Assessment of the combined effect of laser phase noise and intercore crosstalk on the outage probability of DD OOK systems

João L. Rebola, Tiago M. F. Alves, Adolfo V. T. Cartaxo
Optical Communications and Photonics Group, Instituto de Telecomunicações, Lisboa, Portugal
Instituto Universitário de Lisboa (ISCTE-IUL), Lisboa, Portugal
e-mail: joao.rebola@iscte-iul.pt, adolfo.cartaxo@iscte-iul.pt, tiago.alves@lx.it.pt

ABSTRACT
We study the influence of the combined effect of laser phase noise and intercore crosstalk on the outage probability of direct-detection 10 Gbit/s on-off keying optical communication systems. We show that the laser phase noise can affect significantly the outage probability, for lasers with linewidths in the MHz range, for low and high skew-bit rate products. We also show that the laser phase noise effect on the received eye-pattern is qualitatively similar to the one found for high skew-bit rate product in the absence of laser phase noise.

Keywords: intercore crosstalk, laser phase noise, multicore fiber, on-off keying, outage probability.

1. INTRODUCTION

Owing to the random behavior of intercore crosstalk (ICXT) in weakly-coupled multicore fiber (MCF)-based optical communication systems, the outage probability is a performance metric that has to be taken into account to ensure the quality of service in both coherent and direct-detection (DD) systems [1]-[4]. It has been shown that the ICXT-induced performance degradation in DD on-off keying (OOK) communication systems depends significantly on the skew-bit rate product, $S_{mn}R_b$. For $S_{mn}{\cdot}R_b << 1$, where the bit rate of the OOK signal is much lower than the ICXT decorrelation bandwidth [5], the ICXT creates well-defined amplitude "rails" in the eye-patterns [6]. For $S_{mn}{\cdot}R_b >> 1$, the bit rate of the OOK signal is much higher than the ICXT decorrelation bandwidth [5], and the amplitude fluctuations created in the eye-patterns by the ICXT seem to exhibit a "noise" like-behavior. As a consequence, the impact of ICXT on the outage probability is higher for $S_{mn}{\cdot}R_b << 1$ [6]. The impact of laser phase noise on the photodetected ICXT has been also shown that can lead to fast fluctuations on the bit error rate (BER) in DD systems [3], [7]. However, it remains to assess the combined effect of laser phase noise and ICXT on the outage probability.

In this work, we study the influence of the laser phase noise and ICXT induced by interfering cores on the outage probability and on the eye-patterns in DD OOK weakly-coupled MCF-based systems.

2. SYSTEM DESCRIPTION MODEL AND OUTAGE PROBABILITY CALCULATION

In this section, the system model used to assess the influence of laser phase noise on the ICXT induced by interfering cores in weakly-coupled MCF-based DD OOK systems is presented. The BER estimation using simulation and the calculation of the outage probability are also explained.

2.1 Equivalent system model

To assess the combined effect of laser phase noise and ICXT induced by interfering cores on the performance degradation of the DD OOK system supported by weakly-coupled MCFs, a single interfering core is considered. OOK signals are transmitted in the interfered core n and interfering core m. The equivalent system model is depicted in Fig. 1. Two ideal chirpless optical transmitters, which perform linear conversion from the electrical to the optical domain, generate OOK signals with rectangular pulse shape, for their corresponding cores. The OOK signals at the input of cores n and m are generated with the same bit rate. Laser phase noise is only considered in the interfering core to focus the analysis on the effect of laser phase noise on the induced ICXT. The phase noise is modeled by a Wiener process [8] with zero mean and variance $t\Delta\nu_L/(2\pi)$, where t represents the time and $\Delta\nu_L$ is the laser linewidth. In each iteration of the simulation, a different sample function of the laser phase noise is considered in the interfering core.

The propagation in the interfered core is modeled by fiber dispersion (up to second order) and propagation delay. The fiber attenuation level is not relevant in our analysis since the same fiber attenuation is assumed for the two cores. We model the ICXT by the discrete changes model developed for signals with dual-polarization [9]. In each iteration of the simulator, the bits of the interfering signal are randomly generated, and a particular MCF realization (ICXT generated with independent random phase shifts (RPSs) [9]) is generated. The RPSs associated with phase-matching points (PMPs) [9] are modeled using a uniform distribution between $[0,2\pi[$. The skew between cores m and n is defined by $S_{mn} = d_{mn}{\cdot}L$, with d_{mn} the average walkoff parameter between cores m and n [9] and L is the MCF length. For equal powers at the MCF cores input and same core losses, the ratio between the average crosstalk power at the output of the interfered core n and the average power of the signal at the output of the interfering core m, X_c, is defined by $X_c = N_p|K_{nm}|^2$ [10], where K_{nm} is the average discrete coupling coefficient of the two polarizations and N_p is the number of PMPs.

