Outage Probability due to Intercore Crosstalk in Dual-Core Fiber Links with Direct-Detection

João L. Rebola, Adolfo V. T. Cartaxo, Tiago M. F. Alves, and André S. Marques

***Abstract*— The outage probability (OP) in short-haul direct-detection (DD) optical links supported by weakly-coupled multicore fiber (MCF) impaired by intercore crosstalk (ICXT) and using on-off keying signaling is assessed theoretically and through simulation. A closed-form expression for the OP is proposed for a single interfering core. This expression is useful to provide fast and reliable performance estimates in preliminary studies of weakly-coupled MCF-based systems where the ICXT is highly correlated along the signal bandwidth, i. e., when the skew-bit rate product is small. Particularly, results for a 20 km-long link at 10 Gbit/s and walk-off below 1 ps/km are detailed. For high skew-bit rate products, i. e., when the ICXT is decorrelated along the signal bandwidth, simulation results show that, for a typical OP of 10^{-4}, the tolerance to ICXT increases above 4 dB, when compared with low skew-bit rate products. It is also shown that DD links with finite extinction ratio are more robust to outage induced by the ICXT than those with ideal extinction ratio.**

***Index Terms*— Bit error rate, direct-detection, intercore crosstalk, multicore fiber, outage probability.**

I. Introduction

Multicore fibers (MCFs) have been recently proposed to increase the capacity of short-haul links, such as datacenters interconnects or 5G fronthauls, where optical amplification is not required and direct-detection (DD) ensures low cost and complexity [1]-[3]. Weakly-coupled MCFs provide the solution for the required capacity, as individual cores can be used as independent channels with similar propagation delays. However, the effect of intercore crosstalk (ICXT) limits the MCF reach and performance [4], [5]. The ICXT effect is reasonably well studied in the literature [6]-[8] and, due to the random evolution of ICXT over time, ICXT-impaired systems may experience: (i) random variations of the bit error rate (BER) over short time periods [4], and (ii) system outage over long time periods due to high ICXT levels [9], [10]. In weakly-coupled DD MCF-based systems, the outage probability (OP) has been used as a figure of merit to show the effectiveness of a memory bit loading technique to improve the performance of ICXT-impaired orthogonal frequency division multiplexing systems [5]. However, a more in-depth analysis of the OP in DD systems is still to be performed.

In this work, the OP in DD unamplified short-haul links using weakly-coupled MCFs and on-off keying (OOK) signaling impaired by ICXT is studied. A theoretical closed-form expression for the OP is derived for systems with low skew-bit rate product. The dependence of the OP on the skew-bit rate product is also investigated by numerical simulation.

This work was supported in part by Fundação para a Ciência e a Tecnologia (FCT) from Portugal under the FCT researcher contract IF/01225/2015/CP1310/CT0001 and the project of Instituto de Telecomunicações UID/EEA/50008/2019. J. Rebola, T. Alves and A. Cartaxo are with Instituto de Telecomunicações, 1049-001, Lisboa, Portugal, and with ISCTE - Instituto Universitário de Lisboa, 1649-026, Lisboa, Portugal (corresponding author e-mail: joao.rebola@iscte-iul.pt). A. Marques is with ISCTE - Instituto Universitário de Lisboa, 1649-026, Lisboa, Portugal.

II. System Model and Outage Probability Derivation

The MCF-based system model with DD and OOK signaling considered in this work is detailed in [11]. Two ideal optical transmitters, which perform a linear electro-optical conversion, generate two uncorrelated OOK signals with same bit rate, extinction ratio and aligned bit transitions. At the transmitter output, the electrical field of the signals, within one bit period, is modeled by $s_c(t)=\sqrt{\zeta_c}\,a_c\mathbf{x}+\sqrt{1-\zeta_c}\,a_c\mathbf{y}$, where $\mathbf{x}$ and $\mathbf{y}$ refer to the polarization directions, ζ_c controls the signal power distribution between the polarization directions with $c\in\{n,m\}$, with n and m referring to, respectively, the tested and interfering cores; and a_c is the level corresponding to the bit transmitted in core c, with $a_{c,1}=\sqrt{2\overline{p}_c/(1+r)}$, for a bit '1' and $a_{c,0}=\sqrt{r}\,a_{c,1}$, for a bit '0', where $\overline{p}_c$ is the average power of the signal at the input of core c and r is the ratio between the average powers corresponding to bits '0' and '1', which is related to the extinction ratio by $r_{ext}=1/r$.

