ISCTE IUL
REPOSITÓRIO
INSTITUTO UNIVERSITÁRIO DE LISBOA

Repositório ISCTE-IUL

Deposited in *Repositório ISCTE-IUL*:
2023-12-28

Deposited version:
Accepted Version

Peer-review status of attached file:
Peer-reviewed

Citation for published item:
Rebola, J. L. & Cartaxo, A. V. T. (2023). Statistical dependence of average intercore crosstalk on random loss in long-haul uncoupled MCF links. In Dagenais, D. (Ed.), 2023 IEEE Photonics Conference (IPC). Orlando, FL, USA: IEEE.

Further information on publisher's website:
10.1109/IPC57732.2023.10360484

Publisher's copyright statement:
This is the peer reviewed version of the following article: Rebola, J. L. & Cartaxo, A. V. T. (2023). Statistical dependence of average intercore crosstalk on random loss in long-haul uncoupled MCF links. In Dagenais, D. (Ed.), 2023 IEEE Photonics Conference (IPC). Orlando, FL, USA: IEEE., which has been published in final form at https://dx.doi.org/10.1109/IPC57732.2023.10360484. This article may be used for non-commercial purposes in accordance with the Publisher's Terms and Conditions for self-archiving.

Use policy

Creative Commons CC BY 4.0
The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a link is made to the metadata record in the Repository
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Serviços de Informação e Documentação, Instituto Universitário de Lisboa (ISCTE-IUL)
Av. das Forças Armadas, Edifício II, 1649-026 Lisboa Portugal
Phone: +(351) 217 903 024 | e-mail: administrador.repositorio@iscte-iul.pt
https://repositorio.iscte-iul.pt

Statistical Dependence of Average Intercore Crosstalk on Random Loss in Long-haul Uncoupled MCF Links

João L. Rebola[1,2], Adolfo V. T. Cartaxo[1,2]
1. Optical Communications and Photonics Group, Instituto de Telecomunicações, Lisbon, Portugal
2. Instituto Universitário de Lisboa (ISCTE-IUL), Lisbon, Portugal
Email (corresponding author): joao.rebola@iscte-iul.pt

***Abstract*— Random core dependent loss (CDL) in long-haul uncoupled multicore fiber links is shown by simulation to lead to gaussian-distributed average crosstalk power. Due to CDL randomness, the excess of average crosstalk power relative to its mean is below 0.2 dB in 2000 km-long links.**

Keywords—core dependent loss, crosstalk, multicore fiber.

I. Introduction

Multicore fibers (MCFs) are seen as a future solution to cope with current capacity constraints imposed by single-core singlemode fiber transmission [1]. However, the crosstalk (XT) between cores, i.e., intercore XT, may degrade signal transmission quality in MCFs, even with uncoupled (weakly-coupled) cores. The XT in uncoupled MCFs is typically investigated considering equal core losses [2], [3]. However, due to imperfect manufacturing, uncoupled MCFs usually exhibit core dependent loss (CDL) [4]. The impact of CDL on XT in two-core one-segment uncoupled MCFs has been studied theoretically for unidirectional transmission [2], [3] and bidirectional transmission [3]. For both unidirectional and bidirectional transmissions, the XT power variations with constant CDL can reach 2 dB (for CDL between ±0.04 dB/km) in comparison with MCFs with equal core losses [3]. For unidirectional transmission, we have shown that, in links with concatenated MCF segments (as in long-haul terrestrial links), where each segment can have a random low magnitude CDL, for specific arrangements of the MCF segments, the average XT powers at the MCF output can vary about 1 dB due to the enhanced total CDL at the link output [5].

This work extends the analysis presented in [5] by studying the statistical dependence of average XT power on random CDL in long-haul optical links with concatenated MCF segments.

II. Numerical Model

We consider a long-haul uncoupled two-core MCF link with total length L_{tot}, which is divided in N_s spans with equal length. Each span consists of N concatenated MCF segments, where each segment can exhibit random CDL, which is independent from the CDL in other segments.

