Outage Probability Due to Intercore Crosstalk in Weakly-Coupled MCF Systems with OOK Signaling

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Abstract: The outage induced by intercore-crosstalk in multicore-fiber systems employing on-off-keying signaling is theoretically and experimentally characterized. It is shown that a crosstalk level below −16 dB is required to obtain an outage probability below 10^{-4}.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2330) Fiber optics communications

1. Introduction

Weakly-coupled homogeneous multicore fibers (MCFs) have been identified as a solution to increase the capacity of short-reach and long-haul networks [1,2]. These fibers present similar core properties and high potential to support spatial super channels with shared transmitter hardware and digital signal processing. However, data transmission along weakly-coupled homogeneous MCFs may be impaired by the intercore crosstalk (ICXT), which becomes more relevant as MCFs with higher core count and shorter core-to-core distance are used [3]. Previous works have shown that the ICXT power changes randomly over time and frequency [4-7] and that direct detection MCF systems using carrier supported signals, as on-off keying (OOK), are particularly impaired by ICXT power fluctuations [7]. Recently, the experimental transmission of 56 Gbaud 4-pulse amplitude modulation over a short-reach 7-core weakly-coupled MCF has shown that the dynamic behavior of the ICXT induces instantaneous bit error ratio (BER) levels that may substantially differ from the mean BER, leading to performance fluctuations over time [8]. This is far more relevant as high ICXT power levels are observed over several minutes or even hours [4,5,9] leading to service shutdown or outage over large time periods. In this work, the outage induced by the ICXT in weakly-coupled MCF-based systems employing OOK and low skew between cores is modeled analytically and validated experimentally. With this model, the maximum ICXT power and, thus, some of the MCF features required to guarantee a given service availability in conventional short-reach OOK systems can be easily inferred.

2. Theory

We assume an optically pre-amplified direct-detection receiver and consider the discrete changes model presented in [5,10] to characterize the ICXT in the MCF. 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 ζ_c controls the signal power distribution between the polarization directions (with c referring to the test core n or the interfering core m). If bit '1' or '0' is transmitted in core c, then $a_{c,1}=\sqrt{2\overline{p}_c/(1+r)}$ and $a_{c,0}=\sqrt{r}\cdot a_{c,1}$, respectively, where $\overline{p}_c$ is the average power of the signal at the input of core c and r is the extinction ratio between the average powers corresponding to bits '0' and '1'. Neglecting the ICXT-ICXT and the ICXT-amplified spontaneous emission (ASE) beatings, the electrical current due to ICXT after photodetection in core n is approximated by Eq. (1), where Re{z} is 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 transmitted signal at the MCF output in b direction of core n, with $b \in \{x,y\}$. For skew between cores much smaller than the symbol period and negligible dispersion in core m, the ICXT electrical field at the MCF output in the b direction of core n, $E_{n,b}(t)$, is given by Eq. (2), where $\overline{K}_{nm}$ is the average discrete coupling coefficient, N_p is the number of phase-matching points (PMPs), and $\phi_k^{(b,d)}$, with $b,d \in \{x,y\}$, is the k-th random phase shift associated with the k-th PMP [10]. For equal powers at the output of cores n and m and cores with the same losses, the ratio between the mean ICXT and signal powers at the output of core n, i. e., the mean ICXT level, is $X_c = N_p\left|\overline{K}_{nm}\right|^2$ [10].

By neglecting the intersymbol interference induced by filtering and dispersion effects on the transmitted signal,

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

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

$$P_b=1/2\cdot Q\left[\left(a_{n,1}-i_L+i_{ICXT}^{(1)}\right)/\sigma_1\right]+1/2\cdot Q\left[\left(i_L-a_{n,0}-i_{ICXT}^{(0)}\right)/\sigma_0\right] \quad \mathbf{(3)}$$

$$P_b\approx 1/2\cdot Q\left[\left(a_{n,1}-i_L+i_{ICXT}^{(1)}\right)/\sigma_1\right] \quad \mathbf{(4)}$$

the BER conditioned to ICXT is given by Eq. (3), where $Q(x)=1/\sqrt{2\pi}\int_x^{\infty}\exp\left(-\lambda^2/2\right)d\lambda$, i_L is the decision threshold, σ_1 and σ_0 are the noise standard deviations at the decision circuit input, and $i_{ICXT}^{(1)}$ and $i_{ICXT}^{(0)}$ are given by Eq. (1), when the bit transmitted in core *n* is '1' or '0', respectively. Taking into account that bits '1' in core *n* have a major role to the BER degradation due to ICXT, Eq. (3) can be simplified to Eq. (4). As $i_{ICXT}^{(1)}$ is higher when bits '1' occur in core *m* and smaller for bits '0', the main BER contribution results from the ICXT generated by bits '1'.
The outage probability, P_{out}, is the probability of the system becoming unavailable [11], i. e., the probability of the BER becoming above a BER limit, P_{lim}. From Eq. (4), for a pre-defined BER in the absence of ICXT, $P_{b,NICXT}$, and choosing adequately the decision threshold, the outage probability for directly-detected OOK systems impaired by the ICXT can be approximately written as

