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Simulation of Chromatic Dispersion Effects in a Metropolitan ITU-T G.652.D Optical Fiber Link at 10 Gbps, 100 Gbps and 200 Gbps with NRZ and RZ Modulation Format

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Abstract

For decades, telecommunication networks have been evolving with the use of optical fiber as transmission medium. Data is transmitted through optical fiber in the form of light. Light pulses, while propagating in the optical fiber, undergo effects of different nature due to certain phenomena. Among these phenomena, Chromatic Dispersion (CD) is a phenomenon that results from the dependence of the optical fiber core's refractive index with the wavelength. Thus, the components of the light pulse propagate with different speeds in the optical fiber. This results in a broadening of the light pulses, thus causing signal degradation. CD limits the performance of optical fiber telecommunication systems, especially when transmission rates are increased. It is therefore important to study it in order to find mechanisms to reduce its negative impact on signals. From a simulation, we study and analyze, in this work, the effect of CD in an ITU-T G.652.D optical fiber link of a metropolitan network to be deployed in Lomé, the capital city of Togo. The NRZ and RZ modulation formats are considered using bit rates of 10 Gbps, 100 Gbps and 200 Gbps and the study is operated at a wavelength of 1550 nm with a power of 10 dBm (10 mW). We use eye diagram, Min BER and Q-Factor to carry out the performance analysis of the transmission link with the different links. The distortion of the signal is a function of the distance. RZ format is good for short distance and NRZ is good for long distance. At 100 Gbps, the signal is much more distorted than 10 Gbps.

Keywords

Optical Fiber, Chromatic Dispersion, NRZ, RZ, Optisystem, Metropolitan Network

1. Introduction

It is undeniable that the world of telecommunications has experienced profound changes with the advent of optical fiber as a transmission medium [1]. Optical fibers are manufactured by glass or plastic or silica; they are usually used to transmit signals in the form of light. The most important breakthrough due to optical fiber is in broadband services, because it offers the highest speed for data transmission in long-distance communications [2]. There are two types of conventional optical fibers used in telecommunications networks: single-mode optical fibers and multimode optical fibers. For long-distance transmissions, such as in submarine cable networks or in terrestrial backbone networks, single-mode optical fibers are highly recommended for use. Single-mode optical fibers are also used in fiber optic access networks with fiber to the home (FTTH) technologies. Optical fibers used in telecommunications and data transport networks are standardized under the guidance of several international organizations, such as International Telecommunication Union (ITU) and the International Electrotechnical Commission (IEC). ITU's Telecommunication Standardization Sector (ITU-T) is developing standards, also known as ITU-T Recommendations, describing the geometrical properties and transmission properties of multimode and single-mode fiber optic cables. These ITU-T standards, also known as ITU-T Recommendations for various optical fibers used in telecommunications, are ITU-T G.651.1, ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656, and ITU-T G.657 [3]. Among these optical fibers, G.652.D optical fiber is widely used in telecommunications networks in Africa. Due to certain physical phenomena, the optical signal, as it propagates through the optical fiber, undergoes several effects that negatively affect its quality [2] [4] [5]. Attenuation and distortion of the signal are some examples of these phenomena. The signal distortion results from the broadening of the light pulse as it propagates through the fiber. Chromatic dispersion is a factor that broadens the signal, increases the spectral width and limits the quality of signal [2]. It originates from the variation of the refractive index of the optical fiber depending on the wavelength or frequency of the signal [6]. This variation causes the different components forming the light pulse to propagate with different speeds, which gives rise to Inter-Symbol Interference (ISI) [7] and causes a broadening of the signal. In fiber optic communication networks, the resulting chromatic dispersion effects lead to pulse distortion and degradation of the transmitted signal, causing data loss, which limits the transmission capacity of the fiber. Chromatic dispersion is still attracting researchers working in the field of optical fiber communication [2] [8]. In this work, we consider for the study a metropolitan telecommunication backbone network to be deployed in Lomé, the capital city of Togo, West Africa. This metropolitan fiber optic backbone network consists of five nodes organized in a ring architecture. The nodes are deployed in different locations of the city; the longest distance between two nodes is 30 km. We investigate through simulations the effects of chromatic dispersion in different fiber optic links of this optical network using a signal propagating in the C band at bit rates of 10 Gbps, 100 Gbps and 200 Gbps, the modulation formats used are NRZ and RZ. In Section 1, we present an introduction; Section 2 presents a brief theoretical approach to chromatic dispersion, followed by Section 3, which presents the simulation. We will continue in Section 4 with an analysis and discussion of the simulation results with reference to the theory and Section 5 presents the conclusion.

