Designing the Next Generation of Intra-and Inter-Datacentres Interconnects

Vasiliki Vgenopoulou[1], Nikolaos Raptis[1], Evangelos Grivas[1], Ioannis Tomkos[1]

[1]Athens Information Technology (AIT), 44 Kifissias Avenue, 15125 Marousi, Greece
Tel: +30 210 668 2700, Fax: +30 210 6682729, e-mail: vvge@ait.gr

ABSTRACT

In this work, we investigate the performance specifications of the components comprising the suggested intra- and inter-Data Centres (DCs) systems according to DIMENSION project. More specifically, we deal with the performance specifications of the laser sources and the respective modulators. The intra-DC system employs a novel Directly Modulated Laser (DML) grown on Silicon Photonics (SiPh) and targets links up to 10km. A coherent solution is selected for the inter-DC system that employs a carrier-depletion Mach–Zehnder Modulator (MZM) based on a SiGe Bipolar Complementary Metal-Oxide Semiconductor (BiCMOS) technology and targets links that exceed 80 km. In both systems, the considered aggregate data rate is 400 Gbit/s.

Keywords: Intra-DC, Inter-DC, component specifications, simulations.

1. INTRODUCTION

Emerging applications, such as video streaming, social networking and cloud computing, have led to an unprecedented traffic increase, rendering the current data storage facilities insufficient. Therefore, there is an emerging need for more powerful, scalable and efficient warehouse DCs to effectively host all the previous applications. In the frame of DIMENSION project, the system requirements and characteristics have been identified and targeted to cover the aforementioned needs [1].

The present study concerns the simulation models of an intra- and inter-DC system, through which we perform extensive runs, to extract the ranges of the optimum values for their component parameters. More specifically, we deal with the performance specifications of the laser source and the electro-optical modulators. The intra- and inter-DC demos are modelled using the VPI software tool, while some components are integrated as MATLAB functions. Our target is to develop accurate transceiver models so as to be able to gain a good insight of the performance potential and limitations of these systems at the design stage.

The results are grouped in two categories: one for the intra-DC and one for the inter-DC. First, we simulate each scenario, second, we extract the performance specifications, and finally, we estimate the real systems performance at the design stage. In the intra-DC study, we identify the minimum laser bias current and the corresponding bandwidth in terms of Extinction Ratio (ER) and Bit Error Rate (BER) set as target [2], while meeting the 400GBASE-LR8 specifications [3], in order to extract the laser driver requirements. In the case of inter-DC study, polarization multiplexed Quadrature Amplitude Modulation (QAM) signals were generated using MZMs with carrier depletion phase shifters on their arms. As the signals were distorted by the finite static ER due to the imbalance in the power splitting at the MZMs' arms, the proper biasing and voltage swing applied to each phase shifter determined the best performance. We also study the impact of the laser linewidth of the source and the local oscillator (LO) at the receiver, with and without Wavelength Division Multiplexing (WDM) through the fiber spans.

This paper is organized as follows: Sections 2 and 3 are devoted to the intra- and inter-DC studies, respectively, presenting the simulation setups and the related results. Finally, the conclusions are drawn.

2. SIMULATION STUDY ON THE PERFORMANCE SPECIFICATIONS OF INTRA-DC SYSTEMS

2.1 Simulation setup

The simulated system is a short-reach transceiver for intra-DC environment used for the propagation of single-polarization PAM4 signals at a total net bit rate of 400 Gb/s in an optical link comprised of 10 km of Standard Single Mode Fiber (SSMF). It employs an array of DMLs emitting at 8 different wavelengths in the telecom O-band. Each one of them supports a net bit rate of 50 Gb/s. The simulation setup is depicted in Figure 1. At the transmitting side, the laser source is based on the rate equations model described in [4]. The symbol rate was set to 26.5625 Gbaud/s in all cases leading to a raw bit rate of 53.125 Gb/s per wavelength. The laser driver has been modeled as an 8-bit current output DAC followed by a Low Pass Filter (LPF). The LPF has been modeled as a 2nd order Butterworth filter with a –3 dB cut-off frequency ranging from 0.5 × baud rate to 1.5 × baud rate depending on the case investigated. The ER is kept constant at 4.5 dB, in all cases. The total transmitter optical losses were set equal to 4.5 dB. This value includes 1 dB loss for laser coupling, 0.5 dB for laser monitoring, 2 dB for Tx AWG and 1 dB for fiber coupling. Moreover, wavelength channel crosstalk in the fiber was not considered since channel spacing is rather high (i.e. 800 GHz).

