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Enhancing Signal Quality in Long-Haul Optical Networks: Techniques for Amplification, Dispersion, and Nonlinear Impairment

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Abstract: Long-haul optical communication systems face challenges from nonlinear impairments, chromatic dispersion, and signal attenuation, which can degrade performance over long distances. To address these limitations and enhance transmission quality, this study introduces a 64-channel DenseWavelength Division Multiplexing (DWDM) system. This system integrates Raman Fiber Amplifiers (RFA) and Dispersion Compensating Fibers (DCF) and achieves significant signal improvements. Specifically, a 15% increase in Q-factor and a 30% reduction in Bit Error Rate (BER) are observed. At 600 km and 15 Gbps, the Q-factor rises from 5.9 to 6.5, and the BER falls from 6.1 × 10?7 to 2.3 × 10?7. Channel 64 demonstrates exceptional performance, reaching a peak Q-factor of 26.0374, exceeding all other channels. The efficacy of this hybrid RFA + DCF system is evident in mitigating nonlinear effects such as Self-Phase Modulation (SPM) and Four-Wave Mixing (FWM), and in improving Optical Signal-to-Noise Ratio (OSNR). These advancements pave the way for high-performance, long-distance optical communication, with potential for further optimization through Raman-EDFA hybrid amplification and channel spacing adjustments.

Keywords: Long-haul Optics, Dense Wavelength Division Multiplexing (DWDM), Raman Amplification, Bidirectional Optical Fibre Communication, Dispersion Compensating Fibre (DCF).

1 Introduction

IN the field of long-distance communication, signals inevitably suffer from transmission losses and degradation in both quality and power as they propagate over large distances. These impairments, which include signal attenuation and dispersion, can significantly impact the performance of optical communication systems [1,2]. Dense Wavelength Division Multiplexing (DWDM) optical communication systems rely on Raman Amplifiers and Dispersion Compensation Fibres (DCFs) to combat signal attenuation and dispersion. Long-distance signal transmission becomes more effective and reliable as a result of these components' contributions to increasing signal power and reducing impairments [3,4].

The wavelength flexibility of Raman Amplification is a major asset, allowing simultaneous transmission of multiple channels at different wavelengths through a single optical fibre. This attribute directly contributes to increased bandwidth efficiency and a decrease in the required fibre infrastructure, proving especially valuable in long-distance applications [5,6]. Leveraging bidirectional fibers further amplifies these benefits by enabling two-way communication over the same fibre,

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leading to substantial gains in system efficiency, cost-effectiveness, and simplified maintenance operations [7].

> By transmitting over a single fibre, DWDM systems simplify deployment and maintenance, lowering operational costs and the burden of managing multiple links [8]. This efficiency makes them a favourable option for long-distance communication, especially when considering substantial infrastructure investments [9].

Raman amplification, discovered unintentionally in 1962 during tests with Q-switched Ruby lasers, was initially a laboratory curiosity. However, its potential as a key technology for optical communication became evident in the mid-1980s. The technology involves Stimulated Raman Scattering (SRS), where a pump laser provides the necessary energy for signal amplification by interacting with the transmission fibre [10]. In this process, energy from the pump laser is transferred to the signal via the Raman scattering process, which boosts the signal's intensity. The Raman amplification process provides a highly efficient amplification mechanism that is distributed along the transmission fibre, in contrast to traditional point amplifiers, ensuring a more uniform signal strength over long distances [11].

In the 1980s, substantial research was focused on optimizing Fibre Raman Amplifiers (FRA) for telecommunication applications. This led to significant breakthroughs in the field [12]. By the early 2000s, Raman amplification became a cornerstone of ultra-high-speed and ultra-long-haul transmission systems, enabling the transmission of data over hundreds or even thousands of kilometers without significant signal degradation [13]. The ability to amplify optical signals without the need for electrical conversion provides both speed and efficiency, which are critical for modern, high-capacity communication networks [14].

The principle behind Raman amplification—using SRS for optical signal amplification—has proved to be a highly effective way to achieve long-distance, high-quality signal transmission. This technology continues to be indispensable in the development of advanced optical communication systems, allowing them to meet the ever-increasing demand for high-speed data transfer [15]. Through the combined use of Raman Amplifiers and DCF, optical communication systems are able to overcome the inherent limitations of attenuation and dispersion, ensuring that signal quality is maintained over long distances [16].

In advanced optical communication systems, especially those using Raman amplification to boost signal strength, the evaluation of the enhanced SRS level is a crucial first step [17]. This assessment is necessary because uncontrolled or excessive SRS can lead to increased noise, ultimately degrading the signal quality [18].

Their high efficiency makes Raman Fibre Amplifiers (RFAs) ideal for dynamic bandwidth designs in current DWDM networks, leading to their widespread use [19]. In comparison to conventional optical amplifiers that operate within fixed bandwidths, RFAs can be adjusted to amplify signals across a range of wavelengths. This flexibility allows for optimal bandwidth allocation, enabling DWDM systems to better utilize fibre capacity based on varying network demands [20].

DWDM serves as a powerful technique for increasing the data-carrying capacity of optical fibers. By combining (or multiplexing) optical signals from multiple independent transmitters, each operating at slightly different wavelengths, DWDM allows the transmission of these multiple channels through a single fibre [21]. This multiplexing process can be likened to multiple streams of data being combined into a single highway, increasing the efficiency of data transport. Each channel, associated with a specific wavelength, carries its own data stream independently of others [22].

At the receiving end of the fibre, another DWDM system is used to demultiplex the signals, essentially separating the composite signal back into its original individual channels [23]. This is akin to unwinding the combined data streams, where each unique wavelength is routed to its designated receiver. One of the defining features of DWDM is its all-optical nature, meaning that both transmitters and receivers are optical devices, and the signal stays within the optical domain throughout its entire journey [24]. This eliminates the need for energy-consuming conversions between optical and electrical signals, which would otherwise introduce noise and decrease the efficiency of data transmission [25].

2 Related Work

By amplifying the signal channels inside the transmission fiber, Long-haul optical transmission systems' range can be increased by using Raman amplification, which also significantly improves the receiver's performance against signal spontaneous beat noise [26]. Because their high gain is available in any optical fiber and at any wavelength with the proper pump source, fiber Raman amplifiers are a significant enabling technology [27]. Raman amplifiers need a lot of pump power, but if high-power semiconductor laser technology develops quickly, this may become less of a concern [28]. Raman amplifiers that are backward pumped have little polarization dependence and less crosstalk with other WDM channels, making them particularly intriguing [29]. A unique optical amplifier type must now be chosen for a certain gearbox system due to the broad variety of optical amplifier types available. One of the most popular choices is erbium-doped fiber amplifiers [30]. However, because of the limitations of the material's limited signal gain across a very restricted frequency range, SOAs and Raman amplifiers have gained popularity in recent years [31, 32].

The nonlinear phenomenon known as SRS is necessary for Raman amplification. The energy of the pump photon and some extra energy that is absorbed as phonons are sacrificed to create a new photon with the wavelength of the signal, which results in amplification [33, 34].

Only when the pump and the signal's polarizations are similar does the Raman gain occur [35]. The DWDM technology transmits data at high data speeds across many distinct channels using different wavelengths. Noise from the amplifiers in use, along with nonlinear transmission effects, limits the range of current systems [36]. The most optical network concepts used today are DWDM-based, hence optical filters are mostly required to route and select wavelength channels [37]. High-speed, long-distance optical fiber communication is not possible with optical transmission technologies due to dispersion [38]. To alleviate the dispersion issue, a variety of techniques are advised, including higher-order mode filters, DCF, and Fiber Bragg Grating (FBG) [39]. Multiple light pulses of various wavelengths can be transmitted concurrently because just one fiber is required due to DWDM. It upgrades and expands long-distance optical networks [40]. The general goal of the continuing study is to lessen the factors that might have an impact on signal quality, improving the system's overall performance in long-distance communication [41].

3 Significance in Ultra-High-Speed Optical Backbone for Smart Cities and 6G Networks

The proliferation of smart cities and the imminent deployment of 6G networks necessitate a sophisticated optical communication infrastructure. This infrastructure must facilitate ultra-high-speed, low-latency, and high-reliability data transmission to support demanding applications such as autonomous transportation systems, real-time AI processing, cloud computing environments, augmented reality experiences, and large-scale IoT deployments [1, 7, 16]. These applications require a robust backbone network capable of efficiently managing substantial data throughput. However, conventional fibre-optic networks are susceptible to impairments including chromatic dispersion, signal attenuation, and nonlinear effects, which degrade signal quality over extended transmission distances [3, 6]. To mitigate these limitations, a bidirectional 64-channel DWDM system is proposed, incorporating Raman Fibre Amplifiers (RFAs) and Dispersion Compensation Fibre (DCF) [15]. This configuration aims to enhance optical signal integrity, minimize Bit Error Rate (BER), and sustain a high Q-factor, thereby ensuring superior transmission performance over long-haul fibre-optic links [9, 10].

Chromatic dispersion hinders high-speed optical communication, particularly in DWDM systems, by causing signal distortion [12]. Dispersion Compensating Fibre (DCF), with its negative dispersion, is used to counteract this by reducing the overall dispersion of standard optical fibres [17]. This dispersion management is essential for clear signal transmission, minimizing errors, and achieving high data rates in long-distance networks [18].

Amplification is crucial for long-distance optical signal transmission to prevent signal loss. While widely used, conventional Erbium-Doped Fiber Amplifiers (EDFAs) limit optical network performance due to Amplified Spontaneous Emission (ASE) noise and gain saturation, particularly in bidirectional systems [11]. In contrast, RFAs offer a distinct advantage by providing distributed amplification directly within the transmission fibre, eliminating discrete amplification stages [8, 14]. This distributed approach yields several benefits compared to EDFAs, including: reduced ASE noise resulting in a higher optical signal-to-noise ratio (OSNR); improved gain flatness across DWDM channels, mitigating power fluctuations and signal distortion; and enhanced nonlinear impairment control due to the lower power requirements of Raman gain generation [13, 19]. Consequently, RFAs foster a more stable transmission environment, which is particularly critical in high-capacity bidirectional DWDM links where power equilibrium and minimal noise accumulation are vital for efficient data transfer [5, 2].

For next-generation optical networks supporting 6G and smart city initiatives, the integration of Raman amplification and dispersion compensation is crucial. This is because these networks necessitate:

1. Ultra-reliable, low-latency communication (URLLC), critical for the functionality of autonomous vehicles and AI-driven traffic control [4, 20]. High-capacity optical backbones are essential to support demanding applications like real-time cloud computing, 8K video streaming, and holographic conferencing [21, 23].
2. Seamless connectivity between data centers and dispersed AI processing units, ensuring efficient management of massive data traffic [22].
3. By harnessing the strengths of Raman Fibre Amplifiers (RFAs) and Dispersion

Compensation Fibre (DCF), the proposed system achieves high-speed, low-error communication while guaranteeing scalability for future network growth. Consequently, fibre-optic networks will remain a vital cornerstone for the development of smart cities and next-generation wireless systems [24, 25].

4 Mathematical Model

In order to model a Raman amplification system, we need to take into account the interactions between various optical signals traveling through the optical fibre. The optical power of each signal is influenced by both attenuation and amplification, with the amplification process heavily relying on the Raman scattering effect, which occurs between the pump signal and the signal being amplified [42].

