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Propagation impairments due to Raman effect on the coexistence of GPON, XG-PON, RF-video and TWDM-PON

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Abstract *We analyze propagation effects in the coexistence of GPON, XG-PON, RF-Video and TWDM-PON. We show that high power TWDM-PON channels excite Stimulated Raman Scattering inducing extra-loss on GPON due to power depletion. We address the problem through simulations and propose and validate a simple analytical model for the effect.*

Introduction

FSAN has recently defined the architecture for NG-PON2, which will be based on the TWDM-PON, that is extensively described in [1]. It will be a WDM solution completely compatible with existing PON Optical Distribution Networks (ODN). Therefore, this PON evolution will use a splitter-based ODN transmitting a 100 GHz WDM comb using $N_{TWDM}=4$ λ 's per direction, each carrying the same modulation format already used for XG-PON: direct detection NRZ binary modulation at 10 Gbps downstream (DS) and 2.5 Gbps upstream (US). The proposed architecture also includes the option for the upgrade to up to 8 λ 's and to symmetrical bit-rates. Details of the λ plan and power levels have not been defined yet as the architecture is on the way of a complete ratification into ITU-T Recommendations entitled G.989.x "40-Gigabit-capable passive optical networks (NG-PON2)". It is anyway expected that, in order to guarantee a complete back-compatibility of TWDM-PON with GPON, XG-PON and RF-Video systems, a possible option could be the λ assignment of TWDM-PON US and DS channels in C- and L+ bands, respectively.

In this work, we focus on the evaluation of possible fiber propagation impairments on the full coexistence DS scenario. We show that fiber attenuation, linear effects and nonlinear Kerr effect are completely ineffective on G.652 fiber signal propagation up to 40 km, while Stimulated Raman Scattering (SRS) may become detrimental, since the 110 nm spectral separation from GPON (1490 nm) to TWDM-PON (1600 nm) corresponds to the maximum SRS efficiency [2]. In particular, GPON acts as a Raman pump for the TWDM-PON. Thanks to spectral separation, large chromatic dispersion, birefringence and PMD effects, SRS does not create time-dependent crosstalk. Anyway, considering power levels that are required to meet class E1 and E2 power budgets (33 dB and 35 dB ODN losses, respectively), we show

by simulation that SRS-induced gain on TWDM-PON is practically negligible, while power depletion on GPON may become important. Then, we propose and validate a simple analytical model giving possible quick support in defining power budgets including SRS-induced GPON extra loss.

Simulative investigations

We took into account the following system scenario corresponding to a DS transmission in a PON full coexistence scenario:

- Up to $L_{feed}=40$ km of G.652 (SSMF) fiber (feeder fiber before the passive splitter)
- GPON: 1490 nm, 2.5 Gbit/s, NRZ, launched power from +3 to +7 dBm
- RF-video at 1555 nm, up to +16 dBm
- XG-PON: 1577 nm, 10 Gbit/s, NRZ, launched power from +8 to +12 dBm
- TWDM-PON: $\Delta f=100$ GHz, 1595-1600 nm for the first four λ 's, 1600-1605 nm for the possible upgrade to other four λ 's, launched power per channel from +9 to +13 dBm.

We carried out a comprehensive investigation based on full split-step simulations. We took into account $L_{feed}=5, 10, 20$ and 40 km and $N_{TWDM}=4$ or 8. We considered only DS transmission because of the following motivations.

- Nonlinear propagation effects will mostly happen on the feeder fiber, as the distribution fiber after the splitter is usually too short to allow nonlinearity to significantly act. On the feeder fiber, the US signals have much lower power than the DS ones, as they have already experienced the splitter attenuation. Thus, even though SRS acts independently of propagation direction, the SRS effect caused by US signals on DS ones is practically negligible.
- At most, the US TWDM-PON signals, if placed in the C- band, may be depleted by the DS TWDM-PON signals (just like DS GPON). For space limitation, this topic is left for future analyses.

In our simulations, we evaluated Rx spectra, power levels and eye-diagram distortions. We observed that no practical propagation impairments are experienced by digital channels due to chromatic dispersion, PMD and nonlinear Kerr effect. Results dramatically changed in case SRS was considered, since we observed a power depletion on DS GPON that increased with the increasing of power levels on the other channels. We name such an effect “SRS-induced GPON extra-loss” (A_{GPON} in the following formulas). The worst-case appeared to be simultaneous transmission of $N_{TWDM}=8$ channels, RF-video and XG-PON, each at their maximum expected power levels ($P_{TWDM}=13$ dBm per channel, $P_{XGPON}=12$ dBm and $P_{RF}=16$ dBm). Input and output spectra for this scenario are depicted in Fig. 1. The typical SRS spectral tilting, inducing a relevant $A_{GPON}=4$ dB (see zoomed inset on GPON in Fig. 1), can clearly be observed. A complete set of measured A_{GPON} for different fiber lengths and N_{TWDM} is given in Tab. 1. We observe that transmitting 8 TWDM-PON channels, GPON experiences 1 dB extra loss already after 5 km propagation, that increases to - likely unacceptable - 4dB penalty at 40 km.

