Effect of core-dependent loss on the intercore crosstalk in multicore fiber systems with concatenated random loss fiber segments

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ABSTRACT

We investigate the impact of core-dependent loss (CDL) on the signal and crosstalk (XT) powers at the output of a link composed by several concatenated multicore fiber (MCF) segments, by considering random CDL in each MCF segment. We show that, with random CDL, for a 100 km optical link and specific arrangements of MCF segments, the forward, signal, coupled and direct XT powers may increase around 1 dB (with respect to the absence of CDL). We show also that, at the output of the concatenated MCF segments, the probability density functions of these powers follow a Gaussian distribution with random CDL generated from different statistical distributions.

Keywords: coupled power, intercore crosstalk, multicore fiber, space-division multiplexing.

1. INTRODUCTION

Nowadays, multicore fibers (MCFs) are considered as a promising space-division multiplexing transmission solution to overcome the capacity limitations imposed by single-core singlemode fiber transmission, both for long-haul or short reach optical networks [1], [2]. Even with uncoupled transmission, intercore crosstalk (XT) imposes performance limitation in such networks that must be dealt with. There are many works studying XT in MCFs; however, most of these works consider that the different cores inside the MCF have the same losses [3]. Actual available uncoupled MCFs exhibit imbalance between their core losses, i.e., core-dependent loss (CDL), due to manufacturing variation [4]. The influence of CDL on XT has been studied analytically in [3] and it was concluded that the XT between cores is practically independent of CDL. However, the previous analysis has been performed assuming unsegmented MCFs, when it is known that, in long-haul terrestrial transmission links, each link consists of multiple concatenated fiber segments (typically with length of ~2 km) [5]. Each MCF segment can exhibit random CDL typically with low magnitude; but the concatenation of several MCF segments with random CDL can enhance the total CDL at the MCF link output and the effect of the total CDL on the intercore XT is still to be quantified.

In this work, we numerically study and discuss the effect and performance limitations induced by CDL on the intercore XT at the output of a link composed by several concatenated MCF segments with random CDL.

2. NUMERICAL MODEL

In this section, the numerical model developed to study the limitations induced by random CDL on the XT considering the concatenation of several segments of MCF is presented.

In Fig. 1, the equivalent model of N concatenated segments of a link with a total length of L_{tot} is shown. Each MCF segment with length L_i (with $i = 1,\ldots, N$) has two cores denoted as core 1 and core 2. At the MCF input, there is power launched only in core 1, with average denoted as P_{in}. At the end of the N MCF segments, to perform our analysis, the average powers P_{sig}, P_{for} and P_{rec} are obtained at the output of core 1, while the power P_c is obtained at the output of core 2 and represents the average power coupled to core 2 induced by the signal launched in core 1. The forward power P_{for} is directly obtained at the output of core 1 and has two contributions, the signal power P_{sig} that results only from the power launched in core 1, and the recoupled power, which comes from the coupled power in core 2 that is again recoupled to core 1 and is obtained from $P_{rec} = P_{for} - P_{sig}$ [7].

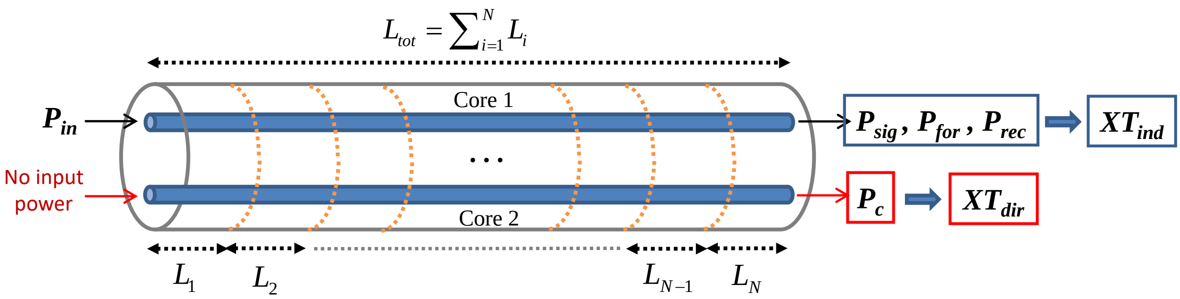

Figure 1. Equivalent model of a link with N concatenated MCF segments with two cores.

