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Polarization Dependent Loss (PDL) in Polarization Multiplexed and Hybrid Optical Networks

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Problem Description

Study of the Polarization Dependent Loss caused by the combined effect of orthogonality degradation and dynamic power fluctuations in a hybrid network, which combines circuit switching with packet switching to transmit applications with very different quality requirements on the same wavelength channel.

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Supervisor: Dag Roar Hjelme, IET

A mis padres, J. Antonio y Felisa,
y a mi hermana, María, sin ellos
nunca hubiera llegado hasta aquí

ABSTRACT

In this research study the reduction of the eye area caused by the combined effect of orthogonality degradation and dynamic power fluctuations in an optical network that uses polarization multiplexing for QoS segregation. The main task is to compare traditional PolMUX to PolTDM.

With this aim we study, firstly, different configurations to see statistical difference between use one or more PDL elements. Secondly, we introduce the main simulation model with the different variants, with 3, 10 and 15 PDL elements. For all these cases we analyze PolTDM and PolMUX configurations.

After 10.000 of each scheme we can conclude that many PDL elements with small PDL values are preferable to few PDL elements with larger PDL values. The distribution shifts towards to smaller angles as the number of elements increases and PDL value of each device decreases. This is good since PDL in real-life communication systems tend to come from many components with a small PDL value each. The other interesting thing to notice is that the maximum deviation from orthogonality is the same for all the cases when the addition of the PDL values of the components in the system is the same.

In PolTDM configuration, for GST signal, results obtained are exactly the same than in the conventional configuration. That is because SOP of GST signal in this case is aligned to the PBS axis. With the SM signal, however, we experiment loss

In PolMUX configuration, statistics of SM signal are broader than GST signal, since SM will experience both worst case (destructive), best case (constructive) and every intermediate case.

When the number of elements with PDL increases, deviation from orthogonality is greater and the width of the distribution augments.

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ACRONYMS USED IN REPORT

APC	Automatic Polarization Controller
BER	Bit Error Rate
CoS	Class of Service
EA	Eye Area
GST	Guaranteed Service Transport, High priority service class
IEEE	Institute of Electrical and Electronics Engineers
NTNU	Norges Teknisk-Naturvitenskapelige Universitet, Norwegian University of Science and Technology
OpMiGua	Optical packet switched Migration capable network with service Guarantees
PB	Polarization Beam Combiner
PBS	Polarization Beam Splitter
PC	Polarization Controler
PD	Photo Detector
PDL	Polarization Dependent Loss
PDG	Polarization Dependent Gain
PLR	Packet Loss Rates
PM	Polarization Monitor
PMD	Polarization Mode Dispersion
PolMUX	Polarization Multiplexer
PolTDM	Polarization Time Domain
QoS	Quality of Service
R&D	Research and Development
SM	Statistically Multiplexed
SMF	Single-Mode Fiber
SNR	Signal to Noise Ratio
SOP	State of Polarization
WRON	Wavelength Routed Optical Network

DEFINITIONS

Analyzer - an element whose intensity transmission is proportional to the content of a specific polarization state in the incident beam. Analyzers are placed before the detector in polarimeters. The transmitted polarization state emerging from an analyzer is not necessarily the same as the state which is being analyzing.

Birefringence - a material property, the retardance associated with propagation through an anisotropic medium. For each propagation direction within a birefringent medium there are two modes of propagation with different refractive indices n1 and n2. The birefringence Δn is $\Delta n = | n1 - n2 |$

Linear polarizer - a device which when placed in an incident unpolarized beam produces a beam of light whose electric field vector is oscillating primarily in one plane, with only a small component in the perpendicular plane.

Polarization - any process which alters the polarization state of a beam of light, including diattenuation, retardance, depolarization, and scattering.

Polarized light - light in a fixed, elliptically (including linearly or circularly) polarized state. A fully polarized beam can be extinguished by an ideal polarizer. For polychromatic light, the polarization ellipses associated with each spectral component have identical ellipticity, orientation, and helicity.

Polarizer - a strongly diattenuating optical element designed to transmit light in a specified polarization state independent of the incident polarization state. The transmission of one of the eigenpolarizations is very nearly zero.

Polarization element - any optical element which alters the polarization state of light. This includes polarizers, retarders, mirrors, thin films, and nearly all optical elements.

1. Introduction

Traditional polarization multiplexing (PolMUX) is a technique used with the purpose of doubling the data rate capacity of an optical transmission link. With this method we can transmit two orthogonally polarized data channels on only one wavelength simultaneously. As the state of polarization (SOP) of a signal varies when the fiber is exposed to changing temperature and mechanical stress, polarization dependent loss (PDL) in optical fiber transmission systems causes the fluctuation of the signal-to-noise ratio (SNR), resulting crosstalk penalties.

OpMiGua network concept introduces an alternative use of polarization in optical networks. The intention is to use the SOP to distinguish two Classes of Service (CoS), both classes share the same wavelength and are orthogonally polarized. One of them must satisfy strict service guarantees. This class follows an all-optical path with no header processing in intermediate nodes.

In this network, data packets are routed through network nodes based on their SOP, thus using the polarization as a label. If we time interleave the data packets of these two QoS classes, we will eliminate coherent crosstalk and will reduce the demand on the polarization control system. This polarization and time division multiplexed (PolTDM) system is illustrated in figure 1, we can see that in PolMUX there is simultaneous traffic on channel 1 and 2 while in PolTDM only one channel transmits at a time [1].

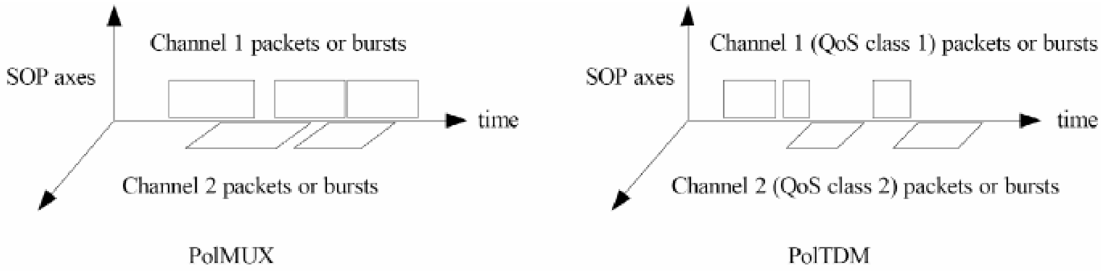

Figure 1. Schematic illustration of PolMUX (left) and PolTDM (right) [1].

In this research we are going to study the reduction of the eye area in the eye diagram caused by the combined effect of orthogonality degradation and dynamic power fluctuations in an optical network that uses polarization multiplexing for QoS segregation. The main task is to compare traditional PolMUX to PolTDM. We use this method to transmit applications with very different quality requirements on the same wavelength channel. It is what we call a hybrid network, which combines circuit switching with packet switching. A big advantage is that we make sure that the entire vacant times of the wavelength are used.

An alternative method is to use different wavelengths for different applications, but this is not such as efficient because we would then use more wavelengths and may risk that some wavelengths have long periods without traffic. The use of wavelength is more cost-effective, but using the state of polarization also has some drawback that must be taken care of.

The next points contain background information necessary to understand the work discussed in this study. A description of the OpMiGua project, the motivation of the research, and the principles involved are shown in chapter 2. Some basic concepts about light and polarization are shown in the section 3.1, PDL are developed in section 3.2, and theory about crosstalk is exposed in section 3.3.

In the chapter 4, we are going to introduce the simulation models, the first things we are going to study are different configurations to see statistical difference between use one or more PDL elements (section 4.1). In the point 4.1.1, we will see the statistical difference between one large PDL element and many small PDL elements. In the next point, 4.1.2, we will develop how fast the width of the distribution increases as the number of elements increases but with the value of each element kept constant. Secondly, in the section 4.2, we are going to introduce the main simulation model with the different variants, with 3, 10 and 15 PDL elements. In all of them we will implement both PolTDM and PolMUX configurations.

Then, in the chapter 5, we will show the results obtained with the different configurations. In the part 5.1 we will show statistical difference between use one or more PDL elements. In the section 5.2.1, we will represent the values found in PolTDM configuration, in the next one, 5.2.2, the results obtained with PolMUX and, finally, deviation from the orthogonality will be depicted in the section 5.2.3.

At last, in the last section (chapter 6) we will summary all the research in the part of conclusions.

2. The OpMiGua project

The OpMiGua project is the main motivation of this thesis. It was launched in 2004 by the initiative of Telenor R&I in collaboration with Network Electronics and NTNU.

OpMiGua (**Op**tical packet switched **Mi**gration capable network with service **Gua**rantees) is a hybrid optical network architecture that combines beneficial properties of circuit- and packet-switching with optimal utilization of the network resources, while being able to provide guaranteed service.

2.1 Quality of Service

OpMiGua separates between two different service classes, statistically multiplexed (SM) and guaranteed service transport (GST).

The GST class has a circuit-switched quality of service (QoS). It has total priority and strict requirements for the quality of transmission like low packet loss and a minimal difference in propagation times. This is because we use this class for audio/video broadcast and interactive gaming, and even more critical applications such as remote-assisted surgery which are sensible to jitter and packet loss.

On the other hand, the **SM** class is a lower priority class and can be allowed lower quality of service (QoS). It has lower demands for packet loss rates (PLR) and jitter. It performs as well as possible under the given conditions, but is not prioritized in the case of congestion. Typical applications for the SM class are web surfing, e-mail, file transfer and similar applications which can tolerate some jitter and packet loss.

2.2 Hybrid network

An essential part of the OpMiGua concept is cost efficiency. A maximal utilization of the resources is desirable. To be able to utilize the resources optimally, a hybrid approach has been proposed using a combination of circuit and packet switching on the same path. This combination has the advantages of both switching methods while reduces the drawbacks of each. Because of the strict requirements for GST traffic, this service class is circuit switched. It provides low jitter and absolute priority for the GST traffic. For low traffic amounts circuit switching has low efficiency as the path is reserved for one channel and rarely fully utilized. The SM packets are statistically multiplexed (SM) and inserted on the path when idle. When GST traffic is present, incoming SM traffic will be halted and buffered until the link is not busy.

