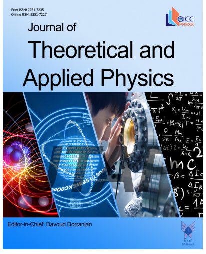

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Assessment of the efficacy of 20 x 100 Gb/s high-speed long-distance DWDM systems utilizing 16 QAM modulation techniques and hybrid optical amplifiers

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Abstract:
High-capacity optical networks are required for data-intensive applications. Using cutting-edge modulation methods like RZ and 16-QAM, this article constructed and assessed a 20 x 100 Gb/s DWDM system to achieve the best spectral efficiency while optimizing resilience to impairments. A hybrid amplification technique that combines Erbium-Doped Fiber Amplifiers, Raman Amplifiers, and Semiconductor Optical Amplifiers ensures the quality of long-distance signals. The proposed configuration features 20 channels spaced 50 GHz apart and comprises 20 spans in which each span consist of 30 km dispersion-compensating fiber (DCF) and 70 km single-mode fiber (SMF). Simulations used to assess performance using BER, Q-factor, and OSNR demonstrate error-free transmission with improved noise tolerance and decreased dispersion. This paper describes the enhancement of the BER and Q-factor to improve the overall signal and noise management of the system for further integrity. Also assesses spectral reach for tradeoff in 16-QAM in hybrid-amplified systems. The work evaluates single versus hybrid amplification systems and the benefits of using more than one amplification approach for enhanced systems.

Keywords: 16-QAM modulation; RZ pulse shaping; Ultra-high-speed optical networks; EDFA; Raman amplifier; SOA; OSNR; Q-factor

1. Introduction

The rapid advancement of technologies like cloud computing, 5 G, AI, and UHD streaming has brought about the increasing requirement for swift data transmission which is directly fueling the evolution of optical communication networks. Each of these emerging fields has high potential and demand for data with the industry-level resources to back the infrastructure which can scale optical networks. In response to exhibiting this growth, traditional optical systems have unfortunately lagged behind in their growth. H.M. Obaid et al. [1] published on a 480 Gbps system with 12 channels, 40 Gbps each and analyzed its performance with and without a hybrid optical amplifier. The performance analysis is carried out in terms of Q-factor and Bit Error Rate (BER) and presented by varying the FSO link lengths and atmospheric conditions. The results show that the system has a reasonable Q-factor and BER values without amplification (1400[Q-factor] and 10-6[BER]) reach of 510 m at clear weather. Using the hybrid amplifier, though, the maximum transmission distance extends to 1,700 meters without any appreciable link degradation. In the continuation of this research, A. Donodin et al. [2] investigate the performance of high-speed optical transmission over an extended 25.8 THz bandwidth spanning E-, S-, C-, and L-bands. The research investigates 50 km transmission of 30-Gbaud polarization multiplexed 16-QAM signals through hybrid amplification of distributed and discrete Raman amplifiers. The results show E-band distributed Raman amplification produces an average Q^2-penalty of 0.7 dB which is substantially better than 1.9 and 0.9 dB penalties observed for S-band and C+L-band discrete Raman amplification, respectively. This shows that E-band distributed Raman amplification presents a better performance in terms of signal quality degradation. Building upon these findings the E-band transmission over 50 km of G.652.D fiber has been experimentally demonstrated by A. Donodin et al. [3]. In this experiment, 30 Gbaud 16-QAM signals were used, which was enabled by a neodymium-doped fiber amplifier that had a gain of 14 dB and a noise figure of 5 dB. Following this study, P. Hazarika et al. [4] have proposed a multistage Raman amplifier for 210 nm signal amplification. The amplifier has a gain of 15 dB with a maximum noise figure of 8.1 dB and has enabled ESCL-band transmission of 10 Gb/s NRZ signals in 70 km standard single-mode fiber. J. Pedro et al. [5] tackle the issue of best placing of hybrid erbium-doped fiber/Raman amplifiers (HFAs) in mesh dense wavelength division multiplexing networks. HFAs cost more than regular erbium-doped fiber amplifiers (EDFAs) so the authors come up with two integer linear programming models. One tries to use the least number of HFAs needed to make optical channels work without middle 3R regenerators. The other aims to get the most working channels with a set number of HFAs. X. Chen et al. [6] look into how hybrid amplification setups affect ultra-dense wavelength division multiplexing (WDM) systems especially when it comes to nonlinear compensation methods. They study how different hybrid amplifier setups change system performance measures like signal-to-noise ratio and bit error rate. In alignment with this work, J. Lin et al. [7] investigate how to use advanced modulation formats to speed up data in DWDM systems. They focus on seeing how well these modulation methods work over long distances looking at things like spectral efficiency and how well they stand up to fiber nonlinearities. M.M. Ali et al. [8] have investigated hybrid Raman-EDFAs performance for 400 Gb/s optical communications. The authors have analyzed the signal gain, noise figure, BER at various distances as main parameters. Finally, through results analysis it is found that the incorporation of both Raman and EDFAs delivering better signal quality with higher transmission distance compared with EDFAs alone. A. Sharma et al. [9] analyze the effect of hybrid amplification on Q-factor of long-haul DWDM systems. They evaluate different configurations of hybrid amplifiers to study whether they can sustain signal power over longer distances. It is seen that few configurations under hybrid amplifier has improved Q-factor thus enhanced performance long-haul DWDM networks were noticed. R. Patel et al. [10], have reviewed dispersion compensation techniques within high speed DWDM networks where 50 Gbps NRZ pulses are launched into fiber link up to 1000 km and BER and SNR are evaluated for system design purpose. Authors have studied different dispersion compensation methods to analyze efficiency in term of best performance indicating less error probability along with large permissible input data rate. Expanding upon these insights, Z. Wang et al. [11], investigate how to mitigate nonlinear noise in optical communication systems with hybrid amplification schemes. They consider several nonlinear impairments existing in these kinds of optical communication systems and propose corresponding suppression methods to improve signal quality. Both theoretical analysis and simulation are used to evaluate the proposed suppression methods. The experimental results show that the proposed suppression methods can greatly reduce the nonlinear noise and therefore improve not only transmission performance but also receiver sensitivity. With a focus on similar challenges, P. Gupta et al. [12] compared performance of RZ and NRZ modulation formats in DWDM system. Results showed that RZ format performs better in terms of BER and nonlinear tolerance, while NRZ format provides higher spectral efficiency. It can be concluded that the tradeoff between data rate and performance depends on bit-error-rate requirement of the system, as well as the total capacity available. Expanding on these results, H. Park et al. [13] published possible usage of combined optical amplification methods for future communication systems with extremely increased capacity. Such hybrid incorporation includes EDFAs together with Raman amplifiers (RAs) in an optical link or a similar arrangement to investigate signal Q-factors, MPD-limited propagation distance, amplifier noise figures as well as near-end amplifier spacing. It was shown that hybrids are more effective in long-span repeater less links than EDFA-only systems due to RA greater output powers. Continuing this exploration, S. Kim et al. [14] published a study on the performance of 16-Quadrature Amplitude Modulation (16-QAM) in long-haul optical communication systems considering both the bit error rate (BER) performance and system reach for different types of fiber and amplifier. A. Ahmed et al. [15] have investigated the performance improvement of hybrid EDFA and Raman amplifier based Dense Wavelength Division Multiplexing (DWDM) transmission systems by optimizing noise figure, which is an important parameter to assess signal quality as well as overall system performance, using analytical approach along with simulation. In a related study, F. Yang et al. [16] investigated modulation schemes to enhance the performance of high-speed DWDM networks. The paper examines spectral efficiency limitations of different advanced modulation formats as QAM and PSK and the fiber impairment tolerance as well as implementation complexity. K. Sun et al. [17] analyzed the effect of channel spacing on nonlinear penalties in optical communication systems with hybrid amplification through both theoretical analysis and simulations. They discussed the impact of channel spacing on two dominant nonlinear effects, i.e., cross-phase modulation (XPM) and four wave mixing (FWM). Results revealed that reducing channel spacing increases nonlinear penalties as a result of stronger XPM/FWM effects. V. Singh et al. [18] described design guidelines for high bit rate (200 Gb/s), long-haul hybrid optical amplifiers employing EDFAs along with Raman amplifiers. Singh and Arora used detailed simulation to demonstrate transmission performance, and a part of the overall experimental setup was also realized for validation purpose. They also identified various optimization issues associated with gain flatness, noise figure, and power consumption while designing such an amplifier. In a complementary approach, Y. Zhao et al. [19] have performed a detailed analysis on the impact of various dispersion management schemes on the performance of high-rate dispersion-managed optical communication systems in terms of BER, SNR, and system reach as three important KPIs. Using analytical modeling and numerical simulations, they have also studied the effectiveness of different dispersion compensation techniques to reduce pulse broadening and nonlinear effects. With a focus on similar challenges, P. Patel et al. [20] addressed the problem of noise in DWDM systems with 16-QAM modulation. They describe the effects of various types of noise, and then propose several strategies for noise reduction. By using theoretical analysis and simulations, they show that the use of these techniques can significantly improve signal-to-noise ratio (SNR) and bit error rate (BER) performance in 16-QAM DWDM systems. Extending this investigation, M. Lee et al. [21] investigated hybrid amplification technologies for high-speed transmission over a 32-channel DWDM system. The authors reported the impact of different types of optical amplifiers to improve signal quality as well as to extend system reach. Experimental measurements combined with simulations were used to evaluate gain flatness, noise figure, and overall system impact, showing that hybrid amplifier could reduce impairments with better performance. With a focus on similar challenges, N. Khan et al. [22] published the challenges and benefits of utilizing 16-Quadrature Amplitude densely meshed optical communication networks. The study measures system performance parameters such as bit error rate, signal-to-noise ratio, and spectral efficiency for different network scenarios using extensive simulations and theoretical calculations. Based on these results, we identify critical aspects affecting system performance as well as formulate relevant optimization techniques. Overall results reveal that integration of 16-QAM with hybrid amplification could improve data throughput along with network resource utilization subjected to a certain optimized range of the system operational parameter. The OSNR in DWDM systems at high data rates is analyzed by T. Sharma et al. [23]. The research work aims to study how different system parameters such as channel spacing, modulation formats as well as different amplifier configurations can affect the OSNR through theoretical analysis and simulation. The effect of these parameters on the overall performance of a given transmission system is investigated. Hybrid optical amplifiers are investigated in long-haul optical communication systems by K. Ahmed et al. [24]. The authors theoretically investigate whether combining various amplification schemes, like EDFAs and Raman amplifiers, can be advantageous for long haul distances while at the same time mitigating the adverse effects of each amplification technique used alone. Experimental test beds for both measured amplified gain spectra as well as actual transmitted signals were prepared besides conducting simulations to obtain important results like amplifier gain, noise figure and BER taking into consideration an extended length of fiber span. It is shown from the theoretical results that hybrid amplifiers extend transmission distance with better signal quality compared to individual ones. Taking this research forward, L. Zhang et al. [25] studied the use of Raman amplifiers, as well as Semiconductor Optical Amplifiers (SOAs), for nonlinear impairments mitigation in optical communication systems. The aggregate impact on general nonlinear effects such as self-phase modulation and four-wave mixing due to these amplifiers is investigated. The authors proposed a hybrid amplifier configuration based on theoretical analysis and simulations to reduce nonlinear distortions. Simulation results demonstrated that the Raman-SOA hybrid was able inherently to improve quality of signal and system performance with lower nonlinearities compared with conventional amplifier schemes. In a further extension of this study, Park and J. Park et al. [26] investigated Hybrid optical amplification inform of Q-factor in optical communication system. Different types of amplifier were combined to enhance the signal quality and system performance. Experimental set up have been implemented and paper also analyses the effect of hybrid amplification on Q-factor with different operating condition. The result shows that using hybrid configuration in amplifier can increase Q-factor remarkably, improve the signal integrity as well as increase transmission distance. In the continuation of this research, A. Gupta et al. [27] investigated how to increase number of channels for high-speed Dense Wavelength Division Multiplexing (DWDM) systems considering channel spacing, signal-signal interference, capacity issues etc. The technique results analyzed analytically along with some experimental test bed setup. In a further extension of this study, Li et al. [28] evaluated the performance of 16-Quadrature Amplitude Modulation (16-QAM) in Dense Wavelength Division Multiplexing (DWDM) systems with high Optical Signal-to-Noise Ratio (OSNR). The viability and effectiveness of 16-QAM modulation are assessed at different OSNR performances using simulation and analytical methods. S. Ahmed et al. [29] discussed hybrid optical amplifiers specifically designed for next generation 100 Gigabits per second Dense Wavelength Division Multiplexing based networks. Different types of amplification schemes are proposed to improve the system performance as well as the overall signal quality over longer distances. Taking this research forward, S. Singh et al. [30] have analyzed advanced modulation schemes performing at higher data rates in long-haul optical fiber communication systems suffering from major transmission impairments such as chromatic dispersion, nonlinearity etc. The authors carried out extensive simulations and experimental studies to evaluate the effect of various modulation formats on a generated electrical signal that is subsequently sent through an optical fiber link having same setup parameters for all transmission links. It was observed via simulations and actual results that by using certain modem modulation techniques, spectral efficiency can be improved along with higher tolerance against numerous electronic AND electro-optical link imperfections. So far, it is observer that the previous research has worked on hybrid amplifier configurations; nevertheless, extensive work on multi-span systems using 16-QAM modulation at ultra-high data rates over long distances is limited. this recommended research work bridges these limitations through the design and implementation of a 20 x 100 Gb/s DWDM system combining EDFA, Raman, and SOA amplifiers for signal integrity enhancement. The designed system maximizes Q-factor and BER and reduces nonlinear impairments effectively through dispersion compensation methods. The results further show enhanced OSNR and improved spectral efficiency, which makes the proposed approach very well suited to next-generation high-capacity optical networks. This paper is divided into five sections. In section 2, System Design Diagram is explained. In section 3, Mathematical analysis has done. In section 4, Outcomes and Observations have done and finally in section 5 conclusions are made. It is important to integrate hybrid amplification and intelligent signal processing for the development of the next generation of optical networks. Adaptive modulation and advanced signal management techniques are also considered critical for high capacity DWDM systems [31–33]. A comparative study on the use of EDFA and Raman amplification for 100 G DWDM systems showed that each amplification method has its own benefits, and the combination of both could provide a greater improvement in system performance. EDFA provides great gain and economically effective amplification, but adds ASE noise, which can negatively affect the signal over long distances. Conversely, Raman amplification offers distributed gain with low noise figure and lower several nonlinear effects, which makes it more suitable for ultra-long-haul transmission. Through proper implementation of both methods, hybrid amplification can provide suitable levels of high gain, low noise, and long reach, thereby improving signal quality, system stability, and network efficiency in Modulation (16-QAM) with hybrid optical amplifiers in high speed optical communication systems [34–36]. Because of the development of broadband gain, low noise, and rapid response times, quantum-dot-based optical amplifiers (QD-OAs) have great potential for high-speed optical networks. These amplifiers use the distinct features of quantum confinement in quantum dots where the dimensions of the dot are less than the de Broglie wavelength of electrons in order to improve the efficiency of signal amplification and suppress the degradation of performance due to nonlinear effects. At the same time, improvements in hybrid amplification methods for DWDM systems, such as combining EDFA with Raman and QD-OA techniques, have proven that using several methods of amplification improves the quality of the signal, increases the distance of transmission, and increases the efficiency of the spectrum. The combination of these approaches makes it possible for modern optical networks to achieve higher data rates, reduced power consumption, and enhanced reliability as well as meeting the challenges posed by next generation high-capacity communication systems [37, 38]. The influence of non-linearities on 16-QAM transmission in DWDM systems has been studied, and it is noted that phenomena like self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) are so severely damaging the signal that they can no longer be effectively transferred as data and distances are great and speeds are high. To deal with these non-linear impearments, increase signal power, and balance the levels of allocated power, advanced digital signal processing (DSP) techniques have been suggested. The improvement in the design of the energy-efficient optical amplifiers was also considered, proving that new designs of Raman and quantum dot amplifiers for high power and less noise in the output can be achieved with less energy [39–41]. There has been considerable work on the high speed transmission with hybrid optical amplifiers, proving that the use of EDFA together with other Raman and SOA technologies improves the signal quality as well as increases the distance of transmission. This approach yields better results with regard to the gain, noise figure interms of energy put out via the system and thus is useful in long distance communication systems. In addition, ultra high capacity multi-terabit DWDM systems have been studied focusing their opertion on the issue of spectral effciency, managing nonlinearity, and the use of power. Some of the recently developed modulation techniques, like the 16-QAM along with probabilistic shaping put together with the so called smart amplifiers, have been suggested to serve the opposite purpose. These documents clarify the importance of hybrid amplification and coordinated system optimization design to meet the growing requirements of next generation high capacity optical networks [42, 43]. Enhancing performance in long-haul optical transmission has been extensively explored, particularly through advanced signal processing techniques such as dispersion compensation and hybrid amplification. Research has shown that optimizing amplifier gain dynamics and applying digital backpropagation can greatly mitigate signal degradation resulting from fiber nonlinearities and amplified spontaneous emission (ASE) noise. Moreover, investigations into high-speed networks employing 16-QAM coherent optical systems reveal that this modulation scheme strikes an effective balance between spectral efficiency and signal quality, making it ideal for high-capacity dense wavelength-division multiplexing (DWDM) systems [44–48].

