Journal of Electromagnetic Analysis and Applications, 2026, 18(5), 83-96
https://www.scirp.org/journal/jemaa
ISSN Online: 1942-0749
ISSN Print: 1942-0730

Study by Simulation of the Impact of Stimulated Brillouin Scattering in a 30 km G.652.D Optical Fiber Link of an 8-Channel DWDM Metropolitan Backbone Network

Agbessignale Lato[1], Barerem-Melgueba Mao[1,2*]

[1]Laboratoire de Physique des Matériaux et Composants à Semi-Conducteurs (LPMCS), Département de Physique, Faculté des Sciences, Université de Lomé, Lomé, Togo
[2]Ecole Polytechnique de Lomé, Département de Génie Informatique, Université de Lomé, Lomé, Togo
Email: fannylatoson@gmail.com, *bmao@univ-lome.tg

How to cite this paper: Lato, A. and Mao, B.-M. (2026) Study by Simulation of the Impact of Stimulated Brillouin Scattering in a 30 km G.652.D Optical Fiber Link of an 8-Channel DWDM Metropolitan Backbone Network. *Journal of Electromagnetic Analysis and Applications*, **18**, 83-96.
https://doi.org/10.4236/jemaa.2026.185005

Received: March 2, 2026
Accepted: May 26, 2026
Published: May 29, 2026

Abstract

Stimulated Brillouin Scattering (SBS), a nonlinear optical phenomenon, critically impacts the performance of high-capacity metropolitan backbone networks. In dense wavelength-division multiplexing (DWDM) systems, SBS induces power depletion, signal distortion, and transmission efficiency degradation, posing significant challenges to network reliability and data throughput. This study investigates SBS effects in a metropolitan backbone network using OptiSystem simulation software. As modern fiber networks increasingly operate at elevated optical power levels, nonlinear impairments such as SBS compromise signal integrity and system scalability. Focusing on an 8-channel DWDM architecture over a 30 km G.652.D single-mode fiber link, we evaluate SBS threshold power levels under real-world metropolitan network conditions. By integrating theoretical analysis with simulations, we quantify the trade-offs between input power, data rates, and their cumulative effects on signal-to-noise ratio (SNR) and channel capacity. Results demonstrate that SBS-induced performance degradation intensifies sharply when input power exceeds a critical threshold, leading to reduced channel fidelity and constrained network scalability. This study delivers actionable insights for optimizing power budgets and proposes strategies to balance optical power, SNR, and transmission reach in metropolitan-scale DWDM deployments.

Keywords

Optical Fiber, Nonlinear Effect, Stimulated Brillouin Scattering (SBS), Optical Transmission

1. Introduction

In 1972, the Stimulated Brillouin Scattering (SBS) effect in optical fibers was first observed by E.P. Ippen and R.H. Stolen [1] [2]. Several research works [3]-[7] have been carried on Stimulated Brillouin Scattering in optical fibers. From these different works, it appears that the SBS phenomenon presents several drawbacks such as limitation in the optical fiber transmission signal distortion, and noise, thereby reducing the efficiency and reliability of data transmission [8]. The limitation of the power transmitted due to SBS through optical fibers affects areas such as long-haul optical networks, metropolitan optical networks, access networks like passive optical networks, fiber lasers and high-power fiber amplifiers [7]. However, SBS phenomenon finds several applications [9] in areas like Brillouin fiber-optic sensors, Brillouin lasers, Brillouin amplifiers, slow light, delay lines, pulse compression. Recently, several latest generations of International Telecommunication Union optical fibers have been used for the Brillouin backscattering strain sensor application [9]. 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 [10].

In this work, we study by simulation the effects of the SBS phenomenon in different optical links of a metropolitan network backbone. We consider the practical case of a DWMD transmission system deployed on a 30 km consisting of 5 nodes fiber optic network in the city of Lome, capital of Togo. This DWDM system consists of 8 channels and each channel operates in the C band at a data rate of 10 Gbps. The wavelengths of the DWDM system are chosen in accordance with the ITU-T G.694.1 standard. Using ITU-T G.652.D optical fiber and varying input power levels, we analyse the effects of SBS on signal quality, focusing on modulation formats such as Gaussian, Non-Return to Zero (NRZ) and QAM. The bit rate per wavelength of the optical link is set at 10 Gbps and 100 Gbps. The input optical power injected in each channel varies from 0 to 35 dBm. When the optical power reaches a trigger threshold (around 10 dBm), SBS-induced backscattering and frequency shifts, occur whatever be the modulation format with a severe deterioration of signal's quality. The impairment arises when intense light interacts with the acoustic phonons in the fiber, leading to the backward scattering of light [11]. it causes power loss, signal distortion, and noise, thereby reducing the efficiency and reliability of data transmission [12]. Our findings aim to optimize network design, enhance performance, and ensure scalability for future data demands.

This paper is structured as follows: Section I introduces the theoretical foundations of SBS and describes the metropolitan backbone network under study. Section II outlines the simulation methodology using OptiSystem, with focus on pump power and SBS threshold analysis. Section III presents the results and discusses mitigation strategies for SBS in metropolitan backbone networks.

2. Nonlinear Effects in Optical Fiber Networks

Nonlinear effects are intrinsic to optical fibers, where intense electromagnetic fields interact with the material medium, producing various undesired phenomena. These nonlinearities become more pronounced as the power of transmitted optical signals increases. With backbone networks typically carrying multiple wavelengths using DWDM technology and operating at high power levels, the risk of encountering nonlinear scattering effects like SBS and SRS becomes significant. Nonlinear effects are broadly divided into two categories [11]: Kerr nonlinearities (self-phase modulation, cross-phase modulation, and four-wave mixing), which are based on the intensity-dependent refractive index of the fiber and Scattering effects, which involve energy transfer between photons and the optical medium [12]. SBS and SRS belong to the latter category and are of particular concern in metropolitan and long-haul networks. SBS and SRS can arise over much shorter distances, making them relevant in metropolitan networks. They result in energy loss or redistribution, leading to significant performance degradation.