Tab. 1: Simulation results of worst-case SRS-induced loss on GPON in case of 4 and 8 TWDM-PON channels at different G.652 feeder fiber lengths.

N_{TWDM}	A_{GPON} [dB]			
	5 km	10 km	20 km	40 km
4	0.6	1.1	1.8	2.4
8	1.0	1.8	2.9	4.0

Analytical model

From the simulation analysis, we understood that the SRS causes only a “static” extra loss on the GPON signal, while dynamic crosstalk is negligible. This is due to chromatic dispersion inducing such a large walk-off effect between GPON and TWDM-PON signals that all time-dependent impairments are averaged out. Moreover, birefringence and PMD generates a full relative polarization-scrambling excluding any polarization related cross-talk.

Full split-step time domain simulations of such a system scenario are heavily time-consuming (the previously shown results required approximately 1 week of CPU-time), so extensive investigation on all the involved parameters is prohibitive. Hence, we developed a simplified analytical model focused on the SRS induced power transfer from the lower λ 's to the higher ones.

SRS is a wide-bandwidth effect with maximum efficiency at the spectral distance in the range

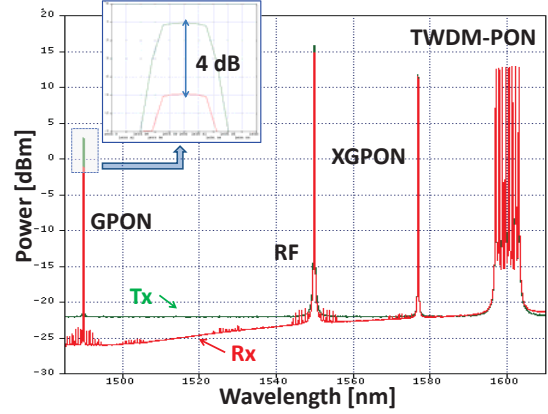


Fig. 1: Normalized optical spectra of the simulated scenario at the input and at the output of 40 km of SSF for the worst-case scenario. The zoomed insert clearly displays the SRS extra loss on the GPON.

100 to 120 nm [2]. Therefore, the maximum power transfer will be from GPON to TWDM-PON. On the other hand, the DS GPON launched power is much smaller than the expected launched TWDM-PON power. We are thus dealing with a SRS propagation scenario in some way opposite to the typical Raman amplification situation. It means that the SRS gain experienced by channels at larger λ 's is negligible, while depletion of the channel at lower λ can be relevant.

In order to derive a simple mathematical model we assume that RF, XG-PON and TWDM-PON channels experience only fiber loss, while GPON is affected by SRS depletion as well. So, the propagation equation for GPON power P_{GPON} can be assumed to be [2]:

$$\frac{\partial P_{GPON}}{\partial z} = - \left\{ \alpha_{GPON} + C_{R,XGPON} P_{XGPON} + C_{R,RF} P_{RF} + N_{TWDM} C_{R,TWDM} P_{TWDM} \right\} P_{GPON} \quad (1)$$

where α_{GPON} is the fiber loss [1/km] at the GPON λ , $C_{R,i}$ [1/km/mW] are SRS efficiencies at $(\lambda_i - \lambda_{GPON})$ and P_i are the power levels [mW] per channel, with $i=XGPON, RF, TWDM$. Eq. (1) can be easily analytically solved [2], obtaining that GPON experiences an extra loss given by:

$$A_{GPON}^{dB} = 10 \log_{10} \left(e^{\left\{ C_{R,RF} L_{e,RF} P_{RF} + C_{R,XGPON} L_{e,XGPON} P_{XGPON} + C_{R,TWDM} L_{e,TWDM} N_{TWDM} P_{TWDM} \right\}} \right) \quad [dB] \quad (2)$$

where $L_{e,i}$ are the effective lengths at different λ 's [2], whose expressions are:

$$L_{e,i} = 10 \log_{10} \left(e^{\frac{1 - 10^{-\frac{\alpha_{dB,i} L}{10}}}{\alpha_{dB,i}}} \right) \quad [km] \quad (3)$$

and $\alpha_{dB,i}$ [dB/km] are the fiber loss coefficients in the used spectral regions. Considering the spectral placing of the DS channels and the λ dependence of the $C_{R,i}$ coefficients, we can