The direct crosstalk power XT_{dir} at the output of core 2 for N concatenated MCF segments and the indirect XT power XT_{ind} at the output of core 1 (from core 1 to core 2 via core 2) are given, respectively, by [7]

$$XT_{dir} = P_c\left(L_{tot}\right)/P_{sig}\left(L_{tot}\right) \quad \text{and} \quad XT_{ind} = P_{rec}\left(L_{tot}\right)/P_{sig}\left(L_{tot}\right) \tag{1}$$

Notice that the definition used for the direct XT level is directly related with the optical signal-to-noise ratio penalty induced by XT [6]. The power at the output of N concatenated MCF segments ($z = L_{tot}$) is obtained from the power at the MCF input ($z = 0$) using [3]

$$\begin{bmatrix} P_{for}\left(z = L_{tot}\right) \\ P_c\left(z = L_{tot}\right) \end{bmatrix} = \mathbf{T_N T_{N-1}} \cdots \mathbf{T_2 T_1} \begin{bmatrix} P_{in} \\ 0 \end{bmatrix} \tag{2}$$

Each matrix $\mathbf{T_i}$ (with $i = 1,\ldots, N$) describes the power coupling between the two cores within segment i and is given by [3]

$$\mathbf{T_i} = \exp\left[-\left(\bar{\alpha} + h\right) L_i\right] \cdot \begin{bmatrix} \cosh\left(\eta_i L_i\right) - \delta_{\alpha,i} L_i \cdot \dfrac{\sinh\left(\eta_i L_i\right)}{\eta_i L_i} & h L_i \dfrac{\sinh\left(\eta_i L_i\right)}{\eta_i L_i} \\ h L_i \dfrac{\sinh\left(\eta_i L_i\right)}{\eta_i L_i} & \cosh\left(\eta_i L_i\right) + \delta_{\alpha,i} L_i \cdot \dfrac{\sinh\left(\eta_i L_i\right)}{\eta_i L_i} \end{bmatrix} \tag{3}$$

where $\bar{\alpha}$ is the average of the attenuation coefficients of cores 1 and 2, h is the power coupling coefficient between the cores (where we assume that $h_{12} \approx h_{21} = h$, which is verified in the practical range of CDL [3], and that h does not vary from segment to segment) and η_i is given by

$$\eta_i = \sqrt{h^2 + \delta_{\alpha,i}^2} \tag{4}$$

The CDL within each segment i is characterized by the loss coefficient imbalance $\delta_{\alpha,i}$, which is assumed as a r.v., since concatenated MCFs can come from different lots and exhibit an arbitrary CDL. In this work, we randomly generate $\delta_{\alpha,i}$ assuming a uniform distribution between $[-\delta_{\alpha,max}, \delta_{\alpha,max}]$, where $\delta_{\alpha,max}$ represents the maximum variation of the core loss imbalance that is considered. CDL ranges of [–0.02, 0.02] dB/km have been reported [4], and it is very unlikely that this range exceeds 0.1 dB [3]. Hence, within each i-th MCF segment, the attenuation coefficients in cores 1 and 2 vary between $\bar{\alpha} - \delta_{\alpha,i}$ and $\bar{\alpha} + \delta_{\alpha,i}$, respectively. The signal power P_{sig} is obtained at the output of core 1 from (2), considering that the power coupling between the two cores within each segment is null (by setting the elements outside the main diagonal of (3) to zero).

By assuming $hz << 1$, $(\delta_{\alpha,i} z)^4 << 1$ and $(h z)^4 << 1$, (3) can be approximated by [3]

$$\mathbf{T_i} \approx \exp\left[-\bar{\alpha} L_i\right] \cdot \begin{bmatrix} \exp\left(-\delta_{\alpha,i} L_i\right) & h L_i \\ h L_i & \exp\left(\delta_{\alpha,i} L_i\right) \end{bmatrix} \tag{5}$$

3. NUMERICAL RESULTS AND DISCUSSION

In this section, the effect induced by CDL on the XT at the output of several concatenated MCF segments are assessed, considering constant (section 3.1) and random (section 3.2) CDL along the link.