2.1. Nonlinear Effect Origin

The electric field $\boldsymbol{E}$ of a light wave propagating in matter induces elementary movements of charges at the atom level [12]. The induced dipole moments create a polarization $\boldsymbol{P}$ of the medium on the macroscopic scale. Polarization resulting from wave-matter interaction is $\boldsymbol{P} = \boldsymbol{P}_L + \boldsymbol{P}_{NL}$, where $\boldsymbol{P}_L$ is the linear polarization vector, and $\boldsymbol{P}_{NL}$ is the nonlinear polarization vector.

Let's consider a polarization given by:

$$P_x = \varepsilon_0 \chi^{(1)} E_x + \varepsilon_0 \chi^{(3)} E_x^3 \tag{1}$$

Let's consider a monochromatic wave whose electrical field $\boldsymbol{E}$ is given by:

$$E_x = E_0 \mathrm{e}^{-j\omega t} \tag{2}$$

The polarization at frequency ω, is given by:

$$P_x = P_0 \mathrm{e}^{-j\omega t} \tag{3}$$

With:

$$P_0 = \varepsilon_0 \chi^{(1)} E_0 + \frac{3}{4} \varepsilon_0 \chi^{(3)} \left|E_0\right|^2 E_0 \tag{4}$$

$$P_0 = \varepsilon_0 \chi_{eff} E_0 \Rightarrow \chi_{eff} = \chi^{(1)} + \frac{3}{4} \chi^{(3)} \left|E_0\right|^2 \tag{5}$$

χ_{eff} is the effective susceptibility.

The density of the electric field is then written as:

$$D = \varepsilon_0 E_0 + P_0 \quad (6)$$

$$D = \varepsilon_0 \varepsilon_r E_0 \quad (7)$$

We have:

$$n^2 = \varepsilon_r \Rightarrow n^2 = 1 + \chi^{(1)} + \frac{3}{4}\chi^{(3)} |E_0|^2 \quad (8)$$

$$n^2 = n_0^2 + \frac{3}{4}\chi^{(3)} |E_0|^2 \quad (9)$$

$$n = n_0 + n_2 |E_0|^2 \quad (10)$$

where n_0 is the linear refractive index and $n_2 = \frac{3}{8n_0}\chi^{(3)}$ is the Kerr coefficient.

The refractive index n is a function of the intensity E_0 according to (10).

2.2. Pulse Propagation in the Fiber

The propagation of an electromagnetic field in a single core optical fiber is described by using Maxwell's equations [12] [13]. As the optical fiber is a non-magnetic medium, the magnetic polarization is null. The propagation of the electromagnetic wave in the optical fiber will be described, using only the electric field $\boldsymbol{E}$ [12] by:

$$\Delta \boldsymbol{E} - \frac{1}{C^2}\frac{\partial^2 \boldsymbol{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \boldsymbol{P}_L}{\partial t^2} + \mu_0 \frac{\partial^2 \boldsymbol{P}_{NL}}{\partial t^2} \quad (11)$$

3. Stimulated Brillouin Scattering (SBS)

Stimulated Brillouin Scattering is a nonlinear optical phenomenon caused by the interaction between light waves and acoustic phonons in an optical fiber. When an intense pump laser propagates through the fiber, it generates acoustic waves (phonons) via electrostriction; the tendency of the material density to vary in response to an electric field [12] [13]. These acoustic waves modulate the refractive index of the fiber, creating a Brillouin grating that scatters the light. If the scattered light's frequency matches the Brillouin frequency shift (determined by the material properties of the fiber), energy is transferred from the pump wave to the scattered wave, resulting in backward-propagating light. This effect is a significant effect in limiting the maximum power that can be transmitted through optical fibers. The acoustic waves create a periodic density variation in the medium, forming a moving refractive index grating [14]. At low optical power, the scattering is spontaneous and week. The amplification of the backscattered wave defines the stimulated nature of the process [15] [16].

3.1. Mathematical Description

The interaction between the pump wave, stokes wave, and the acoustic wave is described by the following coupled equations [17]:

- **Pump wave amplitude**

$$\frac{\partial A_p(z,t)}{\partial z} + \frac{1}{v_g}\frac{\partial A_p(z,t)}{\partial t} = -\alpha A_p(z,t) - g_B \left|A_s(z,t)\right|^2 A_p(z,t) \quad (12)$$

where:

$A_p(z,t)$: Amplitude of the pump wave.

$A_s(z,t)$: Amplitude of the Stokes wave.

g_B: Brillouin gain coefficient defined by:

$$g_B = \frac{2\pi n_e^2 p^2}{\lambda^2 \rho_0 v_a \Gamma_B} \quad (13)$$

Γ_B is the Brillouin linewidth.

- **Stokes wave amplitude**

$$\frac{\partial A_s(z,t)}{\partial z} - \frac{1}{v_g}\frac{\partial A_s(z,t)}{\partial t} = -\alpha A_s(z,t) + g_B \left|A_p(z,t)\right|^2 A_s(z,t) \quad (14)$$

- **Acoustic wave amplitude**

$$\left(\frac{\partial^2}{\partial t^2} - v_a^2 \frac{\partial^2}{\partial t^2}\right)\rho(z,t) = \Gamma_B \rho(z,t) + K A_p(z,t) A_s^*(z,t) \quad (15)$$

where:

$\rho(z,t)$: Amplitude of the acoustic wave.

K: coupling constant linking the optical wave and of the acoustic wave.

v_a: acoustic velocity.

3.2. SBS Threshold Power

The threshold pump power, P_{thd}, is given by:

$$P_{thd} = \frac{21 A_{eff}}{g_B L_{eff}} \quad (16)$$

where:

A_{eff}: effective mode area of the optical fiber.

L_{eff}: effective length of the fiber.

4. Metropolitan Backbone Network Description

The metropolitan backbone network includes five DWDM nodes that are connected in a ring configuration and deployed in Lome city in Togo (**Figure 1**). It is designed in a ring configuration, to ensure redundancy and fault tolerance. The backbone nodes are: MPEN, CACAVELI, OUA, LOME PORT and LOME CENTRE. This backbone serves as the core infrastructure of the e-government network in the capital of Togo. Its total length is 30 km different and the distances between the nodes are shown on **Figure 1**. ITU-T G.652.D optical fibers are used as transmission media to interconnect the nodes. To ensure high transmission in different links, dense wavelength division multiplexing (DWDM) technology has been implemented in the backbone network. 8-channels in the C-band, C-even, are used.

