Low-Complexity Experimental Model for Submarine Link Performance Prediction

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Abstract: We propose a low-complexity experimental model that predicts the OSNR of submarine links, considering both EDFA homogeneous and inhomogeneous responses. We tested it with random input pre-emphases, obtaining a mean RMSE of 0.29 dB after 24 spans when trained with simple single-span datasets. © 2024 The Author(s)

1. Introduction

With the advent of open submarine systems, accurate models for system design are increasingly necessary. Cable owners need a clear understanding of the latent cable capacity even before it is deployed and of the impact of a cable repair once deployed. It is well known that Erbium-doped fiber amplifiers (EDFAs) cause distortions in the signal power over the link. These distortions are partially mitigated by adding gain-flattening filters (GFFs) after each amplifier and periodic fixed corrections. However, even minor imperfections in the filtering can yield a significant distortion in the OSNR measured at the output since they accumulate over a cascade of amplifiers. This is why models that predict power variations over frequency are essential.

Many recent studies have been published to predict the EDFA gain response under non-flat input spectrum conditions [1-3]. Most of them focused on the homogeneous response (HR) of a single amplifier based on machine learning (ML) approaches. These techniques simply consider the system as a “black box”, requiring a large training dataset and time because of their lack of physical intuition. It is why we proposed in [4] a hybrid “white-box” model that leveraged the physical intuition given by the extended Saleh model [5] to reduce the required training data and complexity. We achieved a root-mean-square error (RMSE) of 0.05 dB in the prediction of a single amplifier gain, which, as far as we know, is the same error as state-of-the-art ML models (see Fig. 1a)), but with way lower complexity. We also predicted the gain response after a cascade of 12 spans with an RMSE of 0.15 dB. Beyond that, the model’s performance is compromised by the rise of inhomogeneous broadening effects such as spectral hole burning (SHB). Then, a second model was introduced [6] to account for these effects at high amplifier count, submarine distances. We followed the same “white-box model” philosophy that requires only a few simple experimental measurements to train it. Since inhomogeneous effects are way more important at longer distances, at this stage, we neglected the impact caused by homogeneous effects just for simplicity. We showed that this model provides good optical signal-to-noise ratio (OSNR) predictions at typical submarine distances with a mean RMSE of 0.5 dB. Each model shows low prediction error in their domain of validity, but it slightly increases at middle distances because both homogeneous and inhomogeneous effects have comparable contributions, so none of them can be neglected and, furthermore, every parameter mismatch has a large impact. Fig.1a) summarizes all the mean RMSE of the discussed gain models (GM) versus amplifier count.

In this paper, we present a generalized model that can predict the OSNR dependency on wavelength of a submarine link considering most of the effects that cause frequency distortions, such as the EDFA homogeneous and inhomogeneous effects, as well as the imperfect response of GFF and the span losses. We tested it over 200 random input spectra in a 24 spans submarine link under realistic conditions, achieving a mean RMSE of 0.29 dB in OSNR estimation. We then stressed it by applying a 6 dB loss at the input, simulating the behavior after a severe cable failure, and the model kept similar RMSE values. Another novelty shown in this paper is that we have experimentally isolated for the first time the inhomogeneous response (IR) of pre-emphasized channels at the input of a single EDFA by using the knowledge obtained with homogeneous model. These measurements are later used to train the inhomogeneous contribution of our generalized model. It is a step forward with respect to [6], which was trained using the response of several EDFAs to average out the residual HR.

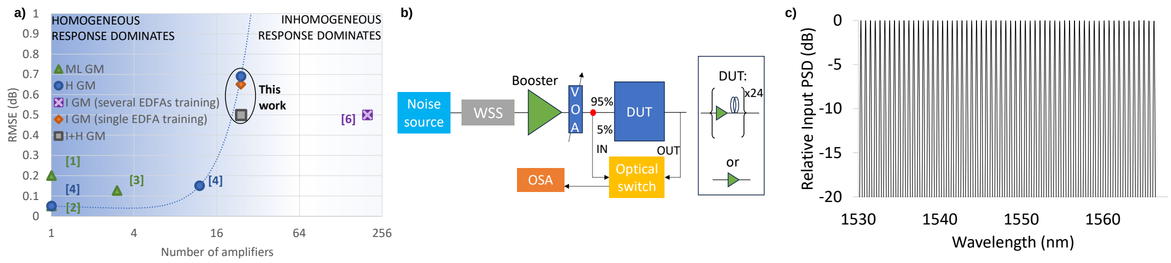

Fig. 1a) RMSE vs number of amplifiers state-of-the-art models. b) Experimental setup. c) Relative input power spectral density in dB.

2. Experimental set-up and training

The experimental set-up is shown in Fig.1b). We fulfilled 36nm of bandwidth using a noise source that was shaped with a wavelength selector switch to emulate a 75-GHz noise channel frequency grid. Every channel had 20 GHz of bandwidth to enable access to noise level (see Fig.1c). Then, the noise channels were boosted before entering the device under test (DUT). A variable optical attenuator (VOA) was placed before the DUT to control its total input power. With a 95/5 coupler, we recovered the input signal. Finally, this signal, together with the output one, entered an optical switch connected to an optical spectrum analyzer (OSA). In all the conducted experiments, the DUT was put into a controlled temperature room to simulate seabed temperature conditions.

