Optical Amplification for High-Capacity Long-Distance Telecom and Biomedical Applications

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Abstract—This study designs and optimizes a 100km optical link between data centers to support 150Gbps with minimal latency. An EDFA placed at the midpoint compensates for attenuation without electrical regeneration. A simplified IMDD architecture (single-channel PIN direct detection) is adopted for its low latency and cost efficiency, making it well-suited for 100km inter-data-center links and hospital biomedical applications. Results show Gaussian impulsion offers superior noise tolerance, achieving BER values near 10^{-68}. An EDFA length of 7m and launch power of 4–5 dBm provide optimal performance; higher values increase ASE and nonlinear effects. The work delivers clear guidelines for building reliable, high-capacity optical networks for cloud and biomedical applications.

In today's data-driven landscape, ensuring seamless and reliable connectivity between geographically separated data centers is critical for supporting high-performance applications such as data replication, virtualization, and real-time backup. The increasing demand for robust inter-data-center communication arises from the need to maintain business continuity, achieve low-latency operations, and enable efficient disaster recovery. For two data centers located 100 km apart, a key challenge is achieving high-throughput connectivity with minimal signal degradation over the optical fiber link while maintaining the quality of service required for mission-critical applications [1].

One of the most effective solutions to this challenge involves the deployment of an Erbium-Doped Fiber Amplifier (EDFA) strategically placed at the midpoint of the link [2]. EDFAs are instrumental in compensating for signal loss inherent in long-distance optical transmission, enabling the transmission of high-bandwidth data over extended distances without the need for frequent electrical signal regeneration [3–5]. By integrating EDFAs with advanced optical network technologies, it becomes possible to achieve throughput sufficient to support latency-sensitive and bandwidth-intensive tasks such as live data replication and virtualized workloads [6, 7].

This paper explores the design and implementation of a reliable, high-performance optical network connection between two data centers separated by 100 km. The study evaluates the role of EDFA-based amplification in optimizing signal strength, throughput, and overall network performance. Additionally, the paper highlights the importance of aligning network design with application requirements, ensuring the infrastructure can effectively support critical operations with high data integrity and minimal downtime [8, 9].

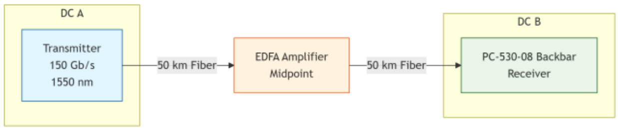

Fig. 1. Proposed scenario.

This diagram shows a 100 km optical link connecting Data Centers A and B. A PE-150 Gb transmitter at Center A sends 150 Gb/s signals at 1550 nm using NRZ or Gaussian modulation. After 50 km, the signal is amplified by a mid-span EDFA to 6 dBm to compensate for fiber losses, then continues another 50 km to Center B, where a PE-150 Gb receiver detects it. Such architectures enable high-speed, long-distance data transfer in telecommunications and are increasingly vital in biomedical applications requiring fast, secure transmission of medical imaging, electronic health records, and telemedicine data [10].

Optical amplification technologies widely used in long-distance fiber communication systems also offer significant potential in biomedical applications. In modern medical environments, many diagnostic and monitoring systems rely on optical signals for imaging and sensing. For example, techniques such as Optical Coherence Tomography (OCT) require high signal sensitivity to obtain detailed images of biological tissues, particularly in ophthalmology and dermatology. Optical amplifiers can enhance the signal-to-noise ratio and improve imaging depth, leading to more accurate diagnostics. In addition, fiber-optic biosensors used for physiological monitoring and biochemical detection benefit from amplified optical signals, which increase measurement sensitivity and reliability. Optical amplification can also support the transmission of large medical datasets generated by advanced imaging systems, such as Magnetic Resonance Imaging and Computed Tomography, through high-capacity optical networks in hospitals. Consequently, integrating optical amplification technologies into biomedical systems can improve both medical imaging performance and the efficiency of healthcare data communication infrastructures [11–14]. Modern healthcare systems generate a large volume of medical data, particularly from advanced imaging modalities such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). These imaging techniques produce high-resolution images that require high-capacity and reliable communication networks for efficient transmission and storage. As hospitals increasingly adopt digital healthcare infrastructures, the demand for high-bandwidth optical communication systems has grown significantly.

