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Impact of the Overall Electrical Filter Shaping in Next-Generation 25 and 50 Gb/s PONs

Pablo Torres-Ferrera, Valter Ferrero, Maurizio Valvo, and Roberto Gaudino

Abstract—Next-generation high-speed passive optical networks (HS-PONs) supporting 25, 50, and 100 Gb/s are in the early stages of their standardization process. One key aspect under discussion is the choice of the best modulation format for the transceivers. Performance comparisons among several modulation formats against different physical constraints have been presented in literature and are still being examined. In our present contribution, we performed an exhaustive analysis on the impact of the electrical frequency response of transceivers on the performance of two-level pulse amplitude modulation (PAM-2), 4-level PAM (PAM-4), electrical duobinary, and optical duobinary modulation formats with adaptive equalizers on the receiver side. We show, by means of numerical simulations, that the specification of the typically used -3 dB bandwidth is insufficient, since out-of-band electrical frequency response specifications (such as the -20 dB bandwidth) have a huge impact on the performance of the analyzed modulation formats. We believe that the normalized performance graphs given at the end of the paper in terms of -3 dB and -20 dB bandwidths can thus be useful for the design of next-generation HS-PON transceivers.

Index Terms—Adaptive equalization; APD; Duobinary; Filtering; PAM; PON.

I. INTRODUCTION

Standardization efforts to define the physical layer characteristics of next-generation high-speed passive optical networks (HS-PONs) are currently being carried out in the International Telecommunication Union (ITU), Full Service Access Network (FSAN) Group, and the Institute of Electrical and Electronics Engineers (IEEE) standardization bodies [1–5]. Several research analyses are currently ongoing to choose the best modulation format for HS-PON transceivers for different bit rates under consideration (such as 25, 40, and 50 Gb/s) [6–17]. Due to a low cost constraint, particularly for the optical network unit (ONU) (i.e., user) side, several groups are considering if the transmitter and receiver optoelectronics developed for lower bit rates can be re-used for the new

higher capacity transceivers when associated to more bandwidth efficient modulation formats and/or adaptive equalization (AEQ). In particular, it would be interesting to re-use the optoelectronics developed for a 10 Gb/s PON for the 25 Gb/s target (and even for the 40 or 50 Gb/s ones), and similarly re-use the 25 Gb/s technology developed for the intra-datacenter short-range transceivers, also for 40–50 Gb/s PONs.

The motivation of this work is thus to analyze the feasibility of these goals, focusing on the fact that these transceivers would be severely electrically band-limited when used for the new target bit rates envisioned for HS-PONs (25 and 50 Gb/s). While previous papers in this area usually only focus on the -3 dB bandwidth [18,19], or experimentally on a single given transceiver, we believe our approach is unique because this paper demonstrates, through extensive analyses, the strong impact of the overall frequency transfer function on system performance. We analyzed traditional intensity-modulation transmitters and direct-detection (DD) receivers followed by a digital signal processing (DSP)-based adaptive equalizer. We show that the *out-of-band* transceiver electrical frequency response is important for the modulation formats under consideration that are PAM-2 (i.e., binary on-off keying), PAM-4, electrical duobinary (EDB) [6,11], and optical duobinary (ODB) [8]. Specifically, we provide normalized graphs showing the joint impact of the -3 dB and -20 dB parameters of the frequency response on the system performance. We believe that these graphs offer a useful contribution to the current discussion in the aforementioned HS-PON standardization bodies and to the transceiver vendors that, depending on the details of their optoelectronic technology, can better select how to optimize their component design.

Thanks to our simulative approach, we were able to span a very large set of parameters (-3 dB bandwidth, -20 dB bandwidth, accumulated dispersion, etc.) and then obtain power penalty curves at a specific bit error rate (BER) value for the four different modulation formats. Moreover, we superimposed on our simulative results the expected bandwidths of several existing transmitters and receivers, thus giving a very broad review of the existing literature in this field.

Summarizing our previous considerations, we believe that the main contribution of this paper is in offering design rules for the transceivers' full electrical frequency

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response for different modulation formats. Consequently, our analysis points out the different resiliencies of each modulation format to variations in the available bandwidth and provides information that again can be interesting for component designers. We also report an extensive review of the transfer function of many transmit and receive options (TXs and RXs) presented in the literature, and we give their positioning in our performance estimation graphs.

To this end, the paper is organized in six sections. In Section II, we present the details of the considered transceiver and link architecture and of our simulation environments. In Section III, we discuss different frequency response characteristics, and apply it in Section IV, evaluating the resulting power budget penalty versus filter shape parameters. In Section V, we also introduce the impact of the typical chromatic dispersion accumulated in a PON for different choices of the wavelength band. Finally, we draw a conclusion in Section VI.

II. SIMULATION SETUP

The transceiver and link architecture that we considered in our simulation setup is shown in Fig. 1, where the variable optical attenuator (VOA) is used to span different values of link loss, including the impact of the $1 \times N$ PON splitting ratio. For space limitation, we will not consider the penalty arising from burst mode transmission. Apart from this (important [20]) consideration, our analysis can be applied to both the downstream and upstream directions of a PON link.

At the transmitter side, a binary signal at bit rate R_b (equal to either 25 or 50 Gb/s) is generated by means of a pseudorandom bit sequence (PRBS) $2^{17} - 1$ bits long. The bit stream feeds the electrical TX that creates the appropriate driving signal to generate PAM-2, PAM-4, EDB, or ODB signals in the optical domain. We considered the use of external modulation in this paper or more in general optical transmitters characterized by negligible chirp. The generated electrical signal indicated as $x(t)$ in Fig. 1 is obtained in different ways depending on the modulation format:

(i) In PAM-2 and PAM-4 cases, the binary signal is mapped into a 2-level or 4-level symbol stream, respectively. Gray coding is used in PAM-4.

(ii) In both EDB and ODB cases, the binary signal is digitally pre-coded by applying a standard XOR-based scheme [11]. The resulting 2-level pre-coded signal will eventually turn into a 3-level DB signal thanks to the intrinsic low-pass filtering response of the transceiver. We avoid the use of additional add-and-delay encoding or low-pass electrical filter circuits.

Time-domain simulations are performed using internally developed code fully written in a well-known commercial numerical software. Eight samples per bit (spb) were set. The signal $x(t)$ is normalized to $0 \leq x(t) \leq 1$. We then assume that the DSP can compensate the Mach-Zehnder modulator (MZM) $\cos^2(\cdot)$ instantaneous nonlinear response by applying the pre-distortion,

$$x_D(t) = \frac{A}{\pi} \arccos(1 - 2x(t)) - V_b, \quad (1)$$

where A is an amplitude factor and V_b is the bias-voltage of the MZM. The pre-distorted signal $x_D(t)$ is then filtered using an electrical low-pass filter (LPF) that emulates the electrical frequency response of the TX. The shape of this filter (and the following one at the RX) is one of the main goals of our investigation. Details on the assumed filter shapes will be given in the Section III. The resulting electrical signal after filtering, $x_F(t)$, drives an optical modulator, optically fed by a continuous wave (CW) electrical field, $E_{CW}(t)$, generated by the TX laser. The electrical LPF, the optical modulator, and the laser compose the externally modulated laser (EML) block. The optical signal at the output of the EML is modeled using a classical (chirpless) MZM equation,

$$E_{EML}(t) = E_{CW}(t) \cos \frac{\pi x_F(t)}{V_\pi}, \quad (2)$$

where V_π is the π -voltage of the modulator. By setting both parameters, A and V_b , of Eq. (1) equal to $V_\pi/2$ for PAM-2, PAM-4, and EDB, or equal to V_π for ODB, the MZM is operated in quadrature or null, respectively. The modulated optical signal is then propagated through a conventional single-mode fiber (SMF). Only chromatic dispersion is considered in the fiber model since the nonlinear effects are assumed to be negligible for the relatively short reach (≤ 20 km) applications and power levels under study. The received optical signal is detected by means of an avalanche photodetector (APD) at the receiver (RX) side followed by a transimpedance amplifier (TIA). The APD + TIA configuration currently seems to be the most likely to be applied for a 40-gigabit-capable PON (NG-PON2) and a 10-gigabit-capable symmetric PON (XGS-PON), which is why we decided to focus on it. The photocurrent that outputs the APD + TIA is evaluated by

$$i(t) = \text{GRP}(t) + n_S(t) + n_T(t), \quad (3)$$

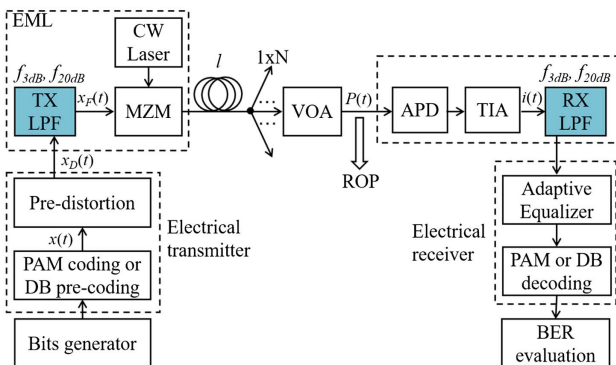


Fig. 1. Simulation setup.