The equivalent model of each MCF span with length L_{span} follows closely the model presented in [5]. Each fiber segment has length L_i (with i = 1,...,N). To assess the coupled power, power is launched in one core with average denoted as P_{in}. The power at the output of N concatenated MCF segments is obtained from the power at the MCF input using the matrices $\mathbf{T_i}$ proposed in eq. (10) of [2], with i corresponding to each i-th MCF segment [5]. Those matrices describe the power coupling between the two fiber cores within each i-th MCF segment. For each segment, the power coupling coefficient between the cores m and n is $h_{nm,i} \approx h_{mn,i} = h_i$, which is verified in the practical range of CDL [2], [3]. The CDL in segment i is characterized as a r.v., since concatenated MCFs can come from different lots and have arbitrary CDL. CDL ranges of [−0.04, 0.04] dB/km have been reported [4], and very unlikely this range width exceeds 0.1 dB [2]. Hence, the loss coefficients $\alpha_{c,i}$ (with $c = m$ or n) in the i-th MCF segment are randomly generated using a uniform distribution in the range $[\alpha_{c,min}, \alpha_{c,max}]$. In the i-th segment, the average of the loss coefficients is $\overline{\alpha}_i = (\alpha_{m,i} + \alpha_{n,i})/2$ and the loss coefficient imbalance (equivalent to CDL) is $2\delta\alpha_i = \alpha_{m,i} - \alpha_{n,i}$. Notice that the CDL random generation performed in this work differs from the one used in [5], as it allows for variations of the average loss coefficient $\overline{\alpha}_i$ of each segment, while in [5], the average loss coefficient is kept the same in all MCF segments. At the output of each fiber span (after N MCF segments), the optical loss in cores m and n is perfectly compensated by optical amplifiers with gain equal to the overall loss of each core in that MCF span.

The direct average XT power, XT_{dir}, and the indirect average XT power, XT_{ind}, (as defined in [3]) at the output of the long-haul MCF link (after N_s spans) are obtained as described in [5].

III. Numerical Results and Discussion

In this section, the statistical dependence of the XT on random CDL in long-haul links composed of uncoupled two-core MCF spans is assessed by simulation.

All results presented are obtained for an input power of P_{in} = 1 mW, considering link lengths from L_{tot} = 100 km (N_s = 1) to L_{tot} = 2000 km (N_s = 20 and L_{span} = 100 km). Each span has N = 50 segments with equal length L_i = 2 km. The power coupling coefficient is considered equal in all MCF segments, $h_i = h$.

Fig. 1 shows the PDFs of the direct average XT power for the link lengths of a) 100 km and b) 2000 km and of the indirect XT power for c) 2000 km. The gaussian PDFs with the same mean and standard deviation as the ones obtained by simulation are also shown. The PDFs have been obtained with a XT level hL_{tot} = 0.1 (-10 dB) after 2000 km and 10^6 realizations of MCF segments arrangements. This very pessimistic XT level is considered to illustrate a situation where the non-gaussianity of the PDF is more perceptible. The loss coefficients $\alpha_{c,i}$ are generated using a uniform distribution between [0.15, 0.23] dB/km, being the maximum loss core imbalance $2\delta\alpha_{max}$ = 0.08 dB/km. As shown in Fig. 1, the gaussianity of the PDFs of XT_{dir} is more pronounced for long-haul links (2000 km) than for shorter links (100 km) due to the higher number of concatenated MCF segments with random loss (1000 against 50). For other

This work was supported in part by Fundação para a Ciência e Tecnologia/Ministério da Ciência, Tecnologia e Ensino Superior (FCT/MCTES) under Project UIDB/50008/2020.

link lengths, we have observed an enhanced PDFs gaussian behavior with the increasing link length. After 2000 km, the excess kurtosis is κ_E=0.0043 (as a reference, a gaussian PDF has null excess kurtosis). The PDFs of XT_{ind} also follow this enhanced gaussianity as the link length becomes longer, as can be observed in Fig. 1 c). Hence, it is only sufficient to assess the mean and standard deviation of XT_{dir} and XT_{ind} to have a good description of its statistical dependence on random loss caused by concatenated MCF segments.