Single-mode propagation is considered in each core. Fiber attenuation is assumed similar in the two cores. We model the ICXT by the dual-polarization discrete changes model [7], which has been developed to keep the complexity and time of simulation at acceptable levels. We study the ICXT impact evolution on the performance in short time fractions separated by time intervals longer than the ICXT decorrelation time, which is typically in the order of a few minutes [6]. Hence, within each time fraction, several thousands of bits are generated to have the BER statistics properly characterized. From time fraction to time fraction, the ICXT is uncorrelated, and is evaluated from the ICXT field transfer function [7].

At the optical receiver, the signal is photodetected by a PIN with unit responsivity and bandwidth much larger than the OOK signal bit rate, and is electrically filtered. Only electrical noise is considered in our analysis, since the short-haul links considered in this work do not employ optical amplification.

Neglecting the ICXT-ICXT beating, the electrical current due to ICXT after photodetection in core n is approximated by

$$i_{ICXT}(t)\approx 2\,\mathrm{Re}\left\{E_{n,x}(t)\cdot s^*_{out,x}(t)+E_{n,y}(t)\cdot s^*_{out,y}(t)\right\} \quad (1)$$

where $\mathrm{Re}\{z\}$ stands for the real part of z, $s^*(t)$ stands for the complex conjugate of $s(t)$, and $s_{out,b}(t)$ is the electrical field of the signal at the MCF output in core n in the b direction, with $b\in\{x,y\}$. For low skew between cores and negligible fiber dispersion, the electrical field at the output of core n in the b

direction induced by ICXT, $E_{n,b}(t)$, is given by [7]

$$E_{n,b}(t) = -j\frac{K_{nm}}{\sqrt{2}}a_m\sum_{k=1}^{N_p}\left[\sqrt{\zeta_m}e^{-j\phi_k^{(b,x)}} + \sqrt{1-\zeta_m}e^{-j\phi_k^{(b,y)}}\right] \quad (2)$$

where the same power splitting as in $s_m(t)$ is assumed, K_{nm} is the average discrete coupling coefficient of the two polarizations [7], N_p is the number of phase-matching points (PMPs), and $\phi_k^{(b,d)}$ is the random phase shift (RPS), associated with the k-th PMP [7], with $d \in \{x,y\}$. Each RPS is modelled by a random variable (r.v.) uniformly distributed between $[0,2\pi[$ and different RPSs are uncorrelated [7]. Each time fraction assumes different sets of N_p RPSs generated randomly. For equal powers at the output of tested and interfering cores, the ICXT level, i.e., the ratio between the ICXT and signal mean powers at the output of core n, is $X_c = N_p|K_{nm}|^2$ [7].

Neglecting intersymbol interference (ISI) caused by electrical filtering and dispersion on the signal $s_{out,b}(t)$, Eq. (1) can be written as $i_{ICXT}(t) = a_n a_m x_m$, where

$$x_m = \left\{\sqrt{\zeta_n}\sum_{k=1}^{N_p}\left[\sqrt{\zeta_m}\sin\phi_k^{(x,x)} + \sqrt{1-\zeta_m}\sin\phi_k^{(x,y)}\right] + \sqrt{1-\zeta_n}\sum_{k=1}^{N_p}\left[\sqrt{\zeta_m}\sin\phi_k^{(y,x)} + \sqrt{1-\zeta_m}\sin\phi_k^{(y,y)}\right]\right\}\sqrt{2}|K_{nm}| \quad (3)$$

which, for large N_p and according to the central limit theorem, is a Gaussian r. v. with null mean and variance X_c.