178 where R is the APD responsivity (assumed to be
179 $R = 0.8$ A/W), G is the APD gain factor [assumed to be $G =$
180 25 (14 dB)] [21,22], and $P(t)$ is the optical signal instantane-
181 ous power that feeds the APD. The signals $n_S(t)$ and
182 $n_T(t)$ emulate the shot noise and thermal noise, respec-
183 tively. They are modeled as Gaussian random processes
184 with zero-mean and variances given by [23]

$$\sigma_S^2(t) = qG^2FRP(t)\Delta f_s, \quad (4)$$

$$\sigma_T^2 = N_0\Delta f_s, \quad (5)$$

185 respectively, where F is the APD excess noise factor (we as-
186 sume $F = G^{0.75} = 10.5$ dB), q is the electron charge, N_0 is
187 the input-referred electrical current thermal noise power
188 spectral density ($N_0 = 1.024 \times 10^{-21} \text{A}^2/\text{Hz}$), and Δf_s is
189 the bandwidth of the simulation ($\Delta f_s = \text{spb} \cdot R_b$). The over-
190 all thermal noise of APD and TIA contributions are in-
191 cluded in the $n_T(t)$ noise term. The numerical values
192 assumed here are just indicative values for today's typical
193 10G PON receivers. Since we present our results in terms
194 of the relative power penalty among different modulation
195 formats (see Sections IV and V), their actual values, how-
196 ever, will have relatively little impact on the penalty
197 graphs.

198 After the APD + TIA, an electrical LPF emulates the RX
199 frequency response. The characteristics of this RX LPF are
200 the same as the TX LPF, and they are described in the next
201 section. We know that this is not the more general case
202 since the TX and RX filter shapes are independent. We in-
203 troduce this assumption to limit the number of free param-
204 eters to be spanned. In the next section, an extended
205 discussion regarding this consideration is presented.

206 Since we want to focus on severely band-limited trans-
207 ceivers, we assume that the received electrical signal is
208 equalized by an adaptive feed-forward equalizer (FFE) us-
209 ing least-mean square (LMS) as an adaptation algorithm
210 [19,24] with two samples per symbol and 20 taps. This
211 number of taps was selected to guarantee the right opera-
212 tion of the system in very dispersive and band-limited
213 scenarios. In some cases, however, the system can operate
214 with fewer taps without an additional penalty. The equal-
215 izer is trained with a proper pilot sequence, which for
216 PAM-2, PAM-4, and ODB is simply the original transmit-
217 ted symbol sequence. For EDB, we use a 3-level DB symbol
218 stream obtained after encoding the input pre-coded signal
219 by means of an add-and-delay block. The equalized signal
220 is then decoded according to the employed modulation for-
221 mat. Finally, the bit error rate (BER) is evaluated using di-
222 rect error counting over 1.3×10^5 bits (after the training
223 sequence), a situation that is very CPU-time demanding,
224 but allows very precise estimation of the BER around
225 the 10^{-3} target value.

226 The main figure of merit employed in this work to evalu-
227 ate the performance of the system is the sensitivity (S),
228 defined as the received optical power (ROP) in dBm to
229 reach a BER target of 10^{-3} (i.e., the pre-FEC value selected,
230 for instance, for NG-PON2 in ITU-T G.989.2 for 10 Gb/s).

III. FILTERING CONSIDERATIONS

231

232 We emulate narrowband transceivers using two
233 electrical LPFs, one at the TX side and one at the RX side.
234 One key parameter of a transceiver frequency response is
235 obviously its -3 dB electrical bandwidth ($f_{3\text{dB}}$). Most of the
236 experimental and commercial device characterizations pro-
237 vide information about this parameter. However, as the
238 main target of our work, we focus on the fact that not only
239 the $f_{3\text{dB}}$ parameter is fundamental, but the out-of-band (i.
240 e., $f > f_{3\text{dB}}$) frequency response of the devices also has a
241 strong impact on the overall system performance. We show,
242 for instance, that for the same $f_{3\text{dB}}$ value, very different
243 performance can be achieved depending on the actual value
244 of, say, the -20 dB bandwidth. Moreover, we will show that
245 the sensitivity versus this last parameter is very different,
246 depending on the modulation format used. To the best of
247 our knowledge, this is a novel analysis for the HS-PON
248 scenario, since the out-of-band transceiver electrical fre-
249 quency characterization is barely ever considered in detail
250 in the available literature. To investigate the relevance of
251 this out-of-band filter shaping, we introduce the -20 dB
252 bandwidth parameter ($f_{20\text{dB}}$) in our present analysis.
253 The joint impact of the $f_{3\text{dB}}$ and the $f_{20\text{dB}}$ parameters is
254 then tested, providing an extra degree of information re-
255 garding the impact of the filtering shape on the perfor-
256 mance. We present most of our results using the
257 parameters $B_{3\text{dB}}$ and $B_{20\text{dB}}$, which are a representation
258 of $f_{3\text{dB}}$ and $f_{20\text{dB}}$, respectively, normalized to the bit rate,
259 expressed in percentages, and thus defined as

$$B_{3\text{dB}}[\%] = \frac{f_{3\text{dB}}}{R_b} \times 100 \quad \text{and} \quad B_{20\text{dB}}[\%] = \frac{f_{20\text{dB}}}{R_b} \times 100. \quad (6)$$

260 The degrees of freedom in electrical filter shapes are ob-
261 viously infinite, so we had to make a somewhat arbitrary
262 decision and select a few canonical transfer functions used
263 in the literature [25]. We opted for the Butterworth (BF)
264 and super-Gaussian filter (GF) profiles. Because the former
265 is straightforward, it was selected to exactly set the desired
266 $f_{3\text{dB}}$ parameter and to characterize it in terms of the num-
267 ber of poles [25]. Moreover, the BF frequency response is as
268 flat as possible in the passband [25], thus reducing, as com-
269 pared to other filter types, the in-band shape variations (for
270 a fixed passband bandwidth) when changing the out-of-
271 band steepness. This feature is useful if researchers want
272 to analyze the impact of the out-of-band shape variations
273 as independently as possible on the in-band shape changes
274 (as in the present contribution). However, in BF and for a
275 fixed $f_{3\text{dB}}$, the value of the $f_{20\text{dB}}$ parameter is subject to the
276 choice of the number of poles of the filter (that is, an integer
277 number) and, consequently, $f_{20\text{dB}}$ can be only changed
278 over given (and quite coarse) discrete values. Therefore,
279 for BF, it is not possible to set any arbitrary combination
280 of the $f_{3\text{dB}}$ and $f_{20\text{dB}}$ parameters. The use of GFs overcomes
281 this limitation by allowing an independent variation of
282 $f_{3\text{dB}}$ and $f_{20\text{dB}}$. The frequency profile of a GF is defined here
283 as [26]

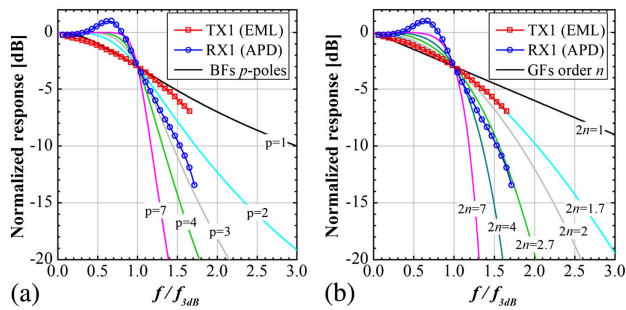


Fig. 2. (a) Butterworth (BF) and (b) Super-Gaussian filter (GF) profiles, for different numbers of poles and order, respectively. The normalized experimental response of the TX (EML) and the RX (APD) found in literature [17] are also shown.

$$H(f) = \exp\left(-\frac{1}{2}\left(\frac{f}{f_0}\right)^{2n}\right), \quad (7)$$

where n is the order of the GF filter (which now does not necessarily need to be an integer) and f_0 is a free parameter. The two free and real values, n and f_0 , can be set to obtain a frequency response having any possible combination of $f_{3\text{dB}}$ and $f_{20\text{dB}}$ (as long as $f_{20\text{dB}} \geq f_{3\text{dB}}$). In Figs. 2(a) and 2(b), the filter shape profiles of the BF and GF models, respectively, are presented for different numbers of poles and order, using on the x -axis as the frequency normalized to $f_{3\text{dB}}$. The frequency responses of a realistic TX-RX pair experimentally reported in [17] are also displayed in the figure. From Fig. 2 it can be seen that, after a proper fitting of its two degrees of freedom, the GF model allows a good emulation of the out-of-band frequency response of the realistic TX and RX. The fitting using the BF model is less precise, due to the aforementioned discretization on the number of poles. This result also shows that a realistic transceiver cannot be easily modeled using zeros and poles rationale transfer functions if one must emulate accurately the frequency response also above the 3 dB band. Having said this, most of the results in Sections IV and V will be presented for both GF and BF models to have a full view of the filter shaping problem.

