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Outage Probability due to Intercore Crosstalk from Multiple Cores in Short-Reach Networks

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

***Abstract*— The outage probability (OP) due to intercore crosstalk (ICXT) arising from multiple interfering cores in short-reach binary intensity modulation-direct detection optical links supported by homogeneous weakly-coupled multicore fibers is assessed through numerical simulation. The maximum acceptable ICXT level for a given OP is extracted from simulation results, for low and high skew-bit rate products (SBRPs). (i) For high SBRP, a 3 dB reduction of the maximum acceptable ICXT level per core for a given OP is observed when the number of interfering cores doubles. In this case, as a very large number (>>1) of bits of each interfering core is contributing to ICXT, the total detected ICXT tends to a Gaussian distribution that makes the maximum acceptable total ICXT level independent of the interfering core count. (ii) For low SBRP, the number of bits contributing to ICXT is similar to the interfering core count and the total detected ICXT assumes a set of discrete amplitudes, which deviates it from the Gaussian distribution. Hence, the reduction of the maximum acceptable ICXT level per core, when the number of interfering cores is doubled, is about 2 dB, and the maximum acceptable total ICXT level increases with the interfering core count, by around 3 dB, when the interfering core count increases from 1 to 8.**

***Index Terms*— direct-detection, intercore crosstalk, multicore fiber, outage probability, short-reach networks.**

I. INTRODUCTION

Multicore fibers (MCFs) are nowadays thought as one of the main techniques to deploy space-division multiplexing and support the foreseen huge increase of data traffic transmission in optical networks. Homogeneous weakly-coupled (WC)-MCFs, which enable using individual cores as independent channels, exhibit low latency and avoid the use of multiple input/multiple output equalization when compared with other MCF solutions [1], [2]. Due to these advantages, WC-MCFs have been proposed for short-reach networks, such as radio over fiber fronthauls, datacenter connections and optical access networks [3], [4]. Due to their low cost nature, WC-MCF-based short-reach networks rely on intensity modulation-direct detection (IM-DD) systems [4]. Transmission in WC-MCFs is impaired by intercore crosstalk (ICXT), which becomes more significant for higher core count and shorter core-to-core distance. In WC-MCFs, the ICXT changes randomly over the fiber longitudinal direction and also over time and frequency [1], [5]. The time variation of the ICXT may lead to significant performance fluctuations and to service outage, and can become an issue in IM-DD optical links [2], [6]. Hence, the outage probability (OP) must be evaluated to ensure the quality of transmission in IM-DD WC-MCF-based systems. So far, the OP in IM-DD WC-MCF systems has only been assessed considering the ICXT induced by a single interfering core [2], [7]. However, it is known that several interfering cores may contribute significantly to ICXT [5], [8] and recent results have shown significant dependence of the OP in IM-DD links on the skew-bit rate product (SBRP) [6], [7].

In this work, the OP in IM-DD short-reach optical links supported by homogeneous WC-MCFs is investigated in presence of ICXT induced by several interfering cores. General rules to estimate the maximum acceptable ICXT level for a given OP as function of the number of interfering cores for low and high SBRPs are provided.

II. SYSTEM MODEL AND SIMULATION PARAMETERS

The IM-DD WC-MCF short-haul link model considered in this work is similar to the one presented in [6], but adapted for signal transmission in multiple cores. Each optical transmitter launches chirpless binary signals with bit rate $R_b = 10$ Gbps, rectangular pulse shape and uncorrelated to the signals transmitted in other cores. The number of bits considered in each bit stream of the simulation is 2^{10}. The extinction ratio r of each binary signal launched in a fiber core is defined as the ratio between the average powers of the bits '0' and '1'.