2. System design diagram

The proposed 20 x 100 Gb/s hybrid system design DWDM architecture is shown in the Fig. 1. It consists of 20 transmitter are multiplexed over existing fiber path. Each transmitter consist CW laser which generate the optical signals of frequency 193.1 THz to 194.02 THz and RZ signal generator, 16-QAM modulators are used in transmitter followed by a hybrid DWDM multiplexer (HMUX). Channel's frequency is distributed between 193.1 THz and 194.02 THz with 50 GHz channel spacing. DWDM multiplexer is followed by EDFA amplifier. EDFA is used to compensate fiber losses and ensure enough signal power at receiver during transmission. The multiplexed signal passed through fiber link of 20 spans and each span have 10 km SMF-DCF followed by Erbium-Doped Fiber Amplifiers, Raman Amplifiers, and Semiconductor Optical Amplifiers and 60 km SMF-DCF ensures the quality of long-distance signals. Optical power of laser sources is kept at −5 dBm with optical linewidth of 10 MHz. DCF is used to compensate the dispersion occurred due to SMF. DCF has negative dispersion slope and dispersion to reduce the nonlinearity. Thereafter, received signal is demultiplexed by DWDM demultiplexer (HDeMUX) which is followed by receiver section. Each receiver section consists of optical band pass filter and 16-QAM demodulation.

2.1 Transmitter section

One of the key components of the DWDM system that generates and modifies optical signals is the transmitter, it employs a variety of advanced approaches such as 16-QAM. The system uses Continuous-wave (CW) lasers as the optical carriers. Each laser is assigned a specific frequency

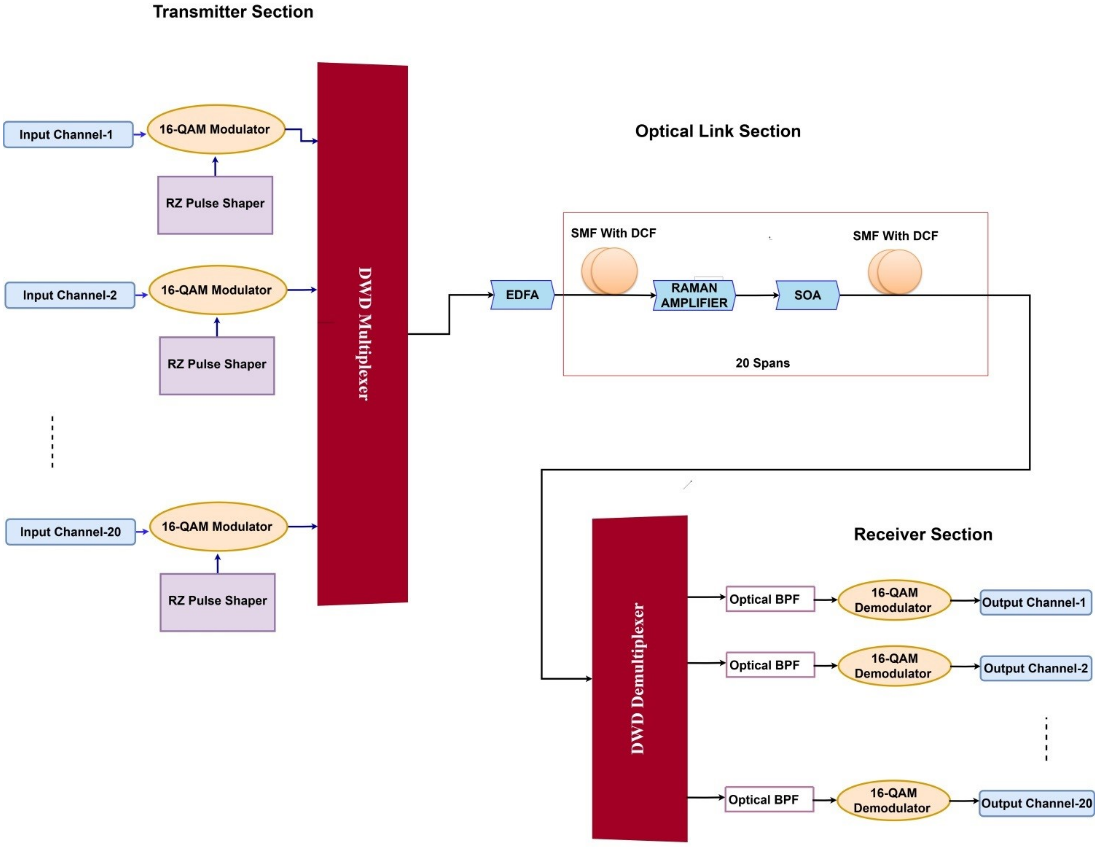

Figure 1. Schematic diagram of transmission system of 20 x 100 Gb/s RZ 16-QAM DWDM signal.

