Algorithm for the dynamic compensation of Chromatic Dispersion in XGS-PON network architecture

A Trujillo, G Gomez and A Zemanate.

1 GNTT – (Grupo de Nuevas Tecnologías en Telecomunicaciones) Departament of Telecommunications, Faculty of Electronic Engineering and Telecommunications, University of Cauca, Colombia. angievti@unicauca.edu.co

Abstract. Nowadays, communication system by 10 gigabit capable symmetric passive optical network (XGS-PON), provide the highest bandwidth and speed of all modern communication networks, however, these networks present difficulties on responding to degradations in transmission in optical fiber communication systems. Effects such as dispersion, attenuation and nonlinear effects lead to the degradation and/or lossing of information in the link. In the case of optical fiber, chromatic dispersion (CD) is the degradation that most affects communication systems, this effect happens because of the pulses emitted by the source are made up of different wavelengths, which in turn travel at different speeds, which generates different arrival times to the receiver, causing a temporary widening of the pulse and giving rise to the emergence of intersymbolic interference [1]. The CD impact is highly significant in the quality of the transmitted optical signal, since it restricts the transmission speed and link length. Therefore, it is necessary to implement compensation techniques that contribute to reduce the degradations caused by chromatic dispersion. This article presents the elaboration of a chromatic dispersion compensating module implemented and co-simulated in Matlab of MathWorks and OptSim of Rsoft, in order to mitigate the degrading effects that the CD brings, and in this way to find solutions in the field of digital processing of signals that support the demands of modern architectures.

1. Introduction
The demand by more users and better services, promotes the study of methods that allow a more efficient use of the resources present in the communication systems. In this context, fiber optic is proposed as an alternative in the design of wired networks due to the handling of high data transmission rates, low attenuation and implementation in long distance links [1]. XGS-PON, provides solutions based on the handling of high access capacities, long transmission distances and high bandwidth. However, when an optical signal is transmitted on the fiber, it suffers the effects of linear and non-linear degradations that may significantly affect the performance of the system. The CD is the linear phenomenon that most affects the quality of the signal, which makes required the implementation of advanced compensation techniques in order to counteract this effect.

2. XGS-PON (ITU-T G.9807.2)
The International Telecommunications Union (ITU), defines the G.9807.2 standard, that specifies an XGS-PON type network, where a symmetric speed of 10Gbps is reached, obtaining higher bandwidths. The figure
1, represents an XGS-PON technology where a simultaneity of various types of channels on an only network is admitted, allowing to extend the usability of the network, in terms of speed, capacity and bandwidth, improving the spectral efficiency without needing to intervene in the physical network infrastructure. This implies that more information can be transported on the same bandwidth, obtaining that four optical channels of 10Gbps occupy the same bandwidth that four optical channels of 40Gbps [2].

![Architecture XGS-PON](image)

Figure 1. Architecture XGS-PON [2].

Despite the efficiency of this type of networks in the transmission of information, they must face to physical characteristics of the fiber and the quality of the optical components that could eventually be limiting in their performance and implementation costs can also be increased [3].

3. Dispersion

The dispersion defines the effect in which pulses of the signal transmitted through optical fiber travel with different speeds, therefore, the arrival at the receiver is at different times. Aspects as diameter core, refractive index, wavelength, influence in the behavior and state of the transmitted signal, causing the pulse to widen. The effect of the dispersion affects the performance of the optical link implemented, causing the pulses to overlap, thus generating intersymbolic interference (ISI) [4].

![Dispersion at different speeds](image)

Figure 2. Dispersion at different speeds [5].

The figure 2 shows that the signal is more vulnerable to dispersion if it is transmitted at high speeds, therefore the dispersion is proportional to the length of the link and transmission speed, thus, these aspects are limiting in an optical communication link.

3.1. Chromatic Dispersion.

The CD is caused, mainly, because different spectral components of the transmitted signal are propagated at different speeds over the fiber length, as a result, these components have different times of arrival at the receiver. In figure 3 it can be seen how the pulse width increases and the space between bits is reduced. The
result is that in reception it isn’t possible to correctly recognize if the data received at a given moment corresponds to a logical value of one or zero [1].

Figure 3. Pulse dispersion due to wavelengths [5].

As consequence of this effect, the pulse in the receiver arrives distorted, causing intersymbolic interference. CD is a cumulative effect, where the longer link length, the greater the total accumulation will be, therefore, the distance that a digital signal can travel before needing regeneration or compensation is limited [6]. Chromatic dispersion occurs due to two components: material dispersion and waveguide dispersion.