$$P_{out}=\Pr\left\{P_b\geq P_{lim}\right\}\approx Q\left(\frac{1}{W}\cdot\left[1-\frac{Q^{-1}\left(4P_{lim}\right)}{Q^{-1}\left(P_{b,NICXT}\right)}\right]\right)\quad\text{with}\quad W=\sqrt{X_c}\Big/2\left[4-\left(1+\sqrt{r}\right)^2\right]\Big/\left(1-r\right)\qquad\textbf{(5)}$$

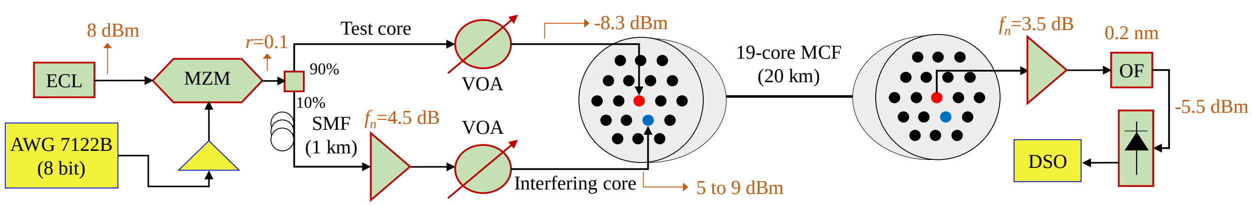
which is independent of the signal power distribution between polarization directions in the two cores.
From (5), the outage probability is the complementary cumulative distribution function (CCDF) of the BER. Hence, a theoretical estimate of the probability density function (PDF) of the BER can be obtained numerically by differentiating 1−CCDF with respect to P_{lim}, with the CCDF given by Eq. (5).

3. Experimental Setup

The setup employed to investigate the impact of the ICXT on the performance of the OOK signal is depicted in Fig. 1. An external cavity laser (ECL) with 100 kHz linewidth and a Mach-Zehnder modulator (MZM) are employed for the generation of an optical OOK signal with extinction ratio of 0.1. The OOK waveform, generated by an arbitrary waveform generator at 20 Gsamples/s, comprises 2^{14} bits with bit duration of 6 ns. The OOK signal is then amplified and applied to the MZM arm. After the MZM, the modulated signal is split in order to get the two signals to be launched into the test and interfering cores. Decorrelation between these two signals is attained by using a spool of 1 km-long single mode fiber (time delay close to 5 μs) prior to the interfering core. The power launched into the test and interfering cores is adjusted with an optical amplifier and optical attenuators. The power injected into the interfering core is higher than the power injected into the test core in order to increase the ICXT power and assure that the system performance is impaired by ICXT. The MCF is a 20 km-long weakly-coupled homogeneous 19-core fiber whose main features are shown in Fig. 1. The skew between the two cores is 0.4 ns, which is much shorter than the bit duration. The decorrelation bandwidth and the decorrelation time of the ICXT of the pair of cores under analysis is 2.5 GHz and a couple of minutes, respectively [5,6]. At the MCF output, the OOK signal impaired by the ICXT is amplified to increase the power injected in the photodetector, filtered to remove noise, and photodetected. A real-time oscilloscope operating at 20 Gsamples/s is used to capture the OOK signal. The OOK is then digitally filtered by a 4th-order Bessel low-pass filter with bandwidth of 80% of the bit-rate. The BER of the received OOK signal, evaluated from the 2^{14} bits, is monitored at each 55 seconds.

4. Experimental and Analytical Results

Fig. 2(a) depicts the evolution of the BER of the OOK signal measured experimentally over a 90-hour period for a mean ICXT level of −11 dB. Significant BER fluctuations over time of more than two orders of magnitude induced by the random time nature of the ICXT are observed [5]. The eye diagrams of the OOK signal obtained in the absence of ICXT and with high ICXT power are presented as insets of Fig. 2(a). In the case of high ICXT power, the eye diagram shows two distinct amplitude levels in bit "1". This occurs mainly for two reasons: (i) the ICXT can be



MCF features			
Cladding diameter	180 μm	Loss (incl. fans)	Between 14-18 dB
Core diameter	≈9 μm	Dispersion param.	≈20 ps/nm/km
Core pitch	32 μm	Skew	0.4 ns

AWG	Arbitrary waveform generator	OF	Optical filter
ECL	External cavity laser	SMF	Single mode fiber
DSO	Digital storage oscilloscope	VOA	Variable optical attenuator

Fig. 1. Experimental setup used for monitoring the performance of the OOK signal in the presence of ICXT.

