Fiber-induced nonlinear limitation in 400-Gbps single-channel coherent optical interconnects

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***Abstract*— Coherent optical interconnects with up to 400-Gbps transmission rates and distances exceeding 80 km have been proposed to meet the increasing capacity demand of inter-datacenter communications. The interplay between the fiber Kerr effect and the receiver noise posses an upper-bound to the transmission distance. In this paper, we used numerical simulations to find the maximum achievable range of 400-Gbps unrepeated single-wavelength links with single and dual polarization. Simulations reveal that, for a forward error correction code limit of 10^{-3}, the maximum distance is 145 km for dual-polarization, which can be used as a benchmark to assess the transmitter/receiver-induced penalties.**

***Keywords*— Optical interconnects; Digital coherent optical communications; Kerr effect.**

I. INTRODUCTION

Last years have seen an unprecedented rise in the size and number of hyper-scale datacenters, where the massive concentration of resources leads to an improved efficiency and reduced operational costs [1]. As the size of a datacenter increases above a certain threshold, however, the scale economy of its energy consumption and occupation area saturates [2]. These limitations are forcing service providers to undergo a geographic distribution process in which data are stored and processed in clusters separated by distances that can exceed 100 km [3]. In this context, a consortium of market-leading companies, denominated Open Interconnect Forum (OIF), joined efforts to develop a unified standard that enables interoperability of different vendors. According to the recently published Interoperability Agreement (IA) [4], the newly developed 400ZR standard aims to support 400GbitE transmission employing low-consumption coherent optical technology based on dual-polarization 16-ary quadrature amplitude modulation (DP-16-QAM) format [5]. This standard considers two point-to-point applications: on the one hand, amplified dense-wavelength division multiplexed (DWDM) links and, on the other hand, single-wavelength unamplified links. As in any other optical communication system, the overall performance will be impacted by the fiber, transmitter, and receiver impairments [6]. However, inter-data optical interconnects (OICs) are subject to more stringent cost and consumption requirements compared to traditional long-haul coherent systems [7]. Therefore, the performance of both transmitter and receiver are expected to be sacrificed in order to improve the energy efficiency and the reduce their cost. In this scenario, fiber-induced impairments can be considered as an upper-bound limit to the transmission performance. In particular, the combination of the Kerr nonlinear effect, the chromatic dispersion (CD), and the transmission loss will ultimately limit the maximum achievable link range [8]. Given the high bandwidth and the multilevel nature of the transmitted signal, alongside with the adoption of polarization multiplexing, make difficult to predict and quantify the complex interplay among the different impairments.

In this paper, we focus on the single-wavelength unrepeated case where the Kerr effect gives rise not only to self phase modulation (SPM) but also to nonlinear polarization crosstalk. Thus, we perform numerical simulations to assess the signal quality in terms of the launch optical power (LOP) and fiber link length considering both single polarization (SP) and dual-polarization (DP), which allowed us to discriminate the impact of self-phase modulation and nonlinear polarization crosstalk. These results are important because they represent the upper-bound to the link range and, hence, may be considered as a benchmark to quantify the penalty of transmitter and receiver imperfections. Furthermore, we show that in this kind of systems the nonlinear polarization crosstalk plays an important role and quantify the effect of the fiber length on the optimum LOP. Therefore, it is important to compensate both the SPM-induced nonlinear phase-noise, as well as the nonlinear polarization crosstalk. In addition, we quantify the optimum power levels in terms of the length of the fiber link. The rest of the paper is organized as follows: In Section II, we describe the system model and the simulation setup. Numerical results are presented in Section III and finally, in Section IV, we conclude the paper.