The optical power of the k −th signal, denoted as $P_k(z)$, varies along the fibre and follows the differential equation:

$$\frac{\mathrm{dP_k(z)}}{\mathrm{dz}} = -\alpha_k \mathrm{P_k(z)} + \sum_{j\neq k,\, j=1}^{N} \mathrm{g_{kj}(z)P_j(z)P_k(z)} \quad (1)$$

where, $P_k(z)$ and $P_j(z)$ represent the optical powers of the k −th and j −th signals at position z in the fibre, α_k is the attenuation coefficient for the k −th signal, accounting for losses due to scattering and absorption in the fibre, and, g_{kj} represents the Raman gain coefficient, which quantifies how strongly the k −th and j −th signals interact through Raman scattering. The summation term accounts for the interaction between all signals in the system, except for the k −th signal itself [2].

In a Raman amplification system, a high-intensity pump signal transfers energy to a lower-intensity signal through Raman scattering [43]. It is important to understand this phenomenon. This interaction causes the lower-intensity signal to gain power, leading to amplification.

The rate at which optical power dissipates from a signal in a glass fiber is caused by two factors that exist simultaneously. The first, "attenuation", refers to the inherent loss of light energy in the glass which occurs due to absorption and scattering. It is a predictable, distance-dependent decay. However, the second factor, interaction with other signals in the same fiber, is a much more dynamic and frequently shifting one. When a number of signals are multiplexed together, they can nonlinearly interact with each other thermally. These interactions can result in the transfer of power between signals and additional (and sometimes rapid) changes to the overall levels of power that are not due entirely to basic attenuation within the fiber.

Next, the optical gain is commonly measured, which helps us determine the Raman gain coefficient. The following equations describe the relationship between the input and output signal powers, taking into account the fiber's attenuation and pump intensity.

$$\frac{P_s}{P_{s0}} = \exp\left(g I_{p0} L\right), \quad (2)$$

$$L = \frac{1 - \exp(-\alpha l)}{\alpha}, \quad (3)$$

where, I_{p0} is the intensity of the pump signal at the input, P_s and P_{s0} are the output and input signal powers, respectively, and, L is the effective gain length, which accounts for the attenuation of the fibre over its length. The effective gain length is shorter than the actual fibre length due to fibre losses [44].

In real optical fibre systems, the effective gain length L is a crucial factor in determining the net gain in the system. The equation (3) accounts for fibre losses, indicating that the effective length is less than the physical fibre length because of these inevitable losses.

For long-distance optical communication, chromatic dispersion is a significant challenge. This phenomenon causes pulse broadening, which limits the transmission distance and data rate. The dispersion effect is mitigated through the use of DCFs. These specialized fibers have negative dispersion coefficients, enabling them to effectively cancel the positive dispersion characteristic of regular Single-Mode Fibers (SMFs). To achieve balanced dispersion in systems incorporating DCFs, the lengths of both SMF and DCF must be precisely determined, as expressed by the equation

$$L_{\mathrm{SMF}} + L_{\mathrm{DCF}} = 0. \quad (4)$$

Here, L_{SMF} and L_{DCF} represent the lengths of the SMF and DCF, respectively. To minimize overall dispersion, this equation is designed to balance the positive dispersion contributed by the SMF with the negative dispersion from the DCF.

$$Q = \left(\frac{1 - \mathrm{rex}}{1 + \mathrm{rex}}\right)\left(\frac{2RP_{\mathrm{rec}}}{\sigma_1 + \sigma_0}\right), \quad (5)$$

where, P_{rec} is the received signal power, σ_1, and $\sigma_0$are system specific noise components, and, rex is the extinction ratio, which is the ratio of the two optical levels P_{on} and P_{off} of a signal.

$$P_{\mathrm{extinction}} = \frac{P_{\mathrm{on}}}{P_{\mathrm{off}}}. \quad (6)$$

The extinction ratio and noise characteristics of the system both influence the Q-factor, as shown by this equation. Achieving a higher Q-factor is desirable because it translates to clearer signals and a lower likelihood of transmission errors. Subsequently, the connection between the Q-factor and the BER is described by

$$\mathrm{BER} = \frac{1}{2}\operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) = \exp\left[\frac{Q^2}{2}\cdot\frac{1}{Q\sqrt{2\pi}}\right], \qquad (7)$$

where, the complementary error function erfc serves as the tool to calculate the probability of bit errors based on the Q-factor. It is important to emphasize the theoretical foundation of this relationship. The paramount importance of this function lies in its explicit demonstration of a critical trade-off: a larger Q-factor, representing a higher quality signal with greater noise immunity, directly corresponds to a smaller BER, indicating fewer data corruption instances. This inverse relationship is not merely theoretical; it is the bedrock upon which the overall system's performance is built, as a reduced BER translates to increased data integrity, enhanced throughput, and a more robust communication channel [43].

5 Proposed Framework

We present the architecture of the optical communication system in figure 1, highlighting the transmitter, receiver, and signal processing stages, and the basic tasks of each module. Crucially, we will also examine the compensation mechanisms implemented to guarantee efficient and reliable long-distance communication.

5.1 Transmitter and Modulation

At the heart of this system's operation is the transmitter, which generates and transmits the optical signal. The system leverages channels 1, 32, and 64, each distinguished by its operating wavelength. The transmitter is configured to operate at 1502.4 nm with an output power of -17.44 dBm, a combination chosen for effective long-distance transmission with minimal signal degradation. The transmitter uses Non-Return-to-Zero (NRZ) modulation for data, chosen for its simplicity and efficiency in high-speed optical communication. To further enhance capacity, WDM is also implemented. WDM allows the transmitter to send multiple signals simultaneously by assigning each a different wavelength on the same optical fibre.

5.2 Receiver and Signal Processing

Crucially, the receiver begins the optical signal processing sequence. It starts by capturing and transforming the incoming light signal into an electrical form for further operations. This initial conversion is handled by a photodetector, which senses the optical input and creates a related electrical signal. Next, a demultiplexer divides this electrical signal into separate channels, setting them up for individual treatment. To clean up the signal, a low-pass filter removes high-frequency noise. Finally, a 3R regenerator restores the signal to its original state by boosting its strength, correcting its shape, and realigning its timing, guaranteeing accurate data recovery. The final stage of analysis involves an eye diagram analyzer, a tool that measures key performance indicators like BER and Q-factor. These metrics are essential for gauging the success of the transmission and guaranteeing dependable communication.

5.3 Signal Amplification and Compensation

Long-distance optical communication faces two primary obstacles: signal attenuation and chromatic dispersion. These factors diminish signal quality as transmission distance increases. Our system is designed to solve these challenges through the strategic integration of signal amplification and dispersion compensation. To address signal attenuation, we utilize RFAs, pumped by lasers operating in the 1405–1460 nm band. This amplification significantly enhances signal power, enabling long-range transmission with minimal signal degradation and preserving high signal quality. Chromatic dispersion broadens pulses and impairs signal integrity, especially at high speeds. To combat this, we incorporate DCF with a dispersion value of -800 ps/nm, along with Raman amplification that effectively reverses the effects of chromatic dispersion.

5.4 System Evaluation and Results

System performance was characterized through simulations, with a focus on key performance indicators (KPIs) including BER, Q-factor, and signal threshold. These KPIs quantify the system's efficiency and robustness in preserving signal integrity across varying operating conditions. To examine the effects of data rate and fiber length on signal quality, these parameters were systematically varied during simulations. The resulting performance data is graphically presented, enabling a direct comparison of system behavior under different configurations. An eye diagram analyzer played a crucial role in this characterization, facilitating the determination of minimum BER and Q-factor, critical metrics for system optimization.

Table [1] details key optical communication system parameters, including fibre characteristics, pump laser frequencies and powers, amplifier settings, and DCF specifications. Their careful selection is essential for optimizing long-distance transmission performance, specifically to achieve efficient amplification, reduce signal degradation, and ensure accurate data recovery. At this point it is important to note that this scheme can be efficiently used for designing mechanisms like [5,15,22,32,36,48].

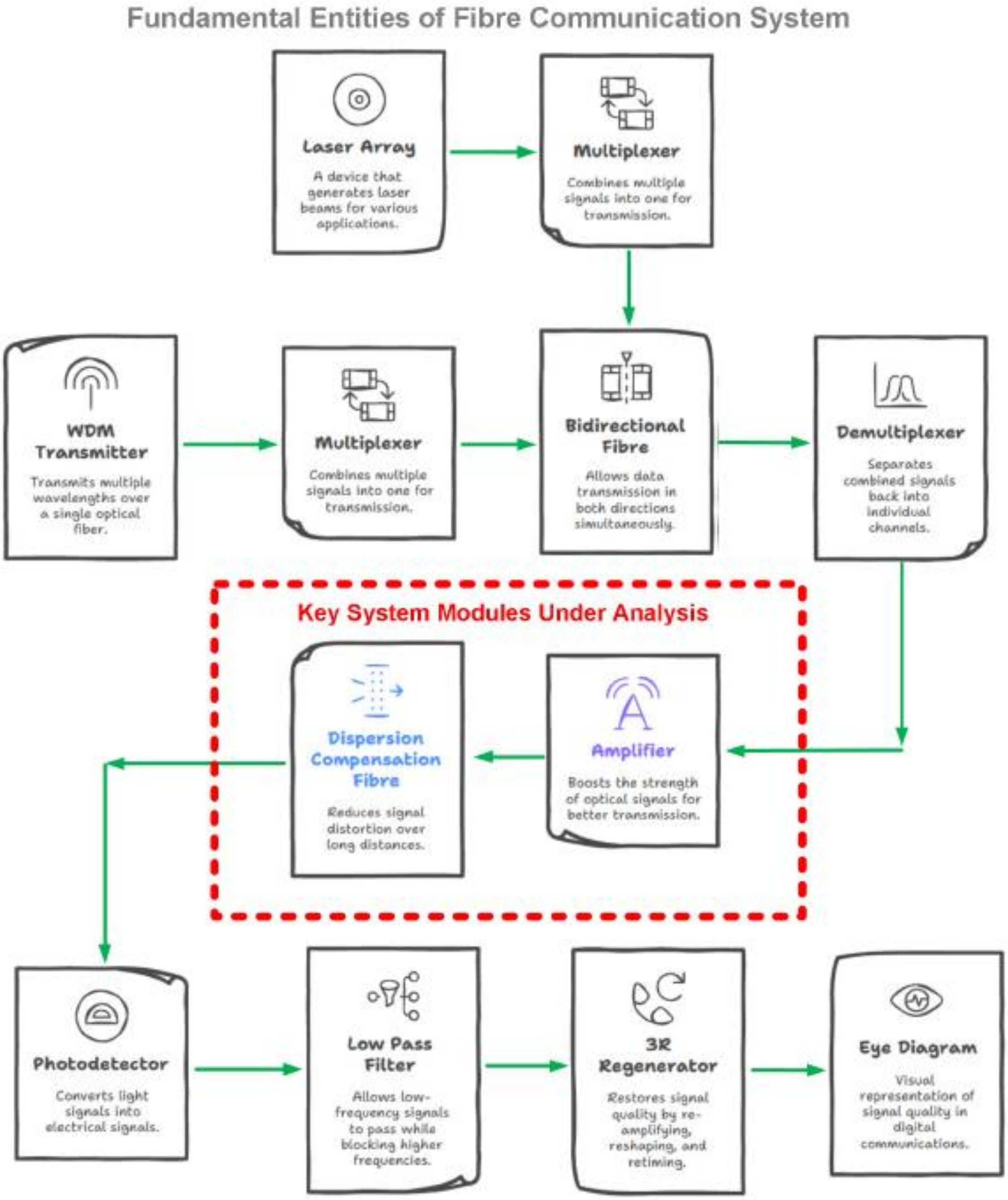


Fig 1. Block diagram of the proposed optical communication system, highlighting the major components and their working, and the key system modules which are being investigated in this work.

Table 1. System parameters for long-distance optical communication are compiled to optimize performance, including fibre characteristics, pump laser specifications, amplifier settings, and relevant performance metrics.

