Optimization of Shared-Laser Coherent Transceiver for Short-Reach Links

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***Abstract*—We report on the numerical study of coherent detection applied to short-reach transmission systems employing transceivers equipped with a single laser used both for transmission and as local oscillator. Our findings show optical power budget (OPB) well above 30 dB using, for instance, PM-QPSK modulation at 56 $GBaud$, with a maximum at 70% laser split ratio. We analyze how such systems are affected by key parameters, showing remarkable power budget even for higher order modulations.**

***Index Terms*—optical communications, coherent detection, data center interconnects, short-reach**

I. Introduction

Short-reach optical communication links are rapidly evolving in terms of transmission speed in bit rate per wavelength. Speeds above 100 $Gbps$ will likely be very difficult to achieve with the traditional direct-detection (DD) approach. Therefore, following what has happened in other fiber transmission segments, advanced modulation formats and coherent detection (CD) will likely be introduced also in short-reach systems for data center interconnects (DCI). Primary concerns regarding coherent for short-reach are complexity and cost. In order to reduce the cost associated with the laser, some recently developed integrated coherent transceivers are equipped with a single laser followed by a splitter that feeds both the signal modulator and the local oscillator (LO).

Here we extend the work presented in [1], [2] focusing on this transceiver architecture, and report on the numerical analysis of the performance of this kind of coherent detection systems under different conditions, in terms of the achievable optical power budget. We base our study on the analytical model first presented in [3] and validated in [2]. The impact of many relevant parameters is investigated in order to verify the viability of the coherent solution in a broad range of situations, varying modulation formats, intensity of the local oscillator at the receiver and noise levels including thermal and relative intensity noise. We start by considering scenarios without optical amplification, much as the current implementation of the short-reach transmission schemes. Then we refine the analytical model introducing the effect of the optical signal to noise ratio (OSNR) at the receiver input, and study two different scenarios where an optical amplifier, such as a semiconductor optical amplifier (SOA), is used either as a booster at the transmitter side or as a pre-amplifier at the receiver.

II. Analytical Model and System Setup

A detailed description of the model, of its validation through fitting with experimental measurements and of the main parameters, can be found in [2]. It computes the equivalent signal-to-noise ratio (SNR) on each of the four output electrical signals (corresponding to each of the four available quadratures) of a coherent receiver, in terms of the relevant system parameters:

$$SNR_{RX} = \frac{P_s}{\frac{\sigma_{th}^2}{P_{LO}} + P_{LO} \cdot \sigma_{n_{LO}}^2 \cdot CMRR + \sigma_{shot}^2 + \frac{P_s}{SNR_Q} + \frac{P_s}{OSNR_{ASE}}} \quad (1)$$

where P_s is the received modulated signal optical power, P_{LO} is the CW optical power of the local oscillator, $CMRR$ is the Common Mode Rejection Ratio of the balanced photodetector, $\sigma_{n_{LO}}^2$ is the variance of the LO relative intensity noise (RIN) contribution, σ_{th}^2 is the variance of the transimpedance amplifier (TIA) thermal noise and σ_{shot}^2 is the variance of the shot noise generated in the photodetection process. Moreover, the $OSNR_{ASE}$ parameter represents the effect of the amplified spontaneous emission noise introduced by the amplification stage (see Section IV), and the SNR_Q parameter accounts for the additional implementation penalties associated with the power-independent effects occurring in a high-speed coherent system such as quantization noise, phase noise, imperfect constellation generation, etc.

The SNR obtained through Eq. (1) is then translated to bit error rate (BER) for a specific modulation format, to describe the performance of the system depicted in Fig. 1. A continuous wave (CW) laser emits light with P_L^{CW} optical power. A 1x2 splitter then allows to use the same CW laser as both the transmission laser and the local oscillator. The data transmission signal is then modulated and sent to the coherent receiver at the other end of the communication link, whereas the other output of the splitter is used at the integrated coherent receiver as the local oscillator. The optical link loss is simulated varying the received useful signal power P_S, as if there was a variable optical attenuator (VOA) at the receiver input. The OPB is thus computed as the difference (in dB) between P_S and the average optical power at the external modulator output, whose loss depends on the considered modulation format [2]. The modulator total insertion loss and the modulation formats are: 10 dB for single polarization

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QPSK, 14 dB for polarization multiplexed (PM) QPSK, 18.2 dB for PM-16QAM and 20.2 dB for PM-64QAM.

