Optimal Combiners in Optical Wireless Systems with Spatial Diversity and Pre-Amplification

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***Abstract*—We present analytical results on the operation of a pre-amplified optical wireless communication (OWC) system that also takes advantage of spatial diversity to improve its outage probability and average bit-error-rate (BER) performance against turbulence induced fading. The paper focuses on the design of an optimal electronic combiner that minimizes the instantaneous BER for any given channel state by properly adjusting the gains that are provided to each receiver output after detection. We demonstrate that the optimal combiner performs in a similar manner to an equal gain combiner for a limited number of receiving elements in moderate turbulence, while its potential can be harvested in systems with high diversity factors or under the strong-to-saturated turbulence regime.**

***Index Terms*—Bit-error-rate, outage probability, γ–γ fading, outdoor optical wireless, semiconductor optical amplifiers, diversity reception.**

I. INTRODUCTION

Outdoor OWC systems have emerged as a viable alternative for the implementation of easy to setup, low-cost, truly broadband communication links between buildings and private networks in urban environments [1]. The capacities of OWC links have increased in a trend similar to the fiber-based solutions, and multi-Gb/s links with a reach of a few km are currently available by commercial vendors. The full exploitation of the OWC bandwidth, however, can be hindered by weather effects and the volatile nature of the atmosphere [2]. Variations in the atmospheric temperature and pressure result in fluctuations of the refractive index and the transmission of optical beams is affected by time-dependent loss, beam wandering and spreading. These effects manifest as scintillations in the received optical power and degrade the receiver performance to a significant extent.

The adverse impact of scintillation on the receiver operation is particularly deleterious in high-capacity OWC links, as the number of bits that are lost during a fade event grows with the transmission rate. The mitigation of fades has been therefore extensively studied and a number of techniques have been proposed within the context of improving the OWC link availability and BER. These techniques include beam focusing [3], aperture averaging [4], spatial and temporal diversity [5]–[10], coding [11]–[14], relaying [15]–[17] and amplification [17]–[20], as well as combinations of techniques. The combination of spatial diversity and amplification is particularly appealing, and previous works have reported high link gains by using multiple optical amplifiers and equal gain combiners (EGC) in the electronic domain [20], [21].

Even though the EGCs provide a significant gain without introducing significant complexity in the receiver electronics, it is of interest to investigate optimal combiners that further enhance the diversity gain in an amplified OWC system. Optimal combiners have been previously reported in RF communications, and it is well established that the optimal maximal-ratio combiner (MRC) is required to provide unequal gain to each receiving branch. The respective gain of each branch is proportional to the received signal, thus branches that are temporarily experiencing a fade contribute less than non-faded branches to the overall signal-to-noise ratio. This approach is also valid in OWC systems with constant noise powers at the receiver, including receivers that are dominated by thermal and background noise. Optically amplified systems, on the other hand, are typically impaired by a noise component that arises from the beating of the amplifier noise with the signal on the photodiode. In this work, we analytically show for the first time to our knowledge that the MRC approach is not optimal for such systems, but the branch gains of the optimal combiner become signal independent when the signal-spontaneous beating noise dominates. As a result, the optimal combiner operation bears a closer resemblance to the EGC one in this regime. Moreover, we perform an assessment of the optimal combiner in terms of the outage probability and average BER that can be attained in moderate γ–γ fading. The presented results verify that the optimal combiner provides a better link gain than the EGC, but the improvement is relatively small unless a large number of receiving elements is deployed. Finally, we argue that the optimal combiner is better suited for deployment in a strong-to-saturated turbulence environment.

The rest of this paper is organized as follows: in Section II we present a basic mathematical model for the description of the OWC channel, the amplifier and the diversity receiver. Section III calculates the outage probability and the average BER of the selection combiner (SC) and the EGC, and also presents novel analytical results for the optimal combiner structure, operation and performance in terms of the aforementioned metrics. The performance of the optimal combiner is evaluated in Section IV, where it is also compared with the SC and the EGC in a moderate fading environment. Finally, Section V summarizes the most important findings of this work and concludes the presentation.

