Outage probability due to Stimulated Raman Scattering in GPON and TWDM-PON coexistence

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Abstract: TWDM-PON (ITU-T G.989) may induce relevant extra-attenuation on coexistence with GPON due to Raman nonlinearity. We give a compact theoretical framework to study this problem considering polarization statistical effects, leading to outage probability characterization.

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1. Introduction

ITU-T is currently releasing the new standard for NG-PON2 under Recommendations G.989 and acronym TWDM-PON [1]. As schematically shown in Fig. 1, *left*, and focusing on the downstream (DS) only, 4 λ's (with envisioned upgrades to 8) are used in the L-band (just below 1600 nm, 100 GHz spacing): an allocation allowing complete backward compatibility with previous PON standards, including GPON, XG-PON and RF-Video. Anyway, Stimulated Raman Scattering (SRS) may become detrimental in these "full compatibility" scenario. As shown in [2], if the TWDM-PON channel power is above a given threshold, SRS becomes critical for GPON, because GPON acts as a Raman pump for the TWDM-PON channel comb, transferring optical power from GPON to TWDM-PON. Consequently, GPON may experience relevant power depletion because the SRS presents maximum efficiency [3] at the spectral separation of about 100-110 nm from GPON (1490 nm) to TWDM-PON. After detailed time-domain numerical simulations, we showed in [2] that the walk-off among channels induced by the chromatic dispersion is sufficiently fast (due to the large spectral separation) to average out any time-dependent effects on GPON, so that the SRS-induced GPON depletion can be simply accounted for as an extra-loss, named A_{GPON}, that depends on TWDM-PON power level. Hence, given the maximum tolerable A_{GPON}, we have a limit on the maximum admissible TWDM-PON power level. Moreover, very simple analytical formulas can be derived to estimate it, making use of literature results originally developed 10 to 15 years ago to assess functioning of distributed Raman amplifiers [3,4].

In this work, we show that, due to the fiber Polarization Mode Dispersion (PMD), A_{GPON} is actually not deterministic, but it turns out to be a random process. Its properties depend on several polarization parameters, and specifically on the link PMD given by the fiber δ_{PMD} [ps/sqrt(km)] and on the degree of polarization (*DOP*) [7] of the TWDM-PON channel comb. The main novelties of this work are in particular the following:

- we extend the analysis presented in [2] to include random polarization-related effects;
- we fully characterize the resulting A_{GPON} probability density function (pdf);
- we evaluate the resulting out-of-service probability induced by A_{GPON} exceeding a given system margin.

For fibers with δ_{PMD} above 0.1 [ps/sqrt(km)] and/or for *DOP*=0, we show that the depletion A_{GPON} is deterministic and can be modeled by results presented in [2]. Typical system scenarios are indeed characterized by δ_{PMD}<0.1 [ps/sqrt(km)] and random *DOP,* consequently A_{GPON} must be accounted for as random. It worsens performances compared to the deterministic case and, given the maximum tolerable out-of-service probability on the GPON, the maximum admissible TWDM-PON power level must be further reduced of up to 3 dB.