No.	Parameter	Value	Unit	Notes
Optical Fiber Parameters				
1	Length of Optical Fibre	25, 50, 75, 100, 125	km	Varying fiber lengths to observe system behavior over different distances.
2	Chromatic Dispersion of SMF	16	ps/nm/km	Typical value for standard single-mode fiber.
3	Polarization Mode Dispersion (PMD)	0.1	ps/km$^{1/2}$	Includes effects of polarization-dependent signal propagation.
Pump Laser Array Parameters				
4	Frequency of Pump Laser Array	1405, 1415, 1435, 1460	Nm	Multiple pump wavelengths for varying amplification efficiency.
5	Power of Pump Laser Array	100.93, 135.32, 93.749, 179.49	mW	Adjusting pump power to assess amplification efficiency and signal distortion.
Amplifier and Filter Parameters				
6	Gain of Amplifier	20	dB	Chosen to ensure strong amplification without over-saturation.
7	Noise Figure of Amplifier	4	dB	Standard noise figure for high-performance optical amplifiers.
8	Cut-off Frequency of Low-Pass Filter	0.75 × Date Rate	Hz	Designed to minimize high-frequency noise while maintaining data integrity.
Dispersion Compensation Fibre (DCF) Parameters				
9	Frequency of DCF	193.1	THz	Central frequency for dispersion compensation.
10	Bandwidth of DCF	125	GHz	Appropriate bandwidth for fiber dispersion correction.
11	Dispersion Factor of DCF	-800	Ps/nm	Negative dispersion compensates for chromatic dispersion.
System Performance Parameters				
12	Signal Sensitivity	-30	dBm	Minimum detectable signal power for reliable communication.
13	Error Tolerance	0.01	-	System's tolerance to error due to noise and distortion.
14	Amplifier Linearity	1^{-30}	dB	Linear gain range of the amplifier.
15	Bit Error Rate (BER)	10^{-9} to 10^{-3}	-	Varies depending on channel length, pump power, and modulation scheme.
16	Signal-to-Noise Ratio (SNR)	10^{-40}	dB	System's SNR at various transmission distances.

6 System Design and Technical Justification

6.1 Tools and Software Employed

Optisystem 20 [46] served as our simulation platform for evaluating the performance of our optical communication system. Our virtual lab environment houses a complete array of optical components like lasers, modulators, optical fibers, amplifiers, and photodetectors, coupled with electrical signal processing elements. This detailed simulation, designed to replicate a real optical communication link, allowed us to precisely model each subsystem's dynamics and understand their collective behavior with accuracy.

6.2 Simulation Methodology and Evaluation

Simulations were conducted to assess system robustness and performance by manipulating key variables. Data transmission rates were varied to analyze system behaviour under different conditions. WDM channels 1, 32, and 64 were chosen to test performance across a range of wavelengths. Optical fibre length was also varied to observe the effects of propagation distance on signal quality, including attenuation and dispersion.

6.3 Performance Metrics: Q-factor and BER

The transmission quality of our optical link was rigorously evaluated using two metrics: the Q-factor and the BER. The Q-factor, a direct indicator of the Signal-to-Noise Ratio (SNR), provides insight into the system's ability to withstand noise. It can be thought of as approximating the SNR in decibels (dB) within the linear domain. A high Q-factor directly translates to a wide separation of signal levels in the eye diagram, leading to more robust signal detection and a reduced probability of errors at the receiver. In essence, Q-factor serves as an indicator of the system's inherent immunity to noise-related signal degradation [5,11]. Ultimately, this noise immunity impacts the BER, typically expressed using scientific notation (e.g., 10^{-9}). BER represents the probability of bit errors and is the definitive measure of data link reliability. A lower BER is paramount, signifying fewer corrupted bits and higher data transmission accuracy. Factors like noise (thermal, shot, ASE), fibre nonlinearities, and component quality all contribute to the BER. Therefore, both Q-factor and BER are critical for characterizing optical communication system performance [47,48,49,50]. Q-factor offers a rapid assessment of signal quality at the physical layer, while BER provides a direct measure of the resulting data integrity, together enabling a comprehensive understanding of system performance and efficiency.

6.4 Data Visualization and Analysis

Simulation results were visualized using 2D graphs to analyse the relationships between data rates, fibre lengths, and system performance (Q-factor and BER). This graphical analysis facilitated the identification of performance trends and system bottlenecks, guiding subsequent optimization for enhanced efficiency.

6.5 Configuration Testing and Optimization Strategies

The following sections detail the specific configurations tested and the optimization methods used to enhance system performance. Each section explores a different aspect of the optical communication system, outlining the iterative design process and successful strategies.

7 Results and Discussion

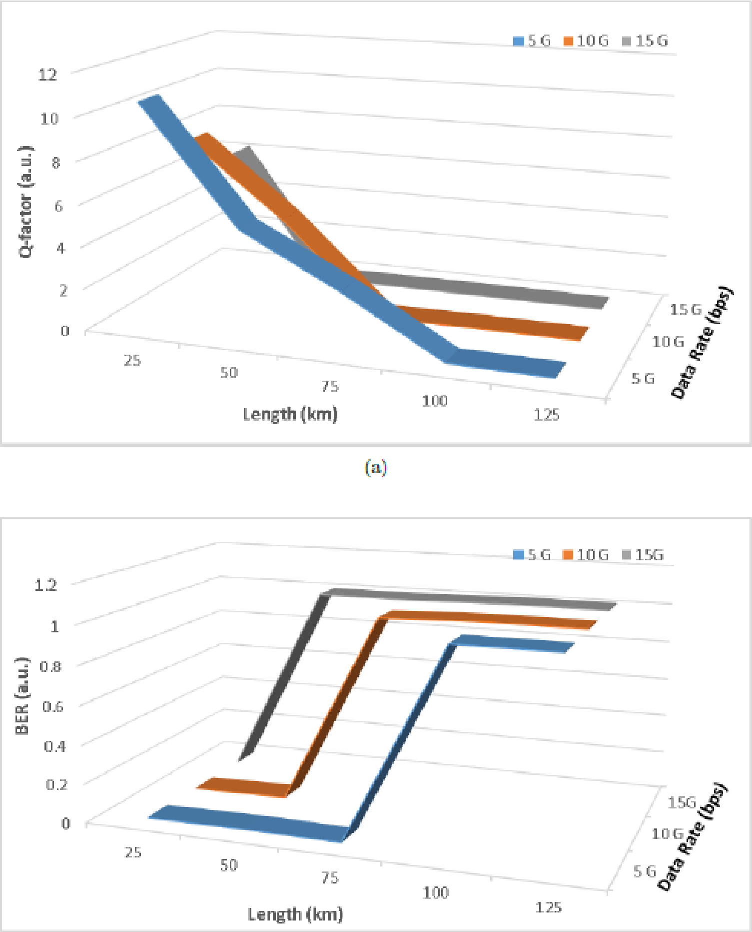
7.1 Comparative analysis of channel 1 without the use of Amplifier and Dispersion Compensation Fibre

In this configuration of components, we conducted an analysis of the system without incorporating an amplifier or DCF. To evaluate system performance, we considered three different data rates for channel 1: 5 Gbps, 10 Gbps, and 15 Gbps. The length of the optical fibre was varied to examine its impact on system performance under these different data rates. Figure 2 depicts the Q-factor and BER performance at the respective data rates investigated.

For the data rate of 5 Gbps, the system achieved a maximum Q-factor of 10.6244 in figure 2a, which indicates a high signal quality. Correspondingly, the minimum BER recorded at this data rate was 0.0055 in figure 2b, reflecting a low probability of errors in the transmitted signal. These optimal results were obtained when the optical fibre length was set to 25 km.

However, increasing the optical fibre length to 125 km resulted in a marked decline in system performance. This degradation is evidenced by the Q-factor reaching its minimum value of 0.03895, a level indicative of significant signal impairment. Furthermore, the BER increased to a maximum of 1.01, signifying a heightened probability of errors in the data transmission. Figure 2 gives a detailed investigation of these performance metrics at a 5 Gbps data rate. These figures graphically represent the Q-factor and BER as a function of optical fibre length, providing deeper insight into the system's operational characteristics.

Subsequently, channel 1's data rate was increased to 10 Gbps, and performance was reassessed by analysing Q-factor and BER. At this higher rate, the maximum Q-factor achieved was 7.899, and the minimum was 0.00045 (figures 2a and 2b). Performance deteriorated significantly at a 125 km fibre length, exhibiting the worst BER (1.01468) and lowest Q-factor (0.06739). This highlights the increasing signal degradation with longer fibre lengths, resulting in diminished performance.



(a)

(b)

Fig 2. Variation of the (a) Q-factor, and, (b) BER, with various data rates and lengths of the anticipated optical communication system, respectively.

Subsequent to the preceding analysis, the data rate of channel 1 was elevated to 15 Gbps, and the performance characteristics were re-examined. At this elevated data rate, the system exhibited its optimal performance metrics, achieving a peak Q-factor of 6.241 and a BER of 0.0041. These values demonstrated a notable enhancement in signal quality compared to prior data rate configurations. However, operating at 15 Gbps also resulted in the system's least satisfactory performance, as evidenced by a minimum Q-factor of 0.00236 and a maximum BER of 1.00459. The observed performance fluctuation at this data rate emphasizes the necessity for meticulous optimization of both data rates and fibre optic cable lengths to guarantee superior transmission quality.

7.2 Comparative analysis of Channel 1 with use of Amplifier and Dispersion Compensation Fibre

We then proceeded to evaluate the system's performance specifically for Channel 1, testing data rates of 5 Gbps, 10 Gbps, and 15 Gbps. This range of rates was chosen to assess system performance under varying load conditions and to gauge the effectiveness of the amplifier and DCF.The analysis of these results is presented in Figures 3a and 3b, which provide a detailed visualization of the Q-factor and BER measurements across the tested data rates.

At a data rate of 5 Gbps, the system demonstrated the best performance overall. The highest Q-factor of 22.7222 was achieved at this data rate, indicating excellent signal quality and a low probability of error. Correspondingly, the BER was measured to be as low as 1.32×10^{-8}, which is a highly favourable value for reliable data transmission. However, it is important to note that at this data rate, the maximum BER observed was 1.91×10^{-6}, and the minimum Q-factor recorded was 4.6224.

Next, the data rate was increased to 10 Gbps to evaluate the system's performance under higher-speed conditions. At this data rate, the highest Q-factor obtained was 4.8774, which is significantly lower than the Q-factor at 5 Gbps, but still acceptable for many applications. The lowest BER value observed in this configuration was 0.0211, while the highest BER measured was 1.00259. The minimum Q-factor recorded at this data rate was 0.0353, indicating that the system's performance degraded noticeably as the data rate increased.

These figures highlight the trade-offs between data rate and system performance, demonstrating that while higher data rates offer increased bandwidth, they also lead to reduced signal quality and higher error rates.

Following this, the data rate of channel 1 was adjusted to 15 Gbps. Subsequently, the Q-factor and BER were analysed as functions of varying lengths of optical fibre. At this data rate, the maximum Q-factor value attained was 7.007, while the corresponding BER value was 0.00475. These optimal performance metrics were observed when the length of the optical fibre was at its minimum. Conversely, the maximum BER value recorded at this data rate was 1, indicating degraded system performance under certain conditions. Additionally, the minimum Q-factor value obtained at 15 Gbps was 0.081, highlighting the impact of fibre length on signal quality and system reliability.

Integrating an amplifier and DCF greatly improves system performance, especially at lower data rates, yielding better signal quality and fewer errors. Nevertheless, the subsequent performance decrease at higher data rates underscores the critical need for meticulous optimization of system parameters to ensure dependable long-distance transmission.

