Statistical Characterization of Bit Patterning in SOAs: BER Prediction and Experimental Validation

Amirhossein Ghazisaeidi,[1] Francesco Vacondio,[1] Alberto Bononi,[2] and Leslie Ann Rusch[1,*]
[1]Center for optics, photonics and lasers (COPL), Dept. of Electrical and Computer Engineering, Université Laval, G1V 0A6, Canada
[2]Dipartimento di ingegneria dell'informazione, Università di Parma, 43100 Parma, Italy
[*]Corresponding author: leslie.rusch@gel.ulaval.ca

Abstract: We present a novel simulation tool for optical systems employing in-line nonlinear SOAs, able to correctly estimate the bit error rate even in the presence of significant SOA-induced intersymbol interference.

OCIS codes: (060.2330) Fiber optics communications

1. Introduction

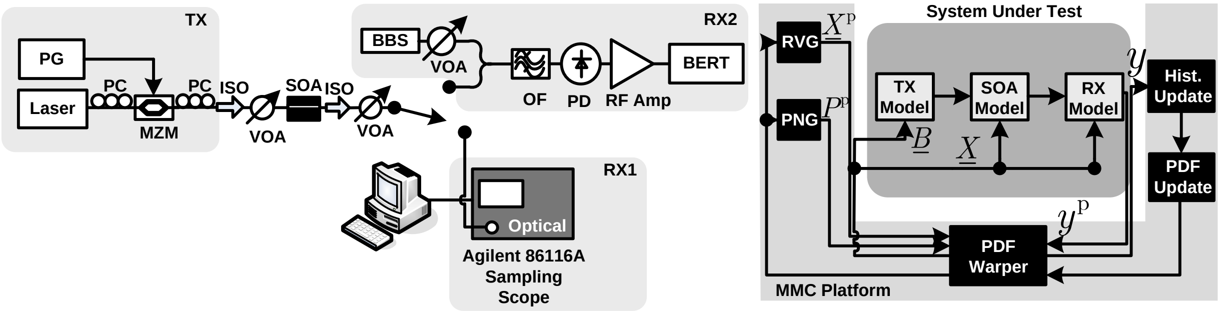
As a versatile and potentially cost-effective functional block, the semiconductor optical amplifier (SOA) is now a key component in many solutions proposed for wavelength conversion [1], all-optical regeneration [2], and in-line amplification [3]. Accurate estimation by simulation of low bit-error-rates (BER) down to 10^{-10} in optical links incorporating SOAs may require prohibitively long simulation times, since the SOA is a complex nonlinear element with memory. The pattern-induced inter-symbol interference (ISI) due to SOA finite memory can significantly affect the precision of the BER estimation, and an accurate evaluation of such memory is essential. For a given SOA, the pattern-induced ISI is most prominent when the bit duration is comparable to the SOA's carrier lifetime [4]. While increasing the bit-rate beyond this value results in almost pattern-free operation, this is not the case with SOA-MZI structures, where the phase dynamics of the SOA and the phase-to-intensity conversion result in pattern-dependent operation even at very high bit-rates [5].

Although the Karhunen-Loeve semi-analytic method [6] for performance analysis of optical links considers the ISI from the optical and electrical filters, it cannot account for any nonlinearity other than the square-law photodetector. The interaction between signal and the SOA ASE is also not captured by this semi-analytic method. While Monte Carlo methods can capture these nonlinear interactions, the complexity of SOA dynamics makes simple Monte-Carlo-based simulations prohibitively long. Some authors have proposed to use instantaneous nonlinear elements to model in-line SOAs [7], or "nonlinearity + filter" models borrowed from optoelectronic regenerators [8], but such methods lack precision.

In this paper, for the first time to our knowledge, we introduce a simulation tool able to correctly estimate the conditional probability density functions (PDFs) of received marks and spaces, and thus the BER, of a large-memory optical system containing in-line SOAs operating in the highly nonlinear regime at 10 Gb/s. To overcome computational complexity, we use the Multicanonical Monte-Carlo (MMC) algorithm equipped with a new pattern warping technique to accurately treat the ISI [9]. We introduce an experimental technique to probe the memory depth of the SOA-based system and to measure the conditional PDFs to calibrate and cross-validate the simulations.

