QoT Impairments Induced by Statistical Filtering Variations with a Realistic Equalizer

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Abstract *We analyze filtering penalty in ASE-impaired optical links, including transceiver noise effects. A mathematical model for FSE equalization is validated via time-domain simulation and exploited to perform Monte Carlo analyses, incorporating stochastic variations in optical filters' bandwidth and central frequency.*

Introduction

Reconfigurable Optical Add-Drop Multiplexers (ROADMs), leveraging Wavelength Selective Switches (WSSs), are the cornerstone of modern optical networks, due to their flexible switching capability. Nevertheless, they are also responsible for the introduction of many impairments, among which filtering penalty is becoming more and more significant, due to state-of-the-art transceivers throughput increment[1]. Metro networks are characterized by cascades of several switching nodes, short links and low optical power, leading to negligible fiber nonlinear interference[1] (NLI). On the other hand, the spectral narrowing due to cascaded ROADMs filtering effect can significantly impact the quality of transmission (QoT)[2]. Evaluation of such impairment is pivotal in the development of an optical network digital twin (DT). Currently, Gaussian-Model-based DTs[3] still need for a reliable filtering penalty model. In addition, statistical system margin assessment must be considered, given the impossibility to characterize each network device. The DT must account for optical filters' bandwidth and central frequency variation (for instance due to changes of lightpath route), which can lead to performance fluctuations.

Filtering penalty has been experimentally characterized in several contributions[4],[5], and mitigation techniques have been proposed[6]. From the modeling point of view, many efforts have been done leveraging classical equalization theory for both in continuous domain[7],[8] and in discrete domain[9]–[11], which is closer to commercial transceivers' real implementation. In particular,[9] proposes an equalizer model based on Minimum Mean Square Error (MMSE), while[10] focuses on Zero Forcing Equalization, considering a worst-case conservative scenario. Regarding the statistical evaluation of filtering impairment, in[8] the filters central frequency variation, uniformly distributed, has been analyzed in terms of sensitivity penalty. In[12] fitting has been performed on optical WSS filters experimental shapes, exploiting the model provided in[13]. Measurements demonstrated that both filters' central frequency and bandwidth parameters distributions are Gaussian.

However, a study of the impact of filtering penalty on QoT, when optical filters' parameters are stochastic, is missing. In addition, rigorous analysis of the interplay between ASE injection position and where filtering effect is applied is yet to be developed.

In this paper we fill this gap by evaluating the QoT of a reference optical link in terms of received SNR, adopting an highly realistic Fractionally Spaced Equalizer (FSE) model[11]. We consider all the impairments as due to ASE noise, filtering effect and transceiver penalty and we validate the FSE model in case of asymmetric filtering, exploiting time domain simulation. Finally, we perform an extensive Monte Carlo analysis, in order to inspect the effect of statistical variation of optical filters' parameters and to determine how the reciprocal position of ASE sources and filtering elements impacts on the QoT.

Methodology

The reference optical system is provided in Fig. 1. It is composed by two amplified links at transmitter and receiver side, connected to a cascade of ROADMs, each equipped with booster and preamplifier, representing a metro-network portion, responsible for any filtering impairment. The number of spans of amplified links can be selected, whereas the ROADM number is fixed to 8.

The QoT metric is the SNR at received side in electrical domain, which in absence of filtering and NLI is expressed by[14]:

$$\mathrm{SNR} = (\mathrm{SNR}_{\mathrm{ASE}}^{-1} + \mathrm{SNR}_{\mathrm{TRX}}^{-1})^{-1} \qquad (1)$$

Where $\mathrm{SNR}_{\mathrm{ASE}} = P_{\mathrm{RX}}/P_{\mathrm{ASE}}|_{Bw=R_s}$ is due to ASE noise in optical domain and $\mathrm{SNR}_{\mathrm{TRX}}$ accounts for the transceiver impairment in electrical domain. $\mathrm{SNR}_{\mathrm{TRX}}$ value is obtained through the characterization performed in past works[10],[11]. In addition, optical front-end converts the optical signal into electrical domain without applying additional filtering. Square-root raised cosine pulse shaping with $\alpha = 0.15$ rolloff, baud rate of $R_s = 63.1$ GBaud and DP-16 QAM modulation is assumed. The central frequency is $f_0 = 193.9$