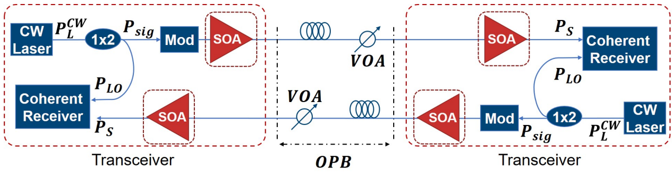

Fig. 1. Setup of the coherent transmission system. CW: Continuous Wave; Mod: Modulator; SOA: semiconductor optical amplifier; VOA: Variable Optical Attenuator; OPB: Optical Power Budget; SIG: Signal; LO: Local Oscillator.

The amplified configuration analyzed in Section IV includes also a SOA either at the modulator output or at the receiver input. Throughout the paper we use RIN=-145 dB/Hz and i_{TIA} = 19 $pA/\sqrt{Hz}$ (see [2] for details) and we define the split ratio as $\rho = P_{sig}/P_L^{CW}$, where P_{sig} is the signal power at the external modulator input and P_L^{CW} is the total power emitted by the laser before the splitting stage.

III. Analysis of Unamplified Shared Laser Coherent Transceiver

In this Section we presents the results for six different configurations using the aforementioned modulation formats (single-polarization QPSK, PM-QPSK, PM-16QAM and PM-64-QAM) at the typical data rates of 28 and 56 $GBaud$, when no optical amplification is used in the system and for two BER levels, assuming a hard-decision forward error correction (HD-FEC) threshold at BER= $4 \cdot 10^{-3}$, and a more advanced soft-decision FEC (SD-FEC) with $2 \cdot 10^{-2}$ BER threshold. For this non amplified case, Eq. (1) obviously does not include the OSNR-dependent term. We decided not to consider single polarization QPSK at 28 $GBaud$ as it would result in a raw total bit rate of 56 $Gbps$, which is already being achieved with DD systems and it is, therefore, irrelevant for our analysis of future short-reach communications.

Fig. 2a shows the optical power budget as a function of the split ratio when the CW laser power P_L^{CW} is 16 dBm. The optimal split ratio is always at 70%. Only QPSK modulation can provide OPB in excess of 30 dB and up to 40 dB when combined with SD-FEC, while higher order modulations such as 28 $GBaud$ (56 $GBaud$) PM-16QAM, or even 28 $Gbaud$ PM-64QAM if coupled with SD-FEC (BER does not reach the HD-FEC threshold), can ensure more than 15 dB OPB, enabling transmission at 224 $Gbps$ (448 $Gbps$) raw bit rates for PM-16QAM, and 336 $Gbps$ for PM-64QAM. Fig. 2b highlights how the OPB changes with the CW laser power at the 70% optimal split ratio. Depending on the system constraints, the requirement on the laser power can be strongly relaxed down to below 10 dBm, while still ensuring large tolerable OPB.

The contour plot of OPB as a function of the split ratio and of the CW laser power is depicted in Fig. 3a. The optimal split ratio strongly depends on P_{laser} starting from 65% for low P_{laser} and moving towards 80% for very high P_{laser}, suggesting that the impact of increased RIN contribution has