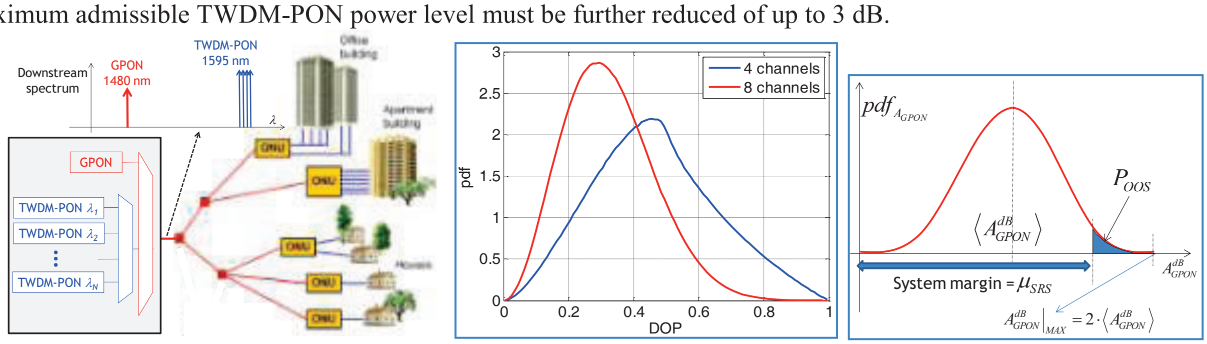


Fig. 1: Left: The considered system scenario characterized by full-coexistence of GPON and TWDM-PON.
Center: DOP_{TWDM} pdf for N_{TWDM}=4 and 8. **Right**: qualitative description of the A_{GPON} probability density function and the related P_{OOS}.

2. Theory of polarization dependent SRS depletion on GPON.

We consider the scenario described in Fig. 1, *left*, for DS only, where a GPON coexists with N_{TWDM} TWDM-PON λ's. Let P_{GPON} and P_{TWDM} be the launched power levels per channel. In [2], to simplify the analytical treatment, we assumed that the polarization scrambling induced by PMD along the fiber was large enough to induce complete polarization-averaging, so that SRS becomes completely depolarized and thus deterministic. Anyway, from the extensive literature on Raman distributed amplifiers [4] results that, under most common conditions [4], polarization statistics are relevant, leading to random gain in Raman amplifiers or, in our case, random GPON depletion A_{GPON}. Physically, it is caused by SRS being most efficient for co-polarized signals, and almost null for orthogonal polarized signals [3]. Due to fiber PMD, the relative state of polarization (*SOP*) of two λ's changes randomly along the fiber, with a correlation length that decreases vs. PMD and spectral separation. Since PON links are limited to 20-40 km and typically fibers are SMF with δ_{PMD}<0.1 [ps/sqrt(km)], we use the following simplifying assumptions.

- The relative *SOP's* of the N_{TWDM} TWDM-PON λ's remain stable along the full PON fiber link, being the TWDM-PON overall spectral width of the order of a few hundreds of GHz, and so relatively narrow. Thus, the resulting global *DOP* of the TWDM-PON channel comb is constant with length and equal to the value DOP_{TWDM} set at the transmitter. Four our purposes, we can identify the entire TWDM-PON comb as an equivalent single optical source with an average power $N_{TWDM} \cdot P_{TWDM}$ and a given DOP_{TWDM}. If all lasers are polarization aligned, we have $DOP_{TWDM}=1$ while if they are alternatively orthogonal we have $DOP_{TWDM}=0$.
- On the contrary, the relative *SOP* between GPON and TWDM-PON changes quickly along the fiber link, due to the very large spectral separation (more than 100 nm), and follows a statistics determined by PMD

Reusing distributed Raman amplifier theory, we can adapt to the PON scenario the results derived in [4], from which the differential equation determining the evolution with distance z of the GPON power P_{GPON} in the fiber is:

$$\frac{\partial P_{GPON}}{\partial z} = -\frac{\alpha_{dB}}{10\log_{10}(e)} P_{GPON} - N_{TWDM} C_R P_{TWDM} \left\{1 + DOP \cdot \left[\hat{s}_{GPON}(z) \cdot \hat{s}_{TWDM}(z)\right]\right\} P_{GPON} \quad (1)$$

where α_{dB} is the fiber loss coefficients in [dB/km], C_R is the polarization average Raman efficiency at the GPON-to-TWDM-PON spectral distance (for SMF, C_R≈0.3 1/W/km) and $\hat{s}_{GPON}(z)$ and $\hat{s}_{TWDM}(z)$ are the GPON and TWDM-PON Stokes vectors [5] randomly evolving with distance z. From Eq. (1) and adapting the theory in [4], it is straightforward to derive the solution of Eq. (1) giving the GPON depletion, in useful dB unit. Its expression is:

$$A_{GPON}^{dB} = \left[10\log_{10}(e)\right] \cdot C_{R,\max} \cdot N_{TWDM} \cdot P_{TWDM} \cdot L_{eff} \left\{1 + \eta \cdot DOP_{TWDM}\right\} \quad [dB] \quad (2)$$

where L_{eff} is the fiber effective length given by $L_{eff} = \frac{10\log_{10}(e)}{\alpha_{dB}} \cdot \left(1 - 10^{-\frac{\alpha_{dB}}{10}L}\right)$, L is the fiber length in km, while η is a key parameter for the presented theory, corresponding to the following polarization-dependent random variable:

$$\eta = \frac{1}{L_{eff}} \int_0^L 10^{-\frac{\alpha_{dB}}{10}z} \left[\hat{s}_{GPON}(z) \cdot \hat{s}_{TWDM}(z)\right] dz \,. \quad (3)$$