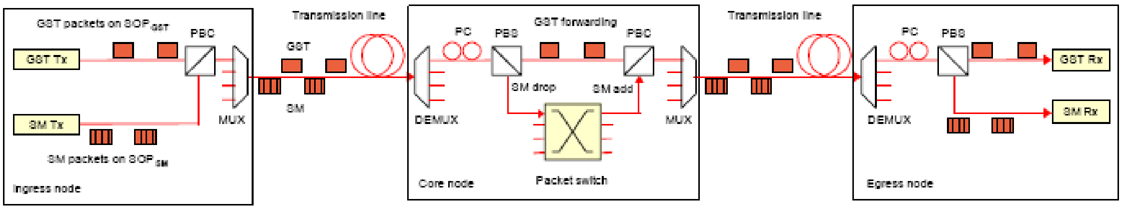

Figure 2.2: Principle of operation of the OpMiGua optical hybrid network [2].

where Tx: transmitter; PBC: polarization beam combiner (polarization multiplexer); PC: polarization controller; PBS: polarization beam splitter (polarization demultiplexer); MUX: wavelength multiplexer; DEMUX: wavelength demultiplexer; Rx: receiver.

Figure 2.2 represents how GST packets on SOP_{GST} follow a dedicated path using one wavelength while SM packets on SOP_{SM} are interleaved with GST packets on the same wavelength when there are vacant times.

2.3 Optical aspects

OpMiGua uses the polarization of the light to distinguish the service classes on the path. The service classes are separated by their state of polarization (SOP) using a polarization time division multiplexing (PolTDM) scheme. During propagation, the polarization will change due to physical effects on the fiber, but the states will retain their orthogonality. This scheme eliminates coherent crosstalk between the service classes, in this way the system is more robust than traditional polarization multiplexing.

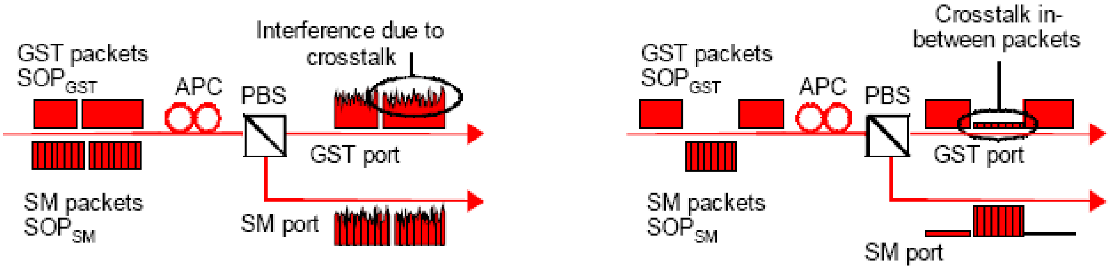

Figure 2.3: De-multiplexing of GST and SM packets; PolTDM (right) compared to PolMUX (left). APC: Automatic Polarization Control [3]

The difference between PolTDM and polarization multiplexing is illustrated in Figure 2.3. Concretely it shows the setup for the polarization demultiplexing. An automatic polarization controller (APC) controls the polarization through feedback signals from both traffic classes. The signal is separated in the polarization beam spliter (PBS) and the traffic is received at its respective ports.

3. – BACKGROUND

3.1 Light and polarization

Light can be described as an electromagnetic wave that propagates via a sinusoidal oscillation of an electric field. We can describe it using different characteristics as intensity or wavelength. Another important attribute of the light is the State of Polarization (SOP). The SOP to the wave is defined by the direction to the electric field vector E.

In a monochromatic optical field with the angular frequency ω propagates in the z direction, the electric field can, on general basis, be written as a transversal mode Ψ(x,y) in the (x,y) plane perpendicular to and independent of the propagation direction [4]:

$$E = \left(\vec{\mathrm{E}}_x(\mathrm{z,t}) + \vec{\mathrm{E}}_y(\mathrm{z,t})\right)\Psi(x,y) \qquad (1)$$

$$\begin{aligned} \vec{\mathrm{E}}_x(\mathrm{z,t}) &= \mathrm{E}_{0x}\cos(\mathrm{kz} - \omega\mathrm{t})\ \vec{\mathrm{x}} \\ \vec{\mathrm{E}}_y(\mathrm{z,t}) &= \mathrm{E}_{0y}\cos(\mathrm{kz} - \omega\mathrm{t} + \varepsilon)\ \vec{\mathrm{y}} \end{aligned} \qquad (2)$$

where ε represents the phase difference between the x and y components of the electrical field.

JONES VECTORS

Jones method provides a mathematical description of the polarization state of light, as well as means to calculate the effect that an optical device will have on input light of a given polarization state. The method of Jones deals with the instantaneous electric field. For this reason, it is preferred when using coherent sources such as lasers.

Since light is composed of oscillating electric and magnetic fields, Jones reasoned that the most natural way to represent light is in terms of the electric field vector. When written as a column vector, this vector is known as a Jones vector and has the form:

$$E = \begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} \qquad (3)$$

where $E_x(t)$ and $E_y(t)$ are the instantaneous scalar components of the electric field. Note that these values can be complex numbers, so both amplitude and phase information present.

STOKES PARAMETERS

Stokes parameters describe a time-averaged optical signal. For this reason they are often chosen for use with light of rapidly and randomly changing polarization state, such as natural sunlight

To get the Stokes parameters, we do a time average (integral over time) and operating we arrive to:

$$\left(\mathrm{E}_{0x}^2 + \mathrm{E}_{0y}^2\right)^2 - \left(\mathrm{E}_{0x}^2 - \mathrm{E}_{0y}^2\right)^2 - \left(2\mathrm{E}_{0x}\mathrm{E}_{0y}\cos\varepsilon\right)^2 = \left(2\mathrm{E}_{0x}\mathrm{E}_{0y}\sin\varepsilon\right)^2 \qquad (4)$$

where ε is the phase difference between x and y components of the electrical field.

The four Stokes parameters are, described in terms of the electrical field:

$$\begin{aligned} S_0 &= \mathrm{E}_{0x}^2 + \mathrm{E}_{0y}^2 \\ S_1 &= \mathrm{E}_{0x}^2 - \mathrm{E}_{0y}^2 \\ S_2 &= 2\mathrm{E}_{0x}\mathrm{E}_{0y}\cos\varepsilon \\ S_3 &= 2\mathrm{E}_{0x}\mathrm{E}_{0y}\sin\varepsilon \end{aligned} \qquad (5)$$

And these parameters described in geometrical terms are:

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} a^2 \\ a^2\cos 2\beta\cos 2\phi \\ a^2\cos 2\beta\sin 2\phi \\ a^2\sin 2\beta \end{pmatrix} \qquad (6)$$

where β, ϕ and a are described in the next figure of the polarization ellipse:

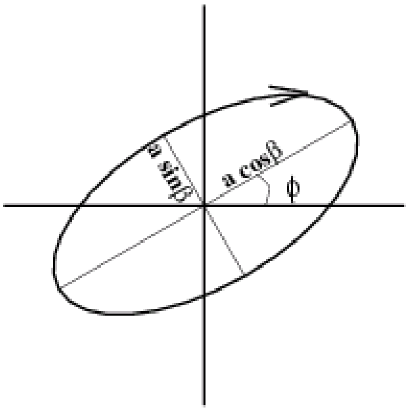

Figure 3.1: Polarization ellipse

3.2. PDL theory

Long-haul optical fiber transmission systems are susceptible to problems due to polarization effects, such as polarization dependent loss/gain (PDL/PDG) and polarization mode dispersion (PMD) [5].

PDL is defined in the paper by Fukada [6] as the ratio of minimum to maximum optical transmission coefficient of a device (or a transmission system) when the input totally polarized light sweeps all polarization states.

Multiplexers, couplers, isolators, circulators, connectors and other devices are all sources of PDL. A transmission system may occasionally have a large value although the PDL of individual components may be small. Loss accumulates along the transmission line and causes the fluctuation of the signal-to-noise ratio (SNR) with the time, resulting in the variation of bit error rate (BER). Non-perfect recovery will result in crosstalk penalties, and stringent requirements are put on the polarization control system necessary to limit these penalties.

If we study the transmission coefficient of the transmission system (X) we see that it depends on the polarization state of the input lightwave and the transmission function of each fiber. The probability density function of the transmission coefficient $P_x(X)$ can be written as [6]:

$$P_x(X) = \frac{1-K}{\sqrt{2\Pi n\left\{(1-K)^2 - K(\ln K)^2\right\}}}\exp\left(-\frac{\left\{(1-K)\ln X + n(1-K+K\ln K)\right\}^2}{2n\left\{(1-K)^2 - K(\ln K)^2\right\}}\right)\frac{1}{X} \qquad (7)$$

where n is the number of PDL devices in the transmission system and K (linear) is the value of PDL of each PDL device in the transmission system.

Since PDL alters the state of polarization, any device with PDL will tend to rotate the two initially orthogonal fields. It causes a degradation of the degree of orthogonality between them, we can see this effect illustrated in figure 3.2.1. Assuming that PDL is aligned with the vertical axis of the transmission, then the SOP_1 and SOP_2 represent two orthogonal states of polarization at the input of the device. PDL varies the SOPs' vectors, resulting in the modified SOP_1' and SOP_2', with the degree of orthogonality, therefore, changed.

