First Order Statistics of Semiconductor Optical Amplifier Assisted Optical Wireless Systems under Log-normal Fading

A.C. Boucouvalas, N.C. Sagias and K. Yiannopoulos
Department of Telecommunications Science and Technology
University of Peloponnese
Terma Karaiskaki, Tripoli 22100, Greece
{acb, nsagias, kyianno} @uop.gr

***Abstract*—In this paper, we evaluate the utilization of a semiconductor optical amplifier (SOA) at the receiver of an outdoor optical wireless system for fade mitigation purposes. Due to its instantaneous gain response, the SOA provides saturating gain to incoming pulses and partially alleviates power variations between fade impaired and non-impaired instances of the received signal. We discuss this unbalanced SOA operation and analytically derive the first order statistics of the optical signal at the SOA output, giving emphasis on the scintillation index and the fade probability. Our results show that both the scintillation index and the fade probability are improved significantly by deploying the SOA, when the system operates in the weak turbulence regime.**

Keywords-Outdoor optical wireless, Semiconductor Optical Amplifiers, Fade Mitigation, Scintillation Index, Fade Probability.

I. Introduction

Outdoor optical wireless communication (OWC) systems are envisaged as a viable alternative for implementing low-cost, semi-permanent broadband connections in last-mile applications, for example enterprise local-area-networks or office interconnects, as well as metro area networks [1]. A key challenge, however, in implementing these systems is associated with the propagation of light through the atmosphere, since its volatile nature induces a number of impairments on the OWC signal, including static and time-dependent power losses, beam steering and beam de-coherence [2]-[4]. As a result, the received signal power exhibits power fluctuations (scintillations) that can lead to severe degradation of the OWC system performance or even outage, and a number of techniques have been proposed so as to limit scintillations and their impact. These include aperture averaging [5], [6], spatial and temporal diversity [7]-[12], coding [12]-[16] and signal equalization in semiconductor optical amplifiers [17].

Signal equalization in SOAs is a promising candidate for mitigating the impact of scintillations in high-capacity OWC systems [17] due to the SOA ultra-fast gain recovery time, which can be lower than 100 psec for commercially available devices. This allow for SOA operation at link speeds of up to 10 Gb/s and in a previous work we have discussed the applicability of utilizing a SOA at the OWC system receiver so as to minimize turbulence induced fading [18]. We have also demonstrated that the SOA makes it is possible to significantly enhance first and second order signal statistics, including the fade probability and average fade duration, when the OWC channel operates under medium-to-strong turbulence (gamma-gamma statistics). In the current work, we focus on SOA-assisted OWC systems that operate under weak turbulence conditions and derive a mathematical framework that allows for the calculation of OWC link metrics such as the scintillation index and the fade probability. Furthermore, we utilize this framework to demonstrate that a decrease of 70%-80% is achieved on the scintillation index at the SOA output as compared to the uncompensated system. Finally, we show that the fade probability is also improved at the SOA-assisted system and this corresponds to an improvement on the dynamic range of the receiver by 5 dB or more, depending on acceptable fade probability level.

II. Principle of Operation and Mathematical Formulation

The proposed setup utilizes SOA before the electronic receiver at the OWC system, as shown in Fig. 1. The SOA gain is saturated by incoming optical pulses and, due to the instantaneous gain response of the amplifier, the degree of saturation is determined by the power of each respective pulse. As a result, an unimpaired pulse deeply saturates the SOA and receives very limited gain, while, on the other hand, a fade-impaired pulse saturates the SOA gain only partially and receives a sizeable amount of gain. Provided that gain recovery time of the SOA is limited to less than the bit period, this unbalanced operation serves to alleviate power fluctuations at the SOA output and therefore provide partial compensation for the stochastic channel response.

