Electro-Optical Modulator Requirements for 1 Tb/s per Channel Coherent Systems

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Abstract— **The electro-optical bandwidth and extinction ratio requirements of in-phase and quadrature modulators to enable 1 Tb/s per channel optical transmission rates are evaluated through numerical simulations. Employing sixty-four quadrature amplitude modulation (64QAM), the simulation results indicate that the best trade-off between the number of optical carriers per channel and the technological complexity of designing and manufacturing an integrated transceiver is achieved for a superchannel composed by 2 optical carriers, since it allows modulator requirements in terms of electro-optical bandwidth and extinction ratio equal to 27 GHz and 18 dB, respectively. The systemic optimization of the carrier launch power employing the approximate enhanced Gaussian noise model indicates that this configuration could achieve transmission reaches up to around 1080 km. These results point out to 1 Tb/s optical superchannels as a viable solution for next generation coherent systems in metropolitan and long-haul scenarios.**

Index Terms— electro-optical modulator, electro-optical bandwidth, extinction ratio, high-capacity optical transmission.

I. INTRODUCTION

Optical transmission systems with higher capacities and longer reaches are an ever increasing demand, as they are the communication technological foundation based on which the expansion of well-established applications (*e.g.*, media streaming and cloud storage and computing) and the rising of new technological paradigms (*e.g.*, low-latency high-bit-rate 5G networks and the Internet of Things) are supported [1]. As a consequence, a virtuous cycle of new scientific paradigms and technological approaches have been established in the last two decades, creating an ecosystem that allowed the evolution of single-carrier optical systems from a few hundreds of megabits per second in the late 80's to the state-of-the-art wavelength-multiplexed modern systems close to two hundreds of terabits per second per fiber [2].

However, even with the exponential growth in optical systems capacity in the last decades, to avoid capacity crunch projected to occur in the next few years [3], several solutions are being researched and developed by academia and industry, spanning from incremental improvements (as systemic optimization techniques [4]) to ground breaking technologies (such as spatial division multiplexing [5]). Regardless of the system configuration, increasing each channel transmission bit rate is one of the most frequent approaches to expand the system overall capacity per fiber core. In general terms, this can be achieved through three main approaches: increasing the modulation format order [6], increasing the symbol rate [7], and/or increasing the number of optical or electrical carriers composing a superchannel [8]. Besides the fact that presently the vast majority of deployed optical networks is still based on legacy

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systems employing transmission rates up to 200 Gb/s per optical channel, the industry is moving forward to define the standards for 400 Gb/s [9] and even 800 Gb/s [10], aiming to deploy this new generation of systems in the next few years. However, developments in the design and manufacture of optical transceivers supported by the research of new materials and techniques in the integrated photonics field allow us to foresee the deployment of even higher transmission rates systems in the next decade. As a matter of fact, several works in the technical literature have been published proposing design and optimization strategies to achieve 1 Tb/s transmissions per channel and above. In [11] the authors comparatively analyze the performance of high-order modulation formats to support 1 Tb/s transceivers employing the spectral multiplexing of three independent carriers. Following, in [12], the same research group explored the systemic impact of electro-optical limitations on the performance of 1 Tb/s channels, with focus on the routing problem in a elastic optical network scenario. A complementary approach is presented in [13], in which linear and nonlinear pre-distortion approaches are implemented on the transmitter digital signal processing stack, allowing one to reduce the impact of distortions introduced by the transfer function of electro-optical devices employed to generate or receive 1 Tb/s channels. Finally, in [14], a comparative study between two subcarrier multiplexing techniques for 1 Tb/s transmissions is carried out in terms of number of subcarriers, laser linewidth, and DAC/ADC quantization and bandwidths, but without evaluating the requirements of the modulator, which is a key component to enable high-capacity transmissions.