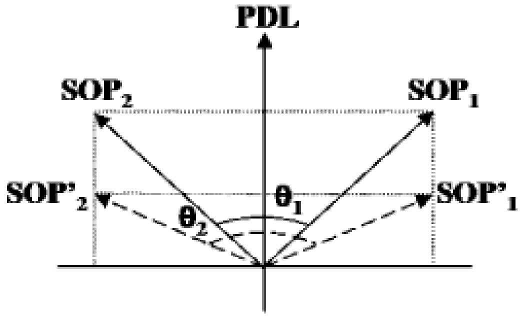

Figure 3.2.1: Degradation in orthogonality due to PDL represented in Jones space. Solid vectors represent the input orthogonal SOPs, dashed represent the output SOPs [7].

The new angle θ_2 between both SOPs (GST and SM) can be found by measuring the Stokes vectors of the two signals at the fiber output and is given by:

$$2\theta_2 = \cos^{-1}\left(\frac{s_{SM} \cdot s_{GST}}{|s_{SM}| \cdot |s_{GST}|}\right) \qquad (8)$$

s_{GST} and s_{SM} are the Stokes vectors of the GST and SM signal, respectively [2].

With a short paper by Widdowson [8], we can calculate the maximum deviation from orthogonality. Assuming all *i* PDL elements are aligned with the low loss axis bisecting the two fields, then by summing the rotations of the fields caused by every element it can be shown that

$$\theta = \frac{\Pi}{2} - 2\tan^{-1}\tanh\left[\frac{i\ln 10}{40} PDL(dB)\right] \qquad (9)$$

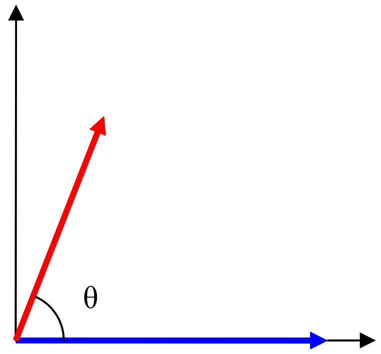

Figure 3.2.2: Representation of the angle θ

In general, polarization effects are stochastic processes and can occur on short or long time scales. It means that a system can randomly vary their penalty values. Consequently, the objective is to reduce the probability that the penalty will exceed a certain level (typically minute per year).

A main source of this randomness is nonidealities in the optical fiber. Ideally, the single mode fiber core is circularly symmetric and the two polarization modes are degenerate, it means that light in either mode propagates with the same speed. However, real single mode fibers have some intrinsic birefringence due to random geometric and stress variations along the fiber core as a result of the manufacturing process, cabling and laying processes. In combination with environmental perturbations, this generates PMD in the fiber that varies randomly with time and frequency. Additionally, the aggregate PDL value of several in-line optical components in such a fiber link becomes a time-varying function due to random fluctuations of the signal polarization states between each component [9].

3.3. Crosstalk

We have seen before that rotation of the SOP and unpredictable SOP fluctuations caused by temperature and environmental changes origin deviation from orthogonality of the two SOPs, it means that some power from one SOP will couple into the wrong PBS output, as illustrated in the figure 3.3.

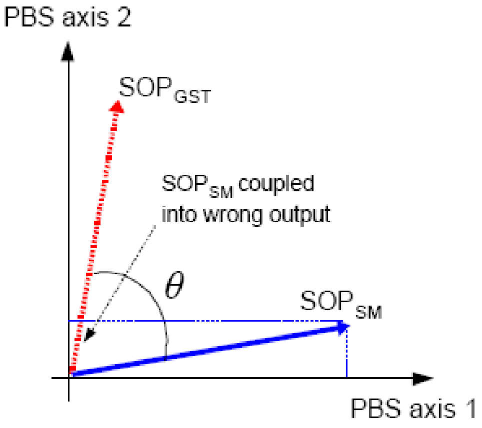

Figure 3.3: SOP of the two QoS classes relative to the axes of a PBS, represented in Jones space [2].

where θ is the relative angle (in Jones space) between the two SOPs, then θ=90° represents ideal orthogonality. The coordinate axes are the axes of the PBS. Thus, the projections of the two SOPs onto a PBS axis represent the optical field amplitude coupled into this PBS output.

3.3.1. Crosstalk in PolTDM

The case of PolTDM signals is illustrated in the figure. 3.3.1, where the GST class is aligned to its PBS axis. A fraction of the SM signal amplitude then couples into the GST output.

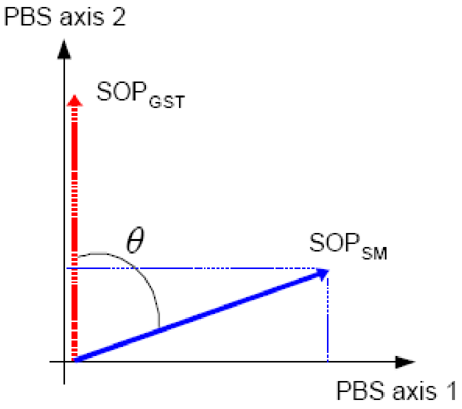

Figure 3.3.1: PolTDM configuration with SOP$_{GST}$ aligned to PBS axis [2].

As SM and GST packets are interleaved in time, this orientation introduces **incoherent crosstalk** in the form of noise in-between GST transmission, not interfering with the GST signal itself.

3.3.2. Crosstalk in PolMUX

The configuration of PolMUX signals is the opposite of the PolTDM orientation, as depicted in the figure 3.3.2. In this case, SOP$_{SM}$ is aligned to the PBS while the GST class experiences a power loss caused by misalignment with its PBS axis.

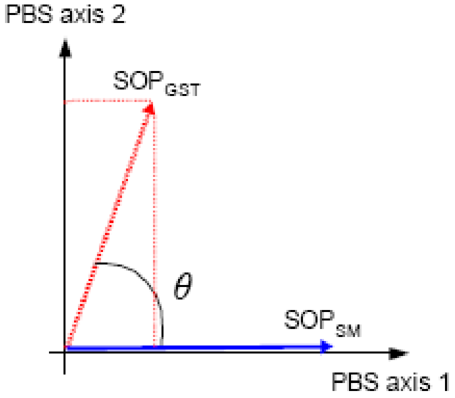

Figure 3.3.2: PolMUX configuration with SOP_{SM} aligned to PBS axis [2].

In this way crosstalk from the SM signal into the GST output is eliminated. Although, a fraction of the GST signal couples into the SM output, introducing **coherent crosstalk**. PolTDM is therefore more robust towards orthogonality degradation than PolMUX.

If we calculate the power of the signal at the output we have:

$$P = (\kappa_{SM} E_{SM} + \kappa_{GST} E_{GST})^2 = \kappa_{SM}{}^2 E_{SM}{}^2 + \kappa_{GST}{}^2 E_{GST}{}^2 + 2\kappa_{SM}\kappa_{GST} E_{SM} E_{GST} \sin\theta \quad (10)$$

where κ_{GST} is the quantity of GST signal coupled into the SM output, κ_{SM} is the quantity of GST signal coupled into the SM output ($\kappa_{GST}, \kappa_{SM} <<1$) and θ is the phase difference between the x and y components of the electrical field.

In The last expression, $\sin\theta$ can fluctuate between values included in [-1, +1] interval, between the worst (destructive interference) and the best case (constructive interference), respectively.

For PolTDM, to measure crosstalk due to PDL is easy, since loss of orthogonality will only cause loss of power. However, for PolMUX, find a good way to measure it is more difficult since crosstalk does not necessarily mean a power reduction in this case. A possible solution would be to use an eye diagram.

An **Eye Diagram** is an illustration that shows if a digital system works properly. The "openness" of the eye relates to the BER that can be achieved. It is generated by superposition of random bit sequences, giving a statistical mean of signal pulses sequences.

The eye diagram allows the characterization of the quality of the signal at the end of a trace. We obtain better quality of the signal at the end of the line if the eye openness is larger. It means that amplitude distortion of the signal along the trace, due to discontinuities or losses, reduces the eye opening and the noise margin, so that the receiver at the end of the line has difficulties in correctly detecting the signal. The eye diagram width gives information about the time interval where the data can be sampled at the receiving end without problems due to intersymbol interference (ISI). Such a width can be reduced by the jitter due to the dispersion along the interconnection [10].

Concretely, in the eye diagram we are going to study the Eye Area (EA). This is the area included between the high and the low level in the eye diagram. Eye Area is represented in the figure 3.3.3.

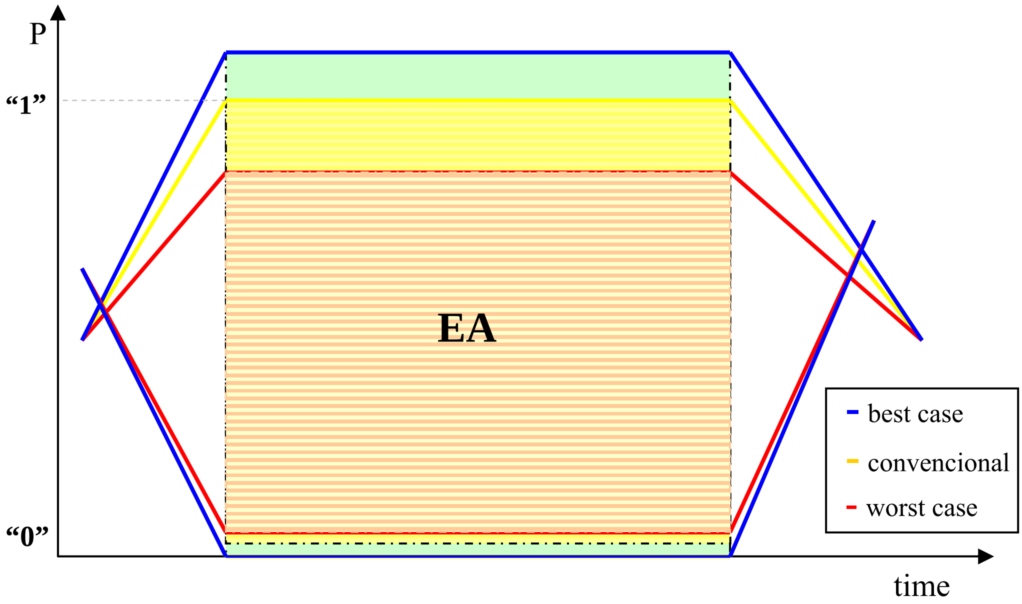

Figure 3.3.3: Eye diagrams of the conventional case (yellow), best case (blue) and worst case (red). EA in each case is represented by the striped boxes

4. Simulation Model

4.1 - Statistical difference between use one or more PDL elements

In this point we want to have a statistical overview of loss power and orthogonality deviation of several configurations. We make all these measurements in order to study first, the difference between use one or more PDL elements keeping global PDL constant and secondly how fast the width of the distribution increases as the number of elements increases but with the value of each element kept constant.

