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(Article begins on next page)

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Assessing Pre-Emphasis Filter Effectiveness in Metro-Access Optical Networks via Digital Twin

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***Abstract*—We utilize a network digital twin to evaluate the efficacy of a novel, filtering-aware pre-emphasis scheme. The framework, incorporating a realistic transceiver and equalizer model, mitigates filtering-induced performance penalties in converged metro-access optical networks.**

***Index Terms*—Digital Twin, filtering penalties, pre-emphasis filtering, equalization, pre-compensation techniques**

I. Introduction

As next-generation services such as cloud computing, immersive media, and AI/ML-enabled IoT systems drive exponential growth in data traffic, optical networks face escalating performance and efficiency demands [1], [2]. To address these challenges, it is necessary to integrate digital twin paradigms, which provide comprehensive virtual representations and predictive insights that are essential for designing and optimizing future optical communication systems [3]. The convergence of metro and access networks introduces additional requirements that demand accurate knowledge of filtering penalties and transceiver characteristics [4]. This can be achieved through comprehensive modeling and the joint characterization of all filters and noise sources along the transmission line, as discussed in [5], which also proposes a conservative approach to account for nonlinear interference (NLI) by modeling it as an Additive White Gaussian Noise (AWGN) source introduced immediately before the receiver.

Filtering penalties have been widely discussed in previous works. In [6], it was shown that optical filters along the transmission line can introduce performance degradation due to noise enhancement induced by digital equalizers at the receiver. In [7], [8], different equalization strategies were investigated to recover performance under tight filtering conditions, highlighting the effectiveness of Maximum Mean Squared Error (MMSE) equalization. The goodness of MMSE equalization modeling in the presence of filtering impairments has also been demonstrated in [9], [10], supported by extensive modeling efforts and experimental validation.

The additional knowledge of inline filtering impairments can be exploited not only for transmission quality estimation, but also for the design of pre-emphasis (PE) filters within the digital signal processors (DSP), enabling pre-compensation of the filtering effects and thereby enhancing overall system performance. PE filter techniques have already been used to compensate the digital to analog converter (DAC) bandwidth [11], [12] and the linear and non-linear distortions of the electrical and optical transmitter components [13]. However, a filtering-aware PE scheme is still missing. The possibility to rely on an accurate filtering penalty model to perform PE has not been explored yet, and significant work is still needed to understand its potential.

The novelty of this work lies in the combined use of a complete network digital twin (DT), incorporating inline filters and noise sources, together with a PE filter strategy based on line probing and leveraging the transceiver and equalization models from [7]. This framework enables an a priori assessment of the PE filter's effectiveness in the specific network under test, allowing determination of whether its deployment is beneficial for enhancing line performance.

II. PE Filter and Equalization Models

The starting point of this work is the definition of a PE filter applied at the transmitter, which shapes the signal to pre-compensate for the distortion introduced by optical filters along the line. The definition of the PE filter may vary depending on the applications, but for simpler implementations it is convenient to define it as the inverse of the channel transfer function. This is similar to the implementation of the Zero Forcing Equalizer, i.e. $H_{\mathrm{PE}}(f) = (\Pi_i \, H_i(f))^{-1}$, where $H_i(f)$ represents the Fourier transform of the i-th filter in the line. This approach does not consider the position or intensity of noise sources along the line and is therefore not necessarily optimal. Nevertheless, neglecting noise contributions allows a much simpler determination of the PE filter through line probing. In practice, instead of transmitting a modulated signal, an AWGN source with flat power spectral density is injected in the line, and it is filtered by the wavelength-selective switches (WSS) embedded in ROADMs. At the receiver, the observed signal spectrum reflects the aggregate inline filtering and can be directly inverted to obtain the PE filter.