Figure 4. Total CD. Material Dispersion + Waveguide Dispersion [1].

The material dispersion involves the refractive index, which consists in the ratio between the speed of light in the material and the speed of light in vacuum. This type of dispersion is caused by the variation in the refractive index of the material used to make the fibers with respect to the wavelength [4]. Furthermore, the waveguide dispersion depends on several parameters [1] such as: i) the difference of the refractive index between the core and the coating ($\Delta n$), ii) reduction in the diameter of the core and, iii) the manufacture of the fiber. As a result, the material dispersion and waveguide dispersion, produce the same effect on the signal transmitted by the fiber, therefore, the concept chromatic dispersion is used in a general way. Figure 4 illustrate how the total CD in a fiber results from the sum of material dispersion and waveguide dispersion.
3.2. Chromatic Dispersion Compensation.

The impacts of the effects of the CD are highly significant in the quality of the transmitted optical signal, since they restrict the transmission speed and link length. Therefore, in the fiber optic communication links it should be considered the implementation of a compensating module that allows a proper operation of the optical link [7][8].

3.2.1. DCF: Dispersion Compensating Fiber.

These are fibers that have a very high negative CD value and are capable of compensating the total dispersion in an optical link. The compensation is done by inserting sections of standard transmission fiber with DCF compensating fibers. The length of these sections depends on the total length of the standard fiber link, thus, the effects caused by the cumulative total dispersion are compensated and minimized. The insertion of the DCF fiber in the links can be done in different ways: at the beginning of the link (Pre-compensation), at the end of the link (Post-compensation), or inside of the link (Symmetric compensation) [9][10].

However, despite the great utility of this type of optical compensator, it has drawbacks [11] since it adds high attenuation (0.6 dB / km of DCF), requiring more complex optical amplifiers, where these can cause additional dispersion by polarization mode.

3.2.2. Electronic compensation.

Electronic Dispersion Compensation (EDC), is composed of techniques that make use of Digital Signal Processing (DSP) and electronic equalization [12], which makes it possible to eliminate the total accumulated CD at the end of the link and allows to reduce installation costs compared to DCFs. The EDC is described in recommendation ITU-T G.959.1 [13], where is contained information about the long distance networks with standard G.652 fibers [14].

4. Characterization of the simulation environment.

The tools used for signal processing and the integration into modules are Matlab [15] and OptSim® [16], respectively. These tools are characterized by their usefulness in integrated development, simulation and modeling environments, providing precision in the obtained results. One of the functionalities that OptSim presents is co-simulation with the Matlab tool. This interface allows OptSim users to run Matlab simulations that interact completely with the OptSim data structure and leads to a joint simulation. The step-by-step tutorial of its interconnection is reported on the article “Methodology of co-simulation environments for Matlab/OptSim tools” [17], where environments that allow the interaction of modules and processes based on algorithms are generated, to increase the collective and individual capacities of the mentioned tools.

For the simulation environment, XGS-PON technology is defined at a distance of 100Km according to the definition of the standard G.691 [3][18], the optical fiber used along the link is single-mode Corning SMF-28e+ standard, the dispersion coefficient is obtained from the datasheet provided by the manufacturer; being in this case around 17 ps/nm*Km and the attenuation value around 1550 nm corresponds to 0.275 db/Km. The general characteristics of the model are defined in table 1 [14][19].
Table 1. Characteristics of the simulation scenario.

| SECTIONS | DEVICES |
|----------|---------|
| TX       | Mach-Zehnder Optical modulator  
|          | Bessel Filter of order 6  
|          | Laser CW, 2.5MHz of FWHM, 0dBm  
|          | 100Ghz channel spacing  
|          | C Band, arround of 1530nm  
|          | 2.5Ghz Transmission speed  |
| CHANNEL  | ITU-T G.652 standard  
|          | SSMF-28 fiber  
|          | EDFA, 15dBm  
|          | EDFA BOOSTER, 20dBm  
|          | DCF fiber  |
| RX       | -28 dBm sensitivity  
|          | Bessel electric filter of order 6  
|          | Cosine optical filter |

5. Algorithm design.

The elaboration of the compensating code starts from the theoretical formulas that generate the dispersion [12], which include waveguide dispersion \( (D_G) \) and material dispersion \( (D_M) \) defined in equation (1):

\[
CD_T = D_G + D_M
\]  