2. Description of System under Test and Simulator

Fig. 1a illustrates the experimental set-up of our case-study optical link. The output light of an externally modulated semiconductor laser is boosted by an SOA and then received by a conventional 10 Gb/s PIN-based optical receiver, where the BER is measured (RX2). The optical filter bandwidth was 30 GHz. The SOA-boosted signal could also be observed on an Agilent 86116A sampling scope (RX1) where after off-line processing the conditional PDFs were measured. Fig. 1b shows the block diagram of the corresponding simulator, where the system under test is a time-domain numerical model of the link shown in Fig. 1a. The TX model subsystem accepts logical ones and zeros and constructs a band-limited bit-stream waveform by filtering the ideal bit stream with a fourth-order Bessel-Thompson filter (BT4) of bandwidth 8 GHz. The BT4 was chosen because of the low ringing of its step response. The Mach-Zehnder modulator (MZM) was modeled as in [10], and its four-dimensional parameter set was exhaustively searched to find the best mean-square fit between a measured training sequence and its simulated version. The SOA was simulated using the Cassioli-Mecozzi model [11], with ten sections. ASE was modeled as an input equivalent white noise source and its power was treated as a fitting parameter to match the experimental PDFs. Ultrafast terms in the SOA response were neglected. The receiver model was an ideal square-law device with additive Gaussian

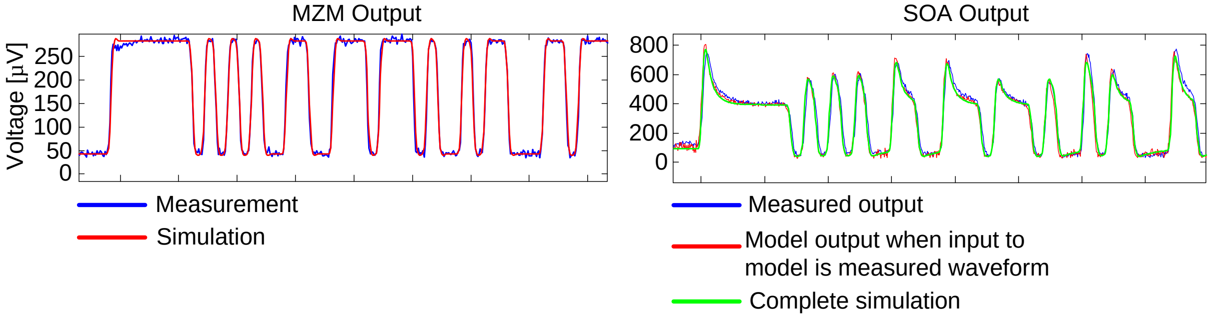


(a) (b)

Fig. 1 a) Experimental setup, b) simulator block diagram; PG: pattern generator, PC: polarization controller, MZM: Mach-Zehnder modulator, ISO: isolator, VOA: variable optical attenuator, BBS: broadband source, OF: optical filter, PD: photodetector, BERT: BER tester, RVG: random vector generator, PNG: pattern number generator.

noise. Fig. 2 illustrates the MZM and SOA output waveforms when RX1 was used, and attests to the excellent fit between experiment and simulation.

Fig. 1b makes reference to our use of an MMC platform that adaptively warps both the noise ***and the bit pattern*** to favor low probability events. Details of this computational method are presented in [9]. The random vector generator (RVG) and the pattern number generator (PNG) are two independent Metropolis-Hastings machines. During each MMC cycle, the RVG proposes the noise vector $\underline{X}^P$, and the PNG proposes pattern number P^P to the pattern warper module, which in turn decides the random vector $\underline{X}$, and bit pattern vector $\underline{B}$ that should be fed into the system under test. $\underline{B}$ is a binary vector of length M equal to the memory depth in number of bits. The MMC is run for multiple cycles until the desired resolution in the BER is achieved.



(a) (b)

Figure 2: measured and simulated waveforms at the output of TX model, and SOA model. The noise sources in the simulator were turned off, and the scope averaging function was turned on to facilitate waveform matching.

3. Probing the memory depth of the SOA

To determine the effective memory length M of the SOA we resort to measurement of the conditional PDFs of received marks and spaces. Estimating the conditional PDFs (one for marks and one for spaces) requires the transmitted bits be captured, synchronized and processed. To this end, we construct a “packetized De Bruijn sequence”, *i.e.*, a De Bruijn sequence of length 2^M preceded by a header comprised of N_1 ones followed by N_0 zeros. We transmit 1000 packets, record the received packets, and process them off-line to calculate the conditional PDFs. The first trace in Fig. 3a illustrates the received packet for M=7; next the offline processing is shown: the packet is zero-averaged and then filtered by a moving average filter of length $N_1>M$. The peak of the resulting signal occurs at the one-to-zero transition edge of the packet header, and consequently the transmitted packet can be reconstructed error-free as shown in the final trace of Fig.3a. Both N_1 and N_0 should be longer than the “true” memory depth Experimentally N_1 is chosen by trial and error, and N_0 is chosen such that the pulse overshoots at the beginning of the header and at the beginning of the DeBruijn have the same level. The marks and spaces are then sampled at any desired sampling point within the bit and the histograms are calculated. Fig. 3b shows the measured conditional PDFs for M=3, 5, and 7. Convergence of the two latter PDFs tells us that M=7 is a reliable estimate of the SOA memory depth in our experiment.