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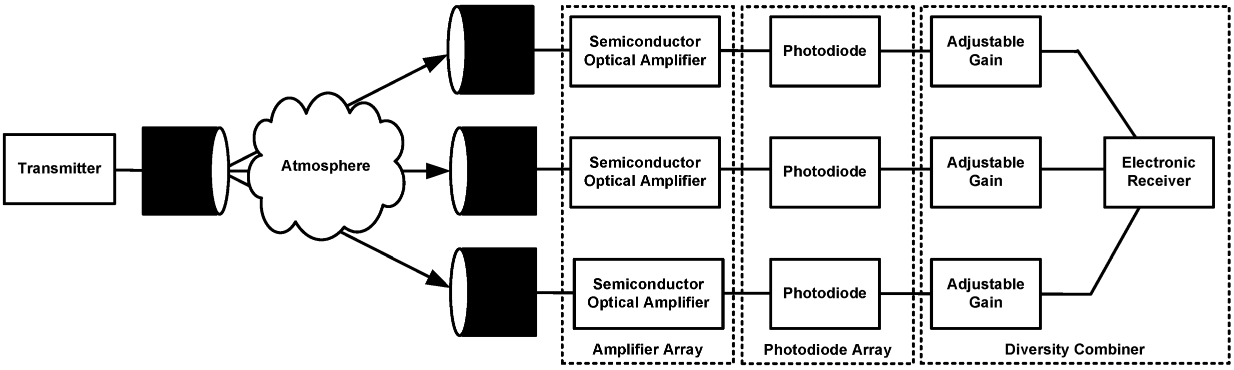

Fig. 1. Optically pre-amplified system with diversity.

II. CHANNEL, AMPLIFIER AND RECEIVER MODEL

The system under study is presented in Fig. 1. The OWC signal propagates through the atmosphere and experiences turbulence induced fading. At the receiver side, L identical receiving elements (optical antennas) are deployed and the output of each element is fed to a semiconductor optical amplifier (SOA). The role of the SOA is to improve the corresponding branch sensitivity and therefore enhance its resilience against fades. In the multi-branch setup of Fig. 1, the SOA outputs are applied to photodetectors (PD), where the photocurrent outputs are then linearly combined prior to signal detection. The combiner scales the signal from each PD by a gain factor prior to combining them. Adjustable gains are provided at each branch of the combiner, so as to implement the most popular combiner types (selection, equal-gain or optimal).

For the rest of the analysis, we assume that the received signals are identically distributed and statistically independent (*i.i.d.*) random variables. Note that, since the spatial coherence length of the atmospheric channel only measures a few centimetres, it follows therefore that the photodetectors only need to be separated by a few centimetres to achieve uncorrelated reception. Moreover, the channel stochastic response may follow log-normal, γ–γ or negative-exponential statistics, depending on the intensity of the fading. In this work we focus on γ–γ statistics that can be tailored to describe any fading scenario and the received power z_i at each branch is distributed according to [4], [22]

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

where $\overline{P}_{\text{in}}$ is the average input optical power at each SOA, $\Gamma(\cdot)$ and $K_v(\cdot)$ denote the Gamma and second kind modified Bessel functions, respectively, and m_x and m_y are γ–γ distribution parameters related to the effective numbers of large- and small-scale scatterers in the OWC link.

The received optical signals traverse the corresponding SOAs and receive a static gain equal to G. In addition, each SOA generates an optical noise component due to the amplified spontaneous emission (ASE), which is described by the ASE spectral density

$$P_n = n_{sp}\,h\,\frac{c}{\lambda}\,, \tag{2}$$

where c is the speed of light in a vacuum, h is the Planck constant, n_{sp} is the population inversion factor and λ denotes the wavelength. The optical signal and the ASE beat on the photodiodes (square-law detectors) of the receiver and as a result a number of electrical noise components will be present at the PD output [23], [24]. The associated noise variances are denoted as thermal, shot, signal-spontaneous beating and spontaneous-spontaneous beating, respectively, and are calculated from

$$\sigma_{th}^2 = \frac{4\,k_B\,T\,F_n\,B_e}{R_L}\,, \tag{3a}$$

$$\sigma_{shot}^2(z_i) = 2\,q\,R\,\left(G\,z_i + (G-1)\,P_n\,B_o\right)\,B_e\,, \tag{3b}$$

$$\sigma_{sig-sp}^2(z_i) = 4\,R^2\,G\,z_i\,(G-1)\,P_n\,B_e\,, \tag{3c}$$

and

$$\sigma_{sp-sp}^2 = R^2\,\left((G-1)\,P_n\right)^2\,(2\,B_o - B_e)\,B_e\,, \tag{3d}$$