The BER conditioned to ICXT is given by

$$P_b = \frac{1}{2}Q\left(\frac{a_{n,1}^2 - i_L + i_{ICXT}^{(1)}}{\sigma}\right) + \frac{1}{2}Q\left(\frac{i_L - a_{n,0}^2 - i_{ICXT}^{(0)}}{\sigma}\right) \quad (4)$$

where $Q(x) = 1/\sqrt{2\pi}\int_x^\infty \exp(-\lambda^2/2)d\lambda$, i_L is the decision threshold, σ is the standard deviation of the electrical noise, and $i_{ICXT}^{(1)}$ and $i_{ICXT}^{(0)}$ correspond to (1), when the bit transmitted in core n is '1' or '0', respectively. In absence of ICXT and with the decision threshold optimized, the BER simplifies to the very well-known result for OOK binary systems, $P_{b,NICXT} = Q\left[\left(a_{n,1}^2 - a_{n,0}^2\right)/(2\sigma)\right]$. We have observed from analysis of the eye-patterns obtained from simulation that, in the presence of ICXT and low skew, the optimized threshold is obtained at half distance between the average of the amplitudes of bits '1' and the average of amplitudes of bits '0'. Hence, the optimized threshold can be written as

$$i_{L,opt} = \left(a_{n,1}^2 + a_{n,0}^2\right)/2 + Ax_m \quad (5)$$

with $A = \left(a_{n,1} + a_{n,0}\right)\left(a_{m,1} + a_{m,0}\right)/4$.

Taking into account that bits '1' in core n have a major role to the BER degradation, the second term in (4) is neglected. Then, by considering that $i_{ICXT}^{(1)}$ is higher when bits '1' occur in core m and is smaller for bits '0', (4) can be simplified to

$$P_b \approx \frac{1}{4}Q\left(\frac{a_{n,1}^2 - a_{n,0}^2}{2\sigma} - \frac{F}{\sigma}\right) \quad (6)$$

where $F = \left(A - a_{n,1}a_{m,1}\right)x_m$ is a zero mean Gaussian r. v. with standard deviation given by $\sigma_F = W\left(a_{n,1}^2 - a_{n,0}^2\right)/2$, with $W = \sqrt{X_c}/2\left[4 - \left(1+\sqrt{r}\right)^2\right]/(1-r)$.

The OP, P_{out}, is the probability of the BER becoming above a BER limit, P_{lim}, [9], [10], and is given by

$$P_{out} = \Pr\{P_b \geq P_{lim}\} = \Pr\left\{F \geq \left(a_{n,1}^2 - a_{n,0}^2\right)/2 - \sigma Q^{-1}(4P_{lim})\right\} \quad (7)$$

Taking into account that F has a Gaussian distribution, the OP in DD systems impaired by ICXT is given by

$$P_{out} = Q\left(\frac{1}{W}\cdot\left[1 - \frac{Q^{-1}(4P_{lim})}{Q^{-1}(P_{b,NICXT})}\right]\right) \quad (8)$$

which is independent of the signal power distribution between polarization directions in the two cores.

Analysis of (8) and the dependence of W on the extinction ratio shows that, for the same BER in absence of ICXT, non-ideal extinction ratio leads to lower OPs, increasing the system robustness to ICXT. For $P_{out} = 10^{-4}$, typically considered for an adequate system operation [10], $P_{lim} = 10^{-3}$ and $P_{b,NICXT} = 10^{-5}$, by solving (8) with respect to the ICXT level, we obtain $X_c = -23.4$ dB, for $r = 0$, and $X_c = -21.9$ dB, for $r = 0.1$, i. e., the maximum ICXT level allowed with $r = 0.1$ is 1.5 dB higher than the maximum ICXT level allowed with $r = 0$. From (8), the maximum allowed ICXT levels increase 1.0 dB, 2.1 dB and 3.8 dB, respectively, for $P_{out} = 10^{-5}$, 10^{-4} and 10^{-3} in comparison with the ICXT level that leads to $P_{out} = 10^{-6}$. These ICXT level differences are independent of the extinction ratio.

III. Numerical Results and Discussion

In this section, a DD OOK short-haul link with a bit rate of $R_b = 10.1376$ Gbps at $\lambda = 1550$ nm is considered as an example. This bit rate is standardized in the Common Public Radio Interface and can be deployed in 5G fronthauls [11]. The MCF length, L = 20 km, is the maximum defined for the 5G fronthaul leading to low ISI for a dispersion parameter $D_\lambda = 17$ ps/nm/km. The number of PMPs, $N_p = 1000$, is set to describe accurately the ICXT mechanism [7]. The number of bits in each simulation iteration is 2^9. The -3 dB bandwidth of the 4th order Bessel electrical receiving filter is equal to R_b and the noise equivalent power is 1 pW/Hz$^{1/2}$. The receiver sensitivity is set to obtain $P_{b,NICXT} = 10^{-5}$, and $P_{lim} = 10^{-3}$ is considered.