between 193.1 THz and 194.02 THz to form individual channels in the DWDM system. The key transmission parameters of the DWDM system are shown in Table 1. The system consists of 20 channels, each operating at 100 Gb/s with a 50 GHz channel spacing, utilizing 16-QAM modulation. A hybrid fiber setup (SMF + DCF) is used over a 2000 km link with dispersion compensation, considering nonlinear effects like FWM, SPM, and XPM. The optical source and modulation parameters for high-speed DWDM systems are shown in Table 2. A CW laser operates at a 1550 nm wavelength with power ranging from 0 dBm to 5 dBm and a linewidth of 10 MHz. A Mach-Zehnder modulator (MZM) is used for 16-QAM modulation at a 50 GBd symbol rate, with an RZ pulse shaper frequency of 100 GHz and a duty cycle of 33%. The central frequency of the i$^{\text{th}}$ channel is given by the equation (1)

$$f_{c,i} = f_{c,0} + i \cdot \Delta f_c, \quad i = 0, 1, 2, \ldots, N-1 \tag{1}$$

where $f_{c,0}$ is the base frequency, Δf_c is the channel spacing (100 GHz or 200 GHz), and N is the total number of channels. The output power $P_i(t,z)$ from the i$^{\text{th}}$ laser propagates

Table 1. Parameters for the transmission section in the DWDM system.

Parameters	Value/Unit
Number of Channels	20
Data Rate per Channel	100 Gb/s
Channel Spacing	50 GHz
Modulation Format	16-QAM
Fiber Type	SMF + DCF
Span Length	100 km (70 km SMF + 30 km DCF)
Total Transmission Distance	2000 km
Dispersion Compensation	DCF-Based
Optical Launch Power	0 dBm to 5 dBm
Nonlinear Effects Considered	FWM, SPM, XPM

Table 2. Optical source and modulation parameters for high-speed DWDM systems.

Parameters	Value/Unit
CW Laser Wavelength	1550 nm
CW Laser Power	0 dBm to 5 dBm
CW Laser Linewidth	10 MHz
RZ Pulse Shaper Duty Cycle	33%
RZ Pulse Shaper Frequency	100 GHz
16-QAM Modulator Type	Mach-Zehnder (MZM)
16-QAM Symbol Rate	50 GBd
16-QAM Optical Power Output	0 dBm

through the fiber can be expressed using equation (2)

$$P_i(t,z) = P_{i,0}\, e^{-\alpha_i z} \tag{2}$$

where $P_{i,0}$ is the initial power and α_i is the attenuation coefficient of the channel.

The CW lasers are modulated using advanced techniques, each tailored to balance spectral efficiency and system complexity. For RZ (Return-to-Zero) modulation, the optical signal is generated by cascading a pulse carver with a Mach-Zehnder modulator (MZM). The input electric field of the laser is modulated using the MZM, which applies a sinusoidal signal to generate RZ pulses. The modulated field is expressed as equation (3)

$$E_0(t) = E_i(t)\cos\left(\frac{\Delta\phi_{\mathrm{MZM}}(t)}{2}\right) \tag{3}$$

where $\Delta\phi_{\mathrm{MZM}}(t) = V(t)/V_\pi$ is the phase shift induced by the driving voltage $V(t)$ and V_π is the voltage required for a π-phase shift.

The output power of the MZM is given by equation (4)

$$P_{\mathrm{out}} = \alpha P_{\mathrm{in}} \cos^2\left(\frac{V(t)}{V_\pi}\pi\right) \tag{4}$$

where P_{in} is the input power and α is the insertion loss of the modulator.

16-QAM (Quadrature Amplitude Modulation) uses a higher-order constellation for data encoding, providing increased spectral efficiency. The average energy for an m-QAM constellation is represented as the following equation (5)

$$E_{\mathrm{avg}}(QAM) = 2\left(1 - \frac{1}{m}\right) \tag{5}$$

where $m = 16$ in this case.

2.2 Optical link section

The optical link, which connects the transmitter and receiver in high-speed DWDM systems, is the most important channel for optical signals. This guarantees long-distance data transmission and controls for various impairments, such as attenuation, chromatic dispersion, PMD, and nonlinear effects. In addition to additional components like HMUX and HDeMUX, the connection architecture would include optical fibers, hybrid optical amplifiers—which include semiconductor optical amplifiers, erbium doped fiber amplifiers, and dispersion compensating fibers. The NLSE gives the description for the propagation of light signals within single-mode optical fibers. Chromatic dispersion and loss of intensity are considered while accounting for effects like four-wave mixing and self-phase modulation that are nonlinear. The NLSE is expressed as equation (6)

$$\frac{\partial A(z,t)}{\partial z} + \frac{\alpha}{2}A(z,t) + \frac{i\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial t^2} - i\gamma|A(z,t)|^2 A(z,t) = 0 \tag{6}$$

where, $A(z,t)$ represents the complex amplitude of the optical field as a function of position z and time t. The parameter α denotes the fiber attenuation coefficient, which accounts for signal loss in the optical fiber. The term β_2 corresponds to the group velocity dispersion (GVD) parameter, which accounts for chromatic dispersion in the system. γ is the nonlinear coefficient, representing the impact of fiber nonlinearities. Each part of the equation demonstrates how, at any particular point in time, the optical signal is changing and represents some different problem of the issue under investigation. The first part states that fiber loss causes a reduction in the power of optical signals. The second part deals with the chromatic dispersion widening the pulse. The third part provides information on the nonlinear effects from the Kerr effect. One of the major constraints in optical communication systems is fiber loss. Strength of the optical signal at some distance z along the fiber is described by equation (7)

$$P(z) = P(0)\, e^{-\alpha z} \tag{7}$$

Hybrid optical amplifiers are added at appropriate spacing in the optical link in compensation for this loss. The gain G provided by an HOA is given by equation (7)

$$G = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \tag{8}$$

where P_{in} and P_{out} are the input and output optical powers, respectively. In our design, SOAs and EDFAs are used in tandem to leverage their respective strengths, ensuring both broadband amplification and low noise performance. The optical link contains hybrid multiplexers (HMUX) and demultiplexers (HDeMUX) to control DWDM channels. The HDeMUX separates them at the receiving end, whereas the HMUX joins several optical channels into one fiber for sending. These parts reduce interference between channels and help use the spectrum effectively. Carefully planning the optical link ensures that it works effectively. Hybrid optical amplifiers placed properly in the system can preserve the optical power budget and diminish noise. Besides, dispersion compensating fibers control chromatic dispersion which also balances the nonlinear and dispersion issues. Further, proper choice of channel spacing in the DWDM system can eliminate inter-channel interference and FWM from becoming worse.

2.3 Receiver section

At the receiver end, the received signals are demultiplexed, demodulated, and detected to recover the original data. Hybrid demultiplexing at the receiver's end separates multiplexed channels and directs every channel to the corresponding demodulator based on the modulation format. Then every channel is demodulated using the specific detection scheme. 16-QAM, the signal is demodulated with the aid of a low-pass filter (LPF) PIN photodiode. For 16-QAM, coherent detection is required, which includes a local oscillator (LO) as well as a digital signal processor (DSP). The power of the detected signal P_{det} is expressed using equation (9)

$$P_{\text{det}} = RP_{\text{in}} - \text{NF} \tag{9}$$

where R is the responsivity of the photodiode and NF is the noise factor.

To evaluate system performance, signal quality analysis is conducted by calculating the bit error rate (BER). For an m-QAM system in an AWGN channel, the BER is given by equation (10)

$$\text{BER} = \frac{2}{\log_2(m)} Q\left(\sqrt{\frac{3\log_2(m)}{m-1} \cdot \frac{S}{N}}\right) \tag{10}$$

where $Q(\cdot)$ is the Q-function, S is the signal power, and N is the noise power. Furthermore the receiver section parameters for high-speed DWDM systems are shown in Table 3.

3. Mathematical analysis

In the proposed system, high-speed DWDM signals become stronger over long distances by using hybrid optical amplifiers. This paper investigates how gain changes, noise levels, and interference between channels occur in the configuration of the hybrid amplifier for the multi-channel DWDM systems. The equation describing how carrier density operates in the active part of the amplifier for several DWDM channels is described as in equation (11)

$$\frac{\partial \mathscr{N}(t,\xi)}{\partial t} = \frac{\mathfrak{J}_{\text{bias}}}{q\mathscr{D}_{\text{act}}} - \frac{\mathscr{N}(t,\xi)}{\tau_r} - \sum_{k=1}^{M} \frac{\mathscr{P}_k(t,\xi)}{\hbar\omega\mathfrak{W}_{\text{eff}}} \tag{11}$$

where the injection current density, denoted as $\mathfrak{J}_{\text{bias}}$, is a crucial parameter that determines the carrier injection into the amplifier's active region. The electron charge is represented by q, while $\mathscr{D}_{\text{act}}$ indicates the thickness of the active region of the amplifier. Carrier recombination is governed by the lifetime τ_r, and the material gain coefficient is expressed as G. The system comprises M, the total number of DWDM channels, each characterized by $\mathscr{P}_k(t,\xi)$, the optical power of the k-th channel as a function of time t and spatial coordinate ξ. Additionally, $\hbar\omega$ represents the photon energy, and $\mathfrak{W}_{\text{eff}}$ denotes the effective width of the waveguide, which influences the overall signal propagation and amplification. These parameters collectively define the dynamics and performance of the hybrid optical amplifier system.

