Filtering Power Penalty Evaluation of Coherent Systems Affected by ASE and Transceiver Noise

(Article begins on next page)

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***Abstract*—We experimentally evaluate the filtering penalties of coherent transmission, for applications in future metro-access converged systems limited by a mix of ASE and receiver noise, and present and validate an analytical model to predict them.**

***Index Terms*—modelling, performance evaluation, fiber optics, filter**

I. Introduction

Several telecom operators and some recent EU projects are today considering new architectures for converged metro-access networks based on coherent transmission [1], for instance for high-speed fronthauling or novel industrial/campus ultra-high bandwidth terminals. Moreover, an ITU-T workgroup is currently considering future technical solutions for the next generation standard in Passive Optical Networks (PON) that, targeting 200G-PON, may consider coherent transmission as a possible solution, also for the so-called "extended reach PON" options, targeting more than 20 km and/or more than 64 users. In both cases, coherent transmission will likely be implemented on lower-grade (to achieve lower cost) hardware compared to today commercial coherent transceivers for long-haul. Thus, in these future systems, bit error rate (BER) performances may be limited by a mix of both nonlinear effects and amplified spontaneous emission (ASE) noise (characterized by the available generalized optical signal-to-noise ratio, G-OSNR, as in long-haul coherent systems) but also by low received optical power (P_{RX}) and thus by the internal noises that are present in the coherent receiver and, finally, by tight or not-centered optical filtering.

In this paper, we present an experimental evaluation of the filtering penalties in a 400G transmission using commercial PM-QAM16 coherent transceivers. We also present and validate an analytical model to predict these penalties, accounting for generic end-to-end optical transfer functions (determined typically by the cascade of several ROADMs) as a function of G-OSNR and P_{RX} at the receiver. As discussed in the Conclusion section, we believe the proposed analytical model (and its validation) can be a very useful tool for the dimensioning of the aforementioned metro+access converged networks and, due to its very fast computational time, also in quasi-real time network planning tools. The novelties of the paper are in (i) merging the analytical approaches presented in previous papers [2]–[4] (ii) presenting system results in a metro-access or extended-reach PON scenarios and (iii) the experimental validation of the model for generic G-OSNR and P_{RX} combinations.

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II. Analytical model

In [3]–[6] we have presented several analytical models for performance prediction of both coherent and direct detection-based transmission systems. In particular, in [3], [4] we considered a coherent transmission scenario including generic additive noise (both electrical and optical) with frequency and polarization dependent PSD and generic filtering transfer functions. In the following, we extend the work in [3], [4], deriving an analytical equation to model the sensitivity penalty due to filtering for the situation in which optical noise is added after filtering, at the receiver input (lumped noise loading), as shown in the block diagram in Fig. 1(a), together with all the other transceiver internal noises. The frequency resolved $SNR(f)$ at the receiver for the case of lumped amplified spontaneous emission (ASE) noise loading in combination with transceiver (TRX) noise is evaluated as follows:

$$SNR(f) = SNR_G \cdot |H_{PS}(f) \cdot H_{SGF}(f)|^2 \tag{1}$$

$$SNR_G = \left[(SNR_{ASE})^{-1} + (SNR_{TRX})^{-1} \right]^{-1} \tag{2}$$

where SNR_G is the generic SNR accounting for different AWGN sources. SNR_{ASE} is the G-OSNR defined on a band equal to the baud rate R_S and SNR_{TRX} is the SNR related to the TRX-related noises, here evaluated as $SNR_{TRX} = P_{RX}/(R_S \cdot N_0)$ [4], where N_0 [W/Hz] is the equivalent noise power spectral density at the input of the receiver (please see [3] for more detailed info). $H_{PS}(f)$ and $H_{SGF}(f)$ are respectively the transmitter pulse shaping (PS) profile and the super gaussian filter (SGF) used to investigate the filter penalty. At the receiver output, assuming that the receiver performs analog-to-digital conversion and ideal MMSE equalization, we compute the SNR_{eq} as follows [7]:

$$SNR_{eq} = \left(T \cdot \int_{-\frac{1}{2T}}^{\frac{1}{2T}} \left(1 + \overline{SNR}(f)\right)^{-1} df \right)^{-1} - 1 \tag{3}$$