2. Theoretical Approach to Chromatic Dispersion

Chromatic dispersion in optical fibers arises because the refractive index of the fiber core varies with the wavelength of the transmitted signal. The Group Velocity Dispersion (GVD) $\boldsymbol{\beta}_2$ is responsible for the chromatic dispersion, which is the second derivative of the propagation constant. The physical interpretation of values of this parameter depends on the degree of broadening of the signal [9], and it is related to the chromatic dispersion by Equation (1) [6] [10]:

$$\boldsymbol{D} = \frac{\boldsymbol{d}}{\boldsymbol{d\lambda}}\left(\frac{1}{\boldsymbol{v_g}}\right) = -\frac{2\boldsymbol{\pi c}}{\boldsymbol{\lambda}^2}\boldsymbol{\beta}_2 \tag{1}$$

where $\boldsymbol{\lambda}$ is the wavelength and $\boldsymbol{v_g}$ is the group velocity.

Chromatic dispersion can be expressed in two types of dispersion: waveguide dispersion and material dispersion.

2.1. Material Dispersion

The dispersion of the material in optical fibers comes from the variation of the refractive index of silica as a function of the wavelength. It expresses the absorption of electromagnetic radiation by silica. It is determined by the relation (2):

$$D_M = \frac{1}{c}\frac{dn_{2_g}}{d\lambda} \tag{2}$$

where n_{2_g} is the refractive index of the cladding.

2.2. Waveguide Dispersion

The waveguide dispersion can be approximated by considering that the refractive index of the fiber does not vary with wavelength, which is obviously false. It results from the difference in signal power distribution between the core and the cladding of the fiber, especially when the wavelength is large [10]. It is determined by the relation (3) [6]:

$$D_w = -\frac{2\pi\Delta}{\lambda^2}\left(\frac{n_{2_g}^2}{n_2\omega}\frac{Vd^2(Vb)}{dV^2} + \frac{dn_{2_g}}{d\omega}\frac{d(Vb)}{dV}\right) \tag{3}$$

where the parameter V represents the normalized frequency and b is the normalized propagation constant. The waveguide dispersion depends essentially on the parameter V. The two types of dispersion combined give chromatic dispersion.

$$D = D_M + D_w \tag{4}$$

In the presence of chromatic dispersion, the spectral components of the signal propagate with different group velocities, thus causing signal broadening and distortion.

3. Simulation of Chromatic Dispersion

3.1. Network Description

The government of Togo with the aim of offering high-speed digital services to all the ministries and state institutions located in the capital city, Lomé, built up an E-Government and high-capacity network. The structure of this E-Government network falls into three layers: backbone layer, convergence layer and access layer. The backbone layer of E-Government network connects all the backbone nodes as a whole support body. The ring network topology has been chosen for improving the reliability. There are five backbone nodes organized in a ring configuration that are MPENTD, which serves as the Network Operation Center (NOC), CACAVELI, OUA, LOME PORT and LOME CENTER. In order to extend the bandwidth and improve the utilization of optical fiber, a Dense Wavelength Division Multiplexing (DWDM) transmission system has been deployed. C-band wavelengths have been chosen, and each wavelength can operate at 10 Gbps, 100 Gbps or 200 Gbps. Optical fiber cables containing YOFC Fullband Low Waterpeak single-mode [11] optical fiber compatible with ITU-T G.652.D [12] recommendation are chosen as the transmission medium between the different nodes of the network. Reels of optic cables of 3 km each are considered. Figure 1 shows the design of the network architecture with different nodes and the distances between the nodes. The longest distance between two nodes is 30 km.

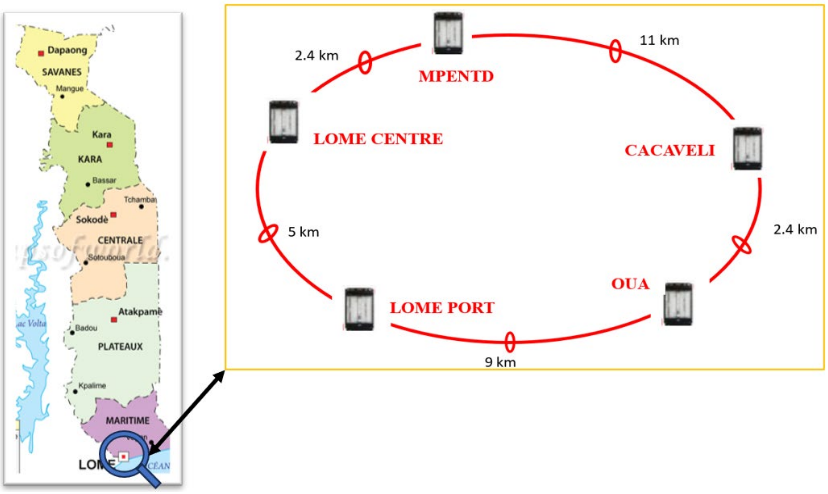

Figure 1. Design of the network architecture.

