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Simulation and Optimization of High-Speed Backbone Optical Fiber Link Based on Dense Wavelength Division Multiplexing

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Abstract. *With the demands increasingly imposed by many new applications on existing networks, long-reaching high data rate links are crucial. One of the ideal ways to deal with such an advanced telecommunications system is to use Dense Wavelength Division Multiplexing (DWDM). This work proposes an optical communication system based on 32-channel DWDM and designed for a high data speed of 40 Gbps per channel. In addition, this study investigates different dispersion and attenuation compensation mechanisms. The primary aim is to extend the transmission distance of a high data rate DWDM system. On the other hand, this study aims to find the best parameters setting for the 32-DWDM channels by comparing the performance of numerous optimization algorithms to achieve better performance compared to prior studies. This paper presents a novel method to improve various system characteristics, particularly the signal-to-noise ratio, as the main goal of improving the system's performance in general and making it suitable to become a mainstay for networks with high data rates by determining the optimal values for essential DWDM system parameters. To realize this, Optimization techniques are applied to multiple critical variables such as filter bandwidth, input power, and dispersion modulation. Optisystem program is utilized to simulate the proposed system and analyze the variables that play a vital role in raising the performance to a higher level. Three different algorithms for dispersion compensation and optimal power levels are also compared and implemented. The optimized scheme proposed demonstrates the achievability of reaching long distances with a data rate of 1.28 Tbps. The results of system performance in this study push the DWDM technique to be a candidate for high-speed backbone optical fiber link offering an interesting practical solution for the growing network.*

Keywords: *Dense Wavelength Division Multiplexing (DWDM), Erbium-Doped Fiber Amplifier (EDFA), Dispersion Compensating Fiber (DCF), Fiber Bragg gratings (FBG).*

1. INTRODUCTION

Nowadays, due to the tremendous progress in many areas that require high data speed such as cloud services, the Internet of Things, and high-precision live applications, many researches are focusing on optical fiber communications as a solution that can meet the current user requirements and the expected growth in capacity demand in the future. This focus comes on this type of communication because of its wide bandwidth, data security, extended transmission ranges, and resistance to electromagnetic interference [1, 2]. Although optical communications are considered a promising technology that is well suited to provide high and reliable data transfer speeds in future generations of communications, it requires many improvements to increase its ability to transmit data at a faster rate and longer distances [3, 4]. Technologies that rely on integrating signals from multiple users provide excellent possibilities for increasing system capacity. WDM is considered one of the most powerful multiple-user technologies, which allows multiple optical signals to be transmitted simultaneously over the same fiber without interference, making it a good solution for modern communications. WDM signals are greatly affected by the dispersion within optical fiber media than other multiplexing technologies, thus led to a significant system performance reduction [5].

The factor that most affects the performance of a system using optical fibers is the chromatic dispersion. For standard single mode fiber, choosing the operating wavelength at not in the zero-dispersion region led to the light waves travel through the fibers at different propagation speeds relative to each other. This can delay spectrum elements, thus distorting the signal mostly [6]. Over time this can lead to a particular wavelength propagation highly affected by this dispersion. Indeed, the WDM based transmissions is more susceptible to interference and distortion than other optical communication technologies [7]. This problem is especially severe when using high data rates where can increase the error rates and provide poor communication quality. Several studies have addressed the fact that dispersion and power transmission are very sensitive parameters for WDM technology especially for long reach link. Combining a larger number of wavelengths with certain powers can significantly increase the overall power delivered by the optical fiber, which can have a nonlinear effect on the transmitted signal. To try to reduce the effects of optical fibers and increase the possibility of higher data rates and longer link range in the transmission of WDM signals. One has to consider the intensity of the optical signal at the optical fiber tip. These nonlinear fluctuations can change the signal directly, causing partial or total loss of data. It is therefore recommended to calibrate the power of each input signal and add optical amplifiers to increase the signal strength and compensate for remote losses due to attenuation in optical fibers [8]. Optical amplifiers play a vital role in WDM communication systems in modern communication systems, this by intensifying signal strength and mitigating nonlinear effects. Erbium-doped fiber amplifiers (EDFAs) are important components in fiber-optic networks and are widely used due to their ability to amplify signals across a wide spectrum, reduce noise, and enhance gain [9]. The use of this type of amplifier is concentrated in long distances, as it is commonly used in high-capacity networks that send data over long distances in order to prevent signal degradation and enable the transfer of huge data.

