Study and Optimization of core allocation in multi-core optical fibers

José Pedro Pile Mendes Pinto

Abstract— **Space-division multiplexing (SDM) is regarded as a promising solution for the capacity crunch looming just around the corner. The exponential growth of network traffic that has us gravitating towards this crunch has created the need for high-capacity optical systems, which is where homogeneous single-mode multi-core fibers (SM-MCF) step into the scene.**

A method for the estimation of crosstalk inside a MCF is introduced, along with several layouts that seek to minimize the inter-core crosstalk (XT) amongst the cores. A method for choosing the best layout for the cores on a given MCF is devised and three fibers differing only in cladding diameter ($C_d = 125, 260, 300\ \mu m$) are analysed.

Index Terms— Core allocation, inter-core crosstalk (XT), layout, multi-core fiber (MCF), space-division multiplexing (SDM).

I. INTRODUCTION

Network traffic demand has been growing unceasingly in recent decades, showing growth rates in-between 20% and 60% per year in this last decade [1]. Forecasts show this demand isn't likely to slow down the pace anytime soon, which is the result of a variety of factors.

The emergence of new technologies and applications, changing the rate at which we consume data, combined with the recent rise of machine-to-machine communications and the advent of the so called "Internet of Things", has caused demand to skyrocket to heights never before imagined by network engineers.

Despite technologies such as Dense Wavelength-Division Multiplexing (DWDM) and Coherent detection that allowed for a multiplicative increase of capacity in optical systems, engineers still struggle to cope with the exponential growth traffic demand is experimenting nowadays. Furthermore, current systems are quickly approaching the limit for the maximum amount of information that can be transmitted over a given channel [2], leading to the looming capacity crunch.

In order to overcome the capacity limits in the existing optical fiber communication infrastructure, increasing the spatial efficiency within the available fiber cross-section is the most effective solution. Multi-core fibers (MCFs), in the scope of space-division multiplexing (SDM), make up a promising solution to the aforementioned efficiency problem.

Performing SDM, with the use of uncoupled MCFs, consists of a simple and robust solution that doesn't require complex multiple-input multiple-output signal processing at the receiver side. The main issue and focus of this article is, however, being able to increase the number of cores inside the fiber while keeping the inter-core crosstalk (XT) low.

Different strategies have been employed to achieve this. The use of a trench, originally proposed to reduce the fiber bending loss in FTTH applications [3], has proven to be very effective for XT reduction in MCFs when applied to each core; making up the so called "trench-assisted" structures.

By making use of these trench-assisted structures, we will analyze the XT of different proposed core arrangements (layouts) in an attempt to minimize the crosstalk in the fiber. Finally, in a bid to maximize the fiber's capacity, we describe a method for spatially arranging identical cores inside a MCF using the layouts that were previously proposed.

II. BACKGROUND

A. Space Division Multiplexing

Data transmission, either through copper or fiber, makes use of electromagnetic waves, which are governed by Maxwell's equations in a classical context. These equations describe an electromagnetic field that can vary across five physical dimensions, which can be used for modulation and multiplexing, as shown in figure 1.

This article will focus on the spatial dimension, which is seen as a means to overcome the problem of capacity that optical transmission systems are currently facing. This dimension can be exploited by sending information over different parallel spatial paths and entails a wide variety of techniques across many communications segments, ranging from data buses on printed circuit boards to more complex multi-antenna techniques in cellular wireless systems.

In recent years, optical communications research has focused on fibers with multiple parallel cores within a common cladding (MCFs) as well as on "few-mode fibers", which support multiple independent spatial patterns of light (modes) across their core areas. A particular challenge with these systems, as well as with many other whether electrical or optical, is the presence of crosstalk among the parallel spatial paths. While in some applications this crosstalk can be dealt with interference cancellation and multiple-input-multiple-output digital signal processing techniques, this article will exploit low-crosstalk waveguide designs.

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José Pedro Mendes Pinto is a student of Electrical and Computer Engineering at Instituto Superior Técnico, University of Lisbon, 1049-001 Lisboa, Portugal (pedropile2009@hotmail.com).