To better illustrate the equalization capabilities of the SOA, we aim to derive the probability density function (pdf) of the signal power at the output of the SOA, assuming that the OWC system operates under weak turbulence and therefore the input signal power follows log-normal statistics given by

978-1-4799-1188-2/13/$31.00 ©2013 IEEE

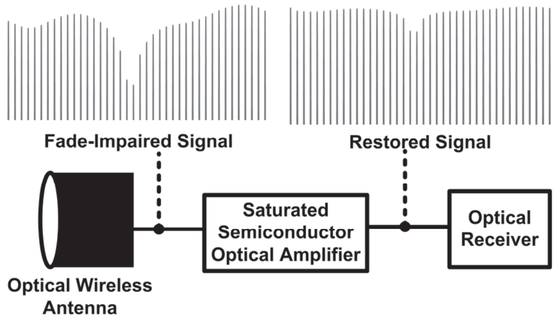

Figure1. SOA-assisted fade equalization.

$$f\left(P_{in}\right)=\frac{1}{\sqrt{2\pi}\cdot\sigma\cdot P_{in}}\cdot\exp\left[-\frac{\left(\log P_{in}-\mu\right)^{2}}{2\cdot\sigma^{2}}\right]. \quad (1)$$

μ is the mean log-intensity and σ is the log-intensity standard deviation that relates to the scintillation index σ_v of the OWC channel as

$$\sigma^{2}=\log\left(1+\sigma_{v}^{2}\right). \quad (2)$$

We have also detailed in a previous work that the pulse power at the SOA output P_{out} relates to its input power P_{in} as [18]

$$\exp\left(\frac{P_{out}}{P_{s}}\right)-1=G_{0}\cdot\left(\exp\left(\frac{P_{in}}{P_{s}}\right)-1\right), \quad (3)$$

where G_0 is the small signal gain of the SOA and P_s is the rate-dependent saturation parameter

$$P_{s}=\frac{U_{sat}}{T_{b}}. \quad (4)$$

U_{sat} is the saturation energy of the SOA and T_b is the bit period of the OWC system.

The pdf of the signal power at the SOA output is then calculated after performing the change of variables of (1) in the log-normal pdf of (3), and the resulting pdf is shown in (5). For discussion purposes, we further simplify (5) by defining the normalization parameters r (normalized average input power) and u (normalized output power)

$$r=\frac{E\{P_{in}\}}{P_{s}}=\frac{\exp\left(\mu+\frac{\sigma^{2}}{2}\right)}{P_{s}},$$
$$u=\frac{P_{out}}{E\{P_{in}\}}=\frac{P_{out}}{\exp\left(\mu+\frac{\sigma^{2}}{2}\right)}, \quad (6)$$

to finally obtain the normalized pdf at the SOA output in (7).

III. Scintillation Index and Fade Probability Analysis

The performance enhancement that is achieved by the SOA deployment will be presented in terms of the attainable scintillation index and the fade probability of the signal at the SOA output. The scintillation index of the signal at the SOA output σ_u is calculated from the relation

$$\sigma_{u}=\frac{\sqrt{u_{rms}^{2}-u_{mean}^{2}}}{u_{mean}}. \quad (8)$$

The mean (u_{mean}) and root-mean-square (u_{rms}) values of the normalized output power are obtained numerically after integrating (7) and the results are shown in Fig. 2 against the normalized input power r for SOAs with 20 and 30 dB gains. The scintillation index of the input signal σ_v^2 is set to values below 0.3, so as to remain within the weak turbulence regime.

$$f\left(P_{out}\right)=\frac{e^{\frac{P_{out}}{P_{s}}}}{\sqrt{2\pi}\cdot\sigma\cdot P_{s}\cdot\log\left(\frac{G_{0}-1+e^{\frac{P_{out}}{P_{s}}}}{G_{0}}\right)\cdot\left(G_{0}-1+e^{\frac{P_{out}}{P_{s}}}\right)}\cdot\exp\left(-\frac{\left(\log\left(P_{s}\cdot\log\left(\frac{G_{0}-1+e^{\frac{P_{out}}{P_{s}}}}{G_{0}}\right)\right)-\mu\right)^{2}}{2\cdot\sigma^{2}}\right) \quad (5)$$

$$f_{u}\left(u\right)=\frac{r\cdot e^{r\cdot u}}{\sqrt{2\pi}\cdot\sigma\cdot\log\left(\frac{G_{0}-1+e^{r\cdot u}}{G_{0}}\right)\cdot\left(G_{0}-1+e^{r\cdot u}\right)}\cdot\exp\left(-\frac{\left(\log\left(\frac{\log\left(\frac{G_{0}-1+e^{r\cdot u}}{G_{0}}\right)}{r}\right)+\frac{\sigma^{2}}{2}\right)^{2}}{2\cdot\sigma^{2}}\right) \quad (7)$$