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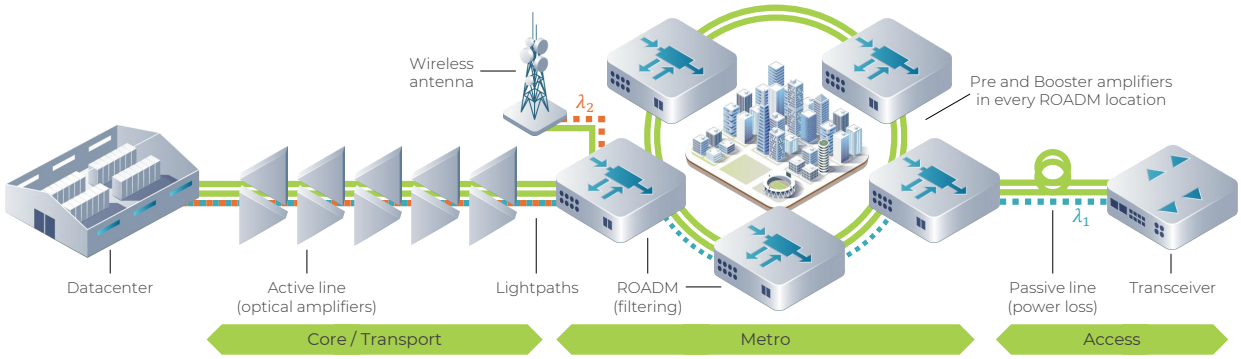


Fig. 1: Realistic example of line topology with two possible connections (λ_1 and λ_2).

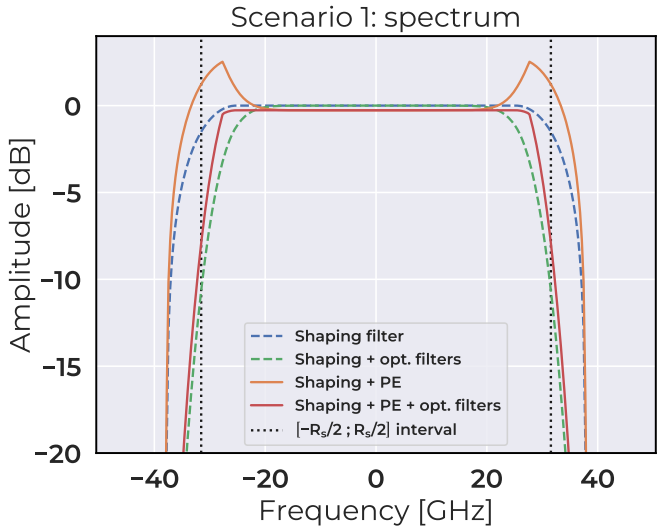


Fig. 2: Shape of the 63.1 GHz signal filtered by the PE filter and by three optical filters, each characterized by bandwidth $B_{\text{ch}} = 63$ GHz and $BW_{\text{OTF}} = 11$ GHz, following the definition in [14].

For practical implementation, the amplitude of $H_{\text{PE}}(f)$ can be constrained. In the following, it is considered with a maximum amplitude of 3 dB and 6 dB above that of the shaping filter, although other values may be selected depending on practical requirements. While larger values can improve shape recovery, they are generally more challenging to implement in realistic scenarios.

To ensure that performance variations do not depend on differences in received power, the PE filter is appropriately scaled such that the area of the shaping filter convoluted with the cascade of all the filters in the line is the same with and without the PE filter. Equivalently, this condition is translated into having the followint relation:

$$\int |H_{\text{RRC}}(f) H_{\text{PE}}(f) \prod_i H_i(f)|^2 \, df = \int |H_{\text{RRC}}(f) \prod_i H_i(f)|^2 \, df \tag{1}$$

Finally, receiver equalization is modeled using the Finite-Length Equalizer (FLE) proposed in [7], [10], based on the MMSE strategy. This model is realistic, as it assumes a digitally implemented equalizer, here configured with 32 taps and 2 samples per symbol (sps), representing plausible settings. The same parameters are employed in time-domain simulations to validate the PE strategy. The simulator in [15] uses the Least Mean Square (LMS) algorithm and allows configuration of both the number of taps and sps.