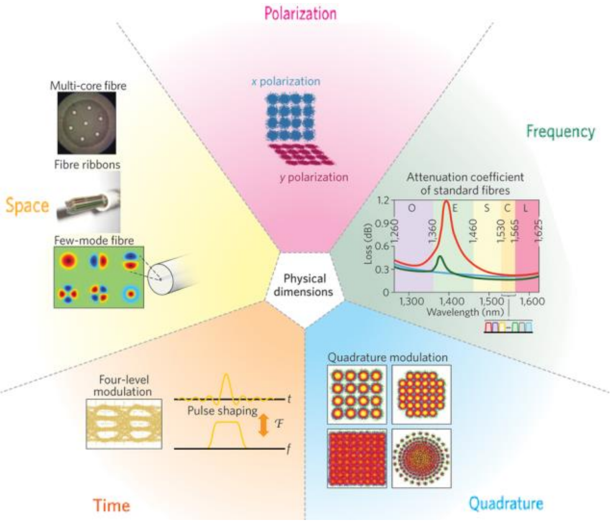

Fig. 1. Physical dimensions for modulation and multiplexing of electromagnetic waves [1]

B. Multi-Core Fibers

First manufactured by Furakawa Electric in 1979, MCFs consist of a structure enclosing multiple cores in a single cladding.

Presently a hot topic for its promising potential in improving the efficiency of SDM, MCFs can be classified into coupled-type and uncoupled-type fibers. Whereas coupled-type fibers consist of several cores placed in such a way that allows cores to couple with each other, uncoupled-type fibers require each core to be properly arranged inside the fiber to keep the inter-core crosstalk low and allow for long-distance transmission applications. These latter, considered in these article, have their main parameters illustrated in the seven core trench-assisted MCF depicted in figure 2.

It's relevant to mention that in order to minimize the micro-bending loss [4] the Outer Cladding Thickness (OCT) must not be any smaller than 30 µm. Also, a minimum distance of 3 µm between trench edges must be ensured as to safeguard any contact between trenches when the fiber bends [5].

C. Crosstalk Estimation

Crosstalk, by definition, is the disturbance of a signal by the electric or magnetic field of another adjacent telecommunications signal.

Considering the way in which cores are densely packed inside a single cladding of a MCF, it shouldn't come as a surprise that crosstalk management is crucial when dealing with coupling and the consequent degradation of transmitted signals.

For crosstalk to be properly dealt with, an accurate method for its estimation in MCFs is required. Two methods exist for doing so: Coupled-Mode Theory (CMT) and Coupled-Power Theory (CPT).

We use coupled-power theory, which is based on the principle of measuring the amount of power that the signal being transmitted in one core is transferring to its neighbouring core. Unlike CMT, CPT is able to provide a fast and accurate estimation of inter-core crosstalk in MCFs by averaging the bending and twisting effects along the fiber using a predetermined correlation length d_c [6].

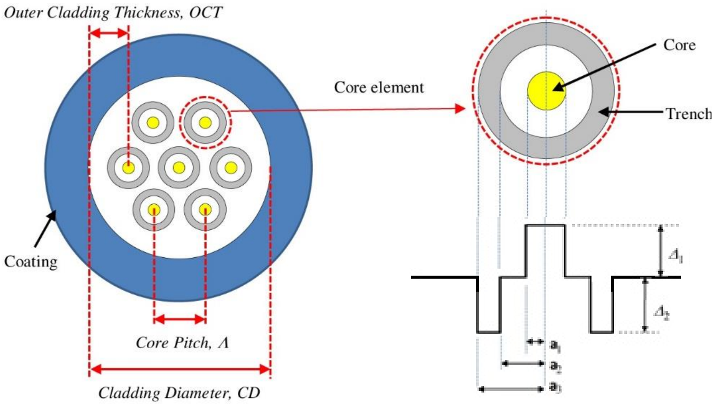

Fig. 2. Main parameters of a multi-core fiber

Using CPT we can, in those cases in which crosstalk is very small, determine the crosstalk between two cores within a fiber with length L using:

