Impact of Intercore Crosstalk on Achievable Information Rates

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***Abstract*—We investigate the impact of intercore crosstalk in a 7-core fiber on signal to noise ratio and achievable information rates for PDM-QPSK, PDM-16QAM, and PDM-64QAM formats. The achievable rate is reduced by 8%, 5.4% and 1.5%, at a crosstalk of -25.6dB/100km respectively**

Keywords—Multicore fiber, Cross-Talk, Information Rates

I. Introduction

Space-division-multiplexing (SDM) technologies have been widely proposed as a cost-effective solution to increase the transmission capacity in a single fiber by utilizing multiple cores or spatial-modes [1,2]. Single-mode multi-core fibers (MCFs) offer a migration path into SDM technology in the short term. Such fibers have been shown to support high spectral efficiency modulation formats without the complexity of high-order multiple input-multiple output (MIMO) based receivers [3] needed my multimode fibres. MCFs have been used in long-haul transmission, access, data-center and networking demonstrations.

MCFs with different core layout, core pitch, and cladding refractive index profiles and various strategies for reducing the crosstalk interaction and its impact have been investigated [4,5]. It was observed that a cross talk (XT) of less than -32.2dB/100km can reduce transmission distances by up to 40% [6]. Since XT can be engineered to any required level, here we investigate how it affects the achievable rate of MCF transmission. We transmit polarisation division multiplex (PDM) 4, 16, 64-ary quadrature amplitude modulation (QAM) signals with varying levels of XT over short and long haul distances and measure the signal to noise ratio (SNR). Information theory answers the question regarding the maximum amount of information that can be reliably transmitted over a communication channel [7]. In this work, an ideal coding scheme is assumed in order to investigate the effect of XT independent of coded modulation. The mutual information (MI) between the transmitted and received symbols represents the largest achievable information rate (AIR). For the ideal coding scheme, MI is correct AIR.

II. Experimental Setup

An experimental strategy was devised to emulate different XT values using the same fiber. The set-up is shown in Fig. 1, and was based on a recirculating transmission loop. The signal laser was a 100 kHz linewidth external cavity laser tuned to 1550.116 nm and modulated in a dual parallel Mach-Zehnder modulator (DP-IQ-Mod). The modulator was driven by four independent arbitrary waveform generators (AWGs). Each AWG had an analogue bandwidth of 14 GHz and used a sampling rate of 49 GS/s to generate pre-equalized PDM-4QAM, PDM-16QAM and PDM-64QAM signals at 24.5 GBd with a root-raised cosine pulse shape with a roll-off of 0.01. After modulation, an EDFA boosted the signal power before transmission over a 7-core MCF. Each recirculation of the loop used the centre core of the 53.7 km MCF span.

The loop contained two EDFAs and 30 GHz bandpass filter set by a wavelength selective switch (WSS) to limit ASE. Optical taps and variable optical attenuators (VOAs) were used to set and monitor the launch power into the interfering cores. Intercore XT (IC-XT) was emulated by using dummy channels generated from the loop output after each recirculation. The dummy channels were amplified and decorrelated with fiber patch cords before being re-injected into fiber. Taking the dummy channels from the inside the loop ensured that they had experienced transmission and noise degradation similar to the signal channels, emulating a real MCF link. The signal power was maintained and the launch power of the dummy channels varied to give a range of XT/span values of -45.7 dB to -21.2 dB, equivalent to -43.0 dB to -18.5 dB per 100 km.

Acousto-optic modulators (AOMs) were used to control the recirculation time and the receiver was triggered for the required distance. The receiver path from the loop output contained an EDFA, a polarization scrambler (PS) and a VOA for polarization and power control. Signal detection was performed in a polarization-diverse optical coherent receiver connected to a digital sampling oscilloscope with 31 GHz analog bandwidth operating at 80 GS/s. Offline processing was used to recover the signal, consisting of resampling to 2 samples per symbol, followed by normalization and dispersion compensation. Polarization de-multiplexing was performed using a MIMO structure whose equalizers were 33-tap filters

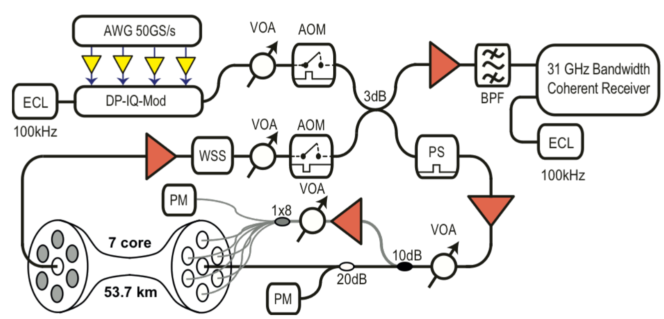

Fig. 1. Experimental Setup to emulate different intercore crosstalk levels

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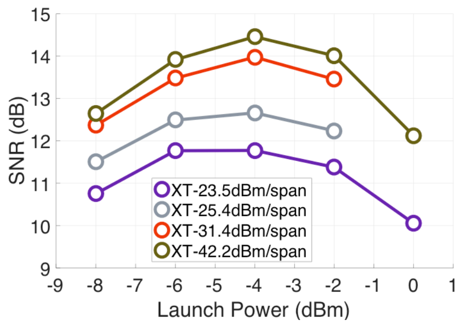