where B_e and B_o are the electrical and optical bandwidths, 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. Given (3), the signal and noise powers for the '1' and '0' bits are directly given by

$$I_1(z_i) = R\,G\,z_i\,, \tag{4a}$$

$$\sigma_1^2(z_i) = \sigma_{th}^2 + \sigma_{shot}^2(z_i) + \sigma_{sig-sp}^2(z_i) + \sigma_{sp-sp}^2\,, \tag{4b}$$

and

$$I_0 = 0\,, \tag{5a}$$

$$\sigma_0^2 = \sigma_{th}^2 + \sigma_{shot}^2(0) + \sigma_{sp-sp}^2\,, \tag{5b}$$

respectively.

III. OUTAGE PROBABILITY AND AVERAGE BER

A. Selection Combiner

The SC samples all the received signals and selects the one with the highest irradiance level, therefore

$$z_{\mathrm{sc}} = \max z_i \,. \tag{6}$$

An outage occurs when all branches simultaneously experience a fade, and since the received signals are independent it follows that

$$\begin{aligned} P_{\mathrm{out,sc}} =& \prod_{i=1}^{L} \Pr\left\{BER\left(z_i\right) > BER_0\right\} \\ =& \Pr\left\{BER\left(z\right) > BER_0\right\}^L \,, \end{aligned} \tag{7}$$

where BER_0 is the desired BER level of the OWC system. Equivalently, one can calculate the outage probability from the receiver sensitivity P_{s}

$$P_{\mathrm{out,sc}} = \Pr\left\{z \le P_{\mathrm{s}}\right\}^L = \left(\int_0^{P_{\mathrm{s}}} f_{P_{\mathrm{in}}}(z)\, dz \right)^L \,, \tag{8}$$

which is obtained after solving

$$\frac{1}{2}\,\mathrm{erfc}\left(\frac{Q(P_{\mathrm{s}})}{\sqrt{2}}\right) = BER_0 \,. \tag{9}$$

The Q-factor of the receiver equals

$$Q(z) = \frac{I_1(z)}{\sigma_0 + \sigma_1(z)} \,, \tag{10}$$

assuming that each receiver is capable of estimating the channel state (CSI-capable) and setting its decision threshold on a bit-by-bit fashion to

$$I_{th}(z_i) = \frac{\sigma_0\, I_1(z_i)}{\sigma_0 + \sigma_1(z_i)} \,. \tag{11}$$

With respect to the average BER, it is calculated from the probability density function of z_{sc} as

$$\begin{aligned} \overline{BER}_{\mathrm{sc}} =& \int_0^\infty BER(z_{\mathrm{sc}})\, f_{\mathrm{sc}}(z_{\mathrm{sc}})\, dz_{\mathrm{sc}} \\ =& \frac{1}{2} \int_0^\infty \mathrm{erfc}\left(\frac{Q(z_{\mathrm{sc}})}{\sqrt{2}}\right) f_{\mathrm{sc}}(z_{\mathrm{sc}})\, dz_{\mathrm{sc}} \,. \end{aligned} \tag{12}$$

$f_{\mathrm{sc}}\left(z_{\mathrm{sc}}\right)$ is obtained by differentiating the cumulative distribution function of the SC

$$F_{\mathrm{sc}}\left\{z_{\mathrm{sc}} \le x\right\} = \Pr\left\{z \le x\right\}^L = \left(\int_0^{x} f_{P_{\mathrm{in}}}(z)\, dz \right)^L \,, \tag{13}$$

and the result is

$$f_{\mathrm{sc}}\left(z_{\mathrm{sc}}\right) = L \left(\int_0^{z_{\mathrm{sc}}} f_{P_{\mathrm{in}}}(z)\, dz \right)^{L-1} f_{P_{\mathrm{in}}}(z_{\mathrm{sc}}) \,. \tag{14}$$

After combining (12) and (14) we finally obtain

$$\begin{aligned} \overline{BER}_{\mathrm{sc}} =& \frac{L}{2} \int_0^\infty \mathrm{erfc}\left(\frac{Q(z_{\mathrm{sc}})}{\sqrt{2}}\right) \\ & \times \left(\int_0^{z_{\mathrm{sc}}} f_{P_{\mathrm{in}}}(z)\, dz \right)^{L-1} f_{P_{\mathrm{in}}}(z_{\mathrm{sc}})\, dz_{\mathrm{sc}} \,. \end{aligned} \tag{15}$$