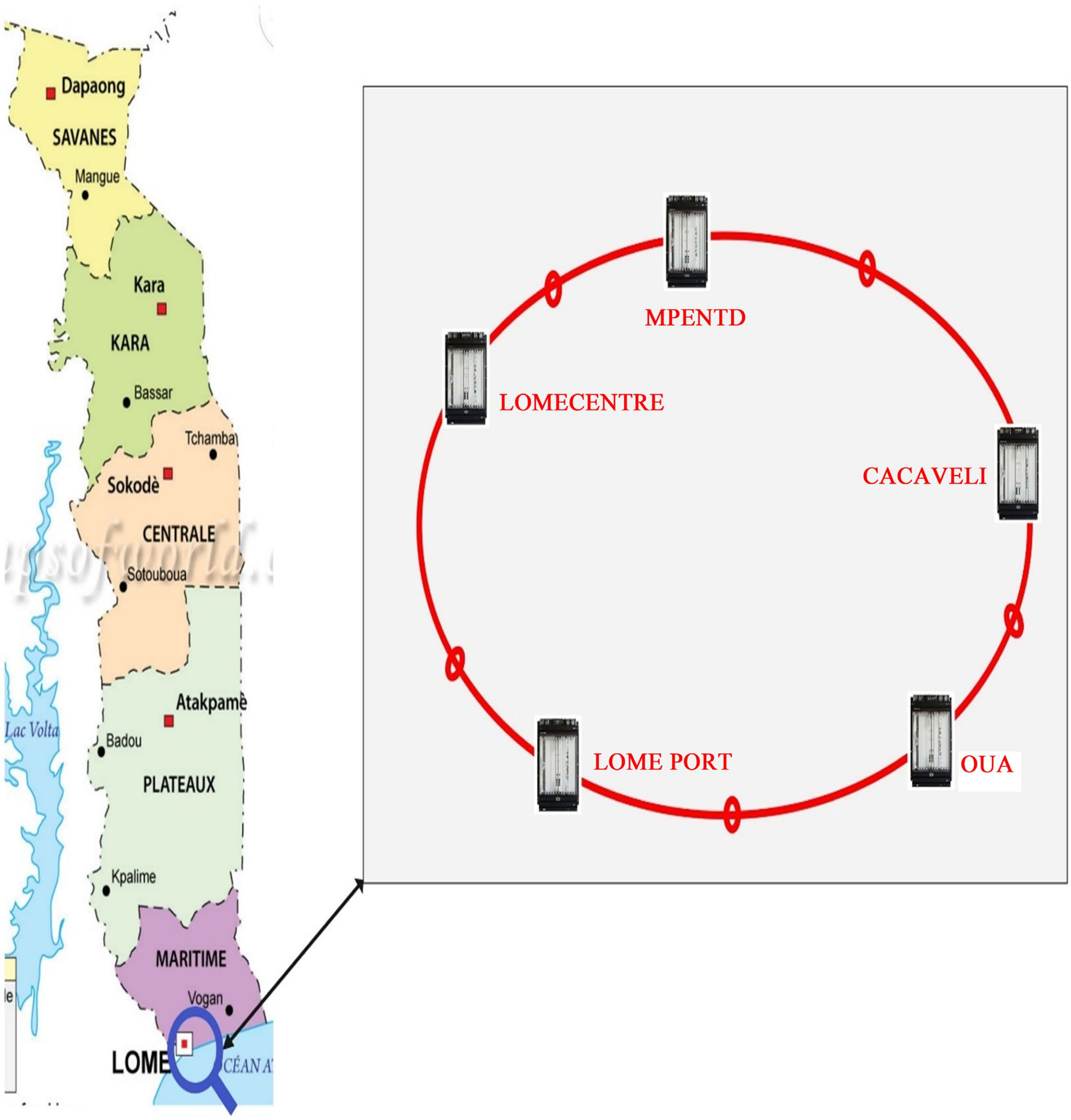


Figure 1. 30 km Backbone Network architecture.

5. Simulation Setup

The simulation and analysis of SBS effects in optical networks involve complex interactions between optical signals, acoustic phonons, and material properties [18]. Accurate modelling with real parameters is crucial to understanding the conditions under which SBS arises and its impact on system performance. In this section, we analytically model and simulate an 8-channels DWDM system highlighting the impact of SBS effects in each channel of a metropolitan backbone network using the Optisystem tools (see Figure 2). The distances implemented are corresponding to the lengths of a case study in a metropolitan backbone network of a telecommunication company in Lome (Togo). The Optisystem software is an environment essentially developed for the modelling and simulation of optical fiber transmission systems. It contains almost all the components necessary for modelling an optical transmission chain, with real parameters [19]. We simulate the system with real-world parameters of the metropolitan network system in the way to find out the stimulated Brillouin scattering impairments.

Simulation Methodology

The simulation was performed using OptiSystem 15.0, configured to model an 8-channel DWDM optical transmission link over a 30 km ITU-T G.652.D fiber. The objective was to evaluate the impact of Stimulated Brillouin Scattering (SBS) on system performance under varying power levels, modulation formats, and bit rates. Each channel was generated using a continuous-wave (CW) laser centered at 1550 nm with a linewidth of 10 MHz. The DWDM grid was defined with 100 GHz spacing between adjacent channels, ensuring realistic inter-channel nonlinear interactions. The optical carriers were modulated using several formats NRZ, RZ, Gaussian, 16-QAM, and DP-64QAM, with bit rates of 10 Gbps and 100 Gbps to compare the sensitivity of different modulations to SBS. The optical multiplexed signal was launched into the G.652.D fiber characterized by standard parameters and only Self Phase Modulation was activated to enable nonlinearity impacts. To isolate SBS effect, the Brillouin gain coefficient was set to 45×10^{-12} m/W, and the gain linewidth to 35 MHz, typical for standard silica fibers. The launch power per channel was varied from 0 to 35 dBm to determine the onset of SBS and its influence on system metrics.

Table 1 below shows the configured parameters.

Table 1. Simulation parameters overview.