4.1.1 Statistical difference between one large PDL element and many small PDL elements

In this point we study the statistical difference between one large PDL element and many several PDL elements but with the global kept constant in each configuration. It means that the addition of all PDL devices values in the system is the same in all the configurations.

In order to find out this difference, we do some simulations. Specifically we are going to compare several transmission lines:

a) with one PDL element of 2,5 dB
b) with two PDL elements of 1,25 dB
c) with five PDL elements of 0,5 dB
d) with ten PDL elements of 0,25 dB

In this way, the maximum value of the addition of all the PDL values in the system is the same in all four cases (2,5 dB).

With the purpose of getting a statistically good result from the simulations we are going to do 10.000 simulations of each transmission link. At this stage we want to measure optical power at the end of the link, so a power monitor is necessary at the output.

In the laser module we specify the input (launch) SOP, so in the first set of simulations we use one SOP (GST signals), and in the second set we use the orthogonal launch SOP (SM signals).

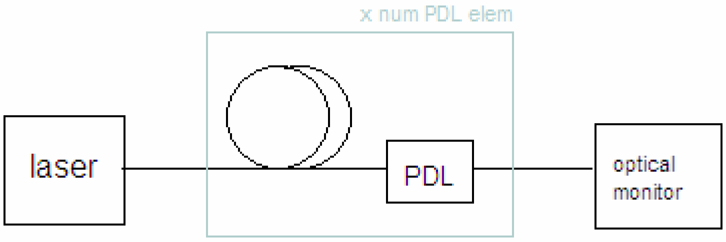

Figure 4.1.1: Basic schematic of the different simulations

In the figure 4.1 we can see the basic configuration of the simulations, the number of PDL elements (x) will be 1, 2, 5 or 10, and the value of PDL will be 2,5dB, 1,25dB, 0,5dB and 0,25dB, respectively. In all these cases we set the PMD coefficient to zero.

4.1.2 Statistical difference when the number of elements increases but with the value of each element kept constant

In this section we are going to see how fast the width of the distribution increases as the number of elements increases but with the value of each element kept constant. With this purpose we are going to do 10.000 simulations of several configurations, we are going to use the same schematic that in the last point (see figure 4.1.1) but now all the PDL elements have the same value, in our case 0,25dB.

In this case also we set the PMD coefficient to zero for all the configurations.

4.2. MAIN SIMULATION MODEL

In the following we study a single wavelength channel at third window (1550 nm) in a link between two OpMiGua nodes in a metro network. Focusing on PDL-induced dynamic power fluctuations and excess penalty caused by orthogonality degradation, and ignore therefore crosstalk due to PMD.

The link is unamplified and consists of several passive PDL elements separated by standard single-mode fiber, assuming no PDL in the fibers. Concretely, we are going to study the cases of 3, 10 or 15 PDL elements. Total propagation distance is 100 km in all the cases.

Chromatic dispersion is neglected, and signal power is assumed low enough to avoid non-linear effects. Launch power is 2,6 dBm. For simplicity, every element has a PDL value of 0.5 dB and the same orientation of PDL axes. We have chosen 0.5 dB because is close to PDL values of many optical components exhibit today. Fiber birefringence randomizes the polarization of the light impinging on the PDL elements.

In order to do the simulations of the PolTDM configuration we create the link shown in the figure 4.2.1.

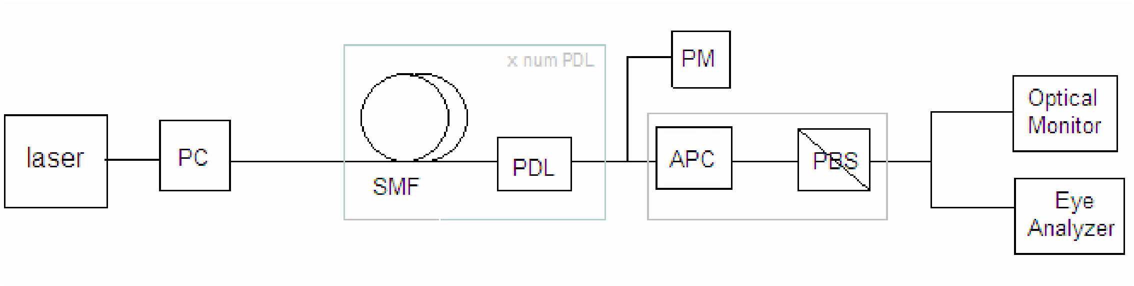

Figure 4.2.1: PolTDM configuration

Where:

PC is the polarization controller where we choose the SOP of the signal, 0 or 90 degrees depending of the signal we want to analyze (SM or GST).

SMF is single-mode fiber.

APC is the Automatic Polarization Controller.

PBS is a polarization beam splitter.

These two last elements are implemented with a Matlab block model (AEP).

PM is the Polarization Monitor, which gives us the Stokes vectors in the GST configuration. We need these values to introduce them in the AEP device in both GST and SM configuration.

The AEP simulates an APC in front of a PBS. The purpose of the controller is to align the polarization state of the light at the fiber output to the axes of a polarization beam splitter, according to the figures 3.3, 3.3.1 and 3.3.2 shown in the last section. However, this is the same as aligning the controller/PBS to the polarization of the light. Therefore we measure the polarization state of the light and enter these coefficients into the Jones matrix of the controller. The polarization state is characterized by Stokes vectors while the Jones matrix uses linearly polarized Jones vectors as basis, so a conversion from Stokes to Jones is necessary. Unfortunately Optsim cannot do this automatically so we use Matlab to do this task. Matlab can communicate with Optsim. The script basically reads Stokes parameters from a file and calculates the coefficients of a Jones matrix. It then multiplies the optical field with this matrix (see the AEP.m file in the appendix).

With the purpose of studying PolMUX configuration we generate the schematic represented in the figure 4.2.2. It is similar at the last one, but in this case we require a Polarization Beam Combiner (PBC) to combine both signals.

Another difference is that we do not need the Polarization Monitor. For this configuration we use the Stokes vectors from the PolTDM configuration.

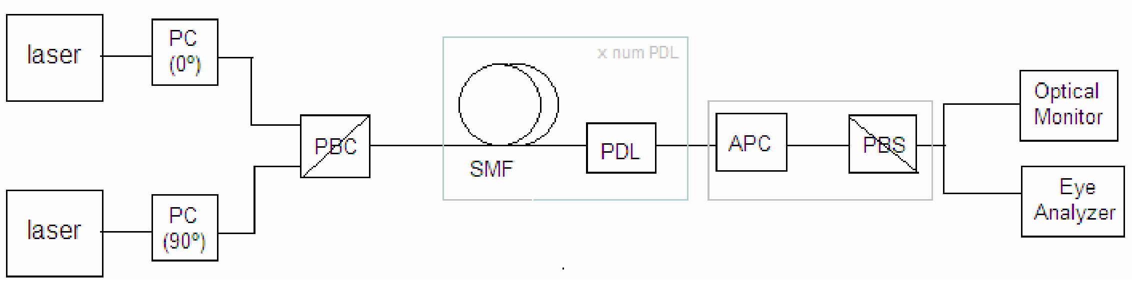

Figure 4.2.2: PolMUX configuration

The transmission line up was simulated numerically by using a Fourier split-step algorithm and a PMD coarse-step method implemented in a commercially available software package. PMD correlation length was 10 m. Signal power and Stokes vectors were monitored at the link just before the AEP block, as indicated in the figure 4.1.

10000 realizations of the link were explored by iterating the seed for the PMD generator, each fiber having different seeds, and keeping the launch SOP constant. The orthogonal launch SOP was then simulated with the exact same seeds.

There is especially one thing to be aware of when simulating PolMUX and that is the phase difference between the two polarizations. In OpMiGua this phase difference may be totally random, since SM and GST signals have either travelled different distances or come from different lasers that may have a small difference in center frequency. We have to implement the difference in phase between SM and GST signals in PolMUX. With this aim we look at the statistical average of all phase differences (a uniformly random phase). Then the statistics of SM will be broader than GST, since SM will experience both worst case (destructive), best case (constructive) and every intermediate case.

Furthermore, for each configuration we set one of the patterns type in the worst case. That means when we study de GST signal we set the pattern of the SM laser to “1” (invariable) and the GST laser pattern to “PRBS”. When we study the SM signal we do just the opposite. Because of that, we will have interference between two signals. Otherwise we will always have logical “1” in SM when there is a “1” in GST; and a logical “0” in SM when there is a “0” in GST.

5. Results

5.1 Statistical difference between use one or more PDL elements

5.1.1 Statistical difference between one large PDL element and many small PDL elements

In the next figure, the 5.1.1.1, we can see the power loss with one of the states of polarization; with the orthogonal SOP the results are quite similar.

The probability distribution shows a Gaussian-like distribution when the number of components with PDL is equal or larger than 2.