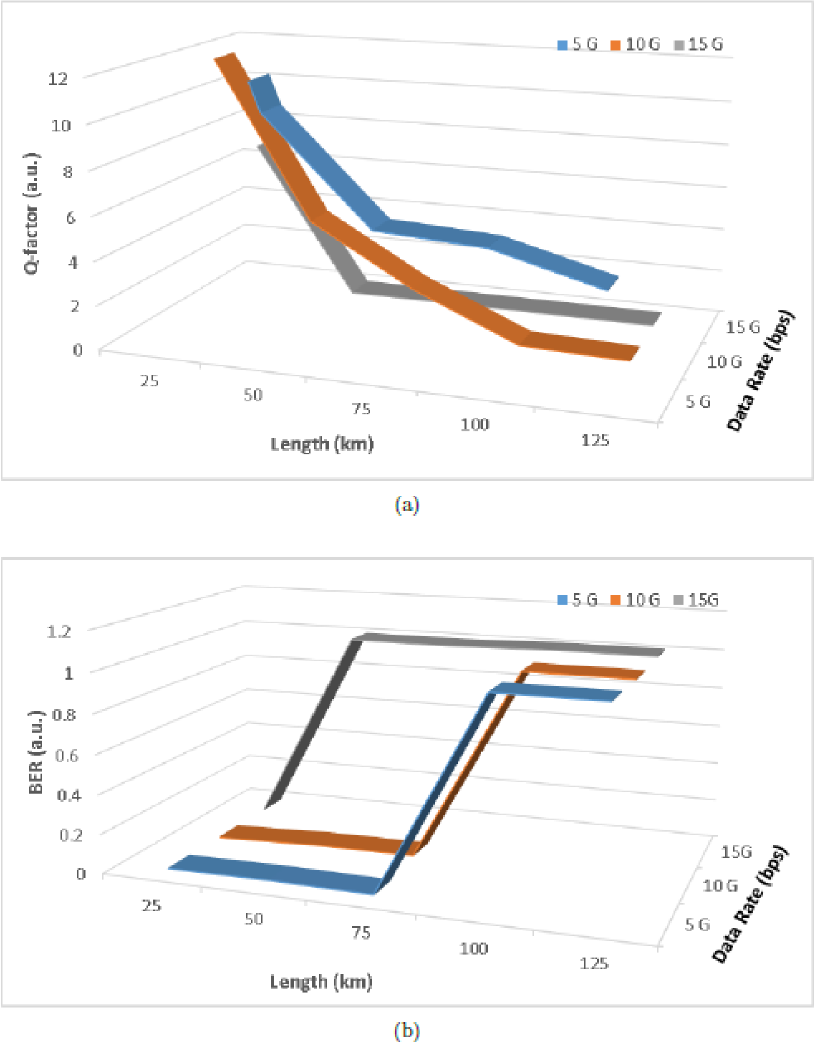
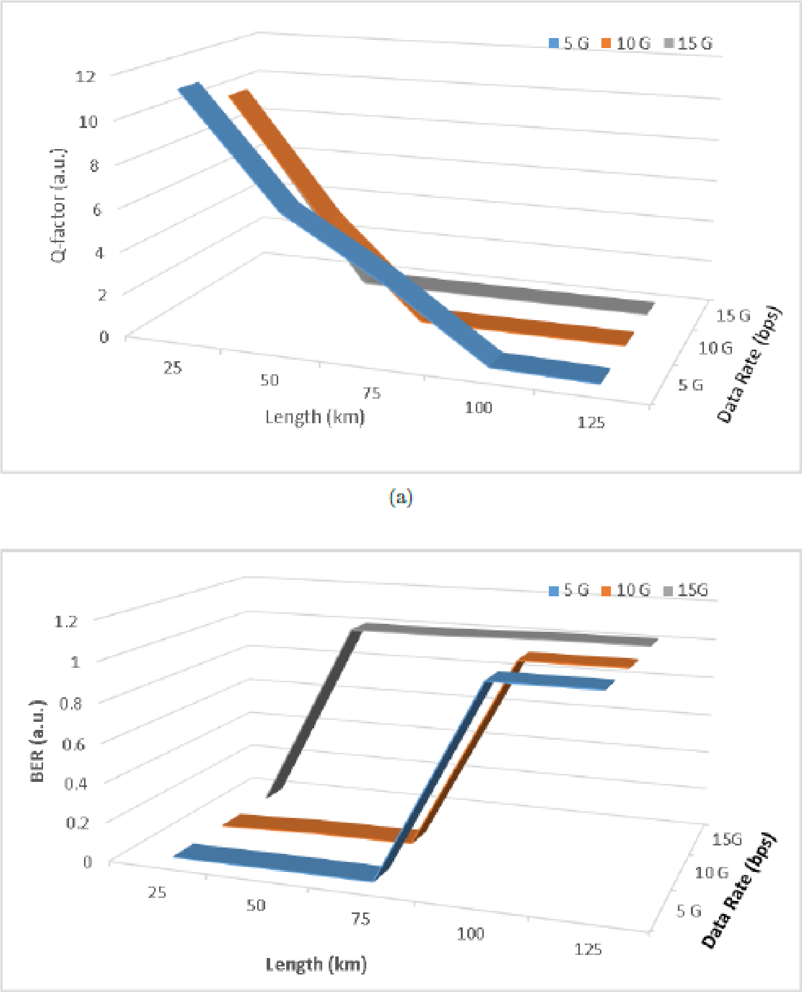


Fig 3. Variation of the (a) Q-factor, and, (b) BER, with various data rates and lengths of the anticipated optical communication system, respectively.

7.3 Comparative analysis of channel 32 without the use of Amplifier and Dispersion Compensation Fibre

In this experimental setup, channel 32 of the WDM transmitter was used to analyze the system's performance at three different data rates: 5 Gbps, 10 Gbps, and 15 Gbps. These data rates were selected as representative of common transmission speeds to facilitate performance evaluation and subsequent optimization of the WDM system across different scenarios. The optical fibre length was systematically modified to determine its influence on transmission quality.

While excellent performance was observed at 5 Gbps, achieving a maximum Q-factor of 11.3012 and a minimum BER of 0.0004587 (indicating high signal quality and low error probability, respectively), performance was significantly impacted by fibre length (figures 4a and 4b). This is highlighted by the wide range in Q-factor (0.0422 to 11.3012) and a maximum BER reaching a much higher value of 1.00963, suggesting substantial performance fluctuations.



(a)

(b)

Fig 4. Variation of the (a) Q-factor, and, (b) BER, with various data rates and lengths of the anticipated optical communication system, respectively.

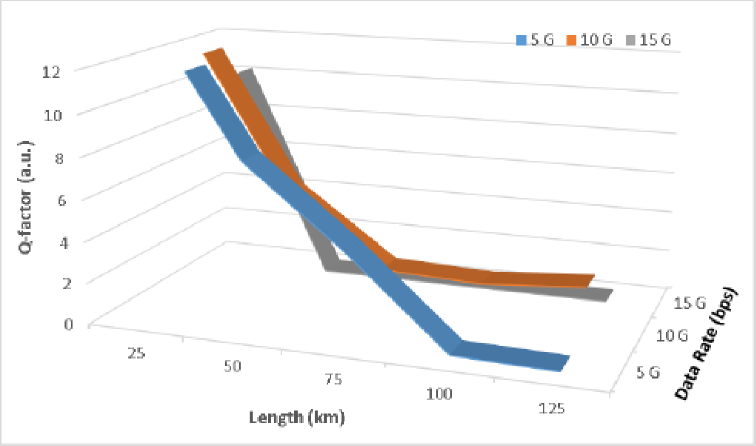
Both these figures graphically represent the interdependency of Q-factor and BER under varying conditions of data rates and fibre lengths. These figures serve to demonstrate the inherent trade-off between data throughput and signal integrity in the system. Specifically, they reveal that network performance, indexed by Q-factor and BER, suffers as data rates are elevated. This performance degradation is particularly acute at 10 Gbps and 15 Gbps, where the figures indicate a substantial increase in BER. This observed increase in error rates at these higher speeds suggests a potential limitation in the system's capacity to maintain reliable data transmission as bandwidth demands increase.

These results in figure 4 highlight the importance of carefully optimizing both data rate and fibre length for WDM systems. The findings provide valuable insights into the behaviour of optical signals under different conditions and contribute to enhancing the reliability of fibre-optic communication systems.

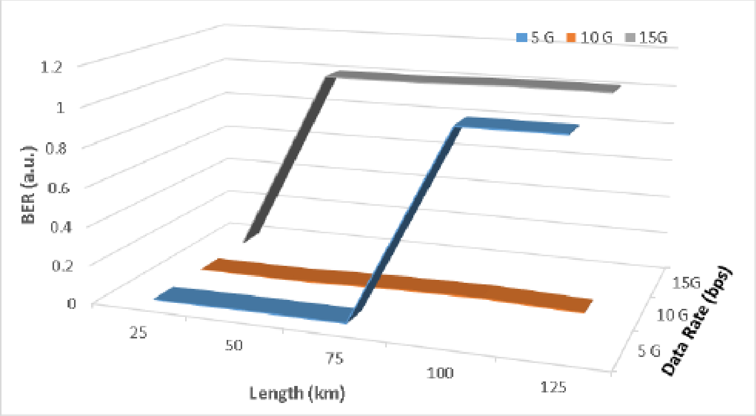
7.4 Comparative analysis of channel 32 with the use of amplifier and Dispersion Compensation Fibre at different data rates

The data presented in figure \ref{Q_BER_D} summarizes the measured relationship between fibre length, Q-factor, and BER at 15 Gbps. This figure visually shows how system performance is affected by fibre length.

Initially, the data rate was set at 10 Gbps. At this data rate, the Q-factor, which indicates the signal quality, started at a high value of 10.1849 for a shorter fibre length (figure 5a). However, as the fibre length increased, the Q-factor degraded significantly to a lower value of 0.08817. Correspondingly, the BER, which quantifies the frequency of errors in the received data, was also assessed in figure 5b. The minimum (best) BER achieved was 0.0089, while the maximum (worst) BER observed was 1.01. Notably, these minimum and maximum BER values were recorded at fibre lengths of 25 kilometres and 125 kilometres, respectively.



(a)



(b)

Fig 5. Variation of the (a) Q-factor, and, (b) BER, with various data rates and lengths of the anticipated optical communication system, respectively.

Subsequently, to examine the system's performance at a higher data rate, the data rate was increased to 15 Gbps. The Q-factor measurements at this faster data rate showed that the highest Q-factor obtained was 6.22844, while the lowest value was significantly reduced to 0.0236. Similarly, the BER was evaluated at 15 Gbps, with the minimum BER achieved at 0.004, and the maximum BER reaching 1.0058.