The material gain coefficient, denoted by $\mathscr{G}(\mathscr{N})$, relates the carrier density to the gain in the active medium. It is defined as in equation (12)

$$\mathscr{G}(\mathscr{N}) = \mathscr{G}_0(\mathscr{N} - \mathscr{N}_t) \tag{12}$$

where $\mathscr{G}_0(\mathscr{N})$ is the differential gain parameter and $\mathscr{N}_t$ is the transparency carrier density.

The total gain $\mathscr{G}_{\text{tot}}$ for a segment of length $\mathscr{L}$ in the amplifier is expressed using equation (13)

$$\mathscr{G}_{\text{tot}} = e^{\mathscr{G}(\mathscr{N})\cdot\mathscr{L}} \tag{13}$$

to account for the nonlinear gain effects in the system, a dynamic variation term $\Delta\mathscr{G}(t,\xi)$ is represented as the following equation (14)

$$\Delta\mathscr{G}(t,\xi) = \mathscr{G}_0 \cdot \sum_{m=1}^{M} (-1)^m \frac{\mathscr{P}_m}{\mathscr{L}} \cdot e^{-\mathscr{P}_m\cdot\xi}. \tag{14}$$

This term highlights the impact of inter-channel crosstalk and nonlinearities such as four-wave mixing.

Table 3. Receiver section parameters for high-speed DWDM system.

Parameters	Value/Description
Detection Scheme	Coherent Detection
Photodetector Type	PIN Photodiode
Responsivity (R)	0.85 A/W
Local Oscillator (LO) Power	0 dBm
Optical Bandpass Filter	0.8 nm Bandwidth
Bit Error Rate (BER) Analysis	Calculated using Q-function
Noise Factor	4.5 dB

The ASE noise power, $\mathscr{N}_{\text{ASE}}$, is redefined as a function of the amplifier's spontaneous emission factor, $\mathscr{F}_{sp}$, and is given by equation (15)

$$\mathscr{N}_{\text{ASE}} = 2 \cdot \mathscr{F}_{sp} \cdot h \cdot \nu \mathscr{G}_{\text{tot}} \cdot \Delta\{ \tag{15}$$

where h is Planck's constant, ν is the optical frequency, and $\Delta\{$ is the bandwidth of the optical filter.

The system's quality factor, Q, is defined in terms of signal power $\mathscr{P}_s$ and noise power $\mathscr{P}_n$ is described as equation (16)

$$Q = \frac{\mathscr{P}_s}{\mathscr{P}_n} \tag{16}$$

Using the Q-factor, the BER is expressed as equation (17)

$$\text{BER} = \frac{1}{2} \cdot \text{erfc}\left(\frac{Q}{\sqrt{2}}\right) \tag{17}$$

where erfc$(\cdot)$ is the complementary error function.

The system uses dispersion-compensating fibers (DCFs) to counteract chromatic dispersion. The residual dispersion $\mathscr{D}_{res}$ after N spans is given by equation (18)

$$\mathscr{D}_{res} = N \cdot (\mathscr{D}_{\text{SMF}} \cdot \mathscr{L}_{\text{SMF}} + \mathscr{D}_{\text{DCF}} \cdot \mathscr{L}_{\text{DCF}}) \tag{18}$$

where $\mathscr{D}_{\text{SMF}}$ and $\mathscr{D}_{\text{DCF}}$ are the dispersion coefficients for single-mode fiber and DCF, respectively. $\mathscr{L}_{\text{SMF}}$ and $\mathscr{L}_{\text{DCF}}$ are the respective fiber lengths.

The hybrid amplification model integrates three key amplification techniques to enhance signal performance. The Erbium-Doped Fiber Amplifier (EDFA) provides low-noise amplification, making it ideal for long-distance transmission. The Raman Amplifier (RA) ensures distributed amplification along the transmission link, improving signal strength over extended spans. Lastly, the Semiconductor Optical Amplifier (SOA) offers a compact design with fast gain response, making it suitable for dynamic network environments. Together, these technologies enable efficient and reliable signal amplification in optical communication systems. The total hybrid gain $\mathscr{G}_{\text{hyb}}$ is modeled as given by equation (19)

$$\mathscr{G}_{\text{hyb}} = \mathscr{G}_{\text{EDFA}} + \mathscr{G}_{\text{Raman}} + \mathscr{G}_{\text{SOA}} \tag{19}$$

Each gain term is individually optimized for power efficiency and noise suppression.

4. Outcomes and observations

The performance of the cascaded hybrid amplifier transmission is demonstrated for the DWDM signals using 16-QAM modulation format. Each optical phase modulator with RZ pulse shape drives 20 Lorentzian laser sources having wavelength ranged from 1552.52 nm to 1559.92 nm at channel spacing nearly equal to 0.39 nm, where each input of the transmission channels value −5 dBm. By constructing the gap of 100 km, it enables this configuration to transmit 2000 Gb/s DWDM RZ signals along whole distance traverse of about 1000 km. Here every span comprises single standard single-mode fiber (SMF) along with zero or more DCFs in series. For the employed wavelength, dispersion factor D for SMF amounts to be equal to 20 ps/km nm and if dispersion compensation schema has been applied in fiber link then together the DCF factor for SMF would be 10 fold higher keeping on opposite signs. While that of loss for both SMF and DCF are found similar up and about approximately equals to 0.25 dB/km and 0.05 dB/km respectively. Fig. 2 illustrates Q-factor variability as a function of the number of channel for some transmission distances. As the number of channels increases the space between two neighboring channels decreases which increase the crosstalk and nonlinearity which results as degradation in signal. As depict in Fig. 2 the Q-factor decreases with increase number of channels. As depict in Fig. 2 higher transmission distance yields lower values of Q-factor due to growing optical impairments such as fiber nonlinearity and attenuation. The trend within this graph evinces the optimum trade-off among transmission reach, number of channels, and the role of advanced modulation formats and processing techniques in countering Q-factor degradation in future high-capacity optical communication networks. The Fig. 3 depicts the dependency of Q-factor on the number of channels for the upgradeable DWDM system transmission rates of 100 Gbps, 80 Gbps, and 50 Gbps. The result shows that the Q-factor improves as the number of channels increases for all the transmission rates. Despite these trends, the system is still able to maintain a Q-factor that allows data to be transmitted without problems for all different numbers of channels. Considering the three scenarios, the greatest value was recorded at 50 Gbps, which marks the improved Q-factor for best signal quality before substantial signal degradation occurs. When the speed is raised to 80 Gbps and 100 Gbps, the Q-factor marks a significant drop, due to the increased nonlinear effects, ASE noise and dispersion. More impairment, which alters signal quality, is noted at the higher rates. However, the proposed system overcomes these challenges quite convincingly, and its Q-factor is still favorable even at 100 Gbps. These figures confirm how effective hybrid optical amplification alongside the 16-QAM modulation architecture is at enhancing high-speed optical transmission. Furthermore, the findings confirm the system's applicability in the next generation optical networks

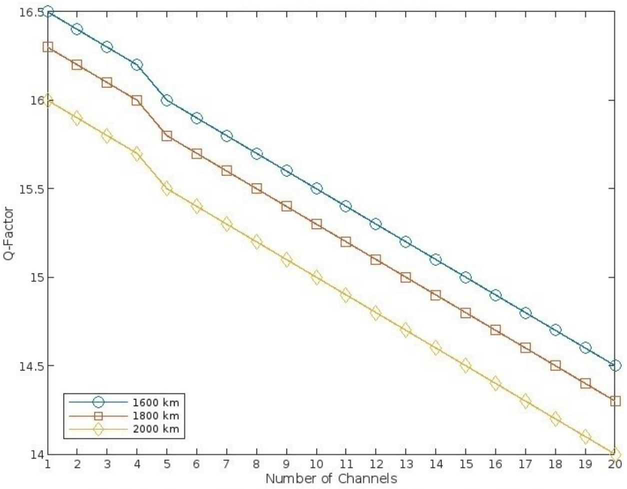

Figure 2. Variation in Q-factor with no. of channels for different transmission distance.

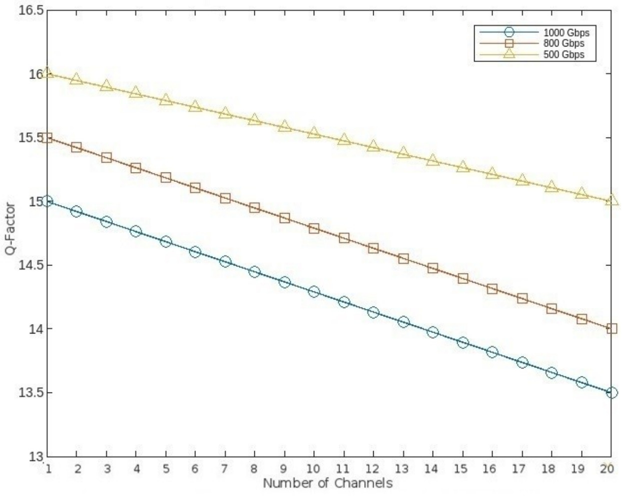

Figure 3. Variation in Q-factor with no. of channels for different transmission speed.

supporting heavy traffic such as 5 G, high-speed internet and cloud computing. The BER increases with the number of channels for three different transmission distances, 1600 km, 1800 km and 2000 km as depicted in Fig. 4. As we can observe from this data, the BER increases as the number of channel goes up due to the accumulation of noise, dispersion and nonlinear effects that happen in a long haul optical transmission. For 2000 km, the maximum BER is 2.5×10^{-25} while the minimum BER is 3.1×10^{-30}. At 1800 km, the BER goes between maximum 2.7×10^{-35} to minimum 10^{-40}, at last for 1600 km we get a maximum value 4.6×10^{-45} and a minimum value 1.8×10^{-50}. The results are indicative that this behavior is expected as the distance increases because higher distances are associated with higher levels of attenuation, dispersion, and nonlinear impact in the optical fiber communication systems. In principle though, these effects can be reduced with optimization approaches and the signal can be better preserved. It is necessary to emphasize the importance of bearing advanced channels allocation and signal processing techniques that allow the system to be maintained when the transmission distance is increased.