Initially, the size of the vector coming out of the modulator should be considered, because this will be the signal from OptSim to be treated in Matlab, for this procedure, the Matlab command window is used, since it allows to see values, size and orientation of the vector, in this case 1 x 55296 values corresponding to the size of the vector. The minimum and maximum wavelength value \( (\text{lambda}) \) expressed in nanometers is taken according to the single-mode fiber working windows recommended by ITU-T G.652 [14]. The values present in figure 5 characterize the optical fiber mathematically, these are necessary in the development of this algorithm.

\[
\text{lambda} = [1900:0.006111:3007770:1489999999:185971]'*1e-9
\]

\[
C = 299792458;  
\pi = 3.1415926;  
\rho = 4.1e-6;  
\delta = 0.003;  
\Delta n = 1.3024  
\]

Figure 5. Parameters that characterize the fiber [12].

5.1 Material dispersion calculation.

The calculation concerning to the material dispersion; equation (2), is determined in terms of the wavelength vector \( (\lambda) \) of size 1x55296 and the vacuum speed of light \( (c) \), which for conversions between frequency and wavelength must be equal to 2,99792458*10^8 m/s, according to ITU G.694.1 [12]:

\[
D_M = -\frac{\lambda}{c} \cdot \frac{dn}{d\lambda^2}
\]  

5
The material dispersion occurs due to the variation in the refractive index, depending on the wavelength [12]; this is equation (3):

\[
\frac{d^2n}{d\lambda^2} = \frac{d^2}{d\lambda^2} \sqrt{1 + \frac{4(G \cdot \lambda^2)}{\lambda^2 - \lambda_1^2}}
\]

Figure 7 contains the total material dispersion obtained, getting the expected behavior according to [1].

\[
\text{Matdisp} = -\left(\frac{\lambda}{c}\right) \cdot \text{ps/nm.Km}
\]

\[
\text{Matdisp} = \text{Matdisp} \cdot 10^{-3}
\]

\[
B = \text{Matdisp}, 1;
\]

\[
\text{figure}(1)
\]

\[
\text{clf}
\]

\[
\text{hold}
\]

\[
\text{xlabel('\mu m')}
\]

\[
\text{ylabel('ps/nm.Km')}
\]

\[
\text{title('Dispersión de Material')}
\]

\[
\text{plot}([\lambda, \text{Matdisp}, '.-'])
\]

\[
\text{grid on}
\]

Figure 6. Total Material Dispersión Calculation.  
Figure 7. Material Dispersion.

5.2. Waveguide dispersion calculation.

According to [12], considering that for Corning smf-28e + single mode optical fiber, for the respective simulations, it is determined how many propagation modes the fiber supports, it must be less than 2.5, to ensure that the fiber propagates a single mode, however, the line of code necessary for multimode fibers has been commented, for general interest. In order to facilitate and guarantee a correct obtaining of calculations in the Matlab tool, it is decided to split the total formula in two [12]; remaining as evidenced in equations (4) to (6) and in figure 8.

\[
D_{\lambda_1} = -\sqrt{\frac{4(G \cdot \lambda^2)}{\lambda^2 - \lambda_1^2} \cdot \Delta}
\]

\[
D_{\lambda_2} = 0.80 + 0.549 \cdot (2.83 - V)^2
\]

Now, the calculation of the total waveguide dispersion is performed, resulting

\[
D_G = D_{\lambda_1} \cdot D_{\lambda_2}
\]
5.3. Total Dispersion Calculation (Chromatic Dispersion)

Having the two types of dispersions that compose the chromatic dispersion, the total dispersion value is obtained. It can be seen how the slopes of the mentioned dispersions complement each other, adding point to point and thus generating; the total dispersion, as shown in figure 10.

![Figure 10. Total Dispersion. (CD).](image)
An important and fundamental part for the development of the work, and that allows to reach the objective of reducing the CD immersed in the link, is presented in figure 11, in the framed code line. When changing the slope of the total dispersion obtained, dispersion is subtracted from the signal from the OptSim® modulator, that is that a dispersion is being generated that is counteracts point to point to the accumulated in the simulation link. Figure 12 shows the result of this change of slope.

![Figure 11. Change of slope of total dispersion obtained.](image1)

![Figure 12. Total dispersion with negative slope.](image2)

Through the development and implementation of the chromatic dispersion compensating algorithm, it was found that it is possible to modify some configuration variables, which leads to the generation of different degrees of liberty, focused on the control of the core radius, the refractive index and the working wavelength, thus allowing to change the dispersion slope to achieve different compensation percentages in the digital treatment of the signal, without any need to make physical changes in the communication link.