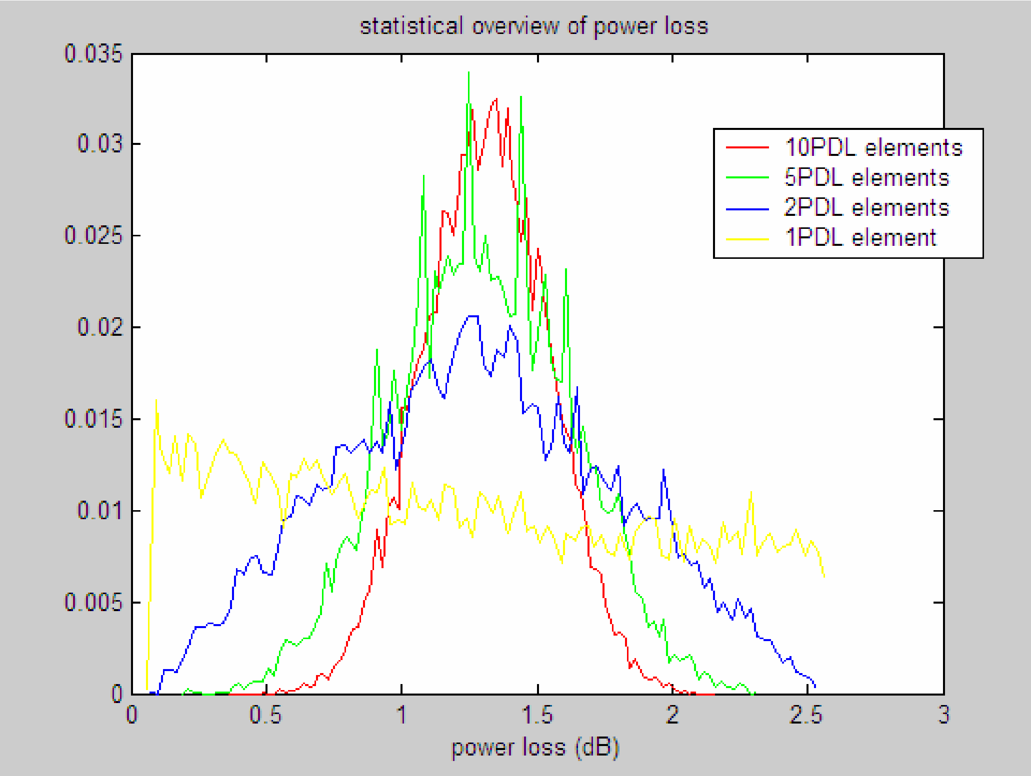

Figure 5.1.1.1: Statistical overview of power loss

The results are quite interesting. When we have more than one PDL device the behaviour of the graphics are comparable with the theoretical expression of the probability density function of the transmission coefficient.

We have to consider that one of the outputs from the simulations is the polarization dependent output power. The difference between this power and the reference power (as we have calculated before) is loss that depends on the polarization, but this is not the official definition of PDL. If we also do a scan of the input SOP through every possible state for every simulation, then we will find one SOP that gives us a maximum output power for this special simulation, and one SOP that provides the minimum output power. PDL is defined in the paper by Fukada [6] as the ratio of minimum to maximum optical transmission coefficient of a device (or a transmission system) when the input totally polarized light sweeps all polarization states.

If this procedure is repeated for all 10.000 simulations, we will have the probability distribution of PDL. However, in our network we keep the input SOP fixed, so the distribution of PDL is not the most interesting thing. This is the distribution of the transmission coefficient, and if we compare our results with the theoretical probability density function of the transmission coefficient $P_x(X)$ (see equation 7) we will see that the results are similar. If we use Matlab to do a representation of the theoretical results we observe a similar behaviour of the probability density function as we can see in the figure 5.1.1.2. The values are not the same because the expression (7) does not correspond exactly with our configurations. In the theoretical expression is considered one section of fiber more than in our configurations, for that reason the behaviour is similar but the graphic is shifted. Anyway, we can see how the statisticals are broader when the number of PDL elements decrease and all four cases has a maximum in the same value.

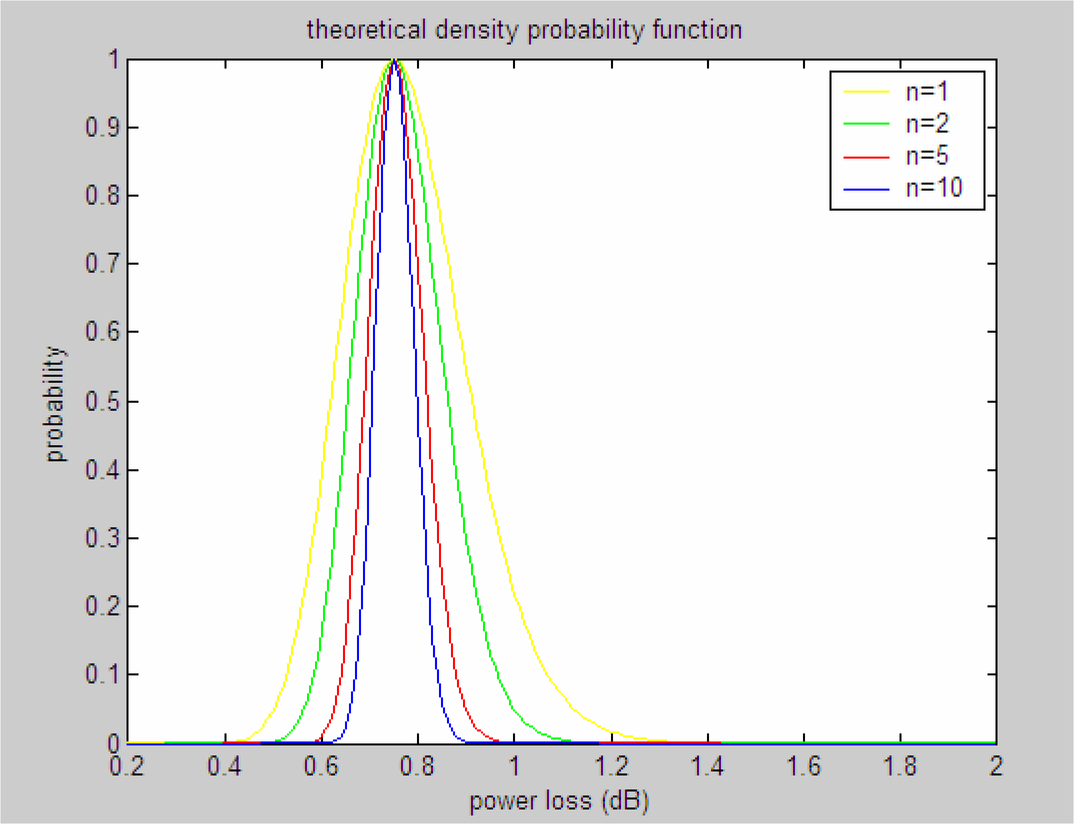

Figure 5.1.1.2: Representation of theoretical expression of probability density function (with *n* number of PDL devices in the transmission system and *K* (linear), the value of PDL of each PDL device in the transmission system)

In addition, we need to know the deviation from orthogonality of the signals at the output. It means that we also need to measure the Stokes parameters for both input SOPs. When both input SOPs have been simulated, it is possible to calculate the angle between the output polarizations (and deviation from orthogonality) using the expression (8).

If we represent the deviation from orthogonality we obtain the graphic depicted in the figure 5.1.1.3.

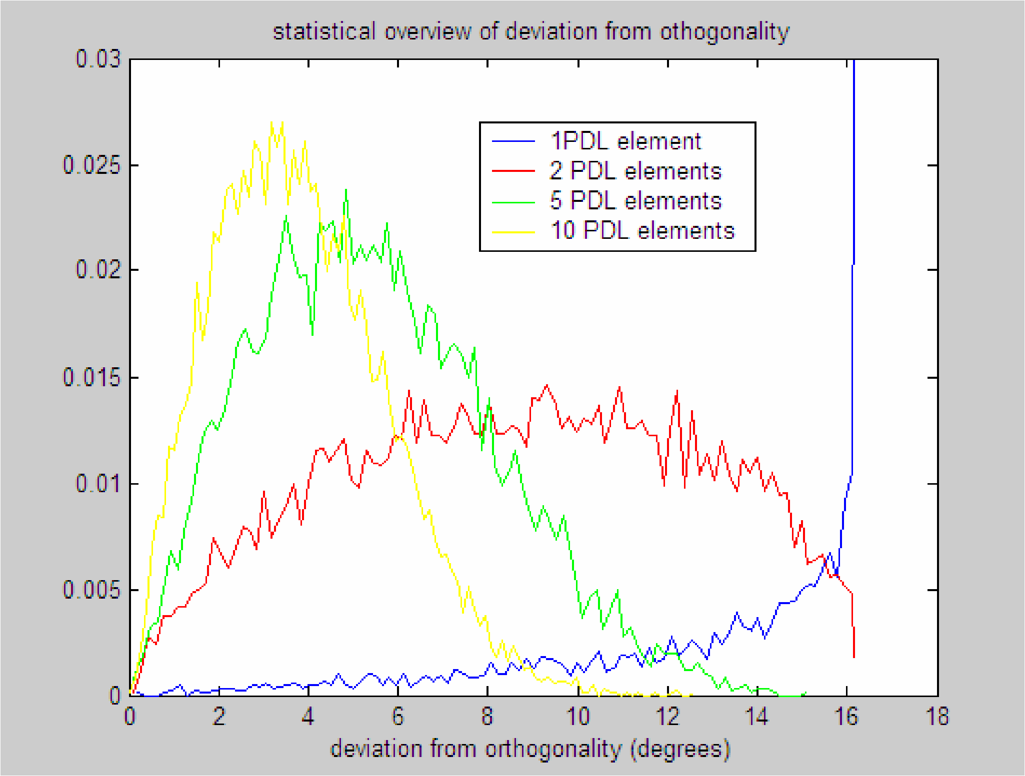

Figure 5.1.1.3: Statistical overview of deviation of orthogonality

From the results, we can see that many PDL elements with small PDL values are preferable to one, two or a few PDL elements with larger PDL values. The distribution shifts towards to smaller angles as the number of elements increases and the PDL value decreases. This is good since PDL in real-life communication systems tend to come from many components with a small PDL value each.