3.1 With constant CDL along the link

Firstly, we assess the accuracy of obtaining the coupled power P_c using eq. (5) in comparison with eq. (3), in the case of concatenated equal length MCF segments. For this study, we simply set $\delta_{\alpha,i} = \delta_{\alpha,max}$ in all MCF segments, to achieve constant CDL along the overall MCF link. Fig. 2 shows the coupled power P_c, in dBm, as a function of the number of concatenated segments N, for $L_{tot} = 100$ km, $P_{in} = 1$ mW, $\bar{\alpha} = 0.25$ dB/km and $\delta_{\alpha,max} = 0.1$, 0.04 and 0.01 dB/km. Figs. 2 a), b and c) refer, respectively, to $h = 10^{-8}$, 10^{-7} and 10^{-6} m^{-1}, which correspond to a direct crosstalk XT_{dir} at the output of core 2 after 100 km of –30, –20 and –10 dB. The number of segments is varied from 1 (a unique 100 km segment) to 200 (segments of 0.5 km).

From Fig. 2, eq. (5) provides good estimates of the coupled power for $N > 10$ (segment lengths of about 10 km). Only, for high coupling between the two MCF cores ($h = 10^{-6}$ m^{-1}), discrepancies of 0.434 dB between the estimates of eqs. (3) and (5) are observed for a very high number of segments, for all values of $\delta_{\alpha,max}$ considered. These discrepancies in the coupled power estimation can be corrected by considering a multiplying term $\exp(-hz)$ in eq. (5), which it has been neglected in its derivation [3]. For a low number of segments, the accuracy of the estimates given by eq. (5) is reduced and reaches differences of about 4.7 dB for $N = 1$ (a unique segment of 100 km), when $\delta_{\alpha,max} = 0.1$ dB/km This means that eq. (5) is not suitable to estimate the coupled power in long MCF segments, such as the ones that can be found in submarine systems, where the fiber spans have very few splices [4]. Fig. 2 shows also that the $\delta_{\alpha,max}$ variation does not have much influence on eq. (5) accuracy.

3.2 With random CDL along the link

An unlikely $\bar{\alpha} = 0.25$ dB/km and $\delta_{\alpha,max} = 0.1$ dB/km have been considered in the previous results, to provide a conservative view of eqs. (3) and (5) estimations. From now on, a more realistic average attenuation coefficient and core imbalance, $\overline{\alpha}$ = 0.19 dB/km and $\delta_{\alpha,max}$ = 0.04 dB/km are considered, which correspond to the attenuation coefficient range inside one MCF segment of [0.15, 0.23] dB/km. Furthermore, all subsequent results are obtained with eq. (3), and assume N = 50 segments with equal length, L_i = 2 km.

Next, we study the effect of CDL when the concatenated MCF segments are taken from arbitrary lots, by generating, for each realization of N MCF segments, N loss coefficient imbalances $\delta_{\alpha,i}$ using a uniform distribution.

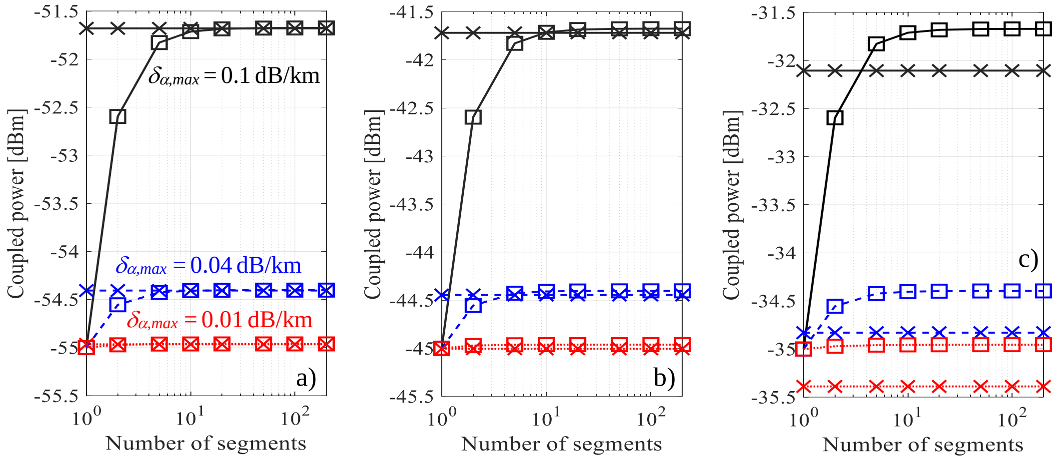

Figure 2. Coupled power as a function of the number of MCF concatenated segments, for $\delta_{\alpha,max}$ = 0.1, 0.04 and 0.01 dB/km *calculated using (3) (crosses) and (5) (squares) and* a) $h = 10^{-8}$ m^{-1}, b) $h = 10^{-7}$ m^{-1}, c) $h = 10^{-6}$ m^{-1}.