Then, in the present work, the performance of 1 Tb/s channels is investigated in terms of the electro-optical modulator requirements, exploring the combination of high-order modulation formats and wide bandwidth electrical and optical devices to assess the best trade-off between the number of required optical carriers and the technological complexity of designing and manufacturing an integrated transceiver. The proposed analysis, as described on the methodology in Section II, is based on numerical simulation, ranging the modulator electro-optical bandwidth and extinction ratio to evaluate the degradation imposed by these parameters on the transmitted superchannel, composed by multiple optical carriers. Following, the obtained results are presented in Section III, where a systemic analysis is carried out in terms of received bit error rate (BER) and required optical signal-to-noise ratio (OSNR), being complemented with the evaluation of the link reach using the enhanced Gaussian noise (EGN) model. Finally, in Section IV, the conclusions arising from the proposed analysis are discussed and future works are outlined.

II. Methodology

The proposed analysis was carried out based on the simulation setup depicted in Fig. 1, whose parameters are defined in Table I, where up to three optical carriers (OC) are characterized in terms of required OSNR in a back-to-back (B2B) configuration, employing a noise loading technique based on waveform simulations to estimate the received BER, or in terms of system reach based on semi-analytical simulations, using the enhanced Gaussian noise (EGN) model, emulating a series of spans composed by standard single mode fibers (SSMF) and Erbium-doped fiber amplifiers (EDFA). As the proposed analysis aims to investigate the electro-optical modulator impact in high capacity optical systems, all other components had its specifications adjusted to reduce further penalties on the modulated carrier, keeping the systemic constraints at values consistent with practical implementations. In this way, the bandwidths of the digital-to-analog converters (DACs), analog-to-digital converters (ADCs),

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and photodetectors (PDs) were adjusted to a value slightly wider than that of each modulated carrier, introducing a filtering attenuation lower than 1 dB within the carrier −3 dB bandwidth. Furthermore, the DAC and laser parameters were previously investigated in [14], where DAC resolution and laser linewidth related penalties were characterized in terms of signal degradation for multicarrier optical channels, allowing the definition of the optimum values here adopted. In a practical implementation, the systemic penalty will be the result of the joint impact from the impairments imposed by all optical and electrical components employed in a given optical link, and, as a consequence, there will be a trade-off between the specifications of all devices. However, as this work aims to investigate specifically the electro-optical modulator requirements, all other devices parameters were set to impose only a negligible degradation, allowing one to isolate the modulator's response impact on system performance.

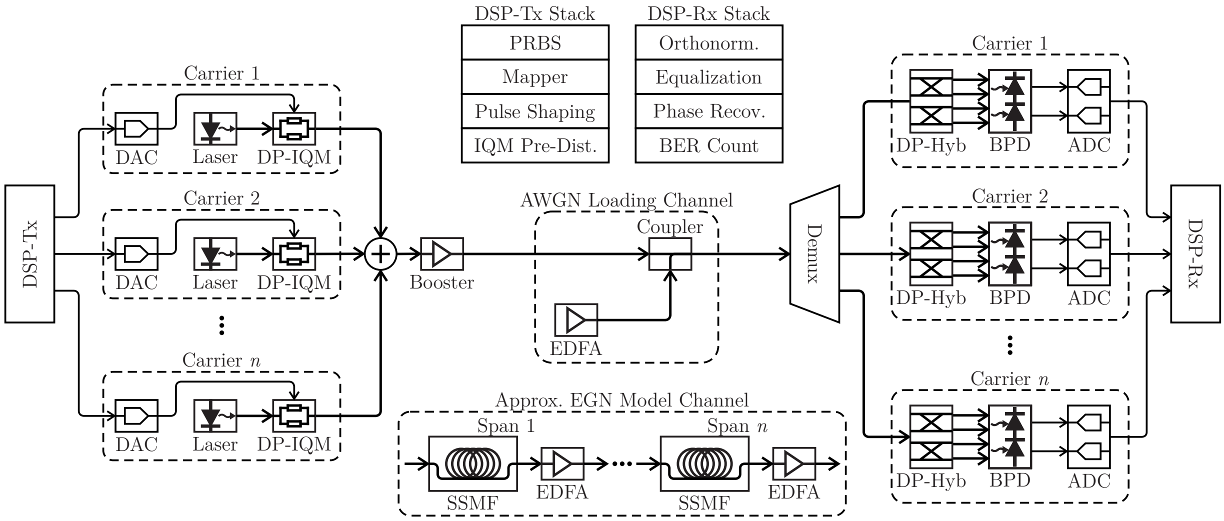

Fig. 1. Simulation setup to assess modulator requirements.