Single-mode propagation is considered in each core. As homogeneous core fibers are considered, all cores have similar characteristics, such as attenuation coefficient and ICXT level per core. The ICXT level per core is defined as the ratio between the mean ICXT power induced by one interfering core and the signal power at the interfered core output [5]. For multiple interfering cores equally contributing to the ICXT, the total ICXT level is equal to the product of ICXT level per core by the number of interfering cores. The intercore skew, S_{mn}, is assumed equal for all pairs of cores. The MCF length is 20 km. In each core, a dispersion parameter of 17 ps/nm/km is considered. The ICXT is modelled by the dual-polarization discrete changes model (DCM) with 1000 phase-matching points [5], [9]. The DCM considers the random ICXT power fluctuations and relative signal-ICXT polarization changes [10], which are known to have a significant influence on the ICXT impact on the system performance [2]. As independent random phase shifts are considered for the ICXT induced by different cores, independent ICXT random polarization changes and contributions are induced by each interfering core. In this work, the maximum number of interfering cores considered is 8. This is roughly the maximum adjacent cores count that occurs at shorter core-to-core distances in typical MCF layouts and that have a relevant contribution to ICXT [11].

At the optical receiver, the signal is square-law photodetected by a PIN with unit responsivity and filtered by a 4th order Bessel filter with −3 dB bandwidth equal to R_b. Due to the short link

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length, optical amplification is not required, and only electrical noise is considered. The noise equivalent power of the electrical noise is 1 pW/Hz$^{1/2}$. For each extinction ratio, r=0 and r=0.1, the received signal power is adjusted to reach a specific bit error rate (BER) in absence of ICXT, which is denoted as $P_{b,NICXT}$.

III. NUMERICAL RESULTS AND DISCUSSION

To evaluate the BER and the OP using numerical simulation, we use Monte Carlo (MC) simulation combined with a semi-analytical technique [6]. The electrical noise impact on the BER is evaluated analytically and ICXT, fiber dispersion and filtering impact on BER are evaluated through their effect on the signal waveform. In each MC simulation iteration, an ICXT sample function is generated from the ICXT field transfer function [9]. The OP, P_{out}, is defined as the probability of the BER becoming above a BER threshold, P_{th}, [6], [8], due to the performance degradation caused by the ICXT fluctuations along time. The OP is estimated numerically by the ratio between the number of occurrences of BER above the BER threshold and the total number of MC simulation iterations. The BER threshold is set to P_{th}=10^{-3}. The number of BER occurrences above the BER threshold considered to get reasonably accurate OP estimates is 200 [6]. However, for $P_{out} \leq 10^{-4}$, due to the much longer required computational time, this criterion is relaxed to 50 BER occurrences, with acceptable loss of accuracy. As an example, to reach 50 BER occurrences above the BER limit, for $P_{out} \approx 10^{-4}$ and one interfering core, the simulation time is about 1 month in a computer with i5™ 2.67 GHz processor and 4 GB RAM.

The OP in an IM-DD MCF system depends strongly on the SBRP [6], [7]. In the following, the OPs are obtained for a low SBRP of $|S_{mn}R_b|$=0.01, which means that only one bit of a particular interfering core is contributing to ICXT induced in an interfered core [6], and for a high SBRP of $|S_{mn}R_b|$=1000. In this case, around 1000 bits of each interfering core are contributing to ICXT [6]. In the simulation, the desired SBRP is set by adjusting the walk-off between cores [1], [5].

A. Low Skew-Bit Rate Product

In this subsection, the OP dependence on the number of interfering cores is studied for systems with low SBRP, with $P_{b,NICXT}$=10^{-5}, which is reached for the received signal powers of -33.5 dBm and -32.9 dBm, for r=0 and r=0.1, respectively.

Fig. 1 shows the OP as a function of the ICXT level per core, obtained by MC simulation, for N_i=1, 2, 4, 6 and 8 interfering cores, with r=0.1. From Fig. 1, a reduction of the allowed ICXT level per core of about 6 dB can be seen when the interfering core count increases from 1 to 8. Fig. 1 is presented to show how the subsequent figures of this work have been obtained. For example, from Fig. 1, for P_{out}=10^{-4}, we can extract the maximum acceptable ICXT level per core as a function of the number of interfering cores, which for one interfering core is -21.5 dB and for 8 interfering cores is -27.8 dB.