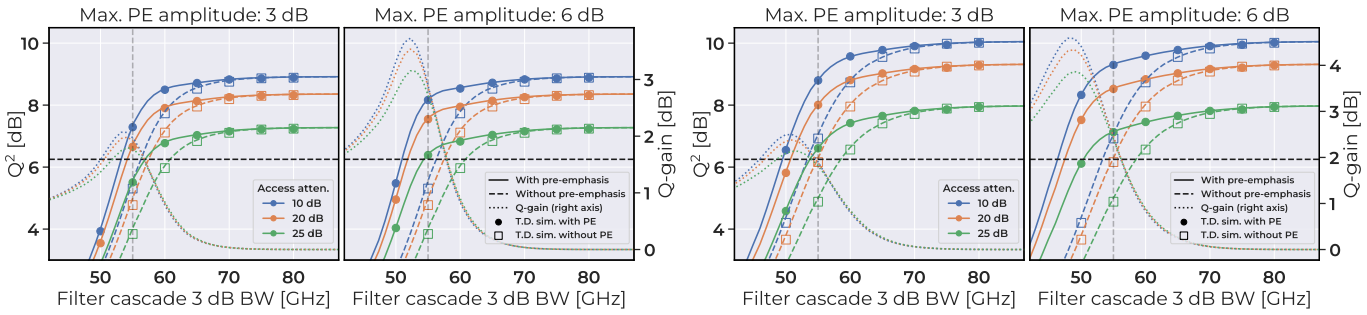
III. Practical Use Cases

We evaluate the effectiveness of the additional PE filter by comparing the performance in presence and absence of the filter itself in two real-case scenarios. We consider the topology shown in Figure 1, which illustrates the convergence of the core, metro, and access networks.

A datacenter is connected to a metro network through a long line of 5×80 km spans, which primarily introduce ASE noise due to four amplifiers (characterized by a noise figure $F = 6$ dB) used to fully-compensate for fiber losses ($\alpha = 0.2$ dB/km). The core section is also responsible for introducing NLI. The corresponding NLI noise power is assumed to be half of the ASE noise power, considering to operate at the optimal working point [16]. The metro network portion, responsible for the filtering effect, includes ROADMs with 14 dB loss along with pre and booster amplifiers ($F = 10$ dB), introducing additional ASE noise.

Finally, the passive access segment introduces uncompensated losses, causing variations in the received optical power (ROP) and, consequently, in the SNR_{TRX} at the receiver, modeled as in [4].

In this framework, we define two propagation scenarios (marked with λ_1 and λ_2 in Figure 1) on which the PE is tested using a 63.1 GHz DP-16-QAM signal. In the first scenario (λ_1) the transmitted signal propagates through the core section and crosses three ROADMs in the metro network, before entering the passive line. The noise is spread before, after, and between sequences of filters, yielding to a general and realistic result. The second scenario (λ_2) consists of a shorter path that crosses only one ROADM in the metro network before entering a passive line, with predominant noise generated in the core network before the filter. All the specifics of amplifiers and optical filters are the same as in the first scenario, as well as the amount of NLI introduced in the core network part. The main



(a) (b)

Fig. 3: Comparison between the longer metro-access line (a) and the shorter core-dominant line (b). Lines depict model predictions, while circles and squares correspond to time-domain simulation validation. The horizontal dashed lines indicate the pre-FEC BER threshold (2×10^{-2}), and the vertical ones mark the equivalent bandwidth of 55 GHz filters.

difference lies in the significantly reduced noise introduced in the metro segment. The comparison of these two alternative configurations is used to comment on the importance of the noise position in the line for effective PE deployment and accurate performance estimation.

In both scenarios the $\mathrm{SNR}_{\mathrm{ASE}}$ is distributed along the transmission link as illustrated in Figure 1, whereas $\mathrm{SNR}_{\mathrm{NLI}}$ and $\mathrm{SNR}_{\mathrm{TRX}}$ are evaluated at the end of the line, following the conservative approach described in [5].

Assuming centered filters, Figure 2 illustrates the procedure used for deriving the PE filter. This is accomplished by inverting the channel transfer function, constraining the filter peak amplitudes, and normalizing the overall gain, as detailed in section II. Nonetheless, the same methodology can be readily extended to account for non-centered or frequency-shifted filters, as demonstrated in [17].

IV. Results and Validation

A digital twin of the transmission line is constructed to replicate the noise sources and filter placements shown in Figure 1. The ASE noise sources are kept constant across simulations, while the filter frequency responses are defined by the well-known equation:

$$S(f) = \frac{1}{2}\sigma\sqrt{2\pi}\left[\mathrm{erf}\left(\frac{\frac{B_{\mathrm{ch}}}{2} - f}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{-\frac{B_{\mathrm{ch}}}{2} - f}{\sigma\sqrt{2}}\right)\right] \quad (2)$$