At the transmitter side (Tx), firstly, a digital signal processing (DSP) stack is performed, on which a 2^{24} pseudo-random bit sequence (PRBS) is generated and mapped into 64 constellation symbols of the sixty-four quadrature amplitude modulation (64QAM) format. The aggregated symbol rate (R_S), in all cases, is equal to 100 GBd per polarization, thus corresponding to a total bit rate of 1.2 Tb/s, which will result in a net bit rate of 1 Tb/s considering a 20 % forward error correction (FEC) overhead. On the simulations, considering an optical superchannel composed by 2 or 3 optical carriers, the symbol rate per carrier ($R_{S,c}$) is defined as the aggregated symbol rate equally divided between the considered carriers. Next, the symbols are oversampled at two samples per symbol and filtered by a raised cosine filter [15] to be shaped as a Nyquist pulse with roll-off factor (β) equal to 0.1, which allows to achieve high spectrum efficiency with low performance degradation. Finally, on the transmission DSP (DSP-Tx) stack, the in-phase and quadrature modulator (IQM) nonlinear electro-optical amplitude response is linearized by a pre-distortion algorithm. Following, the digital signals generated by the transmission DSP are converted to the analog domain by DACs with 8 bits quantization levels (N_{DAC}), sampling rate (R_{DAC}) equal to $2 \cdot R_{S,c}$, and −3-dB bandwidth equal to $0.6 \cdot R_{S,c}$. In the simulation of the analog part of the system, 32 samples per symbol are used.

The optical carriers are generated by independent lasers with linewidth ($\Delta\nu$) equal to 100 kHz and optical power adjusted to obtain the desired optical power at the booster output ($P_{booster}$). We assume that lasers do not drift their emission wavelengths over time, which, in the case of few carriers, could

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be achieved by using an optical frequency comb [16]. In all cases, the superchannel central wavelength (λ_{ch}) is allocated at 1550 nm with carriers spacing equal to $(1+2\beta)\cdot R_{S,c}$. Then, employing a dual-polarization (DP) in-phase and quadrature modulator (IQM), each optical carrier is 64QAM modulated by analog radio-frequency signals generated at each DAC output. The outgoing modulated optical field of the IQM is given by [17] with the inclusion of the extinction ratio factor as follows:

$$E_{out}(t)=\frac{1}{2}E_{in}(t)\left\{\left[-\sin\left(\frac{u_I(t)}{2V_\pi}\pi\right)+j\frac{1}{\sqrt{ER_{mod}}}\cos\left(\frac{u_I(t)}{2V_\pi}\pi\right)\right]+\right.$$
$$\left.+j\left[-\sin\left(\frac{u_Q(t)}{2V_\pi}\pi\right)+j\frac{1}{\sqrt{ER_{mod}}}\cos\left(\frac{u_Q(t)}{2V_\pi}\pi\right)\right]\right\} \quad (1)$$

where $E_{in}(t)$ is the incoming optical carrier, $u_I(t)$ and $u_Q(t)$ are the DAC output signals for the in-phase (I) and quadrature (Q) components, respectively, V_π is the driving voltage required to induce a phase shift of π, and ER_{mod} is the modulator extinction ratio. The electro-optical frequency response of the modulator is modeled as a super-Gaussian filter with transfer function given by:

$$H_{mod}(f)=e^{-0.5\ln(2)\left(\frac{f^2}{B^2_{mod}}\right)^n} \quad (2)$$

where B_{mod} is the -3-dB bandwidth and n is the filter order that was set equal to 2.

To perform the proposed analysis (*i.e.*, to assess the impact of the modulator characteristics into the system overall performance), the modulator bandwidth (B_{mod}) and the extinction ratio (ER_{mod}) were ranged from values close to the ideal down to minimum values that allowed the information recovery after the reception DSP. At the transmitter unit output, each individually modulated carrier was ideally combined, composing the proposed superchannel, and amplified by a booster with operational parameters adjusted to achieve feasible values of total optical power ($P_{booster}$) and OSNR ($OSNR_{booster}$).