The maximum acceptable ICXT level per core and maximum acceptable total ICXT level as a function of the number of interfering cores are shown in Fig. 2, for $|S_{mn}R_b|$=0.01, P_{out}=10^{-3} and P_{out}=10^{-4}, for a) r=0.1 and b) r=0. Fig. 2 reveals that, in the log-scale, the variation of the maximum acceptable ICXT level per core is practically linear with the increase of the number of interfering cores.

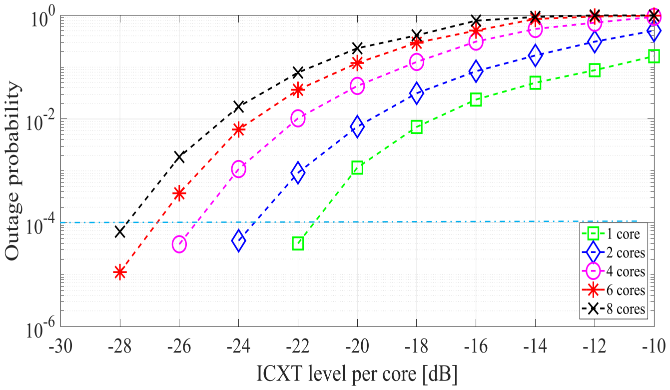

Fig. 1. OP as a function of the ICXT level per core for 1 (□), 2 (◊), 4 (O), 6 (∗) and 8 (×) interfering cores (symbols) with r=0.1.

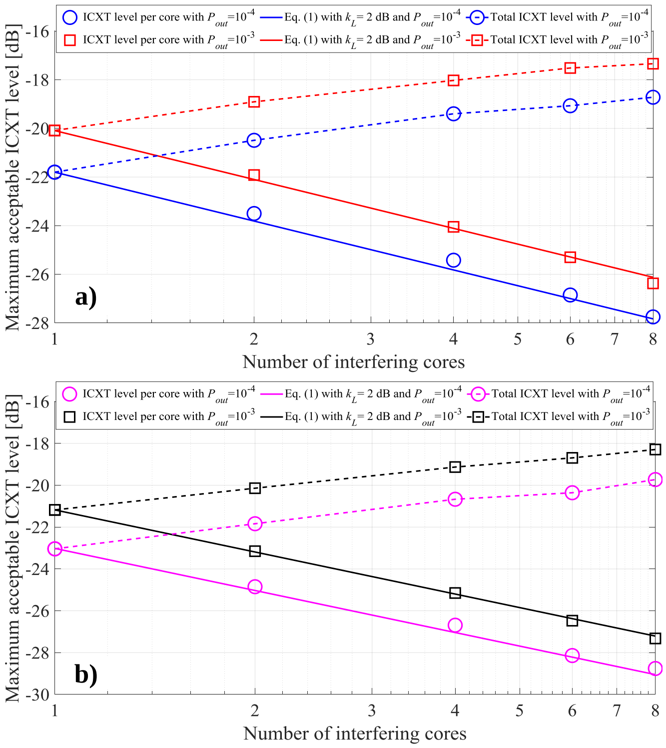

Fig. 2. Maximum acceptable ICXT level per core and maximum acceptable total ICXT level as a function of the number of interfering cores, for a) r=0.1 and b) r=0, obtained by MC simulation for P_{out}=10^{-3} (□) and P_{out}=10^{-4} (O) and $|S_{mn}R_b|$=0.01. Maximum acceptable ICXT level per core estimates (solid lines) obtained using eq. (1) with k_L=2 dB are also shown.

By performing a linear regression (using log$_2$(x) for the x data) of the simulated results shown in Fig. 2, the estimated slope allows us predicting the ICXT level per core reduction with the interfering core count increase. After performing the linear regression, the estimated slopes in Fig. 2 a) are -2.1 dB, for P_{out}=10^{-3}, and -2.0 dB, for P_{out}=10^{-4}. In Fig. 2 b), the estimated slopes are -2.1 dB, for P_{out} = 10^{-3}, and -1.9 dB, for P_{out}=10^{-4}. This means a reduction of the maximum acceptable ICXT level per core of about 2 dB when doubling the number of interfering cores. This degradation of the maximum acceptable ICXT level per core for N_i interfering cores can be written as