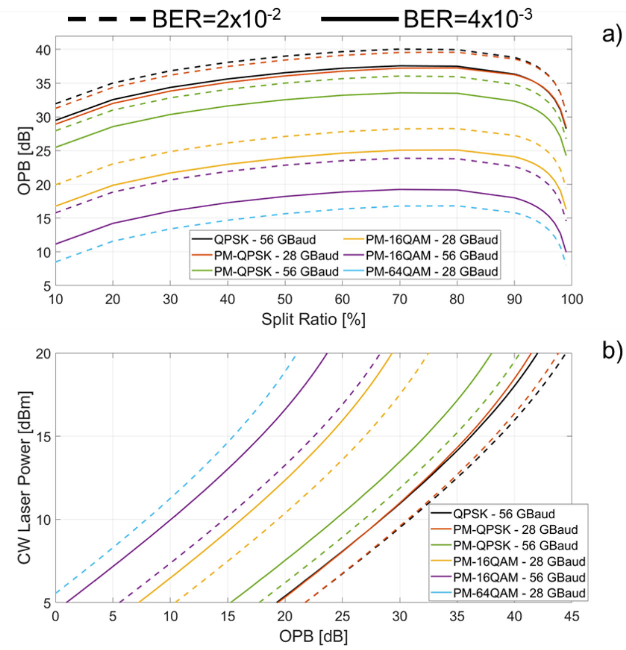

Fig. 2. Optical power budget a) as a function of the split ratio and b) for variable CW laser power, for the four investigated modulation formats at 28 and 56 $GBaud$, at the HD-FEC threshold (solid curves) and at the SD-FEC threshold (dashed cruves). Single polarization QPSK at 28 $GBaud$ is not shown for lack of interest.

to be mitigated by re-balancing the signal and LO power at the receiver (see Eq. (1)). For a 16 dBm CW laser power the achievable OPB is about 28 dB with a split ratio in the range 70-80%.

The effect of different input referred noise density (IRND) values on the optimal split ratio is shown in Fig. 3b for a 16 dBm CW laser power. For low i_{TIA} values, the optimal ratio is again in the order of 80%, but reduces down to about 60% when the thermal noise becomes dominant. Finally, Fig. 3c shows how RIN affects the optimal split ratio and the overall OPB. As expected, when the RIN coefficient is low, a stronger LO is advantageous, whereas for high RIN values the optimal split ratio moves towards a higher percentage of signal power. Similar results were obtained (but not shown for space limitations), and therefore similar conclusions can be drawn for the other three modulation formats under analysis, regardless of the selected FEC threshold.

IV. Analysis of Amplified Shared Laser Coherent Transceiver

In case OPB should be further increased beyond the values presented in previous Sections, one can think of introducing a SOA at either the transmitter (as booster amplifier) or at the receiver (as pre-amplifier before CD). The OSNR is

$$OSNR_{ASE} = \frac{G_{SOA} \cdot P_{in}^{SOA}}{F_{SOA} \cdot hf \cdot (G_{SOA} - 1)B} \tag{2}$$

where G_{SOA} is the SOA gain, F_{SOA} is the SOA noise figure (7 dB), P_{in}^{SOA} is the optical power at the SOA input,

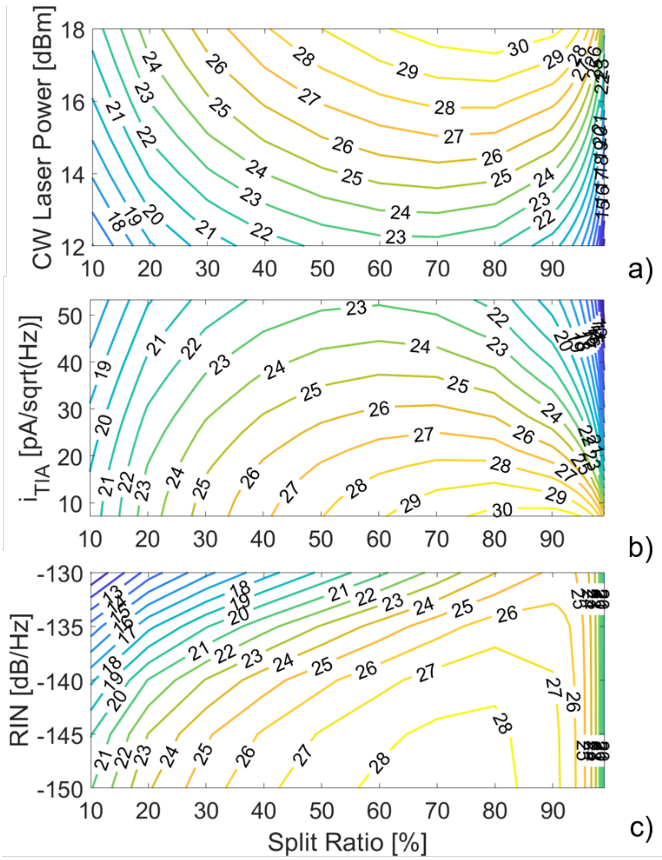

Fig. 3. a) OPB as a function of split ratio and CW laser power. b) OPB as a function of split ratio and TIA noise current density for 16 dBm laser power. c) OPB as a function of split ratio and laser RIN for 16 dBm laser power. 28 $GBaud$ PM-16QAM modulation at $BER = 2 \cdot 10^{-2}$ (SD-FEC).

h is Plank's constant, f is the signal frequency (wavelength is 1550 nm) and B is the bandwidth equal to the baud rate. The SOA saturation power is chosen to be 13 dBm.