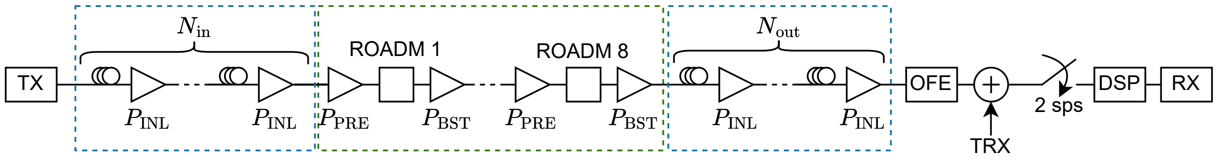


Fig. 1: Reference optical link

THz, the launch power is set to 0 dBm, and amplifiers are assumed to restore completely the power losses, therefore, operating in transparency, the received optical power is 0 dBm. Consequently, $\mathrm{SNR}_{\mathrm{TRX}} = 17.26$ dB. DSP performs matched filtering and equalization in discrete domain at $\ell = 2$ samples per symbol (sps), according to MMSE strategy, therefore FSE model derived in[11] is considered:

$$\mathrm{SNR}_{\mathrm{FSE}} = \frac{\mathrm{SNR}}{k_{\mathrm{FSE}}} - 1 \tag{2}$$

$$k_{\mathrm{FSE}} = \frac{1}{R_s}\int_{-\frac{R_s}{2}}^{\frac{R_s}{2}} \frac{\ell}{\left|\left|\mathbf{H}\left(e^{-j\frac{2\pi f}{R_s}}\right)\right|\right|^2 + \frac{\ell}{\mathrm{SNR}}} df \tag{3}$$

Where $\mathrm{SNR}_{\mathrm{FSE}}$ is the QoT metric that we consider accounting for the the equalization strategy, k_{FSE} is the filtering penalty with respect to SNR in absence of filters, and the minus one term in Eq. 2 accounts for unbiased equalization[11]. ASE noise power injected by optical amplifiers is computed according to a real metro-network scenario, considering $\mathrm{NF}_{\mathrm{INL}} = 6$ dB and $G_{\mathrm{INL}} = 15$ dB as inline amplifiers' noise figure and gain, while for boosters and preamplifiers such values are set to $\mathrm{NF}_{\mathrm{BST}} = \mathrm{NF}_{\mathrm{PRE}} = 9$ dB and $G_{\mathrm{BST}} = G_{\mathrm{PRE}} = 8$ dB. Finally, in this work is assumed that the total number of spans out of the metro portion is equal to $N_{\mathrm{in}} + N_{\mathrm{out}} = 6$. Such amplifiers' specifics lead to a value of $\mathrm{SNR}_{\mathrm{ASE}} = 19.43$ dB at receiver.

Optical filtering is applied by ROADMs according to[13], and each filtering element can be tuned by setting its central frequency f_{WSS}, so that asymmetric filtering can occur, and its bandwidth parameters B_{ch} and B_{OTF}, leading to the coexistence of smoother or sharper filters' shapes along the line.