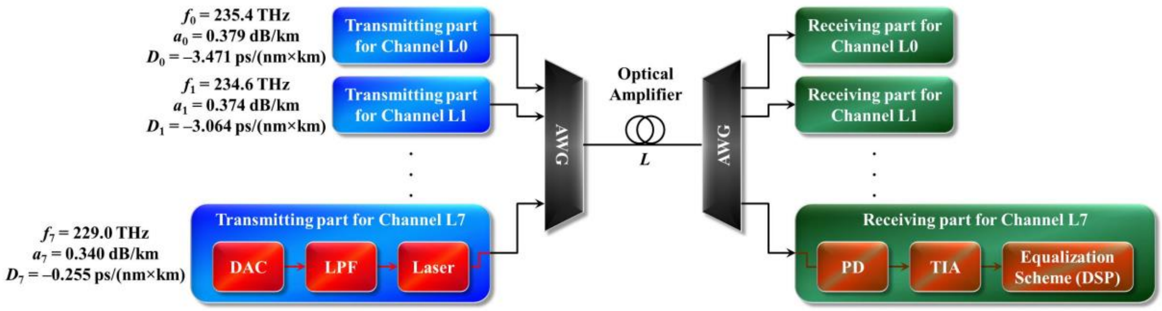

Figure 1. Simulation set up of the intra-DC demo. DAC: Digital-to-Analog Converter.

At the other side of the link, the receiver is modeled as a 4th-order Butterworth filter with –3 dB cutoff frequency equal to 18.6 GHz (0.7 × baud rate) for the cases presented here. The photodiode (PD) responsivity is set to 0.45 A/W, whereas the transimpedance amplifier (TIA) gain is set to 1000 A/V. For compensating the transmission impairments, two equalization schemes are applied, a Feed Forward Equalizer (FFE) and a Decision Feedback Equalizer (DFE), each employing 4 or 8 taps. An 8-bit Analog-to-Digital Converter (ADC) is used for signal sampling while the employed equalizer models use integer arithmetic and are trained with up to 768 bits. The training is performed using the Least Mean Square (LMS) algorithm while monitoring the Q-factor of the equalized signal.

2.2 Simulation Results

We consider two cases in order to explore the limits of the intra-DC transceiver: (a) the best-case scenario (i.e. channel L7) and (b) the worst-case scenario (i.e channel L0), in terms of losses and dispersion. The laser bandwidth strongly depends on the bias current (i.e. the higher the bias current, the higher the bandwidth achieved). A high bias current has a direct impact on power consumption and the laser driver requirements given that it requires higher modulation current to satisfy the minimum ER. Hence, the target of this section is to identify the minimum laser bias requirements that can reach the BER target (i.e. 2.4×10^{-4}).

In Figure 2, we show the BER performance as a function of the laser bias current. The laser driver bandwidth was set equal to the baud rate. We observe that the BER target cannot be reached in the worst-case scenario, even if the bias current (I_{bias}) is set to 12 times the threshold current (I_{th}), unless an equalization scheme is employed with 4 taps and $I_{bias} < 8\times I_{th}$. For $I_{bias} = 8\times I_{th}$ = 48 mA, the modulation current was equal to 44 mA.