$$XT = \bar{h}_{mn}L \tag{1}$$

Furthermore, for a fiber with trench-assisted structures and without an infinitely large size of the first cladding and trench, we have knowledge of the mode coupling coefficient and by replacing it in (1) we obtain:

$$\mathrm{XT} = \frac{2k_{mn}^2 R_b}{\beta\Lambda}L \tag{2}$$

D. Crosstalk Constraints

In order to further increase transmission capacity, greater spectral efficiencies are sought by means of higher-level quadrature amplitude modulation (QAM) schemes. These modulations, along with the OSNR (Optical Signal-to-Noise Ratio) penalty they bring about, set some limitations for the maximum value of crosstalk allowed inside each core of a multi-core optical fiber.

Figure 3 illustrates the OSNR penalty as a function of the crosstalk, that represents the SNR per symbol required to achieve a bit error rate (BER) of 10^{-3} for two ideal square 4-, 16-, 64- and 256-QAM constellations with different interferers (the red and blue interferers are seen on the top left corner).

Two scenarios for an optical fiber link are conceived, alike in fiber length and different in the chosen modulation format, having different limits for the maximum amount of crosstalk tolerated in any core of the fiber.

First Scenario: Optical fiber link $1000\,km$ in length, QPSK modulation, $4\,dB$ OSNR penalty, $10\,dB$ $(20\,dB/100km)$ crosstalk tolerance.

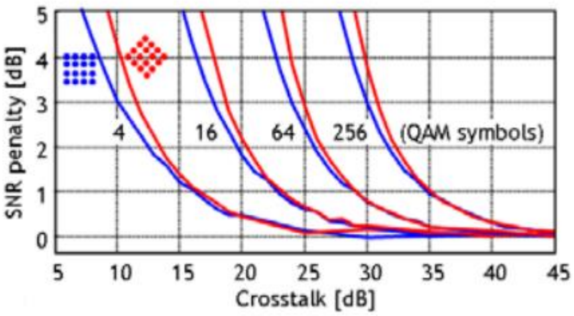

Fig. 3. Monte Carlo simulations of crosstalk penalties for ideal, square 4-, 16-, 64-, and 256-QAM [5]

Second Scenario: Optical fiber link $1000\,km$ in length, 256-QAM modulation, $4\,dB$ OSNR penalty, $30\,dB$ ($40\,dB/100km$) crosstalk tolerance.

Throughout this article the crosstalk is always expressed as $dB/100km$ and with a negative sign, hence the crosstalk tolerances of these two previously described optical links are, respectively, $-20\,dB/100km$ for the first and $-40\,dB/100km$ for the second scenario.

III. PROPOSED LAYOUTS

There are countless ways of organizing the cores inside a SM-MCF such as placing them in rings, hexagonally, or simply without any geometrical form at all. The proposed layouts will strive to balance the crosstalk across the cores, making it as low as possible while assuming a commercially viable geometrically symmetric structure. Given that the crosstalk is heavily influenced by the core pitch, maximizing the distance between neighbouring cores seemed the logical approach for when designing the layouts.

An illustration of the core structure in each layout, for an arbitrary number of cores, is provided in figure 4.

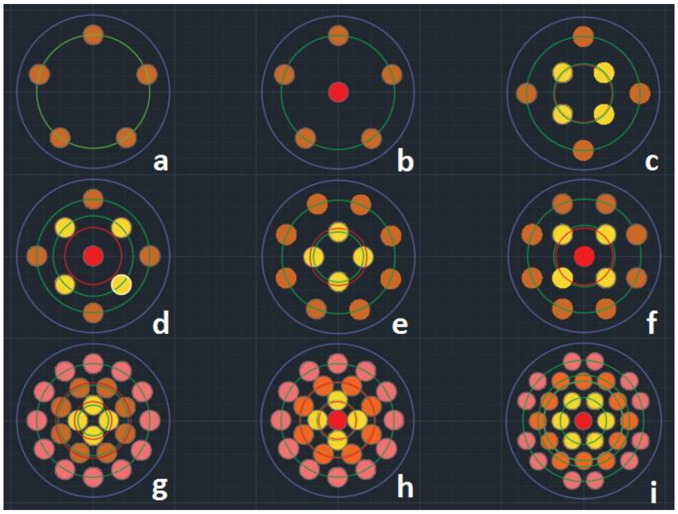

Fig. 4. Proposed Layouts; (a): One Ring, (b): One Ring with Central Core, (c): Two Rings, (d): Two Rings with Central Core, (e): Two Different Rings, (f): Two Different Rings with Central Core, (g): Three Different Rings, (h): Three Different Rings with Central Core, (i): Hexagonal Placement