B. Equal Gain Combiner

The EGC adds the electrical signals from all branches after providing a common gain. Assuming that the combiner is CSI-capable, the instantaneous BER is calculated as

$$BER\left(P_{\mathrm{egc}}\right) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q_{\mathrm{egc}}}{\sqrt{2}}\right) \,, \tag{16}$$

where Q_{egc} is the EGC Q-factor that equals

$$Q_{\mathrm{egc}} = \frac{\sum_{i=1}^{L} I_1(z_i)}{\sqrt{\sum_{i=1}^{L} \sigma_1^2(z_i)} + \sqrt{L\,\sigma_0^2}} \,. \tag{17}$$

Eq. (17) can be written in a simpler form as

$$Q_{\mathrm{egc}}\left(z_{\mathrm{egc}}\right) = Q_A \, \frac{z_{\mathrm{egc}}}{\sqrt{z_{\mathrm{egc}} + L\, z_0} + \sqrt{L\, z_0}} \,, \tag{18}$$

where

$$Q_A = \frac{R\, G}{\sigma_A} \,, \tag{19a}$$

$$\sigma_A^2 = 2\, q\, R\, G\, B_e \, + 4\, R^2\, G\, \left(G - 1\right)\, P_n\, B_e \,, \tag{19b}$$

$$z_0 = \frac{\sigma_0^2}{\sigma_A^2} , \tag{19c}$$

and

$$z_{\mathrm{egc}} = \sum_{i=1}^{L} z_i \tag{20}$$

is a random variable that is obtained from the sum of *i.i.d.* γ–γ variables. As a result, the performance evaluation of the EGC requires the knowledge of the pdf of z_{egc}, which can be derived by a number of techniques [25]–[27]. In this work, this pdf is calculated by the inverse Fourier transform of the characteristic function of the γ–γ distribution according to

$$F_{P_{\mathrm{in}}}(\omega) = \mathcal{F}\{f_{P_{\mathrm{in}}}(z)\}, \tag{21a}$$

$$f_{\mathrm{egc}}\left(z_{\mathrm{egc}}\right) = \mathcal{F}^{-1}\{F_{P_{\mathrm{in}}}(\omega)^L\} \,. \tag{21b}$$

Following (21), the EGC outage probability is given by

$$\begin{aligned} P_{\mathrm{out,egc}} =& \Pr\left\{z_{\mathrm{egc}} \le P_{\mathrm{s,egc}}\right\} \\ =& \int_0^{P_{\mathrm{s,egc}}} f_{\mathrm{egc}}\left(z_{\mathrm{egc}}\right)\, dz_{egc} \,, \end{aligned} \tag{22}$$

with the EGC sensitivity $P_{\mathrm{s,egc}}$ being calculated by

$$\frac{1}{2}\,\mathrm{erfc}\left(\frac{Q_{\mathrm{egc}}\left(P_{\mathrm{s,egc}}\right)}{\sqrt{2}}\right) = BER_0 \,. \tag{23}$$

Finally, the average BER is obtained in a straightforward manner from (18) and (21) as

$$\overline{BER}_{\mathrm{egc}} = \frac{1}{2}\int\limits_0^{\infty} \mathrm{erfc}\left(\frac{Q_{\mathrm{egc}}(z_{\mathrm{egc}})}{\sqrt{2}}\right) f_{\mathrm{egc}}(z_{\mathrm{egc}})\, dz_{\mathrm{egc}}\,. \tag{24}$$

C. Optimal Combiner

The optimal combiner provides unequal gains w_i to branches, thus the Q-factor can be written as

$$Q_{\mathrm{opt}} = \frac{\sum_{i=1}^{L} w_i\, I_1(z_i)}{\sqrt{\sum_{i=1}^{L} w_i^2\, \sigma_1^2(z_i)} + \sqrt{\sum_{i=1}^{L} w_i^2\, \sigma_0^2}}\,. \tag{25}$$

By using the definitions of (19) we re-write (25) as

$$Q_{\mathrm{opt}} = Q_A\, \frac{\sum_{i=1}^{L} w_i z_i}{\sqrt{\sum_{i=1}^{L} w_i^2\, (z_i + z_0)} + \sqrt{\sum_{i=1}^{L} w_i^2\, z_0}}\,. \tag{26}$$