In Fig. 4 we show the OPB as a function of the split ratio and of the SOA gain. For space limitations we only show results for 28 $GBaud$ PM-16QAM modulation at the SD-FEC threshold. Fig. 4a refers to the case where the SOA is used at the transmitter. The optimal split ratio is again around 70% and the gain of the SOA is transferred entirely to the achievable OPB. For instance, for 70% split ratio and 10 dB gain Fig. 4a shows about 37 dB OPB, whereas Fig. 4 shows 27 dB, meaning that ASE noise does not affect system performance in this case.

Fig. 4b is referred to SOA pre-amplification at the receiver side. Here P_s in Eq. (1) is the SOA output power ($P_s = G_{SOA} \cdot P_{in}^{SOA}$). With respect to the unamplified case, it shows only a marginally improved OPB lower than 30 dB for 70% split ratio and 10 dB gain. Further increasing the SOA gain up to 15 dB does not result in a better OPB, thus showing that SOA pre-amplification can only provide limited gain (about 3 dB at the optimum 70% split ratio) when applied before a coherent receiver. This result can be explained as follows: without SOA, among the different noise terms in Eq. (1) the

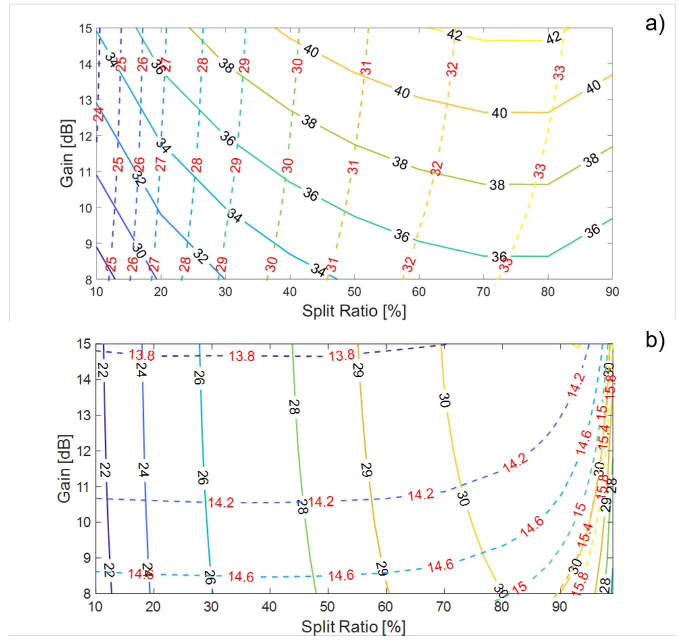

Fig. 4. Optical power budget at the SD-FEC threshold (solid lines) and OSNR (dashed lines) as a function of the split ratio and the SOA gain, when a) the SOA is used as booster at the transmitter side and b) the SOA is used as pre-amplifier at the receiver side. The modulation format is 28 $GBaud$ PM-16QAM and the CW laser power is 16 dBm.

prevailing one is the shot noise one for the typical parameters assumed in this paper. Numerically, the resulting SNR_{RX} for shot noise only is actually higher than $OSNR_{ASE}$ only. With a pre-amplifier SOA, this is true only for low gain values. As the gain increases ASE noise becomes predominant, limiting the amount of gain that can actually be transferred to the OPB.

Conclusion

We have analyzed coherent detection for short-reach communication employing a single laser in the transceiver. Our numerical results show remarkable optical power budget above 15 dB, even with 64-QAM modulation at an optimal 70% laser split ratio. The OPB can be further increased placing a SOA at the transmitter side, by an amount equal to the SOA gain. On the other hand, only a smaller benefit of about 3 dB can be obtain by an optical pre-amplifier at the receiver end.

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