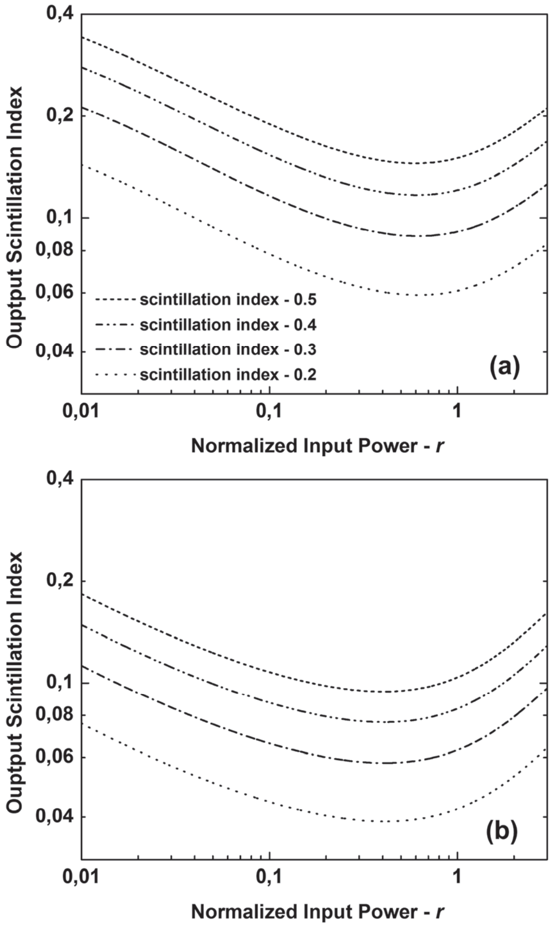

Figure 2. Scintillation index the output of the SOA versus the normalized input power r. The SOA small signal gain G_0 equals 20 dB (top) and 30 dB (bottom).

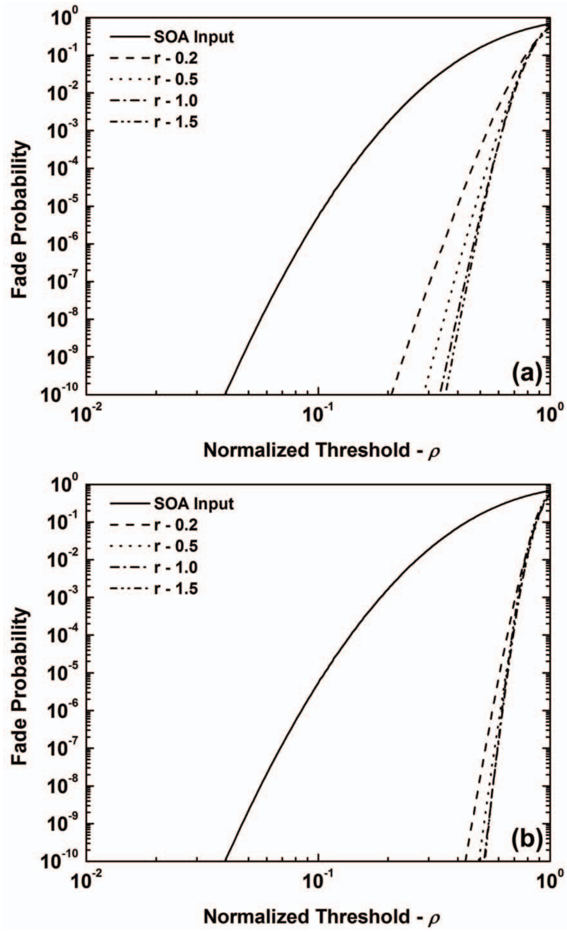

Figure 3. Fade probability the output of the SOA versus the normalized power threshold ρ. The SOA small signal gain G_0 equals 20 dB (top) and 30 dB (bottom). The scintillation index σ_I equals 0.5.

