Extension of the Measurement-Based Gain Model for non-Flat WDM Inputs and various pump currents

Vitória Maria C. Mathias(1), Alexis Carbo Meseguer(1), Jean-Christophe Antona(1), Alberto Bononi(2), Stephen Grubb(3), Olivier Courtois(1), Vincent Letellier(1)

(1) Alcatel Submarine Networks, Nokia Paris-Saclay, 96120 Nozay (France), alexis.carbo_meseguer@asn.com
(2) Università di Parma, Dip. Ingegneria e Architettura, 43124 Parma (Italy), (3) Facebook, Menlo Park, CA (USA)

Abstract *We extend our measurement-based model to accurately predict the gain of an EDFA for arbitrary input spectrum to the case of arbitrary pump currents with low root-mean square error and no extra training data and then, we analyze its accuracy against numerical simulations and experiments.*

Introduction

Since the popularization of SDM systems for power-constrained subsea links, new techniques have recently been investigated to improve the balance between capacity and energy consumption. Some of them [1-2] have proposed to operate the system in non-flat WDM conditions to optimize the power per wavelength and reduce energy consumption. In [3] we stressed the need for an erbium-doped fiber amplifier (EDFA) model to predict the gain in these regimes with high accuracy and low complexity: an agnostic model was introduced and referred to as hybrid since it was found using a similar procedure as machine learning (ML) models but considering all the intuition of parametric physical models developed in last decades: this model assumed an homogeneous gain amplifier (like Saleh extended model [4-5]) enabling to analytically relate the total powers of an arbitrary spectrum and a flat spectrum entering an EDFA and yielding the same population inversion, or gain; thus a calibration of an EDFA response for different flat spectrum input powers and a given pump current enables to extrapolate the behavior of the EDFA to arbitrary input spectra. This model was tested with a commercial full C-band EDFA showing 0.05 dB root mean square error (RMSE) when validated using WDM random channel pre-emphases with up to 12 dB wavelength excursion, which was the lowest error reported so far. The model was trained using only few sets of flat input spectra at fixed pump current.

In this paper, we extend this model to any pump current by adding the minimum number of changes. We follow the same assumption used to develop our model i.e., that the gain is fully determined by the amplifier population inversion. First, we thoroughly analyze the accuracy of the single pump power model through numerical simulations leveraging the extended Saleh model [4-5] and experiments, in the following directions: we investigated the impact of wavelength, the impact of the input power step ΔP in the calibration process to train the model look-up table, and the impact of the closed-form expression used in [3] to determine the equivalent flat input power instead of using an iterative process. Eventually, the generalized model is assessed and its domain of validity is determined.

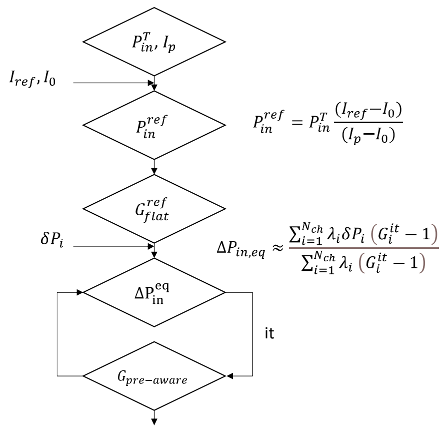

Fig. 1: Extended method to predict $G_{pre\ aware}$ (x)

Generalization to any pump current

We propose here to extend our model to any given pump current I_p. Only a few measurements in flat input conditions to train the look-up table, following the same principle explained in [3], obtained for a reference pump current I_{ref} are enough to characterize the EDFA gain. The procedure to predict the gain at a given total input power P_{in}^{T} is depicted in Fig. 1.

Let us now refer G_{flat}^{ref} to the flat input model obtained at the reference pump current. The first step is to find an equivalent total power for the reference system yielding the same inversion conditions than P_{in}^{T} at I_p. Considering an affine law between power and pump current, we propose to express equivalent power P_{in}^{ref} as:

$$P_{in}^{ref} = P_{in}^{T} \frac{(I_{ref}-I_0)}{(I_p-I_0)} \tag{1}$$

being I_0 a transparency current. This affine (rather than linear) law could be understood as the joint impact of the pump diode-like response and the need to feed the EDFA with a minimum optical pump power to reach the desired

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population inversion. Hereafter we assume I_0 is independent of population inversion.