To evaluate the BER using numerical simulation, we use a Monte Carlo (MC) simulation combined with a semi-analytical technique [11]: the impact of electrical noise on the BER is taken into account analytically, and the effects of fiber dispersion and ICXT on the BER are evaluated using waveform simulation in each time fraction. In the numerical simulation, a BER is evaluated in each time fraction, and the OP is estimated by counting the number of occurrences of BER above the BER limit and dividing it by the total number of time fractions. To obtain reasonably accurate OPs, 200 BER occurrences above the BER limit are enough [11].

A. *Low Skew-Bit Rate Product*

In this subsection, the ICXT effect on the eye-pattern and

BER of a DD MCF short-haul link with low skew-bit rate product is analyzed to show how ICXT can lead to system unavailability. Then, the OP in such systems is studied.

Fig. 1 shows the BER in each time fraction and the average BER, considering $X_c = -12$ dB, $r = 0.1$ and 1000 time fractions. A skew-bit rate product, $S_{mn}R_b \approx 0.2$, is considered. The skew between cores m and n is defined by $S_{mn} = d_{mn}L$, with d_{mn} the walkoff parameter between cores m and n [7]. Notice that $S_{mn}R_b \approx 0.2$ can be met experimentally with current MCFs in DD short-haul links [12]. Taking into account that the signal bandwidth is similar to the bit rate and with $S_{mn}R_b \approx 0.2$, the ICXT along the signal bandwidth is highly correlated [12], [13]. Fig. 1 shows that the average BER is nearly stable at about 4.6×10^{-4} after averaging the BERs in 800 time fractions. Fig. 1 shows also that the ICXT random mechanism can lead to several time fractions in which the BER is well above the average BER. Fig. 1 exhibits a best BER in each time fraction of 6.8×10^{-6} and a worst BER in each time fraction of 5.1×10^{-2}. The eye-patterns corresponding to these BERs are presented in Fig. 2. These eye-patterns do not include the effect of electrical noise to make clear the ICXT effect. The amplitude of bit '1' in the absence of ISI and ICXT is normalized to unity. Fig. 2 a) shows the eye-pattern that leads to the best BER in Fig. 1. The eye-opening at the optimum sampling instant is the same as the one obtained in the absence of ICXT (shown in the inset of Fig. 2 b)). The BER improves because, in the presence of ICXT, the amplitudes of some bits '1' are higher than in case of absence of ICXT. Fig. 2 b) shows the eye-pattern corresponding to the worst BER with a very small eye-opening. Fig. 2 shows that the ICXT creates new amplitude levels in bits '0' and '1' of core n due to the two possible amplitude levels corresponding to bits '1' and '0' in core m. From the decision threshold optimized in the simulation to minimize the BER in each time fraction, we have confirmed the optimum threshold given by (5).

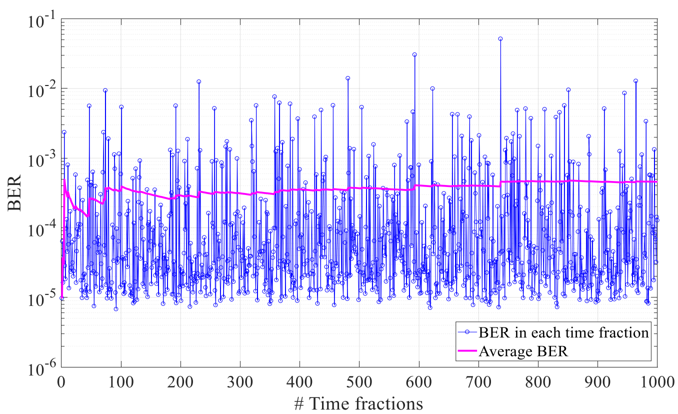

Fig. 1. BER in each time fraction (blue) and average BER (magenta) as a function of the order of time fractions, for $X_c = -12$ dB, $S_{mn}R_b \approx 0.2$ and $r = 0.1$.