3.2. Simulation Parameters

In order to have a closer look at the impact of chromatic dispersion on a signal, we have carried out simulations using the Optisystem software, which allows modeling transmission systems. For the simulation, we consider the 30 km metropolitan network link and the different sections of this link with lengths 2.4 km, 11 km, 5.2 km and 9 km as shown in **Figure 1**, and a power of 10 dBm (10 mW) [1]. The different sections were considered in order to evaluate their individual contribution to the effects of chromatic dispersion throughout the line. **Tables 1-3** present respectively the parameters of the optical fiber, the equivalent attenuation coefficients at each section of the link considered and the parameters of the injected signal.

Table 1. Optical fiber parameters.

Settings	Values
Length	30 km
Attenuation at 1550 nm	0.26 dB/km
Chromatic dispersion	17 ps/nm/km
GVD	-20 ps^2/km

Table 2. Attenuation of each section considering splice and interconnection losses.

Length	Attenuation
2.4 km	0.61 dB/km
11 km	0.31 dB/km
9 km	0.33 dB/km
5.2 km	0.41 dB/km

Table 3. Signal parameters.

Settings	Values
bit rate	10 Gbps, 100 Gbps, 200 Gbps
Wavelength	1550 nm
Power	10 dBm (10 mW)
Binary sequence	0101101110
Frequency	193.41 THz
Modulation format	NRZ and RZ

These attenuation coefficients were evaluated taking into account the linear loss of the fiber, the splice and interconnection losses. In order to evaluate the impact of chromatic dispersion in this metropolitan network during an increase in the bit rate, we carried out the simulation considering bit rates of 10 Gbps, 100 Gbps and 200 Gbps. **Figure 2** shows the simulation diagram used under Optisystem.

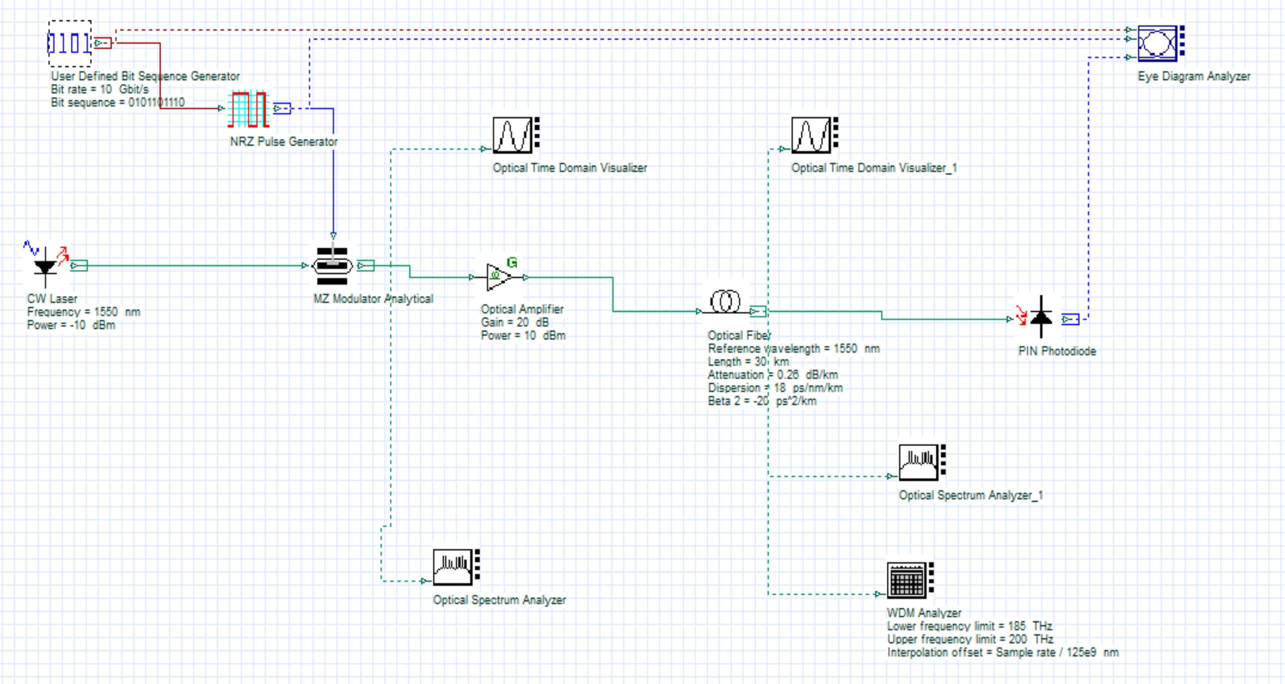

Figure 2. Simulation scheme.