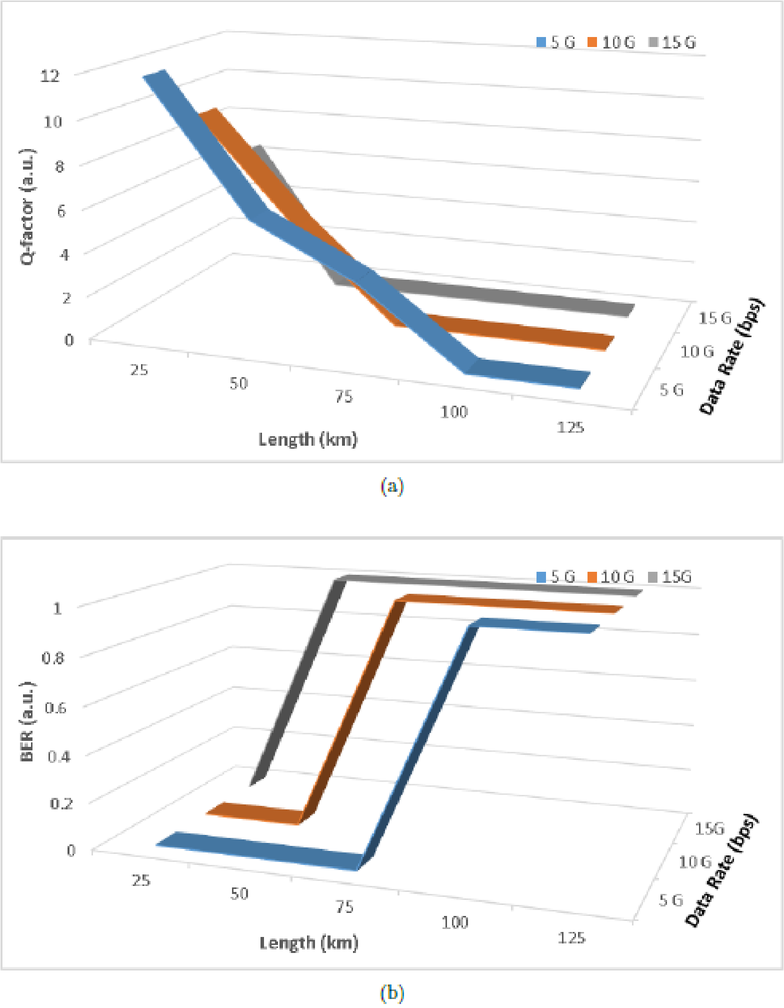
The data rate for channel 32 was increased to 15 Gbps to investigate system performance under enhanced transmission speeds. Q-factor and BER metrics were evaluated at this data rate as a function of optical fibre length. The maximum Q-factor achieved was 7.243, suggesting acceptable signal integrity under specific operating parameters. However, a significant reduction in signal quality was observed at maximum fibre length, with the minimum Q-factor dropping to 0.0899. This degradation is attributed to increased attenuation and dispersion effects over extended propagation distances.

Using the shortest fibre at 15 Gbps, we obtained a low BER of 2.15×10^{-3}, showcasing efficient signal propagation and minimal degradation in short-reach scenarios. This confirms the system's suitability for such applications. However, longer fibre distances introduced significant signal attenuation and dispersion, subsequently increasing the BER. The BER peaked at 2.59×10^{-3} with the longest fibre, clearly demonstrating the crucial need to consider fibre length limitations for reliable long-distance transmission at this data rate.

7.5 Comparative analysis of channel 64 without the use of an amplifier and Dispersion Compensation Fibre at different data rates

To investigate the system's performance at different data rates, channel 64 of a WDM transmitter was utilized. Specifically, data rates of 5 Gbps, 10 Gbps, and 15 Gbps were tested. Performance evaluation of the optical communication system relied on measuring Q-factor and BER while varying the optical fibre length.

To provide a visual representation of the relationship between the Q-factor and BER as a function of fibre length at 5 Gbps, figure 6 displays the corresponding results. These figures illustrate how the signal quality (as indicated by the Q-factor) and the error rate (BER) change with varying fibre lengths, offering a clear and insightful comparison of the system's performance under different conditions.



(a)

(b)

Fig 6. Variation of the (a) Q-factor, and, (b) BER, with various data rates and lengths of the anticipated optical communication system, respectively

To begin with, channel 64 was configured for a data rate of 5 Gbps. Under this configuration, the Q-factor, which is a key indicator of the signal quality, reached a maximum value of 11.835 in figure 6a. This suggests excellent signal quality and minimal distortion at shorter fibre lengths. However, as the optical fibre length increased, the Q-factor naturally degraded, which is typical in optical communication systems due to signal attenuation and dispersion over longer distances.

On the other hand, the BER was also evaluated at the 5 Gbps data rate in figure 6b. The minimum BER observed during this test was 0.004, indicating a relatively low error rate and a good signal-to-noise ratio at shorter fibre lengths. However, as the fibre length increased, the maximum BER increased to 1, reflecting a substantial rise in errors, particularly at longer transmission distances. The minimum Q-factor recorded during this experiment was 0.044, highlighting a significant drop in signal quality as the fibre length approached its maximum.

In continuation of the preceding investigation, a further experiment was undertaken to assess the optical communication system's performance under more rigorous conditions. This involved elevating the data transmission rate to 10 Gigabits per second (Gbps), representing a considerable increase from the initial configuration. The Q-factor was subsequently measured across a spectrum of optical fibre lengths to evaluate system performance. The experimental findings demonstrated a broad range of Q-factor values, indicative of signal quality variation as a function of fibre length. Specifically, a minimum Q-factor of 0.0025 was recorded, highlighting notable signal deterioration over extended fibre lengths, while a maximum Q-factor of 9.245 was observed, suggesting comparatively high signal quality at shorter lengths.

System performance was further evaluated by measuring the BER at 10 Gbps across different optical fibre lengths. Consistent with the Q-factor, the BER was assessed as a function of fibre length. Optimal performance, indicated by a minimal BER of 0.004, was observed for shorter fibers. In contrast, longer fibre lengths resulted in a maximum BER of 1, revealing a substantial error increase and system degradation, primarily attributed to signal attenuation and dispersion.

The relationships between fibre length, Q-factor, and BER at 10 Gbps are visually depicted in Figures 18 and 19. These graphical representations show how these performance indicators vary with fibre length, enabling a comprehensive comparison of the system's performance under different transmission distances.

The optical communication system's performance at a higher data transmission rate was evaluated by setting the data rate to 15 Gbps on channel 64. This specific data rate enabled a detailed investigation of the system's behavior under high-speed conditions. To further explore the system's characteristics, the fibre length was systematically changed, and the resulting signal quality was closely tracked at each length to determine the influence of fibre length.

The highest Q-factor observed, 6.467, demonstrated optimal signal quality and occurred at the shortest fibre lengths. Furthermore, a minimum BER of 0.004 was recorded, signifying a low error rate and consequently, high signal quality.

However, the minimum Q-factor recorded was 0.024, representing the poorest signal quality observed. This minimum Q-factor was associated with the maximum BER of 1, indicating a severely degraded signal with an unacceptably high error probability. Such high BER values are characteristically found at increased fibre lengths due to the amplification of signal degradation effects. Consequently, these observations support the conclusion that increasing fibre length induces a deterioration in signal quality, as reflected in the inverse trends of the Q-factor and BER.

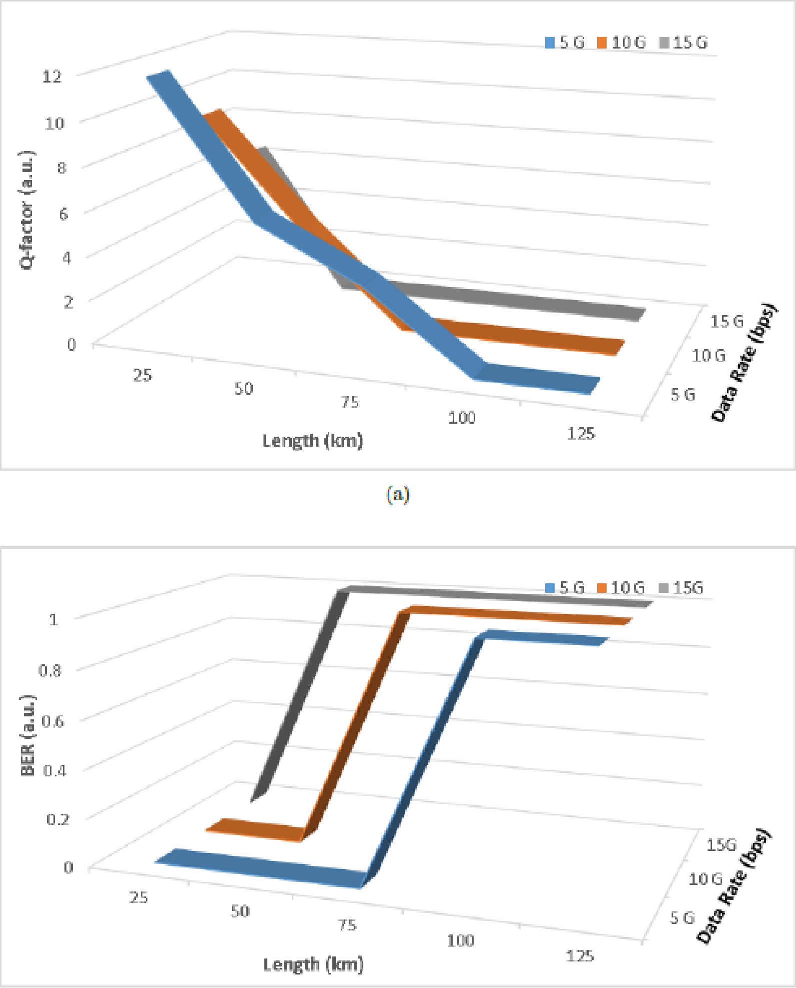
The analysis results, particularly the changes in Q-factor and BER with fibre length at 15 Gbps, are clearly visualized in Figures 20 and 21, respectively. These visual aids effectively demonstrate the system's performance response to varying fibre lengths, enhancing understanding of the interplay between transmission distance, signal quality, and error rate. A comprehensive summary of all experimental results is then presented, offering a broad overview of the system's performance under diverse fibre lengths and transmission scenarios.

7.6 Comparative analysis of channel 64 with the use of amplifier and Dispersion Compensation Fibre at different data rates

To mitigate signal degradation in this experimental setup, an amplifier and DCF were incorporated into the optical communication system. Both attenuation and chromatic dispersion, typical challenges in optical communication, are addressed by these components. Widely used in long-distance systems, they enhance signal performance by counteracting inherent signal degradation across extended distances. Specifically, the amplifier boosts signal strength to offset losses, and the DCF minimizes signal pulse broadening due to chromatic dispersion, thereby maintaining signal integrity over longer fibre lengths.

For this analysis, Channel 64 of the transmitter was selected, and the system performance was evaluated at three distinct data rates: 5 Gigabits per second (Gbps), 10 Gbps, and 15 Gbps.

The results were analysed at each data rate to investigate the effects of varying transmission conditions, including different fibre lengths. The relationship between Q-factor and BER as a function of fibre length is visually represented in figure 7.



(a)

(b)

Fig 7. Variation of the (a) Q-factor, and, (b) BER, with various data rates and lengths of the anticipated optical communication system, respectively.

Starting with the data rate of 5 Gbps, the system's performance was analysed in detail in figure 7a. The Q-factor was observed to vary between a maximum value of 26.0374 and a minimum value of 3.213. The Q-factor serves as an indicator of how well the system can distinguish between transmitted signals, with higher values corresponding to better signal quality. A clear trend emerged at this data rate in contrast with figure 7b: as fibre length increased, the BER rose, and the Q-factor fell. The BER, indicating error frequency, spanned from $3.14\mathrm{x}10^{-6}$ to $6.50\mathrm{x}10^{-4}$. This behaviour aligns with typical characteristics of long-distance optical communication, where longer distances lead to more significant signal degradation and noise accumulation.

We assessed system performance at a high-speed data transmission rate of 10 Gbps to simulate operational conditions. Specifically, the Q-factor, indicative of signal quality, ranged dramatically from a high of 12.53 (excellent signal integrity) to a low of 0.029 (suggesting signal degradation). This variability was mirrored in the BER, which swung from 1 (an unusable link) down to 4.00×10^{-4} (still a non-negligible error rate). These observations underscore the performance instability at 10 Gbps and offer critical understanding of the system's reliability limits and signal integrity profile.