First, we calibrate our model using a single EDFA as DUT. To isolate the HR of the EDFA under test, we characterize its gain when operating with a flat input spectrum at different total input powers P_{in}, from 0 to 12 dBm. This allows us to build a homogeneous EDFA gain model, converting any input spectrum into a flat input spectrum with an adjusted equivalent input power yielding the same EDFA population inversion and gain, as in [4]. Fig. 2a) shows the measured EDFA gains used to train the model once the expected contribution of the GFF is removed. The dashed curve corresponds to the gain at nominal power P_{ref}, which will be denoted as the reference gain G_{ref}. To measure the inhomogeneous contribution, we measured the gain distortion induced by every channel as in [6]. However, as discussed in [4] and shown in Fig. 2c) of [6], when we apply a channel pre-emphasis, homogeneous effects are also stimulated. The novelty of this paper is that we directly isolated the IR of a single EDFA. In the presence of a channel pre-emphasis, we adjust the total input power to match the equivalent power corresponding to the flat reference conditions. In these conditions, the HR is minimized. To ensure that we obtained the closest population inversion to the flat input case, we adjusted the VOA attenuation by a gradient descent algorithm to minimize the differences between the measured gain and G_{ref}. Fig.2b) shows results without applying the power adjustment and the IR isolated with it. Later, we verified the match between the experiment without power adjustment and the built cascade of homogeneous + inhomogeneous models in Fig.2b). Finally, we smoothed the predicted IR to remove quantization noise coming from the OSA. We compared the exploitation of the averaged IR after the 24 spans cascade and scaled to a single amplifier or the use of the simple technique of a moving average. Both ways yield a similar performance in the model implementation.

Then, we tested our model in a submarine link using a submarine repeater and a 12-fiber pairs tube spool. Every span comprised an EDFA equipped with a GFF, followed by a 70 km optical fiber with conventional parameters i.e., 0.155 km/dB of attenuation, 21 ps/(nm·km) of chromatic dispersion and 110 µm² effective area. The fiber was directly spliced to the EDFAs and vice versa. Fiber spans were inside a 12-fiber pairs tube spool and amplifiers operated at constant pump current, reproducing realistic conditions. We selected 24 spans because we wanted to work in a region where neither the HR nor IR are negligible and, indeed, this number is representative of the number of spans before a second order shape equalization in a submarine section. The fiber transfer function was obtained using an experimental characterization and the stimulated Raman scattering shape was estimated using the formula proposed in [7]. Fig. 2c) shows the average response of the 24 fibers used.

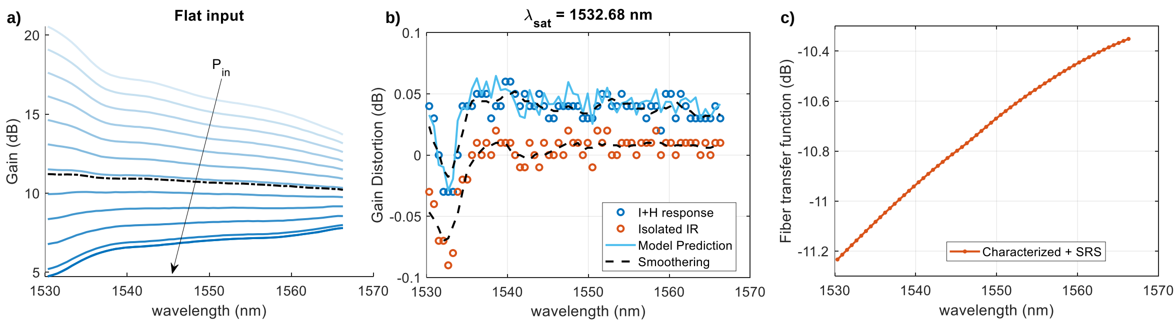

Fig. 2a) EDFA gain under flat input conditions and different input powers. b) Symbols: measured HR + IR and isolated IR. Solid: experimental IR with homogeneous gain estimated by the model. Dashed: smoothed curves. c) Fiber characterization + estimated SRS.

