The Interplay of Modal Dispersion with Nonlinear Impairments on Mode Division Multiplexed Fibers

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***Abstract*—Space division multiplexed fibers represent a promising solution to the upcoming capacity crunch in single-mode fibers, but such fibers introduce new challenges due to the interactions among the propagating modes. In ideal optical fibers, birefringence does not exist, and thus in a multi-mode fiber, random birefringence leads to spatial mode dispersion among the different spatial modes. This paper investigates the impact of spatial mode dispersion on optical fiber transmissions focusing on its interaction with the nonlinear interference arising during the signal propagation. The obtained results show that modal dispersion can be beneficial in reducing the cross-phase modulation in various optical transmission scenarios.**

***Index Terms*—Cross-phase modulation, modal dispersion, mode division multiplexing, nonlinear interference, space-division multiplexing.**

I. Introduction

The demand for network traffic is increasing by 30% each year and is expected to grow even further as more people and devices are connected to the internet. For now, major optical networks are made up of single-mode fibers (SMF) and studies have shown that we are approaching the capacity crunch [1] [2] of SMF resulting from non-linear Kerr effects, and as such, new technologies are imperative to meet these increasing demands.

Space division multiplexing (SDM) seems like a viable solution to combat the upcoming capacity crunch in SMF fibers in form of multi-core, multimode fibers or fibers installed as bundles. Even-though SDM proves to be able to theoretically increase the capacity, its throughput will still be influenced by the non-linear Kerr effects. While some effects like mode dispersion which exist in SMF as polarization mode dispersion can be neglected, the same cannot be true in SDM fibers, especially in mode division multiplexed fibers (MDM) fiber systems, and hence their interplay with optical fiber transmission system must be analyzed. Studies [3] have shown that we can take the advantage of linear effects like strong coupling resulting from introduced perturbation together with mode dispersion to reduce the effects of nonlinear impairments in MDM fibers.

This study aims to investigate the benefits that can be accrued in combating nonlinear impairments when high values mode dispersion are allowed on the MDM optical fiber links

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II. Theory

Modeling of SDM fibers becomes more complex in nonlinear regimes compared to SMF because of the several nonlinear coefficients involved in the coupled nonlinear Schroedinger equation. Several models have been developed to help analyze and predict the effects of nonlinear impairments on system performance. Gaussian noise model [4] initially developed for SMF was extended to include SDM systems in [5], unfortunately, the authors didn't include the effects of mode dispersion on it.

The authors in [6] developed a model to compute the effect of mode dispersion on cross-phase modulation (XPM) and as such, the variance of XPM for a two-channel scenario with ultra-long span length can be calculated as follows:

$$\lim_{L_s \to \infty} \sigma^2_{\text{xpm}} = \frac{2N+1}{2N}\Bigg((2N+1)\sigma^2_{\text{xpm,1}} + \frac{(2N-1)(\alpha + \frac{\Delta\omega^2\mu^2}{N})}{\alpha}\sigma^2_{\text{xpm,1}}\left(\alpha + \frac{\Delta\omega^2\mu^2}{N}\right)\Bigg). \tag{1}$$

where α is the attenuation coefficient, $\Delta\omega$ is the channel spacing, μ is the value of mode dispersion, N is the number of modes, and $\sigma^2_{\text{xpm,1}}$ is the varience of the scalar case given by:

$$\sigma^2_{\text{xpm,1}} = \frac{\gamma^2 \frac{P_{test}P^2_{int}}{R^3} L^2_{eff}(\frac{2}{3})^3}{\pi\beta_2 L_{eff,a}} \times \sum_{k=-\frac{Nch-1}{2}, k\neq 0}^{\frac{Nch-1}{2}} \Bigg(\text{asinh}(\pi\beta_2 L_{eff,a} B_{ch} \times [k\Delta\omega + \frac{B_{ch}}{2}]) + \text{asinh}(\pi\beta_2 L_{eff,a} B_{ch} \times [k\Delta\omega - \frac{B_{ch}}{2}])\Bigg) \times R.$$

L_{eff} is the effective length, B_{ch} is the channel bandwidth, R the symbol rate, P_{test} is the power of the channel under test, and P_{int} is the power of the interfering channel.

In [7], we analyzed the variance of XPM with polarization mode dispersion in a single-mode fiber case while in this study we extended our findings to the MDM scenario.

III. Simulation and Results

To analyze the effects of XPM with modal dispersion in MDM, we simulated different scenarios and made the following assumptions. The optical link was composed of lossless optical amplifiers with a gain of 20 dB and a noise figure of 6 dB. The link was dispersion uncompensated with full, and ideal GVD compensation before the receiver. Because of the analysis, we focused on an optical link with one span. Two channels, each with a symbol rate of 49 Gbd, were transmitted in the system at different spacings starting from 50 GHz. The digital signal used sinc pulses with Gaussian distributed complex symbols. We assumed that only inter-modal dispersion was in the play and that intra-modal dispersion between the channels did not exist as was by the authors in [6]. We further performed Split Step Fourier Method (SSFM) simulations to determine the model accuracy.