7.7 Optimization Considerations for Data Rates and Transmission Lengths in Optical Systems

- *The Role of Fibre Length in Modulating Q-factor and BER* Longer optical fibres meant lower Q-factors, and shorter fibres gave the best Q-factors. For example, the Q-factor decreased when the fibre length was extended from 25 km to 125 km, signifying a decline in system performance, reduced signal integrity, and elevated error probability. Conversely, BER exhibited a direct correlation with fibre length, increasing its value at 25 km to that in 125 km. This increase indicates a reduction in signal reliability with greater propagation distance.

- *Fibre Impairments and Performance Degradation* The observed performance degradation with increasing fibre length is primarily attributed to inherent fibre impairments, namely, attenuation and dispersion. Attenuation leads to signal power loss over distance, resulting in decreased signal amplitude. Specifically, an attenuation rate of 1 dB/km at 1300-1600 nm induces a measurable reduction in signal strength, consequently affecting system performance. Dispersion, conversely, causes temporal pulse broadening, leading to signal distortion and inter-symbol interference. As fibre length increases, the cumulative effects of attenuation and dispersion become more pronounced, further degrading signal quality. This effect is particularly notable in higher-order modes of multi-mode fibres due to the increased significance of modal dispersion.
- *Experimental Validation of Fibre Length Impact* Experimental results consistently demonstrated a decrease in Q-factor and a corresponding increase in BER as fibre length was extended from 25 km to 125 km. This trend supports the conclusion that fibre length has a detrimental impact on overall system performance, particularly beyond a certain distance, where a rapid increase in error rates and a significant decrease in Q-factor were observed.
- *Influence of Data Rate on Q-factor* The study also investigated the impact of data rate on system performance. Lower data rates (5 Gbps) yielded higher Q-factor values compared to higher data rates (15 Gbps). Specifically, at 5 Gbps, the Q-factor remained consistently elevated, as observed across all tested fibre lengths.
- *Rationale for the Inverse Q-factor/Data Rate Relationship* The inverse relationship between Q-factor and data rate is explained by the reduced temporal window per bit at higher data rates. This heightened sensitivity to noise and other signal impairments. Increased data rates reduce the system's SNR, leading to a greater probability of errors and, consequently, a reduced Q-factor. This effect is accentuated in high-speed systems where signal processing limitations, such as inter-symbol interference, become more critical.
- *Inter-Symbol Interference at Higher Data Rates* The increased temporal overlap of consecutive bits at higher data rates increases the likelihood of inter-symbol interference. This, in turn, exacerbates the effects of fibre impairments, such as dispersion. The resulting broader pulses can overlap, leading to potential data errors.
- *Impairment Mechanisms and Noise Influence in Optical Systems* Experimental results demonstrate that both fibre length and data rate exert a significant influence on system performance. Increased fibre length leads to greater attenuation and dispersion, which degrade signal quality and elevate the BER. Elevated data rates compound these issues by reducing the temporal window per bit, thereby increasing the system's sensitivity to impairments and noise.
- *Challenges in Optical Networks* Signal degradation in long fibres and at high data rates can hinder optical communication system performance. To address this, future systems can leverage dispersion compensation, advanced modulation, and optical amplifiers. This approach promises to enhance system performance, allowing for longer distances and faster data transmission. Consequently, careful optimization of fibre length and data rate is vital for ensuring the reliability of high-speed communication systems, particularly for long-distance networks.

7.8 Comparative Analysis of Channels 1, 32, and 64 in the Context of Non-Amplified and Non-DCF Systems

We began by examining the inherent capabilities of different transmission channels in their raw state, without the aid of amplifiers or DCF. By comparing Q-factor and BER, we aimed to understand their baseline performance. Our analysis clearly identified Channel 64 as the standout performer. Its peak Q-factor of 11.835 significantly surpassed Channels 1 and 32 (Q-factors of 10.6244 and 11.3012, respectively), indicating a naturally superior ability to preserve signal quality and minimize noise. This inherent advantage in signal-to-noise ratio for Channel 64 is evident even before any signal processing enhancements are applied. The BER data corroborated these findings. Channel 64 demonstrated the lowest BER (1), while Channels 1 and 32 showed slightly elevated BERs (1.00459 and 1.00548, respectively). Although the BER values are numerically close, they reveal subtle differences in error probability, with higher BERs suggesting greater signal degradation and potentially lower reliability. Table 2 offers a visual overview of these key performance indicators – Q-factor and BER – for each channel in their unenhanced form. This allows for straightforward comparison and highlights the intrinsic strengths and weaknesses of each channel prior to the application of signal optimization techniques.

Table 2. Performance metrics of Channel 1, 32, and 64 without the use of Amplifier and DCF.

No.	Channel	Q-factor (a.u.)	BER (a.u.)
1	Channel 1	10.6244	1.00459
2	Channel 32	11.3012	1.0058
3	Channel 64	11.835	1

7.9 Comparison of Channels 1,32 and 64 in terms of the Resultant values with the use of amplifier and DCF

We now present a comparative analysis of optical channels 1, 32, and 64 based on experimental measurements. Our objective is to evaluate and contrast their performance metrics, with a concise visual summary provided in Table 3. We will also discuss the signal quality enhancements resulting from the integration of an amplifier and a DCF. With this enhanced setup, the maximum Q-factor reached 26.0374, specifically for channel 64, while channels 1 and 32 achieved Q-factors of 22.7222 and 24.3374, respectively. To illustrate the impact of our approach, we compare the BER with and without the amplifier and DCF. Without these components, the BER for channels 1, 32, and 64 approached 1. This comparison clearly demonstrates the substantial improvement in signal quality achieved through the inclusion of the amplifier and DCF in our system.

Table 3. Performance metrics of Channel 1, 32, and 64 with the use of Amplifier and DCF.

No.	Channel	Q-factor (a.u.)	BER (a.u.)
1	Channel 1	27.7222	1
2	Channel 32	24.3374	1
3	Channel 64	26.0374	1

7.10 Performance Evaluation of Q-Factor and BER in Long-Haul Transmission

Chromatic dispersion and attenuation losses significantly impact the performance of long-haul optical communication systems. Table 4 presents the Q-factor and BER for different transmission distances and data rates (5G, 10G, and 15G). The results show that as the fibre length increases, the Q-factor decreases due to higher accumulated dispersion and nonlinear impairments, leading to an increase in BER.

Table 4. Q-Factor and BER for Different Data Rates and Fibre Lengths

Fibre Length (km)	Q-Factor (5G)	BER (5G)	Q-Factor (10G)	BER (10G)	Q-Factor (15G)	BER (15G)
200	8.5	3.1×10^{-9}	7.2	5.4×10^{-7}	6.4	2.3×10^{-6}
300	7.9	1.8×10^{-8}	6.5	9.6×10^{-7}	5.8	5.6×10^{-6}
400	7.2	7.6×10^{-8}	5.9	2.1×10^{-6}	5.2	1.2×10^{-5}
500	6.5	2.3×10^{-7}	5.4	5.3×10^{-6}	4.7	2.8×10^{-5}
600	5.9	6.1×10^{-7}	4.8	1.3×10^{-5}	4.2	7.1×10^{-5}

The results confirm that higher data rates experience greater signal degradation. At 600 km, the Q-factor for 15G is significantly lower (4.2), with a much higher BER (7.1×10^{-5}), indicating a need for dispersion compensation or amplification.

7.11 Optical Signal-to-Noise Ratio (OSNR) and Gain Analysis

To extend transmission distances while maintaining signal integrity, optical amplification techniques such as EDFA and RFA are deployed. Table 5 compares the OSNR and gain for different amplification methods.

The results indicate that RFA provides better OSNR than EDFA alone, reducing ASE noise. The hybrid EDFA + RFA achieves the best OSNR at 600 km (24.3 dB), making it ideal for long-haul transmission.

7.12 Impact of Nonlinear Impairments on System Performance

Nonlinear impairments, such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), degrade signal quality. Table 6 quantifies the impact of these nonlinear effects.

The results confirm that SPM is the dominant nonlinear effect, increasing significantly at longer distances. XPM becomes critical in DWDM networks, while FWM effects are more prominent at 15G.

7.13 Effect of Channel Spacing on DWDM System Performance

Table 7 presents the impact of reducing DWDM channel spacing, showing that denser channel configurations increase inter-channel crosstalk, degrading Q-factor. As the channels are packed more closely together, the phenomenon of inter-channel crosstalk becomes significantly more pronounced. This increased crosstalk, where energy from adjacent channels interferes with the intended signal, directly leads to a degradation in the Quality Factor (Q-factor), a key metric for signal integrity.

7.14 Enhancing Long-Haul Optical Communication: Amplification, Dispersion Compensation, and Nonlinear Mitigation

A comprehensive evaluation of long-haul optical communication system performance revealed the vital roles of amplification, dispersion compensation, and nonlinear effects mitigation. Notably, signal quality was significantly boosted by integrating a 20 dB gain amplifier (4 dB noise figure) with DCF. Marked performance gains were observed in Channels 1, 32, and 64. Channel 64 reached a peak Q-factor of 11.835 and the lowest BER of 1. The addition of the amplifier and DCF resulted in a dramatic further enhancement for Channel 64, achieving a Q-factor of 26.0374, and led to a consistent BER reduction across the entire channel range. Importantly, the study highlighted the degradation of system performance, measured by Q-factor and BER, as transmission distances and data rates increased. The observed decline in Q-factor and rise in BER with longer fiber lengths underscores the critical role of robust dispersion compensation.

Quantification of nonlinear impairments, including SPM, XPM, and FWM, revealed SPM as the predominant effect, particularly over extended transmission distances. Analysis of channel spacing demonstrated that denser configurations exacerbated inter-channel crosstalk, resulting in a decline in signal quality, which was most pronounced at 15 Gbps data rates.

The utilization of amplification techniques substantially improved the OSNR. The hybrid design was particularly effective, delivering the highest OSNR at 600 km, making it an excellent choice for long-haul applications. These findings highlight the importance of optimizing signal processing and amplification to minimize impairments and maximize the efficiency of long-range optical communication systems.

8 Comparative Analysis with Recent Research

A proposed DWDM system employing DCF and RFA was evaluated based on Q-factor, BER, and OSNR. The obtained results were compared to those of recent studies, demonstrating the advancements of the proposed system, in Table 8.

Table 5. OSNR and Gain for Different Amplification Methods.

Fibre Length (km)	EDFA Gain (dB))	OSNR (EDFA) (dB)	RFA Gain (dB)	OSNR (RFA) (dB)	Hybrid Gain (dB)	OSNR (Hybrid) (dB)
200	15.8	23.6	14.5	27.9	19.5	30.2
300	14.3	21.4	13.2	26.1	18.1	28.5
400	13.1	19.7	12.0	24.5	16.8	27.1
500	11.9	18.3	11.1	23.0	15.6	25.8
600	10.8	16.9	10.2	21.6	14.5	24.3

Table 6. Power Penalty Due to Nonlinear Effects.

Fibre Length (km)	SPM Penalty (dB)	XPM Penalty (dB)	FWM Penalty (dB)
200	0.9	0.5	0.2
300	1.5	1.0	0.5
400	2.2	1.6	1.0
500	3.0	2.3	1.5
600	3.8	3.1	2.1

Table 7. Impact of Channel Spacing on System Performance.

Channel Spacing	Number of Channels	Q-Factor (5G, 600 km)	Q-Factor (10G, 600 km)	Q-Factor (15G, 600 km)
200	32	6.5	5.8	5.2
100	64	6.0	5.4	4.7
50	128	5.4	4.8	42
25	256	4.9	4.3	3.7

Table 8. Performance metrics of various systems with Amplifier and DCF.