The results show that the SOA output scintillation index is significantly decreased and that a reduction of over 70% is observed for a 20 dB small-signal gain SOA, provided that the normalized average input power remains around 0.6. A similar behavior is observed for a 30 dB small-signal gain, as well, where the scintillation index is reduced by at least 80% for normalized input powers around 0.4. Consequently, the SOA can provide a very significant enhancement on the scintillation index, but the degree of enhancement strongly depends on its level of saturation and the average input power should be set around 40%-60% of the saturation parameter P_s to achieve optimal performance. The existence of a power optimal operation point is to be expected from the underlying gain response, since the SOA cannot provide unbalanced gain at very low or very high normalized input powers r. In the former case, the SOA performs almost linearly and provides gain equal to G_0 to all pulses, while in the latter it is always saturated and provides gain equal to $\log G_0$. Given that all pulses receive the same gain in these two extremes, it is not possible to modify the relative power fluctuations and the scintillation index must remain unchanged as r reaches zero or tends to infinity. This trend can be verified from the results of Fig. 2, where the output scintillation index increases monotonically as r deviates from its optimal value.

As far as the fade probability is concerned, it can be analytically calculated from (7) as

$$p_R = p(u < u_R) = \int_0^{u_R} f_u(u)\cdot du = \\ = \frac{1}{2}\cdot\left(1+\operatorname{erf}\left(\frac{\sigma^2 + 2\cdot\log\left(\frac{\log\left(\frac{G_0 - 1 + e^{r\cdot u_R}}{G_0}\right)}{r}\right)}{2\sqrt{2}\cdot\sigma}\right)\right), \tag{9}$$

where *erf* denotes the error function. Eq. (9) is plotted in Fig. 3 against the normalized threshold, defined as

$$\rho = \frac{u_R}{u_{rms}}, \tag{10}$$

so as to have a fair comparison between the unequal average power stochastic signals at the input and the output of the SOA. The results show that the percentile power threshold in the SOA-assisted system is significantly higher than that of the original system for any given fade probability, and consequently the former system requires a more limited dynamic range. For example, if the fade probability is set to 10^{-3} then the dynamic range of the receiver is reduced by approximately 4 dB for a 20 dB small signal gain SOA, while an additional reduction of 1 dB is achieved if the SOA gain is increased to 30 dB. Moreover, an increasing benefit is observed from utilizing a high gain SOA at even lower fade probabilities, and a dynamic range reduction of approximately 7 and 9 dB is observed when the fade probability is lowered to 10^{-6} and 10^{-9}, respectively.

A closing remark relates to the dependence of the dynamic range on the normalized input power r. Fig. 3 shows that the required power threshold increases with the input power, but this trend saturates for power levels beyond the SOA saturation energy. It can be verified from the figure that the fade probability plots practically coincide for powers r above 1.0 for a 20 dB SOA and 0.5 for a 30 dB SOA, and that there is no real benefit from increasing power levels beyond this limit. This is in close agreement with the results that are obtained for the scintillation index, where similar power levels are predicted for optimal system operation. It should also be noted that, in contrast with the results presented for the scintillation index, the fade probability always improves with increasing input powers. This behavior seems counter-intuitive at first, since one would expect that an increase in the scintillation index will lead to an increase in the fade probability as well. Still, the statistics of the signal at the SOA output vary significantly from the original log-normal, according to (6), and each power level r results in a different shape probability density function. Consequently, it is not possible to directly relate the scintillation index with the fade probability, but the exact correlation is determined in a unique fashion by the power level r.

IV. CONCLUSION

We have presented an analytical model for assessing the fade equalization capabilities of a SOA when deployed in an OWC system that is affected by weak turbulence. We have utilized the analytical model to calculate the system improvement that can be achieved in terms of scintillation index and fade probability. The results show a drastic decrease of over 70% is to be expected on the scintillation index, while in the same time fades become far less probable. Following this, it possible to increase the power threshold of the SOA-assisted OWC system, and therefore reduce the dynamic range of its receiver, by at least 5 dB as compared to the original non-equalized setup. Finally, we have utilized the results to derive the operational conditions that optimize the SOA performance and we have demonstrated that optimal performance is achieved when the input power lies in a range within 50%-100% of the SOA saturation parameter.

ACKNOWLEDGMENT

Part of this work was supported by COST Action IC1101 "Optical Wireless Communications - An Emerging Technology."