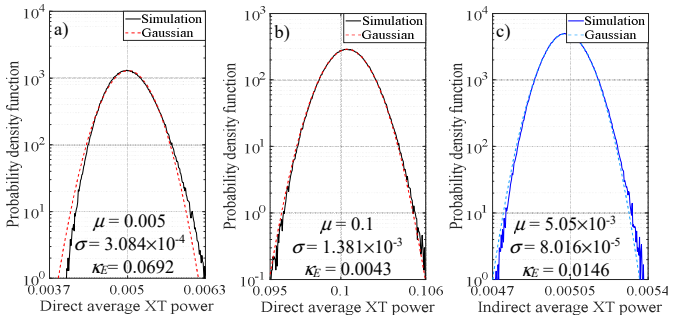


Figure 1. Direct average XT power PDFs, for a) L_{tot}=100 km, b) L_{tot}=2000 km and indirect average XT power PDF, for c) L_{tot}=2000 km, for hL_{tot} = 0.1 after 2000 km. The gaussian PDFs are obtained with the mean μ and standard deviation σ estimated by simulation. The excess kurtosis is also shown.

Fig. 2 a) and b) show, respectively, the mean μ and standard deviation σ of XT_{dir} as a function of hL_{tot} and $\delta\alpha_{max}$, for L_{tot}=2000 km. To obtain these results, we set the loss coefficient to the minimum, $\alpha_{c,min}$ = 0.15 dB/km, and the maximum to $\alpha_{c,max} = \alpha_{c,min} + 2\delta\alpha_{max}$, with the range $\delta\alpha_{max}$ varying as in Fig. 2. Then, the loss coefficients $\alpha_{m,i}$ and $\alpha_{n,i}$ in the i-th MCF segment are generated uniformly in the range $[\alpha_{c,min}, \alpha_{c,max}]$. For each pair $(h, \delta\alpha_{max})$, 10^6 realizations of MCF segments arrangements have been simulated. 110 pairs $(h, \delta\alpha_{max})$ have been considered in Fig. 2. Fig. 2 a) shows that the mean of XT_{dir} is practically independent of $\delta\alpha_{max}$ and is approximately given by hL_{tot} [2]. Fig. 2 b) shows that the standard deviation grows with the increase of the XT level, hL_{tot}, and that this growth also depends on $\delta\alpha_{max}$. For constant hL_{tot}, the standard deviation increases almost two orders of magnitude with $\delta\alpha_{max}$ variation. The maximum and minimum excess kurtosis obtained for all pairs $(h, \delta\alpha_{max})$ shown in Fig. 2 are, respectively, 0.017 and -0.015. These results further support the gaussianity assumption.

It can be shown that the excess of the direct average XT power (with XT_{dir} in the range $[\mu-k\sigma, \mu+k\sigma]$) induced by CDL relative to the case without CDL is maximized by

$$\Delta XT_{dir}\,[\mathrm{dB}] = 10\log_{10}\left(1 + k\,\sigma/\mu\right) \qquad (1)$$

Considering the 3σ rule of thumb (k=3 in (1)), nearly all MCF segment arrangements (99.7%) have direct average XT power in the range $[\mu-3\sigma, \mu+3\sigma]$, and half of them will lead to excess of direct average XT power due to CDL higher than 0 dB. From (1), to keep the excess of direct average XT power below 0.1 and 0.5 dB, the relative spread σ/μ should not exceed 7.8×10^{-3} and 4.1×10^{-2}, respectively. Fig. 3 shows the relative spread σ/μ as a function of hL_{tot} and $\delta\alpha_{max}$ and it can be concluded that the relative spread is practically independent of hL_{tot} and only CDL dependent. Fig. 3 shows that ΔXT_{dir} does not exceed 0.5 dB, for all pairs $(h, \delta\alpha_{max})$ considered. For $\delta\alpha_{max}$ = 0.04 dB/km, the maximum relative spread shown in Fig. 3 is σ/μ = 0.0138, corresponding to ΔXT_{dir} = 0.176 dB. For $\delta\alpha_{max}$ below approximately 0.0225 dB/km, the excess of direct average XT power does not exceed 0.1 dB.