3.3. Simulation Results

At the end of simulations, the following results are obtained depending on the bit rate and the modulation format. To assess the quality of the signal, the eye diagram was considered in the case of the length of 30 km and Min BER and Q-Factor were carried out for all distances.

3.3.1. Results of the Different Sections

For the results of each section, we present the data collected in input and output for 10 Gbps and 100 Gbps, considering the NRZ and RZ modulation formats. Figures 3-10 present the input data and output data for every section. Table 4 presents performance indicator: Min BER and Q-Factor.

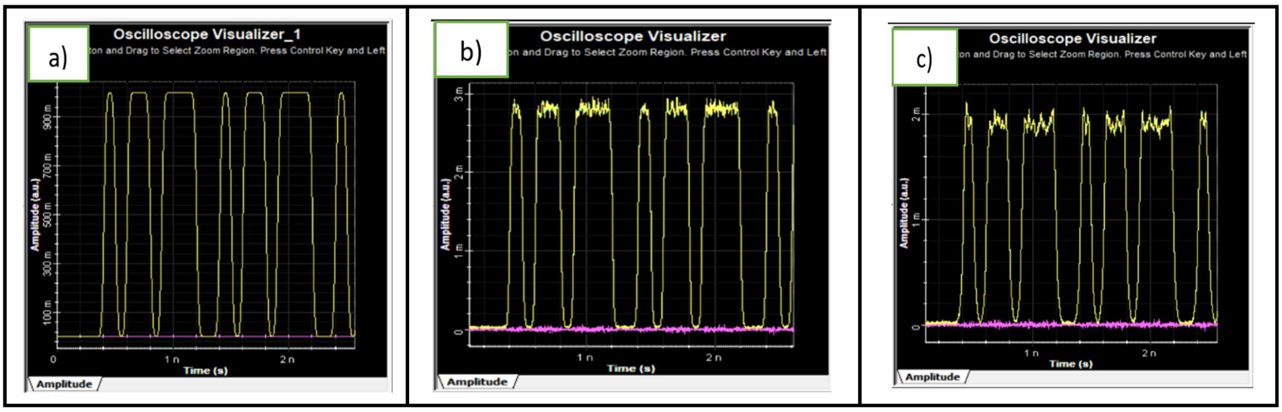

Figure 3. Presentation of the input at 10 Gbps (a), the output of the section of 2.4 km (b) and the output of the section of 11 km (c) for NRZ.

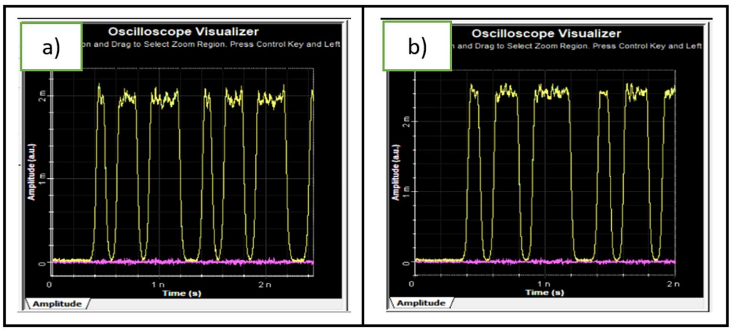

Figure 4. Presentation of the output of the section of 9 km (a) and the output of the section of 5.2 km (b) at 10 Gbps for NRZ.

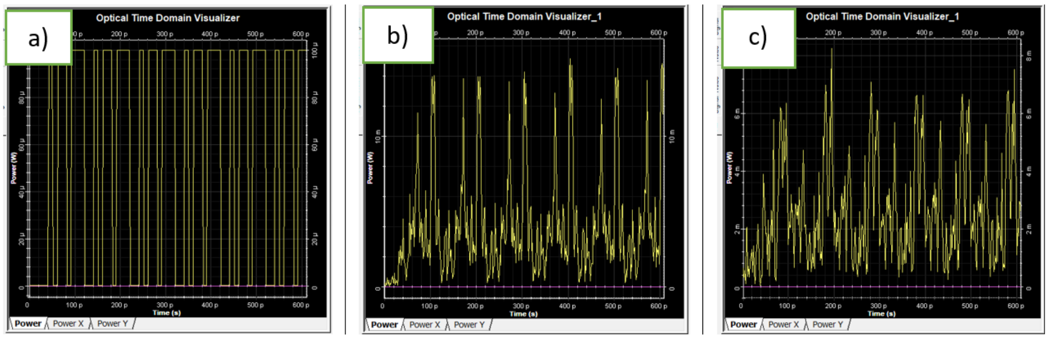

Figure 5. Presentation of the input at 100 Gbps (a), the output of the section of 2.4 km (b) and the output of the section of 11 km (c) for NRZ.