The most significant simplifying assumption made in this work is that the TX and RX LPFs are identical (i.e., they have the same filter shape). Although, this approach may not appear very realistic, a systematic analysis testing different combinations of $f_{3\text{dB}}$ and $f_{20\text{dB}}$ values in both the TX and RX filters would require studying a huge number of cases and several degrees of freedom, which is very impractical. We found that the equivalent filter formed after cascading any pair of TX and RX identical LPFs can approach well the overall equivalent frequency response formed by any particular combination of real TX and RX devices with different filter shaping (i.e., TX and RX with different $f_{3\text{dB}}$ and $f_{20\text{dB}}$ values). As a practical example, the same TX-RX pair taken from [17] and already represented in Fig. 2 (TX1 EML $f_{3\text{dB}} = 8.9$ GHz, RX1 APD $f_{3\text{dB}} = 7.5$ GHz) is used again in Fig. 3 to obtain the concatenated TX + RX transfer function, shown by a solid black curve. On the same figure, the response of the cascade of two identical GFs (or BFs) is shown in dashed green (or dotted pink, for a pair of

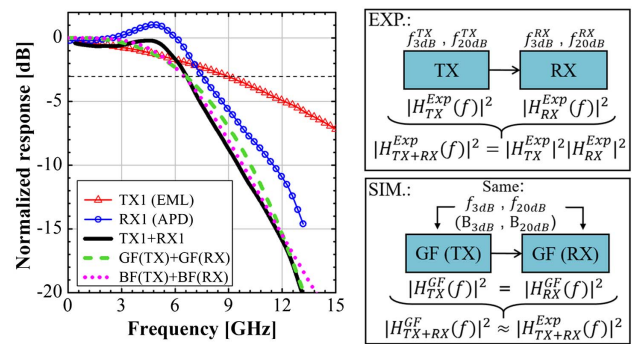


Fig. 3. Left side: TX (EML) and RX (APD) frequency characterization reported in [17]. In solid black, the TX+RX equivalent response. In dashed (dotted), the equivalent frequency response of a pair of identical GFs (BFs), with the same $B_{3\text{dB}}$ and $B_{20\text{dB}}$. Right side: Diagram of our employed best-fitting procedure (EXP, Experimental data, and SIM, Simulation approach).

identical BFs) curve. In the case of GFs, a good matching with the solid black curve was obtained with two identical GFs, each with $f_{3\text{dB}}$ equal to 8.5 GHz and $f_{20\text{dB}}$ equal to 17 GHz. The equivalent pair of identical BFs are 2-pole filters, each with $f_{3\text{dB}}$ equal to 8.1 GHz.

We followed this fitting procedure (shown in Fig. 3) for a large set of experimental devices reported in the literature. In particular, we evaluated the $f_{3\text{dB}}$ and $f_{20\text{dB}}$ values (and corresponding $B_{3\text{dB}}$ and $B_{20\text{dB}}$) of the GFs whose cascaded responses best matched the cascaded response of experimental or commercial TX + RX devices (see Fig. 3, right-hand diagram), and we summarized the results in Table I. Please note that all of these TX and RX devices were developed for standard NRZ 10 Gb/s transmission, which we will label in the rest of the paper as 10G

TABLE I
NORMALIZED (FOR 25 OR 50 Gb/s TRANSMISSION) -3 dB AND -20 dB BANDWIDTH ($B_{3\text{dB}}$ AND $B_{20\text{dB}}$) FOR EACH OF THE IDENTICAL GFs AT TX AND RX WHOSE CASCADE RESPONSE BEST FITS THE EQUIVALENT RESPONSE OF THE TX + RX 10G COMPONENTS REPORTED IN THE REFERENCES

C.	TX (Exp.)		RX (Exp.)		GF, $R_b = 25$		GF, $R_b = 50$		T1:1 T1:2 T1:3 T1:4 T1:5 T1:6 T1:7 T1:8 T1:9 T1:10 T1:11 T1:12 T1:13 T1:14 T1:15
	Ref.	$f_{3\text{dB}}^{\text{TX}}$	Ref.	$f_{3\text{dB}}^{\text{RX}}$	$B_{3\text{dB}}$	$B_{20\text{dB}}$	$B_{3\text{dB}}$	$B_{20\text{dB}}$	
1	[17]	8.9	[17]	7.5	34	68	17	34	T1:3
2	[17]	8.9	[28]	8.8	32.8	112	16.4	56	T1:4
3	[17]	8.9	[29]	8.1	32	136	16	68	T1:5
4	[17]	8.9	[22]	6.8	29.6	96	14.8	48	T1:6
5	[27]	7.7	[17]	7.5	32	56	16	28	T1:7
6	[27]	7.7	[28]	8.8	27.6	80	13.8	40	T1:8
7	[27]	7.7	[29]	8.1	28	96	14	48	T1:9
8	[27]	7.7	[22]	6.8	26.8	72	13.4	36	T1:10
9	^a	9.9	[17]	7.5	34	70	17	35	T1:11
10	^a	9.9	[28]	8.8	35.2	100	17.6	50	T1:12
11	^a	9.9	[29]	8.1	34.8	128	17.4	64	T1:13
12	^a	9.9	[22]	7.5	31.6	92	15.8	46	T1:14
13	[30] ^b	$f_{3\text{dB}}^{\text{Sys}} = 6.3$ GHz			33.2	70	16.6	35	T1:15

C.: Case. $f_{3\text{dB}}^{\text{TX}}$ and $f_{3\text{dB}}^{\text{RX}}$ in GHz. $B_{3\text{dB}}$ and $B_{20\text{dB}}$ in %. R_b in Gb/s.
^aNG-PON2 TX characterization provided by Telecom Italia.
^bIn this particular case, $f_{3\text{dB}}^{\text{Sys}}$ indicates: $f_{3\text{dB}}$ of the overall system.

TABLE II
NORMALIZED (FOR 50 Gb/s TRANSMISSION) -3 dB AND -20 dB BANDWIDTH ($B_{3\text{dB}}$ AND $B_{20\text{dB}}$) OF EACH OF THE IDENTICAL GF'S AT TX AND RX WHOSE CASCADE RESPONSE BEST FITS THE EQUIVALENT RESPONSE OF THE TX + RX 25G COMPONENTS REPORTED IN THE REFERENCES

	TX (Exp.)			RX (Exp.)		GF, $R_b = 50$ Gb/s	
	C.	Ref.	[GHz]	Ref.	$f_{3\text{dB}}^{\text{RX}}$ [GHz]	$B_{3\text{dB}}\%$	$B_{20\text{dB}}\%$
T2:1							
T2:2							
T2:3	1	[31]	18.9	[33]	15.8	34	60
T2:4	2	[31]	18.9	[34]	24.5	40	132
T2:5	3	[31]	18.9	[35]	32	45	140
T2:6	4	[31]	18.9	[36]	19.9	40	88
T2:7	5	[32]	28.2	[33]	15.8	32	58
T2:8	6	[32]	28.2	[34]	24.5	50	130
T2:9	7	[32]	28.2	[35]	32	50	110
T2:10	8	[32]	28.2	[36]	19.9	44	88
T2:11	9	[27]	23.9	[33]	15.8	30	58
T2:12	10	[27]	23.9	[34]	24.5	42	84
T2:13	11	[27]	23.9	[35]	32	44	90
T2:14	12	[27]	23.9	[36]	19.9	38	78

technology. In Table II, the same information is reported for another set of experimental devices reported in literature for the 25 Gb/s transmission, called in this paper 25G technology. The information provided in Tables I and II is very helpful to contextualize our results in the framework of state-of-the-art technology.