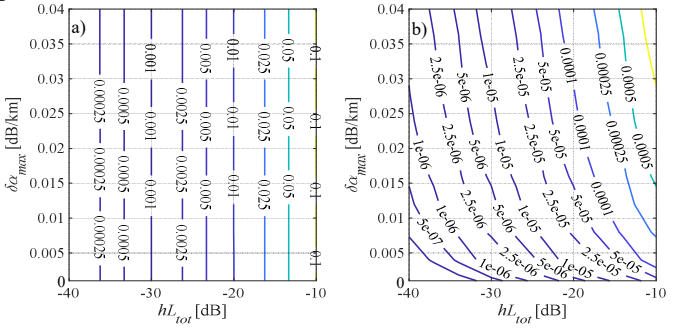


Figure 2. a) Mean μ and b) standard deviation σ of XT_{dir} as a function of the direct XT level hL_{tot} and half the maximum loss coefficient imbalance $\delta\alpha_{max}$, considering L_{tot}=2000 km.

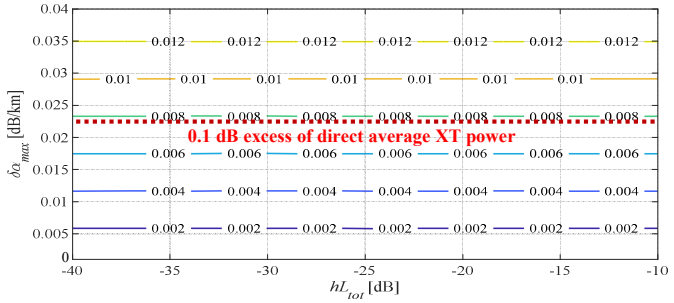


Figure 3. Relative spread σ/μ as a function of the direct XT level hL_{tot} and half the maximum loss coefficient imbalance $\delta\alpha_{max}$, considering L_{tot}=2000 km.

The conclusions regarding the mean, standard deviation and excess kurtosis variation with hL_{tot} and $\delta\alpha_{max}$ of the indirect average XT power are qualitatively similar to the ones taken for the direct average XT power, noticing that the indirect XT impact in unidirectional transmission is much lower [2].

IV. Conclusion

We have studied the statistical dependence of average XT on random loss in long-haul links composed by concatenated MCF segments. For 2000 km-long links, random CDL leads to PDFs of the direct and indirect average XT powers that are nearly gaussian-distributed, being the mean almost CDL independent. For a constant XT level, the standard deviation varies more than one order of magnitude for practical values of CDL. The excess of direct average XT power due to random CDL relative to its mean is below 0.2 dB, for 2000 km-long links.

References

[1] J. Downie, Y. Jung, S. Makovejs, M. Edwards and D. Richardson, "Cable capacity and cost/bit modeling of submarine MCF systems with MC-EDFA alternatives," accepted for publication in *J. Lightw. Technol.*; DOI 10.1109/JLT.2023.3253259.

[2] Y. Kobayashi and T. Hayashi, "Behavior and measurement method of inter-core crosstalk in multicore fibers with core-dependent loss", *Opt. Exp.*, vol. 31, no. 1/2, pp. 502-508, Jan. 2023.

[3] A. Cartaxo, "Loss imbalance effect on inter-core crosstalk in bidirectional uncoupled multi-core fiber transmission," accepted for publication in *J. Lightw. Technol.*, DOI 10.1109/JLT.2023.3273233.

[4] T. Matsui, *et al*, "118.5 Tbit/s transmission over 316 km-long multi-core fiber with standard cladding diameter," in *Proc. OECC*, Singapore, July-Aug. 2017.

[5] J. Rebola and A. Cartaxo, "Effect of core-dependent loss on the intercore crosstalk in multicore fiber systems with concatenated random loss fiber segments," in *Proc. ICTON*, Bucharest, Romania, July 2023.