The other interesting thing to notice is that the maximum deviation from orthogonality seemingly is the same for all four cases. We can confirm this with the expression number (10) shown before. In our particular case we have the next values for i and for PDL.

a) i=1, PDL=2.5;
b) i=2, PDL=1.25;
c) i=5, PDL=0.5;
d) i=10, PDL=0.25;

In all cases we obtain a value θ= 73.73 degrees. It means a deviation from orthogonality of 16.27 degrees, as we can see in figure 5.1.1.3, approximately.

5.1.2 Statistical difference when the number of elements increases but with the value of each element kept constant

In this section we are going to see how fast the width of the distribution increases as the number of elements increases but with the value of each element kept constant. We are going to use the scheme explained in the point 4.1.2.

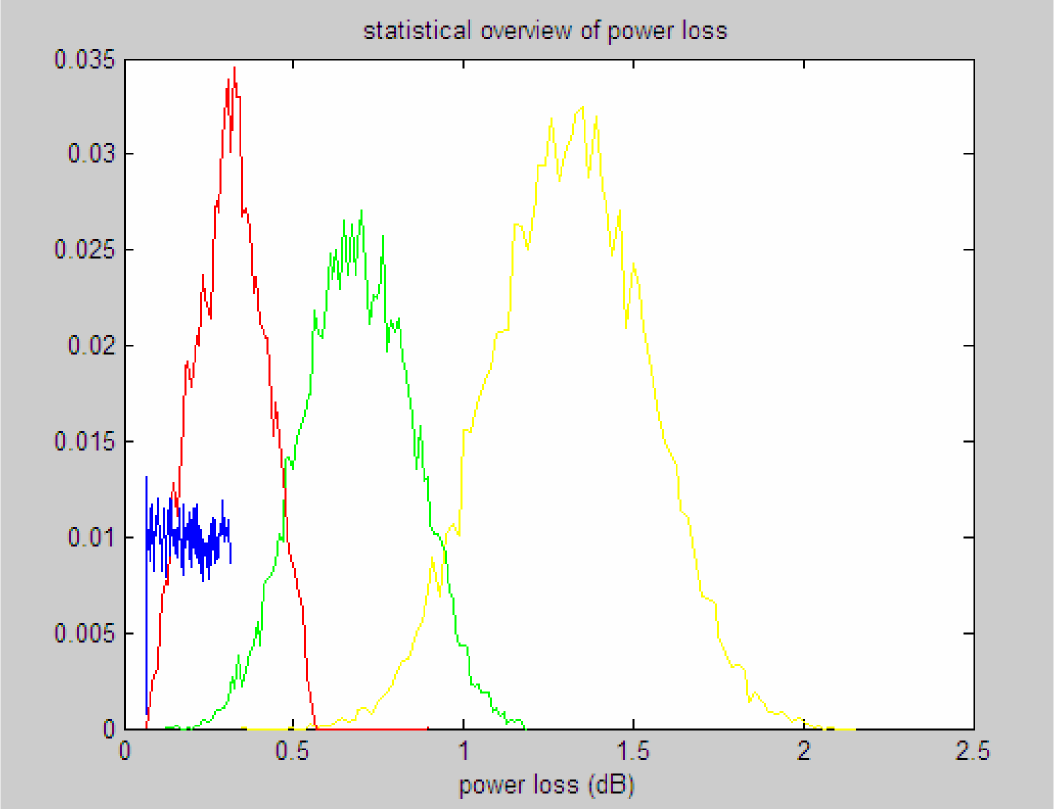

Figure 5.1.2.1: Statistical overview of power loss

If we calculate now deviation from orthogonality of the signals at the output using the expression (8) again, we obtain the results depicted in the figure 5.2.1.2.

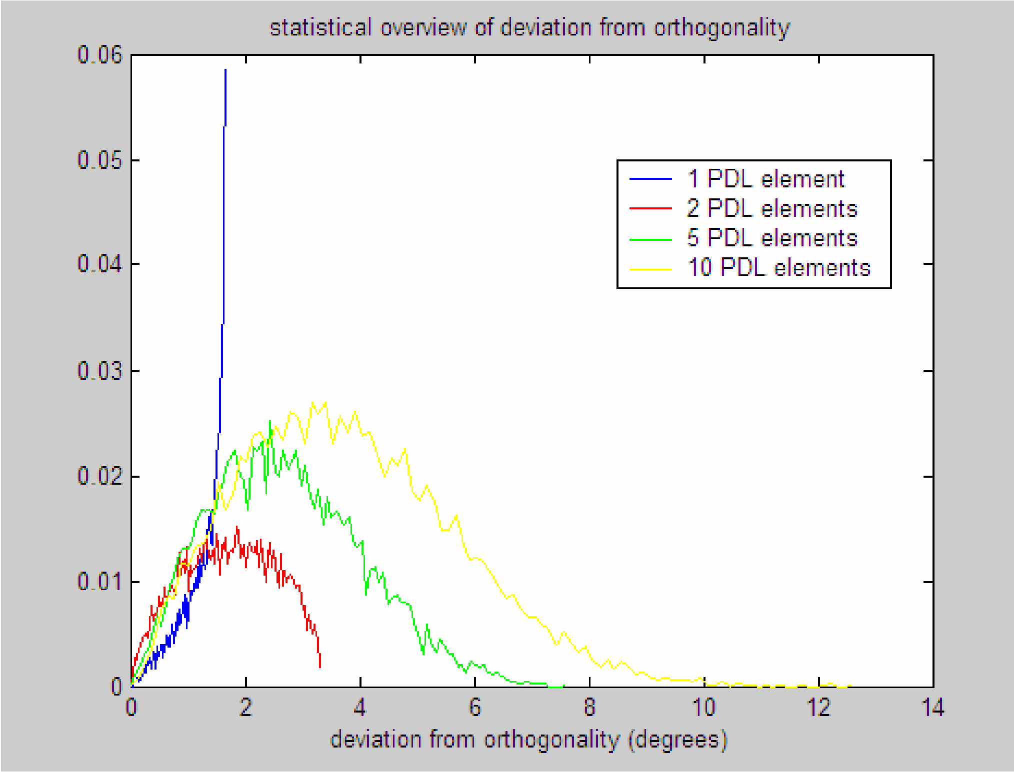

Figure 5.2.1.2: Statistical overview of deviation of orthogonality

We can check the results using again the expression number (10). In our particular case we have now the next values for i and for PDL. Maximum deviation in our graphic corresponds to the theoretical values, approximately.

a) i=1, PDL=0.25; → max deviation = 1.65 º
b) i=2, PDL=0.25; → max deviation = 3.30 º
c) i=5, PDL=0.25; → max deviation = 8.21 º
d) i=10, PDL=0.25; → max deviation = 16.26 º

5.2 Results from the main simulations

In order to see the difference between PolTDM and PolMUX configurations we represent the Eye Area (EA). Concretely, we study the relation between the eye area in each configuration and the eye area in the conventional case. In this way we can see if the configuration is better, worse or the same than the conventional case only seeing if the relation, γ, is greater, lower or equal to one.

$$\gamma_{TDM} = \frac{EA_{TDM}}{EA_{conv}} \qquad \gamma_{MUX} = \frac{EA_{MUX}}{EA_{conv}} \qquad (11)$$

We analyze these relations for both GST and SM signals.

5.2.1 PolTDM configuration

In PolTDM, it does not matter the phase difference, if we change the phase we always obtain the same results, for both GST and SM signal.

In the GST signal, results obtained are exactly the same than in the conventional configuration for all the cases (3, 10 or 15 PDL elements) so γ_{TDM} is always one for all the 10.000 simulations. That is because SOP of GST signal in this case is aligned to the PBS axis, as we could see it in the figure 2.3.1.

With the SM signal, however, we experiment loss as we can see in the figure 5.1, for all the seeds we obtain a γ_{TDM} value lower than one.

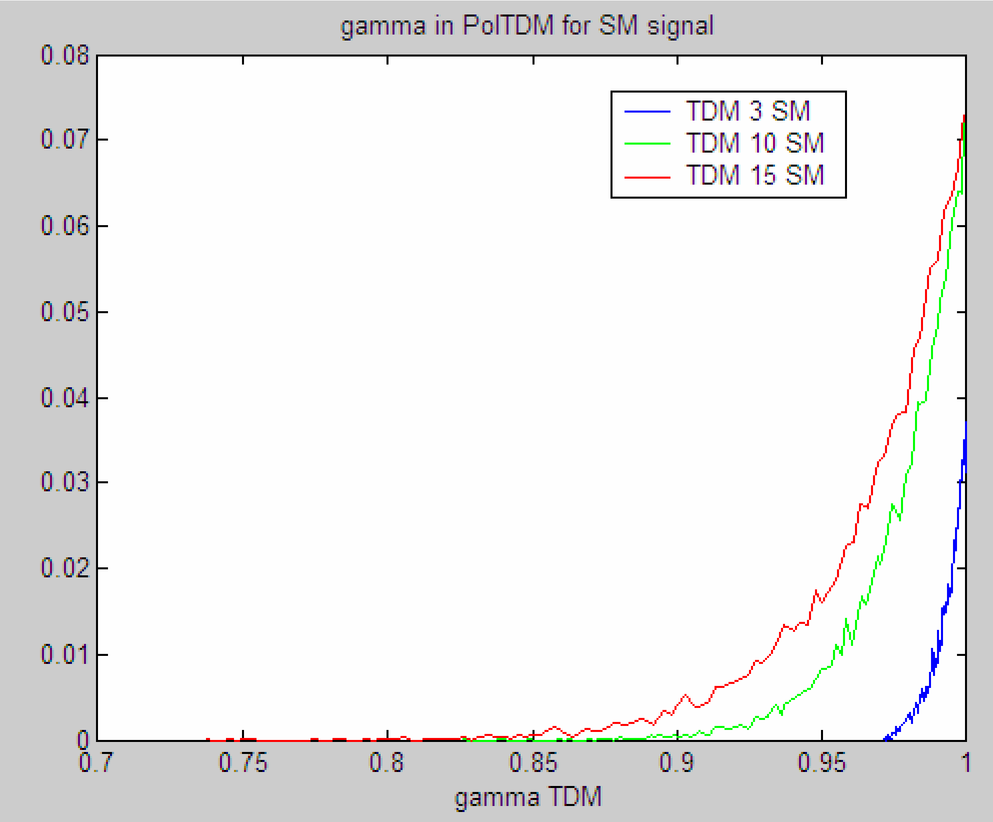

Figure 5.2.1.1: Comparison of γ_{TDM} for the SM signal depending of the number of PDL elements