REFERENCES

[1] Q. Liu, C. Qiao, G. Mitchell, and S. Stanton, "Optical wireless communication networks for first- and last-mile broadband access [Invited]," *OSA J. Opt. Netw.* 4, 807-828 (2005).

[2] V.W.S. Chan, "Free-Space Optical Communications," *IEEE/OSA J. Lightwave Technol.*, vol. 24, no. 12, pp. 4750 – 4762, December 2006.

[3] R.S. Lawrence, and J.W. Strohbehn, "A survey of clear-air propagation effects relevant to optical communications," in *Proc. IEEE* 58, 1523-1545, 1970.

[4] L. C. Andrews, and R. L. Phillips, Laser beam propagation through random media, 2nd edition 2005, SPIE Press, Bellingham, Washington.

[5] H. Yuksel, S. Milner, and C.C. Davis, "Aperture averaging for optimizing receiver design and system performance on free-space optical communication links," *OSA J. Opt. Net.*, 4 (8), pp. 462 - 475, 2005.

[6] M.-A. Khalighi, N. Schwartz, N. Aitamer, and S. Bourennane, "Fading Reduction by Aperture Averaging and Spatial Diversity in Optical Wireless Systems," *OSA J. Opt. Commun. Net.*, 1, 580-593 (2009).

[7] S.G. Wilson, M. Brandt-Pearce, Q. Cao, and M. Baedke, "Optical repetition MIMO transmission with multi-pulse PPM," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 9, pp. 1901-1910, Sept. 2005.

[8] S.M. Navidpour, M. Uysal, and M. Kavehrad, "BER performance of free-space optical transmission with spatial diversity," *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 2813-2819.

[9] A. Goldsmith, S.A. Jafar, N. Jindal, and S. Vishwanath, "Capacity limits of MIMO channels," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 5, pp. 684-702, June 2003.

[10] A. García-Zambrana, C. Castillo-Vázquez, and B. Castillo-Vázquez, "Outage performance of MIMO FSO links over strong turbulence and misalignment fading channels," *OSA Opt. Exp.*, 19, 13480-13496 (2011).

[11] S. Trisno, I.I. Smolyaninov, S.D. Milner, and C.C. Davis, "Delayed diversity for fade resistance in optical wireless communication system through simulated turbulence," in *Proc. SPIE Optical Transmission Systems and Equipment for WDM Networking III*, vol. 5596, pp. 385-393, 2005.

[12] J.A. Greco, "Design of the High-Speed Framing, FEC, and Interleaving Hardware Used in a 5.4 km Free-Space Optical Communication Experiment," in *Proc. SPIE Free-space Laser Communications IX,* vol. 7464, 2009.

[13] X. Zhu and J. M. Kahn, "Performance Bounds for Coded Free-Space Optical Communications through Atmospheric Turbulence Channels," *IEEE Trans. Commun.*, 51, 1233-1239, 2003.

[14] I.B. Djordjevic, "LDPC-coded MIMO optical communication over the atmospheric turbulence channel using Q-ary pulse-position modulation," *OSA Opt. Exp*, 15, 10026-10032 (2007).

[15] H. Henniger, F. David, D. Giggenbach, and C. Rapp, "Evaluation of FEC for the atmospheric optical IM/DD channel," *in Proc. SPIE Free-Space Laser Communication Technologies XV*, vol. 4975, 2003.

[16] A. Anguita, M. A. Neifeld, B. Hildner, and B. Vasic, "Rateless Coding on Experimental Temporally Correlated FSO Channels," *IEEE/OSA J. Lightwave Technol.*, vol. 28, no. 7, pp. 990-1002, April 2010.

[17] M. Abtahi, P. Lemieux,W. Mathlouthi, and Leslie Ann Rusch, "Suppression of Turbulence-Induced Scintillation in Free-Space Optical Communication Systems Using Saturated Optical Amplifiers, *IEEE/OSA J. Lightwave Technol.*, vol. 24, no. 12, pp. 4966-4973, December 2006.

[18] K. Yiannopoulos, N.C. Sagias, and A.C. Boucouvalas, "Fade Mitigation Based on Semiconductor Optical Amplifiers," submitted to *IEEE J. Lightwave Technol.*