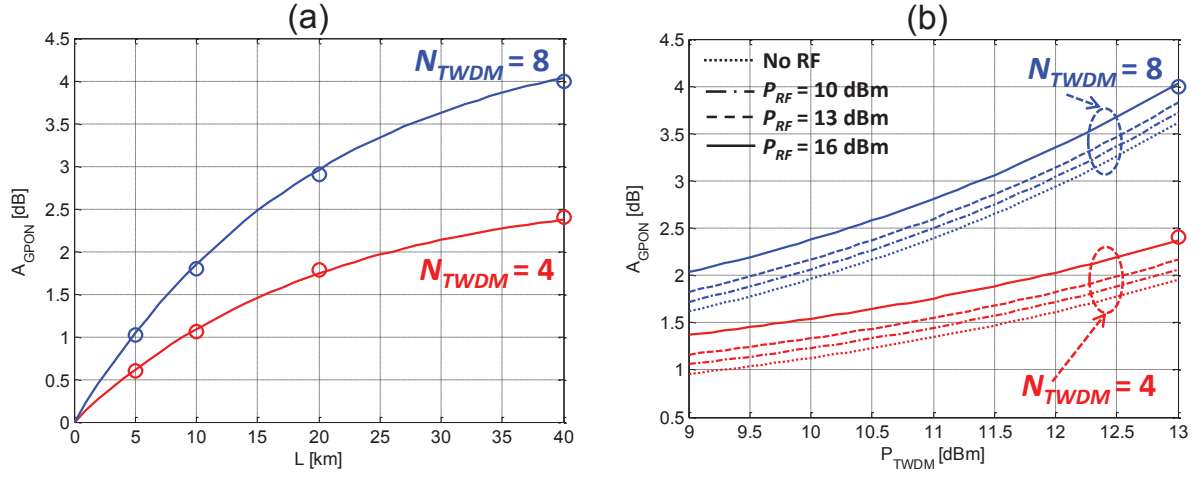


Fig. 2: SRS-induced loss on GPON vs. fiber length in case of $N_{TWDM}=4$ and 8, $P_{RF}=16$ dBm, $P_{XGPON}=12$ dBm, $P_{TWDM}=13$ dBm (a). SRS-induced loss on GPON vs. TWDM-PON power per channel after 40 km in case of $N_{TWDM}=4$ and 8, $P_{XGPON}=12$ dBm (b). Lines refer to theory and circles to simulations.

assume that TWDM-PON channels experience the maximum of Raman efficiency ($C_{R,max}$) from GPON, while XG-PON and RF channels experience approximately $8/9$ and $1/2$ of $C_{R,max}$, respectively, as can be seen from the C_R silica profile presented in [2]. Moreover, we can suppose that at the XG-PON, RF and TWDM-PON λ 's the fiber loss coefficient α_{dB} is almost constant. Using such hypotheses, we can express the SRS-induced GPON loss as:

$$A_{GPON}^{dB} = [10 \log_{10}(e)]^2 \cdot \frac{(1 - 10^{-\frac{\alpha_{dB}}{10} L})}{\alpha_{dB}} \cdot C_{R,max} \cdot \left(\frac{1}{2} P_{RF} + \frac{8}{9} P_{XGPON} + N_{TWDM} P_{TWDM} \right) \quad [dB]. \quad (4)$$

In order to validate this simple analytical model we compared the loss given by Eq. (4) with the simulation results previously obtained. Such a comparison is shown in Fig. 2a as A_{GPON} vs. L for the worst-case scenarios. Solid lines refer to the analytical model, while circles are time-domain simulation results. We can observe an excellent agreement between theory and simulation, validating the proposed simple model given by Eq. (4), that can thus be used when an extensive set of input parameters is to be investigated. For instance, we used the simplified model to show (see Fig. 2b) the influence of TWDM-PON power levels on A_{GPON} for $N_{TWDM}=4$ or 8. For all cases, XG-PON is kept at its maximum expected power level (+12 dBm) as it gives a small contribution on A_{GPON} limited to a fraction of dB's. RF-video is either turned-off or set to 10, 13, and 16 dBm showing that its contribute is about 0.5 dB at most. This analysis confirms that it is mostly the presence of TWDM-PON channels that may induce an impairment on GPON, up to 4 dB for the considered worst-case. In Fig. 2b, two simulative results are also shown as circles, confirming the accuracy of Eq. (4) model.

Conclusions

We have shown that the only "additional" propagation impairment in NG-PON2 full coexistence scenario is SRS, and we have developed and validated a specific simple analytical model for this effect. Main issues we addressed are listed in the following.

- SRS does not generate significant time-varying cross-talk on GPON as the involved λ 's are at wide spectral separation. Hence, the chromatic dispersion walk-off effect *averages out* the modulation. For the only purpose of SRS impact, all involved channels can thus be seen as CW signals.
- Raman gain generated by GPON on TWDM-PON is negligible.
- Depletion of the GPON signal is indeed significant, and it can go up to 4 dB for 8 TWDM-PON channels at 13 dBm. We name it SRS-induced GPON extra loss (A_{GPON}).
- We proposed and validated a simple analytical model giving an accurate prediction for A_{GPON} , including clear and *quick* scaling rules with power levels.
- The problems addressed in this work are critical for Class E1 and E2 ODN, requiring TWDM-PON signals with high launched power. We believe high TWDM-PON power levels should be carefully considered in deployment scenarios including GPON and long feeder spans.

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