$$X_{c,N_i}\left[\text{dB}\right] = X_{c,1}\left[\text{dB}\right] - k_L \log_2\left(N_i\right) \quad (1)$$

where k_L represents the absolute value of the estimated slope and $X_{c,1}$ is the maximum acceptable ICXT level estimated for one interfering core for a specific OP, which can be estimated theoretically from [6], or calculated numerically or measured experimentally. Fig. 2 shows the estimates of the maximum acceptable ICXT level per core obtained using (1) with k_L=2 dB and $X_{c,1}$ estimated by MC simulation. A very good fitting can be observed in Fig. 2. Maximum discrepancies of 0.4 dB between simulation results and the estimates using (1) are found for r=0 and P_{out}=10^{-4}. These discrepancies are attributed, in part, to the possible inaccuracy of the estimations of the ICXT level per core through MC simulation and also to the slight difference between k_L used in Fig. 2 and the absolute value of the slope obtained from the linear regression.

Fig. 2 shows also that the maximum acceptable total ICXT level increases with the interfering count since, when doubling the number of cores, the reduction of the maximum acceptable ICXT level per core is only around 2 dB. As a consequence, from 1 to 8 interfering cores, the maximum acceptable total ICXT level increases about 3 dB.

B. *High Skew-Bit Rate Product*

As the measured skew between different cores can be around 10 ns [4], [5], systems with 10 Gb/s or higher may be operating with $|S_{mn}R_b|$>>1. Thus, in this subsection, the OP is studied as function of the interfering core count for systems with high SBRP and $P_{b,NICXT}$=10^{-5}.

Fig. 3 shows the maximum acceptable ICXT level per core and maximum acceptable total ICXT level estimated by MC simulation as a function of the number of interfering cores, for $|S_{mn}R_b|$=1000, P_{out}=10^{-3} and P_{out}=10^{-4}, for a) r=0.1 and b) r=0. Fig. 3 shows that, when the number of interfering cores doubles, the maximum acceptable ICXT level per core reduces 3 dB. This conclusion holds for both extinction ratios and OPs. This 3 dB reduction has been confirmed by performing the linear regression of the simulation results shown in Fig. 3 and calculating the corresponding slope, as done in Fig. 2. Hence, for high SBRP, the reduction of the maximum acceptable ICXT level per core when the number of interfering cores doubles can be described using (1) with k_L=3 dB. Fig. 3 shows the maximum acceptable ICXT level per core estimated using (1) with k_L=3 dB, and confirms the 3 dB reduction of ICXT level per core when the number of interfering cores doubles. Maximum discrepancies between simulation results and estimates using (1) with k_L=3 dB of 0.4 dB are found. The 3 dB reduction achieved when doubling the number of cores makes, for $|S_{mn}R_b|$>>1, the maximum acceptable total ICXT level from multiple cores practically independent of the interfering core count as confirmed in Fig. 3, for both extinction ratios and OPs. This can be explained as follows. For one interfering core and $|S_{mn}R_b|$>>1, a large number (>>1) of bits contributes to the ICXT induced in the interfered core [7]. As the ICXT generated by a given interfering core is uncorrelated with the ICXT induced by other interfering cores, the total ICXT affecting the interfered core is the incoherent sum of the ICXT contributions of each core, similar to what happens with independent noise sources. Furthermore, as it was shown experimentally in [7], the amplitude of the detected ICXT tends to a Gaussian distribution by the central limit theorem, as a consequence of the ICXT induced by each interfering core being originated from a large number of contributions, each one associated with a different bit. As the ICXT contributions induced by each interfering core are independent of the others, the total detected ICXT tends to a Gaussian distribution with variance equal to the sum of the variances of each ICXT contribution. As each one of the variances is proportional to the ICXT level per core [6], the maximum acceptable total ICXT level becomes independent on the interfering core count for high SBRP.