From Table I, we can observe that the same couple of TX-RX devices has associated with a different pair of $B_{3\text{dB}}$ and $B_{20\text{dB}}$, depending on the value of R_b . This arises because, although the $f_{3\text{dB}}$ and $f_{20\text{dB}}$ parameters of the corresponding identical GFs are the same irrespective of R_b , the $B_{3\text{dB}}$ and $B_{20\text{dB}}$ values are normalized to the bit rate, as indicated in Eq. (6).

IV. BACK-TO-BACK RESULTS

A back-to-back (BtB) performance comparison among the four modulation formats is presented in this section. For BtB, we mean a simulation that emulates the transceiver bandwidth limitations (thus taking into account only the filtering effects in the TX and RX), the electro-optical and opto-electrical conversions, and the noise at the receiver. The effect of the fiber (i.e., chromatic dispersion) will then be introduced in the next section.

We started the BtB analysis by considering 1-pole BF's as the electrical frequency response of each TX and RX device. In the inset of Fig. 4(a), we report the filter profiles of the individual TX, or RX, 1-pole BF (solid) and the cascaded response of them (dotted), for a (single filter) $f_{3\text{dB}} = 7$ GHz. To enable a fair comparison, the performance is evaluated in terms of the power penalty taking as a reference the sensitivity of PAM-2 in its optimal conditions (without any BW limitations and in a BtB scenario). This sensitivity (the ROP to guarantee 10^{-3} BER) is termed S_0 , and, for the APD noise levels reported in the previous section, it is equal to $S_0 = -28.1$ dBm for $R_b = 25$ Gb/s, and $S_0 = -25.7$ dBm for $R_b = 50$ Gb/s. The computed power penalty

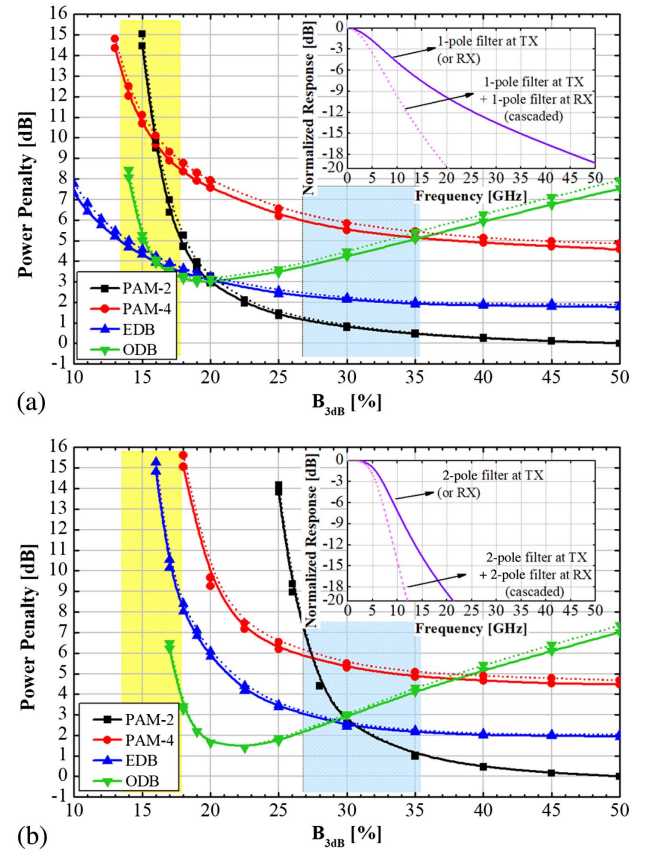


Fig. 4. Performance comparison among modulation formats in terms of the power penalty with respect to S_0 , the PAM-2 sensitivity in the best condition (BtB unlimited bandwidth case, $S_0 = -28.1$ dBm for 25 Gb/s and $S_0 = -25.7$ dBm for 50 Gb/s), as a function of the $B_{3\text{dB}}$ of the filters. (a) 1-pole BF and (b) 2-pole BF (depicted in the inset). Solid lines for $R_b = 25$ Gb/s, dotted lines for $R_b = 50$ Gb/s. Colored regions: In blue (yellow): 10G technology to transmit 25 (50) Gb/s.

of each modulation format as a function of the $B_{3\text{dB}}$ parameter is shown in Fig. 4(a), for both analyzed bit rates: 25 Gb/s (solid) and 50 Gb/s (dotted). Thanks to the employed definition of the power penalty, there is a very close match between the results of the two analyzed bit rates, as demonstrated by the fact that the difference between the solid (25 Gb/s) and dotted (50 Gb/s) curves is negligible irrespective of the modulation format. By using the information provided in Table I, we also superimposed on Fig. 4 a pair of colored regions that qualitatively indicate the range of $B_{3\text{dB}}$ values that current 10G transceivers exhibit when transmitting at 25 Gb/s (in blue) and 50 Gb/s (in yellow).

From Fig. 4 we can observe that in spite of using AEQ, the impact of limited system bandwidths is not completely canceled (as expected for an FFE-LMS-based AEQ [24] operating over a noisy signal). However, we have verified that the penalty due to system bandwidth reduction is much less pronounced using the AEQ scenario considered in this paper than for a not-equalized receiver (we cannot show the relative comparison here due to space limitations).

As discussed in the previous section, a 1-pole filter is very likely too optimistic for most realistic transceivers. To explore the impact of the out-of-band filter shaping on the analyzed modulation formats performance, the procedure to obtain the results presented in Fig. 4(a) is performed again using 2-pole BFs, but keeping the other assumptions the same. The corresponding results obtained under this new situation are presented in Fig. 4(b). One of the key points of our paper can be seen here: The out-of-band steepness of the transceivers' frequency response significantly affects the system performance even for the same -3 dB bandwidth, and changes the performance ranking of the different modulation formats. For instance, let us consider the transmission of 25 Gb/s using 10G technology-based transceivers (case referred here as 25G/10G, shown in the blue-colored area of Fig. 4). In this situation, if the transceiver response is modeled using a 1-pole BF approach, PAM-2 outperforms the rest of the modulation formats in the complete 25G/10G (blue) region. However, if the filter's response model changes from one- to two-pole BF [Fig. 4(b)] PAM-2 starts to become critical, and it is, for instance, surpassed by EDB in part of the 25G/10G region of the graph. As another example, let us now consider the transmission of 50 Gb/s using 10G technology (case referred to here as 50G/10G, shown in the yellow colored area of Fig. 4). From Fig. 4(a), we can observe that EDB, ODB, and even PAM-4 (with a strong penalty) could be feasible alternatives for the 50G/10G transmission if a 1-pole filter case is considered (while PAM-2 is clearly out of the question). If we again change the filter response to a 2-pole profile, we can see from Fig. 4(b) that even EDB, ODB, or PAM-4 would operate in a region with exceedingly high penalty.

These first two examples show the performance dependency of the modulation formats versus the transceivers' frequency response, not only in terms of the -3 dB bandwidth (as commonly done in much of the analysis in the current literature), but also as a function of the out-of-band (i.e., above the -3 dB point) filter steepness.

We thus prosecute our analysis by also considering a parameter that would characterize the out-of-band response. As mentioned in Section III, we selected for this goal the frequency at a -20 dB attenuation (i.e., the $f_{20\text{dB}}$ parameter and its normalized version, $B_{20\text{dB}}$). Note that another reference attenuation value could also have been chosen to quantify the degree of tilting of the out-of-band response. The use of the -20 dB attenuation value was selected arbitrarily but, as we will show, it turned out to be a very relevant parameter.

To start the out-of-band filter impact analysis, we fixed the $B_{3\text{dB}}$ parameter to 28%, which is a representative state-of-the-art case for the 25G/10G transmission as shown in Table I, and varied the number of poles of the BFs. As shown in Fig. 2(a), for a BF with a given $f_{3\text{dB}}$, increasing the number of poles corresponds to an increase in the out-of-band filter steepness, and a decrease in its -20 dB bandwidth. The performance of the four modulation formats in terms of the relative power penalty as a function of the BF number of poles (or the corresponding $B_{20\text{dB}}$ parameter) is shown in Fig. 5 (markers only), for 25 Gb/s transmission.