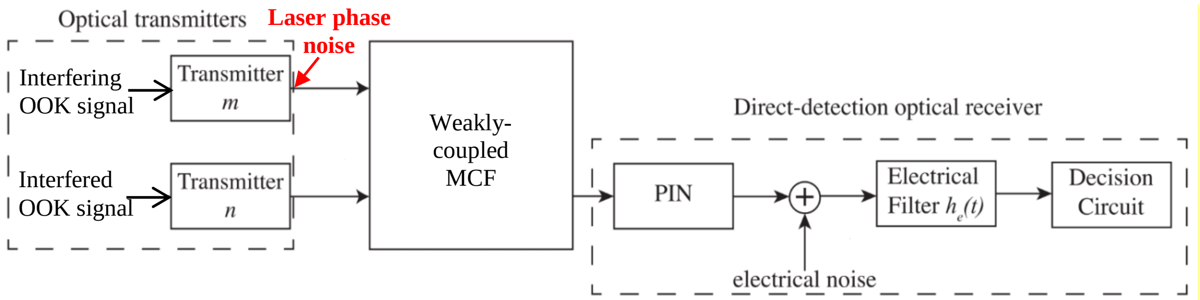

Figure 1. Equivalent system model with two cores used to study the influence of laser phase noise on the outage probability induced by ICXT of weakly-coupled MCFs in DD OOK communication systems.

At the optical receiver input, the signal impaired by ICXT is photodetected by a PIN with unit responsivity and bandwidth much larger than the OOK signal bit rate. At the PIN output, the photocurrent is filtered by an electrical filter modelled by a 4th order Bessel filter with a –3 dB cut-off frequency equal to the OOK signal bit rate. This bandwidth is chosen to minimize the intersymbol interference (ISI) on the received signal, which could mask the effects of laser phase noise and ICXT on the received current. The electrical noise, referred to the electrical filter input, is characterized by a noise equivalent power of $1{\times}10^{-12}$ W/Hz$^{1/2}$ [11]. At the decision circuit, the received signal is sampled at the time instants $t_l = t_{opt} + lT_b$, where t_{opt} is the optimum sampling time extracted from the eye-pattern obtained in the simulation (different in each simulation iteration), T_b is the bit period and l = 1, 2, …, N_b, with N_b, the number of bits considered for the BER assessment in each simulation iteration.

2.2 Outage probability estimation

To estimate the outage probability, we use Monte Carlo (MC) simulation combined with a semi-analytical technique [6]. The impact of electrical noise from the receiver on the BER is taken into account analytically, and fiber chromatic dispersion, laser phase noise and ICXT effects on the BER are evaluated using waveform simulation in each simulation iteration. Let i denote the i-th iteration of the simulator, in which a different MCF realization and laser phase noise sample function are generated. The BER of the i-th iteration is given by [6]

$$BER_i = \frac{1}{N_b}\left\{\sum_{\substack{l=1\\ j=0}}^{N_b} Q\left(\frac{F_i - m_{0,l,i}}{\sigma_{0,l,i}}\right) + \sum_{\substack{l=1\\ j=1}}^{N_b} Q\left(\frac{m_{1,l,i} - F_i}{\sigma_{1,l,i}}\right)\right\} \quad (1)$$

where $Q(x)$ is the Q-function [6], $m_{j,l,i}$ and $\sigma_{j,l,i}$ are the mean and standard deviation of the current at the decision circuit input at the time instants t_l, conditioned on the transmitted bit j (0 or 1). As we consider electrical noise only, $\sigma_{0,l,i} = \sigma_{1,l,i}$. The combined effect of laser phase noise and ICXT, and ISI from fiber dispersion affect the mean $m_{j,l,i}$ components as waveform distortion, which is taken from the waveform obtained in the simulation at the time instants t_l. The decision threshold F_i is optimized in each iteration of the simulator using the bisection method to minimize the BER per simulation iteration. Then, the outage probability (OP), which is the probability of the BER becoming above a BER limit, BER_{limit}, [1], [2], [4], is estimated by simulation using

$$OP = \Pr\left[BER > BER_{lim}\right] = \frac{N_{BER>lim}}{N_{iterations}} \quad (2)$$

where $N_{BER>lim}$ is the number of counted BER_i above the threshold BER_{limit} and $N_{iterations}$ is the number of simulation iterations appropriately chosen to obtain an outage probability estimation with sufficient accuracy.