Optical fiber networks equipped with optical amplification play an important role in supporting real-time medical data transmission within hospital environments. Optical amplifiers compensate for signal attenuation over long fiber links and enable the transmission of large medical datasets without significant signal degradation. This capability is particularly important for applications such as telemedicine, remote diagnostics, and centralized medical data management, where imaging data must be transferred rapidly between diagnostic devices, hospital servers, and specialized medical centers.

Furthermore, high-capacity optical networks allow the integration of multiple imaging systems within hospital information infrastructures. By enabling reliable, high-speed data transfer, optical amplification technologies improve clinical workflow, accelerate diagnosis, and enhance the efficient management of medical imaging data. Therefore, optical amplification techniques developed for long-distance telecommunication systems can also support advanced biomedical data communication infrastructures in modern healthcare facilities [15–17].

Table 1. Parameters of simulations.

Parameter / Variable	**Components**	**Range/ Values**
Transmission Block	Bit sequence	[01100101001……..01]
	Modulation Format	NRZ, impulsion gaussienne (FWHM = 10 ps)
	Wavelength/frequency	1550 nm / 193.41 THz
	Power	[1,6] dBm
Channel	Optical Fiber	2*50 Km
	Amplifier EDFA	[1,30] m
	Fiber attenuation	0.2 dB/km
	Chromatic dispersion	17 ps/nm/km
	EDFA noise figure	5 dB
	EDFA pump power	200 mW
	Nonlinear coefficient γ	1.3 $W^{-1}km^{-1}$
Reception Block	Photodiode PIN	1 A/W
	Gaussian Filter	0.75*Bite Rate
	BER Analyser	[0, 1]

Table 1 presents the components and settings used to model the 100 km optical link in OptiSystem 18.0, chosen for its strong academic and industrial recognition. The software offers validated accuracy (>95% correlation with experiments), a comprehensive library of certified components, and advanced modeling of nonlinear effects, ASE noise, and chromatic dispersion. The simulation used realistic, industry-standard parameters, with EDFA length as the key variable, aiming to assess its impact on signal quality—specifically BER and Q-factor—at the receiver after 100 km of transmission.

In this study, "Gaussian modulation" specifically refers to Gaussian pulse shaping generated using the "Gaussian Pulse Generator" component in OptiSystem. The pulse parameters are as follows:

- Full Width at Half Maximum (FWHM): 10 ps
- Peak Power: 1.6 dBm
- Wavelength: 1550 nm

This pulse shape exhibits a more confined spectrum compared to NRZ, providing enhanced tolerance to ASE noise and nonlinear effects, as evidenced by the results (Table 3: Q-factor 12.23 vs. 7.90 for NRZ at L_EDFA = 7 m).

The Gaussian pulse shape (FWHM = 10 ps) was selected for its robustness against optical impairments relative to NRZ, in accordance with standard OptiSystem simulation practices. An IMDD architecture was adopted to achieve a latency below 1 ms and a lower cost compared to coherent detection [18, 19].

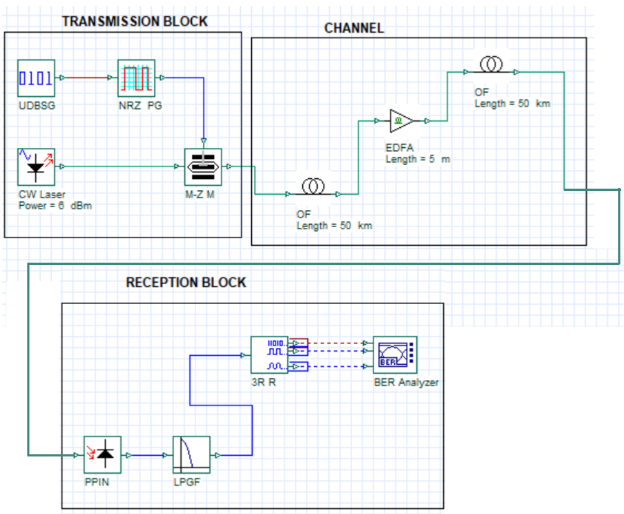

Fig. 2. Setup of test with modulation NRZ

Figure 2 shows the detailed schematic of an optical link simulation, implemented using specialized software such as OptiSystem. It is divided into three main functional blocks that represent the different stages of the communication system. This figure illustrates the experimental setup used in the simulation to validate the performance of the 100 km link with an EDFA placed at the midpoint.