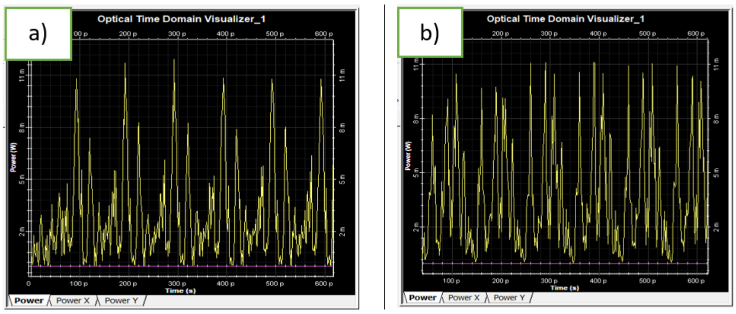

Figure 6. Presentation of the output of the section of 9 km (a) and the output of the section of 5.2 km (b) at 100 Gbps for NRZ.

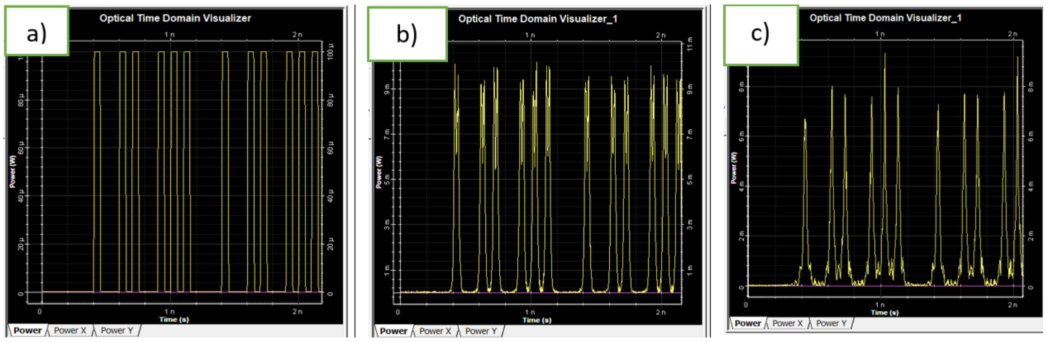

Figure 7. Presentation of the input at 10 Gbps (a), the output of the section of 2.4 km (b) and the output of the section of 11 km (c) for RZ.

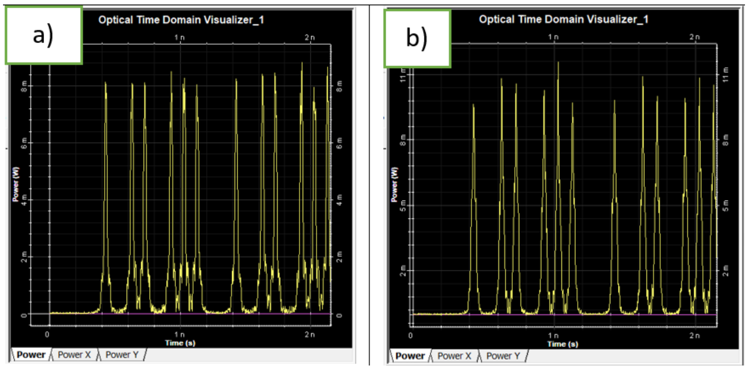

Figure 8. Presentation of the output of the section of 9 km (a) and the output of the section of 5.2 km (b) at 10 Gbps for RZ.

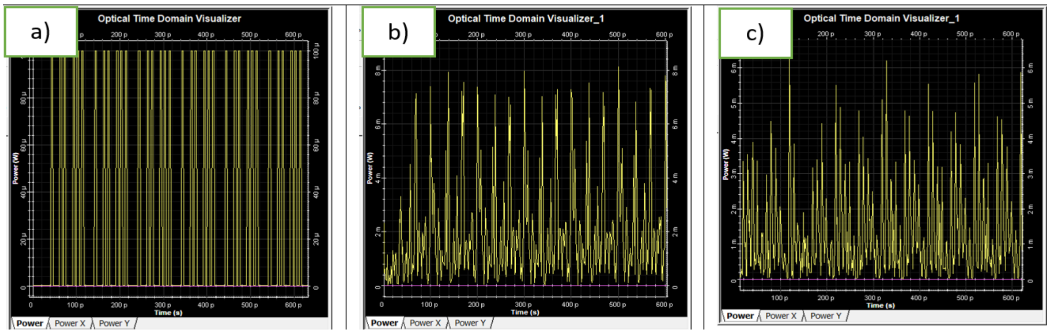

Figure 9. Presentation of the input at 100 Gbps (a), the output of the section of 2.4 km (b) and the output of the section of 11 km (c) for RZ.