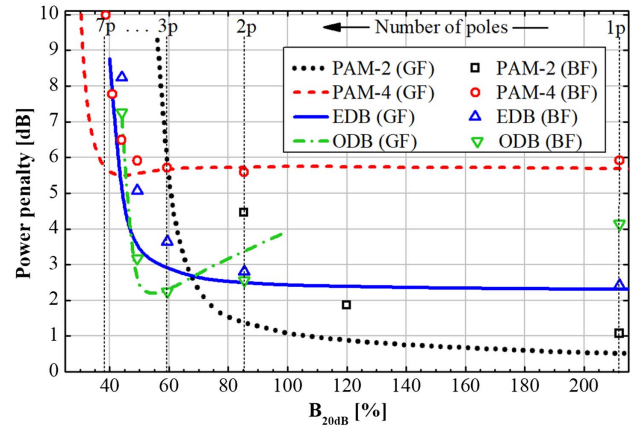


Fig. 5. Performance comparison in terms of $B_{20\text{dB}}$ using BF (only marker curves) and GF (only line curves). A 25 Gb/s transmission is considered. The $B_{3\text{dB}}$ is fixed to 28% ($f_{3\text{dB}} = 7$ GHz for $R_b = 25$ Gb/s). The power penalty is relative to PAM-2 $S_0 = -28.1$ dBm for $R_b = 25$ Gb/s.

Since the number of poles is an integer parameter, only certain discrete $B_{20\text{dB}}$ values can be evaluated. To overcome this too coarse discretization of $B_{20\text{dB}}$, the use of the GF model to emulate the transceiver frequency response is introduced. Under this GF approach, continuous curves of a relative power penalty versus $B_{20\text{dB}}$ can now be obtained, and are depicted in Fig. 5 (curves without markers). Apart from the differences that occur using the BF or GF model, Fig. 5 shows with evidence the great relevance of the exact value of the out-of-band filter shape and, again, the fact that the performance ranking among modulation formats is also greatly affected by this parameter. For instance, although PAM-2 is the best modulation format in the $B_{20\text{dB}} > 120\%$ region, for $B_{20\text{dB}} \leq 70\%$ PAM-2 starts to become exceedingly critical in terms of the penalty. The EDB solution has, on the contrary, a good resilience for low $B_{20\text{dB}}$ values, showing just small penalties down to the $B_{20\text{dB}} = 50\%$ region. PAM-4 also exhibits a good tolerance, even for $B_{20\text{dB}} = 40\%$. ODB has a very peculiar behavior, showing both in Fig. 4 (versus $B_{3\text{dB}}$) and Fig. 5 (versus $B_{20\text{dB}}$) that it may be considered the best modulation format for very low bandwidths, but only if the $B_{3\text{dB}}$ and $B_{20\text{dB}}$ are optimized to their proper values. However, for $B_{20\text{dB}} > 60\%$ values, the ODB sensitivity starts to get worse. The increased penalty shown with the GF approach is attributed to the reduced in-band power that this filter collects with respect to BFs for higher values of $B_{20\text{dB}}$ (see Fig. 2). In the case of PAM-2, a close match between the BF and GF filter shape is only found when the filter steepness is very low (around the 1-pole BF case). Please note that for PAM-2, a point between the 1- and 2-pole cases was plotted. This point was measured by setting a 1-pole filter at the TX and a 2-pole filter at the RX (which corresponds to a 3-pole filter when the TX and RX filters are cascaded, emulating symmetric 1.5-poles at the TX and RX situation). This is the only exceptional point that was evaluated using different characteristics at TX and RX filters in this contribution. However, following the same approach, the performance of the system using a 1-pole filter at the TX and a 3-pole filter

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494 at the RX was also tested for PAM-2 (corresponding to a 4-
 495 pole filter when cascading the TX and RX, equivalent of
 496 having a 2-pole filter at the TX and one at the RX if a linear
 497 system is assumed). The sensitivity measured under this
 498 situation was the same as having 2-pole filters at TX
 499 and RX, which shows that the system behavior is mostly
 500 linear, and the cascaded assumptions described in
 501 Section III can be considered accurate.

502 To summarize, Fig. 5 suggests that when ranking the
 503 modulation format tolerance against the variation of the
 504 $B_{20\text{dB}}$ parameter, PAM-4 and EDB show the best degree
 505 of resilience, PAM-4 being the most robust format for
 506 extremely low $B_{20\text{dB}}$, but obviously starting from its intrinsic
 507 penalty that is present compared to PAM-2 for high
 508 bandwidths. ODB has very interesting performance, but
 509 only for an optimized filter bandwidth, while EDB shows
 510 a very good compromise on a very large range of $B_{20\text{dB}}$
 511 values.

512 Compared to the actual data extrapolated from commercial
 513 transceivers and reported in the aforementioned
 514 Tables I and II, we can see that the $B_{20\text{dB}}$ parameter
 515 can vary from around 60% to even 140%, for different
 516 state-of-the-art devices. This fact highlights the need to
 517 consider the robustness of a modulation format against
 518 both in-band and out-of-band filter shaping variations as
 519 a relevant parameter.

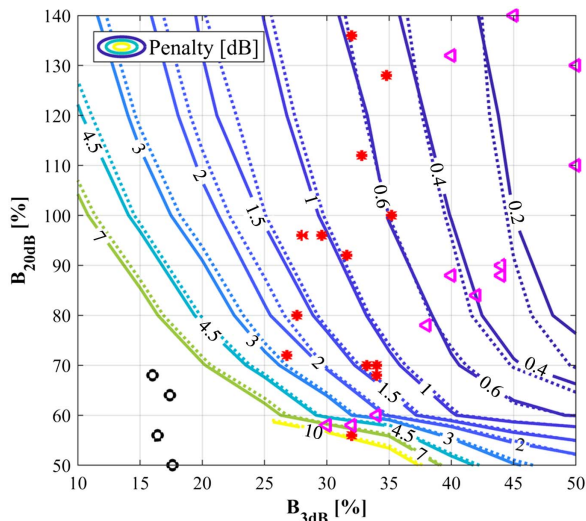
520 The results shown in Fig. 5 were obtained for a fixed
 521 value of $B_{3\text{dB}} = 28\%$. For different $B_{3\text{dB}}$ values, the conclusions
 522 may change. We thus performed an extensive study
 523 on the impact of a joint variation of the $B_{3\text{dB}}$ and $B_{20\text{dB}}$
 524 parameters. Results are presented in Fig. 6, which shows
 525 the power penalty of PAM-2 with respect to its best
 526 sensitivity S_0 ($S_0 = -28.1$ dBm for $R_b = 25$ Gb/s, and

527 $S_0 = -25.6$ dBm for $R_b = 50$ Gb/s) as a function of both
 528 $B_{3\text{dB}}$ and $B_{20\text{dB}}$ variables. We believe this is one of the
 529 key results of our paper, giving transceiver designers an
 530 overview of the best system solutions. Using this graph,
 531 a component designer can trade off the component parameters
 532 that most affect the $B_{3\text{dB}}$ and $B_{20\text{dB}}$, and use the best
 533 design choices.

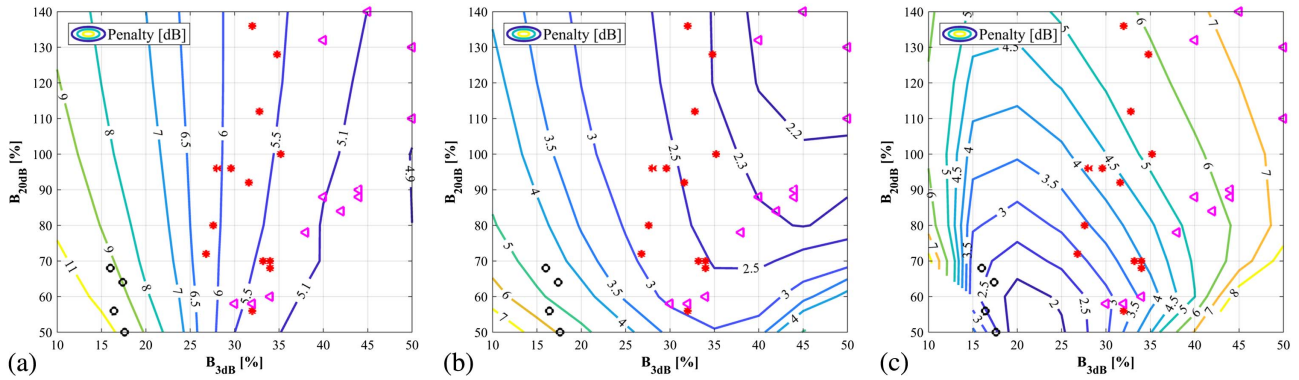
534 In Fig. 6, the contour plots in solid lines correspond to
 535 the 25 Gb/s case, while the ones in dotted lines to the
 536 50 Gb/s transmission. A very good agreement between
 537 the solid and dotted curves is again found. Tables I and
 538 II show the real frequency response characteristics of
 539 the transceivers, which are also displayed in Fig. 6, in
 540 which any pair of $B_{3\text{dB}}$ and $B_{20\text{dB}}$ is considered as the
 541 coordinates of a point in the plane (indicating the operation
 542 regions of the current devices). Note the huge transceiver
 543 filter shaping impact on the performance. For instance,
 544 when using 25G transceivers for 50 Gb/s transmission
 545 (pink triangles), considering different real devices we
 546 can have a negligible penalty (lower than 0.2 dB in some
 547 cases), but in other cases the penalty can reach 10 dB.
 548 The same information is plotted in Fig. 7 for the other
 549 modulation formats, always evaluating the power penalty
 550 with respect to the same PAM-2 S_0 sensitivity values of
 551 Fig. 6. Since the same good agreement between the 25
 552 and 50 Gb/s results found for PAM-2 was also corroborated
 553 for the other modulation formats, only 50 Gb/s curves
 554 (representing both bit rate situations) are shown.