Once P_{in}^{ref} is determined, the gain in flat conditions can be easily found by interpolating the look-up table generated at the reference pump current $G_{flat}^{ref}\,(P_{in}^{ref})$. Next step consists in adding the impact of the pre-emphasis by estimating the equivalent relative power deviation ΔP_{in}^{eq} leading to the actual population inversion. It is obtained using the formula introduced in [3]. Let δP_i be the relative pre-emphasis on channel i, i=1 to N_c, with N_c the total number of WDM channels. In order to reduce the complexity of our model and obtain a closed-form expression of ΔP_{in}^{eq}, we considered that actual gain of the EDFA is close enough to the gain in flat conditions. We can improve this estimation since once the gain $G_{pre\ aware}$ is determined, we can use this value as a more precise value to retrain the estimation of ΔP_{in}^{eq} and improve its accuracy. We can repeat this procedure several iterations (it) until $G_{pre\ aware}(P_{in}^{T},\ \Delta P_{in}^{eq})$ converges.

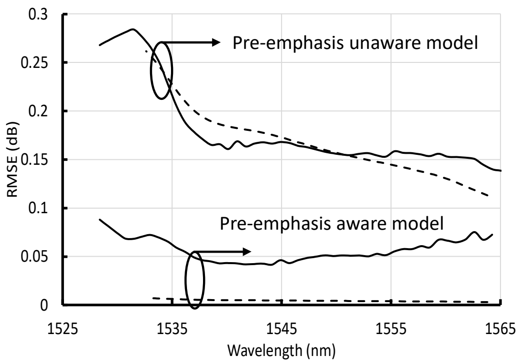

Fig. 2: RMSE versus wavelength: solid lines for experiment and dashed for simulation.

Numerical and experimental assessment

We performed numerical simulations using a theorical EDFA obtained with the extended Saleh model introduced in [4-5] and operated following the same principles as in [6]. The emission and absorption coefficients are taken from [6-7]. The simulated optical bandwidth is from 1532.6 to 1563.8 nm. The set-up replicates the one used in experiments (refer Fig1.a in [3]). Simulations were done at pump powers of 40, 80, 120, 160 and 200 mW and input powers from -10 dBm to 12 dBm in steps of ΔP = 0.4 dB.

Wavelength dependency accuracy of RMSE

In this section we compare the experimental results of the model developed in [3] with the results obtained in numerical simulations. The metric used is RMSE and it is represented in Fig. 2 as a function of wavelength for the pre-emphasis unaware model (formerly known as flat-input model) and the pre-emphasis aware models. The RMSE is plotted for experiments (resp. numerical simulations) in solid lines (resp. dashed lines). Similar error is measured for both cases when the pre-emphasis unaware model is used. These errors stem from gain variations of the input channel pre-emphasis. We can also observe some wavelength dependency, it is attributed to the increase of differential gain at lower wavelengths. If we compare the results for the pre-emphasis aware model, we observe a negligible error for numerical simulations that allow us to validate the model. For experiments, a RMSE around 0.05 dB is observed, as in [3]. The difference between experimental and numerical RMSE estimation is deemed to be due to measurement uncertainties and spectral hole burning (SHB) effects which is not captured by the Saleh model.

Impact of ΔP for the training look-up table

In [3], the ΔP selected to train the look-up table for the pre-emphasis unaware gain model was 1 dB, so as to limit the size of the look-up table. We assess here several values of ΔP to quantify the error made by selecting this parameter.

Fig. 3 shows the mean RMSE as a function of ΔP for experiments and simulations. The error is upper-bounded to 0.006 dB up to ΔP =1 dB for simulations then increases significantly. Similar RMSE trend is observed in experiments. This experiment allows us to claim that ΔP =1 dB is the best value for this parameter since we can reduce the size of the look-up table without compromising the RMSE.

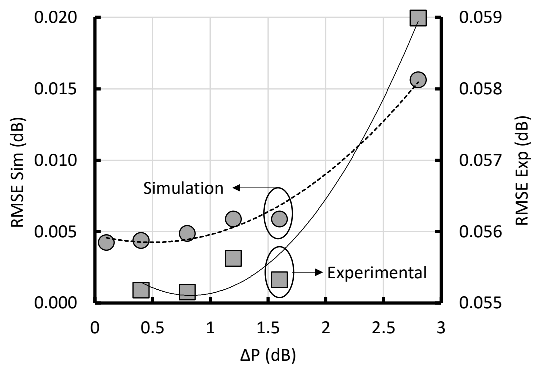

Fig. 3: Evolution of RMSE as a function of ΔP

Impact of number of iterations (it)

An iterative algorithm was not considered in [3] to estimate ΔP_{in}^{eq} because we did not observe a significant performance improvement to justify the increase of complexity. We quantify here the penalty incurred when making this approximation by testing this iterative algorithm and estimating the error for iteration values up to 6. Fig. 4 shows the measured mean RMSE versus the number of iterations, first with simulations. Error for the first iteration is 0.0025 dB and it descends to less than 0.005 dB for it=2 and it stabilizes. In experiments the impact is even much smaller since this error is below the one caused by measurement uncertainties. Our final recommendation is choosing it=1 or 2. No improvement is obtained with more iterations.