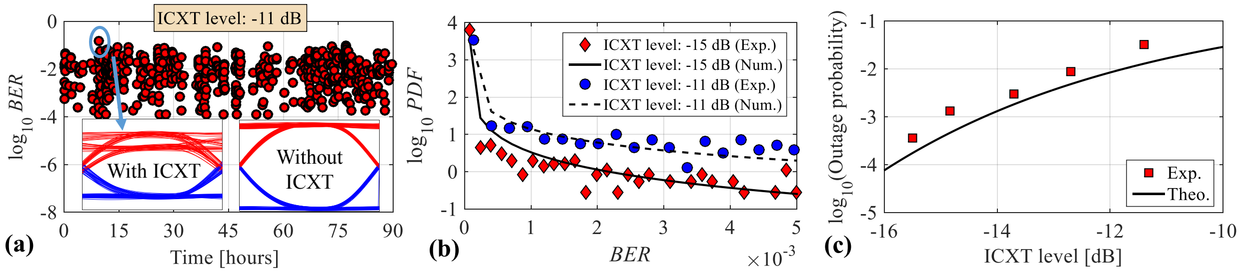


Fig. 2. (a) Time evolution of the BER of the OOK signal over a 90 hour period. (b) PDF of the BER for a mean ICXT level of −11 dB and −15 dB. (c) Outage probability of the OOK signal as a function of the mean ICXT level.

induced by bit "0" or bit "1" of the interfering core, and (ii) as the decorrelation bandwidth of the ICXT is much higher than the signal bandwidth, the strength of the ICXT mechanism does not vary along the bit duration. Therefore, in a time interval much smaller than the decorrelation time of the ICXT, we can understand the fluctuation of the amplitude observed in the test core as a result of the interference caused by these two interfering levels on the amplitude of bit "1" in the absence of ICXT. The lowest BER shown in Fig. 2(a) is close to 10^{-4} because this is the lowest nonzero BER achievable from 2^{14} bits in our experiment.

Fig. 2(b) depicts the PDF of the BER obtained numerically and experimentally, for the ICXT levels of −11 dB and −15 dB. The numerical PDF was evaluated considering a BER in the absence of ICXT of 10^{-10}. Fig. 2(b) shows that the PDF of the BER obtained numerically is in good agreement with the PDF estimated from experimental BER measurements. Fig. 2(b) shows also that the worse BER events occur sporadically while, in most of the time monitoring period, the BER is weakly affected by the ICXT. Nevertheless, the time intervals with remarkable BER degradation due to the ICXT are quite relevant for network operators, as they may lead to service interruption.

Fig. 2(c) shows the outage probability of the direct-detection OOK system in presence of ICXT. Theoretical results estimated from Eq. (5) and measured experimentally are presented. The outage is evaluated for a pre-forward error correction (FEC) BER limit of $10^{-1.8}$ (20.5% FEC). Fig. 2(c) shows that the outage probability caused by the ICXT in OOK systems is adequately estimated from Eq. (5) with an ICXT level discrepancy lower than 1 dB for low and moderate ICXT levels (<−12 dB). From Fig. 2(c) and for an outage probability of 10^{-4} required to ensure quality of service in fiber optic networks [11], the required mean ICXT level must be kept below −16 dB. Current MCFs present ICXT levels below −35 dB for lengths around 30 km [3,4]. This means that the capacity of weakly-coupled MCF-based short-reach OOK systems can still be further increased by developing MCFs with higher core count while keeping a safety ICXT margin to attain acceptable outage probabilities.

5. Conclusion

The outage of direct-detection systems employing OOK signals and weakly-coupled homogeneous MCFs has been modeled theoretically and assessed experimentally. The proposed expression for the outage probability is valid for MCFs with skew between cores shorter than the bit duration. Discrepancies below 1 dB between theoretical and experimental ICXT estimates required for a given outage probability have been observed. An outage probability of 10^{-4} is expected by using MCFs characterized by mean ICXT power levels close to −16 dB. Therefore, MCF-based short-reach OOK systems with higher core count can be designed while keeping the ICXT under a safety margin.

6. Acknowledgement

Fundação para a Ciência e Tecnologia from Portugal by funding this work under the AMEN-UID/EEA/50008/2013 and IF/01225/2015 projects.

7. References

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