Eq. (26) shows that the optimal combiner in pre-amplied OWC systems with diversity is fundamentally different from the optimal combiner in non-amplified systems (maximal ratio), due to the existence of the signal-spontaneous beating noise that grows with the signal itself. By differentiating with respect to the branch gains w_i, we find that the optimal gain values are given after solving

$$w_{i,opt}\left(\frac{z_i + z_0}{\sqrt{\sum_{i=1}^{L} w_{i,opt}^2\, (z_i + z_0)}} + \frac{z_0}{\sqrt{\sum_{i=1}^{L} w_{i,opt}^2\, z_0}}\right) = z_i\, \frac{\sqrt{\sum_{i=1}^{L} w_{i,opt}^2\, (z_i + z_0)} + \sqrt{\sum_{i=1}^{L} w_{i,opt}^2\, z_0}}{\sum_{i=1}^{L} w_{i,opt} z_i}\,. \tag{27}$$

Some insight on the optimal solution can be obtained when the signal-noise beating term dominates ($z_i \gg z_0$), in which case all branch gains become equal and the optimal combiner reverts to an EGC. On the other hand, the optimal combiner will perform similar to an MRC with $w_{i,opt} = z_i/z_0$ whenever the signal experiences an intense fade ($z_i \ll z_0$).

Eq. (27) can not be solved in a closed form and it is challenging to analytically calculate the corresponding Q-factor. Still, we may approximate the optimal combiner operation and provide an upper bound for its Q-factor based on the Cauchy-Schwarz inequality. This results in

$$Q_{\mathrm{opt}} \leq Q_A \sqrt{\sum_{i=1}^{L} z_i}\; \frac{\sqrt{\frac{\sum_{i=1}^{L} w_i^2\, z_i}{\sum_{i=1}^{L} w_i^2}}}{\sqrt{\frac{\sum_{i=1}^{L} w_i^2\, z_i}{\sum_{i=1}^{L} w_i^2} + z_0} + \sqrt{z_0}}\,, \tag{28}$$

and since

$$\sqrt{\frac{\sum_{i=1}^{L} w_i^2\, z_i}{\sum_{i=1}^{L} w_i^2}} \leq \sqrt{\max z_i}\,, \tag{29a}$$

$$\sqrt{\sum_{i=1}^{L} z_i} \leq \sqrt{L\, \max z_i}\,, \tag{29b}$$

an upper bound for the Q-factor of the optimal combiner is given by

$$Q_{\mathrm{opt}} \leq Q_A\, \frac{\sqrt{L\, \max z_i}\, \sqrt{\max z_i}}{\sqrt{\max z_i + z_0} + \sqrt{z_0}}\,. \tag{30}$$

Following the above, the optimal combiner will perform within the limits that are set by EGC (lower bound) and a non-realizable combiner (upper bound) with

$$Q_{\mathrm{opt}}^{'}\left(z_{\mathrm{opt}}^{'}\right) = Q_A \sqrt{L\, z_{\mathrm{opt}}^{'} + L\, z_0} - \sqrt{L\, z_0}\,, \tag{31a}$$

$$z_{\mathrm{opt}}^{'} = \max z_i\,. \tag{31b}$$

Moreover, since both Q_{opt} and $Q_{\mathrm{opt}}^{'}$ are positive and increasing functions of z_i, the inequality of (31) leads to the conclusion that any channel state $\mathbf{z}$ which brings the non-realizable combiner into outage will also lead the optimal combiner into an outage. A lower limit for the outage probability of the optimal combiner is then calculated by

$$\begin{aligned} P_{\mathrm{out,opt}} \geq & P_{\mathrm{out,opt}}^{'} = \Pr\left\{z_{\mathrm{opt}}^{'} \leq P_{\mathrm{s,opt}}^{'}\right\} \\ & = \Pr\left\{z \leq P_{\mathrm{s,opt}}^{'}\right\}^L = \left(\int\limits_0^{P_{\mathrm{s,opt}}^{'}} f_{P_{\mathrm{in}}}(z)\, dz\right)^L, \end{aligned} \tag{32}$$

with $P_{\mathrm{s,opt}}^{'}$ being the combiner sensitivity that is given by

$$\frac{1}{2}\,\mathrm{erfc}\left(\frac{Q_{\mathrm{opt}}^{'}(P_{\mathrm{s,opt}}^{'})}{\sqrt{2}}\right) = BER_0\,. \tag{33}$$