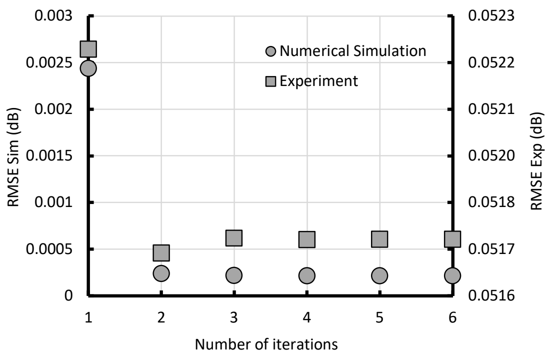

Fig. 4: Graph with RMSE evolution as a function of the number of iterations of the pre-emphasis aware model.

Domain of validity of the variable pump model

Some new experimental measurements were carried out to assess the generalized model. They were obtained using the setup depicted in Fig1.a in [3], where the commercial 39-nm full C-band EDFA was characterized for 6 different pump currents I_p which ranged from 50 to 1000 mA. For each pump current several gain curves versus wavelength were recorded in flat conditions with total input powers from -10 dBm to 12 dBm in steps of 0.4dB.

In order to assess our model in flat conditions, first we tested six different pump currents as $I_{ref} = 50, 125, 275, 550, 800\ and\ 1000\ mA$ to determine which one was the best choice to train the flat-input gain model. We observed that $I_{ref} = 550\ mA$ is the one that minimizes the error and therefore we selected it to train our model.

In Fig.5, RMSE of gain curves in flat conditions is shown in solid line as a function of the current I_p and $I_{ref} = 550\ mA$. For simplicity we fixed the transparency current $I_0 = 0\ mA$. We observe that RMSE decreases to 0 dB at $I_p = I_{ref}$ and then increases again. We conclude that the generalized model can be used from 250 mA to 825 mA of I_p with a RMSE below 0.2 dB.

Impact of transparency current I_0

In Fig.5, a dashed line is also plotted. It corresponds to the case with an optimized transparency current $I_0 = 30\ mA$. This value has been estimated taking some measurements in flat conditions at the lowest pump current and minimizing the RMSE by trial and error. A RMSE reduction is observed specifically at low I_p values where the impact of transparency current can play a role. It permits to increase the domain of validity of the extended model from 200 mA to 825 mA with RMSE below 0.2 dB. Further improvements could be expected by considering population inversion dependence of I_0.

Variable pump powers and arbitrary spectrum

Finally, a second campaign of measurements was done varying the input conditions to test the impact of WDM pre-emphases for two different pump currents: 275 mA and 550 mA. 200 random WDM pre-emphases were tested following the same procedure than in [3] and gain is estimated for total input powers from -10 dBm to 12 dBm in steps of 0.4 dB. The RMSE is plotted in Fig. 5 in diamond markers considering the optimum value of $I_0 = 30\ mA$. We observe an error around 0.15 dB when $I_p = 275\ mA$ and $I_{ref} = 550\ mA$ with the optimum transparency value $I_0 = 30\ mA$.

Numerical simulations were also performed for more I_p values leading to similar results.

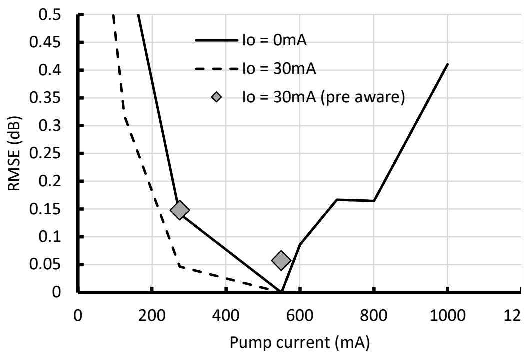

Fig. 5: Experimental RMSE versus EDFA pump current I_p for $I_{ref} = 550\ mA$

Conclusions

We conducted several numerical simulations and experiments to test our EDFA model and establish some key parameters such as ΔP in order to reduce as much as possible the size of the training data base or the number of iterations in the search of ΔP_{in}^{eq}. We then extended the model to any given pump current with no need to extend the training look-up table. We showed that the gain of a commercial Full C-band EDFA can be successfully predicted at 275 mA of pump current using 10-20 measurements in flat conditions at 550 mA with a RMSE ~ 0.15 dB.

Acknowledgements

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