555 By summarizing all the information provided by
 556 Figs. 4-7, we can state the following conclusions with respect
 557 to the filter shape impact on the performance of the four
 558 different modulation formats in the BtB situation. Let us
 559 start by considering the options to transmit 25 Gb/s
 560 using 10G technology transceivers (25G/10G):

- 561 - PAM-4 exhibits the best tolerance against filter shaping
 562 variations, in the sense that its penalty curve versus the
 563 reduction in filter bandwidth (for both $B_{3\text{dB}}$ and $B_{20\text{dB}}$)
 564 remains flat down to very low values. However, this format
 565 has a bigger penalty compared to EDB or ODB in the
 566 25G/10G region [see the red points of Figs. 7(a)-7(c), and
 567 their associated power penalty].
- 568 - ODB exhibits large variations as a function of the $B_{3\text{dB}}$
 569 and $B_{20\text{dB}}$ parameter. In the search for low transceiver
 570 bandwidth solutions, it has a very interesting behavior,
 571 but only around its optimal values. Moreover, it should be
 572 remembered that this is the only format that necessarily
 573 requires an external modulator (while all the other three
 574 modulation formats also can be implemented with
 575 directly modulated lasers).
- 576 - PAM-2 presents a strong filtering-dependent performance
 577 (see Fig. 6). For instance, by using two transceivers
 578 having the same $B_{3\text{dB}} = 30\%$ but very different
 579 steepness (i.e., $B_{20\text{dB}} = 60\%$ and 120% , which is not
 580 far from a real situation, as shown by the red points
 581 in Fig. 6), a very different penalty of >7 dB versus
 582 ~ 1 dB, respectively, can be obtained. Therefore, PAM-2
 583 is a good alternative only if large bandwidth transceivers
 584 are used.



F6:1 Fig. 6. PAM-2 power penalty with respect to the S obtained for
 F6:2 PAM-2 in the best condition (BtB unlimited bandwidth case, $S_0 =$
 F6:3 -28.1 dBm for 25 Gb/s and $S_0 = -25.7$ dBm for 50 Gb/s) as a
 F6:4 function of the GFs $B_{3\text{dB}}$ and $B_{20\text{dB}}$ parameters. Red points:
 F6:5 25 Gb/s using 10G technology transceivers. Black circles:
 F6:6 50 Gb/s using 10G technology transceivers. Pink triangles:
 F6:7 50 Gb/s using 25G technology transceivers.



F7:1 Fig. 7. (a) PAM-4, (b) EDB, and (c) ODB power penalty with respect to the S obtained for PAM-2 in the BtB unlimited bandwidth case, S_0
 F7:2 ($S_0 = -28.1$ dBm for 25 Gb/s and $S_0 = -25.7$ dBm for 50 Gb/s) as a function of B_{3dB} and B_{20dB} of the GFs. Red points: 25 Gb/s using 10G
 F7:3 technology. Black circles: 50 Gb/s using 10G technology. Pink triangles: 50 Gb/s using 25G technology.

585 – EDB shows a good tolerance against filtering, and a penalty between 2 and 3 dB in all the cases reported in Table I.
 586 Accordingly, EDB seems to be a very interesting alternative in terms of resilience against filtering variations (with
 587 respect to both -3 dB bandwidth and steepness).
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590 Let us now consider the option of transmitting 50 Gb/s
 591 using 10G technology (50G/10G):

592 – PAM-2 is not feasible (see the black circles of Fig. 6).
 593 – Neither PAM-4 or EDB seem to be feasible alternatives,
 594 since a large power penalty is achieved in this situation
 595 [see the black circles of Figs. 7(a) and 7(b)].
 596 – The only modulation format that may be used is ODB
 597 [see the black circles of Fig. 7(c)]. However, in the $B_{3dB} < 15\%$
 598 range, the penalty of ODB rapidly increases even
 599 with small -3 dB bandwidth decreases. Therefore, the
 600 performance stability can be critical.

601 Finally, let us consider transmitting 50 Gb/s using 25G
 602 technology (50G/25G):

603 – For PAM-2 and EDB, the same conclusions as in the case
 604 of 25G/10G can be extrapolated. However, most 25G tech-
 605 nology has more relaxed bandwidth limitations to trans-
 606 mit 50 Gb/s (see pink triangles in Fig. 6). PAM-2 then
 607 seems to be a good alternative to transmit 50G/25G.
 608 EDB only outperforms it if transceivers with very strong
 609 bandwidth limitations are employed.
 610 – PAM-4 and ODB are not good candidates since a large
 611 power penalty (>3 dB) arises in this situation.

612 V. DISPERSION ANALYSIS

613 In Section IV, the effect of the transceivers' filtering char-
 614 acteristics on the performance of four IM/DD modulation
 615 formats in a BtB scenario was analyzed. In this section,
 616 the previous analysis is extended by also considering the
 617 presence of chromatic dispersion in the link.

618 As a first approach, the B_{3dB} and B_{20dB} parameters are
 619 fixed to some of the values discussed in the previous section

and the total dispersion of the link is varied to compute the
 relative power penalty of the four modulation formats as a
 function of this last parameter. For the 25 Gb/s transmis-
 sion, two representative $\{B_{3dB}, B_{20dB}\}$ pairs were selected:
 $P1 = \{32\%, 136\%$ and $P2 = \{32\%, 56\%$ (cases 5 and 3 of
 Table I, respectively), to compare the power penalty versus
 dispersion curves obtained when the -3 dB bandwidth of the
 filters is the same, but the steepness is abruptly
 changed. The results are displayed in Fig. 8(a). For the
 50 Gb/s situation, the following $\{B_{3dB}, B_{20dB}\}$ pairs were
 employed: $P3 = \{32\%, 132\%$ and $P4 = \{32\%, 58\%$ (case
 5 of Table II). The corresponding results are shown in
 Fig. 8(b).

From Fig. 8(a) ($R_b = 25$ Gb/s), we can observe that
 PAM-4 is the most robust format against the effect of both
 dispersion and filtering. EDB also exhibits good tolerance
 against dispersion. We now introduce some practical con-
 sideration focusing on the PON scenario, which requires
 using SMF fibers up to $l = 20$ km in different wavelength
 bands, which we have grouped as O-band (about 1300 nm,
 where at the limit of the bandwidth specified by different
 PON standards the accumulated dispersion can go
 up to ~ 100 ps/nm), C-band (1550 nm, accumulated
 dispersion up to 360 ps/nm), and L-band (1580 nm, up
 to ~ 460 ps/nm). Comparing the different modulation

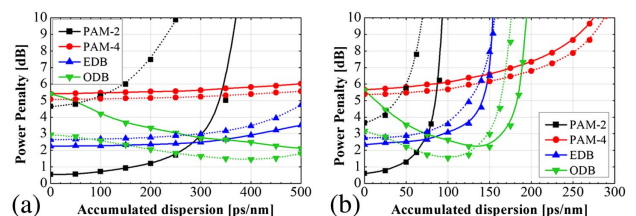


Fig. 8. Performance comparison among the four modulation
 formats in terms of the relative power penalty as a function
 of dispersion. (a) $R_b = 25$ Gb/s; solid: $B_{3dB} = 32\%$ and $B_{20dB} = 136\%$;
 dotted: $B_{3dB} = 32\%$ and $B_{20dB} = 56\%$; (b) $R_b = 50$ Gb/s;
 solid: $B_{3dB} = 32\%$ and $B_{20dB} = 132\%$; dotted: $B_{3dB} = 32\%$ and
 $B_{20dB} = 58\%$. The power penalty is relative to PAM-2 S_0
 ($S_0 = -28.1$ dBm for $R_b = 25$ Gb/s and $S_0 = -25.7$ dBm for
 $R_b = 50$ Gb/s).