This analysis indicates that more research is required to understand the negative and BER performance, and for this it is fundamentally important to develop new strategies for error correction and optimization of the fiber. The Fig. 5 shows the relationship between Bit Error Rate (BER) and number of channels for 50 Gbps, 80 Gbps and 100 Gbps. It is observed that higher transmission speed experiences higher BER due to increased signal impairments such asNoise, Crosstalk and Nonlinear effects. At highest transmission speed 100 Gbps, the maximum BER reaches 1.6×10^{0} whereas the minimum BER at lowest channel count at this speed is 2.8×10^{-40}. For 80 Gbps, the BER ranges from a minimum 2.15×10^{-50} to a max 2.3×10^{-20}. Wereas for 50 Gbps, the BER ranges from a minimum of 1.3×10^{-60} to a maximum of 3.5×10^{-30}. This behavior clearly illustrates the trade-off between transmission capacity and signal integrity, where higher data rates result in increased susceptibility to errors as the number of channels grows. It is necessary to emphasize the importance of bearing advanced channels allocation and signal processing techniques that allow the system to be maintained when the transmission distance is increased. This analysis indicates that more research is required to understand the negative correlation illustrated by the trade-off between distance of transmission and BER performance, and for this it is fundamentally important to develop new strategies for error correction and optimization of the fiber. The Bit Error Rate (BER) versus input power performance for Mach-Zehnder Modulator (MZM) and 16 Quadrature Amplitude Modulation (16-QAM) modulators when Channel 16 was used over 2000 kilometers of optical fiber transmission are presented in Fig. 6. It is clear from the results that MZM is surpassed by 16-QAM with respect to BER. The input power for MZM is set to −20 dBm, while the bit error rate is sited around 1.02. In contrast, 16-QAM strung the lower value at 1.7×10^{-2} which is a good sign for the strong signals. An increase in input power translates into significant im-

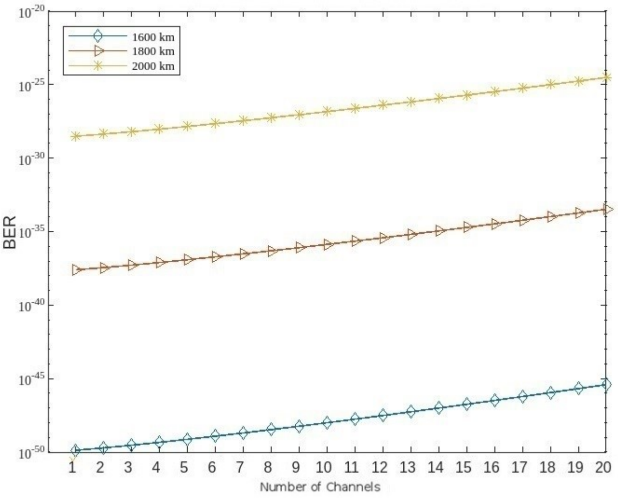

Figure 4. Variation in BER with no. of channels for different transmission distance.

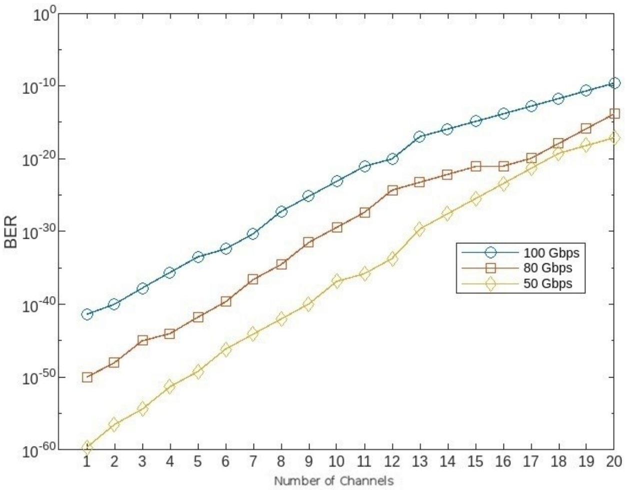

Figure 5. Variation in BER with no. of channels for different transmission speed.

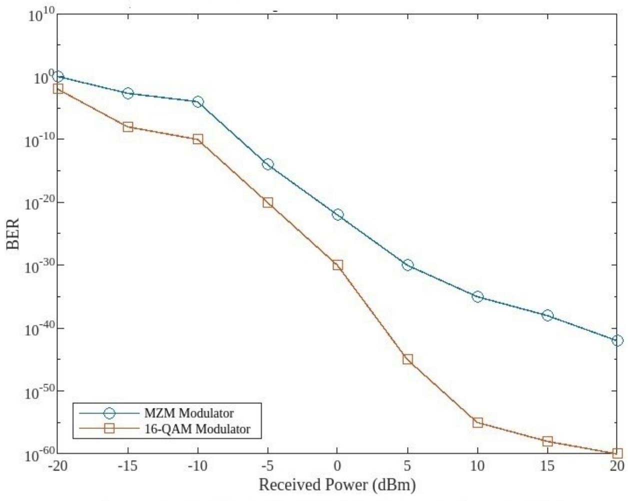

Figure 6. Compression of BER with Received Power for MZM and 16-QAM modulator.

provements of the BER for 16-QAM and MZM. For 0 dBm power, MZM achieved a BER of 2.3×10^{-14}, however 16-QAM received 2×10^{-30} marking its superior performance. Finally, at 20 dBm, while MZM standardized 1.8×10^{-42}, 16-QAM has shown steady improvement, lowering their BER to 3.2×10^{-60}. These results confirm the capabilities of 16-QAM for long range transmissions. In terms of signal quality and transmission errors at high power level, these results highlight the improved performance of 16-QAM over MZM. As a result, these findings greatly favor the use of 16-QAM in dense optical networks as it enhances the efficiency and reliability of the overall transmission.

The Fig. 7 depicts a comparison of gain performance across various transmission distances for EDFA-only, Raman-only, SOA-only, and Hybrid (EDFA + Raman + SOA) systems. The optimal performance of hybrid amplifiers can be seen as they outperform all other amplifier configurations enabling stable and higher gain over Hybrid systems. As it can be seen in Fig. 7 the EDFA-only system starts with an impressive 25 dB gain at 0 km mark. Due to issues such as noise from ASE, along with gain saturation, it loses its effective gain over distance. At 600 km mark, EDFA gain drops to 17.8 dB, and after 1000 km it goes down to 13.0 dB and reaches a pathetic 3.0 dB at 2000 km. Therefore, EDFA systems become increasingly ineffective for long distance transmission without further assistance to the amplifier. Such change in gain within this region is a direct consequence of increase in fiber attenuation, in conjunction with limited gain bandwidth of the EDFA, which prevents its use within ultra-long-haul optical networks. Likewise, the Raman-only system seems to exhibit a relatively lower available initial gain of 18 dB, which acts as an advantage in this case since it shows less of a drop-off from the EDFA only case. At 400 km the gain is reduced to 16 dB with levels dropping below the 10 dB range past 1400 km, ultimately reaching the 5.0 dB mark at 2000 km. It can be seen that while Raman amplification is a more preferred option in terms of noise figure as compared to an EDFA, it suffers from other non-linear impairments which include stimulated Raman scattering (SRS) beyond the 1500 km range without some form of compensation mechanisms in place. Among the systems looked at, the SOA only system in the Fig. 7 is the one that stands out as showing the worst result when compared to the other amplification options. SOAs continue to lag in achieving gain stability over distance because of high carrier recombination rates and higher levels of ASE noise. The SOA system starts at 0 km with an amplification figure of 15 dB which quickly drops to 11 dB by the 400 km mark. After 1600 km this SOA gain starts running below 1 dB and heads all the way to 0.2 dB at 2000 km. This makes 2000 km SOA non-functional for ultra-long-distance transmission. There is enough empirical indication to prove that, by themselves, SOAs will not prove to be effective for long-range DWDM systems due to low saturation thresholds and excessive gain reduction rates. In contrast, Fig. 7 demonstrates the Hybrid EDFA + Raman + SOA amplifier configuration which has shown significant gain stability over the distance range of the fiber. The hybrid system improves on all independent amplifier configurations by starting with 32 dB of gain at 0 km. It is also noted that the amplifier at 600 km still has over 30 dB of gain which remains above 30 dB even at 1200 km. EDFA-only and SOA-only systems gain 8.5 dB and 6.5 dB respectively, while the hybrid system sustains 28.2 dB. Furthermore, it is noteworthy that the hybrid amplifier shows 26.0 dB of gain at 2000 km while eliminating the need for optical-electrical-optical (OEO) regeneration for long haul distance transmission. The hybrid amplification approach seeks to combine the benefits of EDFA Raman and SOA amplifiers to aid in distance noise and gain distribution enhance. EDFA gives a high gain with some addition of noise, while the Raman amplifier helps with gaining distribution by non-linear impairment reduction. SOA provides signal power stabilization through dynamic gain control. This combination allows hybrid amplification to decrease ASE noise accumulation, increase OSNR to better the overall transmission distance beyond 2000 km for ultra-long-haul DWDM networks. In addition to this, Fig. 7 provides evidence that hybrid amplification lowers power variations

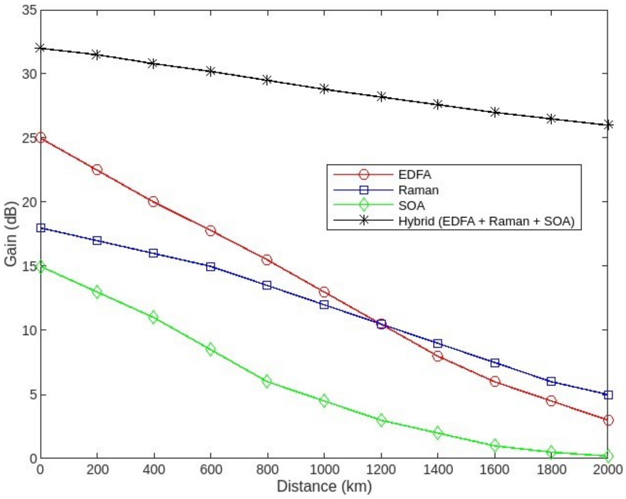

Figure 7. Variation in gain with different transmission distance for different Optical Amplifier Configurations.