Parameter	Symbol/Unit	Typical Value
Fiber type	–	ITU-T G.652.D
Fiber length	L (km)	30
Fiber attenuation	α (dB/km)	0.2
Effective core area	A_{eff} (μm^2)	80
Nonlinear coefficient	γ (W^{-1}·km^{-1})	1.3
Group velocity dispersion	β_2 (ps^2/km)	+17
Brillouin gain coefficient	g_B (m/W)	45×10^{-12}
Brillouin linewidth	$\Delta\nu_B$ (MHz)	30
Optical carrier wavelength	λ (nm)	1550
Channel spacing	Δf (GHz)	100
Number of channels	N_{ch}	8
Modulation formats	–	NRZ, Gaussian, RZ, 16QAM, DP-64QAM
Bit rate per channel	R_b (Gb/s)	10/100
Laser linewidth	$\Delta\nu_L$ (MHz)	10
Sampling frequency	f_s (GHz)	128

In our case, the theoretical threshold power is:

$$P_{thd} = \frac{21 A_{eff}}{g_B L_{eff}} = \frac{21 \times 80 \times 10^{-12}}{45 \times 10^{-12} \times 1.1 \times 10^4}$$, the total attenuation is 0.363 dB/km

$$P_{thd} \approx 3.4 \text{ mW}$$

Figure 2 below shows the designed diagram for analysing the SBS effect in an 8-channels DWDM diagram.

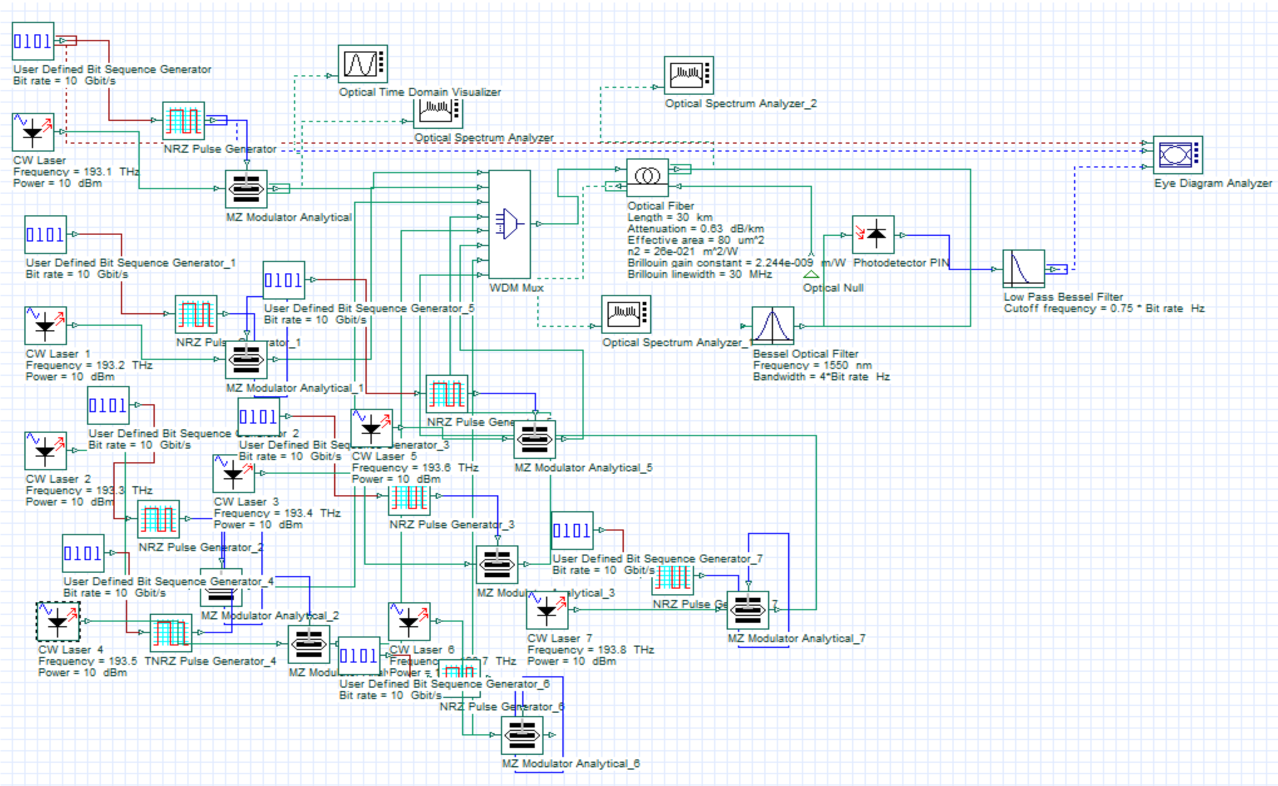


Figure 2. Simulation diagram of SBS effects in an 8-channels DWDM system.

The SBS effect in a single channel is also investigated. Figure 3 shows the designed diagram for analysing the SBS effect in a single channel link at (1550 nm).

The diagram in Figure 2 above shows the simulation of SBS effect in an 8-channels DWDM system, with different source signals at different power levels. A modulated CW laser which passes through a MachZhender (MZ) modulator generates the optical signal and multiplexed by a WDM multiplexer. This signal comes out of the multiplexer and enters the ITU-T G.652.D optical fiber. We considered the G.652.D optical fiber, FullBand® low water peak dispersion unshifted Single-mode fibre (with a maximum attenuation of 0.20 dB/km at 1550 nm). Three (3) km optical fiber cable reels are used to design the optical links between different nodes of the network. For the link budget design, the attenuation of each splice is set at 0.1 dB while the attenuation of each connector is set at 0.5 dB. Several modulation formats are injected at the input at frequencies from 193.1 THz to 193.8 THz (see Figure 2) for the system with a bit rate set at 10 Gbps and 100 Gbps.