From these nine proposed layouts, Two Different Rings with Central Core is particularly useful in minimizing the crosstalk in the MCF's to be analyzed in this paper. This being said, and in an attempt to provide some insights on how the layouts were created, a brief description on this layout's geometry is provided along with some notes regarding the crosstalk computation.

A. *Two Different Rings with Central Core*

This layout organizes its cores in two rings plus a central core, as seen in figure 5. It can be built with as few as seven cores and scaled up with the addition of three cores at a time; two on the outer ring and one on the inner ring. The inner ring, made up of half the cores of the outer ring, has its radius (r_2) adjusted as a function of the number of cores in the layout. This radius adjustment ensures that the distance between an inner core and its closest outer or central core is kept constant, thus bringing the crosstalk levels to a minimum.

When computing the crosstalk of any given core on these proposed layouts an approximation was often made, consisting of only taking into account the interference from those cores closest to the core in question. This approximation can be seen when computing, for example, the crosstalk of an inner core in which only its two closest inner cores, two closest outer cores and central core are considered (3).

$$XT_{Inner\ Core} = XT(r_2) + 2 \times XT(\Lambda_2) + 2 \times XT(\Lambda_x) \quad (3)$$

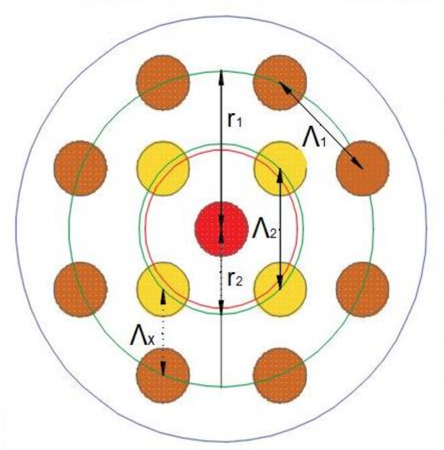

Fig. 5. Two Different Rings with Central Core (15 cores)

IV. NUMERICAL MODEL

A MatLab algorithm was used to determine and plot, for each proposed layout, the different crosstalk values as a function of the number of cores featured in it.

Figure 6 describes the use of this algorithm for the first proposed core arrangement, the "One Ring" layout. In this layout the number of initial cores is two and the way to add more cores is one at a time.

Firstly, the fiber parameters are introduced and some essential values for the crosstalk calculations are determined.

Then, for the smallest number of cores that the layout allows, the distances between different cores are computed along with the mode-coupling coefficient in order to obtain the crosstalk of each core in the layout. As more cores are added to the layout, the algorithm enters into a loop obtaining the crosstalk values for all these possible layout variations, before breaking when it's no longer possible to add more cores to the fiber due to its physical limitations. Lastly, these obtained crosstalk values are plotted as a function of the number of cores.

The accuracy of the developed algorithm was tested by comparing its results with those from a 2014 paper [7] on homogeneous TA-MCF. This comparison revealed discrepancies of less than 1 dB between the results, validating this numerical model.