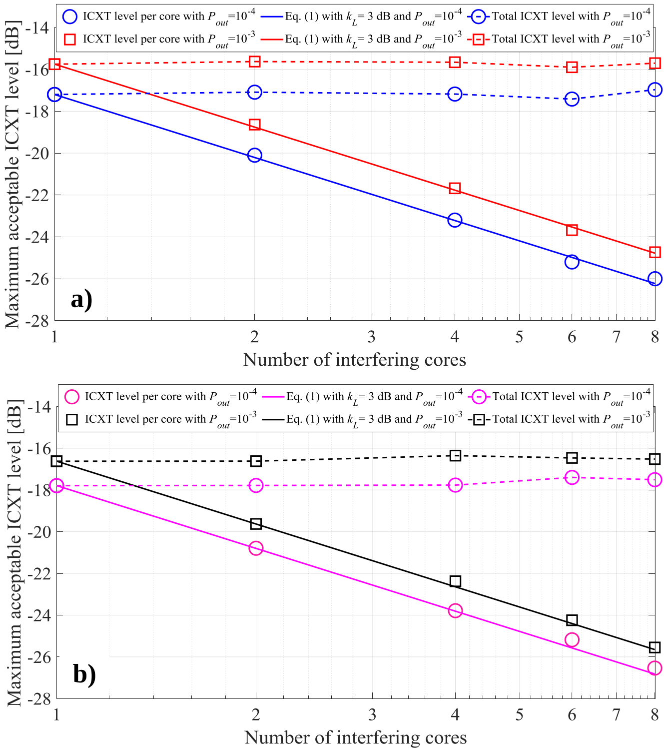

Fig. 3. Maximum acceptable ICXT level per core and maximum acceptable total ICXT level as a function of the number of interfering cores, for a) r=0.1 and b) r=0, obtained by MC simulation for P_{out}=10^{-3} (□) and P_{out}=10^{-4} (o) and $|S_{mn}R_b|$=1000. Maximum acceptable ICXT level per core estimates (solid lines) obtained using eq. (1) with k_L=3 dB are also shown.

For very low SBRP, only one bit in the interfering core contributes to the ICXT field at each time instant [6], [7]. This makes the amplitude of the detected ICXT with one interfering core to take a set of a low number of discrete values (for binary signals with nonzero extinction ratio, there are two values in each interfered bit), as already shown experimentally in [7], taking a distribution that is significantly different from Gaussian. Although the ICXT contributions from several interfering cores are uncorrelated, only few bits (as much as the number of interfering cores) are contributing to the overall ICXT. Consequently, the variance of the detected ICXT increases with the interfering core count increase. However, the distribution of the amplitude of the detected ICXT spreads along a larger range of amplitudes, resembling more a Gaussian distribution. As Figs. 2 and 3 show for one interfering core, the system is more tolerant to ICXT when the detected ICXT is Gaussian-distributed. Hence, with low SBRP, when the core count doubles, the OP degradation is not as effective as with high SBRP, the reduction of the maximum acceptable ICXT level per core is lower than 3 dB, and the maximum acceptable total ICXT level increases with the core count.

C. *Influence of low BERs in absence of ICXT on the OP*

In the absence of ICXT, the BER can be much lower than $P_{b,NICXT}$=10^{-5}, see, for instance, the experimental work presented in [7]. Hence, it becomes relevant to study the influence of the number of interfering cores on the OP, also for much lower BERs in the absence of ICXT. In this subsection, the BER in absence of ICXT is set to $P_{b,NICXT}$=10^{-10} and a study similar to the ones presented in sections III.A and III.B is performed. To reach this BER in absence of ICXT, the received signal power is set to -30.9 dBm, for r=0.1.