6. Implementation and analysis

The compensations are usually made in the form of: zero, normal, anomalous, but due to the characteristics and objectives of the present work, it is carried out in a normal and anomalous way, with percentages of 25, 50, 75 and 100% to perform the respective analysis, and thus generate the relevant case studies.

As presented in Figure 13, and as mentioned in the development of the algorithm, the processing of the signal that is processed in the designed compensator module is carried out in the electrical domain, and for this reason requires prior information of the accumulation of the dispersion and the effects that it produces in the output signal generated by the transmitter, allowing the implementation only of the post compensated mode, due to the high information processing limitations of the electro-optical conversion modules of the OptSim tool, generated by the high data transmission speeds, however, it is possible to implement higher processing capacity equipment in the future, which will mitigate these limitations. A back to back link is generated, in order to obtain ideal values of optical monitoring parameters due to the absence of elements that interfere in the course of the signal. The above is evidenced in table 2.
Figure 13. Simulation scenario.

Table 2. Optical monitoring parameters dependent on system degradations. Back to back link.

| Distance [Km] | BER   | Q Factor [dB] | Jitter[ns] |
|---------------|-------|---------------|------------|
| 100           | 1e-40 | 40            | 0.0170     |

In the same way, a link without compensation is implemented, referring to the case in which the worst OPM values would be obtained, given that there are not devices that recover the signal that arrives at reception. The above is corroborated in table 3.

Table 3. Optical monitoring parameters dependent on system degradations. Link without compensation.

| Distance [Km] | BER   | Q Factor [dB] | Jitter[ns] |
|---------------|-------|---------------|------------|
| 100           | 4.35 e-6 | 13.091    | 0.0282     |

From tables 2 and 3, the significant difference in OPM values can be seen, noting how the network needs regeneration of the transmitted signal. However, in terms of compensation percentages, the method used by the module consists in the variation of a multiplier factor (Matlab®) that interacts with the data vector that represents the input signal in terms of the delay and widening of the pulse introduced by the medium due to the CD accumulated in the system (OptSim®). This factor is related to the possibility of delaying the signal (jitter) allowing to generate a decision interval, for a minimum delay compensating in a 100% the dispersion of the input signal; multiplier factor of 1; and a null compensation for a multiplier factor of 35.
When implementing the simulation scenario with each configuration factor, it was analyzed that only for a 100% compensation percentage, the OPM values were within the ranges established by the ITU; Due to this, the results presented below correspond to the data thrown by the communication link, compensated to 100%.

In order to analyze the behavior of the CD and the vulnerability of the module against it, it is decided to see the shift of the pulses in reception. It is necessary to see the eye diagrams that are generated once the CD increases, therefore, the CD is used as a variable to modify, this results are shown in the figure 18.

17 different CD values have been generated, starting at 100 ps/nm*Km and ending at 1700 ps/nm*Km, with jumps of 100 ps/nm*Km. This is because the maximum accumulated CD value in a 100Km link with SSMF-28 CD fiber = 17 ps/nm*Km is 1700 ps/nm*Km. Figure 18 illustrates the pulse shift once the CD increases, indicating that the expected jitter value in reception will increase. This is done in order to show how the CD increases directly proportional to the increase in link length. To avoid redundancy, the 17 cases are not presented, but only those that generate significant analyzes. These are presented below:
100 ps/nm*Km

![Figure 19](image)

**Figure 19.** Accumulated chromatic dispersion of 100 ps/nm*Km.

Since it is known that the total accumulated CD is 1700 ps / nm * Km for a total length of 100Km, by equivalence it has to be 100 ps / nm * Km accumulated, they correspond to a length of 5.88Km of fiber. The parameters obtained from this configuration are presented below:

**Table 4.** Optical monitoring parameters dependent on system degradations. Accumulated link of 100 ps/nm*Km.

| Distance [Km] | BER  | Q Factor [dB] | Jitter[ns] |
|---------------|------|---------------|------------|
| 5.88          | 1e-40| 27.81         | 0.0167     |

As evidenced in Figure 19 and Table 4, the accumulated CD does not affect the performance of the link, therefore, the CD value is increased, in order to determine the limiting CD for the generated module.