One of the factors that helped the spread of EDFA is that the operating wavelength of these amplifiers matches the lower limits of the attenuation window, and thus the network capacity can be controlled using amplifiers with different wavelengths at the same time and distance. Therefore, this factor ensures high-quality transmission and reduces the impact on the quality of data transmission [10]. At the receiving end, compared to conventional photodetectors, the use of avalanche photodiodes (APDs) as a photodetector can amplify the input low-power optical signals without the need for additional amplifiers. This technology can be adopted in networks that rely on WDM technology with high data rates [11].

In the past few years, researchers have focused on combining WDM and EDFA with dispersion compensation techniques to improve fiber networks and increase the reliability of communication systems. Several scholars have conducted investigations on enhancing optical systems utilizing WDM technology. In research [12], dense WDM (DWDM) is used based on 64 channels with modulation and NRZ. Dispersion was compensated using DCF. The study also tested the proposed system using simulations at different transmission distances and bit rates (up to 2.5 Tbps medium range of optical systems based on DWDM). A hybrid technique of PDM-WDM is proposed to increase the channel capacity exploited by the system. The study relied on 16 wavelengths with 32 dual-polarization channels with a data rate of 20 Gbps, which enables a high data rate of 0.64 Tbps to be achieved [13]. In study [14], a WDM RoF system was proposed based on 32 channels, which gave the best results at two distances of 50 km and 100 km, with a channel spacing of 50 GHz. The study analyzed the system for different distances and channel spacing. Hybrid dispersion compensation techniques have been proposed for a 32 × 40 Gbps DWDM system. Using optical phase conjugation DCF-FBG (OPC-DCF-FBG) with a different pulse generator. As the results showed, the proposed system is able to provide the best performance for transportation systems with a length of 500 km. However, such a system adds complexity and cost to the organization. Ch. Supraja et al., have designed a

32-channel DWDM optical communication system with the use of DCF, thus resulting in transmission at high data rates [15]. The study in the paper [16] used WDM to transfer high-rate data over 8 channels employing 10 Gbps per channel. It also relied on DCF and EDFA to improve system performance and increase the transmitted distance. Another study designed a DWDM system based on a dispersion compensation for the purpose of sending data over long distances of up to 500 km [17]. The researchers in the study [18] proposed and designed the WDM-OOK system with a data transfer speed of 1.28 Tbps for long distances of up to 1000 km.

This study will suggest a system that offers a high data rate across higher distances, building upon the works that have been evaluated before. The system integrates dense WDM (DWDM), APD, and EDFA technologies, comprising 32 WDM channels operating at a data rate of 40 Gbps for each channel. The dispersion compensation is a crucial point in the WDM system, three scenarios are suggested to mitigate the effects of dispersion and attenuation in order to build a long-reach optical link that can be used as a network backbone. Optisystem is the software utilized for simulating, designing, and optimizing various parameters to attain optimal performance and compare the resulting data.

The next of this paper is organized as follows: Section 2 expresses the methodology and the optimization method that were used in the proposed system. Section 3 presents the simulation results. Finally, section 4 concludes this study followed by conflicts of interest and the list of references.

2. METHOD AND DESIGN

This study suggests a 32-channel DWDM system capable of transmitting data at a high data rate of 1.28 Tbps to address the bottleneck issues in present and future communication systems and transmit this data to farther distances. The design model of the proposed system is separated into three main parts; transmitter side, channel path, and receiver, as shown in Fig. 1. The main proposed system parameters are listed in Table 1 for clarification. Before running any link scenario, the transmission bandwidth of the demultiplexer, the cutoff rate for the low-pass Bessel filter, the amplifier gain of the APD, and the EDFA's gain value are optimized. A Continuous Wave (CW) laser diode array produces 32 carrier optical waves with a specific wavelength between a band of 1554-1556.4 nm (0.4 nm of spacing) and a linewidth of 100 KHz, which are used as dense WDM channels. Each light wave of a certain wavelength is fed into an external modulator like the Machzender modulator, which modulates 40 Gbps of information that is encoded using a Non-Return to Zero (NRZ) pulse generator. The 32 modulated light waves (T0 to T31) are multiplexed using a WDM multiplexer, and send this signal through various optical link scenarios. Three scenarios were employed to compare the system performance to determine the optimal choice for the long-reach optical link in the high data rate dense WDM system.