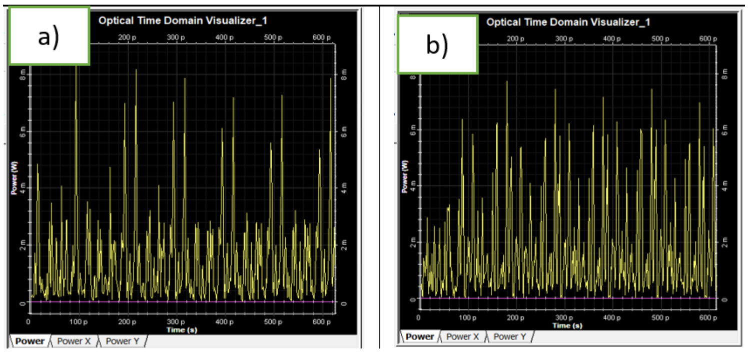

Figure 10. Presentation of the output of the section of 9 km (a) and the output of the section of 5.2 km (b) at 100 Gbps for RZ.

Table 4. Performance indicators.

Modulation format		NRZ		RZ	
Bit rate	Length	Performance indicators		Performance indicators	
		Min BER	Q-Factor	Min BER	Q-Factor
10 Gbps	2.4 km	$7.8388596e^{-111}$	22.3204659	$3.340074e^{-126}$	23.84951215
	11 km	$14.390866e^{-039}$	12.9117180	$0.136556e^{-093}$	20.58840098
	9 km	$11.421477e^{-036}$	12.3968419	$59.83157e^{-081}$	18.88180599
	5.2 km	$0.1057128e^{-075}$	18.4847804	$0.562508e^{-105}$	21.81480987

Continued

100 Gbps	2.4 km	1	0	1	0
	11 km	1	0	1	0
	9 km	1	0	1	0
	5.2 km	1	0	1	0
200 Gbps	2.4 km	1	0	1	0
	11 km	1	0	1	0
	9 km	1	0	1	0
	5.2 km	1	0	1	0

3.3.2. Result of the Complete Link

The simulation results presented below (**Figures 11-16**) are those obtained by considering the total length of the link, which is 30 km. On each figure, we have the input data, output data and an eye diagram. The data are presented for each bit rate according to the chosen modulation format.

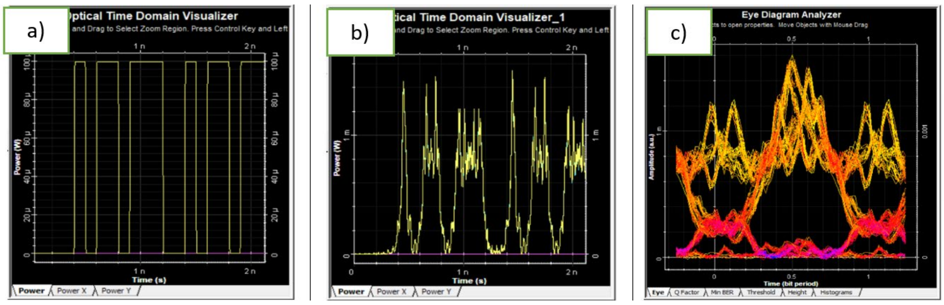

Figure 11. Input signal (a), output signal (b) and eye diagram (c) for 10 Gbps and NRZ format.

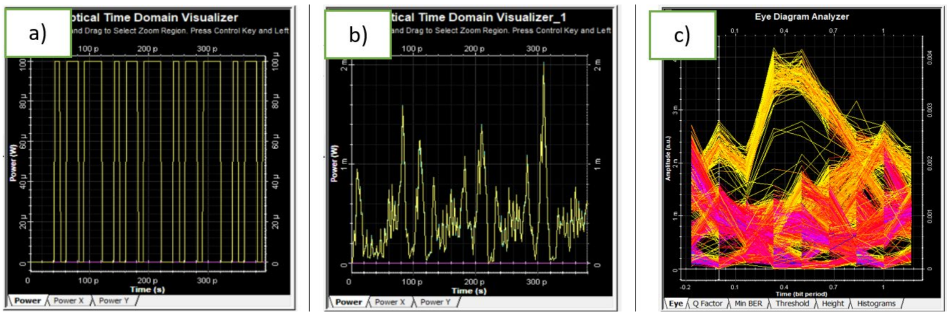

Figure 12. Input signal (a), output signal (b) and eye diagram (c) for 100 Gbps and NRZ format.