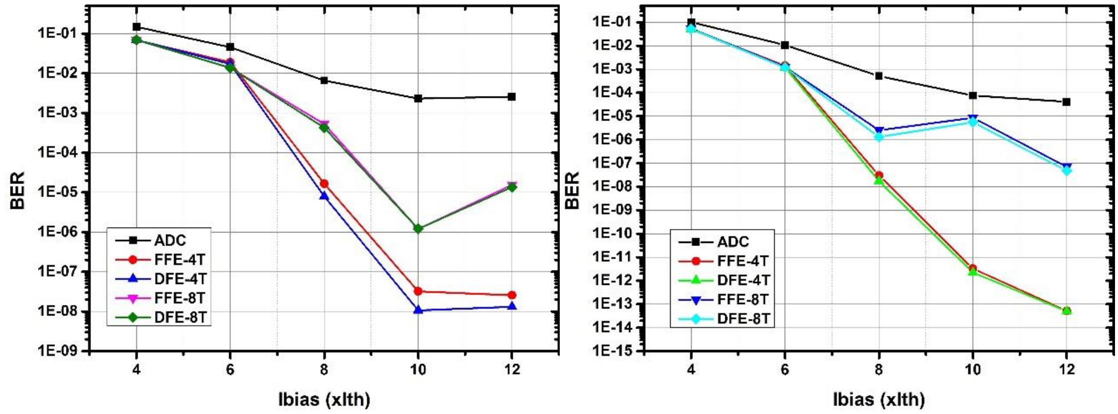

Figure 2. BER as a function of the laser bias current for the worst (left) and the best (right) case.

In Figure 3, the BER for different values of the laser driver –3 dB cut-off frequency is presented when the laser bias current is set to 48 mA. It is obvious that the system performance improves as the driver bandwidth reduces to a value equal to the half of the symbol rate (i.e. 13.28 GHz). In this case, the BER target is reached, even for the worst-case scenario, without equalization. This bandwidth dependence, shown in Figure 3, is due to the fast fluctuations in the laser modulation current leading to a large overshot in the optical signal which is closely related to the dynamics of the laser. Moreover, the frequency response of the laser device is not flat at the lower frequency regime.

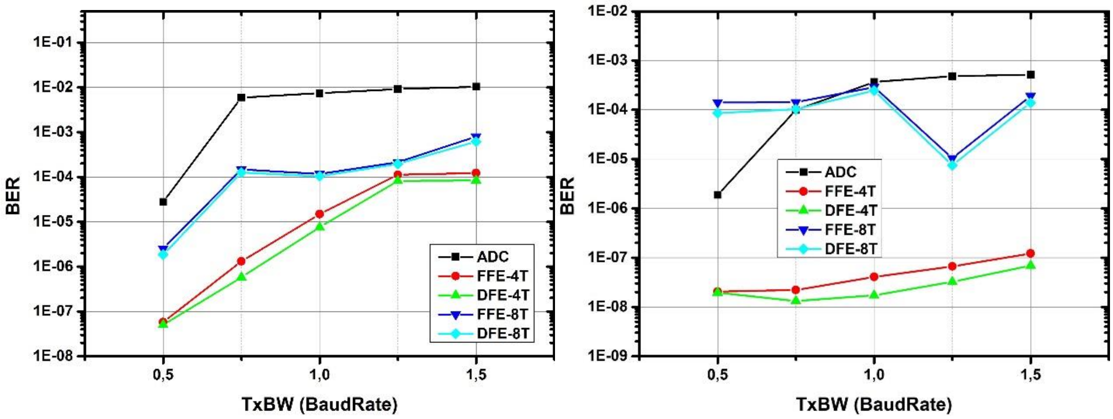

Figure 3. BER as a function of the laser driver bandwidth for the worst (left) and the best (right) case.

3. SIMULATION STUDY ON THE PERFORMANCE SPECIFICATIONS OF INTER-DC SYSTEMS

In metropolitan network scenarios, the increased traffic demands impose the intensive investigation of 400G coherent systems. However, conventional coherent transceivers are bulky and rather expensive. The reduction of implementation cost and footprint could be achieved by adopting silicon photonics integrated circuits [5].

3.1 Simulation Setup

Focusing on the DIMENSION's objectives, a medium-reach coherent transmitter for inter-DC and metro applications for link lengths greater than 10 km and even exceeding 80 km using modulators on silicon was simulated. Parameters of key components in the setup, such as the optical MZM and the lasers at both the transmitting and the receiving side (LO), were investigated. To achieve 400 Gbit/s, two wavelengths were required. For each wavelength, Polarization Division Multiplexing (PDM) was applied. The symbol rate was set to 26.5625 Gbaud and 16-QAM was used per polarization. The raw bit rate per wavelength was 212.50 Gbit/s (200 Gb/s PDM–16QAM) [6].