TABLE 1. SIMULATION SETUP

Parameter	value
Operating wavelength	1554-1556.4 nm
dense WDM channels	32
Modulation	NRZ
Power input	-15 to 0 dBm
Linewidth	100 kHz
Bitrate	40 Gbps
SMF Attenuation	0.2 dB/km
SMF Dispersion	16.75 ps/nm/km
Extinction ratio	30 dB
PD Responsivity	1 A/W
PD Dark current	10 nA

The first scenario comprises 50 km of Single-Mode Fiber (SMF), an optical amplifier of 4 dB noise figure and optimized gain (EDFA), and Fiber Bragg gratings (FBG) as a dispersion compensation. In optical communication systems, FBGs are increasingly used in contemporary networks because they can reflect numerous wavelengths, achieving close to perfect reflected light from a single wavelength with highly precise dispersion level . In the second link scenario, a configuration of SMF, Dispersion Compensating Fiber (DCF) of attenuation coefficient of 0.5 dB/km and dispersion of -80 ps/nm/km, and 12.5 dB EDFA have been utilized. The total length ℓ_T of SMF and DCF is 50 km:

$$\ell_T = \ell_{SMF} + \ell_{DCF} \tag{1}$$

Where ℓ_{SMF} is the range of the SMF and length of the DCF denoted ℓ_{DCF}. The total dispersion of this combination must be zero. Since the dispersion of standard SMF (Λ_{SMF}) is 16.75 ps/nm/km and the dispersion of the DCF (Λ_{DCF}) can be -80 ps/nm/km, the length of the SMF and DCF are 41.3434 and 8.6566 km respectively as in (1-3)

$$\Lambda_T = \Lambda_{SMF}\ell_{SMF} + \Lambda_{DCF}\ell_{DCF} = 0 \tag{2}$$

$$\ell_{DCF} = -\frac{\Lambda_{SMF}\ell_{SMF}}{\Lambda_{DCF}} \tag{3}$$

The third scenario will differ from the last one by incorporating two EDFAs instead of using only one placed after those 50 km of total fiber length. Initially, the EDFA1 will have a gain of 8 dB and be placed after the SMF, while the EDFA2 will have a gain of 4 dB and be placed after the DCF before optimazation running. On the receiving side, the proposed system uses an avalanche photodiode (APD) as a photodetector. In addition, it utilizes low-pass Bessel filters (LPBF) to mitigate the ripples in the electrical signal. Before that, a WDM demultiplexer of 32 output (R_0 to R_{31}) is employed to separate the wavelengths. Then, a photodetector is used to convert those optical signals to electrical form. Furthermore, in terms of showing the result, a power meter and bit error rate (BER) analyzers were utilized. The main parameters that can be read from these visualizers are the received power and BER which helps to evaluate the system performance, as expressed in (4). The BER ($\mathcal{B}$) may calculated by determining the value of signal-to-noise ratio (SNR) using (5):

$$\mathcal{B} = \frac{Number\ of\ errors}{Total\ number\ bits} \tag{4}$$

$$\mathcal{B} = \frac{2}{\pi \times SNR} \times e^{\left(\frac{-SNR}{8}\right)} \tag{5}$$