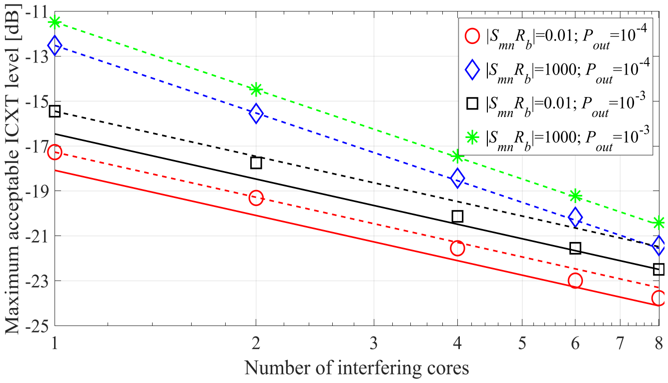

Fig. 4. Maximum acceptable ICXT level per core as a function of the number of interfering cores, for $|S_{mn}R_b|$=0.01 and P_{out}=10^{-4} (o), $|S_{mn}R_b|$=1000 and P_{out}=10^{-4} (◊), $|S_{mn}R_b|$=0.01 and P_{out}=10^{-3} (□) and $|S_{mn}R_b|$=1000 and P_{out}=10^{-3} (*), obtained by MC simulation, for r=0.1 and $P_{b,NICXT}$=10^{-10}. Maximum acceptable ICXT level per core estimates obtained using eq. (1) and $X_{c,1}$ calculated theoretically using the expression presented in [6] (solid lines); and eq. (1) and $X_{c,1}$ obtained from simulation (dashed lines) are also shown.

Fig. 4 shows the maximum acceptable ICXT level per core as a function of the number of interfering cores, for r=0.1 and $P_{b,NICXT}$=10^{-10}. Results for $|S_{mn}R_b|$=1000 and $|S_{mn}R_b|$ = 0.01 and two different OPs, P_{out}=10^{-3} and P_{out}=10^{-4}, are shown. Estimates obtained using eq. (1) and $X_{c,1}$ calculated using the theoretical expression presented in [6], and using eq. (1) and $X_{c,1}$ estimated through MC simulation, are also depicted. For $|S_{mn}R_b|$=1000 and $|S_{mn}R_b|$=0.01, k_L=3 dB and k_L=2 dB, respectively, are used in eq. (1). Fig. 4 confirms that, for $|S_{mn}R_b|$=1000, even for low BERs in absence of ICXT, the ICXT level per core reduces 3 dB when the number of interfering cores doubles, meaning that the maximum acceptable total ICXT level is maintained with the interfering core count increases. For $|S_{mn}R_b|$=0.01, the degradation of the ICXT level per core is around 2 dB when the number of interfering cores doubles. This means that the maximum acceptable total ICXT level is growing with the increased number of interfering cores, as concluded also from Fig. 2. The estimated slopes from linear regression are -2.4 dB and -2.2 dB, respectively, for P_{out}=10^{-3} and P_{out}=10^{-4}, which means that k_L increases slightly for $P_{b,NICXT}$=10^{-10} in comparison with $P_{b,NICXT}$=10^{-5}. For low SBRP, Fig. 4 exhibits maximum ICXT level per core discrepancies of 1 dB between simulation results and estimations using eq. (1) with $X_{c,1}$ obtained by simulation. These discrepancies are attributed, in part, to the possible inaccuracy of the estimations of $X_{c,1}$ through simulation and also to the difference between k_L used in Fig. 4 and the slightly higher absolute values of the slopes obtained from linear regression. Fig. 4 leads also to another conclusion regarding the theoretical expression proposed in [6] for one interfering core and low SBRP. The predictions of $X_{c,1}$, which for $P_{b,NICXT}$=10^{-5} are relatively accurate as shown in [6], reach 1 dB difference in Fig. 4, in comparison with the simulation results. These differences are attributed, in part, to the enhanced weight of the ICXT-ICXT beating for lower BERs, which is neglected in the derivation presented in [6].

IV. CONCLUSION

In this work, the OP in IM-DD short-reach networks supported by WC-MCFs and impaired by ICXT induced by multiple interfering cores has been assessed. General rules to estimate the maximum acceptable ICXT level per core for a given OP with multiple interfering cores are provided for low and high SBRPs. For high SBRP, the degradation of the maximum acceptable ICXT level per core obtained for a given OP is 3 dB when the number of interfering cores doubles. This indicates that the maximum acceptable total ICXT level is independent of the interfering core count. For low SBRP, when the number of interfering cores doubles, the reduction of the maximum acceptable ICXT level per core is around 2 dB, which reveals that the maximum acceptable total ICXT level increases with the interfering core count increases. From 1 to 8 interfering cores, the maximum acceptable total ICXT level increases around 3 dB.

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