3. Generalized model for gain prediction of a submarine link

We propose the association of both homogeneous and inhomogeneous models presented in references [4] and [6], respectively, to predict the output spectrum of a cascade of 24 identical amplifiers-fibers. Firstly, we assume that both contributions can be treated independently and added at span level. Hence, we have that the output spectrum of the k^{th} span is: $p_{out}^{(k)}(\lambda) = p_{in}^{(k)}(\lambda) + G_H^{(k)}\left(\lambda, \Delta p^{(k)}(\lambda)\right) + G_I{}^{(k)}\left(\lambda, \Delta p^{(k)}(\lambda)\right) + H_{gff}(\lambda) + H_{fiber}(\lambda)$, where p_{in} is the input spectrum, G_H is the homogeneous gain (computed with model in Ref. [4]), G_I is the inhomogeneous response (computed with model in [6]), H_{GFF} is the GFF transfer function, H_{fiber} is the fiber transfer function and $\Delta p^{(k)}(\lambda)$ is the spectrum pre-emphasis, all in dB units. In this paper, the look-up tables used to obtain $G_H(\lambda)$ and $G_I(\lambda)$ have been trained with the data of a single EDFA, contrary to [6] where a cascade of spans were used. This allows the iterations of only one span and relax some assumptions done in [6], such as the one that the G_I was set to zero by definition for the flat input. Finally, note that both gains are impacted by each other, since they depend on the power distortion from the previous iteration that, in turn, depends on both homogeneous and inhomogeneous contributions.

4. Experimental validation

In this section, we tested the generalized model when applying over 200 random input spectra in the submarine link under test. When computing the mean root-mean-square error ($\overline{RMSE}$) in the estimation of the output power spectrum over ~150 random inputs at nominal power, we obtained a $\overline{RMSE}$ = 0.49 dB after 24 spans. Fig. 3a) shows the individual RMSE for every random pre-emphasis and the mean values when considering only homogeneous, only inhomogeneous and both effects. The $\overline{RMSE}$ error provided by each model separately is 0.69 dB and 0.65 dB respectively. Notice then that the generalized model permitted to reduce the $\overline{RMSE}$ by a factor of 27% because of the interplay between the two models. Finally, we repeated the same test but now predicting the OSNR at the output of the submarine link obtaining a $\overline{RMSE}$ = 0.29 dB after 24 spans.

Then, we stressed the novel model by adding a 6 dB loss in the total input power, simulating a very pessimistic cable failure since it corresponds to twice the typical loss measured in a deep sea cable break. As an example, Fig. 3b) shows the power spectrum and OSNR prediction for a given input random spectrum, which is then compared with the pre-emphasis unaware model. We clearly observe that the latter is unable to predict the impact of the input pre-emphasis and the 6 dB loss, with a RMSE greater than 1 dB in the output spectrum. In turn, our model achieves RMSE values around 0.45 dB in both power spectra and OSNR prediction for this example. Finally, Fig. 3c) shows the histogram of the RMSE for the OSNR estimation computed over all random inputs for both nominal and failure simulation cases. The generalized model can predict the impact of this cable failure with a $\overline{RMSE}$ of 0.53 dB in the power spectrum prediction and 0.46 dB in the OSNR over 50 random input spectra.

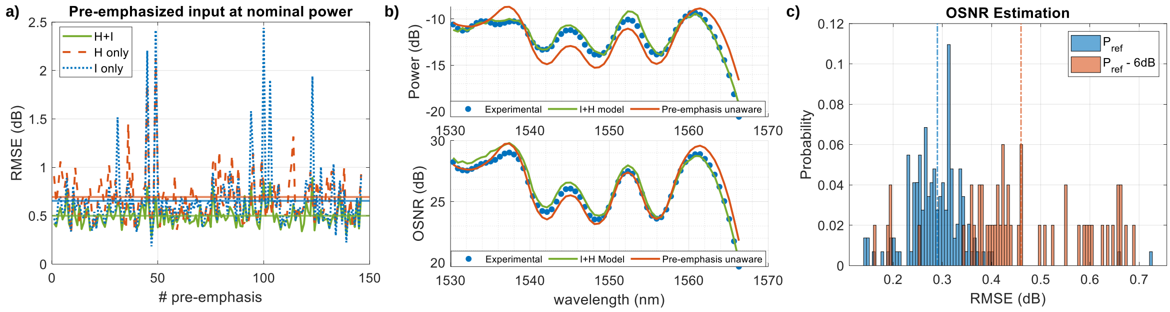

Fig. 3a) RMSE and mean value for every pre-emphasis in the prediction of the power spectra considering homogeneous + inhomogeneous effects, only homogeneous and only inhomogeneous at nominal total input power case. b) Power and OSNR prediction for a random input at 6dB lower than nominal input power. c) Histogram of RMSE in the OSNR prediction at nominal power P_{ref} (blue) and 6dB lower (orange).

5. Conclusion

We first validated an experimental technique to isolate the inhomogeneous response of a single EDFA by using the knowledge gained from the homogeneous model. Secondly, we generalized our model, so it can predict the performance of a submarine link accounting for both homogeneous and inhomogeneous EDFA effects, as well as other span imperfections. It was trained with a very basic dataset obtained experimentally with a single EDFA characterization. Then, we tested it in a submarine link composed of 24 spans in realistic conditions with random input spectra at nominal power and then emulating a cable failure by adding a 6 dB loss in the total input power. We showed respectively 0.29 dB and 0.46 dB of $\overline{RMSE}$ averaged over all the random inputs. Finally, we showed that the interplay between the two EDFA models permitted to reduce the $\overline{RMSE}$ in a factor of 27%.

6. References

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