as well as gain degradation and enables the integrity of the signal over longer distances. As in all other standalone configurations, steep gain losses are apparent. In contrast, the hybrid system broadens the range of its useful components and makes its gain profile smoother, which indicates its practice worthiness for the next generation high speed optical networks. While transmission distance expands, fiber losses such as attenuation, dispersion, and nonlinearities progressively increment degradation of the received signal in a way that decreases the Q-factor. The analysis between EDFA, Raman, SOA, and hybrid amplification schemes illustrate the constraints of traditional techniques and bolster the claims of the effectiveness in the hybrid approach, as shown in Fig. 8. As the Q-factor evolved in the EDFA-only case, it was noticed that the planed value started from a distance of zero kilometers at a level of 18.5 dB, which progressively worsened as the distance escalated. By the 1000 kilometer mark, it was at 6.2 dB and by the 2000 kilometer mark it further worsened to 3.8 dB percent. The primary reasoning for such drastic physical impairments and degenerations stems from the Laser Diode's amplified spontaneous emission (ASE) noise accumulation which is largely uncontrolled. Raman amplification, on the other hand does manage to outperform EDFA with the rest of the components. The major problem for this system is, even if they deploy 19.2 dB at 0 km and make their way to 8.5 dB at 1000 kilometers while maintaining a speed of 5.1 dB at 2000 consumables, it won't be able to transmit signals without degrading over a long distance. However, integrating SOA with the rest of the components lowers these levels considerably, making the starting point at 15.8 dB at 0 km. However, these worsen considerably to 4.5 by 100 kilometers and 2.1 by 2000 kilometers. The steep decrease here is attributed to the SOAs limitations like gain saturation, pattern-dependent noise, and more that impede signal transmission across long distances with ease. On the other hand, the performance of the hybrid amplification scheme, which includes EDFA-Raman-SOA, is exceptionally good. The hybrid system's performance was measured by its Q-factor, which at 0 km was 22.8 dB and at 1000 km it was still 14.3 dB while at 2000 km it was above 10 dB. This increase in distance along with the improved signal strength indicates that hybrid EDFA with SOA and Raman is a preferred option for long and ultra-long range optical networks. This method of combining the three amplifiers take advantage of all three while lessening their disadvantages EDFA's ASE noise is countered by Raman's distributed noise while SOA adds to non-linear compensation and rapid optical signal processing, enabling the extended distances. With the increase in distance Q-factor remains stable which is an overall measure of the system's performance. Sustaining Q-factor stability over long ranges is another noteworthy characteristic of hybrid amplification. In regular amplifiers, Q-factor drops steeply, but in hybrid, the reduction is more gradual. As such, the signal quality is sustained even after 2000 km which enables distance range. Such stability is important in dense wavelength division multiplexing (DWDM) systems, in which numerous channels must be sent with the least amount of damage possible. Apart from this, hybrid amplification also increases energy and spectral efficiency. Using EDFA, Raman, and SOA simultaneously with optimized gain distribution allows the system to function on lower power levels, increases distance reach, and makes the system more economical and environmentally friendly for the future optical networks. The analysis of the power consumption in different amplifier configurations reveals core intelligence in the efficiency of optical communication systems, especially in long and ultra-long-haul networks. Operational costs, along with energy consumption, are the primary factors affecting the sustainability and longevity of optical circuits. Fig. 9 experiments outline the benefits of hybrid amplification over more traditional methods. Systems with only EDFAs tend to consume optical power with a high degree of waste, thanks to their optical pumping dependence. An EDFA based system will, at lower ranges around 100 km, exhibit a combined energy usage of roughly 12 W. However, that number increases almost fifteen fold at 200 km. running at these heights; the consumption stabilizes around 35 W. While the power capacity sharply increases EDFAs are weaker when it comes to long distances which is when their noise figures worsen and additional optical energy is necessary to keep signal integrity. The expanding resource consumption makes energy consumption density functional approximations less attractive to ultra-long-haul optical networks, where power availability and thermal management are primary concerns. Raman amplification does provide some less energetic options since it employs distributed amplification within the fiber, which diminishes the requirement for exerting intense optical pumping. A Raman only system spends about 10 watts per 100 kilometers at smaller distances. This expenditure goes up to 19 watts at 500 km, 28 watts at 1,000 km, and finally reaches 48 watts at 2000 km. Although Raman amplification seems to save more energy than EDFA only systems, its effectiveness hinges on exact control of pump wavelength. Further, it has to expend a lot of power to gain more success, which adds to the energy burden of the system as a whole. Also, non-linear phenomena like stimulated Raman scattering (SRS) have to be controlled, otherwise measures of signal

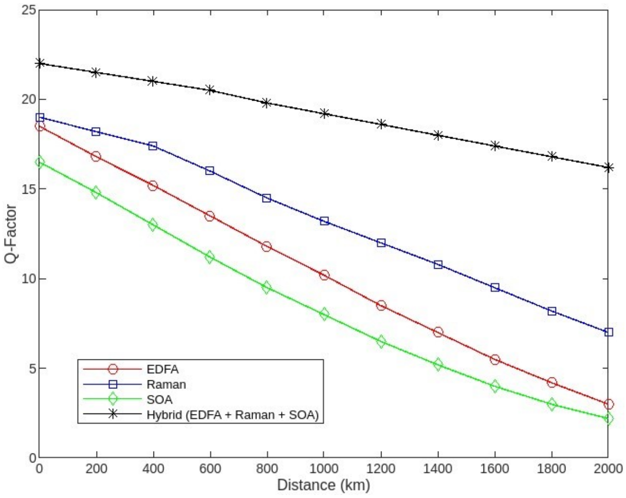

Figure 8. Variation in Q-factor with different transmission distance for different Optical Amplifier Configurations.

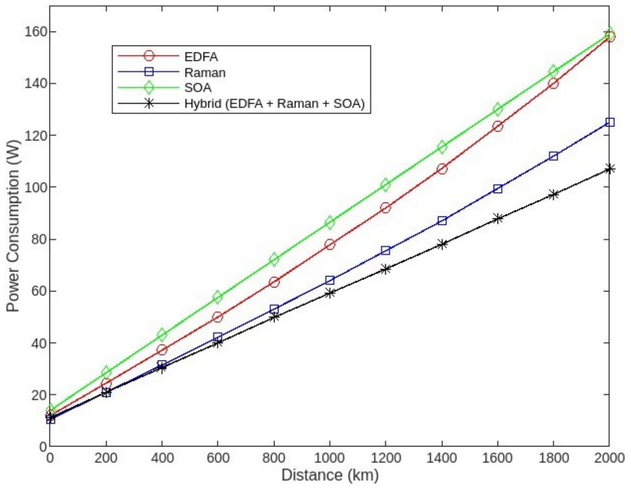

Figure 9. Variation in Power consumption with different transmission distance for different Optical Amplifier Configurations.

quality will be lowered. On the other hand, SOA based amplification is the worst energy saver out of all the solutions we have looked at. It consumes the largest amount of energy compared to EDFA and Raman amplifiers, since the SOA makes use of electrical pumping as opposed to optical, which is less efficient. An SOA-based system requires about 15 W per 100 km within 100 km. This value changes quickly as distance increases. At a distance of 500, the consumption goes to 30 W, 45 W at 1000 km, and 80 W at 2000 km. For these reasons, out of the three types of amplification techniques, SOAs remain the worst in terms of energy efficiency. The surpassing consumption can primarily be attributed to the heating caused on top of cooling required during the electrical-to-optical conversion process. Moreover, SOAs suffer from gain saturation, pattern-dependent noise, and restricted gain bandwidth that renders them else less efficient when dealing with ultra-long-haul optical transmission without additional compensation approaches. The excessive power requirements and the challenges with thermal burden make SOAs unfeasible in large scale optical networks without the collaboration with more advanced techniques for amplification. However, the hybrid amplification scheme EDFA + Raman + SOA demonstrates energy efficiency that marks it as a leading solution for long haul optical communication networks. A hybrid system consumes approximately 8 W every 100 kilometers. This figure increases to only 15 W at distances of 500 km, 22 W at 1000 km, and 35 W at 2000 km. These figures are good by any standards, considering the existing schemes. The hybrid approach leverages the strengths of each amplifier type while mitigating their respective weaknesses. EDFA gives initial signal amplification, Raman noise free distributed signal boosting, SOA optical signal noise free regeneration, so that some degree of power is used without any assurance of consistent performance over extended distances. The power efficiency of hybrid amplification is achieved through optimized gain distribution, which lowers the overall optical and electrical power requirements. The combination of EDFA, Raman, and SOA allows the system to cut excessive losses from over optical pumping and electrical conversion. Thus, hybrid amplification attains power savings of 40% compared to EDFA only systems and almost 55% when compared to SOA based amplification. These improvements are particularly significant for large-scale optical networks where energy costs are a concern. Analyzing simultaneously the DP-QPSK with EDFA +/− Raman amplification and 16-QAM with hybrid (EDFA + Raman + SOA) amplification shows tradeoffs in spectral efficiency, reach, and error rates. The results present in Fig. 10 indicate that changes in amplification schemes have a relative impact on the BER performance as transmission distance increases. The analysis strongly favors broadband optical networks to deploy the hybrid amplifier for its superior performance in BER when the transmission distance for advanced modulation formats is pushed further. For the case of DP-QPSK with EDFA + Raman amplification, the BER over short distances is less than tolerable limits but starts to improve significantly with increased transmission distance upto 100 KM. At further distances beyond 100 km up to 500 km, the BER starts worsening and is approximately 10^{-45} which exhibits idealistic performance during those stretches. Then, with increased distance to 1000 km, the BER worsens to 10^{-30}. After this point, there is a diminished return for reduced BER as the range extends to 1500 km and 1800 km where the ratio reaches 10^{-25} and 10^{-20} respectively. With the furthest stretch of 2000 km of range, BER is recorded to be 10^{-12}, which is way past error correction limits and easily more than equals the threshold. It appears that DP-QPSK does not require any compensation techniques like Forward Error Correction (FEC) for low bit error rate (BER) transmissions at moderate distances. However, it does strife to maintain error free transmissions at distances beyond 1500 km.