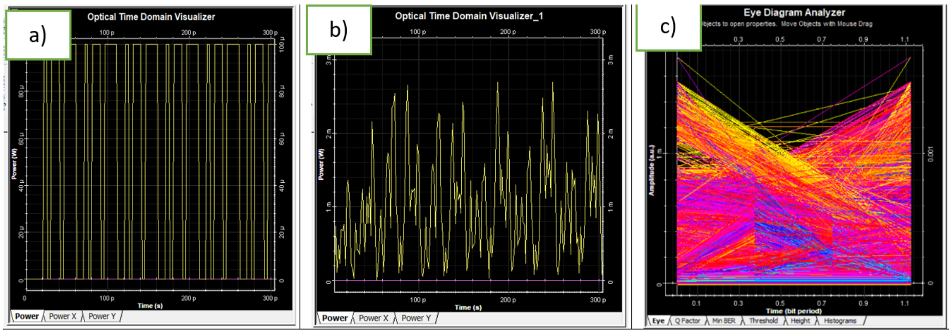

Figure 13. Input signal (a), output signal (b) and eye diagram (c) for 200 Gbps and NRZ format.

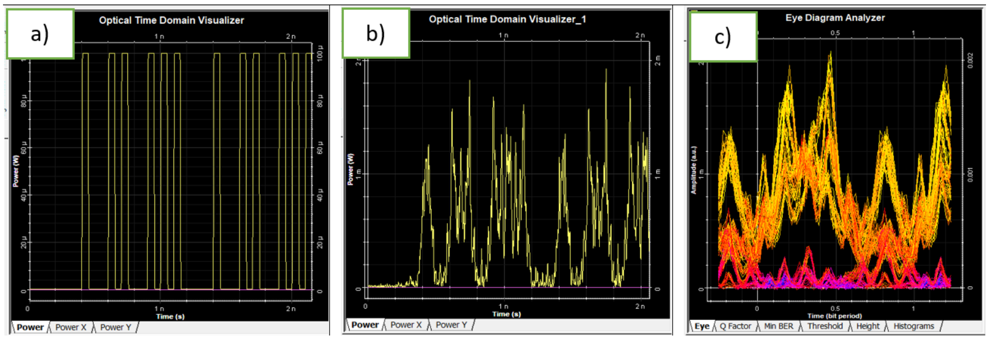

Figure 14. Input signal (a), output signal (b) and eye diagram (c) for 10 Gbps and RZ format.

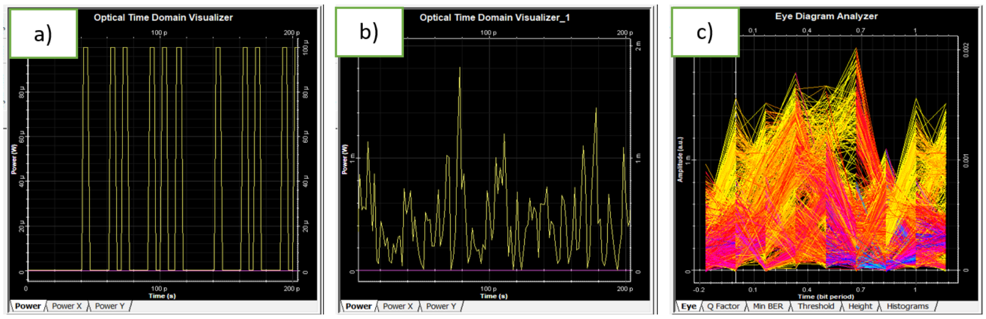

Figure 15. Input signal (a), output signal (b) and eye diagram (c) for 100 Gbps and RZ format.

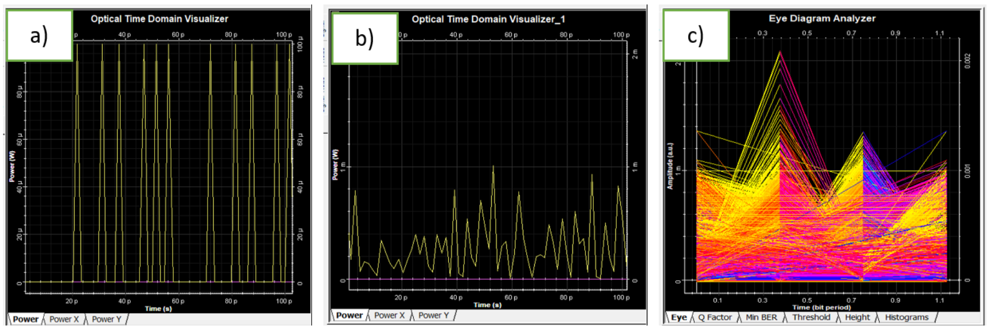

Figure 16. Input signal (a), output signal (b) and eye diagram (c) for 200 Gbps and RZ format.