II. SYSTEM MODEL AND SIMULATION SETUP

Figure 1 shows the block diagram of the simulation setup employed to analyze the system performance in terms of launch optical power and fiber link length. The simulations were performed in a co-simulation environment where the modulation, demodulation, and DSP-based impairment mitigation were implemented in Matlab, whereas the optical modulation, fiber transmission, and signal detection were carried out in VPI TransmissionMaker. On the transmitter side, two independent pseudorandom bit sequences (PRBSs) corresponding to the information to be transmitted by the two

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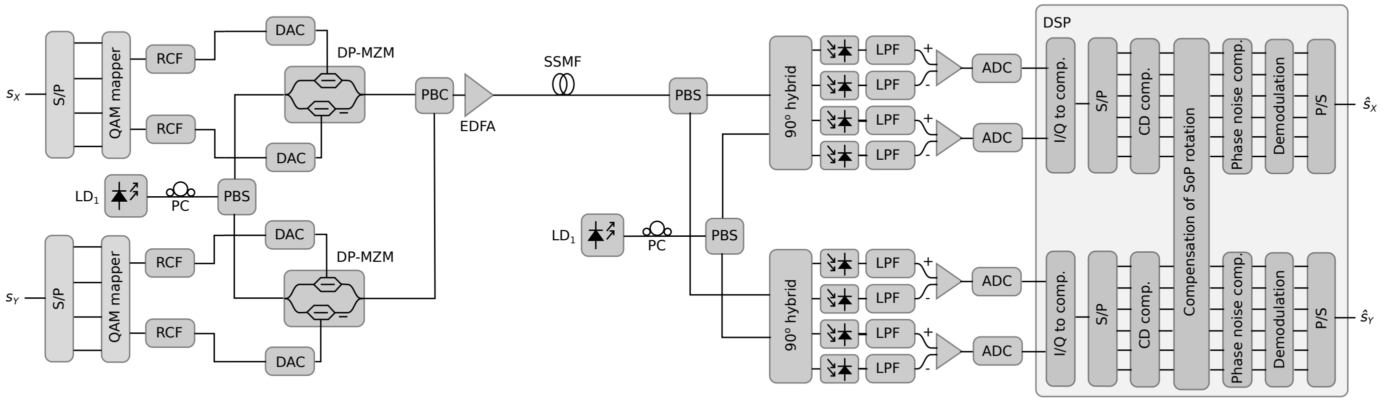

Fig. 1. Simulation setup employed to analyze a general high-capacity coherent DP-16QAM. S/P: serial-to-parallel converter, RCF: rised cosine filter, DAC: digital-to-analog converter, DP-MZM: dual-parallel Mach-Zehnder modulator, LD: laser diode, PC: polarization controller, PBS: polarization beam splitter, PBC: polarization beam splitter, EDFA: erbium-doped fiber amplifier, SSMF: standard single-mode fiber, LPF: low-pass filter, ADC: analog-to-digital converter, DSP: digital signal processing, CD comp.: chromatic dispersion compensator, and P/S: parallel-to-serial converter.

TABLE I

SUMMARY OF SIMULATION PARAMETERS.

Simulation parameters	
Sampling rate (optical domain)	1600 GSa/s
Sampling rate (electrical domain)	200 GSa/s
Number of symbols per run	4096
Number of runs	25
Signal parameters	
Modulation format	SP-16QAM /DP-16QAM
Bit rate	200 Gbps / 400 Gbps
Baud rate	50 Gbaud
Filter shape	Rised cosine
Rolloff factor	0.1
Number of synchronization symbols	64
Number of MIMO symbols	32
Launched optical power (LOP)	0-10 dBm

Model parameters	
Laser linewidth	100 kHz
Laser power	10 dBm
Fiber chromatic dispersion (D)	16 ps/(nm·km)
Fiber attenuation coefficient (α)	0.2 dB/km
Fiber Nonlinear coefficient (γ)	1.3 $\text{W}^{-1}\cdot\text{km}^{-1}$
Fiber polarization-mode dispersion (PMD)	3.16 ps/$\sqrt{km}$
Fiber length	100 km -150 km
PD thermal current noise density	10 pA/$\sqrt{Hz}$
PD responsivity	1 W/A
90° hybrid insertion loss	9 dB
IQ-modulator insertion loss	10 dB
Maximum amplifier gain (G)	20 dB
Ampifier noise figure (NF)	4 dB