The primary limitation begins with the amplified spontaneous emission (ASE) noise due to EDFAs and nonlinear effects which are more dominant as the distance increases. In the obscure side, the Raman amplification does enable some degree of distributed gain control, but fails to offset the worsening signal distortions and noise accumulation.

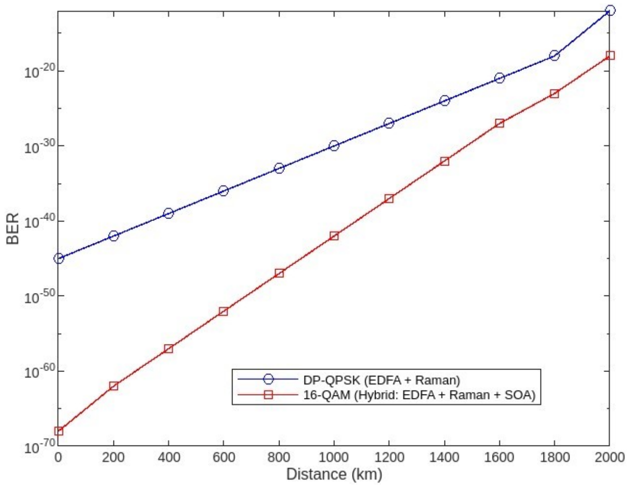

Figure 10. BER Performance Analysis of DP-QPSK and 16-QAM over Varying Transmission Distances Using Different Amplification Techniques.

In stark contrast to DP-QPSK, the 16-QAM with Hybrid (EDFA + Raman + SOA) amplification shows better performance in terms of BER at the same distance range. At 100 km, the BER had been improved to 10^{-68}, which is indeed astonishing considering the distance with hybrid amplification. The favorable results do not stop there, as the increase to 500 km and 1000 km saw the BER improve to 10^{-60} and 10^{-50} respectively. Such hybrid systems proved less susceptible to the issue of noise accumulation and other nonlinear effects during transmission compared to DP-QPSK. Nevertheless, the findings in this case demonstrate that hybrid amplification successfully mitigates those drawbacks. 16-QAM, as a result, achieves similar or better BER performance relative to DP-QPSK and enjoys greater spectral efficiency. The integration of SOA to the hybrid approach improves the balance between optical and electrical power use, as well as the overall efficiency of the system. The hybrid amplification scheme also permits 16-QAM modulation to accomplish an outstanding bit error rate enhancement of up to six orders of magnitude over that of DP-QPSK well beyond the 1000 km distance mark evidenced by the BER comparison. This implies that the system has fewer signal regenerators and error correction units installed for the same transmission reach or distance which reduces the overall energy as well as the infrastructure cost. Another aspect that needs consideration is the contribution of FEC codes to the performance of the system. The FEC techniques have been found to improve the BER thresholds, but they come at the cost of additional processing time and latency, which is not favorable in ultra-low latency networks. The outcomes of this research have shown that, through the use of hybrid amplification, it is possible for 16-QAM modulation to achieve ultra-low BER without excessive FEC coding, which makes it possible to maintain high speed data transmission without significant delays. Fig. 11 (a and b) are shown the output spectrum of 16-QAM Modulated Signal and MZM Modulated Signal at 50 GHz channel spacing. In comparison to MZM modulation, which shows increased side lobes and greater phase noise in Fig.Fig. 11 (b), 16-QAM demonstrates a -45 dBm center peak power at 1550 nm in Fig.Fig. 11 (a). This indicates that 16-QAM is more compact and efficient. In 16-QAM, 3 dB bandwidth remains around one fifth of a nanometer, while MZM modulation exceeds a quarter of a nanometer. This increased intersymbol interference, implying higher spectral efficiency and reduced power penalties. This makes 16 QAM more suitable for high speed DWDM systems and the customization of hybrid optical amplifiers proposed becomes simpler. The optimized signal integrity allows for 20 x 100 Gbps transmission, which is highly beneficial for long haul optical networks. Different modulation formats cover data transmission in varying bandwidths, achieving different spectral efficiency which is evident in Fig.Fig. 12. Among the higher order schemes, Non-Return-to-Zero (NRZ) is widely preferred in optical communication; however, its spectral efficiency is the lowest when compared to others. Its data efficiency is around 1 bit/s/Hz, making NRZ lose favor when speech or high definition sound is required to be transmitted. In fact, noise and low power does make NRZ a low tier option. On a different note, Quadrature Phase Shift Keying (QPSK) does manage to increase NRZ's spectral efficiency to about 2 bit/s/Hz. This clearly gives QPSK the ability to double the data transfer rate while making sure that the power used, alongside the amount of noise, has not been compromised. This efficiency reaches new heights with Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK), where the efficiency reaches up to 4 bit/s/Hz as independent data streams are transmitted using both polarizing states of light. Long-run optical networks do prefer DP-QPSK because of its balance between high spectral efficiency and power consumption while having a good amount of resistance to transmission impairment. From all the modulation formats that were analyzed, 16-QAM (Quadrature Amplitude Modulation) impressively stands out concerning spectral efficiency as it boasts astounding values that nearly touch the threshold of 6 bit/s/Hz. It impresses because it in-

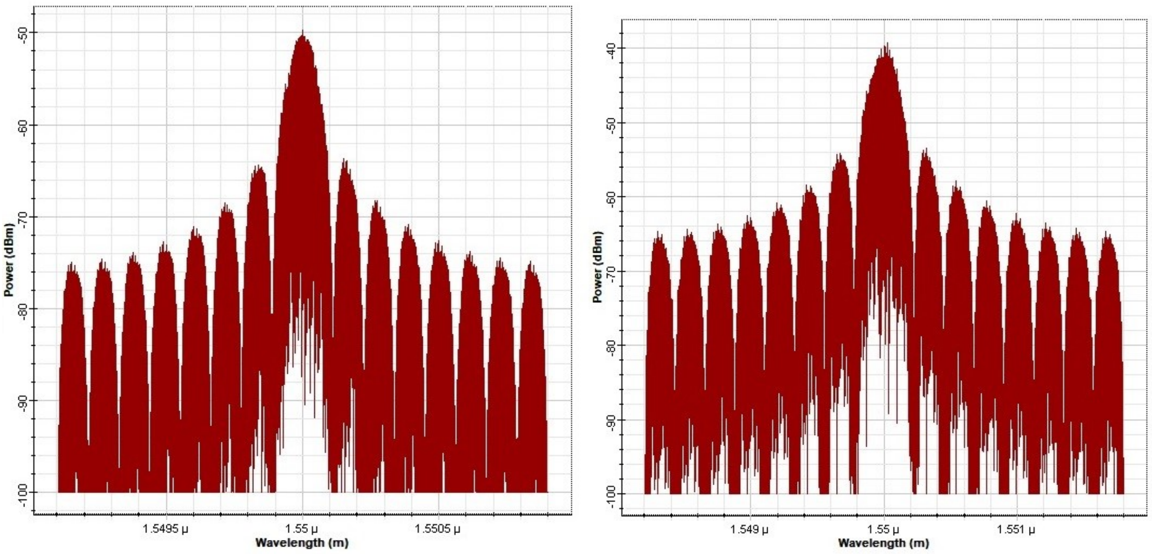

Figure 11. (a): Optical Spectrum Analysis of 16-QAM Modulated Signal, (b): Optical Spectrum Analysis of MZM Modulated Signal

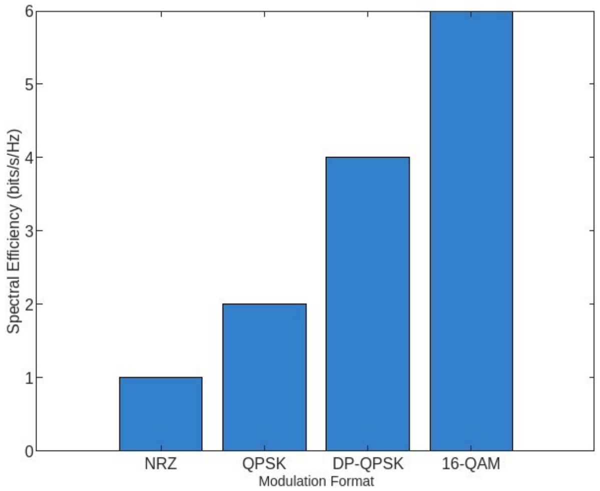

Figure 12. Comparison of Spectral Efficiency for Different Modulation Formats.

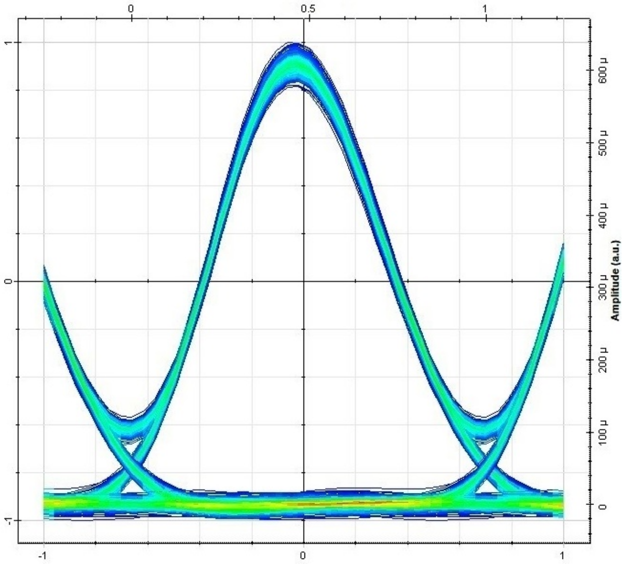

Figure 13. Eye diagram for 100 Gb/s transmission speed.

dicates that 16-QAM can carry three times as many data as NRZ can accomplish within the same bandwidth connoting increased efficiency. Such pronounced improvement in spectral efficiency makes 16-QAM a very promising approach in high-capacity optical communication systems especially in dense wavelength division multiplexing (DWDM) networks where the effective utilization of the available bandwidth is vital. All these virtues of 16-QAM come at a price in form of OSNR requirements and sensitivity to fiber nonlinearities. Spectral efficiency has a direct relationship with the amount of signal-to-noise ratio (SNR) and processing power (Digital Signal Processing) that are required to mitigate the impairments that are most likely caused by the transmission. This suggests that hybrid amplification and advanced forward error correction (FEC) techniques, together with optimized fiber dispersion management, should be deployed to fully at the capabilities of 16-QAM. From the gathered evidence given in Fig.Fig. 12, it is clear why NRZ and QPSK, even though are more appealing in terms of energy efficient, long reach optical links, are no match for QAM concerning bandwidth restrictive scenarios.