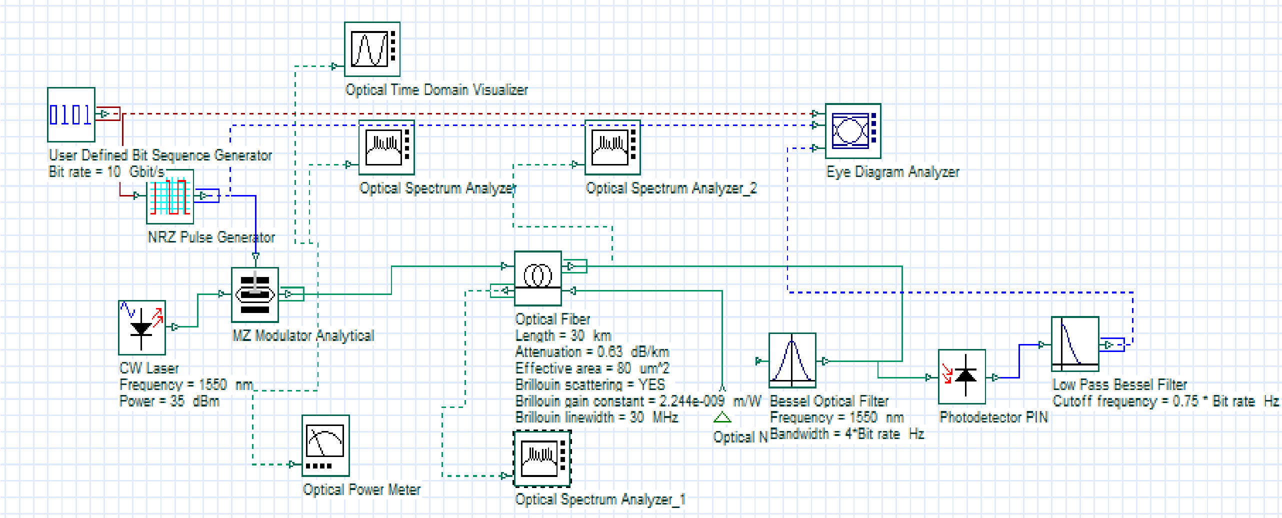


Figure 3. Simulation diagram of SBS effects in a single channel system.

Figure 3 shows the single channel SBS diagram at 1550 nm which is utilized to investigate SBS effect on the different links of the backbone. Additionally, we vary the modulation formats (NRZ and DP 64 QAM) and the input pump power levels (from 0 to 35 dBm) propagating in the fiber optic to carry out the nonlinearity SBS phenomenon.

6. Results and Discussions

The study of the impact on nonlinear SBS effects in an optical transmission system requires the evaluation of the system's performance. Performance's evaluation can be done using several factors. We use optical spectrum analyzers at the input and output of the fiber to understand the impacts of the scattering effects on optical transmission. In metropolitan backbone networks, SBS is more prominent for single channel [19]. We measure the backscattered SBS signal to determine the threshold and assess its impact on the system. For the overall performance of the system, we evaluated the signal-to-noise ratio (OSNR: Optical Signal Noise Ratio) via eye diagram tools considering varying power levels with different modulation formats and rates.

Figure 4 below shows the results of the spectrum analyzer of the input (a), output (b) and the backscattered (c) signals in the backbone with an 8-channels DWDM system. Operating at 10 Gbps with NRZ modulation format.

Figure 4 shows SBS effect simulation diagram in the optical transmission through a 30 km fiber in an 8 × 10 Gbps DWDM system. A signal with NRZ format modulated by MZ modulator is injected in the input an optical link (see Figure 2/Figure 3). At the output (see Figure 4(b) & Figure 4(c)/Figure 5(a) & Figure 5(c), we observe under the SBS effect, a significant signal attenuation, as part of the optical power is transferred to the backward-propagating Stokes wave and the frequency shifted around 11 GHz. However, we observed the distortions due to the noise in the system which degrade the overall signal quality shown by

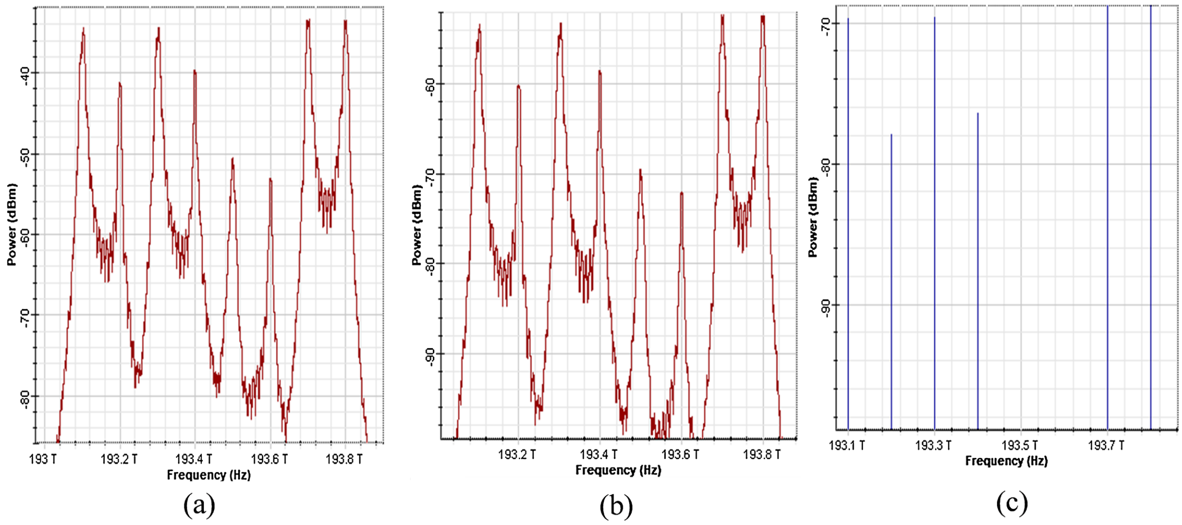


Figure 4. SBS effect in an 8 × 10 Gbps/10 dBm over 30 km (a) input signal; (b) output signal; (c) backscattered signals.