5.2.2 PolMUX configuration

In the GST signal case, we have almost the same results as in the case of SM signal in PolTDM configuration as we can see in the figure 5.2.2.1

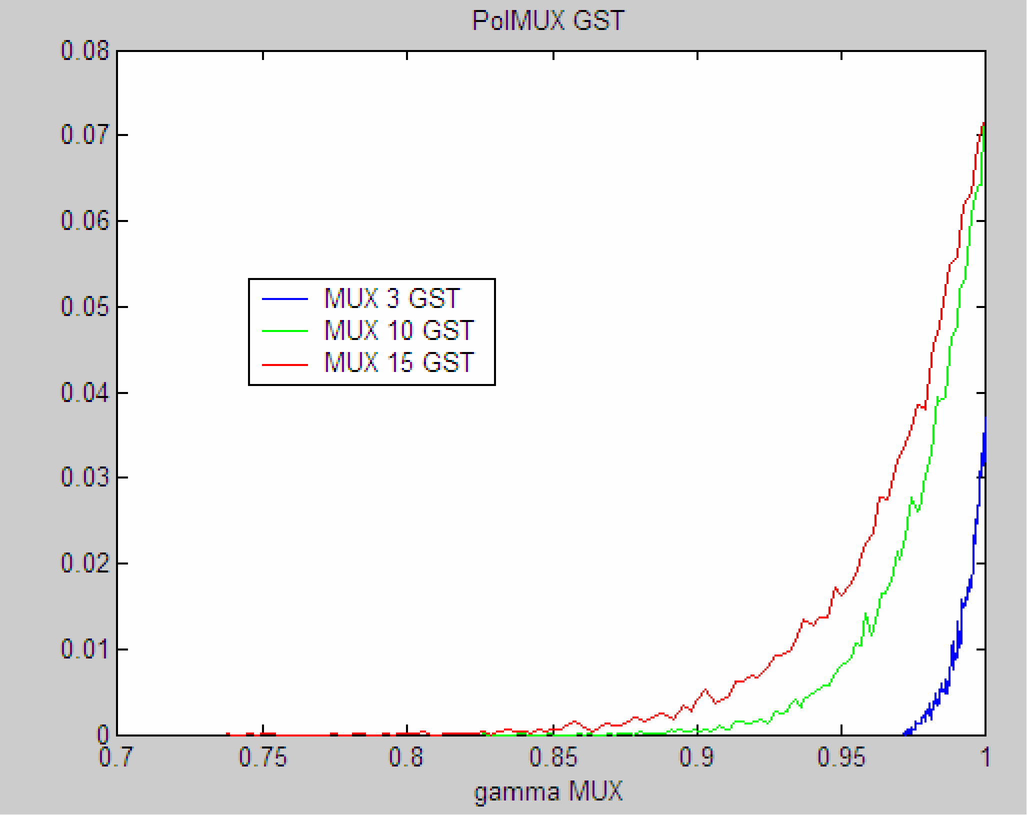

Figure 5.2.2.1: Comparison of γ_{MUX} for the GST signal depending of the number of PDL elements

In the SM signal, however, we notice behaviour completely different, as is shown in the figure 5.2.2.2:

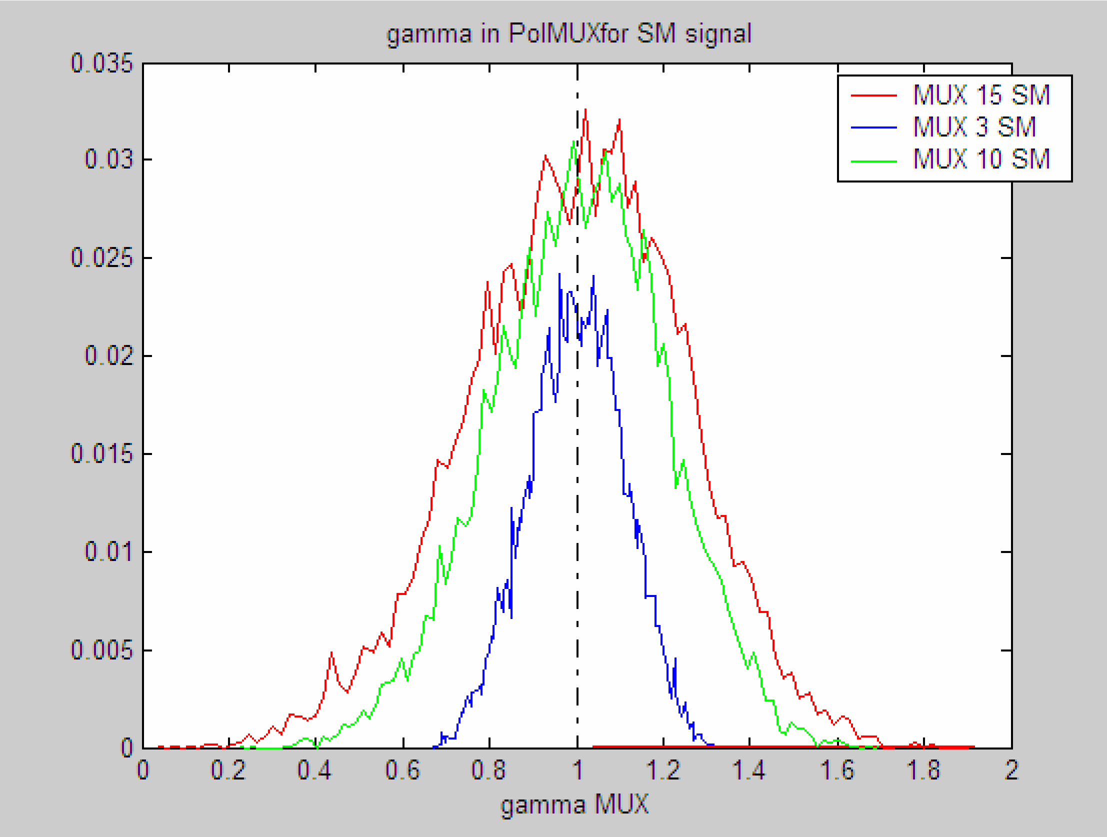

Figure 5.2.2.2: Comparison of γ_{MUX} for the SM signal depending of the number of PDL elements

In this case we can get values greater than one. This is because we have a random phase in the SM laser, thus we have all the possible values getting both constructive and destructive interference as we explained in the section 2.2.

Concretely, in the expression (10) we saw that $\sin\theta$ fluctuated between the interval values [-1, +1], between the worst (destructive interference) and the best case (constructive interference), respectively. In this way for $\sin\theta$ є]0,+1], we experiment an improvement and a worsening for $\sin\theta$ є [-1,0[comparing with the conventional case.

If we represent the cumulative distribution, P ($\gamma_{MUX} < n$), we obtain the graphic depicted in the figure 5.2.2.3.

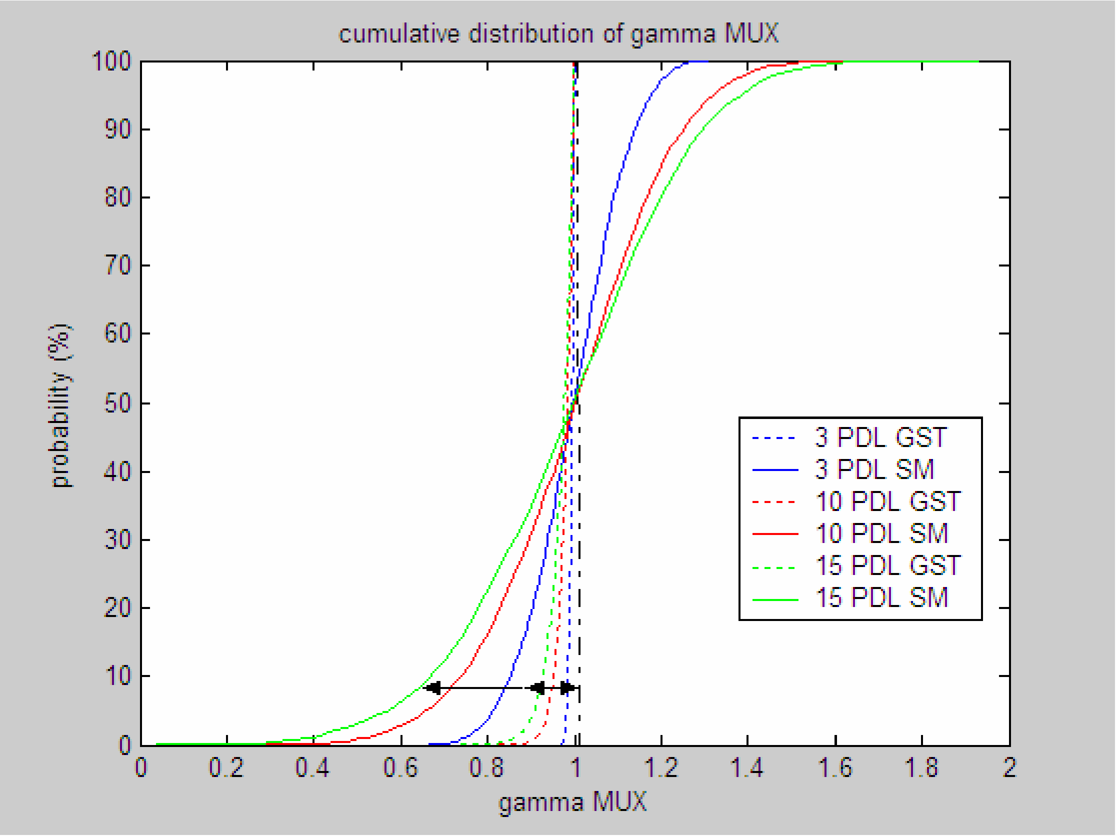

Figure 5.2.2.3: Comparison of the cumulative distribution of γ_{MUX} for the SM (solid line) and the GST (dashed line) signal depending of the number of PDL elements

We can see that statistics of SM are broader than GST, since SM will experience both worst case (destructive), best case (constructive) and every intermediate case.