Figs. 1 and 2 show that the BER is severely degraded in some specific time fractions, leading to outage. In [14], a first validation of the OP given by (8) has been performed experimentally for $S_{mn}R_b << 1$ and $r = 0.1$. Discrepancies not exceeding 1 dB have been found between (8) and experimental results. Fig. 3 shows a more detailed analysis of the variation of the the OP as a function of the ICXT level. This analysis is performed by comparison between theoretical (T) OP estimates given by (8) and numerical simulation (S) in three different situations: 1) without dispersion (considering $D_\lambda = 0$) and ICXT-ICXT beating, and with $S_{mn} = 0$, which matches to the conditions under which (8) has been derived; 2) without dispersion, with ICXT-ICXT beating and $S_{mn} = 0$; and 3) with dispersion ($D_\lambda = 17$ ps/nm/km) and ICXT-ICXT beating, and with $S_{mn}R_b \approx 0.2$.

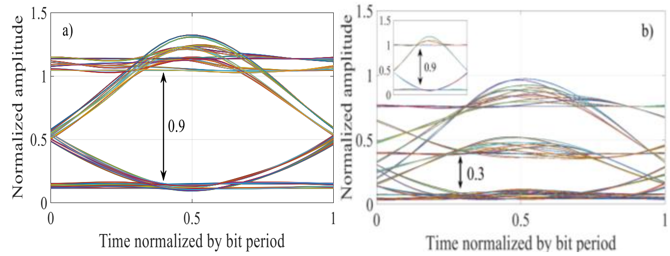

Fig. 2. Eye-patterns (without the electrical noise effect) at the decision circuit input corresponding to a) best BER and b) worst BER obtained in Fig. 1. An inset with the eye-diagram obtained in the absence of ICXT is also depicted. The normalized eye opening is indicated in each eye-pattern.

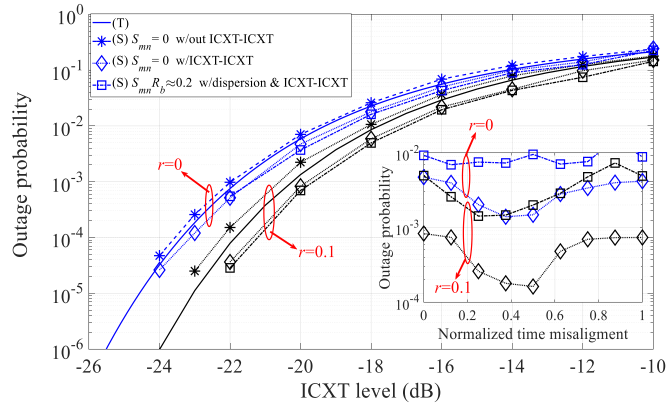

Fig. 3. OP as a function of the ICXT level for $r = 0$ (blue) and 0.1 (black), for three simulation (S) cases: (i) $S_{mn} = 0$ without ICXT-ICXT beating (*); (ii) $S_{mn} = 0$ with ICXT-ICXT beating (◊); and (iii) $S_{mn}{\cdot}R_b \approx 0.2$ with dispersion and ICXT-ICXT beating (□); and for the theoretical (T) OP obtained using (8). The inset shows the OP as a function of the normalized time misalignment obtained using simulation, for $r = 0$ and $r = 0.1$, and for $X_c = -20$ dB with $S_{mn} = 0$ (◊), and $X_c = -18$ dB with $S_{mn}{\cdot}R_b \approx 0.2$ and dispersion (□).