3. NUMERICAL RESULTS AND DISCUSSION

In this section, the dependence of the outage probability on the combined effect of laser phase noise and ICXT is investigated by numerical simulation. The simulation parameters that are kept constant throughout this work are shown in Table 1. A bit rate of 10.14 Gbps (the one defined for the Common Public Radio Interface [6]) per MCF core has been chosen. An identical fiber dispersion parameter is considered for the two cores. The length of the MCF used in the simulation is similar to that one used recently in experimental demonstrations [4]. The number of PMPs is set to characterize accurately the mechanism of the RPSs [9]. The BER in the absence of ICXT and laser phase noise is set two orders of magnitude below the BER limit. Two different skews are considered: the ideal case, emulating the situation where (i) the skew is much shorter than the bit period, $S_{mn}{\cdot}R_b = 0$, and (ii) a skew much higher than the bit period, $S_{mn}{\cdot}R_b \approx 1014$ obtained with d_{mn} = 5000 ps/km. With this, we are analysing two situations: (i) bit rate of the OOK signal much lower than the ICXT decorrelation bandwidth and (ii) bit rate of the OOK signal much higher than the ICXT decorrelation bandwidth.

Table 1. Simulation parameters.

Parameter	Value
OOK bit rate	10.1376 Gbit/s
Carrier wavelength	1550 nm
Fiber dispersion parameter	17 ps/nm/km
Fiber attenuation coefficient	0.2 dB/km
Fiber length	20 km
Extinction ratio	10 dB
Number of PMPs	1000
Number of generated OOK bits per simulation iteration	2^{10}
BER in the absence of ICXT and laser phase noise	10^{-5}
Receiver sensitivity in the absence of ICXT and laser phase noise	–28.9 dBm
BER limit	10^{-3}
Number of occurrences of BER_i above the BER_{limit}	50

Fig. 2 depicts the outage probability as a function of the laser linewidth, for $S_{mn}{\cdot}R_b = 0$ and $S_{mn}{\cdot}R_b \approx 1014$. The ICXT level is set to $X_c = -16$ dB. This ICXT level has been found to ensure an outage probability of 10^{-4} in the experimental work reported in [4] for a BER limit of $10^{-1.8}$. Fig. 2 confirms the conclusions taken in [6] in the absence of laser phase noise effect: higher $S_{mn}{\cdot}R_b$ product reduces the outage probability induced by ICXT. Regarding the influence of the laser phase noise on the ICXT induced by the interfering core, the two $S_{mn}{\cdot}R_b$ products exhibit a similar behaviour. For laser linewidths narrower than about 200 kHz, laser phase noise has no evident influence on the outage probability degradation. For laser linewidths above 1 MHz, the outage probability increases about one order of magnitude for $S_{mn}{\cdot}R_b = 0$, and almost two orders of magnitude for $S_{mn}{\cdot}R_b \approx 1014$, relative to the situation of very low linewidth. This behaviour of the outage probability with the laser linewidth has been also observed for other ICXT levels for the two $S_{mn}{\cdot}R_b$ products.

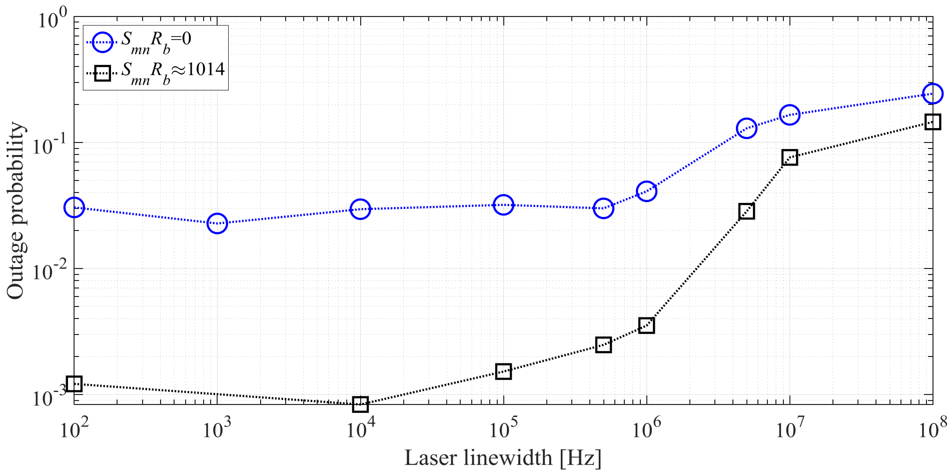

Figure 2. Outage probability as a function of the laser linewidth for $S_{mn}{\cdot}R_b = 0$ (blue circle symbols) and $S_{mn}{\cdot}R_b \approx 1014$ (black square symbols). The ICXT level is set to $X_c = -16$ dB.