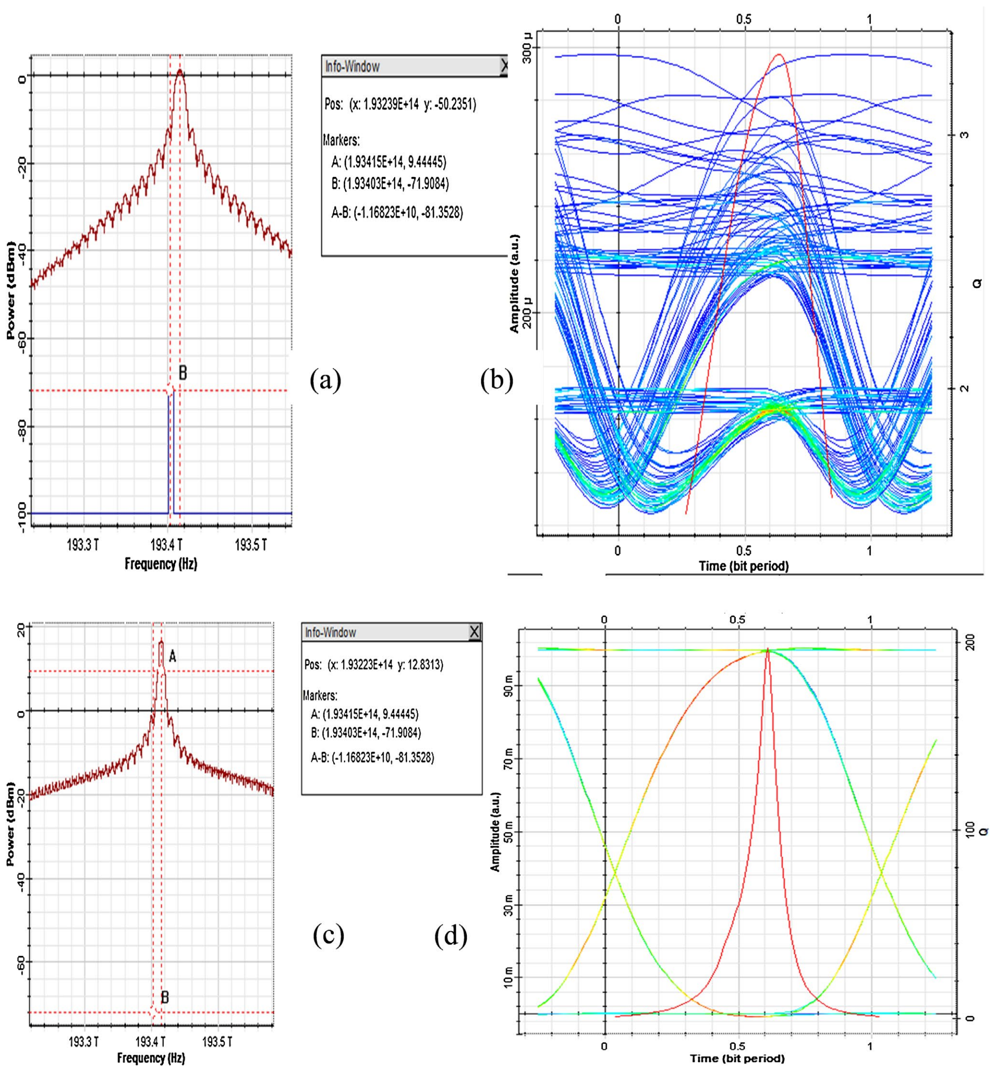
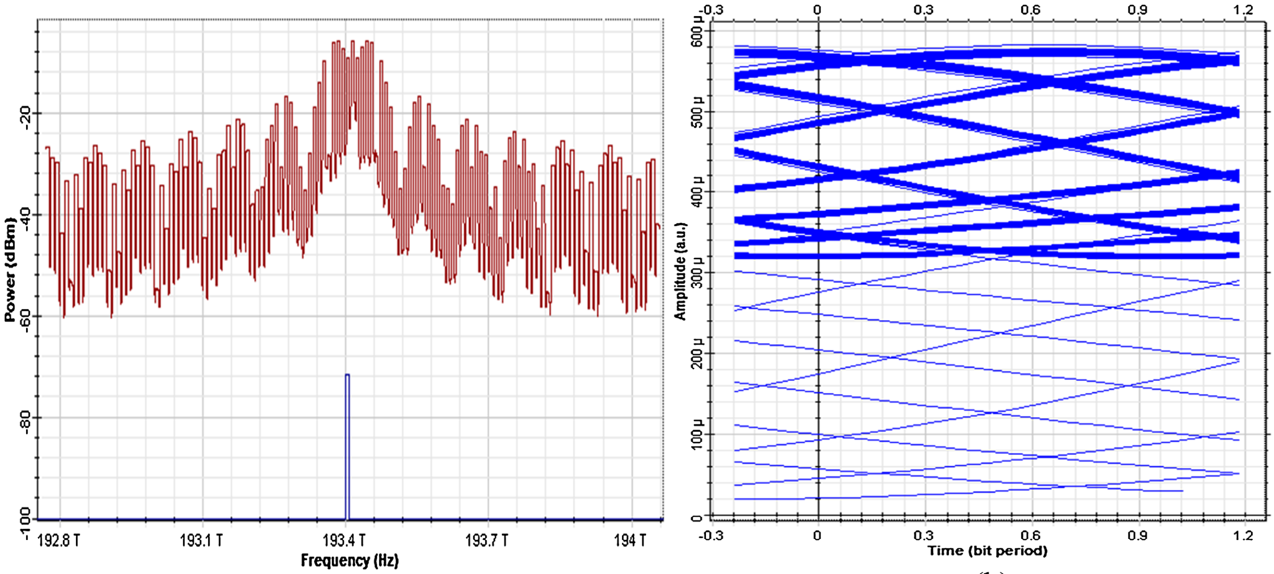