4. PDF and BER predictions

Fig. 4a illustrates measured and simulated conditional PDFs of marks and spaces corresponding to *M*=7, when RX1 was used as the receiver. The measured PDFs are the same as the ones shown in Fig. 3b. The average input power to the SOA was set to -2.65 dBm, resulting in deep saturation, and the bit-rate was 10 Gb/s. 20 samples per bit were taken, and the PDFs were calculated at the middle of the bit. Five MMC cycles of 10^5 samples each were executed, with 71 seconds of simulation time per cycle. Only the PDFs corresponding to the last cycle are shown. Fig. 4b shows measured and simulated BERs when RX2 was used as the receiver. The SOA average input power and the bit-rate were set as in the previous case. For BER measurements, two MMC simulations were run for each point in the BER curve; the BER was computed by integrating the overlapping tails of the two estimated conditional PDFs. Each conditional PDF was estimated by seven MMC iterations, to improve the accuracy. In the inset of Fig. 4b is shown an eye diagram for high OSNR, manifesting a strong patterning effect from the SOA. Also shown in the inset is the set of estimated conditional PDFs used to calculate each BER point.

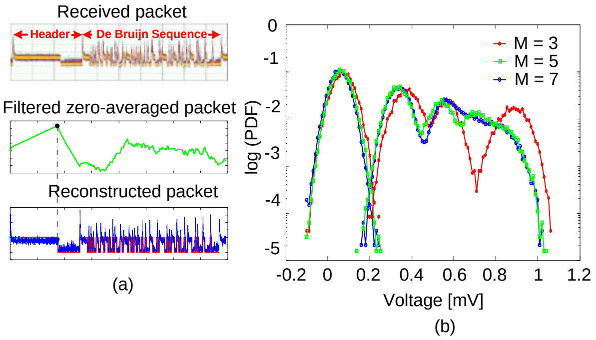


Fig. 3 a) Experimental technique to probe the memory depth of the SOA, and b) measured conditional PDFs for various De Bruijn sequence lengths.

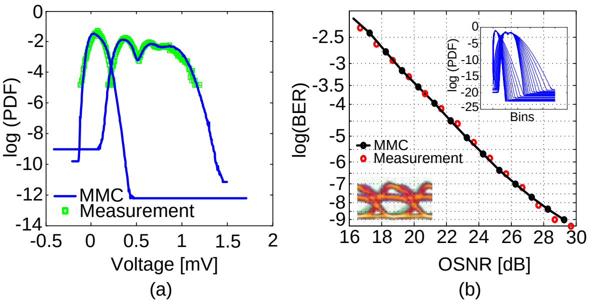


Fig. 4 a) Measured and simulated conditional PDFs for Rx1, and b) measured and simulated BER for Rx2.

The match between the predicted and measured PDFs and BERs demonstrates that our simulator is a reliable tool for performance evaluation of optical links including nonlinear SOAs with sizable patterning effects.

5. Conclusion

We presented a novel MMC simulation tool to accurately estimate the PDFs of the received signal and the BER in the presence of significant pattern-induced ISI resulting from an in-line nonlinear SOA, and validated it experimentally. The pure numerical nature of the simulator allows for the exact nonlinear dynamics of the SOA to be captured, and the use of MMC makes it fast and efficient. Besides being a design and optimization tool per se, it can be used to 1) examine the accuracy of analytical approximations, 2) reduce computation time, and 3) study the impact of changing the modulation format on performance. Moreover, by adding features to the SOA model, the impact of ultrafast processes, nonlinear polarization rotation, enhanced phase dynamics, and interchannel effects in the multichannel regime can in principle be assessed.

6. References

[1] T. Durhuus, et al., JLT 1996, vol. 14, no. 6, pp. 942-954.
[2] O. Leclerc, et al., JLT 2003, vol. 21, no. 11, pp. 2779-2790.
[3] J. D. Downie, et al., Optics Express 2008, vol. 16, no. 20, pp. 15759–15764.
[4] A. A. M Saleh, et al., Transactions of Communications, 1990, vol. 38, pp. 839-846.
[5] I. Kang, et al., JSTQE 2008, vol. 14, no. 3, pp. 758-769.
[6] E. Forestieri, JLT 2000, vol. 18, no.11, pp. 1493-1503.
[7] F. Ohman, et al., JLT 2006, vol. 24, no. 2, pp. 1057-1063.
[8] Z. Zhu, et al., JLT 2008, vol. 26, no. 12, pp. 1640-1652.
[9] A. Ghazisaeidi, et al., "SOA Intensity Noise Suppression in Spectrum Sliced Systems: A Multicanonical Monte Carlo Simulator of Extremely Low BER", to be published in JLT.
[10] G. P. Agrawal, *Applications of nonlinear fiber optics*, Academic press 2001, pp. 138-141.
[11] Cassioli, et al., JQE 2000, vol. 36, no. 9, pp. 1072-1080.