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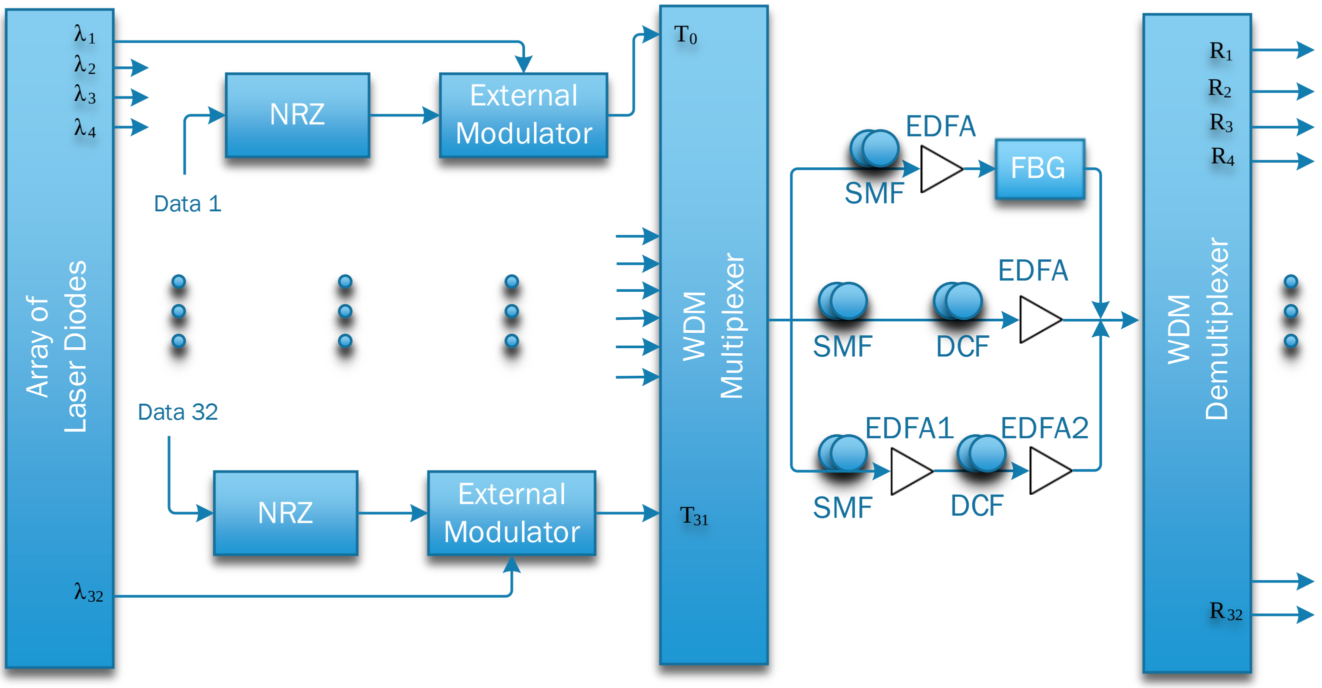

Figure 1. Proposed System Diagram

2.1 OPTIMIZATION TECHNIQUE

In terms of determining the optimal solution for many of the key variables in systems that rely on optical communications technologies, OptiSystem can provide a number of optimization strategies and methods. The software provides easy access methods and uses multiple iteration techniques to implement and perform optimization that is usually effective in terms of results and time. Genetic algorithms, gradient-based optimization, and particle swarm optimization are among the different optimization methods supported by this software to perform the optimization process. In this research, we will rely on an iterative optimization method that begins with defining constraint boundaries and completion criteria. This study aims to maximize the signal-to-noise ratio (SNR) while guaranteeing a high speed of data and dependability. In order to accomplish this, a sequential optimization issue has been developed where the goal is to minimize the BER employing a function f with N variables and to maximize the length or minimize the power supply using a constraint function g which represents the maximum and the minimum possible values of each variable. The objective is to identify the ideal number x* that reduces the issue that arises from (6) [19].

$$f(x^*) \leq f(x), \quad \forall x \; close\ to\ x^* \tag{6}$$

The objective of this step is to determine the solution vector (x*) that satisfies the constraints while minimizing the objective function for all x satisfying the constraints. Where $f(x^*)$ is objective function (f) of the optimum value of the variable (like WDM demultiplexer bandwedth, LPF cutoff frequency, APD gain, and EDFA gain) under the constraint of each variable to obtain the intended goal. The optimization method used is based on iterative loops. This means repeating the solution process with updated values based on previous iterations until the termination criteria are met. In this work, the termination criteria are reaching the minimum BER or exceeding the maximum number of iterations.