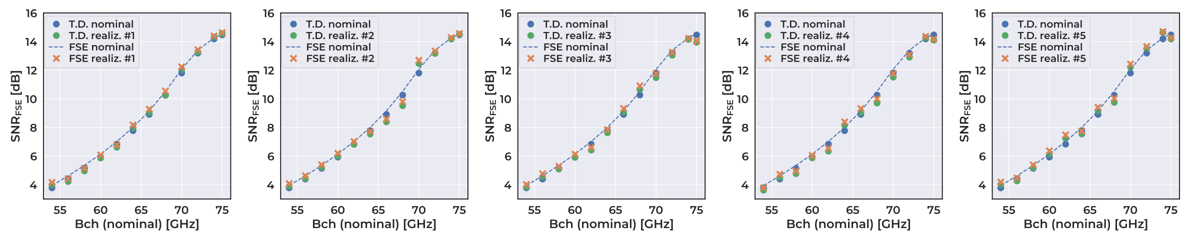
Model Validation

The FSE model experimentally validated in[11] was tested also with respect to time-domain simulation[15], exploring complex filtering configurations which could not be easily deployed in laboratory. For validation, the number of amplified spans at the transmitter and receiver side has been set to $N_{\mathrm{in}} = N_{\mathrm{out}} = 3$. Moreover, each filter parameter has been extracted (independently from other filters and from the other filter parameters) according to a Gaussian distribution[12] as $f_{\mathrm{WSS}} \sim \mathcal{G}(193.9\ \mathrm{THz}, 0.78\ \mathrm{GHz})$ (where the second term in brackets is the standard deviation), $B_{\mathrm{ch}} \sim \mathcal{G}(B_{\mathrm{ch,ref}}\ \mathrm{GHz}, 1.43\ \mathrm{GHz})$ and $B_{\mathrm{OTF}} \sim \mathcal{G}(11\ \mathrm{GHz}, 1.1\ \mathrm{GHz})$. The reference bandwidth $B_{\mathrm{ch,ref}}$ was the same for the entire optical filter cascade and varied from 54 GHz to 75 GHz, repeating the time domain simulation for twelve values. All the process was repeated 5 times extracting independently all the random variables, whose values have been stored to be exploited by FSE model to compute $\mathrm{SNR}_{\mathrm{FSE}}$, which has been compared with the time-domain simulator one. Finally, a simulation with fixed filters' parameters (corresponding to the average values listed before) was performed and taken as reference.

The result of validation is reported in Fig. 2. By comparing the time-domain simulator outcomes for nominal and stochastic filter parameters, the extraction of f_{WSS}, $B_{\mathrm{ch,ref}}$ and B_{OTF} leads to stochastic $\mathrm{SNR}_{\mathrm{FSE}}$ values that are spread around the nominal ones. The FSE model accurately fits both the nominal $\mathrm{SNR}_{\mathrm{FSE}}$ values and the ones corresponding to each realization. A very small shift is present when nominal $B_{\mathrm{ch,ref}}$ is between 65 GHz and 72 GHz, because FSE model assumes infinite equalizer taps, while time-domain simulator equalizer has been set to work with 128 taps. Overall, the FSE model's robustness to filter variation is excellent, as it is clearly exemplified by extreme realizations (for instance looking at Fig. 2b, 2d and 2e), justifying the following Monte Carlo analysis.

Monte Carlo Analyses

The final step of our work is the statistical analysis, through Monte Carlo simulation, of QoT given random variation of optical filters' central frequency (f_{WSS}) and bandwidth parameters (B_{ch}, B_{OTF}). We focused on 3 different strategies for noise injection, which we call ASE pre ($N_{\mathrm{in}} = 5$, $N_{\mathrm{out}} = 1$), ASE distributed ($N_{\mathrm{in}} = 3$, $N_{\mathrm{out}} = 3$) and ASE post ($N_{\mathrm{in}} = 1$, $N_{\mathrm{out}} = 5$), so that the ASE noise contribution is concentrated in different parts of the link. For each strategy, statistical variation is applied on optical filters' parameters. First, the optical filters' central frequencies are randomly distributed



(a) (b) (c) (d) (e)

