &\quad \times \int_0^\infty f_{v,i} \left( \frac{T(BER_0)}{\bar{P}_{in}}, w \frac{T'(BER_0)}{\bar{P}_{in}} \right) w dw \\
 &= \int_0^\infty f_{v,i} \left( \frac{P_s}{\bar{P}_{in}}, q \right) q dq, \tag{22}
 \end{aligned}$$

which is clearly equal to the LCR that is calculated for the  $\gamma - \gamma$  channel at the SOA-assisted receiver sensitivity.

The LCR of the SOA-assisted system is plotted in Fig. 3 against the average input power for target BERs of  $10^{-3}$  and  $10^{-6}$ . The results show that the LCR is modified by the power margin that is provided by the sensitivity increase from the SOA. For the 250 and 500 m link and average powers beyond the original system sensitivity the LCR is decreased by a significant factor, which implies that the SOA may worsen the AFD performance of the system according to (23). In contrast, the SOA increases the LCR of 1000 m link irrespective of the

power level. As a result, it is not possible to draw a definitive conclusion for the SOA-assisted system performance from the LCR alone and an AFD analysis is required.

The AFD is given by

$$AFD = \frac{\Pr \{BER(z) > BER_0\}}{LCR(BER_0)} \tag{23}$$

and can be directly calculated from (15) and (22). The results are plotted against the average input power in Fig. 4 for BER targets of  $10^{-3}$  and  $10^{-6}$ , similar to the previous analysis. The results illustrate that, in contrast with the LCR, the SOA always improves the AFD performance of the system irrespective of the input power. In fact, the AFD in the SOA-assisted system is reduced by more than 80% of its original value for the  $10^{-3}$  BER target and by more than 76% for the  $10^{-6}$  target. Clearly, this corresponds to a very drastic improvement on the AFD, even for relatively long link lengths that exhibit an increased outage probability.

## V. CONCLUSION AND FUTURE WORK

We have presented novel analytical results for a SOA amplified OW system and have demonstrated that the sensitivity

improvement that is achieved by optical amplification also improves the system performance as measured by key first and second order metrics. With respect to first order statistics, the SOA-assisted system exhibits significantly lower average BERs and higher link availabilities. In a similar fashion, the sensitivity improvement can be utilized to partially or fully compensate for the fade margin in medium-to-strong turbulence for link lengths that do not exceed several hundreds of meters. As far as the second order statistics are concerned, we have presented analytical results on the amplified system LCR and AFD for the first time to our knowledge. The results clearly demonstrate a drastic improvement of the AFD irrespective of the link length.

In addition, we have showed that the LCR and AFD can be calculated from the sensitivity of the amplified system alone, and this is of practical importance for future works that will extend the scope of LCR and AFD study to the weak and saturated turbulence regimes. This extension will enable the BER performance assessment of OW links that are longer than those considered in the current work ( $> 1$  km) and operate either in weak turbulence that is described by a log-normal distribution, or in saturated turbulence that is more accurately modeled by negative-exponential rather than  $\gamma - \gamma$  statistics. In both regimes, a similar analysis can be readily performed provided that the outage probability and LCR is known for log-normal and exponential statistics, respectively.

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