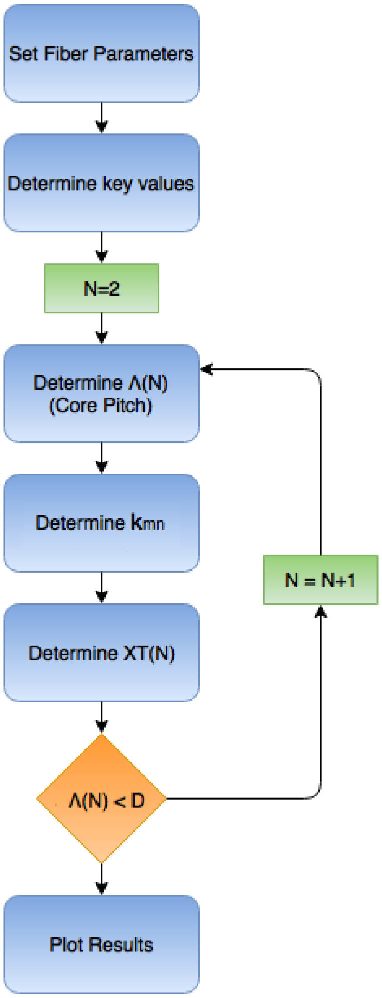

Fig. 6. Crosstalk estimation algorithm's block diagram

V. RESULTS

A. Problem Description

Space-division multiplexing, in the form of single-mode multi-core optical fibers, is regarded as a solution to overcome the capacity limits of current single-mode optical fibers.

Fibers containing multiple cores with reasonable values of crosstalk will achieve larger capacities than those with only one. This being said, a method to spatially set up the cores and minimize their crosstalk is sought.

State-of-the-art solutions for arranging the cores have been put forward, such as this year's article on high-spatial-multiplicity multi-core fibers [9] that makes use of a hexagonal structure to distribute thirty-one homogeneous trench-assisted cores inside a 230 μm fiber. This layout proposal for thirty-one cores is taken into consideration by the "Hexagonal Placement" layout in this article's attempts to maximize the number of cores in the fiber.

Table I illustrates the fiber parameters considered when testing the proposed layouts. Three fibers with different cladding diameters ($C_d = 125, 260, 300\ \mu m$) are analyzed.

TABLE I
STRUCTURAL PARAMETERS OF THE MULTI-CORE FIBER

Parameter	Value	Unit [SI]
C_d	125, 260, 300	$[\mu m]$
OCT	30	$[\mu m]$
L	100	$[km]$
a_1	4.5	$[\mu m]$
a_3/a_1	3	--
a_2/a_1	2	--
wtr/a_1	1	--
n_1	1.4551	--
Δ_1	0.35	%
Δ_2	0.35	%
λ	1550	$[nm]$
R_b	140	$[mm]$

B. Enhanced Solution

By analyzing the performance of every proposed layout, it is possible to determine which layout is most suited for placing a certain number of cores in a fiber. Three fibers will be analyzed and, for the crosstalk limits of the two scenarios defined in chapter II-D, attributed the most appropriate layouts.

1) 260 μm

The dots in figure 7 represent the best crosstalk results obtained for a given number of cores, where their color identifies the layout employed. It's of importance to recall that these dots stand for the crosstalk values of those cores performing worst (with the highest value of crosstalk) within the chosen layout.

When placing a given number of cores in a 260 μm fiber, figure 7 should be consulted regarding the choice of the layout.

For Scenario 1, with a -20 dB crosstalk tolerance, "Two Different Rings with Central Core" should be the chosen layout as with no other is it possible to fit as many cores (twenty-five) in the fiber (figure 8). In this layout, both Inner and Outer cores share -23 dB as the highest value of crosstalk in the structure.

For scenario 2, with a $-40\, dB$ crosstalk tolerance, “Two Rings with Central Core” should once more be the chosen layout; only this time featuring twenty-two cores (figure 9). The highest crosstalk value in this layout, -40 dB, is once again shared by the Inner and Outer cores.