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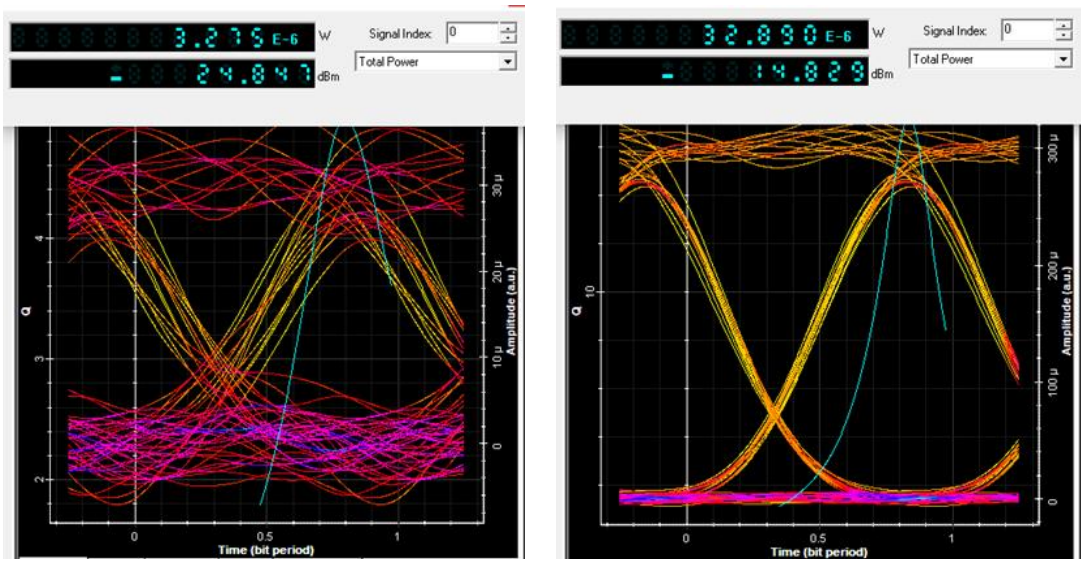
3.SIMULATION RESULTS

The data shown in this part of the article show how the suggested mechanism's performance has been improved thanks to optimization. The Optisystem emulator is used for collecting the findings. Fig. 2 shows the eye diagram of one of those 32 WDM channels before and after optimization where data rate is 40 Gbps, the input power is fixed to -10 dBm for all channels. Optimized parameters include the transmission bandwidth of the demultiplexer, the cutoff rate for the low-pass Bessel filter, the amplifier gain of the APD, and the EDFA's value of gain. Greater efficiency was achieved as a result of these optimizations, as seen in Fig. 2.b notably compared to Fig. 2.a, whereby the minimum BER is 8.01 x 10^{-67}. However, it is lower in the situation of no optimized system (3.04 x10^{-7}). More openness in the eye, illustrations in Fig. 4, indicates reduced Inter-Symbol Interference (ISI) and resilience towards noise. It also signifies that the optimum scenario's obtained power (32.89 versus 2.28 µW) is higher. All optimized parameters will be considered in the following results.

Fig. 3 shows the relationship between varying input power and the 40 Gbps times 32 WDM channels system's minimal log of BER. Three scenarios were considered for the channel in Figures 3 and 4; SMF-EDFA-FBG, SMF-DCF-EDFA, and SMF-EDFA-DCF-EDFA respectively. The distance is fixed for all scenarios at 50 km. In the first two scenarios, the performance is close to the changing of input power. While the case of SMF-EDFA-DCF-EDFA, the system has provided better performance compared to the other scenarios due to using two EDFAs. However, the BER has no change after -4 dBm where the output power of multiplexing 32 channels is enormous. Indeed, adding more power affects the signal by optical fiber nonlinear effects. The relationship between the total distance of the optical link and BER for those three different scenarios is shown in Fig. 4. The third scenario has gained relatively better performance with the distance under optimization of EDFA's gain with each different optical fiber range. This proposed system has successfully reached a long distance with a data rate of 1.28 Tbps and can be a candidate for the communication system backbone.



a. before optimization　　　b. after optimization

Figure 2. The eye diagrams and the received power of same channel before and after optimization.