where $\sigma = BW_{\mathrm{OTF}}/(2\sqrt{2\ln 2})$ depends on the bandwidth of the optical transfer function arbitrary set to $BW_{\mathrm{OTF}} = 11$ GHz of the WSS [14]. The filter widths B_{ch} are the same between the different filters, but are incrementally varied following the validation procedure in [17] in order to test the different filtering conditions. The cascade of multiple WSS filters produces an "equivalent filter bandwidth", defined as the 3 dB bandwidth of the convolution of the individual filter transfer functions. This modeling framework enables precise estimation of the SNR, as in [7], with results subsequently expressed in terms of Q^2-factor, according to [18], so that:

$$\begin{aligned} \mathrm{Q} &= \sqrt{2}\,\mathrm{erfcinv}(2\,\mathrm{BER}) \\ \mathrm{Q}^2_{\mathrm{dB}} &= 10\log_{10}\left(\mathrm{Q}^2\right) \end{aligned} \quad (3)$$

Additionally, as anticipated in section III, the transmitted signal is shaped using a root-raised cosine filter with symbol rate 63.1 GHz and a rolloff $\rho = 0.2$. Since the modulation format is DP-16-QAM, it is possible to compute the received BER given the SNR using the well-known relation:

$$\mathrm{BER} = \frac{3}{8}\mathrm{erfc}\left(\sqrt{\frac{1}{10}\,\mathrm{SNR}}\right) \quad (4)$$

Finally, an arbitrary BER threshold required by the forward error correction (FEC) algorithm has been set to 2×10^{-2}.

The numerical results are reported in Figure 3, comparing the analyzed scenarios and two PE implementations with maximum gains of 3 dB and 6 dB, respectively. As observed, the performance gain provided by the PE filter strongly depends on the filter bandwidth. When the filters are significantly wider than the signal, the filtering effect, and consequently the PE contribution, is negligible, yielding the maximum Q^2-factor achievable for that TRX configuration. Conversely, when the filters are very narrow, the PE provides only limited improvement. Optimal results are obtained for intermediate filter bandwidths, where the equivalent filter width is neither excessively large nor overly restrictive relative to the signal bandwidth. Such result can be observed in Figure 3a, where a maximum Q^2-factor gain of approximately 4 dB is obtained in the considered scenario.

On the contrary, considering the second scenario (λ_2 in Figure 1), the noise is mainly located before the filters: as described in [7], the corresponding filtering penalty is much smaller with the same equivalent filter bandwidth, and thus Q-values are higher as shown in Figure 3b. In this second configuration, the PE filter has a noticeable impact on performance only for very tight filtering conditions. In all considered cases, as expected, a larger maximum gain of the PE filter leads to greater performance improvements, particularly under tight filtering conditions.

To compare the results of the two scenarios, the vertical dashed line in Figure 3 is arbitrarily set at the equivalent filter bandwidth of 55 GHz. As it is possible to observe, the performances of the configuration in Figure 3b with the noise

predominantly located before the filter remains in service even without the additional PE filter, at least with the access loss limited to 20 dB. In this case, the PE gain is not required, and the PE filter can be omitted. Conversely, when considering the results for the first scenario shown in Figure 3a, even the 10 dB and 20 dB configurations are unfeasible with the 55 GHz equivalent filter bandwidth. In this case, the additional Q^2-factor gain due to PE enables the connection to be brought in-service.

In practice, the PE filter becomes essential when operating near the FEC limits in tightly filtered configurations, as its implementation can enable the deployment of additional feasible lightpaths. The possibility to determine whether PE is needed or not is enabled by the accurate DT model, which allows to even adapt the PE to the specific lightpath needs. This marks the importance of comprehensive network knowledge at DT level, encompassing all the possible impairments when evaluating the performance.

To validate the results, a time-domain simulation was performed in all considered cases, both with and without the PE filter, and the results are overlaid with the model in Figure 3. The excellent agreement between the two solutions demonstrates an almost perfect match, confirming that the PE filter, designed according to the proposed method, is correctly handled by the FLE equalizer and achieves the expected performance gain.

V. Conclusions

This work presents a novel and practical approach to leveraging a network digital twin, incorporating precise knowledge of noise sources and filtering devices, along with transceiver and equalizer models, to assess the effectiveness of an additional pre-emphasis (PE) filter applied at the transmitter. The proposed framework enables evaluation of performance gains using a realistic FLE equalizer at the receiver and investigates different practical scenarios, allowing assessment of whether the PE filter provides meaningful benefits in the scenario under consideration or can be omitted, thereby reducing system complexity and cost.

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