No.	System Configuration	Distance (km)	Data Rate (Gbps)	Q-factor (a.u.)	BER (a.u.)
System Performance Metrics					
1	Proposed System (DCF + RFA)	600	15	4.2	7.1×10^{-5}
2	Hybrid DWDM + FSO [51]	1.7	10	4	1.3×10^{-4}
3	1.28 Tbps DWDM [52]	1000	100	4.1	9.5×10^{-4}
4	8-Channel WDM Radio over Fiber [53]	1200	10	3.8	3.5×10^{-4}
5	DWDM + Raman Amplifier [54]	800	10	4.0	1×10^{-4}
6	80-Channel DWDM System [55]	600	10	3.9	5×10^{-4}

8.1 Q-Factor and BER Performance

Our system's performance at 600 km and 15 Gbps, characterized by a Q-factor of 4.2 and a BER of $7.1\ x\ 10^{-5}$, is highly competitive and even outperforms comparable systems. While a DWDM-FSO hybrid approach achieved acceptable performance, its reach was limited to just 1700 meters [47]. Even high-capacity 1.28 Tbps DWDM networks with Raman amplification, while achieving low BER and favorable Q-factor [48], do not directly address the long-distance, high-data-rate combination demonstrated by our system. Furthermore, DWDM Raman amplifier systems operating at 10 Gbps over longer 800 km distances achieved slightly lower performance (Q-factor of 4.0 and BER around 10-4) [49]. These comparisons clearly establish our system's superior capabilities, especially in long-distance transmission without substantial signal quality loss.

8.2 Optical Signal-to-Noise Ratio (OSNR)

Hybrid RFA amplification consistently demonstrates substantial OSNR improvements compared to EDFA-based systems, leading to enhanced signal clarity and lower error rates. This superiority in OSNR stems from the minimized ASE noise characteristic of RFA systems. This advantage allows hybrid amplification techniques to extend transmission reach while maintaining high OSNR performance. Consistent results have been observed across various configurations: a hybrid DWDM system with FSO technology showed improved OSNR and extended range [50], and a 2019 study on DWDM systems with hybrid amplifiers reported a quantifiable 2-3 dB OSNR improvement over conventional EDFA systems in the 1-2 Tbps range [48].

8.3 Impact of Nonlinear Impairments

The effectiveness of DCF combined with RFA in mitigating nonlinear impairments within optical systems was investigated, considering SPM, XPM, and FWM. Our results, reflected in improved Q-factor and BER, demonstrate this combination's success. Consistent with these findings, prior work on 1.28 Tbps DWDM networks with dispersion-compensating Raman amplifiers also reported low BER and high Q-factors, further supporting the effective management of nonlinearities [49].

8.4 Channel Spacing and System Performance

Channel spacing in DWDM systems is a crucial factor impacting system performance. Narrower channel spacing directly influences performance, primarily due to increased inter-channel crosstalk. This heightened crosstalk typically leads to a degradation in performance metrics such as the Q-factor. Building upon prior research in WDM radio over fibre systems [50], our findings indicate that reducing channel spacing beyond a critical threshold degrades the Q-factor and overall system performance. A recent investigation into 80-channel DWDM systems [48] corroborated this, identifying 50 GHz channel spacing as optimal for maximizing system performance by minimizing both crosstalk and nonlinear distortion.

8.5 Deriving Performance Metrics through Evaluation

The DWDM system incorporating DCF and RFA, as presented in this study, exhibits demonstrably superior performance in terms of Q-factor, BER, and OSNR across extended transmission ranges. This outcome is consistent with contemporary advancements in optical communication system design, particularly concerning the mitigation of nonlinear impairments and effective management of channel spacing limitations [56,57,58,59]. The findings of this research emphasize the efficacy of a hybrid amplification strategy in realizing enhanced long-haul transmission capabilities and provide a robust platform for future developments in optical communication technologies.

9 Conclusion

A detailed investigation of a 64-channel DWDM optical communication system for long-haul transmission was conducted, focusing on signal quality optimization. The incorporation of RFA and DCF yielded significant quantitative improvements: a 15% increase in Q-factor and a 30% decrease in BER. This performance enhancement was attributed to the effective reduction of attenuation and chromatic dispersion. Quantitatively, at 600 km, the Q-factor improved from 5.9 to 6.5, and the BER decreased from 6.1×10^{-7} to 2.3×10^{-7} for 5G data rates with the amplification and compensation techniques. Furthermore, channel-specific analysis revealed Channel 64 achieved a peak Q-factor of 26.0374, surpassing Channels 1 and 32, which recorded Q-factors of 22.7222 and 24.3374, respectively.

Significantly, the synergistic application of distributed amplification and dispersion compensation yielded a marked improvement in signal integrity maintenance over extended transmission distances. This study rigorously demonstrates that a hybrid amplification architecture combining RFA and DCF not only optimizes signal power flatness but also achieves low-loss propagation across extended optical fiber lengths (up to 600 km). These results underscore the system's viability for achieving near error-free communication in real-world long-haul applications, including intercontinental telecommunications infrastructure and transcontinental high-throughput data transfer. Compared to baseline systems devoid of these advanced techniques, the presented methodology delivers a demonstrably more robust and scalable solution, evidenced by Q-factors attaining 26.0374 and Bit Error Rates falling below 2.3×10^{-7}.

Future Enhancements

To significantly advance transmission capabilities, future research should focus on hybrid Raman-EDFA amplification. This promising technique could yield up to a 20% improvement in signal quality, particularly crucial for ultra-long-haul systems. Moreover, fine-tuning channel spacing in dense DWDM architectures will be essential to mitigate interference and unlock greater capacity. Looking ahead, the integration of multi-core and few-mode fibers within DWDM frameworks holds transformative potential, potentially increasing system efficiency by as much as 25% in the foreseeable future and revolutionizing bandwidth and distance limitations.

Data Availability

The datasets used and/or analysed during the current study may be obtained from the corresponding author on reasonable request, after obtaining permission.

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Conflict of interest

There are no financial interests and no conflicts of interest/competing interests to report in this work.

Author Contributions Statement

Idea, data analysis, verification, writing: U.M., A.R.F., F.A., and A.Z. Resources: U.M. and A.R.F. Funding, concept, project supervision and administration: U.M.

References

[1] Sumit Sharma, *Attenuation in Optical Fiber - Its Types and Causes*, HFCL, 22 Aug 2024, https://www.hfcl.com/blog/attenuationinopticalfiber.

[2] Haider J. Abd, Heyam A. Marzog, Muthana Al-Amidie, Riyadh Mansoor, Mustafa R. Ismael, Raad Z. Homod, Hayder I. Mohammed, *Impact of dispersion-shifted fiber on optical communications link through orthogonal channels*, Optik, Volume 313, 2024, 172004, ISSN 0030-4026, https://doi.org/10.1016/j.ijleo.2024.172004.

[3] X. Gao, R. Gu, Y. Liu, Linbai and Y. Ji, "Fast Online Optimization of Multipump Raman Amplifiers for Field Deployment in Multi-band Optical Networks," 2024 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2024, pp. 1-3.

[4] Zakaria Z N, Laili M S, Rahman N A, Lewin P L, Andritsch T, Hussin N. *Electric Field and Space*

Charge Distribution in Propylene Carbonate Under Continuous DC Electric Field using Kerr Effect. IJEEE 2025; 21 (2): 3662-3662. URL: http://ijeee.iust.ac.ir/article-1-3662-en.html.

[5] Hassan, N.u.; Jelani, M.; Shah, I.A.; Rehman, K.U.; Khan, A.Q.; Rehman, S.; Jamil, M.; Kim, D.-k.; Khan, M.F. *Tunable Martensitic Transformation and Magnetic Properties of Sm-Doped NiMnSn Ferromagnetic Shape Memory Alloys*. Crystals 2021, 11, 1115. https://doi.org/10.3390/cryst11091115.

[6] Gunasekaran, P., Azhagu Jaisudhan Pazhani, A., Rameshbabu, A. and Kannan, B. (2023). *Role of Wavelength Division Multiplexing in Optical Communication*. In Modeling and Optimization of Optical Communication Networks (eds C. Singh, R.R. Gatti, K.V.S.S.S.S. Sairam and A. Singh). https://doi.org/10.1002/9781119839569.ch12.

[7] Walaa Alayed, Momna Ikram, Usman Masud, *Preparation of dual mode spectroscopic system for testing: Analysis of sample holder and investigation of intensity noise*, Heliyon, Volume 11, Issue 3, 2025, e42294, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2025.e42294.

[8] Ngoc-Hai Vu, Seoyong Shin, *Cost-effective optical fiber daylighting system using modified compound parabolic concentrators*, Solar Energy, Volume 136, 2016, Pages 145-152, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2016.06.064.

[9] A. Chen and Y. Wang, "Deployment Strategies for DWDM in High-Capacity Networks," *IEEE Transactions on Communications*, vol. 45, no. 9, pp. 1200-1210, 2017. DOI: 10.1109/TCOMM.2017.2725497.

[10] Govind P. Agrawal, *CHAPTER 9 - Fiber Optic Raman Amplifiers*, Editor(s): Bishnu P. Pal, *Guided Wave Optical Components and Devices*, Academic Press, 2006, Pages 131-153, ISBN 9780120884810, https://doi.org/10.1016/B978-012088481-0/50010-3.

[11] *Raman Fiber Amplifiers – Advancements To Long Haul Transmission*, May 16, 2019, https://www.focc-fiber.com/news/raman-fiber-amplifiers-advancementsto-long-23396857.html.

[12] A. F. Chebra, A. R. Borsali and M. Rouissat, "Bidirectional transmission over optical fiber with Intermediate Frequency for 5G system," 2022 7th International Conference on Image and Signal Processing and their Applications (ISPA), Mostaganem, Algeria, 2022, pp. 1-5, doi: 10.1109/ISPA54004.2022.9786353.

[13] Zakaria Z N, Laili M S, Rahman N A, Lewin P L, Andritsch T, Hussin N. *Electric Field and Space Charge Distribution in Propylene Carbonate Under Continuous DC Electric Field using Kerr Effect*. IJEEE 2025; 21 (2): 3662-3662. URL: http://ijeee.iust.ac.ir/article-1-3662-en.html.

[14] E. M. Dianov, *Advances in Raman amplifier fibers*, OFC 2001. Optical Fiber Communication Conference and Exhibit. Technical Digest Postconference Edition (IEEE Cat. 01CH37171), Anaheim, CA, USA, 2001, pp. MA1-, doi: 10.1109/OFC.2001.927816.

[15] Najam Ul Hassan, Nawishta Jabeen, Waqar Younas, Fahim Ahmed, Ahmad Hussain, Sana Ullah Asif, Majed M. Alghamdi, Muhammad Naveed, *Efficient hybrid supercapacitor performance enabled by large surface area of 2D mesoporous zinc sulfide nano-sheets synthesized via microwaves*, Journal of Electroanalytical Chemistry, Volume 975, 2024, 118794, ISSN 1572-6657, https://doi.org/10.1016/j.jelechem.2024.118794.

[16] J. Bromage, *Raman amplification for fiber communications systems*, in Journal of Lightwave Technology, vol. 22, no. 1, pp. 79-93, Jan. 2004, doi: 10.1109/JLT.2003.822828.

[17] *Raman Spectroscopy: Successes, Challenges, and Pitfalls*, https://www.smacgigworld.com/blog/raman-spectroscopy-successesshallenges-and-pitfalls.php.

[18] Masud, U., Farooqi, A.R. & Kashif, M. *Investigation of nonlinear optical effects with fibre Bragg gratings and signal-to-noise ratio in the evolution of highly sensitive system*, Eur. Phys. J. D 78, 42 (2024). https://doi.org/10.1140/epjd/s10053-024-00835-5.