Following, two fiber channels were considered throughout the simulations in order to investigate different aspects of the system performance due to the optical modulator limitations. First, a back-to-back (B2B) configuration using additive white Gaussian noise (AWGN) loading was considered, reducing computation time and allowing a thorough investigation in terms of the required OSNR to achieve the maximum acceptable BER before applying the FEC, usually referred to as the FEC limit. Based on the adopted $20\ \%$ FEC overhead, the FEC limit was considered to be equal to 2.4×10^{-2} [18]. Based on the estimation of the required OSNR and considering the higher bandwidth and extinction ratio values (adjusted to avoid any significant penalty) as a reference, it was possible to assess the OSNR penalty for each combination of modulator bandwidth and extinction ratio, as it will be discussed in Section III. Also based on the required OSNR at the FEC limit, the second fiber channel considered employs the approximate enhanced Gaussian noise (EGN) model [19] in order to estimate the system reach (L) in a link encompassing n fiber spans compounded by in-line optical amplifiers and standard single mode fibers (SSMF) with the parameters values described in Table II. The EGN accuracy in predicting the maximum reach of a system was found to be very good on various test cases [20] and the limitations of the approximate EGN model were thoroughly examined in [19]. For the system analyzed in this work, with high values of accumulated chromatic dispersion, the approximate EGN model estimations are very close to the complete EGN model and are much better than the coherent GN model [21]. Our implementation of the approximated EGN model was validated using the maximum reach prediction results from [19] for different modulation formats, fibers, span lengths, and channel spacings. To estimate the maximum system reach, we considered that all optical carriers have the same launch power and the gain of all EDFAs was set to compensate the loss of one fiber span.

Finally, at the receiver side (Rx), each optical carrier compounding the transmitted superchannel is filtered and separated by an optical demultiplexer, modeled as a second order super-Gaussian band-pass filter centered on the carrier frequency and with full width at half maximum (FWHM) bandwidth (B_{demux}) equal to $(1 + \beta) \cdot R_{S,c}$, which introduces negligible spectrally-dependent filtering penalty on the received carriers, as assessed by previous simulations. Following, each carrier is independently converted to the electrical domain by a coherent receiver optical front-end (OFE) composed by a dual-polarization $90°$ optical hybrid (DP-Hyb), which combines each signal quadrature and in-phase component with an optical local oscillator (laser with the same characteristics as that used in the transmitter), and by a set of balanced photodetectors (BPD), which will down convert the channel frequency and convert it to electrical domain. Once again, in order to avoid any additional significant degradation into the received signal, the $90°$ optical hybrid was considered ideal and the photodetector bandwidth (B_{pd}) was set at $0.6 \cdot R_{S,c}$. Next, each analog electrical signal is sampled by analog-to-digital converters (ADCs), with quantization levels, bandwidth, and sampling rate equal to those considered at the transmitter for the digital-to-analog converters (DACs). The frequency response of the DACs, ADCs, and photodetectors are modeled as a second order super-Gaussian filter. Lastly, the transmitted data is retrieved through the reception DSP (DSP-Rx) stack, which is compounded by the following blocks: orthonormalization [22], adaptive equalization based on radius directed equalizer (RDE) [23] using constant modulus algorithm (CMA) [24] for initialization, and phase recovery based on blind phase search (BPS) [25] algorithm. The achieved superchannel bit error rate (BER) is then calculated as the average of the counted BERs of its constituent carriers.

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TABLE I. PARAMETERS EMPLOYED IN THE SIMULATIONS.