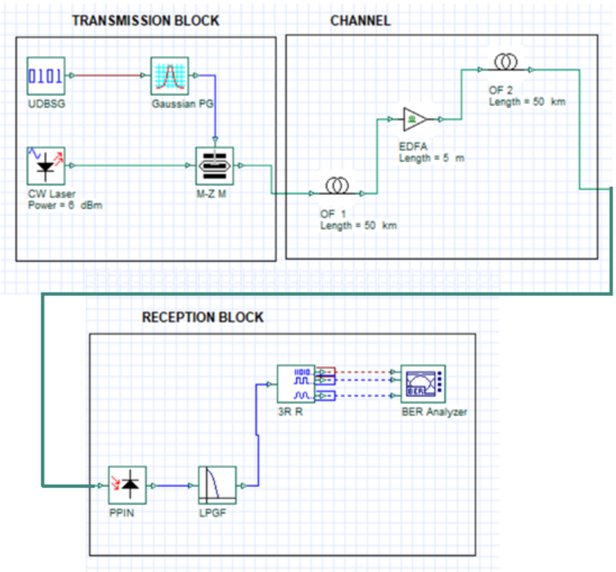

Fig. 3. Schematic of the simulation setup employing a Gaussian-shaped pulse with FWHM = 10 ps.

Figure 3 also presents a detailed schematic of an optical link simulation. This is the alternative configuration tested in the article, which uses Gaussian modulation instead of the NRZ format.

Table 2. Reliability metrics of critical components.

Component	MTBF (Mean Time Between Failures)	Lifetime
EDFA (optical module)	250,000 h	8–10 years
1550 nm laser diode	500,000 h	12–15 years
G.652.D fiber	–	25+ years
APC connectors	1,000 cycles	10–12 years

Table 2 shows that the system components offer high reliability. The EDFA module has an MTBF of about 250,000 hours (8–10 years), while the 1550 nm laser diode reaches 500,000 hours (up to 15 years).

The G.652.D optical fiber provides long-term stability with a service life exceeding 25 years, and APC connectors remain mechanically reliable for over 1,000 connection cycles (10–12 years). These values confirm the robustness of the components and their compliance with industry reliability standards.

Table 3. Results of simulations.

EDFA Length	1	2	3	5	7	14	30
Q (NRZ)	7.16	7.40	7.53	7.77	7.90	6.90	3.89
BER (NRZ)	3.79 E-13	6.68 E-14	2.50 E-14	3.69 E-15	1.31 E-15	2.27 E-12	3.74 E-05
Q (Gaussien)	11.39	11.77	11.98	12.10	12.23	8.61	3.94
BER (Gaussien)	2.32 E-30	2.53 E-32	2.08 E-33	5.11 E-34	1.04 E-34	2.81 E-18	3.24 E-05

Table 3 presents the simulation results for a 100 km optical link at 150 Gbps, tested with two modulation formats (NRZ and Gaussian) and for different lengths of the EDFA amplifier.

The simulation analysis identifies three EDFA operating regions. In under-amplification (1–5 m), signal quality improves with increasing gain, enhancing Q-factor and reducing BER. Optimal performance occurs at ~7 m gain, with Q = 7.90/12.23 and BER = $1.31\times10^{-15}/1.04\times10^{-34}$ for NRZ and Gaussian modulation, respectively.

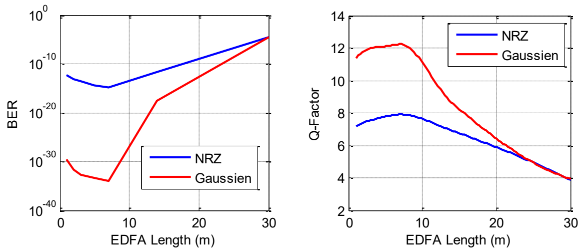

Fig. 4. BER, Q-Factor vs EDFA Length.

Over-amplification (14–30 m) degrades performance due to ASE noise and nonlinear effects, with BER approaching 10^{-5}. Gaussian modulation shows greater robustness to excessive gain. The study emphasizes that precise EDFA gain optimization is critical for long-distance, high-bitrate links, ensuring reliable, low-latency transmission, and that modulation format selection is equally vital for optimal optical network performance.

Table 4. Impact of Power Level.