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645 formats, EDB outperforms PAM-4 in O, C, and L optical
 646 bands. Regarding PAM-2, as in BtB, in presence of
 647 dispersion its performance is also highly affected by the
 648 steepness of the out-of-band transceivers' response. Its
 649 use in C- or L-band is not feasible for $l = 20$ km. In O-band,
 650 its use seems to be strongly constrained to the use of tech-
 651 nology with low steepness filtering characteristics. Under
 652 these conditions, its performance is the best among all
 653 modulation formats. ODB, on the other hand, is the only
 654 format in which the performance improves as both the
 655 dispersion and steepness of the filters increase (at least
 656 in O, C, and L bands with $l = 20$ km). In O-band, ODB
 657 is outperformed by EDB, while in the C- and L-bands it
 658 seems to be the best alternative.

659 Regarding the 50 Gb/s transmission [see Fig. 8(b)] over
 660 20 km of fiber, we observed that no modulation format can
 661 be used to operate the system in the C-band or L-band.
 662 PAM-2 does not work even in the O-band. The only feasible
 663 modulation formats (in O-band, $l = 20$ km) are EDB, ODB,
 664 and PAM-4, being the performance of PAM-4 surpassed by
 665 that of both EDB and ODB in the whole O-band.

666 Although PAM-4 has been found to be the most resilient
 667 format against dispersion and bandwidth limitations in all
 668 the analyzed conditions, due to its higher intrinsic penalty
 669 as compared to EDB in all the practical scenarios, we do not
 670 consider it a feasible alternative for the implementation of
 671 25 Gb/s or 50 Gb/s PON systems over 20 km of fiber.
 672 Therefore, we do not analyze this modulation format in
 673 the rest of this section. A similar consideration has been
 674 performed with respect to PAM-2 operating in the C-band
 675 with $R_b = 25$ Gb/s, and the O-band with $R_b = 50$ Gb/s.
 676 Therefore, other than the 25 Gb/s O-band case in which
 677 PAM-2 can still be considered a feasible format, the rest
 678 of this section will be focused on the comparison between
 679 EDB and ODB formats.

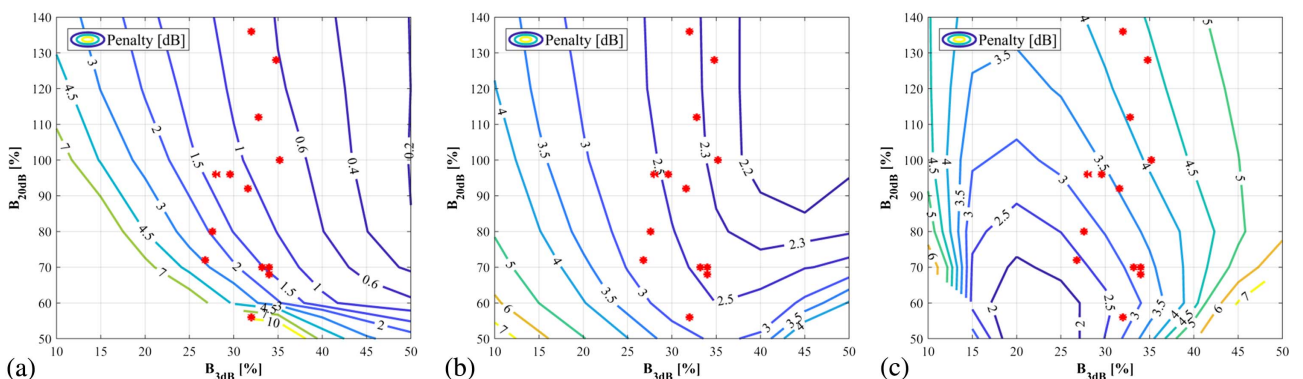
680 Some preliminary results allow us to forecast the fea-
 681 sibility of PAM-2 and PAM-4 using pre-chirping in the
 682 transmission of 50 Gb/s in the O-band and C-band
 683 ($l = 20$ km), respectively, at least under relaxed bandwidth
 684 limitations (1-pole BF's case). However, these alternatives
 685 need to be further explored under more strict filtering

686 conditions, which is an analysis out of the scope of the
 687 present contribution.

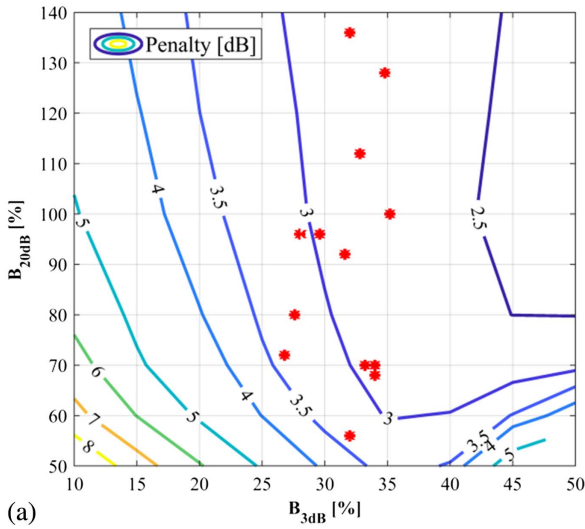
688 We now proceed with some further insight, focusing on
 689 25 Gb/s transmission results. In Figs. 9 and 10 we show,
 690 for the O-band and the C-band operation over 20-km of fiber,
 691 respectively, the contour plots of the power penalty as a
 692 function of $B_{3\text{dB}}$ and $B_{20\text{dB}}$, for different modulation for-
 693 mats and for different accumulated dispersion (using the
 694 previously indicated notation of the O- and the C-band
 695 at 20 km). The power penalty is evaluated in all cases with
 696 respect to S_0 of PAM-2 in BtB conditions ($S_0 = -28.1$ dBm
 697 for $R_b = 25$ Gb/s).

698 Regarding O-band operation (Fig. 9), the three modula-
 699 tion formats exhibit similar results to the BtB situation
 700 (see Figs. 6 and 7), but have a small dispersion penalty
 701 for PAM-2 and EDB. In contrast, ODB exhibits a perfor-
 702 mance improvement thanks to dispersion, which is consis-
 703 tent with the results presented in Fig. 8. The power penalty
 704 of EDB varies between 2.2 and 3 dB when using state-of-
 705 the-art transceivers with different -3 dB bandwidth and
 706 out-of-band filtering steepness. In contrast, in the case of
 707 PAM-2, this penalty can vary from around 0.6 to an exceed-
 708 ingly large value around 10 dB. ODB is an intermediate
 709 case (the penalty varies from 2.5 to 4.5 dB). Therefore,
 710 we consider EDB as the best alternative for 25 Gb/s 20-
 711 km O-band operation with respect to tolerance against
 712 frequency response variations. However, PAM-2 can be a
 713 good solution; its penalty can be as low as <1 dB, which
 714 is a value not achievable by any other format, if *and*
 715 *only if* technology with proper filtering characteristics
 716 ($B_{3\text{dB}} \geq 30\%$ and $B_{20\text{dB}} \geq 70\%$) can be guaranteed.

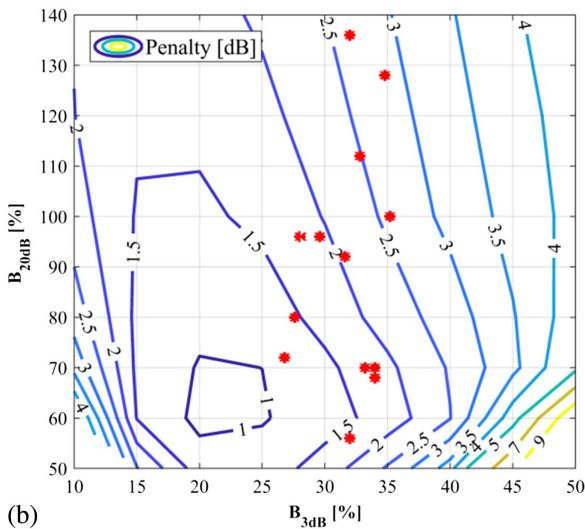
717 When considering C-band operation, we can see from the
 718 contour plots shown in Figs. 10(a) and 10(b), that the per-
 719 formance of ODB is further improved by dispersion while
 720 the opposite occurs for EDB. This situation tips the scales
 721 in favor of ODB in terms of a lower range of power penalty
 722 achievable using state-of-the-art devices (i.e., from 1 to
 723 3 dB, in contrast to 2.5 to 3.5 dB achieved with
 724 EDB). EDB remains the format with less performance vari-
 725 ations as a function of filtering. It is important to note that,
 726 by using ODB and small band-limited transceivers