Parameter	**Symbol**	**Equal to**	**1 OC**	**2 OC**	**3 OC**
Number of Optical Carriers	N_c	–	1	2	3
Total Symbol Rate	R_S	–	100 GBd	100 GBd	100 GBd
Per Carrier Symbol Rate	$R_{S,c}$	R_S/N_c	100 GBd	50 GBd	33.33 GBd
FEC Overhead	OH_{FEC}	–	20 %	20 %	20 %
Nyquist Pulse Shaping Roll-off Factor	β	–	0.1	0.1	0.1
DAC Quantization	N_{DAC}	–	8 bits	8 bits	8 bits
DAC Bandwidth (-3dB)	B_{DAC}	$0.6 \cdot R_{S,c}$	60 GHz	30 GHz	20 GHz
DAC Sampling Rate	R_{DAC}	$2 \cdot R_{S,c}$	200 GSa/s	100 GSa/s	66.66 GSa/s
Superchannel Central Wavelength	λ_{ch}	–	1550 nm	1550 nm	1550 nm
Superchannel Carriers Spacing	Δf_c	$(1{+}2\beta) \cdot R_{S,c}$	–	60 GHz	40 GHz
Laser Linewidth	$\Delta\nu$	–	100 kHz	100 kHz	100 kHz
Modulator Bandwidth (-3dB)*	B_{mod}	–	[46:2:60] GHz	[23:1:30] GHz	[15:1:20] GHz
Modulator Extinction Ratio*	ER_{mod}	–	[13:1:20] dB	[13:1:20] dB	[13:1:20] dB
Booster Output Power	$P_{booster}$	–	0 dBm	0 dBm	0 dBm
Booster Output OSNR	$OSNR_{booster}$	–	40 dB	40 dB	40 dB
Demultiplexer Bandwidth (FWHM)	B_{demux}	$(1+\beta) \cdot R_{S,c}$	110 GHz	55 GHz	36.66 GHz
Photodetector Bandwidth (-3dB)	B_{pd}	$0.6 \cdot R_{S,c}$	60 GHz	30 GHz	20 GHz
ADC Quantization	N_{ADC}	–	8 bits	8 bits	8 bits
ADC Bandwidth (-3dB)	B_{ADC}	$0.6 \cdot R_{S,c}$	60 GHz	30 GHz	20 GHz
ADC Sampling Rate	R_{ADC}	$2 \cdot R_{S,c}$	200 GSa/s	100 GSa/s	66.66 GSa/s

* Parameter values are presented following the notation [minimum value : increment : maximum value]

TABLE II. PARAMETERS USED IN THE APPROXIMATE EGN MODEL FOR MAXIMUM SYSTEM REACH ESTIMATION.

Parameter	**Symbol**	**Value**
EDFA Noise Figure	N_F	5 dB
Span Length	L_{span}	50 km
Fiber Attenuation Coefficient	α_F	0.2 dB/km
Fiber Dispersion Parameter	D	16.7 ps/(nm km)
Fiber Nonlinear Parameter	γ	1.3 1/(W km)
Modulation-Format-Dependent Constant	Φ	$13/21$
Number of Superchannels	N_{ch}	1
Superchannel Central Wavelength	λ_{ch}	See Table I
Superchannel Carriers Spacing	Δf_c	See Table I
Booster Output OSNR	$OSNR_{booster}$	See Table I
Booster Output Power*	$P_{booster}$	[-6:0.1:6] dBm

* Parameter values are presented following the notation [minimum value : increment : maximum value]

III. SIMULATION RESULTS

Fig. 2 presents the simulation results for the 1-Tb/s superchannel transmission in back-to-back configuration. Figures 2(a), 2(b) and 2(c) show the OSNR required at the FEC limit as a function of modulator bandwidth (B_{mod}) and extinction ratio (ER_{mod}) for the three different configurations of the 1-Tb/s superchannel employing 1, 2, and 3 optical carriers, respectively. The OSNR required at the FEC limit was calculated by the linear interpolation of the BER versus carrier OSNR curve at the receiver. The superchannel BER corresponds to the average value of the BERs of its constituent carriers. To reduce the variation of the superchannel BER close to the FEC limit due to the DSP-Rx difficulty in recovering the transmitted signal at this condition, when it is more degraded by bandwidth and extinction ratio limitations, we carried out 10 simulation runs and calculated the final BER as the average of the resulting BERs.