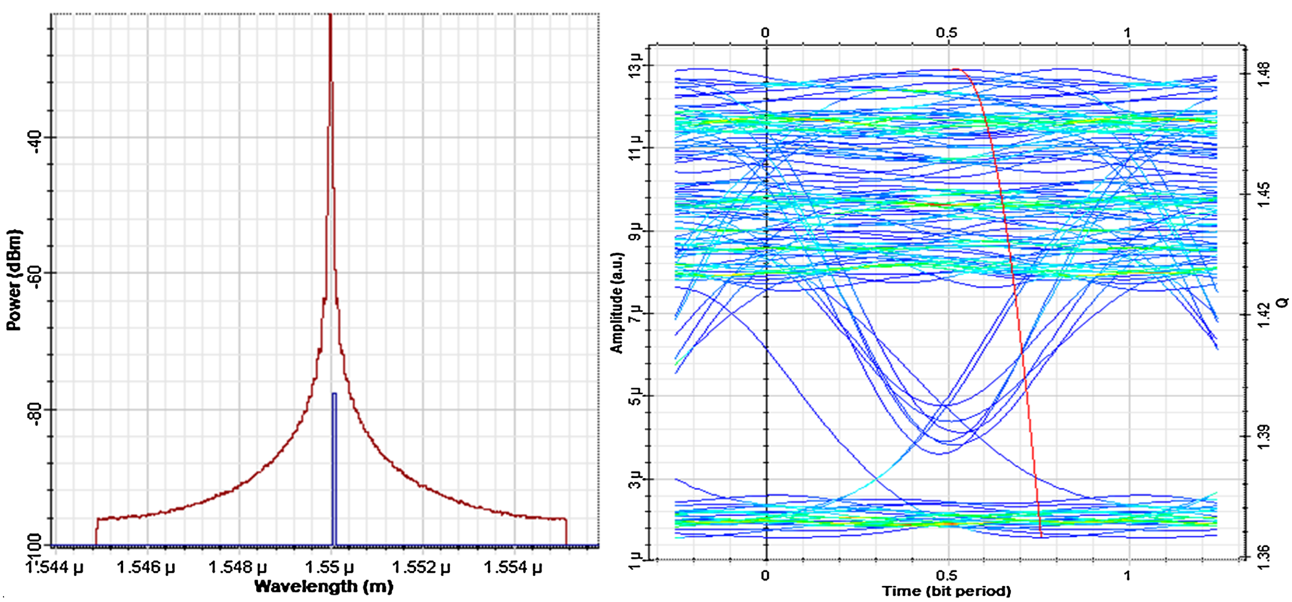
Figure 5. Single channel SBS effect at 10 Gbps over 30 km (a) input/backscattered signal at 0 dBm; (b) eye diagram at 0 dBm; (c) input/backscattered signal at 10 dBm; (d) eye diagram at 10 dBm.

the visualization of eye diagrams (see Figure 5(b), Figure 5(d)). When the rate increases, the overall signal quality is more degraded (see Figure 6(b)). For the different links of the backbone network under this study, the SBS impairment becomes more prominent when the distance is increasing. Using the DP 64 QAM modulation format (see Figure 7(a), Figure 7(b)) shows the occurrence of SBS effect when the trigger power is 20 dBm with a bad signal to ratio, while the NRZ, and Gaussian formats reach their threshold when the trigger power is 10 dBm.



(a) (b)

Figure 6. Single channel SBS effect at 100 Gbps over 30 km (a) input/backscattered signal at 10 dBm; (b) eye diagram at 10 dBm.



(a) (b)

Figure 7. Single channel SBS effect at 10 Gbps over 30 km using DP 64 QAM format (a) input/backscattered signal at 20 dBm; (b) eye diagram.

Figure 8 shows the comparison of the input and output data transmitted through the backbone. We observed some missed data due the SBS effect when the input power is 10 dBm while using NRZ and Gaussian formats.

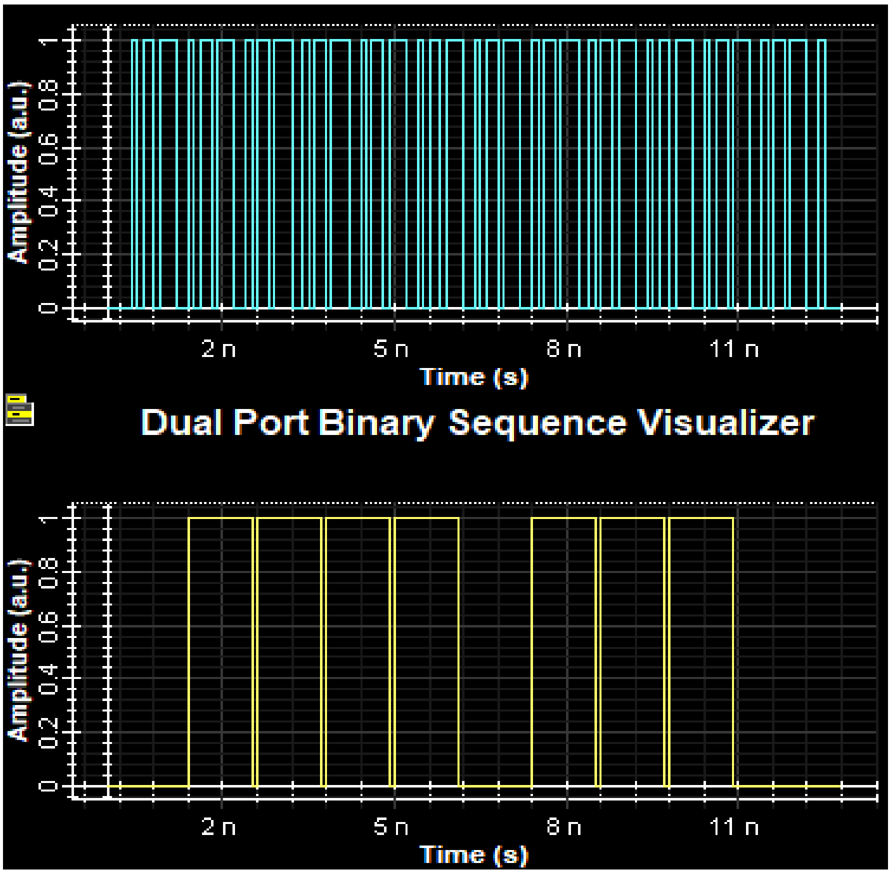


Figure 8. Input/Output data over 30 km optical links under SBS effect.

For performance evaluation, BER and Q-factor are estimated under defined receiver bandwidth (40 GHz) and filtering conditions. This enables a direct quantitative link between eye diagram closure and the resulting system performance penalty.

The SBS threshold is defined as the input power at which the backscattered power exceeds 1% of the launched signal, corresponding to a trigger power of 10 dBm. The discrepancy between the theoretical SBS threshold calculated (~3.4 mW) and the simulated value (~10 mW) is mainly due to practical factors such as signal spectral broadening, fiber losses, which reduce the Brillouin gain and increase the observed threshold.