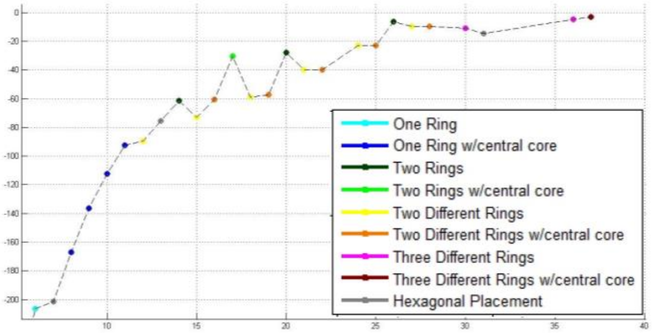

Fig. 7. Crosstalk vs Number of cores – Overview for C_d = 260 µm

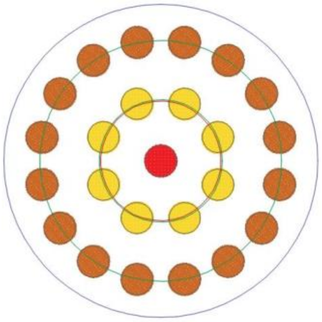

Fig. 8. Two Different Rings - 25 Cores – C_d = 260 µm (Scenario 1)

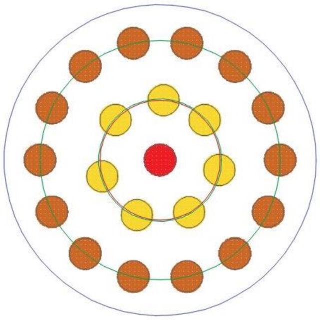

Fig. 9. Two Different Rings - 22 Cores – C_d = 260 µm (Scenario 2)

2) $300\, \mu m$

Choosing a fiber with a larger cladding diameter allows for more cores to be placed inside the fiber, which directly correlates with an increase in capacity. Figure 10, mapping the best crosstalk results obtained for a $300\, \mu m$ fiber, proves helpful in choosing the best core arrangements for the two scenarios defined in chapter II-D.

For scenario 1, with a -20 dB crosstalk tolerance, “Three Rings with Central Core” yields the best results (figure 11). By selecting this layout it’s possible to perfectly balance the crosstalk in all its thirty-seven cores, with no core ever exceeding -24dB of crosstalk.

For scenario 2, with a -40 dB crosstalk tolerance, “Two Rings with Central Core” should be the chosen layout (figure 12). This layout evenly balances the crosstalk in both rings (-47 dB) while leaving the central core with a considerably lower value.

3) $125\, \mu m$

For a fiber as small as this one, only two layouts are deemed relevant. Their crosstalk results are seen in figure 13 along with a dashed line reflecting their trend.

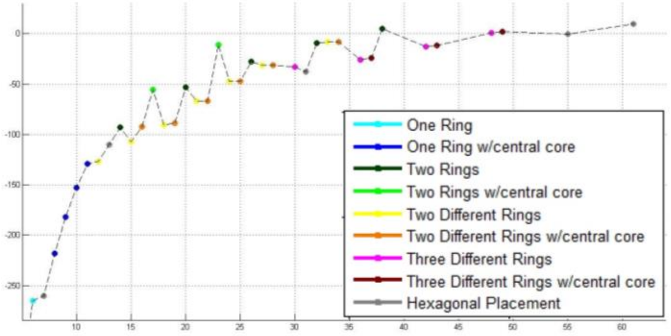

Fig. 10. Crosstalk vs Number of cores – Overview for C_d = 300 µm

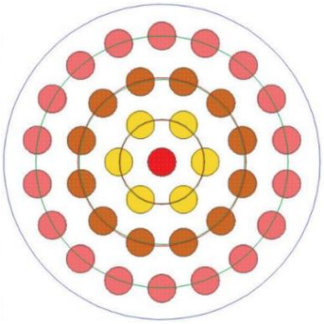

Fig. 11. Three Different Rings – 37 Cores – C_d = 300 µm (Scenario 1)

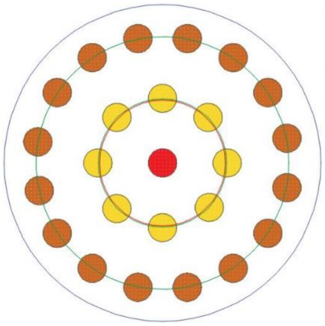

Fig. 12. Two Different Rings – 25 Cores - C_d =300 µm (Scenario 2)