orthogonal polarizations were first packaged in blocks of 4 bits in a serial-to-parallel (S/P) converter. Each block was then mapped into a 16-QAM constellation and its in-phase and quadrature components were oversampled and filtered employing a raised-cosine filter (RCF) with a rolloff factor of 0.1. The signals were oversampled again to emulate the digital-to-analog (DAC) conversion, resulting in 32 samples per symbol. The in-phase and quadrature component of the modulating signals of each polarization drove a dedicated dual-parallel Mach-Zehnder modulator (DP-MZMs) that modulated the two orthogonal polarizations of a laser beam, which were obtained from a single continuous-wave (CW) 100-kHz-linewidth laser diode (LD). The two modulated optical signals were combined in a polarization beam combiner (PBC) and boosted using an erbium-doped fiber amplifier (EDFA), which controlled the launch optical power (LOP) at the input of the transmission link. At this point it is important to note that considering an LD with an output power of 10 dBm and a total optical loss for each polarization of 10 dB, the power input at the EDFA was 0 dBm per polarization. Therefore, since we swept the launch optical power (LOP) from 0 to 10 dBm per polarization, that is, from 3 to 13 dBm for total LOP in dual polarization configuration, the maximum gain was 13 dB, thus for an EDFA with a noise figure (NF) of 4 dB, in the worst case scenario, the noise power added by the amplifier is as low as 0.1887 μW [6]. Alternatively, the amplifier can be integrated with the rest of the transmitter by using semiconductor optical amplifiers (SOAs). In order to avoid the polarization mode loss present in this type of amplifiers, a possible solution maybe to use dedicated SOA for each polarization before combining them in the PBC. Nevertheless, even if SOAs with NFs of 9 dB are employed, the added noise power is still as low as 0.6 μW. The combined signal was transmitted over a span of standard single-mode fiber with a length ranging from 100 to 150 km. At the receiver side, a PBS was used to split the incoming signal into two orthogonal components. Each of these signals was combined with the corresponding polarization of the local oscillator LD in a 90°, whose outputs were detected using two pairs of balanced photodetectors (PDs) and differentially amplified. After differential amplification, the four signals corresponding to the in-phase and quadrature of the two polarization were downsampled to get two samples per symbol to simulate the operation of the analog-to-digital (ADC). Once in the digital domain, we converted the in-phase and quadrature components samples to a stream of a complex samples. This