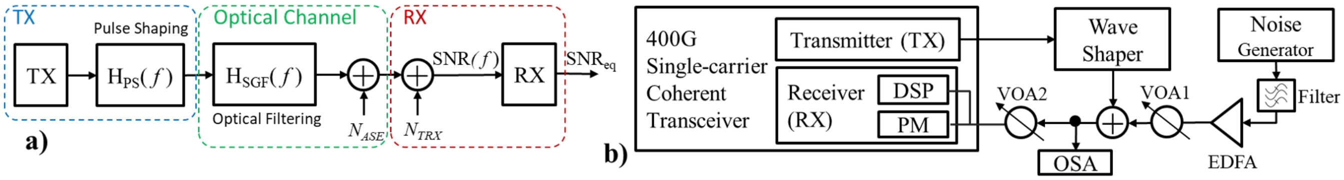

Fig. 1. a) Model abstraction and b) experimental setup.

$$\overline{SNR}(f) = \sum_{\mu} SNR\left(f - \frac{\mu}{T}\right) \tag{4}$$

where $\overline{SNR}(f)$ is the aliased version of $SNR(f)$ due to sampling, μ is the integer number of spectral foldings, and T is the symbol period. Finally, the BER can be computed via the SNR_{eq} as follows: $BER = 3/8\ \mathrm{erfc}(\sqrt{SNR_{eq}/10})$, for polarization multiplexed (PM)-16QAM, to obtain BER vs received power curves and evaluate the sensitivity and the related power penalty ΔP_{RX} (with respect to a reference sensitivity value equal to the back-to-back one). In the next section we compare this theoretical ΔP_{RX} versus the experimental one.

The proposed models are very fast from a CPU computational time, requiring only the numerical evaluation of the one-dimensional integral shown in the previous equation and, compared to time-domain simulations, we showed in previous papers a CPU-time reduction of about 300 and, thus, are very suitable for "real-time" network planning tools.

III. Experimental results

The experimental validation of the model was carried out on the system shown in Fig. 1(b). A commercial coherent transponder (TRX) is used to transmit 400G net bit rate with 63 GBaud PM-16QAM modulation and forward error correction (SD-FEC) with 15% overhead at 0 dBm average optical power. At the TRX output a Finisar 1000S wave shaper is placed to emulate the optical filtering associated with the cascade of wavelength selective switches (WSSs) in a ROADM-based metro-access network. The filter transfer function is modeled with a supergaussian profile with variable order, bandwidth (BW) and central frequency offset (Δf_c) with respect to the central frequency of the signal. An example of the received spectrum measured with the OSA when the BW of the filter is 75% of the symbol rate and for different filter orders is shown later in Fig. 4(c). The additive ASE noise is generated through an EDFA, filtered to obtain spectral flatness, amplified through a second EDFA and finally attenuated through a variable optical attenuator (VOA1) before being added to the filtered signal. VOA1 is used to vary the OSNR, whereas VOA2 is used to vary the P_{RX} at the RX input. The system performance in terms of BER is then characterized as a function of both OSNR and P_{RX} in order to analyze the penalty associated to the TRX operation at very low received optical power levels, as it would be typical in a PON-like communication scenario. Fig. 2 shows the comparison between analytical and experimental results in terms of sensitivity penalty at $BER = 10^{-2}$ as a function of the OSNR for filter bandwidths ranging from 75% to 125% of the symbol rate and for different SGF order. The OSNR is measured on a bandwidth equal to the baud rate. The graphs highlight an increasing penalty with the SGF order. In particular, as the steepness of the filter cutoff increases larger bandwidths are required for the system to work, even at very high OSNR levels. The model is able to predict the experimental performance with a reasonable accuracy within a 1 dB OSNR estimation error.