The transmitter part of the setup is shown in Figure 4(a). Regarding the laser output power, 10 mW were available for each polarization at the input of each Dual-Nested I/Q MZM modulator. The linewidth of each laser was initially set to 100 kHz. Each MZM employs depletion-type phase shifters (Figure 4(a)) and was driven using a push-pull scheme. The simulations were based on the fitted experimental curves of the half-wave voltage (V_π), the insertion losses and the capacitance displayed in Figure 5(a), (b) and (c), respectively. 4 mm phase shifters were considered, while the bias voltages (V_{bias}) were limited between –3 V and –1 V. The static ER was set to 25 dB.

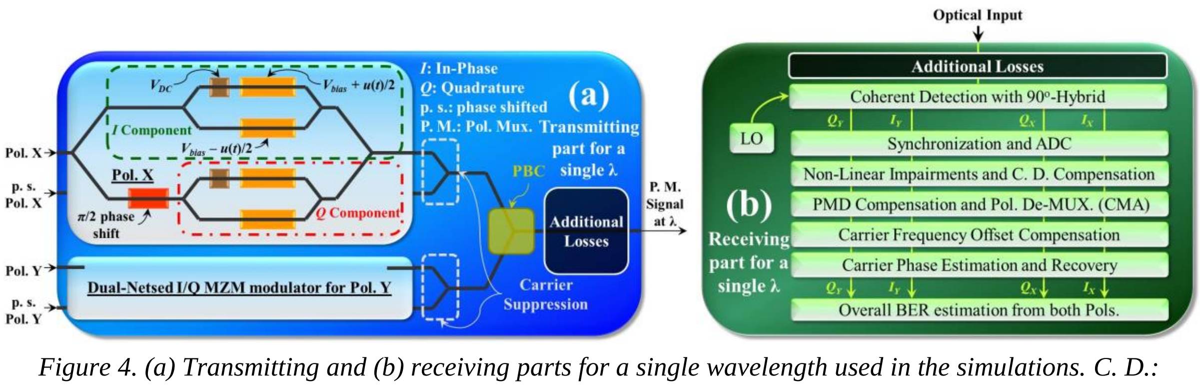

Figure 4. (a) Transmitting and (b) receiving parts for a single wavelength used in the simulations. C. D.: Chromatic Dispersion. CMA: Constant Modulus Algorithm. PMD: Polarization Mode Dispersion.

A thermal [7] or a low speed phase shifter [8] can be considered for adjusting thermally or electrically, respectively, the operation point of each MZM. The operation point of the MZM was set over the quadrature point [9] and a phase shift was considered equal to $\pi \times V_{DC}/V_\pi$ with $V_{DC} = V_{bias}$ and V_π the one of the depletion-type phase shifters for the respective V_{bias}. This operation point adjustment will be further examined in future works for better cancelling second order non-linearity of modulator transfer function [9]. The peak voltages of $u(t)$ were never larger than $|V_{bias}|$, so that the phase shifters always operate at the carrier depletion regime. Pre-distortion of the pulses was applied in the electrical domain. After modulation, the carrier was suppressed by addition of an unmodulated carrier component with proper phase adjustment [10]. Then, the signals on the two polarizations were combined by a Polarization Beam Combiner (PBC). Before launching into the fiber, the PDM signal was subjected to 9 dB additional losses.

At the transmitting side (Figure 6), a constant output power level was considered at the output of the booster amplifier. The gain, saturation output power and noise figure of the rest of the amplifiers in the link were 18 dB, 15 dBm and 7 dB, respectively, which are considered typical values for Praseodymium-Doped Fiber Amplifiers (PDFAs) [11]. SSMF was considered as the transmission medium [12], whereas the losses of each fiber span were compensated by each following amplifier.