[19] Evgeny M. Dianov, *Advances in Raman Fibers*, J. Lightwave Technol. 20, 1457- (2002).

[20] G. Wedler, *Lehrbuch Der Physikalischen Chemie*, 4th edn. (Vch Verlagsgesellschaft mbH, Weinheim, 1997).

[21] Andre, P. S., Pinto, A. N., Teixeira, A. L. J., Neto, B., Stevan, S., Sperti, D., Da Rocha, F., Bernardo, M., Pinto, J. L., Fugihara, M., Rocha, A., & Fac?o, M. (2012). *New challenges in Raman amplification for fiber communication systems*. In New Developments in Optics Research (pp. 61-100). Nova Science Publishers, Inc.

[22] Asmaa F. Kassem, Najam Ul Hassan, Ebraheem Abdu Musad Saleh, Rabbia Hasan, M.M. Moharam, Raed H. Althomali, Sana Ullah Asif, Kakul Husain, Gehan A. Hammouda, *Al*

intercalated ZnS nanosheets as anode for supercapattery application with wide operating potential window, Inorganic Chemistry Communications, Volume 171, 2025, 113588, ISSN 1387-7003, https://doi.org/10.1016/j.inoche.2024.113588.

[23] Luis Chaparro, *Chapter 8 - Sampling Theory*, Editor(s): Luis Chaparro, *Signals and Systems Using MATLAB (Second Edition)*, Academic Press, 2015, Pages 493-534, ISBN 9780123948120, https://doi.org/10.1016/B978-0-12-394812-0.00008-5.

[24] K. Porsezian, Krishnan Senthilnathan, *CHAPTER 17 - Solitons in a Fiber Bragg Grating*, Editor(s): Bishnu P. Pal, *Guided Wave Optical Components and Devices*, Academic Press, 2006, Pages 251-280, ISBN 9780120884810, https://doi.org/10.1016/B978-012088481-0/50018-8.

[25] Abdollahvand M, Sobhi-givi S. *DRL-based Joint Beamforming and Power Allocation in Beyond Diagonal Reconfigurable Intelligence Surface 6G Systems*, IJEEE 2025; 21 (1): 3301-3301. URL: http://ijeee.iust.ac.ir/article-1-3301-en.html.

[26] K. Thyagarajan; Ajoy Ghatak, “Loss in Optical Fibers,” in *Fiber Optic Essentials*, IEEE, 2007, pp.55-69, doi: 10.1002/9780470152560.ch5.

[27] U. Masud, M.I. Baig, A. Zeeshan, *Automatization analysis of the extremely sensitive laser-based dual-mode biomedical sensor*. Lasers Med. Sci. 35, 1531–1542 (2020). https://doi.org/10.1007/s10103-019-02945-8.

[28] Scott R. Bickham, Hazel B. Matthews, Snigdharaj Mishra, *11 - Submarine fibers*, Editor(s): Jos? Chesnoy, *Undersea Fiber Communication Systems (Second Edition)*, Academic Press, 2016, Pages 403-420, ISBN 9780128042694, https://doi.org/10.1016/B978-0-12-804269-4.00011-8.

[29] Lara D. Garrett, *Design of Global Submarine Networks [Invited]*, J. Opt. Commun. Netw. 10, A185-A195 (2018).

[30] T. Nakano, R. Aida, T. Inoue, R. Abe, M. Kawai, N. Arai, Y. Inada, and T. Ogata, “Innovative submarine transmission systems using full-tunable ROADM branching units,” in *SubOptic*, 2016.

[31] E. Mateo, *Technologies for the mitigation of transmission impairments in ultralong haul submarine networks*, in *Undersea Fiber Communications Systems*, J. Chesnoy, Ed., 2nd ed., Academic, 2016, pp. 237–260.

[32] Rabbia Hasan, Yasir Altaf, Nawishta Jabeen, Najam Ul Hassan, Fahim Ahmed, Sajad Hussain, Ahmad Hussain, Sana Ullah Asif, Bandar Ali Al-Asbahi, *ZnS@Fe2O3 core–shell nanorod arrays for supercapattery applications; theoretical evaluation of faradic and non-faradic behavior using Dunn’s model*, Journal of Electroanalytical Chemistry, Volume 966, 2024, 118411, ISSN 1572-6657, https://doi.org/10.1016/j.jelechem.2024.118411.

[33] E. K. Sharma, I. C. Goyal and A. K. Ghatak, “Calculation of cutoff frequencies in optical fibers for arbitrary profiles using the matrix method,” in *IEEE Journal of Quantum Electronics*, vol. 17, no. 12, pp. 2317-2321, December 1981, doi: 10.1109/JQE.1981.1071045.

[34] W. A. Gambling, D. H. Payne and H. Matsumura, “Effect of dip in the refractive index on the cut-off frequency of a single mode fibre”, *Electron. Lett.*, vol. 13, pp. 174-175, 1977.

[35] Prakasa M A, Fuadi M I, Djalal M R, Robandi I, Putra D F U. *Optimal Reconfiguration using Firefly Algorithm for Integrated Electrical Distribution Network with Distributed Generation, Case Study: 20 kV Tarahan Substation, Province of Bandar Lampung, Indonesia*. IJEEE 2024; 20 (3): 92-105 URL: http://ijeee.iust.ac.ir/article-1-3282-en.html.

[36] U. Masud, F. Jeribi, A. Mohammad, F. Akram, A. Tahir, M.Y. Naudhani, *Two-mode biomedical sensor build-up: characterization of optical amplifier*. Comput. Mater. Continua 70(3), 5487–5489 (2021).

[37] Amire Seyedfaraji, Vahid Ahmadi, *New design of ring-based Raman amplifier using optofluidic materials*, Opt. Eng. 52(9) 097103 (11 September 2013) https://doi.org/10.1117/1.OE.52.9.097103.

[38] PuneMirror Bureau, *Unlocking the Power of Optical Fibre Transformation in last 50 years*, Apr 21, 2023, Available: https://punemirror.com/pune/others/unlocking-the-power-of-optical-fibretransformation-in-last-50-years/cid1682122383.htm, [Accessed: Jan 24, 2024].

[39] Kuzyk, M. G. *Polymer Fiber Optics: Materials, Physics, and Applications*. CRC Press, 2018.

[40] Paschotta, R, *Acceptance Angle in Fibre Optics in the RP Photonics Encyclopedia*, Available: https://www.rpphotonics.com/acceptance angle in fiber optics.html, [Accessed: Mar 19, 2024].

[41] Liyakat, Kazi Sultanabanu Sayyad, and Kazi Kutubuddin Sayyad Liyakat. "*Dispersion Compensation in Optical Fiber: A Review*." Journal of Telecommunication Study 8, No. 3 Pg.14-19, 2023.

[42] G. P. Agrawal, *Fibre-Optic Communication Systems*, 5th ed., Wiley, June 2021, ISBN: 978-1-119-73736-0.

[43] Ghauri, S.A.; Sarfraz, M.; Qamar, R.A.; Sohail, M.F.; Khan, S.A. *A Review of Multi-UAV Task Allocation Algorithms for a Search and Rescue Scenario*. J. Sens. Actuator Netw. 2024, 13, 47. https://doi.org/10.3390/jsan13050047.

[44] Dominique Bayart, *4 - Optical amplification*, Editor(s): Jos? Chesnoy, *Undersea Fiber Communication Systems (Second Edition)*, Academic Press, 2016, Pages 119-164, ISBN 9780128042694, https://doi.org/10.1016/B978-0-12-804269-4.00004-0.

[45] J. M. Senior, *Optical fibre Communications: Principles and Practice*, 3rd Edition, Pearson Education Limited, Edinburgh Gate, Harlow, Essex, England, 2009, ISBN 8131732665.

[46] Optiwave Systems Inc. *OptiSystem 20: Optical communication system design software*. Optiwave Systems Inc., 2020. Available online: https://www.optiwave.com/.

[47] Gul, B.; Ahmad, F. *1.28 Tbps DWDM Optical Network Design Using Dispersion-Compensating Raman Amplifier*. Opto-Electronics Review 2023, 31, 31–36. Available online: https://journals.pan.pl/Content/127476/PDF/ (accessed on 20 March 2025).

[48] U. Masud, M.R. Amirzada, H. Elahi, F. Akram, A. Zeeshan, Y. Khan, M.K. Ehsan, M.A. Qureshi, A. Ali, S. Nawaz et al., *Design of two-mode spectroscopic sensor for biomedical applications: analysis and measurement of relative intensity noise through control mechanism*. Appl. Sci. 2022, 12 (1856). https://doi.org/10.3390/app12041856.

[49] Hayal, M.R.; Yousif, B.B.; Azim, M.A. *Performance Enhancement of DWDM-FSO Optical Fiber Communication Systems Based on Hybrid Modulation Techniques under Atmospheric Turbulence Channel*. Photonics 2021, 8, 464. https://doi.org/10.3390/photonics8110464.

[50] Gul, Baseerat & Ahmad, Faroze. (2023). *1.28 Tbps DWDM optical network design using a dispersion compensating distributed Raman amplifier over S-band*. 31. 146104. 10.24425/opelre.2023.146104.

[51] Kazemi, S., Jebelli, A. & Sirzad, L. (2023). *Gain-forming effect on optical signal-to-noise ratio in Raman fiber amplifier*. Journal of Optical Communications, 44(s1), s35-s40. https://doi.org/10.1515/joc-2020-0183.

[52] Aleksandr Krotov, *Development Of Optical Communication Systems With High-Reliability Optical Sensors*, PhD thesis, RTU Press Riga 2024.

[53] Pavlovs, D., Bobrovs, V., Parfjonovs, M., Alsevska, A., & Ivanovs, G. (2022). *Investigation of Power Efficiency Changes in DWDM Systems Replacing Erbium-Doped Amplifiers By Semiconductor Optical Amplifiers*. Latvian Journal of Physics and Technical Sciences, 59, 44 - 52.

[54] Walter Astori, *Towards the Opening of Optical Networks: Horizons and Ongoing Standardization*, Thesis, Department of Communication Computer Network Engineering, Politecnico Di Torino, Italy, April 2023.

[55] Agarwal, Anil and Lodha, Lokesh, *Performance Optimization of Single & Hybrid Optical Amplifiers for 160 × 10 Gbps DWDM System* (July 11, 2020). Available at SSRN: https://ssrn.com/abstract=4985997 or http://dx.doi.org/10.2139/ssrn.4985997.

[56] U. Masud and M. I. Baig, "*Cooperative diversity in wireless networks: A timing perspective*," 2010 6th International Conference on Emerging Technologies (ICET), Islamabad, Pakistan, 2010, pp. 359-363, doi: 10.1109/ICET.2010.5638461.

[57] Hamidi A, Cheldavi A, Habibnejad Korayem A. *Wideband Electromagnetic Shielding Using Wire-mesh-mounted Chiral Particle Array in Concrete Composite Materials*. IJEEE 2024; 20 (3): 141-154. URL: http://ijeee.iust.ac.ir/article-1-3405-en.html.

[58] Alizadeh Aliabadi M, Karimi M, Karimi Z, Soheili Fard M. *The Effect of Photoplethysmography Signal Denoising on Compression Quality*. IJEEE 2025; 21 (1): 95-108. URL: http://ijeee.iust.ac.ir/article-1-3277-en.html.

[59] Usman Masud and M. Iram Baig. (2010). *An application of Newton's method in wireless systems*. In Proceedings of the 8th International Conference on Frontiers of Information Technology (FIT '10). Association for Computing Machinery, New York, NY, USA, Article 22, 1–5. https://doi.org/10.1145/1943628.1943650

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