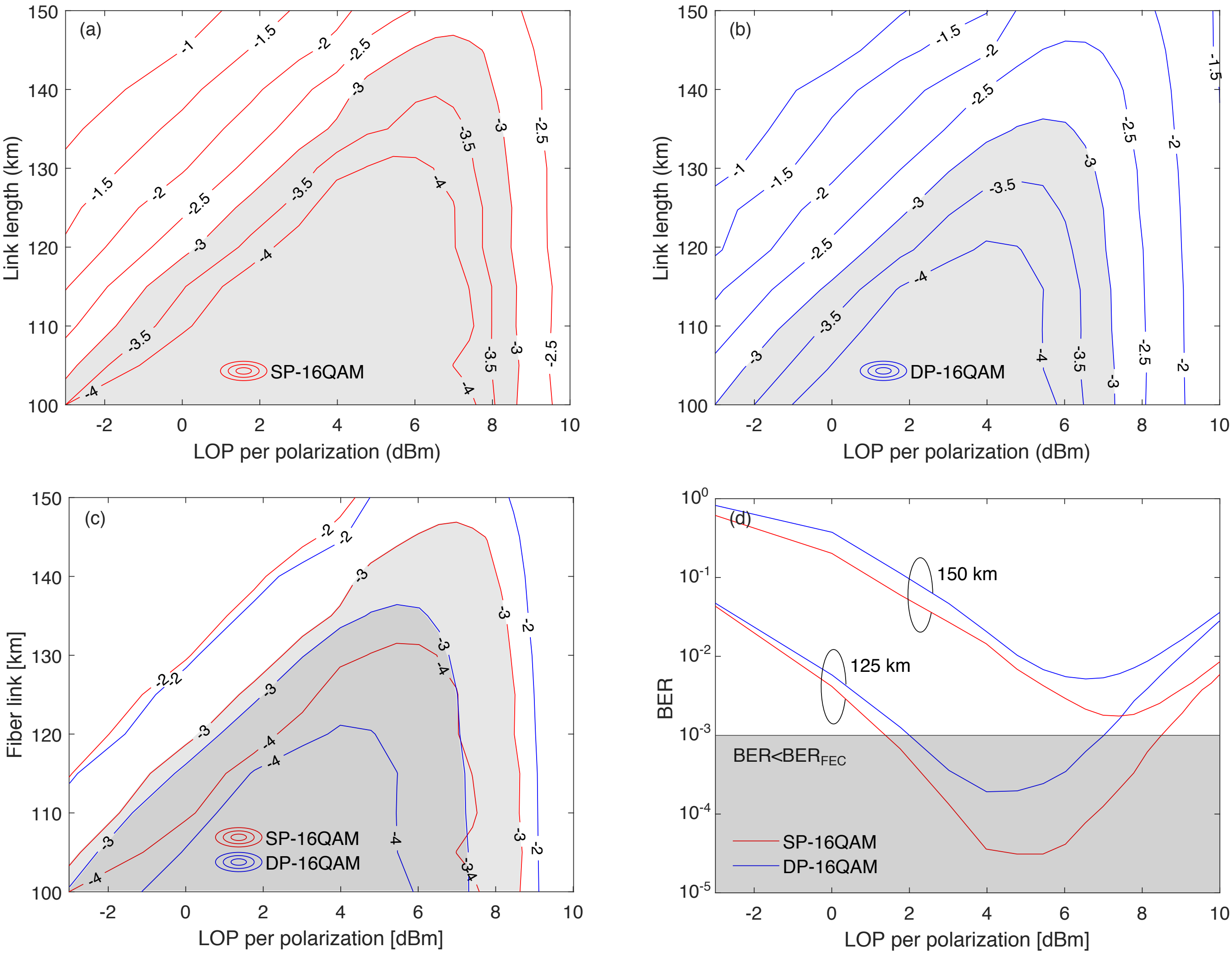

Fig. 2. BER contour lines, in $\log_{10}(\text{BER})$, as a function of the LOP per polarization and link length for (a) single-polarization transmission and (b) dual polarization transmission. (c) Comparison of some BER contour lines for single and double polarization. (d) BER in terms of LOP for transmission distances of 125 km and 150 km and single and double polarization. In all subfigures the shadowed region indicates BER $<$ BER$_{\text{FEC}}$ = 10^{-3}.

stream was parallelized to perform the frequency-domain CD compensation. After the CD was corrected, the signal was resampled to a single sample per symbol, which required a time synchronization process that was implemented employing a pseudorandom binary amplitude training sequence of 64 symbols and cross-correlation method. To analyze the impact of the different impairments on the signal quality, we performed a double sweep varying the LOP per polarization from 0 to 10 dBm and the fiber length from 100 km to 150 km considering both single and double polarization. For each combination, 25 runs of 4096 symbols were carried out, which were configured to have uncorrelated SoP rotations. The signal quality was assessed by the bit error ratio (BER), which was estimated by error counting since error vector magnitude (EVM) is not accurate for elevated values of LOP.

III. NUMERICAL RESULTS

In Fig. 2 we show the performance results for the 400-Gbps OIC in terms of LOP and fiber link length. In particular, Fig. 2(a) and (b) represent the BER contour lines for single polarization (SP) and double polarization (DP), respectively. In both cases, it can be seen that at a fixed fiber link length low LOPs result in poor signal-to-noise ratios and subsequently, high BER values. As LOP increases (moving horizontally in the graph), the BER decreases until an optimum value is achieved. Above this LOP, the BER degrades due to the excitation of nonlinear effects, in our case Kerr effect. It is interesting to observe that for link lengths of up to 120 km, the BER contourlines corresponding to BER values higher than 10^{-4} are almost vertical. This can be explained by noting that for the considered links the effective nonlinear interaction length ranges between 22.0 and 22.2 km. That is, the distortion caused by nonlinear effects concentrates in the first 22 km and extending the link length from 100 to 150 km does not incur in much higher nonlinear distortion. Comparing the SP and DP cases shown in Fig. 2(a) and (b), it can be appreciated that even if the general behavior is similar, they differ quantitatively. The difference is particularly notorious at elevated LOP values.