As can be seen in Fig. 2, for all the superchannel configurations studied here, as the modulator bandwidth is reduced, the higher the signal OSNR required to reach the FEC limit. The same behavior is observed as the modulator extinction ratio is reduced. On the other hand, the trend of the curves indicates that lower required OSNRs could be achieved if the analysis considered higher bandwidth and extinction ratio values. However, the curves presented in Fig. 2 indicate that this reduction occurs at a decreasing rate, being less pronounced at the higher bounds of the analyzed range of values. Furthermore, increasing the modulator bandwidth and extinction ratio requires significant design and manufacturing efforts, being unfeasible for the current state-of-the-art. Comparing the results of the three configurations, it is noted that the required OSNR decreases with the increase in the number of optical carriers due to the lower symbol rate of each carrier.

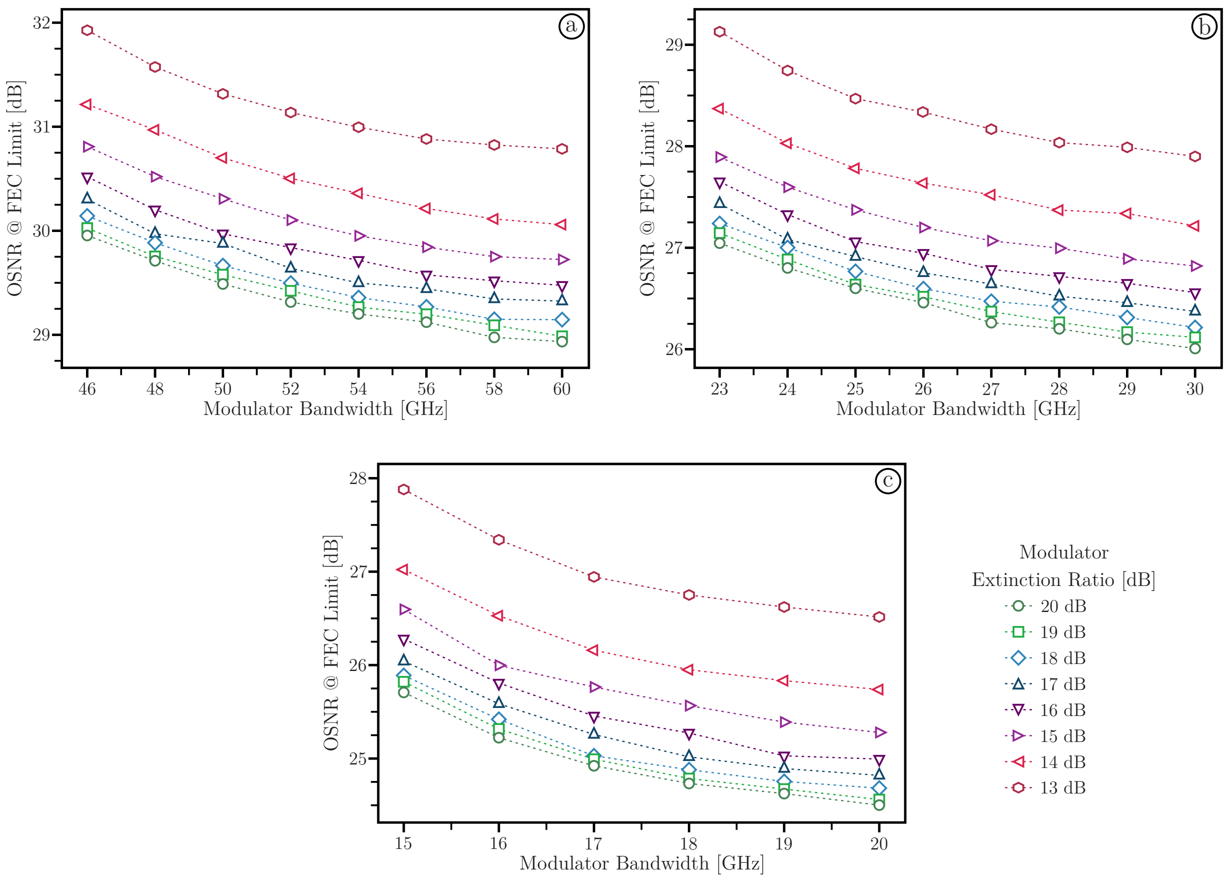

Fig. 2. OSNR required at the FEC limit as a function of modulator bandwidth (B_{mod}) and extinction ratio (ER_{mod}) in back-to-back transmission of a 1-Tb/s superchannel employing (a) 1, (b) 2, or (c) 3 optical carriers. OSNR is the ratio of total signal power of an optical carrier to noise power in a reference bandwidth of 0.1 nm.