5.2.3 Deviation from orthogonality

Deviation from orthogonality is the same for both configurations for the reason that the Stokes vectors are the same, as is shown in the figure 5.2.3. In this graphic we can see that deviation from orthogonality has the same behaviour than in the section 5.1.2.

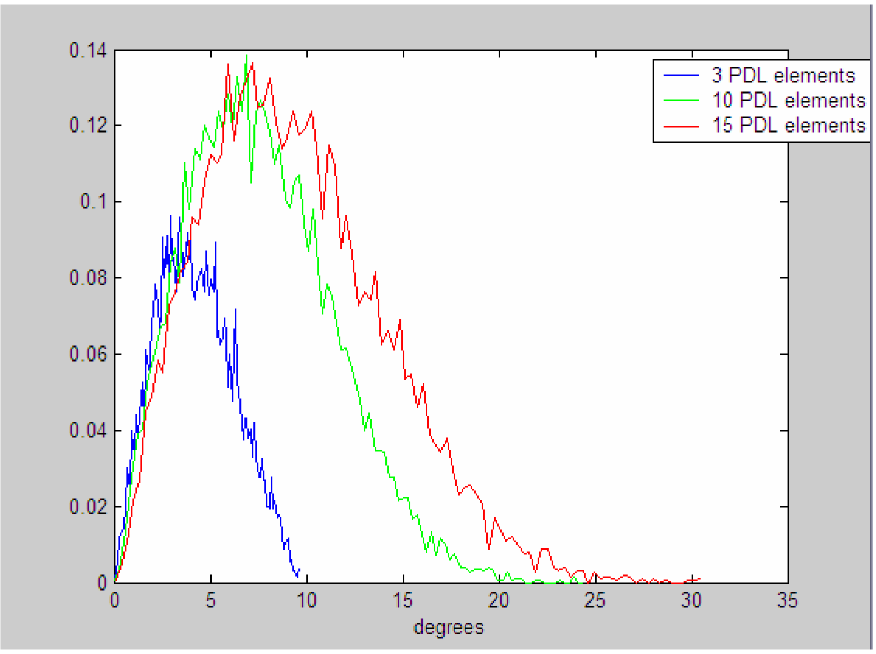

Figure 5.2.3: Deviation from orthogonality (degrees) depending of the number of PDL elements

6. Conclusions

Probability distribution shows a Gaussian-like distribution when the number of components with PDL is equal or larger than 2 in all the cases.

An important thing is that we can conclude that many PDL elements with small PDL values are preferable to one, two or a few PDL elements with larger PDL values. The distribution shifts towards to smaller angles as the number of elements increases and PDL value of each device decreases. This is good since PDL in real-life communication systems tend to come from many components with a small PDL value each.

Other interesting thing to notice is that the maximum deviation from orthogonality seemingly is the same for all the cases when the addition of the PDL values of all the components in the system is the same.

On the other hand, when the number of elements increases but with the value of each element kept constant, we have seen how fast the width of the distribution increases as the number of elements increases.

In PolTDM configuration, it does not matter the phase difference, if we change the phase we always obtain the same results, for both GST and SM signal.

In the GST signal, results obtained are exactly the same than in the conventional configuration for all the cases (3, 10 or 15 PDL elements). That is because SOP of GST signal in this case is aligned to the PBS axis,

With the SM signal, however, we experiment loss, for all the seeds we obtain a γ_{TDM} value lower than one.

In PolMUX configuration, statistics of SM signal are broader than GST signal, since SM will experience both worst case (destructive), best case (constructive) and every intermediate case.

Finally, from the deviation from orthogonality results we can conclude that when the number of elements with PDL increases, the width of the distribution augments and the deviation is greater.

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I would also like to thank to my friends in Spain, for their encouragement from the beginning until the end. Thanks to Marina, Tomas, Pepe, Nimes, Pau, Jordi, Marta, Dani, Oscar, Cinto… Of course, also my friends in the university Gema, Alicia, Tato, Juan, Sergi and mainly to Diana, without her this would be really hard.

I do not forget all my family: uncles, cousins and my grandmother… particularly to Marian, Antonio, Mari and Blas. I am grateful to have them always near of me.

Last but not least, I would like to thank my parents and my sister, without them I would not be here, not only for their economic support. I want to thank them more important things like making me happy in most heavy moments during my studies and during my life and helping me in all I have needed.

APPENDIX

Matlab script that reads Stokes parameters from a file and calculates the coefficients of a Jones matrix

```
%______________________________________________________
%
%             OptSim Matlab Cosimulation
%            Automatic Elliptic Polarizer
%
% Name          : AEP.m
% Author        : Vegard L. Tuft
% Creation Date : Friday Feb. 9 2007
% Update Date   : Tuesday Feb. 13 2007
%______________________________________________________
%
%            MATLAB workspace variables
%
% - Component parameters defined in the .dta file
%
% position :: string
%   parameter position - position of polarizer
%
% sop_file :: string
%   parameter sop_file - name of file to read optimum
polarizer position
%   from
%
% file_sop_position :: integer number
%______________________________________________________
%
```

```
    % Initializing the output port signal equal to the
input port signal

    OutNode{1} = InNode{1};

    % Calculate complex coefficients for transfer matrix

    simno = 1;
    rid = fopen(strcat(sop_file,'_res','.txt'),'at+');
    fseek(rid,0,'bof'); %set pointer to beginning of file
    rline = fgetl(rid);
    if (~ischar(rline)) %file is empty so write header
        fprintf(rid,'Sim#   seed   S1   S2   S3   aux_angle
phase_diff\n');
    else
    %if file is not empty read line-by-line until the end
        while 1
            rline = fgetl(rid);
            if ~ischar(rline)
                % end of file - last line has been passed
                break; %necessary!!
            else
                lastrline = rline;
            end %if ischar
        end %while

        tempvar = sscanf(lastrline,'%f');
        simno = tempvar(1)+1;
        clear tempvar lastrline rline;
    end %if ischar
```

```
fid = fopen(strcat(sop_file,'.txt'),'rt');
if (fid>-1)
    % Read data from file, one line at a time
    teller = 0;
    if (strcmpi(last_line,'No'))
        tline = fgetl(fid); %first line is a header
% it is important that the SOP file has the same number
of lines as the number of iterations in the simulation

        for j = 1:simno
            tline = fgetl(fid);
        end
        simdata=sscanf(tline,'%f');
    else
        while 1
            tline = fgetl(fid);
            if ~ischar(tline)
                % end of file-last line has been passed
                break;
            else
                lastline = tline;
            end
        end
        simdata = sscanf(lastline,'%f');
    end %if strcmpi
else
    position = 'PassThrough';
end %if fid
fclose(fid);
```

```
  if (~strcmpi(position,'PassThrough'))
    % S1 is element no. file_sop_position, S2 is the
next etc.
    aux_angle = 0.5.*acos(simdata(file_sop_position));
    phase_diff = 2.*pi()-
atan2(simdata(file_sop_position+2),simdata(file_sop_positio
n+1));
    % (phase difference is defined as phaseX-phaseY in
OptSim!)
    fprintf(rid,'%d %d %5.4f %5.4f %5.4f
',simno,simdata(1),simdata(file_sop_position),simdata(file_
sop_position+1),simdata(file_sop_position+2));
    fprintf(rid,'%5.4f %5.4f\n',aux_angle,phase_diff);

    c11 = complex(cos(aux_angle).*cos(aux_angle),0);
    c12 =
complex(sin(aux_angle).*cos(aux_angle).*cos(phase_diff),-
sin(aux_angle).*cos(aux_angle).*sin(phase_diff));
    c21 =
complex(sin(aux_angle).*cos(aux_angle).*cos(phase_diff),sin
(aux_angle).*cos(aux_angle).*sin(phase_diff));
    c22 = complex(sin(aux_angle).*sin(aux_angle),0);

    if (strcmpi(position,'Orthogonal_to_Optimized'))
      % switch c11 and c22
      tempvar = c22;
      c22 = c11;
      c11 = tempvar;
      clear tempvar;
      % and change sign of cross terms
      c12 = -c12;
      c21 = -c21;
    end
```

```
        % This routine is for singel channel signals only
        % Check for single or double polarization is set
        if (~isempty(OutNode{1}.Signal(1).Ey))

            for i = 1:InNode{1}.Signal(1).noPoints

                OutNode{1}.Signal(1).Ex(i) = ...
                    c11 .* InNode{1}.Signal(1).Ex(i) + c12
.* InNode{1}.Signal(1).Ey(i);
                OutNode{1}.Signal(1).Ey(i) = ...
                    c21 .* InNode{1}.Signal(1).Ex(i) + c22
.* InNode{1}.Signal(1).Ey(i);

            end % for i

        end % if isempty

    end %if strcmpi

    fclose(rid);
```