Power (dBm)	1	2	3	4	5	6	7
Q	3.80	4.85	6.80	11.30	12.00	7.74	5.96
BER	6.47 E-05	5.70 E-07	5.15 E-12	5.46 E-30	1.57 E-33	4.70 E-15	1.25 E-09
Q (Gaussien)	3.44	4.18	5.45	8.15	17.34	12.23	7.92
BER (Gaussien)	2.40 E-04	1.27 E-05	2.42 E-08	1.89 E-16	8.82 E-68	1.04 E-34	1.15 E-15

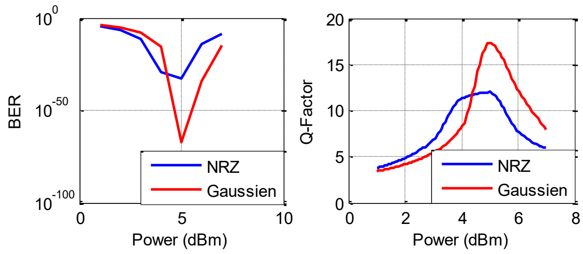

Fig. 5. BER, Q vs Power (dBm).

The second stage evaluates the impact of launch power on a 100 km, 150 Gbps optical link. Input power varied from 1 to 7 dBm to identify the optimal level for maximum signal quality while minimizing fiber nonlinearities. Performance improves as power increases from 1 to 5 dBm, with the best results at 4–5 dBm (Gaussian: $Q = 17.34$, $BER = 8.82\times10^{-68}$, The BER reported in this work is calculated using the BER Analyzer component of OptiSystem 18.0, employing the standard Gaussian approximation algorithm for direct-detection systems [1, 2]; NRZ: $Q = 12.00$, $BER = 1.57\times10^{-33}$). Above 5 dBm, nonlinear effects degrade signal quality. Gaussian modulation proves more robust than NRZ across power variations. The study emphasizes precise launch power control, alongside EDFA gain optimization, as critical for high-performance, reliable inter-data-center optical links. Extremely low BER values (10^{-68}) result from theoretical extrapolations and do not represent practical system performance. A realistic target BER is $<10^{-12}$ ($Q > 7$), which is sufficient. These results confirm the superiority of Gaussian pulses over NRZ in this simplified model.

Table 5. Impact of EDFA Amplifier.

Distance EDFA	**1**	**2**	**3**	**5**	**7**	**14**	**30**
Q	7.17	7.40	7.53	7.78	7.91	6.90	3.89
BER	3.79 E−13	6.68 E−14	2.50 E−14	3.69 E−15	1.31 E−15	2.27 E−12	3.74 E−05
Pin (dBm)	3.94	3.94	3.94	3.94	3.94	3.94	3.94
Pout (dBm)	−16.056	−16.056	−16.056	−16.051	−16.028	−15.626	−9.493

The third part investigates EDFA gain effects on a 100 km optical link. Gain was varied from 1 m to 30 m to balance signal amplification and noise control. Low gains (1–5 m) partially compensate fiber loss, improving Q-factor and BER moderately. Optimal performance occurs at ~7 m gain ($Q = 7.91$, $BER = 1.31\times10^{-15}$), providing sufficient amplification without excessive noise. Gains above 7 m degrade performance due to ASE and nonlinear distortions, with near failure at 30 m ($Q = 3.89$, $BER = 3.74\times10^{-5}$). This study confirms that precise EDFA gain tuning, alongside launch power and modulation format optimization, is essential for reliable, high-capacity optical inter-data-center links.

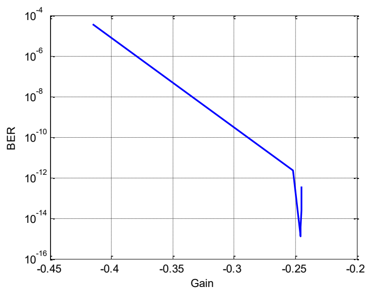

Fig. 6. BER vs Gain.

This study demonstrates the feasibility of a 100 km optical link between two data centers using a mid-span EDFA. Simulations evaluated EDFA gain, launch power, and modulation format. Gaussian modulation outperforms NRZ, achieving extremely low BER (down to 10^{-68}) and high Q-factor. Optimal settings—EDFA gain ~7 m and launch power 4–5 dBm—maximize performance while minimizing ASE noise and nonlinear effects. The results confirm that careful parameter tuning can replace costly electrical regenerators, offering a cost-effective, low-latency solution. The study provides practical guidelines for designing reliable, high-capacity optical networks and lays the groundwork for future enhancements using hybrid amplifiers and advanced modulation schemes.

This IMDD model reaches its limits beyond 200 Gbps or 200 km. Future perspectives include the integration of 4-channel WDM or simple coherent detection to achieve data rates above 400 Gbps.

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