In order to directly assess the degradation imposed by the modulator limitations on the performance of the superchannel, we calculated the OSNR penalty as a function of the modulator bandwidth and extinction ratio, as shown in Fig. 3. For each of the three superchannel configurations, the OSNR penalty was taken in relation to the lowest OSNR value required in the FEC limit of that configuration,

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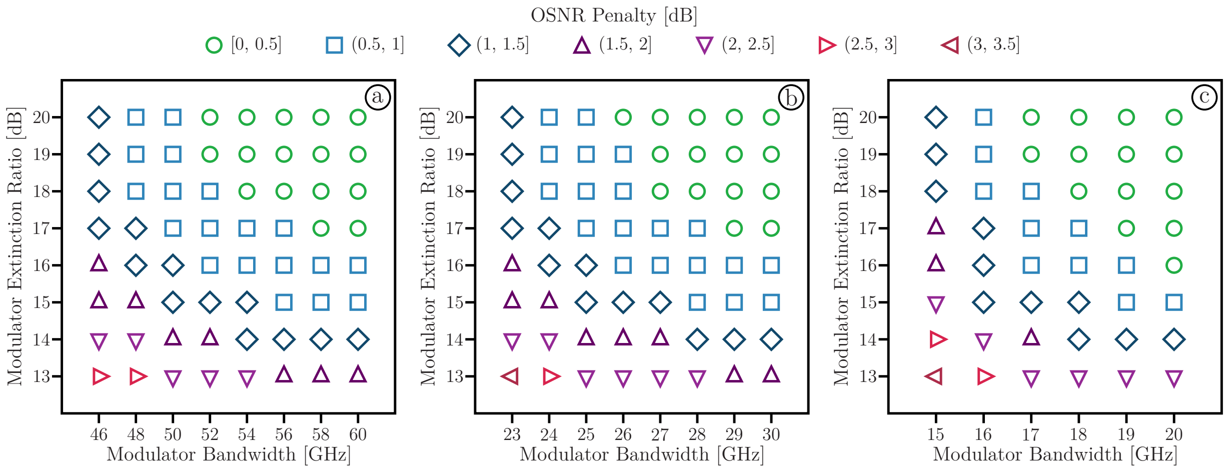

Fig. 3. OSNR penalty as a function of modulator bandwidth (B_{mod}) and extinction ratio (ER_{mod}) in back-to-back transmission of a 1-Tb/s superchannel employing (a) 1, (b) 2, or (c) 3 optical carriers.

which occurs for the highest values of modulator bandwidth and extinction ratio. The OSNR penalty scale was divided into bins of 0.5 dB, each one being represented by a different graphic symbol.

If we assume a value of 0.5 dB as an acceptable OSNR penalty limit imposed by the modulator, it is possible to obtain, from Fig. 3, the combinations of modulator bandwidth and extinction ratio that satisfy this limit for each superchannel configuration. In this case, the smaller the modulator bandwidth, the greater the extinction ratio needed to meet the acceptable penalty limit, and vice versa.

As a general rule, achieving greater bandwidth requires a more elaborate design of the modulator, while achieving a higher extinction ratio is related to the limitations of the device manufacturing process. Thus, in order to achieve a balance between design complexity and manufacturing process limitations, it is more appropriate to choose a parameter combination that has intermediate values of the modulator bandwidth and extinction ratio. Table III shows the chosen values for the modulator parameters and the respective OSNRs required at the FEC limit for the different configurations of the 1 Tb/s superchannel employing multiple optical carriers.

TABLE III. CHOSEN MODULATOR PARAMETERS VALUES AND OSNR REQUIRED AT THE FEC LIMIT.