Fig. 2. Signal to noise ratio as a function of launch power at 2148 km for 16QAM signal with 4 different XT including the highest and lowest

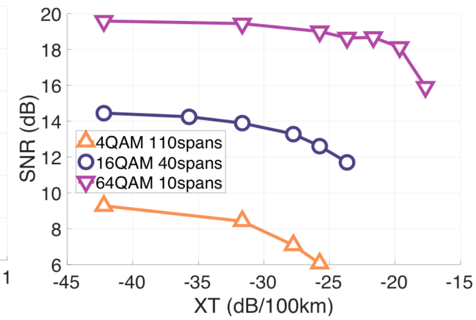

Fig. 4. SNR as a function of XT for 4QAM 16QAM and 64QAM at distances of 5907, 2148 and 537 km respectively.

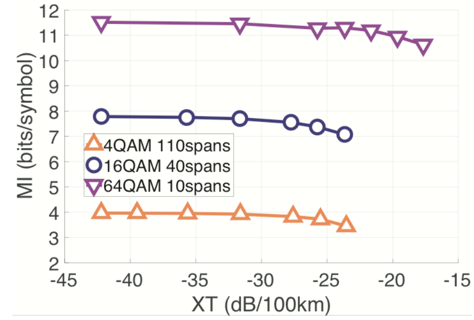

Fig. 3. MI as a function of XT for 4QAM 16QAM and 64QAM at distances of 5907, 2148 and 537 km respectively

updated using a decision-directed least-mean squares algorithm with carrier frequency offset and phase recovery performed in the equalizer loop. Then signal to noise ratio (SNR) measurements were calculated from the average of three traces, (each containing at least 250,000 symbols) using $\mathrm{SNR} = \frac{\mathbb{E}[|X|^2]}{\mathbb{E}[|Z|^2]}$ by assuming an additive white Gaussian channel $Y = X + Z$ with transmitted signal X, received signal Y and $Z \sim \mathcal{N}(0, \sigma^2)$. The MI was calculated per polarisation on the received symbols and then summed together [8].

III. Results

Fig. 2 shows the SNR of a single channel under test carrying PDM-16QAM at 40 spans as a function of launch power for 4 different XT values. At 2148 km the total accumulated XT for the maximum and minimum values of XT/100km -23.5 and -42.2 dB/span correspond to -7.48 and -26.18 dB respectively. As can be seen the higher the values of XT reduce the SNR in all parts of the curve. The optimum launch power was found to be -4 dBm for all XT levels. Changing from minimum to maxiumum XT results in a drop in SNR of 2.7dB at optimum launch power.

The SNR was then measured at optimum launch power for PDM-4QAM, PDM-16QAM and PDM-64QAM at 110, 40 and 10 spans respectively and is shown in Fig. 3. The back-to-back SNR for 4QAM, 16QAM and 64QAM was measured to be 23.7, 24.1 and 23.9dB respectively. The addition of XT again reduces the SNR in what seems like a very significant way for all tested modulation formats. The lower order modulation formats have their SNR reduce quicker as a function of XT/100km due to the greater transmission distances and associated accumulated XT.

In order to understand this in the context of throughput, the effect of XT on AIR is shown in Fig. 4. The back-to-back MI achieved for PDM-4QAM, PDM-16QAM and PDM-64QAM was 4, 8 and 11.98 bits/s/Hz respectively. At these distances (110, 40 and 10 spans) a XT level of -32.2dB/100km (corresponding to the same launch power in all cores [6]), the achievable rate drops by 1.4% for PDM-4QAM, 1% for PDM-16QAM and 0.2% for PDM-64QAM. If a loss of 7% in acheiable rate is permitted XT can be increased to -26, -25.2 and -19 dB/100km, for 4QAM, 16QAM and 64QAM respectively. When maximum reach is not a limiting factor in link design, additional XT can be allowed, leading to finer core pitch, which would accomodate more cores in a fixed fibre diameter. This results in more spatial channels to multiplex over giving higher throughput. For PDM-4QAM after a long haul distance of 5,907 km, a XT of -26.6dB/100km drops the achievable rate by 0.31 bits, a loss of only 7.8%. For PDM-16QAM at a distance of 2148km, the rate drops by 0.42 bits (5.4%) and for PDM-64QAM at drops by 0.17 bits only 1.5% after 537 km. The increasing loss of AIR with lower modulation formats is a result of the total accumulated XT being higher.

IV. Conclusion

By looking at the effect of XT in terms of achievable information rate the impact on throughput was determined. It is found that achievable rates are not strongly affected by XT. An inter-core crosstalk of -26.6 dB/100km leads to a transmission rate loss of less than 8%.

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