On accumulated signal degradation in a cascade of semiconductor optical amplifiers

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Abstract. We study a design and limitations of a wavelength division multiplexing packet-switched network based on semiconductor optical amplifiers (SOAs) under different modulations formats (QPSK, 8-QAM and 16-QAM). A simple convergence rule for accumulated SOA nonlinearities based on the so-called nonlinear threshold is proposed. We calculate the signal reach depending on various SOA and network parameters by means of numerical simulation. We provide a design tool enabling optimization of a SOA-based optical network architecture.

1. Introduction
Emerging bandwidth-on-demand services in optical fiber networks induce new distributed and bursty traffic profiles. Therefore optical packet-switched metropolitan networks have been proposed [1]. In this scenario, optical packets occupy time slots and slot blocker (SB) device either routes or blocks packets of each wavelength in the network. We anticipate semiconductor optical amplifier (SOA) as a promising candidate for the SB, given that it can operate as a fast modulator with sufficient optical gain and high extinction ratio [2]. This scenario implies one SB per wavelength, thus, the SOA is used only in a single-channel configuration.

The SOA limits the signal reach due to the optical signal-to-noise ratio (OSNR) degradation by amplified spontaneous emission (ASE) and nonlinear distortions in the passing signal, mainly self-phase modulation (SPM). An analytical model enabling to characterize the accumulation of SOA nonlinearities over a 10G on-off keying non-return-to-zero (OOK NRZ) signal has been proposed and validated [3].

In this paper, we extend this study to advanced modulation formats such as M-ary quadrature amplitude modulation (M-QAM), to SOAs with various parameters, and to optical fiber-SOA cascades. The capability of SOA to amplify complex modulation formats has been numerically and experimentally investigated for one device [4]. Numerical simulations have been proposed to study the impact of the in-line SOA nonlinear penalty including the channel count and the cumulated chromatic dispersion (CD) [5]. However, general design rules including the accumulation of nonlinear distortions along the SOA cascade are still missing. Here, we establish a simple model to derive and verify rules for cascaded SOAs nonlinearity for advanced modulation formats, various inter-SOA fiber lengths and
various SOA parameters. Using these accumulation rules and the cumulated OSNR degradation, we assess the maximum number of cascaded SOAs while guaranteeing a certain quality of transmission.

2. Simulation setup
We simulate an optical fiber line presented in Figure 1. It depicts a 28 Gbaud optical signal path through a cascade of SOAs in a prospective fiber network. We use root-raised cosine filter with 0.1 roll-off for pulse shaping a payload of $2^{15}$ symbols.

Our SOA model has 14.2 dB unsaturated gain, saturation power of 12 dBm, noise figure of 8 dB, linewidth factor of 5, and 100 ps charge carrier lifetime. We also implement propagation loss of 0.05 respectively to the gain. The implemented space-resolved model with 10 sections for SOA simulation is described in [6].

We use our setup for three types of simulations. First, SOA parameters are fixed and we simulate a cascade of SOAs with three signal modulation formats: quadrature phase-shift keying (QPSK), 8-QAM, and 16-QAM. Second, we simulate a cascade of 25 km, 50 km and 100 km spans of single-mode fiber (SMF) by one SOA and 100G QPSK signal is sent over such network simulation setup. Third, we use 100G QPSK signal and a cascade of SOAs varying their linewidth factor from 3 to 6 and carrier lifetime from 100 ps to 400 ps.

We vary optical power at the input of the first SOA and maintain the same input power for each SOA in the cascade. For the simulation setup with a cascade of optical fiber spans and SOAs input power of -15 dBm corresponds to the launched power into the SMF of -10 dBm (25 km), 5 dBm (50 km), and 5 dBm (100 km).

To evaluate OSNR degradation we measure its level right before the reception. To assess nonlinear distortions we calculate OSNR penalties loading ASE-type complex white Gaussian noise at the receiver input. Noise loading keeps a constant BER = 10^{-3} and we calculate the OSNR penalty as the difference between the required OSNRs (at BER = 10^{-3}) after the SOA cascade and in a back-to-back (B2B) configuration.

Varying both input optical power $P_{in}$ and number of devices $N$ in the cascade we consider OSNR penalty as a function of the product $P_{in} \times N$, referred to as an integrated power (IP) in [3]. By analogy with [3], we also define the nonlinear threshold (NLT) as the minimum value of IP leading to a given threshold penalty. In the case of nonlinear noise occurring in fiber networks without inline CD compensation, the threshold OSNR penalty equals 1.76 dB providing the best transmission quality [7]. We use the same penalty to assess the NLT after the cascade of SOAs.

3. Simulation results and accumulation rules
We investigate the convergence of OSNR penalty curves depending on the IP for different modulation formats in figure 2(a) and in absence of fiber spans. The modeled OSNR penalty is plotted against the IP (in dB scale, i.e. $10 \log_{10}[P_{in} \times N/1 \text{ mW}]$). Convergence to a single curve makes it tempting to approximate the penalty as a function of the IP $P_{in} \times N$ as previously described for OOK signals [3].

For QPSK, we obtain a maximum IP spread of 2.6 dB (1.5 dB after passing through 3 SOAs). Moving to M-QAM formats, the OSNR penalties is also plotted depending on the IP and we achieve less than 1.5 dB overall spreads for OSNR penalties with 8-QAM and 16-QAM signals. Obtained

![Figure 1. The simulation setup for SOA penalties investigation; Tx — transmitter, Rx — receiver.](image-url)
spread of NLT powers is acceptable for all modulation formats under study (spread of 1.6 dB was obtained with OOK signals [3]).