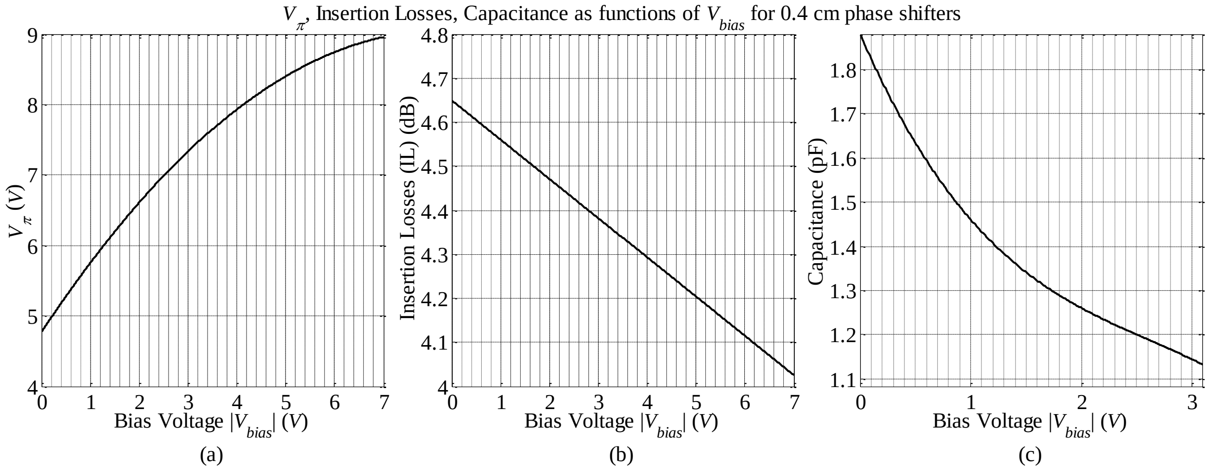

Figure 5. (a) Half-wave voltage (Vπ), (b) Insertion Losses (IL) and (c) Capacitance as functions of the absolute value of the bias voltage for 4 mm phase shifter.

At the receiving side (Figure 4(b)), the signal suffers 9 dB of additional losses. The optical power of the local oscillator was set to 10 mW and its linewidth was initially set to 100 kHz, whereas its frequency could deviate up to 100 MHz. After coherent detection, an ADC was used with a resolution of 8 bits and a sampling rate two times the baud rate. The following blocks included several conventional signal processing procedures for symbols recovery of both polarizations [6], [13]. More specifically, the Non-Linear Impairments and the Chromatic Dispersion of the fiber were compensated using the digital back-propagation method. PMD Compensation and Pol. De-MUX were realized by applying CMA with 19 taps. Afterwards, the carrier frequency offset was estimated and compensated. The next step was the carrier phase recovery for the 16-QAM signals, with 25 symbols used for estimation. Finally, the overall BER per channel was estimated.

Initially, a single wavelength was considered in the grid, for instance λ_2 in Figure 6. The optical noise bandwidth was set to $\Delta\lambda_{baud} = 0.3$ nm.

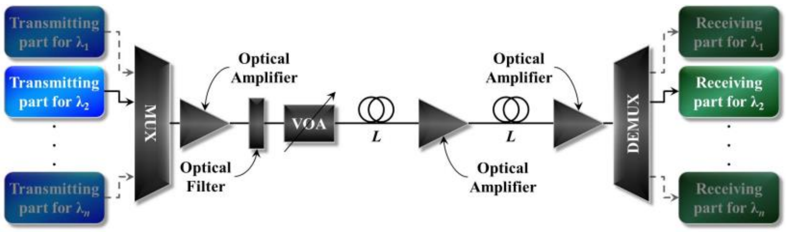

Figure 6. Setup of the Transmission link. The Variable Optical Attenuator (VOA) was used for estimation of the Optical SNR (OSNR).