The BER of the non-realizable combiner is also superior than the BER of the optimal combiner for any possible channel state. The average BER is then bound by

$$\begin{aligned} \overline{BER}_{\mathrm{opt}} \geq & \overline{BER}_{\mathrm{opt}}^{'} \\ = & \frac{1}{2}\int\limits_0^{\infty} \mathrm{erfc}\left(\frac{Q_{\mathrm{opt}}^{'}(z_{\mathrm{opt}}^{'})}{\sqrt{2}}\right) f_{\mathrm{opt}}^{'}(z_{\mathrm{opt}}^{'})\, dz_{\mathrm{opt}}^{'}\,. \end{aligned} \tag{34}$$

The pdf of $z_{\mathrm{opt}}^{'}$ has been previously calculated in (14) and we finally find that

$$\begin{aligned} \overline{BER}_{\mathrm{opt}} \geq & \frac{L}{2}\int\limits_0^{\infty} \mathrm{erfc}\left(\frac{Q_{\mathrm{opt}}^{'}(z_{\mathrm{opt}}^{'})}{\sqrt{2}}\right) \\ & \times \left(\int\limits_0^{z_{\mathrm{opt}}^{'}} f_{P_{\mathrm{in}}}(z)\, dz\right)^{L-1} f_{P_{\mathrm{in}}}(z_{\mathrm{opt}}^{'})\, dz_{\mathrm{opt}}^{'}\,. \end{aligned} \tag{35}$$

TABLE I
SYSTEM PARAMETERS

Parameter	Symbol	Value
γ–γ parameter	m_x	5.93
γ–γ parameter	m_y	1.99
SOA gain	G	20 dB
Wavelength	λ	1550 nm
Population inversion factor	n_{sp}	4.0
Optical bandwidth	B_o	50 GHz
Photodiode responsivity	R	1.25 A/W
Receiver temperature	T	300^o K
Resistor load	R_L	$100\,\Omega$
Electrical noise figure	F_n	3 dB
Electrical bandwidth	B_e	7 GHz

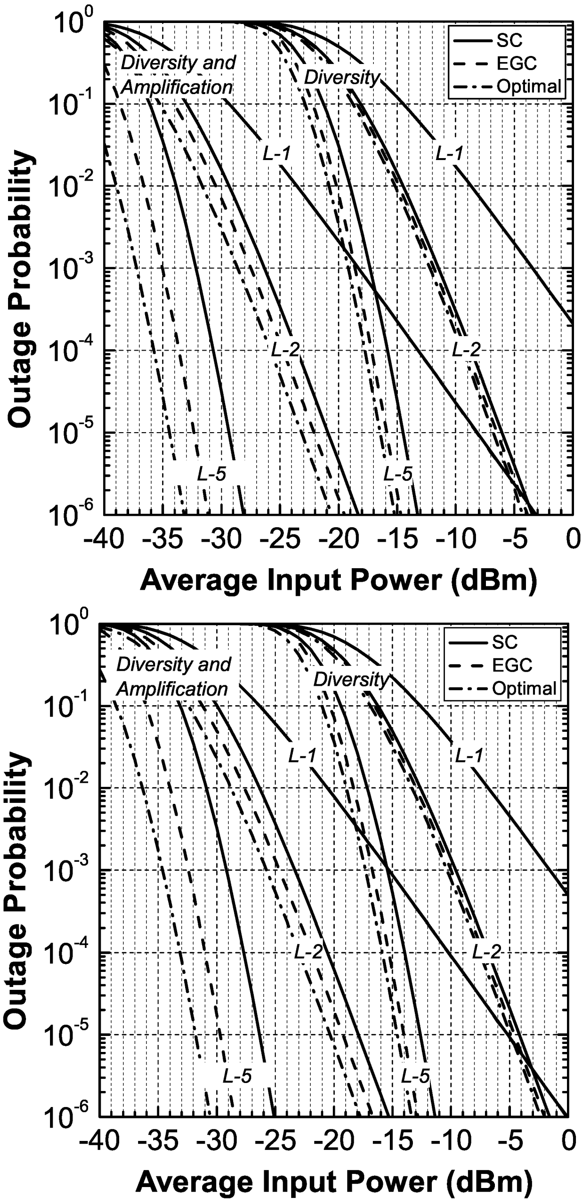

Fig. 2. Outage probability versus the average input power for $BER_0 = 10^{-3}$ (top) and $BER_0 = 10^{-6}$ (bottom).