Fig. 3 shows several eye-patterns (without electrical noise) at the electrical filter output, for $X_c = -16$ dB, for a) $S_{mn}R_b \approx 0$ and a laser linewidth of 100 kHz, b) $S_{mn}R_b \approx 0$ and a laser linewidth of 10 MHz; c) $S_{mn}R_b \approx 1014$ and a laser linewidth of 100 kHz and d) $S_{mn}R_b \approx 1014$ and a laser linewidth of 10 MHz. The average amplitude of the bits '1' in the eye-patterns is normalized to unit. The presented eye-patterns are representative and were obtained for one simulation iteration. Fig. 3 a) shows that, for a narrow laser linewidth (and consequently, lower phase noise variance), the eye-patterns exhibit amplitude rails created by ICXT that are "well-defined", as previously observed in [6] for low $S_{mn}R_b$ and in the absence of laser phase noise. In this case, the ICXT behaves as a static coupling component [5]. In Fig. 3 b), due to the increase of the laser linewidth, laser phase noise induces a very large number of amplitude rails in the eye-pattern. Fig. 3 b) suggests that the combined effect of the laser phase noise and ICXT on the eye-pattern is qualitatively very similar to the effect of ICXT (with lower phase noise variance), shown in Fig. 3 c), when the $S_{mn}R_b$ product is very high. In this latter case, several bits in the interfering core contribute to the numerous amplitude "rails" due to ICXT observed in the eye-patterns of the interfered core, and the combined effect of ICXT and laser phase noise leads to a similar effect as the one encountered with uncorrelated noise [5]. Fig. 3 d) shows a similar behavior to the one shown in Fig. 3 b), with a very high eye-closure.