3.2 Simulation Results

The limits of the MZM were examined in terms of the effect of the reverse bias voltage and the RF signal swing on performance for a link length of 100 km (L = 50 km). V_{bias} on each phase shifter and the peak-to-peak voltage value of $u(t)$ were set to –3 V and 4 V, respectively. The mean optical power after the PBC was –9.71 dBm and the dynamic ER for the two polarizations was 9.47 dB approximately. The extracted BER as a function of the OSNR is depicted in Figure 7(a). The BER target is achieved for an OSNR close to 18 dB. It is noted that a higher peak-to-peak value did not offer any performance enhancement, as the symbols get distorted due to the non-ideal static ER. For higher V_{bias} values, the performance was worse than in the previous case, as well. For OSNR slightly over 19 dB which corresponded to –3 dBm launch power, the constellation diagram for the X Pol. is given in the inset of Figure 7(a). The same procedure and voltage values gave similar results for other wavelengths, as the dispersion is manageable and the only non-linear impairment is the Self Phase Modulation (SPM).

Based on the previous configuration that gave the best results, the impact of the lasers' linewidth on performance of a 100 km link was investigated. The launch power was set to –3 dBm. In Figure 7(b), it can be observed that the required BER can be achieved for values up to 3.5 MHz.

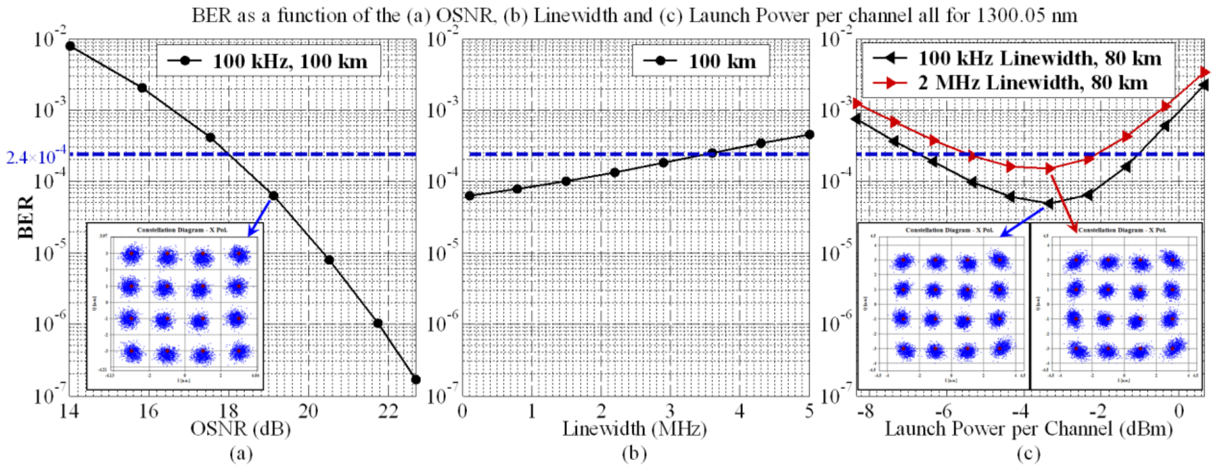

Figure 7. (a) BER as a function of the (a) OSNR (noise measured in 0.3 nm) after a 100km link, (b) lasers' linewidth after 100 km and (c) the launch power per channel, for a 5-channel WDM link of 80 km length, with 100 GHz channel spacing. V_{bias} = –3 V on each phase shifter, the overall peak-to-peak voltage was equal to 4 V and 1300.05 nm was the channel under investigation for (a), (b) and (c).

The case of a WDM transmission of five PDM–16QAM channels was also considered. In Figure 6, λ_1 up to λ_5 were used, whereas the performance of the central one (λ_3) was evaluated. The channel spacing was set to 100 GHz. In general, similar performance was achieved while testing several wavelengths in the O-Band. Therefore, the results for 1300.05 nm wavelength are presented. The values of the lasers' linewidth that were considered were 100 kHz and 2 MHz. For V_{bias} = –3 V and 4 V peak-to-peak of $u(t)$, the mean power of each channel was –18.77 dBm after losses introduction. The power levels per channel that were launched into the fiber lay between –8.35 and 0.65 dBm using a VOA. The length of each span was 40 km (Figure 6) giving a total link distance of 80 km.