1200 ps/nm*Km

![Figure 20](image)

**Figure 20.** Accumulated chromatic dispersion of 1200 ps/nm*Km.
In the same way, by equivalence, for 1200 ps/nm*Km, 70.58 Km are necessary. The parameters obtained from this configuration are presented below:

Table 5. Optical monitoring parameters dependent on system degradations. Accumulated link of 1200 ps/nm*Km.

| Distance [Km] | BER   | Q Factor [dB] | Jitter[ns] |
|---------------|-------|---------------|------------|
| 70.58         | 6.37e-18 | 18.74         | 0.0275     |

The change in the parameters of optical monitoring, indicates how to increasing the length of the link, causes more CD to be generated, causing the quality and performance of the link to decrease considerably. Since the BER still complies with the standards established by the ITU, the accumulated CD is increased again, in order to find the limitation.

- 1300 ps/nm*Km

Therefore, 1300 ps / nm * Km accumulated, correspond to a length of 76.47Km of fiber. The parameters obtained from this configuration are presented below:

Table 6. Optical monitoring parameters dependent on system degradations. Accumulated link of 1300 ps/nm*Km.

| Distance [Km] | BER   | Q Factor [dB] | Jitter[ns] |
|---------------|-------|---------------|------------|
| 76.47         | 4.85e-12 | 16.53         | 0.0279     |

Finally, it has been possible to obtain the minimum value accepted by the ITU in terms of BER, that is, until this link length is capable to compensate for the module generated in the so-simulation environment, complying with international standards. By increasing the distance, the jitter value is increased, however, lower values are achieved to the link without compensation, thus confirming that the compensator is doing its job.
1700 ps/nm*Km

![Figure 22. Accumulated chromatic dispersion of 1700 ps/nm*Km.](image)

**Table 7.** Optical monitoring parameters dependent on system degradations. Accumulated link of 1700 ps/nm*Km.

| Distance [Km] | BER    | Q Factor [dB] | Jitter [ns] |
|---------------|--------|---------------|-------------|
| 100           | ¡Error! | 11.49         | 0.0285      |

As shown in Table 7, this configuration is not acceptable, because the quality of the signal that reaches the receiver is poor. Due to this analysis, and in order to check the maximum length of the link obtained, it is decided to implement the link with 76Km of fiber, where it was obtained (see figure 23).

Given the above, it is concluded that the module designed in the present work, at a speed of 10Gbps, works in systems in which its maximum link length is 76Km; being this the limitation of this compensating module; otherwise, the system would not comply with international standards. Below are the values that were generated from the 17 CD variations, which were mentioned above. Table 8 contains this information.

As shown in Table 7, this configuration is not acceptable, because the quality of the signal that reaches the receiver is poor. Due to this analysis, and in order to check the maximum length of the link obtained, it is decided to implement the link with 76Km of fiber, where it was obtained (see figure 23).

Given the above, it is concluded that the module designed in the present work, at a speed of 10Gbps, works in systems in which its maximum link length is 76Km; being this the limitation of this compensating module; otherwise, the system would not comply with international standards. Below are the values that were generated from the 17 CD variations, which were mentioned above. Table 8 contains this information.

Case studies were generated around the behavior of the DCF immersed in the communication link, this in order to obtain a base behavior of the compensated system and thus be able to generate a comparative analysis of the behavior of the compensated link by means of DCF and designed module. The information obtained from the above is shown in table 9.
Table 8. Results Matlab module configured to 100%.

| CD [ps/nm*Km] | Jitter [ns] | BER    | Q Factor [dB] |
|---------------|-------------|--------|---------------|
| 100           | 0.0167      | 1e-40  | 27.81         |
| 200           | 0.0183      | 1e-40  | 24.44         |
| 300           | 0.0169      | 4.10e-39 | 22.51   |
| 400           | 0.0143      | 9.50e-23 | 19.92   |
| 500           | 0.0152      | 2.27e-18 | 18.75   |
| 600           | 0.0156      | 2.31e-19 | 19.17   |
| 700           | 0.0159      | 5.44e-22 | 19.88   |
| 800           | 0.0171      | 1.29e-32 | 21.46   |
| 900           | 0.0210      | 1.49e-35 | 22.04   |
| 1000          | 0.0244      | 2.58e-29 | 21.10   |
| 1100          | 0.0271      | 2.19e-25 | 20.49   |
| 1200          | 0.0275      | 6.37e-18 | 18.74   |
| 1300          | 0.0279      | 4.85e-12 | 16.53   |
| 1400          | 0.0280      | 1.21e-7  | 14.58   |
| 1500          | 0.0281      | 2.57e-6  | 13.17   |
| 1600          | 0.0281      | 2.89e-5  | 12.10   |
| 1700          | 0.0285      | ¡Error!  | 11.49   |
Table 9. Abstract table.