With a cascade of SOAs and fibers, we found that the basic IP scale produce the spread of 2 dB for 50 km spans and 4 dB for 100 km spans. Moreover, the accumulation of nonlinearities tends to change its character when the fiber length changes, so the scale has to be dynamic. Motivation to get the spread of 1.5 dB or less and study of this accumulation character brought us to a more general law – modified IP $P_{in} \times N^\gamma$ that we implement in Figure 2(b). Varying the exponent $\gamma$, we take into account effects arising in the fiber-SOA cascade: different amounts of cumulated fiber nonlinearities, an interaction between nonlinearities of the fiber and the SOA and an interaction of CD with the SOA nonlinearity.

4. Discussion
The largest count of cascadable devices is obtained at the optimal trade-off between cumulated nonlinear distortions and ASE noise. Both phenomena accumulate from one device to another. We estimate the ASE noise limit with the SOA input power that provides a certain OSNR: the OSNR in B2B for BER=$10^{-3}$ plus 4.5 dB penalty (2.7 dB assumed for aging and implementation penalties as well as 1.8 dB coming from the non-linear threshold). B2B OSNR at BER=$10^{-3}$ are the following: 13.1 dB for QPSK signal, 17.2 dB for 8 QAM signal, and 20.1 dB for 16-QAM signal. The NLT and noise limiting power values against the number of SOA are displayed for different signal modulations in figure 3 (a) and different fiber span lengths in figure 3(b); the impact of the linewidth factor and the carriers’ lifetime of the SOA on signal degradation – in figure 3(c) and figure 3(d).

We propose to use these results as a design tool for SOA-based optical network in the following way. In figure 3 NLT curves characterize maximum tolerable nonlinearity and OSNR curves limit acceptable ASE noise level. Therefore, the maximum number of cascaded devices can be found at the

![Figure 2. OSNR penalties for a cascade of 20 SOAs with QPSK, 8-QAM and 16-QAM signal (a) and for a cascade of 20 SOAs with 25 km, 50 km and 100 km SMF spans (b).](image-url)
The intersection of NLT and OSNR curves. The intersection values are listed in table 1 for various network configurations and in table 2 for various SOA parameters.

The slope of the NLT curves is the same for three formats in figure 3(a) thus the nonlinear distortions have the same fundamental nature (extra phase noise added by the saturated SOAs). We explain a large shift from QPSK to M-QAMs due to the other amplitude levels appearing in 8-QAM and 16-QAM. It demonstrates extra sensitivity due to a decrease in the extinction ratio of the traversing signal (as explained for OOK signals [3]).

In figure 3(b), when different amounts of fiber and CD mix with SOA-induced distortions, the convergence exponent $\gamma$ tends to change. Starting with steep $\gamma=0.9$ for 25 km span extension of the fiber part reduces the slope to $\gamma=0.4$ for 100 km. We explain this phenomenon considering different input powers in optical fiber and large amounts of cumulated CD. Induced by the fiber nonlinearity $\gamma$ is close to 0.67 for 100km-long CD-unmanaged 100G systems as a result of noise dependence on span input cumulated CD and uncorrelated noise contributions from span to span due to the large relative span input cumulated CD [8]. This effect manifests for more than 11 cascaded fiber-SOAs and provides fewer penalties for longer spans.

Increasing the linewidth factor and decreasing the carriers’ lifetime make the SOA more nonlinear due to intensified SPM and patterning effect respectively. Found results in Figure 3(c) and Figure 3(d) conform to this reasoning. We observe the same slope for all the cases and apply a common $P_{in}\times N$ convergence rule to demonstrate identical nature of the penalties. As linewidth factor variations are less influential for high degree M-QAM formats as concluded in [4], SOA with shorter carrier lifetime should be chosen for complex modulation signals.

**Figure 3.** NLT and OSNR limiting power versus number of cascaded SOAs for QPSK, 8-QAM, 16-QAM formats of signal (a), for QPSK signal and 25 km ($\gamma=0.9$), 50 km ($\gamma=0.7$), and 100 km ($\gamma=0.4$) SMF inter-SOA spans (b), for QPSK signal and SOA linewidth factor 3, 4, 5, 6 (c) and for QPSK signal and SOA carriers’ lifetime 100 ps, 200 ps, 300 ps, and 400 ps (d).
5. Conclusion
By the means of numerical simulation, we assessed the impact of the cascade of SOAs on a network transmission varying modulation, fiber length and SOA parameters.

We verified the applicability of the integrated power rule $P_{in} \times N$ to the accumulation of nonlinearities in SOA cascade for QPSK and M-QAM signals. We proposed modified integrated power rule $P_{in} \times N^\gamma$ for a cascade of fibers and SOAs. Both rules provide a spread of OSNR penalties less than 1.5 dB in power scale from 3 cascaded SOAs. Generalizing nonlinearity accumulation for smaller number of SOAs or more precise prediction requires thorough analytical investigation.

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| Table 1. Maximum number of SOAs in various network setups |
|-----------------|-----------------|
| Network configuration | N×SOA |
| QPSK             | 22 |
| 8-QAM            | 7 |
| 16-QAM           | 4 |
| QPSK + 25 km SMF | 15 |
| QPSK + 50 km SMF | 16 |
| QPSK + 100 km SMF| 17 |

| Table 2. Maximum number of SOAs for various SOA parameters |
|-----------------|-----------------|
| SOA parameter and its value | N×SOA |
| $\alpha = 3$    | 29 |
| $\alpha = 4$    | 24 |
| $\alpha = 5$    | 22 |
| $\alpha = 6$    | 19 |
| $\tau = 100 \text{ ps}$ | 22 |
| $\tau = 200 \text{ ps}$ | 29 |
| $\tau = 300 \text{ ps}$ | 35 |
| $\tau = 400 \text{ ps}$ | 41 |

Table 1. Maximum number of SOAs in various network setups
Table 2. Maximum number of SOAs for various SOA parameters