The BER as a function of the launch power per channel is depicted in Figure 7(c). Apart from SPM, other non-linear effects appeared that are related to the WDM case, such as Four Wave Mixing. The impact of non-linear impairments became more intense in the part of both curves over –3 dBm, where the BER started increasing. For a linewidth of 100 kHz, the BER target was achieved for a wide range of power levels. For a linewidth of 2 MHz, the BER target was achieved for power levels between –5.4 dBm and –2.2 dBm. Constellation diagrams of X Pol. are shown in the inset of Figure 7(c) for the two linewidth cases for –3.35 dBm launch power. The larger linewidth gave more perturbed constellation, especially at the edges, justifying the worse performance.

4. CONCLUSION

In this work, simulation results were presented concerning the performance of the components included in the suggested intra- and inter-DCs systems according to DIMENSION project. In the intra-DC study case, given the strong dependence of the laser bandwidth on the laser current, we identified the minimum bias current and the corresponding bandwidth while satisfying the BER limit. The simulation results for the worst-case scenario led to the conclusion that the BER target is achievable with a laser bias current as low as 8 times the laser threshold current, provided that an equalizer of 4 taps is employed. For the same laser bias current, we deduced that limited bandwidth values render feasible to reach the BER target in the worst-case scenario without the contribution of an equalization scheme. Considering the MZMs capabilities in an Inter-DC case, the optimum bias and peak-to-peak voltage levels applied on each phase shifter of each MZM arm were determined to achieve the BER target, when a single 212.5 Gbit/s PDM–16QAM signal was transmitted over a 100 km link. For these voltage and length values, the BER target could be achieved for linewidth values up to 3.5 MHz, for a launch power of –3 dBm. Finally, for a WDM scenario where five 212.50 Gbit/s PDM–16QAM signals were transmitted over two 40 km spans, the system could operate in the required BER limits for lasers with linewidth up to 2 MHz.

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REFERENCES

[1] www.dimension-h2020.eu

[2] R. Motaghiannezam, *et al.*: 52 Gbps PAM4 receiver sensitivity study for 400GBase-LR8 system using directly modulated laser, *Opt. Express*, vol. 24, no. 7, pp. 7374–7380, April 2016.

[3] C. Cole, *et al.*: 400Gb/s 2km & 10km duplex SMF PAM-4 PMD Baseline Specifications, 400 Gb/s Ethernet Task Force, May 2015.

[4] I. Tomkos, *et al.*: Extraction of laser rate equations parameters for representative simulations of metropolitan-area transmission systems and networks, *Opt. Commun.*, pp. 109–129, July 2001.

[5] C. Y. Wong, *et al.*: Silicon IQ Modulator for Next-Generation Metro Network, *J. Lightwave Technol.*, vol. 34, no. 2, pp. 730–736 , January 2016.

[6] Optical Internetworking Forum (OIF): Technology options for 400G implementation, *OIF-tech-Options-400G-01.0*, July 2015.

[7] P. Dong, *et al.*, "50-Gb/s silicon quadrature phase-shift keying modulator," *Opt. Express*, vol. 20, no. 19, pp. 21181–21186, September 2012.

[8] D. J. Thomson, *et al.*, "Silicon carrier depletion modulator with 10Gbit/s driver realized in high-performance photonic BiCMOS," *Laser Photonics Rev.*, vol. 8, no. 1, pp. 180–187, January 2014.

[9] A. Khilo, C. M. Sorace, and F. X. Kärtner: Broadband linearized silicon modulator, *Opt. Express*, vol. 19, no. 5, pp. 4485–4500, February 2011.

[10] Z. Liu, et al.: Modulator-free quadrature amplitude modulation signal synthesis, *Nat. Commun.*, 5:5911, doi: 10.1038/ncomms6911, December 2014.

[11] https://www.fiberlabs-inc.com/1u_amp/1300nm-1u-amp/

[12] G.652: Characteristics of a single-mode optical fibre and cable, ITU-T, November 2009.

[13] S. J. Savory: Digital Coherent Optical Receivers: Algorithms and Subsystems, *IEEE J. Sel. Top. Quantum Electron.*, vol. 16, no. 5, pp. 1164–1179, September/October 2010.