A contour plot of the achievable RX sensitivity in dBm at $BER = 10^{-2}$ is shown in Fig. 3 as a function of the filter bandwidth-to-baud rate ratio and OSNR, for the three SGF orders. Very small differences can be observed in terms of achievable sensitivity (which is a key parameter for instance in downstream PON) at a given OSNR level for different filter orders. The main filter order impact is again observed at low bandwidths below 90% of the baud rate, where increased steepness prevent the RX equalizer from properly converge. Although the transmitted power is 0 dBm and the link length is very short in our back-to-back experiment, the reported sensitivity can easily allow for over 30 dB optical power budget on the access section of the network if we assume a typical 11 dBm transmitted power. This would allow for extended reach access passive links and extra margin for simpler TRX implementations.

Fig. 4 shows the experimentally measured sensitivity penalty at $BER = 10^{-2}$ as a function of the central frequency misalignment between the SGF and the signal, for filter bandwidths ranging from 75% to 150% of the symbol rate and for two different OSNR values. A maximum of 4 GHz and 5 GHz central frequency offset is allowed to keep the penalty below 1 dB, respectively for OSNR = 20 dB (Fig. 4a) and OSNR = 35 dB (Fig. 4b), when an SGF of order 9 (i.e. an almost rectangular filter) with bandwidth equal to the baud rate is used. For a lower bandwidth at 75% of the baud rate the penalty increases sharply even at the highest 35 dB OSNR and with the lowest SGF order. However, for the lowest SGF order 3 and SGF bandwidth equal to the baud rate the system can withstand central frequency offset very close to 10% of the symbol rate even at the lowest considered OSNR = 20 dB.

IV. Final comments

We present an experimental evaluation of the filtering penalties in a coherent transmission system, and an analytical model to assess these penalties, validating it through the experiments. We believe that the model can be successfully applied to the

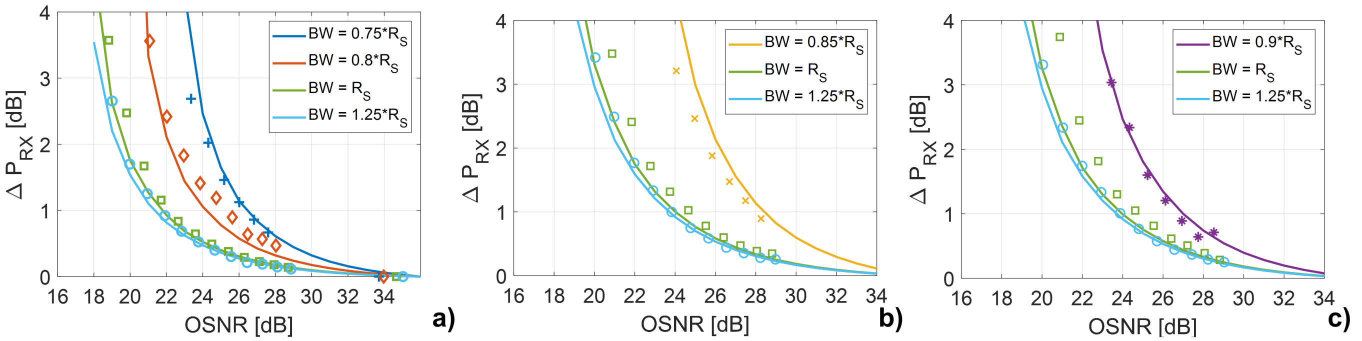

Fig. 2. Measured (markers) and analytical (solid curves) received power penalty at $BER = 10^{-2}$ vs OSNR for different filter bandwidths and (a) SGF order 3, (b) 6 and (c) 9.