In order to evaluate the system performance, we have recorded the transmission quality indicators such as Q-Factor and Min BER for the total 30 km link. We obtain the results presented in Table 5.

Table 5. Performance indicators.

Modulation format	Bit rates (Gbps)	Q-Factor	My BER
NRZ	10	10.961657768	$2.73397560\mathrm{e}^{-028}$
	100	0	1
	200	0	1
RZ	10	4.8631069405	$5.7533422\mathrm{e}^{-007}$
	100	0	1
	200	0	1

4. Analysis and Discussion

The simulation results show the effect of chromatic dispersion on an optical signal transmitted through the network considered. They are presented in **Figures 3-10** for the different sections as a function of bit rate and modulation format. **Figures 11-16** present results for the link of 30 km as a function of the different bit rates considered for each modulation format.

For all figures of the link of different sections, we see that the increase in length is accompanied by a slight modification of the spectrum, accompanied by the decrease in power. The amplitude of the signal decreases regardless of the length. The distortion of the signal is a function of the distance; the longer the fiber, the more the distortion is accentuated. For a bit rate of 100 Gbps, we see a significant distortion of the signal regardless of the length considered. Data can be transmitted securely without more loss at a bit rate of 10 Gbps, which is not the case for 100 Gbps and 200 Gbps.

For all figures of the total link, we note a considerable decrease in the amplitude of the output signal, a broadening of the signal spectrum, and the appearance of new peaks, which leads to the distortion of the signal, whatever the modulation format. By observing the eye diagrams, we note that only the diagram of 10 Gbps is slightly open in both cases compared to the diagrams of the other types of bit rates. The eye diagram of 200 Gbps is completely closed, thus indicating the severity of the signal distortion. This distortion of the signal leads to a total loss of information.

Thus, the network considered is efficient for a bit rate of 10 Gbps compared to the other bit rates and is not able to receive an increase in bit rate unless appropriate measures (compensations) are taken before increasing the bit rate.

In order to evaluate the performance of the network considered, we evaluate the Q-Factor and the Min BER, which are the best performance indicators in the context of the study of chromatic dispersion. The values of these indicators are presented in **Table 4** for different sections and **Table 5** for the long link of 30 km. These values confirm the observations made in **Figures 11-16**. For a bit rate of 10 Gbps, the value of the Q-Factor and the Min BER are high compared to the other bit rates. At 10 Gbps, the Inter-Symbol Interference (ISI) phenomenon and the distortion caused by Chromatic Dispersion (CD) are relatively low. But for the bit rate of 100 Gbps, the transmission speed has increased and the time separating two bits is relatively short. This increases the inter-symbol interference phenomenon and an accentuation of signal distortion, leading to a total loss of information.

By considering the modulation formats, we see that the RZ format causes more data loss than the NRZ if we consider the long-distance link (**Table 5**). For short distance, one can see that the RZ format is better than NRZ format (**Table 4**). For example, we have a Min BER of $3.340074e^{-126}$ for the RZ format at 2.4 km and $7.8388596e^{-111}$ for NRZ format. These observations are due to the fact that the RZ format presents a better temporal distinction between symbols, a good robustness against noise and a wide spectral width (broad bandwidth), while the NRZ format is essential over long distances due to its narrow spectral width (small bandwidth) and its better tolerance to chromatic dispersion [13].

5. Conclusion

Using the Optisystem software, we simulated in this work the impact of chromatic dispersion on a signal modulated with the NRZ and RZ modulation format, which will be transmitted through a metropolitan telecommunication backbone network to be deployed in Lomé (Togo). The results show a distortion of the signal leading to a loss of information. The NRZ format is better than the RZ format for long distance and the RZ is better for short distance. Signal distortion depends not only on the width and shape of the input pulses but also on the propagation distance and the bit rate. The network under consideration cannot support an increase in bit rate. Whatever the bit rate used, especially beyond 10 Gbps, it is important to use compensation systems like the use of Dispersion Compensating Fiber or Fiber Bragg Gratings to improve the quality of the transmitted signal, as well as the performance of the network. These compensation methods will be explored in future work for this network.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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