Fig. 3 shows the a) forward, signal, b) coupled and c) recoupled powers for 50 realizations of N = 50 concatenated MCF segments, for $h = 10^{-6}$ m^{-1}, $\delta_{\alpha,max}$ = 0.04 dB/km and $\overline{\alpha}$ = 0.19 dB/km. Fig. 3 a) shows that there are no perceptible differences between the forward and signal powers, even for strong coupling between cores, $h = 10^{-6}$ m^{-1}, but there is recoupled power (Fig. 3 c)) in core 1, which is more than two orders of magnitude (< 20 dB) below the forward power. There are some realizations of MCF segments that exhibit a fluctuation of the forward power (in relation to the absence of CDL, $\delta_{\alpha,max}$ = 0) of about 1 dB (see, for example, realization #16). These power fluctuations are translated to the recoupled power, although their magnitude is reduced (< 0.5 dB). The coupled power (Fig. 3 b)) also exhibits fluctuations (with respect to the absence of CDL) that can reach 0.55 dB (see realization #29). Fig. 3 d) and e) show that the fluctuations of the direct and indirect XT powers with the MCF segments arrangement can reach a maximum of, respectively, 1.2 dB (realization #16) and 0.8 dB (#40) in relation to the absence of CDL. These realizations correspond to the two lowest values of signal power found in Fig. 3 a). Fig. 3 shows that the impact of CDL on the MCF forward, signal, coupled, recoupled, direct XT and indirect XT powers is much dependent on the N MCF segments arrangement and can be significant (inducing signal and XT power variations that can reach ~1 dB) for specific MCF arrangements. Similar forward, signal, coupled and recoupled, direct XT and indirect XT powers variations have been obtained for lower values of h and $\delta_{\alpha,max}$, but with lower magnitude.

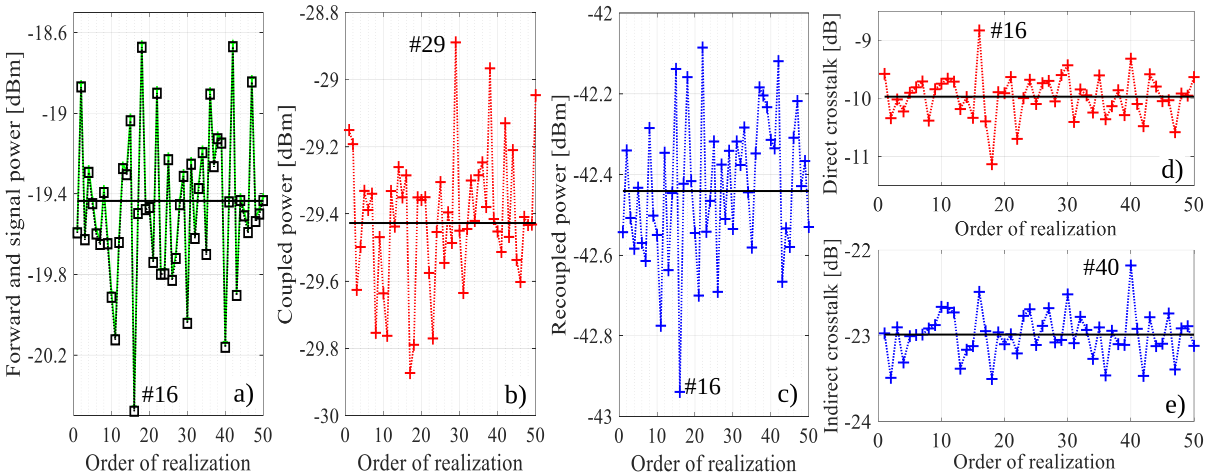

Figure 3. a) Forward (green), signal (black), b) coupled, c) recoupled powers, d) direct XT power and e) indirect XT power as a function of the realization of the MCF segments, for N = 50, $h = 10^{-6}$ m^{-1}, $\delta_{\alpha,max}$ = 0.04 dB/km *and* $\overline{\alpha}$ = 0.19 dB/km. *The results obtained with* $\delta_{\alpha,max}$ = 0 *(solid lines) are also depicted.*