Fig. 3 shows a very good agreement between the OPs obtained from (8) and from simulation with and without the ICXT-ICXT beating. For typical OP of 10^{-4}, the difference between the ICXT levels predicted by the two methods, for $r = 0$ and $r = 0.1$, is only 0.18 dB and 0.42 dB, respectively, without the ICXT-ICXT beating. When this beating is included, the difference increases to 0.26 dB and 0.5 dB, for $r = 0$ and $r = 0.1$, respectively. Nevertheless, these results show that the ICXT-ICXT beating has a reduced impact on the OP, as assumed in the derivation of (8). Eq. (8) underestimates the OP when compared with the simulation results without the ICXT-ICXT beating, since the BER in (6) neglects the contribution of bits '0' from both cores to the BER. The eye-patterns show that the improvement of the OP with the ICXT-ICXT beating inclusion results from the increase of the noise margin of the bits '1'. The inclusion of dispersion (which leads to very low ISI as shown in the inset of Fig. 2 b)) and skew ($S_{mn}R_b \approx 0.2$) in the simulation originates OPs very similar to the ones obtained with $S_{mn} = 0$ and ICXT-ICXT beating. Hence, (8) provides a good prediction of the OP even when considering low dispersion effect, low skew and ICXT-ICXT beating, for the two extinction ratios. Simulation results confirm that ideal extinction ratio signals lead to worse OP relative to the non-ideal extinction ratio case, as predicted by (8). The ICXT level increase of 1.5 dB obtained theoretically for $P_{out}=10^{-4}$, by changing from $r=0$ to $r=0.1$, is in agreement with simulation results. From the eye-pattern analysis, the higher noise margin of bits '1' attained for lower extinction ratio leads to the ICXT level increase. So far, the OPs obtained in this work assume aligned bits at the MCF cores input. Fig. 3 inset shows the OP as a function of the normalized (to the bit period) bit misalignment, for $X_c=-20$ dB with $S_{mn}=0$, and for $X_c=-18$ dB with $S_{mn}R_b\approx0.2$ and dispersion, for $r=0$ and $r=0.1$. The inset shows that, for r = 0.1 and S_{mn} = 0, the time misalignment leads to a decrease of the OP around 5 times at half the bit period, when compared with the OP achieved with aligned bits. The time misalignment impact on the OP decreases in presence of dispersion and $S_{mn}R_b\approx0.2$, and also when $r=0$. These conclusions hold for other ICXT levels.

B. *Skew-Bit Rate Product Dependence*

The impact of ICXT on the performance of OOK communication systems with DD has been shown to be very dependent on the skew-bit rate product [12]. However, Subsection III.A dealt only with skews much shorter than the bit period. Thus, in the following, the dependence of the OP on the skew-bit rate product is studied by simulation including the ICXT-ICXT beating, for $L=20$ km and $D_\lambda=17$ ps/nm/km.

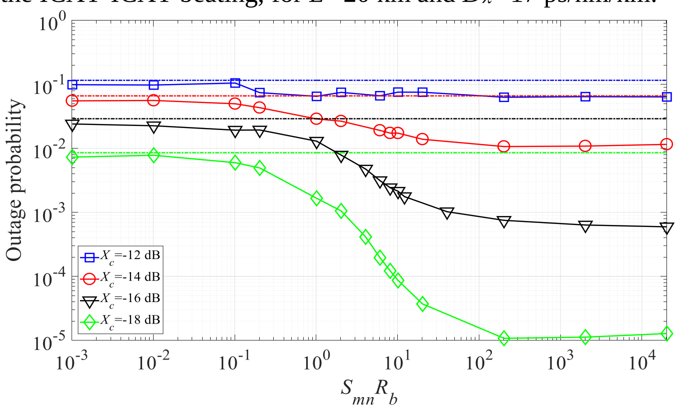

Fig. 4. OP as a function of $S_{mn}R_b$ for $r=0.1$ and $X_c=-12$ dB, −14 dB, −16 dB and −18 dB: simulation (symbols) and theoretical (dashed-dotted lines).

Fig. 4 shows the OP as a function of $S_{mn}R_b$, for several ICXT levels. Although the results have been obtained for r = 0.1, similar conclusions are drawn for r = 0. The theoretical OP obtained using (8) is also depicted. Two distinct behaviors are shown in Fig. 4. For $S_{mn}R_b<0.1$, the ICXT is highly correlated along the signal bandwidth [12], [13], the ICXT effect is stronger and the OP reaches its worst-case value. For $S_{mn}R_b$ > 100, the ICXT is decorrelated along the signal bandwidth [13], and a decrease of the OP is observed [11]. For $0.1<S_{mn}R_b<100$, a transition between the two ICXT behaviors is observed, as reported in [12], when studying the variance of the short-term average ICXT power. Fig. 4 shows also that the OP improvement observed for high $S_{mn}R_b$ is smaller when the ICXT level increases. For $X_c=-12$ dB, the decrease of the OP is below one order of magnitude when increasing $S_{mn}R_b$. For $X_c=-18$ dB, the OP obtained with $S_{mn}R_b>100$ reduces nearly three orders of magnitude when compared with the one obtained for $S_{mn}R_b<0.1$. In Fig. 3, $P_{out}=10^{-4}$ is reached for $X_c\approx-21.4$ dB and $S_{mn}R_b=0$, while, from analysis of the results of Fig. 4, the same OP is reached for $X_c\approx-17$ dB and high $S_{mn}R_b$. This indicates a tolerance to ICXT exceeding 4 dB for high $S_{mn}R_b$ relative to low $S_{mn}R_b$. Figs. 3 and 4 show also that the theoretical prediction of the OP proposed by (8) is valid for DD systems with $S_{mn}R_b$ below 0.2, i. e., when the ICXT along the signal bandwidth is highly correlated.