In order to make this comparison clearer, in Fig. 2(c) we superposed some selected BER contourlines, revealing that for lower LOPs, the curves corresponding to the same BER value appear closer than at larger power levels. This indicates that in addition to the Kerr-induced self phase modulation, the signal experiences a power dependent polarization crosstalk. Finally, in Fig. 2(d), we present the BER in terms of the LOP per polarization for the two configurations considering fiber links of 125 and 150 km. It can be seen that for both fiber link lengths, at low LOPs, the SP and DP BER curves are quite close and for higher LOP the curves separate. The small divergence at low LOPs may be attributed to imperfect polarization rotation compensation in the DSP, while at higher LOPs, in addition, nonlinear polarization rotation is present. Regarding the optimum LOP two tendencies can be identified: when we compare the SP and DP cases, the optimum LOP in the latter it is slightly lower than in the former. This makes sense because DP is more affected by nonlinear distortion. On the other hand, if we compare the same polarization configuration for 125 and 150 km, we can see that higher fiber links results in higher optimum LOP levels, which is a straightforward consequence of the poorer SNR and the relatively stronger effect of the receiver noise.

The impact of the nonlinear polarization crosstalk can be quantised though the length penalty at a particular BER value. In Fig. 3(a) we show the optimum BER in terms of the fiber link length. As can be seen, the length penalty due to the nonlinear polarization crosstalk decreases as the fiber link increases, from almost 15 km at 100 km to around 5 km at 150 km. As expected from Fig. 2, the LOP at which optimum BER is obtained shifts depending on the fiber link length. This effect can be observed in Fig. 3(b) for both the SP and DP cases. Even if for SP and DP, the optimum LOP increases for larger link lengths, the slope is more pronounced for the SP case. The dependency on the fiber link of the optimum the length penalty, and the optimum power, as well as the effect of polarization multiplexing, can all be explained in terms of the interplay between noise and nonlinearties. Thus, the longer the fiber link is, the more important the receiver noise becomes and, consequently, the impact of the nonlinear crosstalk is less significant and the length penalty is reduced. Regarding the optimum LOP, for higher transmission loss, larger LOP are allowed since the SNR at the output of the PDs is poorer and larger nonlinear distortion may be accepted. Furthermore, for the SP case, the LOP increase can be larger than in the DP case because the system is affected by weaker nonlinear distortion.

IV. CONCLUSIONS

In this paper we analyzed the interplay between receiver additive noise and fiber nonlinearities in an unamplified single-wavelength 400-Gbps coherent OIC. We employed numerical simulation to sweep both the fiber link and LOP showing the relative impact of noise and nonlinear distortion. Furthermore, we performed simulations considering SP and DP to discriminate the effects of NPN and the polarization crosstalk. These simulations reveal that the length penalty of DP with respect to SP varies from 15 km to 5 km when the link length is increased from 120 km to 150 km. We also found that the optimum LOP ranges from 2 to 4 dBm for the DP case. For the SP case, the LOP increases up to almost 6 dBm. These results can guide the dimensioning of OICs based on the novel 400ZR standard as well as help to identify the regimes where nonlinear compensation techniques present higher potential. In particular, these results suggest that nonlinear compensation would be more efficient if both polarizations are considered.

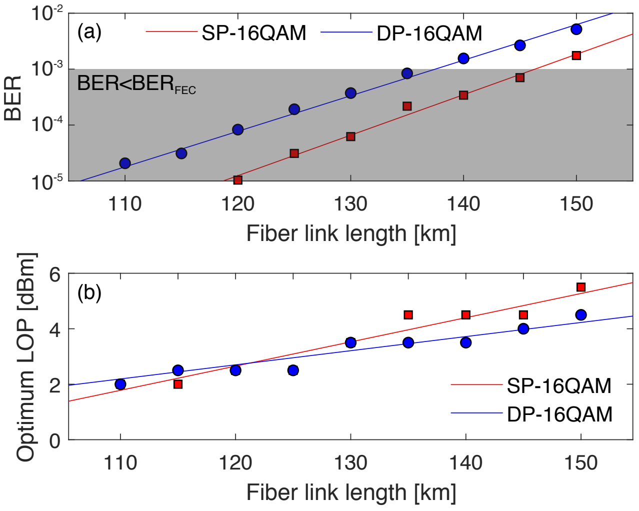

Fig. 3. (a) Optimum BER in terms of fiber link length for single and double polarization transmissions and (b) optimum launch optical power for both transmissions in terms of the fiber link length. In all subfigures the shadowed region indicates BER < $\text{BER}_{\text{FEC}} = 10^{-3}$.

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