Parameter	**Symbol**	**1 OC**	**2 OC**	**3 OC**
Modulator Bandwidth (-3dB)	B_{mod}	54 GHz	27 GHz	18 GHz
Modulator Extinction Ratio	ER_{mod}	18 dB	18 dB	18 dB
OSNR required at the FEC limit	$OSNR_{FEC}$	29.3 dB	26.5 dB	24.9 dB

In order to obtain an estimation for the maximum system reach, we apply the approximate EGN model, using the parameter values shown in Table II, and the OSNR required at the FEC limit, given in Table III. The maximum reach for different values of launch power per optical carrier is depicted in Fig. 4 for the three superchannel configurations. The maximum reach is obtained from the interpolation of the curve of OSNR versus transmission distance calculated using the approximate EGN model at the OSNR required at the FEC limit. As a result, the maximum reach is 1082 km for the superchannel with 2 optical carriers at -1.7 dBm per carrier, 1063 km for the superchannel with 3 optical carriers at -3.4 dBm per carrier and 1031 km for the single carrier configuration at 1.1 dBm. At first glance, these results seem to contradict what was shown in [26], where the authors analyze the reach of superchannels

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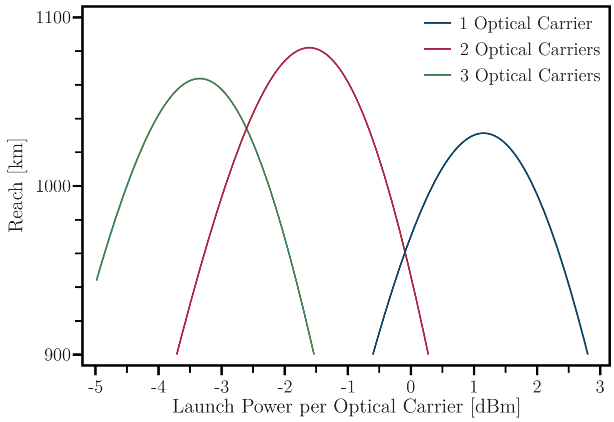

Fig. 4. Optical carrier launch power optimization.

with different number of carriers and show that the optimal carrier symbol rate is around 2 GBd to 6 GBd. However, [26] only considers the detrimental effects of nonlinear interference, without taking into account other effects that hinder the system performance. In this work, we present a more complete analysis by using a back-to-back characterization of the system, and therefore taking into account effects such as the phase noise due to lasers' linewidth in the DSP. Therefore, these results show that there is a trade-off between increasing the number of carriers to reduce the nonlinear effects and the performance of the DSP algorithms, specially the phase recovery algorithm. Increasing the number of carriers while maintaining the total symbol rate reduces the carrier bandwidth and consequently reduce the nonlinear interference [26]. On the other hand, signals with a lower symbol rate are more penalized by the phase noise for constant laser linewidth [14].

IV. Conclusions

This work investigated the electro-optical requirements of in-phase and quadrature modulators (IQM) for the transmission of 1 Tb/s channels in coherent optical systems. First, through numerical simulations, the impact of the modulator bandwidth and extinction ratio on the performance of 64QAM superchannels employing 1, 2, or 3 optical carriers in back-to-back configuration was evaluated in terms of bit error rate (BER) and required signal-to-noise ratio (OSNR). Assuming a maximum OSNR penalty of 0.5 dB imposed by the modulator, the minimum values of electro-optical bandwidth and extinction ratio for each superchannel configuration were chosen. Then, using the required OSNR at the FEC limit for each superchannel configuration, the maximum system reaches were estimated by the approximate enhanced Gaussian noise (EGN) model. The best trade-off between the number of optical carriers per channel and the technological complexity of designing and manufacturing an integrated transceiver is achieved for a superchannel employing 2 optical carriers. The estimated maximum reach using this configuration was around 1080 km.

Based on the requirements of the electro-optical modulator defined for the superchannel configuration employing 2 optical carriers, a dual-polarization IQM was designed on a silicon photonics platform and then sent to be manufactured. Future works include individual and systemic experimental characterization of the device.

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