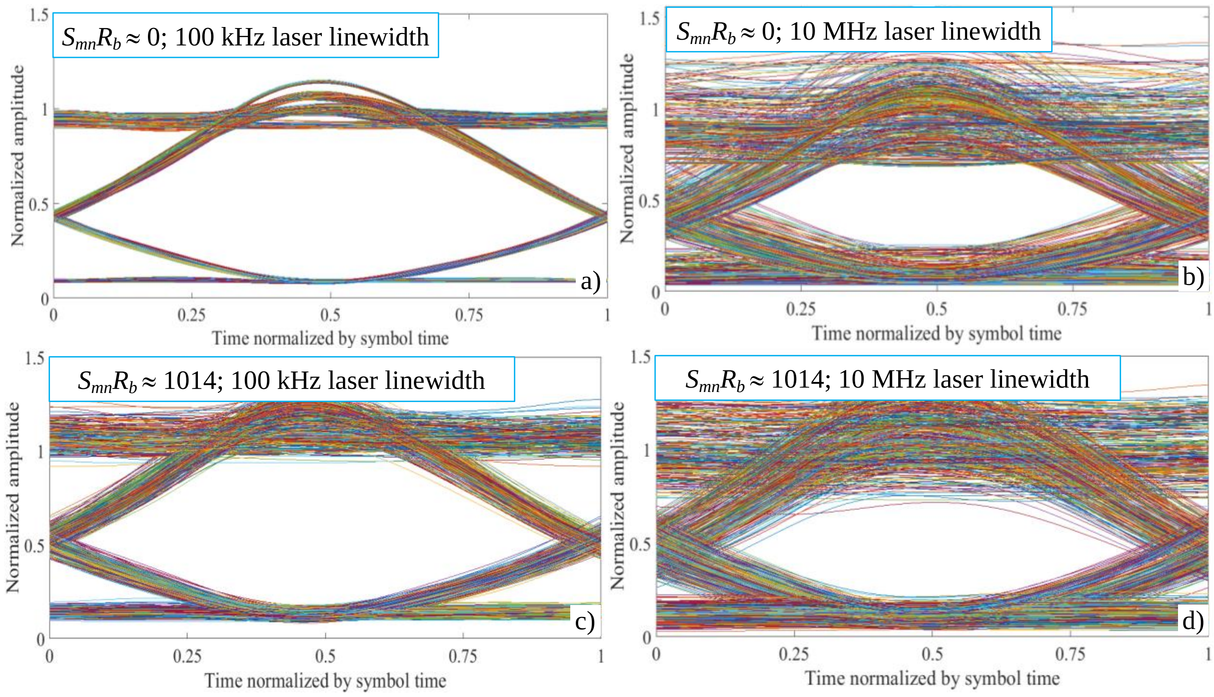

Figure 3. Eye-patterns at the electrical filter output (without electrical noise) obtained for $X_c = -16$ dB. *In a)* $S_{mn}R_b \approx 0$ *and a laser linewidth of* 100 kHz*; b)* $S_{mn}R_b \approx 0$ *and a laser linewidth of* 10 MHz*; c)* $S_{mn}R_b \approx 1014$ *and a laser linewidth of* 100 kHz*; and d)* $S_{mn}R_b \approx 1014$ *and a laser linewidth of* 10 MHz. *Different ICXT realizations are considered for the different eye-patterns.*

4. CONCLUSION

The influence of the combined effect of ICXT and laser phase noise of the interfering core on the outage probability of DD OOK communication systems supported by weakly-coupled MCFs has been discussed. For a 10 Gbit/s OOK signal, we have observed that the impact of laser phase noise on the outage probability becomes significant for lasers with linewidths in the MHz range, i. e., linewidths typical of distributed feedback lasers. In this case, the combined effect of laser phase noise and ICXT creates a very large number of amplitude rails in the received eye-pattern, similar to the effect encountered with high intercore skew-bit rate products (in the absence of laser phase noise), similar to the one found with uncorrelated noise.

ACKNOWLEDGEMENTS

This work was supported in part by Fundação para a Ciência e a Tecnologia (FCT) from Portugal under the project of Instituto de Telecomunicações UID/EEA/50008/2019 and the IF/01225/2015/CP1310/CT0001.

REFERENCES

[1] P. Winzer, and G. Foschini, “MIMO capacities and outage probabilities in spatially multiplexed optical transport systems,” *Opt. Expr.*, vol. 19, no. 17, pp. 16680–16696, Aug. 2011.
[2] B. Puttnam, *et. al.*, “Impact of inter-core crosstalk on the transmission distance of QAM formats in multi-core fibers,” *IEEE Photon. J.*, vol. 8, no. 5, Art. ID. 0601109, Feb. 2016.
[3] T. Alves, *et. al.*, “Intercore crosstalk in direct-detection homogeneous multicore fiber systems impaired by laser phase noise,” *Opt. Expr.*, vol. 25, no. 23, pp. 29417-29431, Nov. 2017.
[4] T. Alves, J. Rebola, and A. Cartaxo, “Outage probability due to intercore crosstalk in weakly-coupled MCF systems with OOK signaling”, *Opt. Fibre Commun. Conference (OFC) 2019*, paper M2I.1, San Diego, USA.
[5] T. Alves, and A. Cartaxo,”Decorrelation bandwidth of intercore crosstalk in weakly-coupled multicore fibers with multiple interfering cores,” *IEEE/OSA Journal of Lightwave Technology*, vol. 37, no. 3, pp. 744-754, Feb. 1 2019.
[6] J. Rebola, A. Cartaxo, and A. Marques, “10 Gbps CPRI signals transmission impaired by intercore crosstalk in 5G network fronthauls with multicore fibers,” *Photon. Commun. Netw.*, doi:10.1007/s11107-019-00828-0, Jan. 2019.
[7] A. Cartaxo, *et. al.*, “DD-OFDM multicore fiber systems impaired by intercore crosstalk and laser phase noise”, *International Conference on Transparent Optical Networks (ICTON) 2017*, paper Tu.D1.1, Girona, Spain.
[8] S. Betti, G. De Marchis, and E. Iannone, “Coherent optical communication systems,” *John Wiley & Sons*, 1995, ch. 4.
[9] R. Soeiro, T. Alves, and A. Cartaxo, “Dual polarization discrete changes model of inter-core crosstalk in multi-core fibers,” *IEEE Photon. Technol. Lett.*, vol. 29, no. 16, pp. 1395-1398, Aug. 15 2017.
[10] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, “Design and fabrication of ultra-low crosstalk and low-loss multicore fiber,” *Opt. Expr.*, vol. 19, no. 17, pp. 16576-16592, Aug. 15 2011.
[11] G. Agrawal, “Fiber-optic communication systems,” 4th edn. *John Wiley & Sons*, 2010.