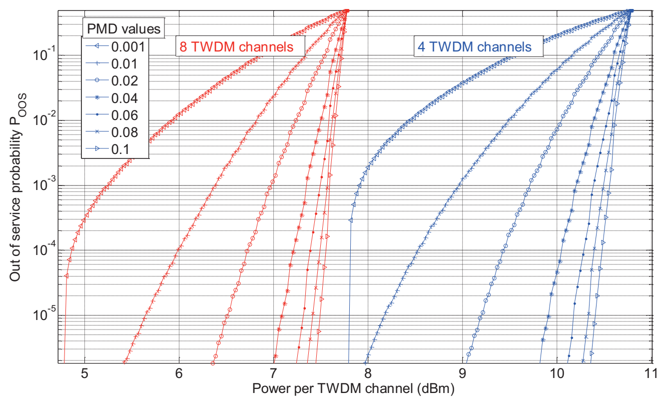
In [4], it has been demonstrated that η is a truncated-Gaussian random process in [-1;1] with an analytical closed form for the variance depending only on δ_{PMD} and L that approaches zero for large values of δ_{PMD}. Hence, Eq. (2) shows that the GPON depletion is a random process depending on DOP_{TWDM} and η, with average value corresponding to the "deterministic" results presented in [2], whose expression is:

$$\left\langle A_{GPON}^{dB} \right\rangle = \left[10\log_{10}(\mathrm{e})\right] \cdot C_{R,\max} \cdot N_{TWDM} P_{TWDM} \cdot L_{eff} \quad [\mathrm{dB}]. \quad (4)$$

Thus, Eq. (2) can be rewritten as: $A_{GPON}^{dB} = \left\langle A_{GPON}^{dB} \right\rangle \cdot \left\{1 + \eta \cdot DOP_{TWDM}\right\}$. Considering that DOP_{TWDM} can only range in [0,1] and η varies in [-1;1], we have that A_{GPON}^{dB} may assume random values from 0 to $2 \cdot \left\langle A_{GPON}^{dB} \right\rangle$, as qualitatively shown in Fig. 1, *right*, and practical effects are the key-issue of the present work. In general, if DOP_{TWDM} is given, A_{GPON}^{dB} is a truncated Gaussian random variable whose maximum value it may assume is 2 times (in dB) its average value. The knowledge of its exact statistics is therefore fundamental in evaluating loss budgets. Its variance is given by η that is fully characterized in [4], but it also depends on DOP_{TWDM}. To have a comprehensive statistical characterization, we assumed that the relative *SOP* of the TWDM-PON channels is completely random, as it practically happens if the N_{TWDM} TWDM-PON line cards are joined using SMF. So, DOP_{TWDM} is a random process as well, and its pdf can be derived, as shown in Fig. 1, *center*, for N_{TWDM}=4 and 8. Then, using the properties of the product of two random processes [6] in Eq. (2), we were able to find the exact A_{GPON}^{dB} pdf and to use it in defining system parameters.