Fig. 2: Model validation through time-domain (T.D.) simulation

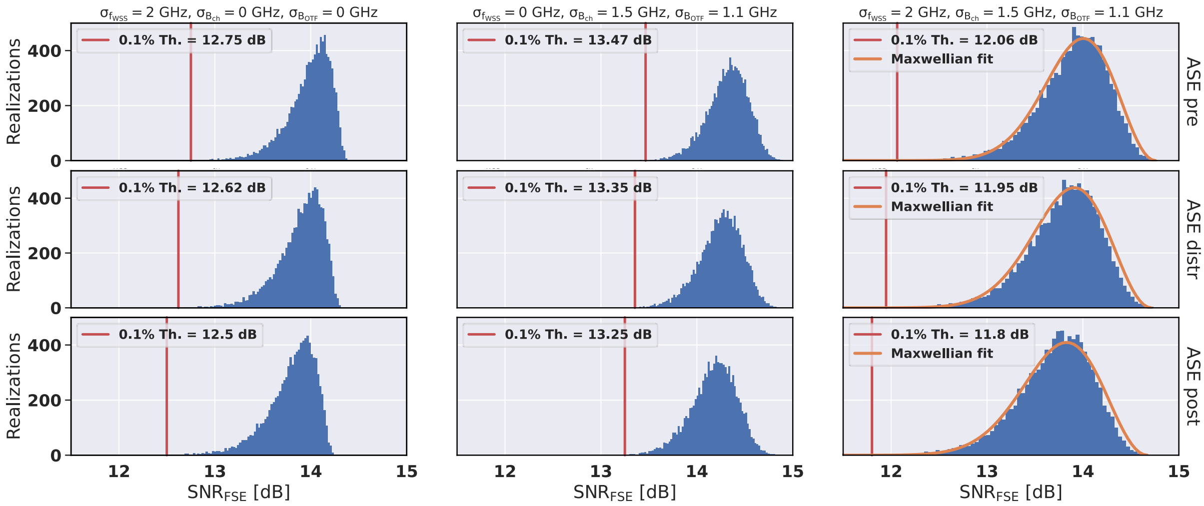


Fig. 3: Monte Carlo simulations results

and the bandwidths are fixed; then central frequencies are fixed and bandwidths are randomly distributed; finally, all the parameters are randomly distributed. In total, 9 scenarios have been simulated, with 10000 runs each. For each filter in the ROADMs cascade, each parameter has been extracted independently at each run, according to the following Gaussian distributions: $f_{\mathrm{WSS}} \sim \mathcal{G}(193.9\ \text{THz}, 2\ \text{GHz})$, $B_{\mathrm{ch}} \sim \mathcal{G}(74\ \text{GHz}, 1.5\ \text{GHz})$ and $B_{\mathrm{OTF}} \sim \mathcal{G}(11\ \text{GHz}, 1.1\ \text{GHz})$, so we fixed the filters reference bandwidth $B_{\mathrm{ch,ref}} = 74$ GHz.

Results are provided in Fig. 3, where along each line we fix the ASE noise injection (pre, distributed, post), while along each column the number of random parameters is the same. We point out that bandwidth parameters variation can lead to higher $\mathrm{SNR}_{\mathrm{FSE}}$, while central frequency misalignment could only worsen the performance, causing asymmetric filtering.

Moreover, when all the filters' parameters are subject to random variations the resulting distribution can be accurately fit by a Maxwellian curve:

$$f_{\mathrm{SNR}_{\mathrm{FSE}}}(x) = k \cdot \frac{(\mathrm{SNR}_{\mathrm{max}} - x)^2}{(\sigma^2)^{3/2}} e^{-\frac{(\mathrm{SNR}_{\mathrm{max}} - x)^2}{2\sigma^2}} \quad (4)$$

Where k is a scaling parameter, σ the standard deviation and $\mathrm{SNR}_{\mathrm{max}}$ is the maximum $\mathrm{SNR}_{\mathrm{FSE}}$ obtained in the simulation. The probability density function is obtained by normalizing $f_{\mathrm{SNR}_{\mathrm{FSE}}}(x)$.

Once the distributions are available, it is possible to perform statistical margin assessment based on a desired out of service (OOS) probability[16]. In this work we set $p_{\mathrm{OOS}} = 0.001$ and we integrated the distributions' left tails, finding a threshold on the SNR: then, $\mathrm{SNR}_{\mathrm{FSE}}$ realizations will be lower than the threshold with probability equal to p_{OOS}. The lower is the threshold value, the higher is the expected penalty, since the distribution is spread towards lower SNR values.

Comparing the thresholds in Fig. 3, an interesting observation can be made on the ASE injection strategy: when ASE noise is "closer" to the receiver (post) the threshold is lower, so the performance is worse, while in the "ASE pre" case thresholds are higher. Such behavior is because the equalizer applies its function based on the transmitted signal. The closer the noise is to the receiver, the greater the difference in number of crossed filter elements, compared to the signal.

The final very important consideration is on the interplay of frequency offset and bandwidth variation. Looking at Fig. 3, the threshold for random central frequency (first column) is way lower than when bandwidth parameters are random (second column). Nevertheless, setting the system threshold as the lower one would be non-conservative, because in the third column it is evident that the interplay between frequency and bandwidth variation leads to an even lower SNR threshold. Therefore, it is highly recommended to consider all the variations operating simultaneously to give a reliable operating margin.

Conclusions

In this paper we evaluated statistical filtering penalty on SNR-based QoT for realistic optical link scenarios and equalization strategy based on the accurate validated FSE model. First, we showed that critical case is when most of the ASE noise is introduced closer to the receiver. Finally, we proved that in assessing a reliable SNR threshold, based on a target OOS probability, the variations of all the optical filters' parameters must be considered simultaneously.

Pursuing the objective of implementing filtering penalty QoT estimation in a DT transmission system, the possibility of computing the OOS threshold exploiting the Maxwellian shape of the filtering-penalty-induced-SNR probability distribution is crucial. In addition the time saving brought by the developed model is huge: time-domain simulation of "Model Validation" section required a couple of days (only 5 realization), while all the 90000 Monte Carlo runs required less than 10 minutes.

Further works will extend the simulation campaign, analyzing the statistical behavior of filtering-penalty-induced-SNR distributions, developing closed formulas to compute system margin.

Acknowledgements

This work has been partially funded by the EU - Next Generation EU under the Italian NRRP, Mission 4, Component 2, Investment 1.3, CUP E13C22001870001, partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART") and by the Telecom Infraproject.

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