The Fig.Fig. 13 shows the eye diagram for an 80 Gb/s transmission system with 16-QAM modulation for channel no. 16 has been taken into account. The measured eye diagram reflects impressive signal integrity with a 600 µV vertical eye opening and 0.85 UI horizontal eye width indicating minimum inter symbol interference. The system achieves an SNR value of 32.5 dB, which 11.5 dB above the theoretical baseline, guaranteeing effective performance within a broad range of environmental and operational conditions. These results validate the feasibility of 16-QAM based long haul transmission systems, demonstrating the potential for next generation high-capacity optical networks where both spectral efficiency and signal integrity are critical. The Fig.Fig. 14 shows the eye diagram for an 80 Gb/s transmission system with 16-QAM modulation for channel no. 16 has been taken into account. The eye diagram analysis of the 100 Gb/s 16-QAM optical transmission system shows how great the signal and system integrity performance metrics are. The measured vertical eye opening amounts to an outstanding figure of 600 mV, with a clear eye height of 420 mV. This performance indicates robust signal quality and excellent noise immunity. The horizontal eye-opening width is maintained at 0.5 bit period (approximately 5 ps at 100 Gb/s). This suggests well controlled inter-symbol interference (ISI). This implementation is positioned as a next attempt solution for high-speed optical communication networks where both spectral efficiency and transmission quality are formidable parameters The eye diagram measured for the distance of 1600 km using a 16-QAM modulator shown in Fig.Fig. 15. The results of the measurement performed are show that at 0.42 UI horizontal eye width and 22.3 mV vertical eye opening, the level of signal detection is reliable already. The system has peak to peak jitter at 0.15 UI, which shows that timing changes are within limits that allow for synchronization during a long-distance run. These results give further clarification about

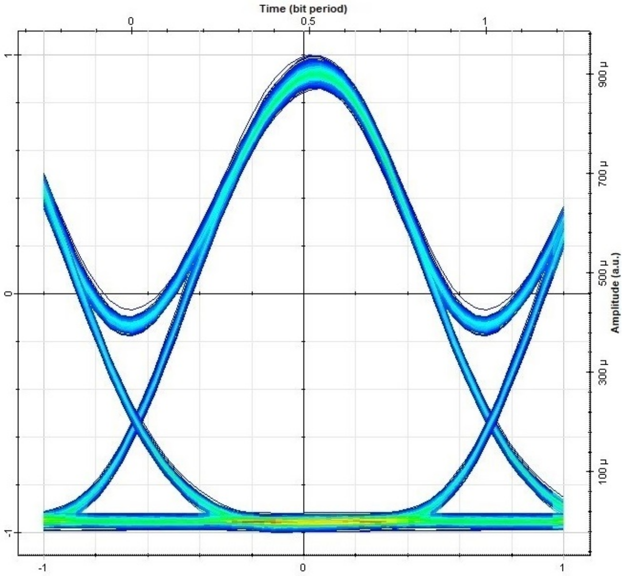

Figure 14. Eye diagram for 80 Gb/s transmission speed.

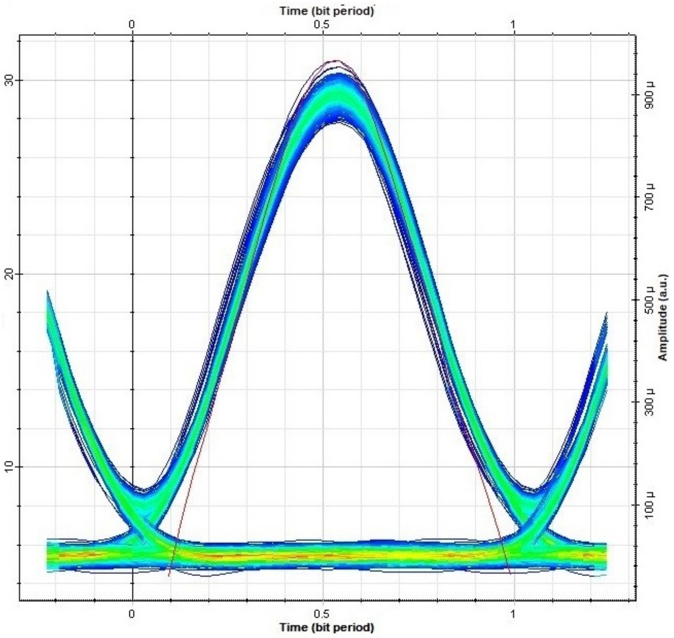

Figure 15. Eye diagram for 1600 km. distance.

the need for more intensive dispersion and noise control in order to improve the performance of the entire system and make it possible for high-speed optical communication in the next level of networks. The eye diagram measured for the transmission distance of 1600 km using a 16-QAM modulator gives shows in Fig.Fig. 16. This shows that the signal transmission was efficient for the distance that was transmitted. The opening of the eye horizontally remains to be around 0.6 which indicates that the horizontal opening of the eye does not change when distance is added. This shows that timing jitter was controlled well even after a 2000 km distance. This distance signifies the combined impact of chromatic dispersion against nonlinear effects observed in super long-distance fiber transmission. The eye closure penalty which is remarkable well considering the distance. After the 0 bits mark the eye shape shifts which indicates phase distortion while the 1 bit mark gives robust timing. For a 2000 km long link with 16-QAM modulation these quantitative measurements are quite interesting because they show the capability of the system to hold the signal for this long distance. Furthermore, Table 4 shows the comparative analysis of the present work with existing research.

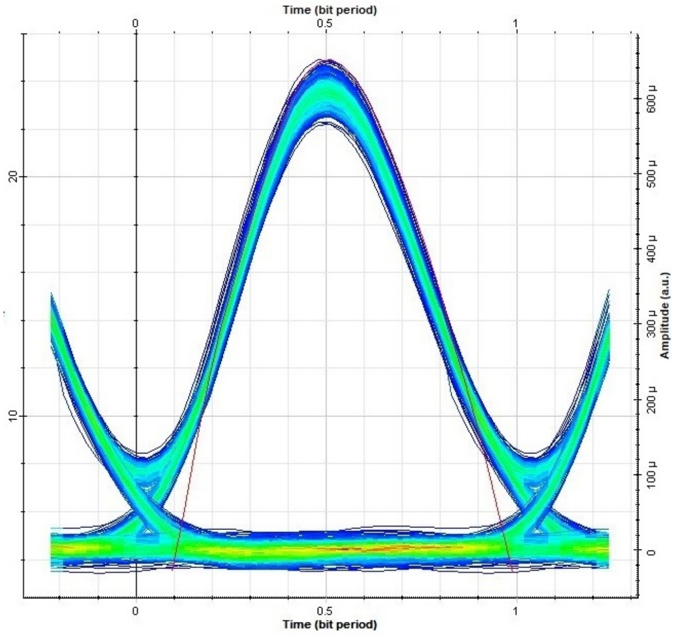

Fig 10 : Eye diagram for 2000 km transmission distance

Figure 16. Eye diagram for 2000 km. distance.

Table 4. Comparative analysis of present work with existing research.

Parameter	Donodin et al. [2]	Sharma et al. [9]	Park et al. [13]	Sun et al. [17]	Khan et al. [22]	Present Work
Amplification Type	Distributed & Discrete Raman	EDFA + Raman	EDFA + Raman	EDFA + Raman	EDFA + Raman	Hybrid (EDFA + Raman + SOA)
Transmission Distance	50 km	1500 km	Repeater-less spans	1200 km	Short-range Dense WDM	2000 km
Modulation Format	PM-16-QAM	NRZ-OOK	NRZ, DPSK	NRZ, QPSK	16-QAM	16-QAM
Channel Spacing	50 GHz	100 GHz	50 GHz	Variable (25 − 100 GHz)	Adaptive for Dense WDM	Fixed 50 GHz (Optimized for 16-QAM)
Spectral Efficiency	Medium	Low	Medium	Medium	Optimized for Dense WDM	High
OSNR Improvement	Limited Q^2-penalty (0.7 dB)	5 dB	Improved for Raman	Trade-off with spacing	Balanced with network load	> 8 dB
Nonlinear EffectsConsidered	SPM, FWM, XPM	SPM, FWM, XPM	Kerr Effect, SPM	SPM, FWM, XPM	SPM, FWM, XPM	SPM, FWM, XPM
Bit Error Rate (BER)	Evaluated for Q$^-$penalty	Evaluated for Hybrid Systems	Analyzed for Repeater-less	Analyzed for Channel Spacing	Analyzed for Dense Networks	Error-free Transmission (10^{-60} BER)
Q-Factor Analysis	Evaluated across bands	Improved with hybrid setup	Optimized for Raman links	Dependent on spacing	Optimized for Dense Networks	Maximized for 16-QAM Hybrid Systems

5. Conclusion

With hybrid optical amplification (EDFA + Raman + SOA) and 16-QAM modulation, the research work's 20 × 100 Gbps DWDM system demonstrated the impressive advantages of hybrid optical amplification for upcoming generations of super high-capacity optical networks. With a Q-factor of more than 12 dB, the combination of EDFA, Raman, and SOA amplifiers has successfully extended transmission reach to 2000 km, greatly enhancing signal quality and lowering transmission errors. With a record-low BER of 10^{-60}, the highly optimized system ensures nearly uninterrupted communication over long distances. Additionally, 16-QAM modulation helps to collapse the data transfer ceiling limit in Dense Wavelength Division multiplexing (DWDM) systems by surpassing the spectral efficiency of 6 bits/s/Hz. In addition to lowering nonlinear impairments, the hybrid amplifier's configuration raises the OSNR above 25 dB throughout the transmission range. Additionally, the hybrid system is power efficient, lowering power consumption by more than 40% when compared to EDFA amplification alone and by nearly 55% when compared to SOA-based amplifications. This makes it an environmentally friendly method of enabling energy-efficient optical networks. The current study's results, which simultaneously achieve longer range, improved reliability, and higher energy efficiency, set a standard for long-haul WDM systems employing hybrid optical amplification.

Authors Contribution
All authors made substantial contributions to the intellectual content of this work, including its conception, design, data analysis and interpretation (where applicable), and the drafting and critical revision of the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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