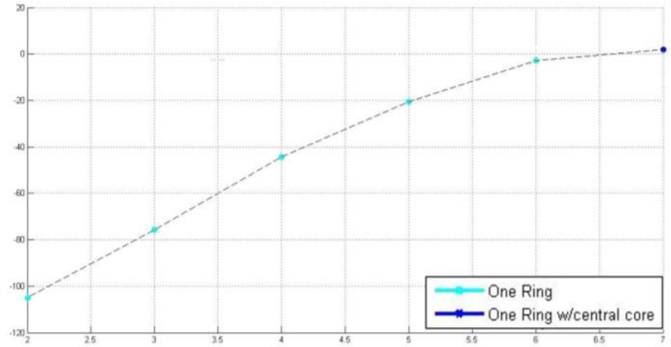

Fig. 13. Crosstalk vs Number of cores – Overview for C_d = 125 µm

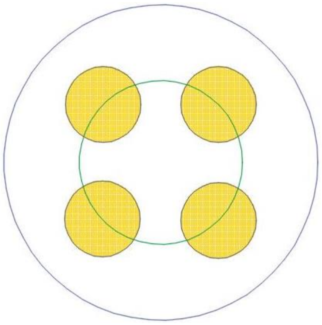

Fig. 14. One Ring - 4 Cores – C_d = 125 µm (Scenario 1)

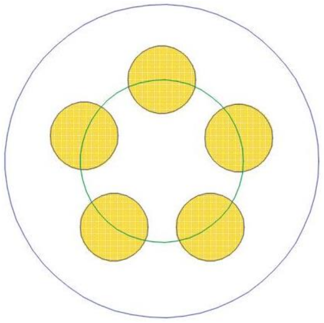

Fig. 15. One Ring - 5 Cores – C_d = 125 µm (Scenario 2)

For scenario 1, with a -20 dB crosstalk tolerance, “One Ring” layout should be the chosen layout (figure 14) to place five cores with -20.5 dB of crosstalk each.

For scenario 2, with a -40 dB crosstalk tolerance, “One Ring” should once again be the chosen layout (figure 15). This time, fitting only four cores, each one would have -44.5 dB of crosstalk.

VI. CONCLUSIONS AND FUTURE WORK

A method for maximizing the throughput of a SM-MCF was proposed, describing how to best spatially arrange the cores inside three different fibers ($C_d = 125, 260, 300\ \mu m$). For doing so, a crosstalk estimation algorithm was designed to study the crosstalk in the nine proposed layouts and, from this study, the best layouts for placing a given number of cores in the fiber were determined.

Two $1000\,km$ long optical fiber links using different modulations were given realistic crosstalk limits of -10dB and -30dB and, in accordance with these pre-established crosstalk limits, were attributed a layout for the spatial distribution of their cores. A different layout was attributed to each link for the three different fibers studied. For the fiber most intensively analyzed in this dissertation, the $260\ \mu m$ fiber, twenty-five cores could be placed in the fiber when using QPSK whereas only twenty-two when using 256-QAM; in both cases making use of the Two Rings with Central Core layout for distributing the cores. On the biggest fiber, $300\ \mu m$ in cladding diameter, 37 cores were able to fit inside using a QPSK modulation whereas only 25 using 256-QAM modulation. As for the smallest fiber, $125\ \mu m$ in cladding diameter, “One Ring” layout should always be the chosen layout for arranging the cores in either of the considered scenarios.

Comparing with state-of-the-art solutions for this problem of core allocation, namely the hexagonal placement of thirty-one cores [9] mentioned in chapter V-A, we conclude that the method for core allocation devised in this dissertation is functionally sound given its results are well-aligned with available cutting-edge solutions.

Concerning future work, the development of a crosstalk optimization algorithm for both heterogeneous and few-mode fibers would be an interesting prospect. Such an algorithm would take the layouts proposed in this article and determine which one best suits a given fiber with a specified cladding diameter.

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José Pedro Mendes Pinto was born in Lisbon, Portugal, in 1992. He received the B.S. degree of Graduate in Engineering Sciences – Electrical and Computer Engineering from Instituto Superior Técnico, Universidade de Lisboa, in 2014.