3. The *outage probability* due to the SRS-induced GPON extra loss.

In dimensioning the loss budget for GPON, a system margin μ=2 dB is allocated according to all ITU-T Recommendations. Considering the depletion problem presented in this paper, it is reasonable to assume to allocate no more than μ_{SRS}=1dB to the SRS-induced GPON extra loss. Therefore, in case the random A_{GPON}^{dB} exceeds μ_{SRS}, the GPON can experience an out-of-service (OOS) situation whose prospect is given by the *outage probability* $P_{OOS} = p\left\{A_{GPON}^{dB} > \mu_{SRS}\right\}$, as qualitatively described in Fig. 1, *right*. Thanks to the analytical tools outlined in Sec. 2, we can evaluate P_{OOS} calculating the integral of the A_{GPON}^{dB} pdf above μ_{SRS}. In Fig. 2, *left*, we show the resulting *outage probability* vs. P_{TWDM} for L=40 km, variable PMD and N_{TWDM}=4 or 8. P_{OOS} grows with P_{TWDM} increasing and with δ_{PMD} decreasing. The latter property is somehow unusual, because, typically, mitigation of propagation impairments requires low PMD, while for the SRS-induced extra loss the larger the PMD, the lower the impairment. In particular, for $\delta_{PMD}\geq$ 0.1 [ps/sqrt(km)], it turns out that the polarization averaging is sufficiently high so that $A_{GPON}^{dB} \cong \left\langle A_{GPON}^{dB} \right\rangle$, i.e., the same performance we would obtain for DOP_{TWDM}=0, and the problem becomes almost deterministic, so that the system is out of service if the average extra loss given in Eq. (4) is above μ_{SRS}. Anyway, for δ_{PMD}< 0.1 [ps/sqrt(km)], as it happens for most modern links, for which δ_{PMD} is often below 0.04 [ps/sqrt(km)], A_{GPON}^{dB} can assume values higher that its average with a non-negligible probability. The graph in Fig. 2, *left*, shows that, if we fix a maximum tolerable outage probability $P_{OOS,max}$=10^{-5}, this determines maximum P_{TWDM} values that depend on δ_{PMD}, which is plotted in Fig. 2, *right*, for L=20 and 40 km, and for N_{TWDM}=4 and 8.



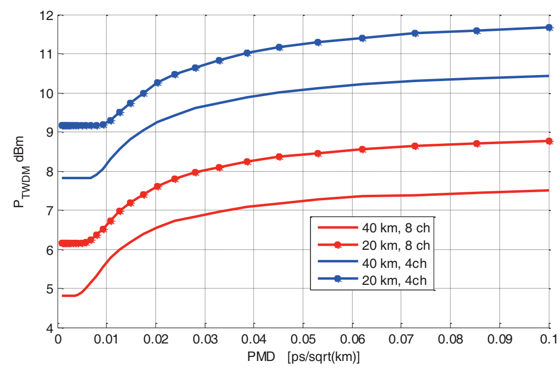


Fig. 2: left: P_{OOS} vs. P_{TWDM} for different values of δ_{PMD} for L=40 km, for N_{TWDM}=4 and N_{TWDM}=4.
Fig. 2: right: $P_{TWDM,max}$ vs. δ_{PMD} for L=20 km and L=40 km, and for N_{TWDM}=4 and N_{TWDM}=8 for $P_{OOS\,max}$=10^{-5} .

Fig. 2, *right*, is the most important result of this work, showing the maximum admissible P_{TWDM} that gives a 1 dB depletion on GPON with probability below 10^{-5}, and can be used to dimension next-generation TWDM-PON systems. It shows that for very low PMD (*$\delta_{PMD}\approx$ 0)* P_{TWDM} should be dimensioned 3 dB below the value reliable for high PMD links, which turns out to be equal to the reliable P_{TWDM} in case DOP_{TWDM}=0. By looking at the actual values of max P_{TWDM}, we note that the SRS impairment can be really significant. In particular, for N_{TWDM}=8 and L=40 km, we have that P_{TWDM} should be below 7.5 dBm for high PMD, and even below 4.5 dBm for very low PMD. Even for N_{TWDM}=8 and L=20 km, P_{TWDM} cannot exceed 11 dBm for very low PMD fibers (δ_{PMD}< *0.04* [ps/sqrt(km)]).

4. Comments and conclusions:

We propose an analytical original characterization of the SRS-induced GPON extra loss due to TWDM-PON. We showed that such an effect may induce an hard limit to the maximum power on TWDM-PON channels, as low as 7.5 dBm/channel in case of N_{TWDM}=8 and L=40 km with high-PMD links. While the use of typical low-PMD modern fibers may require up to 3 dB further reduction on admissible power levels. This problem worsens in case also the RF-video and XGPON wavelengths are present, and worsens even more if a WDM-overly is added in the L-band.

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