Fig. 4 shows the probability density functions (PDFs) of the forward, signal, coupled and recoupled powers, for $N = 50$, $h = 10^{-6}$ m^{-1}, $\delta_{\alpha,max} = 0.04$ dB/km and $\overline{\alpha} = 0.19$ dB/km, and the corresponding means and standard deviations. Each PDF has been obtained with 10^6 realizations of N MCF segments arrangements. All PDFs obtained are nearly Gaussian distributions. In fact, for all values of h, $\delta_{\alpha,max}$ and $\overline{\alpha}$ tested, we have observed that the PDFs become more Gaussian with the N increase (central limit theorem (CLT)), and for N above roughly 10, we have concluded that the PDFs are well-described by a Gaussian distribution. We have also obtained the PDFs by generating the loss coefficient imbalances $\delta_{\alpha,i}$ with the triangular and arccosine distributions and have concluded that the $\delta_{\alpha,i}$ distribution does not particularly affect the conclusions regarding the PDFs gaussianity. If the powers at the MCF output are obtained in dBm, the corresponding PDFs will also be Gaussian, since the CLT is also fulfilled in a log scale. We have also concluded that the mean of the PDFs is practically independent of $\delta_{\alpha,max}$ for all values considered. The standard deviation of the PDFs grows with the increase of h, as there is a stronger power coupling between the cores and with the increase of $\delta_{\alpha,max}$, as expected.

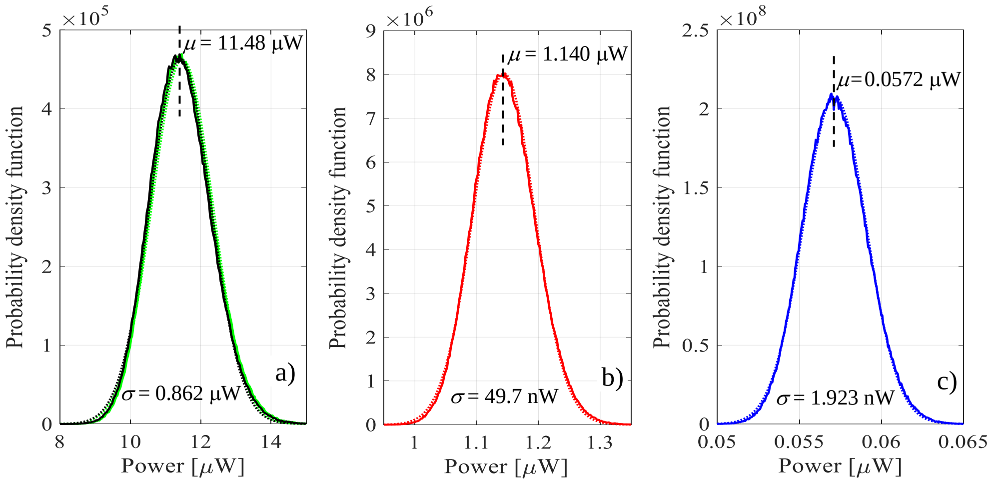

Figure 4. Probability density functions (solid lines) of the forward (green), signal (black), coupled and recoupled powers, for $N = 50$, $h = 10^{-6}$ m^{-1}, $\delta_{\alpha,max} = 0.04$ dB/km *and* $\overline{\alpha} = 0.19$ dB/km. *The Gaussian distributions (dotted lines) calculated with the mean* μ *and standard deviation* σ *estimated numerically are also depicted.*

4. CONCLUSIONS

In this work, we have studied the effect induced by CDL on the forward, signal, coupled, recoupled, direct XT and indirect XT powers of an optical link supported by MCFs, when the link is composed by a high number of concatenated MCF segments with random CDL within each MCF segment. We have concluded that, for a 100 km link length and specific arrangements of MCF segments with arbitrary CDL, the output forward, signal, and coupled powers may increase around 1 dB (with respect to the absence of CDL), while the recoupled power variation is lower. These power variations with the CDL are transferred to the direct and indirect XT powers, which may also increase around 1 dB. We have also seen that, with CDL, the PDFs of the power at the output of the concatenated MCF segments follow a Gaussian distribution, when the number of segments is sufficiently high.

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