|                  | POST       | PRE        | SYMMETRICAL |
|------------------|------------|------------|-------------|
| **DCF - COMPENSATED 100%** |            |            |             |
|                   | ![Graph](image1) | ![Graph](image2) | ![Graph](image3) |
| BER               | 1e-40      | 1e-40      | 1e-40       |
| Factor Q [dB]     | 28.34      | 27.89      | 32.55       |
| Jitter [ns]       | 0.0180     | 0.0257     | 0.0093      |

| MATLAB MODULE – COMPENSATED 100% |            |            |             |
|----------------------------------|------------|------------|-------------|
| ![Graph](image4)                 | ![Graph](image5) | ![Graph](image6) | ![Graph](image7) |
| **Distancia [Km]**               | 5.89       | 76.47      | 100         |
| BER                              | 1e-40      | 4.55e-12   | ![Image](image8) |
| Factor Q [dB]                    | 27.81      | 16.53      | 11.43       |
| Jitter [ns]                      | 0.0157     | 0.0279     | 0.0265      |
7. Conclusions
Through the realization of this article, it was determined the incidence that the linear and non-linear effects generate in relation to the increase of the speed of data transmission was determined, observing the maximum operating limitation for the designed algorithm, for a compensation of 100% of the CD and lower propagation distances. In the same way, by simulating the different scenarios, it was identified that additional amplification stages are required so that the designed modules can work within the target parameters. A dynamic compensation of the Chromatic Dispersion was achieved in an XGS-PON network architecture.

References
[1] Collings B, Heismann F and Lietaert G 2010, Reference Guide to Fiber Optic Testing, JDS Uniphase Corporation 2.
[2] Gómez G 2019, Eficiencia espectral de formatos de modulación avanzados en redes XGS-PON, Visión Electrónica, ISSN: 1909-9746.
[3] Herrera J and Toledo J 2016, Análisis comparativo del desempeño de los formatos de modulación RZ-DQPSK y RZ-PDPSK frente a técnicas de compensación ópticas de la dispersión cromática en redes WDM a 10Gbps, Universidad del Cauca, Colombia.
[4] Pawan D and Vibha S 2014, Dispersion in Optical Fiber Communication, International Journal of Science and Research (IJSR), ISSN (Online): 2319-7064 3 Issue 10.
[5] Stepnæk L 2012, Chromatic dispersion in optical communications, Journal of Electrical and Electronic Engineering 7, No. 2, 142–151.
[6] Shevgaonkar R 2005, Fiber Optics, Dept. of Electrical Engineering, Indian Institute of Technology, Bombay.
[7] Ramaswami R, Sivarajan K and Sasaki G 2009, Optical networks: a practical perspective.
[8] Sethi R and Goel A 2015, Dispersion compensation in optical communication system by employing 16-QAM modulation using OFDM, IMPACT: International Journal of Research in Engineering & Technology (IMPACT: IJRET) ISSN (E): 2321-8843; ISSN (P): 2347-4599 3, Issue 2.
[9] Florez J 2016, Compensación de los Efectos de Propagación en Enlaces Ópticos, Universidad Pontificia Bolivariana, Medellín.
[10] Agrawal P 2012, Fiber-optic communication systems, John Wiley & Sons 222.
[11] Kahlon N and Kaur G 2014, Various dispersion compensation techniques for optical system, open journal of communications and software 1, Number 1.
[12] Binh L 2009, Optical Fiber Communication Systems, CRC Press 1.
[13] ITU-T Rec G.959.1 2012, Optical transport network physical layer interfaces, Telecommunication Standardization Sector of ITU.
[14] ITU-T Rec G.652 2016, Characteristics of a single-mode optical fiber and cable, Telecommunication Standardization Sector of ITU.
[15] Matlab 2014, User Guide, Mathworks.
[16] RSoft, Optsim user guide physical layer division 400 executive boulevard, Suite 100 Ossining, NY 10562.
[17] Trujillo A, Zemanate A, Gómez G and Toledo A 2018, Metodología de entornos de co-simulación para las herramientas Matlab/OptSim, Universidad del Cauca.
[18] Kartalopoulos S 2000, Introduction to DWDM technology: data in a rainbow, SPIE Optical Engineering Press.
[19] UIT-T Rec. G.691 2006, Interfaces ópticas para los sistemas monocanal STM-64 y otros sistemas de la jerarquía digital síncrona con amplificadores ópticos, Telecommunication Standardization Sector of ITU.