From numerical simulation, we have concluded that the bit misalignment impact on the OP decreases when increasing $S_{mn}R_b$, and is negligible for high $S_{mn}R_b$.

IV. Conclusion

The OP in short-haul DD optical links with weakly-coupled MCFs and using OOK signaling impaired by ICXT has been studied theoretically and through numerical simulation. A closed-form expression that provides fast and reliable estimates of the OP has been proposed. This expression is valid when the ICXT along the signal bandwidth is correlated, i. e., when $S_{mn}R_b<0.2$ and low fiber dispersion. It has been shown that the OP decreases with the increase of $S_{mn}R_b$. For a typical OP of 10^{-4}, a higher tolerance to ICXT exceeding 4 dB is observed for high skew-bit rate products relative to low skew-bit rate products. It has been also shown that DD links with non-ideal extinction ratio are more robust to outage caused by ICXT.

References

[1] J. Galve *et al.*, "Reconfigurable radio access networks using multicore fibers," *IEEE J. Quantum Electron.*, vol. 52, no. 1, pp. 1–7, Jan. 2016.

[2] D. Butler *et al.*, "Space division multiplexing in short reach optical interconnects," *IEEE/OSA J. Lightw. Technol.*, vol. 35, no. 4, pp. 677–682, Feb. 15, 2017.

[3] G. Rademacher *et al.*, "Performance fluctuations in direct detection multi-core fiber transmission systems," *in Proc. ECOC 2017*, Gothenburg, Sweden, Sep., paper P2.SC6.16.

[4] T. Hayashi, T. Sasaki, and E. Sasaoka, "Behavior of inter-core crosstalk as a noise and its effect on Q-factor in multi-core fiber," *IEICE Trans. Commun.*, vol. E97-B, no. 5, pp. 936–944, May 2014.

[5] 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.

[6] T. Alves, and A. Cartaxo, "Characterization of the stochastic time evolution of short-term average intercore crosstalk in multicore fibers with multiple interfering cores," *Opt. Expr.*, vol. 26, no. 4, pp. 4605-4620, Feb. 2018.

[7] 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.

[8] A. Macho *et al.*, "Birefringence effects in multicore fiber: Coupled local-mode theory," *Opt. Expr.*, vol. 24, no. 19, pp. 21415-21434, Sep. 2016.

[9] 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.

[10] 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.

[11] J. Rebola, A. Cartaxo, and A. Marques, "10 Gbps CPRI signals transmission impaired by intercore crosstalk in 5G network fronthauls with multicore fibers," *Springer Photon. Netw. Commun.* DOI: 10.1007/s11107-019-00828-0, 2019.

[12] G. Rademacher *et al.*, "Crosstalk dynamics in multi-core fibers," *Opt. Exp.*, vol. 25, no. 10, pp. 12020-12028, May 15, 2017.

[13] T. Alves, and A. Cartaxo, "Decorrelation bandwidth of intercore crosstalk in weakly-coupled multicore fibers with multiple interfering cores," *IEEE/OSA J. Lightw. Technol.*, DOI: 10.1109/JLT.2018.2880076, 2018.

[14] T. Alves, J. Rebola, and A. Cartaxo, "Outage probability due to intercore crosstalk in weakly-coupled MCF systems with OOK signaling", *in Proc. OFC 2019*, San Diego, USA, Mar., paper M2I.1.