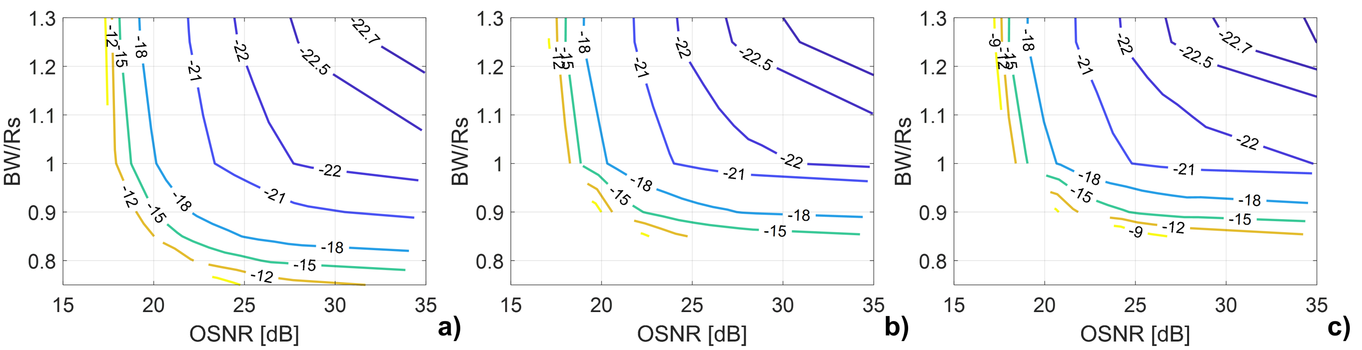

Fig. 3. Measured RX sensitivity at $BER = 10^{-2}$ vs OSNR for several filter bandwidths using SFGs of order (a) 3, (b) 6 and (c) 9.

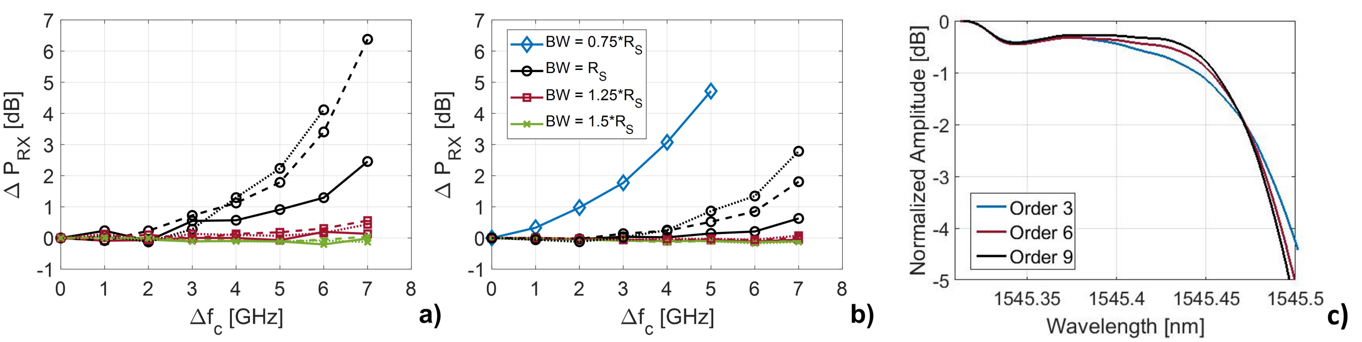

Fig. 4. Measured received power penalty at $BER = 10^{-2}$ vs Δf_c for filter order 3 (solid), 6 (dashed) and 9 (dotted) and (a) OSNR = 20 dB, (b) OSNR = 35 dB. (c) Received spectrum when $BW/R_s = 75\%$ for the three SGF orders as measured with the OSA.

assessment and dimensioning of metro-access or extended-reach PON scenarios. Due to space limitations, we analyzed here only the impact of optical filtering, but we showed in [4] that the proposed model can be applied also when (i) optical transmission has a significant Polarization Dependent Loss, (ii) electrical filtering at the receiver is also relevant and (iii) noise PSD is frequency dependent, and thus, for more general situations in which also the ASE noise goes through generic transfer functions (as it would happen in cascaded EDFA+ROADM systems).

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