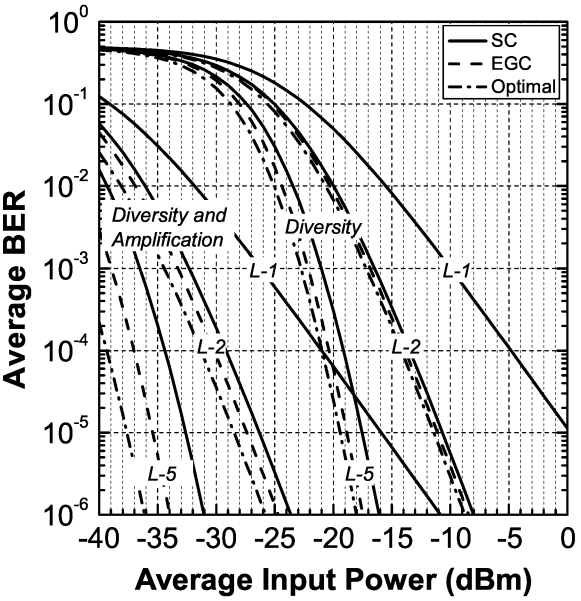

Fig. 3. Average BER versus the average input power.

IV. RESULTS AND DISCUSSION

The performance of the SOA-assisted diversity setup is investigated for a 250 m optical wireless link in the presence of medium-to-strong γ–γ fading. The channel, SOA and receiver parameter values that are used for the analytical results are summarized in Table I. Fig. 2 illustrates the outage probability of the proposed setup for $L = 1, 2$ and 5 diversity branches and required BERs of 10^{-3} and 10^{-6}. The outage probability of a system that relies solely on diversity is also plotted in the figure for comparison purposes. As shown in Fig. 2, both amplification and diversity offer a significant link gain, while the combination of the two methods amounts to a gain of over $25-30$ dB depending on the required BER, the desired outage probability and the number of receiving elements. Similar conclusions can be deducted from the average BER plots in Fig. 3, where a link margin of the same magnitude is predicted for the pre-amplified system with diversity.

The results also suggest that the optimal combiner outperforms the SC by a significant degree, while the EGC and the optimal combiner perform closely in terms of the outage probability and the average BER. Following Figs. 2 and 3, the maximum link gain that can be expected from using an optimal combiner instead of an EGC in a SOA-assisted system amounts to 1 or 2 dB, depending on the number of the receivers. This behavior owes to the presence of the signal dependent component in the receiver noise variance. Any attempt to non-linearly increase the signal in non-faded branches of the optimal combiner, as would happen in an system where the noise variance is constant and MRC is the optimal combiner, will also increase the noise by approximately the same amount, leaving the branch SNR almost constant. The actual optimal combiner gain with respect to EGC primarily comes from fade-impaired branches; their contribution is tuned down in the optimal combiner, in contrast with the EGC which would still provide them with full gain.

The preceding arguments, as well as the presented results, indicate that the extra benefit that is gained from deploying an optimal combiner is only significant when a large number of receivers is used. For more modest setups, the additional complexity that is introduced in the electronic domain from an optimal combiner may not justify using it over an EGC that is much simpler to implement. The same argument holds for less turbulent links, where the expected number of branches that are simultaneously in a fade state decreases and in this regime the EGC will be performing even closer to the optimal combiner. On the other hand, if the fading conditions become worse then the optimal combiner is expected outperform the EGC to a greater extend. A quantitative analysis of more intense fading conditions is beyond the scope of this work, but can be performed in a straightforward manner from the analytical relations by modifying the γ–γ distribution parameters or replacing the γ–γ distribution with a negative exponential.

V. CONCLUSION

We have presented an analytical description of the outage probability and the average BER in pre-amplified OWC systems with multiple receivers. Based on the analytical model, we derived for the first time to our knowledge results on an electronic combiner that optimizes the BER performance of the system. The presented results show that the optimal combiner performs closely, but not identically, to an EGC for a limited number of receivers in medium turbulence conditions. The optimal combiner is potentially better suited to systems with a large number of elements or operating under more intense fading.

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