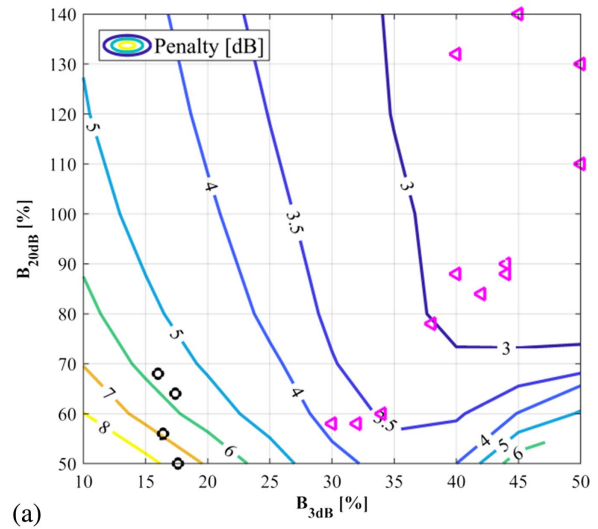
F9:1 Fig. 9. (a) PAM-2, (b) EDB, and (c) ODB power penalty with respect to the S obtained for PAM-2 in the BtB unlimited bandwidth case, S_0
 F9:2 ($S_0 = -28.1$ dBm) as a function of $B_{3\text{dB}}$ and $B_{20\text{dB}}$ of the GFs, for a 25 Gb/s/20 km O-band operation. Red points: 25 Gb/s using 10G
 F9:3 technology.



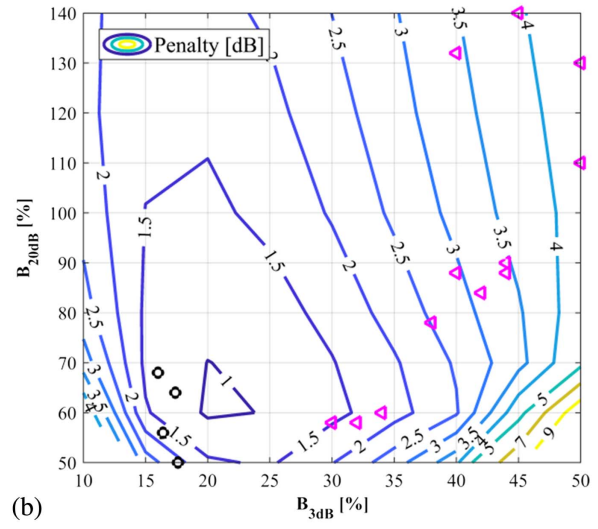
(a)



(b)



(a)



(b)

F10:1 Fig. 10. (a) EDB and (b) ODB power penalty with respect to the S
 F10:2 obtained for PAM-2 in the BtB unlimited bandwidth case, S_0
 F10:3 ($S_0 = -28.1$ dBm) as a function of B_{3dB} and B_{20dB} of the GFs,
 F10:4 for a 25 Gb/s/20 km C-band operation. Red points: 25 Gb/s using
 F10:5 10G technology.

F11:1 Fig. 11. (a) EDB and (b) ODB power penalty with respect to the S
 F11:2 obtained for PAM-2 in the BtB unlimited bandwidth case, S_0
 F11:3 ($S_0 = -25.6$ dBm) as a function of B_{3dB} and B_{20dB} of the GFs,
 F11:4 for a 50 Gb/s 20 km O-band operation. Black circles: 50 Gb/s using
 F11:5 10G technology. Pink triangles: 50 Gb/s using 25G technology.

(i.e., $B_{3dB} \geq 35\%$ and $B_{20dB} \geq 100\%$), it is always possible to increase the performance of the system by intentionally adding an electrical filter at the TX or RX, to enforce a stronger band-limited condition [close to the optimum point that can be seen in Fig. 10(b)] in which the achievable penalty could be only 1 dB. This feature is not achievable using any other modulation format. Another positive (and unique) feature of ODB is that, as can be seen in Fig. 8, the dispersion penalty decreases as the accumulated dispersion increases (i.e., length), which can compensate, to some degree, for the increase of fiber attenuation as the fiber length augments. In favor of EDB is the fact that it can be implemented with both direct modulation and external modulation (using electro-absorption modulators or a MZM) approaches, while ODB must use a MZM.

Let us finally comment on the 50 Gb/s transmission results. In Fig. 11, contour plots of the power penalty as a

function of B_{3dB} and B_{20dB} for 50 Gb/s 20-km O-band operation using EDB [Fig. 11(a)] or ODB [Fig. 11(b)], are shown. The power penalty is referred to the 50 Gb/s PAM-2 $S_0 = -25.6$ dBm. The contour plots displayed in Fig. 11 are very similar to those shown in Fig. 10 (for 25 Gb/s transmission in 20-km O-band). However, the regions of operation of 50G/10G and 50G/25G state-of-the-art devices (see the black circles and pink triangles of Fig. 11, respectively) are different from those of 25G/10G (see the red points of Fig. 10). Therefore, the conclusions between these cases may differ. First, ODB appears to be the only feasible format to transmit 50 Gb/s using 10G technology in O-band. In the black circles of Fig. 11, only the cases 2, 3, 10, and 11 in Table I are plotted. The rest of the cases have a $B_{20dB} < 50\%$, which corresponds to power penalties higher than 2.5 dB [not shown in Fig. 11(b)]. Then, for

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correct operation, the $B_{20\text{dB}}$ of the TX and RX should at least be higher than 50%.

Regarding the transmission of 50 Gb/s using 25G technology, the maximum penalty achievable with EDB [pink triangles in Fig. 11(a)] and ODB [pink triangles in Fig. 11(b)] is similar (around 4 dB). Again, EDB exhibits a more stable penalty, varying between 3 and 4 dB (mostly around 3 dB), while ODB penalty variation is wider, varying from 1.5 to 4 dB. In terms of tolerance against filtering, we should opt for EDB. However, as mentioned before, with the right technology characteristics or by enforcing the frequency response using an additional electrical filter, we could operate close to the optimal point of ODB and achieve a penalty as low as 1 dB.

VI. CONCLUSIONS

In this contribution, we have demonstrated the strong impact on system performance that the overall filter shaping electrical response of the transceivers has on the transmission of 25 and 50 Gb/s using currently available 10 and 25 Gb/s technology and adaptive equalization. Using numerical simulations, we compared the achievable performance of PAM-2, PAM-4, EDB, and ODB under different band-limited and dispersive conditions. We introduced the -20 dB bandwidth parameter to quantify the impact of the out-of-band steepness of the transceivers' response. We demonstrated that this parameter is as relevant as the -3 dB bandwidth when comparing the performance of different modulation formats.

We found that PAM-2 is the best performing format for the transmission of 25 Gb/s using 10G technology in the 20 km O-band, but only if transceivers with relatively small bandwidth limitations can be used. Otherwise, the best alternative is EDB because it is more resilient to filter shaping variations than PAM-2 and outperforms the rest of the formats in terms of penalty.

On the transmission of 25 Gb/s using 10G technology in 20-km C-band, EDB exhibits a slightly higher maximum power penalty than ODB (4 dB versus 3.5 dB). The minimum achievable power penalty of ODB is 1.5 dB lower than that of EDB. However, the performance of EDB as a function of the -3 dB and -20 dB bandwidth is more stable (power penalty variations are less than 1 dB) than in the case of ODB, which has power penalty variations up to 2 dB.

Regarding the 50 Gb/s case, no modulation format works under 20 km of C-band operation. PAM-2 is not even feasible in the O-band. ODB is the only format that can be used if using 10G technology (in the 20 km O-band), but only if some filtering conditions can be guaranteed. If 25G technology is used and the O-band is considered through 20 km of fiber, both EDB and ODB can work, exhibiting a maximum penalty of 4 dB. Again, the penalty of ODB is the minimum under some filtering conditions, but EDB performance is more robust against the filter shaping variations of the transceivers' frequency response.

In all cases, PAM-4 is the most robust format against both dispersion and filtering conditions. However, due to its inherent higher power penalty with respect to the rest of the formats, PAM-4 is always outperformed by any of them in most of the analyzed conditions.

The results presented in this contribution were obtained using identical filters to emulate the frequency response of both the TX and RX. For space limitations, we did not consider more general assumptions and degrees of freedom in our present analysis. Using filters with different characteristics at the TX and RX side, which could give rise to interesting results, is a topic we are currently researching.

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