The SBS phenomenon due to acoustic phonons in the optical medium, as the input power increases, distortions arise, and a significant signal attenuation occurs while the trigger power is around 10 dBm for NRZ, and Gaussian formats but 20 dBm for DP 64 QAM with a bad signal to ratio.

Table 2 below presents the aspects of SBS effect in an optical transmission link over the backbone network studied.

Table 2. SBS aspects.

Aspect	Simulated Brillouin Scattering (SBS)
Nature	Backscattering effect involving acoustic phonons
Trigger power observed	Low power threshold (~10 dBm/10 mW)
Impact on signal	Causes back-reflection, reducing signal strength and frequency shift at ~11 Ghz
Effect on transmission	Reduces power budget, leading to signal loss
Mitigations solutions	Phase Modulation, Input power regulation

7. Conclusion

As metropolitan backbone networks continue to evolve to meet the demands of a digital society, addressing nonlinear impairments such as SBS is critical to ensuring their reliability and performance. Through simulation-based analysis, this study seeks to uncover the complexities of SBS in optical links. Our simulations provide valuable insights into the nonlinear SBS effect in the metropolitan backbone network of a telecommunications provider in Lomé, Togo. Mitigating SBS is crucial for ensuring the reliable operation of metropolitan optical links. As data traffic in urban environments grows, optical networks must ensure both high capacity and signal integrity, which becomes challenging due to this nonlinear scattering effect. SBS introduces severe attenuation and power management constraints, posing significant challenges for metro networks operating with DWDM technology. Our findings not only deepen the understanding of SBS dynamics but also guide the development of high-capacity, future-ready optical networks for an increasingly connected world.

Conflicts of Interest

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

References

[1] Chiao, R.Y., Townes, C.H. and Stoicheff, B.P. (1964) Stimulated Brillouin Scattering and Coherent Generation of Intense Hypersonic Waves. *Physical Review Letters*, **12**, 592-595. https://doi.org/10.1103/physrevlett.12.592

[2] Ippen, E.P. and Stolen, R.H. (1972) Stimulated Brillouin Scattering in Optical Fibers. *Applied Physics Letters*, **21**, 539-541. https://doi.org/10.1063/1.1654249

[3] Cotter, D. (1983) Stimulated Brillouin Scattering in Monomode Optical Fiber. *Journal of Optical Communications*, **4**, 10-19. https://doi.org/10.1515/joc.1983.4.1.10

[4] Yeniay, A., Delavaux, J. and Toulouse, J. (2002) Spontaneous and Stimulated Brillouin Scattering Gain Spectra in Optical Fibers. *Journal of Lightwave Technology*, **20**, 1425-1432. https://doi.org/10.1109/jlt.2002.800291

[5] Kobyakov, A., Sauer, M. and Chowdhury, D. (2009) Stimulated Brillouin Scattering in Optical Fibers. *Advances in Optics and Photonics*, **2**, 1-59. https://doi.org/10.1364/aop.2.000001

[6] Merklein, M., Kabakova, I.V., Zarifi, A. and Eggleton, B.J. (2022) 100 Years of Bril-

louin Scattering: Historical and Future Perspectives. *Applied Physics Reviews*, **9**, Article 041306. https://doi.org/10.1063/5.0095488

[7] Huang, B., Wang, J. and Shao, X. (2023) Fiber-Based Techniques to Suppress Stimulated Brillouin Scattering. *Photonics*, **10**, Article 282. https://doi.org/10.3390/photonics10030282

[8] Chen, L. and Bao, X. (1998) Analytical and Numerical Solutions for Steady State Stimulated Brillouin Scattering in a Single-Mode Fiber. *Optics Communications*, **152**, 65-70. https://doi.org/10.1016/s0030-4018(98)00147-3

[9] Lakomski, M. and Tosik, G. (2022) Brillouin Backscattering Analysis in Recent Generation of Telecom Optical Fibers. *Optica Applicata*, **52**, 405-416. https://doi.org/10.37190/oa220307

[10] ITU-T Recommendations (2026). https://www.itu.int/itu-t/recommendations/index.aspx?ser=G

[11] Agrawal, G.P. (2012) Nonlinear Fiber Optics. 5th Edition, Academic Press.

[12] Keiser, G. (2021) Optical Fiber Communications. Springer.

[13] Ramaswami, R., Sivarajan, K.N. and Sasaki, G.H. (2020) Optical Networks: A Practical Perspective. Morgan Kaufmann.

[14] Boyd, R.W., Rzążewski, K. and Narum, P. (1990) Noise Initiation of Stimulated Brillouin Scattering. *Physical Review A*, **42**, 5514-5521. https://doi.org/10.1103/physreva.42.5514

[15] Chen, C., Nguyen, L.V., Wisal, K., Wei, S., Warren-Smith, S.C., Henderson-Sapir, O., et al. (2023) Mitigating Stimulated Brillouin Scattering in Multimode Fibers with Focused Output via Wavefront Shaping. *Nature Communications*, **14**, Article No. 7343. https://doi.org/10.1038/s41467-023-42806-1

[16] Hoshida, T., Vassilieva, O., Yamada, K., Choudhary, S., Pecqueur, R. and Kuwahara, H. (2002) Optimal 40 Gb/s Modulation Formats for Spectrally Efficient Long-Haul DWDM Systems. *Journal of Lightwave Technology*, **20**, 1989-1996. https://doi.org/10.1109/jlt.2002.806761

[17] Wolff, C., Smith, M.J.A., Stiller, B. and Poulton, C.G. (2021) Brillouin Scattering—Theory and Experiment: Tutorial. *Journal of the Optical Society of America B*, **38**, Article 1243. https://doi.org/10.1364/josab.416747

[18] Wisal, K., Warren-Smith, S.C., Chen, C., Cao, H. and Stone, A.D. (2024) Theory of Stimulated Brillouin Scattering in Fibers for Highly Multimode Excitations. *Physical Review X*, **14**, Article 031053. https://doi.org/10.1103/physrevx.14.031053

[19] Wang, Y. and Guan, Y. (2014) Performance Simulations for a High-Speed Optical Transmission System Based on Optisystem. 2014 7*th International Congress on Image and Signal Processing*, Dalian, 14-16 October 2014, 907-911. https://doi.org/10.1109/cisp.2014.7003907