To simulate only the effects of XPM, we set the power of the channel under test to be 30 dB smaller than the interfering channel, such that self-phase modulation was absent of it. The interfering channel had a power of 0 dBm such that XPM was active only on the channel under test. Furthermore, we did not include amplified spontaneous emission since our objective was the interaction between mode dispersion with the Kerr effects. Different optical system parameters like dispersion, attenuation, span length, symbol rate, were varied to find out the response of quality of transmission, and test the model accuracy evaluated in estimating the variance of XPM. For

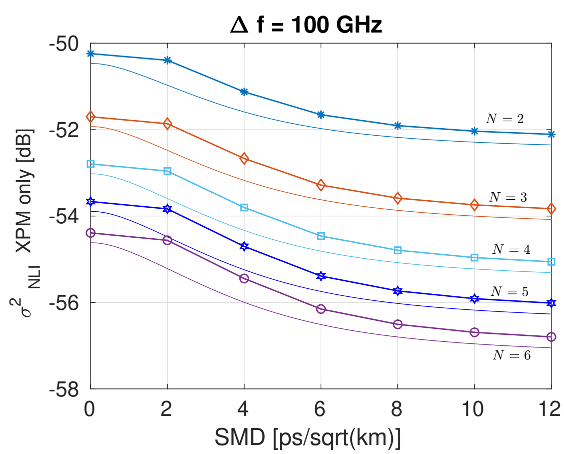

Fig. 1. XPM variance estimated with the GN model (symbols) and the SSFM (no symbols).

example, when N =2 at 0 SMD value, we observed a power normalized XPM variance of -50.2 dB, while when the modal dispersion was increased to 12 ps/sqrt(km), we observed an XPM variance of approximate -52 dB at the same value of N. If N was increased to 6, an XPM variance of -54.5 dB was recorded when the SMD value is 0. A further reduction by almost 3 dB was observed when the modal dispersion value was increased to 12 ps/sqrt(km). Such a result confirms that the variance of XPM reduces with an increasing number of modes because of the new non-linearity coefficient which is dependent on the number of modes as shown in [3]. A close similarity between the GN model and SSFM simulations for any value of N modes with only inter-channel SMD was observed. The discrepancy between the plots results from the approximation errors made in [4].

Figure 2 depicts the XPM variance in SDM for two different numbers of modes N . We observe a different strength of the SMD-modified XPM variance by varying N. For instance, at N=6 the XPM variance decreases by 2.7 dB at a symbol rate of 10 Gbd with respect to the no SMD case, while at N=2 the decrease is only 1.6 dB. By increasing the channel spacing to 1000 GHz, we observed an almost 1.2 dB difference between N=2 and N=6 at 30 ps/sqrt(km). This confirms our observation that the far away channels have a smaller impact on the XPM variance than in SMF. This observation may be useful in reducing the effort of a possible nonlinear mitigation algorithm when applied to a superchannel made of several channels.

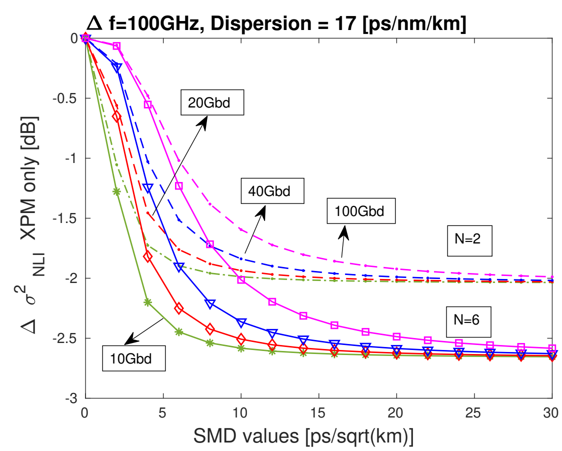

Fig. 2. Comparing the variance of XPM with mode dispersion when the symbol rate is varied. The dotted plots are when N=2.

IV. Conclusion

Space division multiplexing is a promising technology to replace capacity issues in single-mode fibers, but it comes with its challenges; complex modeling of non-linearities. We can use linear effects like modal dispersion when implemented with a variety of other optical system parameters to combat nonlinear Kerr effects especially XPM which is the dominant impairment at higher data rates.

Transmitting several modes on a multimode fiber reduces the impact of the nonlinear impairments on the signal-to-noise ratio, and therefore we can take the advantage of modal dispersion to meet the increasing demands at a better quality of transmission.

References

[1] P. Mitra and J. Stark ‘Nonlinear limits to the information capacity of optical fibre communications ’Letters to Nature, Vol 411, June 2001.

[2] A. Chralyvy, “The Coming Capacity Crunch”, Bell Labs, Alcatel-Lucent, USA-ECOC 2009, 20-24 September, 2009, Vienna, Austria.

[3] C. Antonelli, M. Shtaif, and A. Mecozzi, “Modeling of non-linear propagation in Space-Division Multiplexed fiber optic transmission,” J. Lightw. Technol., vol. 34, no. 1, pp.36–54, 2016
[4] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri, “The GN-Model of Fiber Non-Linear Propagation and its Applications,” J. Lightw. Technol., vol. 32, no. 4, pp. 694–721, 2014.
[5] G. Rademacher and K. Petermann, “Nonlinear Gaussian Noise Model for Multimode Fibers with Space-Division Multiplexing,” J. Lightw. Technol, vol. 34, no. 9, pp. 2280–2287, 2016.
[6] P. Serena, C.Lasagni, A. Bononi , C. Antonelli, and A. Mecozzi, ”A Model of the Nonlinear Interference in Space-Division Multiplexed Systems with Arbitrary Modal Dispersion”- ECOC 2021.
[7] R. Rading, ”Effects of Mode Dispersion on Cross-phase modulation on Mode Division Multiplexed Optical Fibers”- Presented at Junior Wireless and Optical Communications Conference, 2021.