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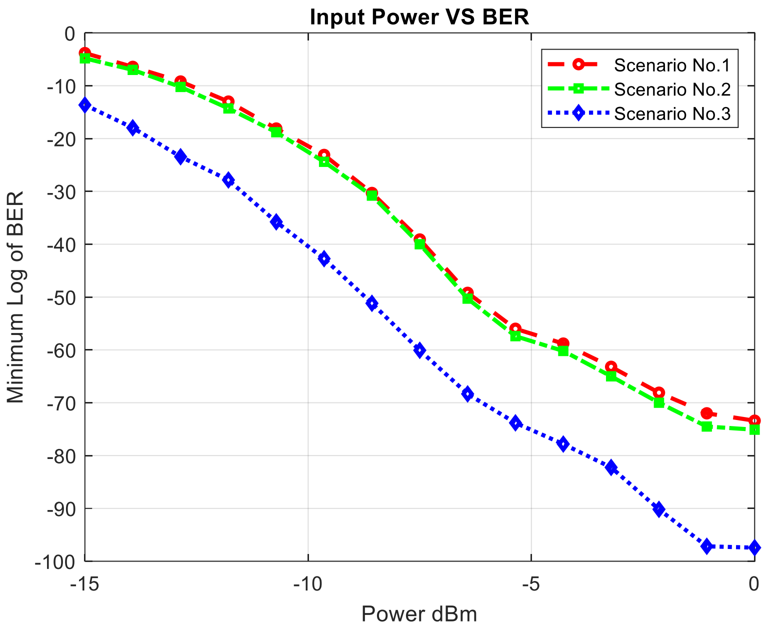

Figure 3. The relationship between the power of CW laser and BER considering three different scenarios for the optical link; SMF-EDFA-FBG, SMF-DCF-EDFA, and SMF-EDFA-DCF-EDFA respectively.

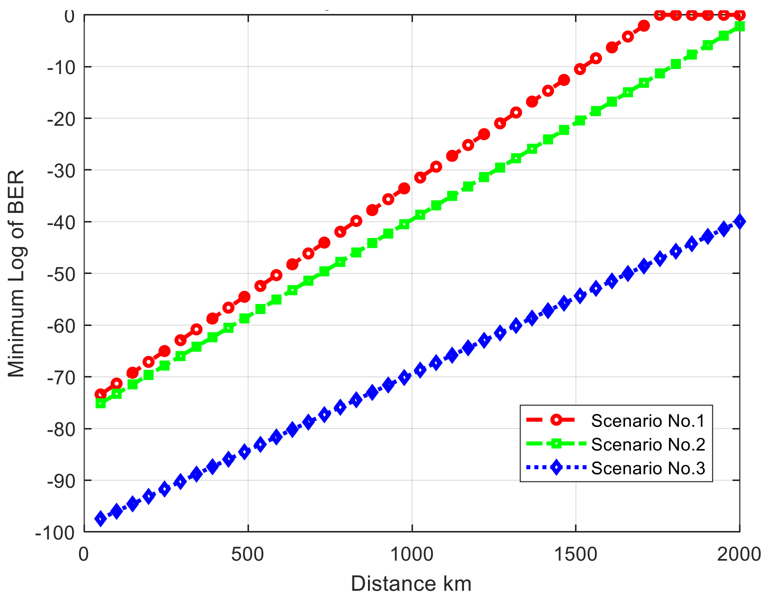

Figure 4. The relationship between the total distance of the optical link and BER considering three different scenarios for the channel; SMF-EDFA-FBG, SMF-DCF-EDFA, and SMF-EDFA-DCF-EDFA respectively.

Table 2 presents a comparison of the simulation results between this work and the recent related studies in terms of the maximum data rate, transmission distance, and number of WDM channels. This comparison shows that the system proposed in this research outperforms previous studies in terms of transmission distance while maintaining a high data rate transmission and acceptable complexity compared to studies that relied on 64 DWDM channels.

TABLE 2. RESULTS COMPARISON

The reference	Publish year	The Method used	Max. data rate	Max. transmission distance	Number of WDM channels
[12]	2023	DCF and EDFA	2.5 Tbps	160 km	64
[13]	2022	Forward Error Correction (FEC)	0.64 Tbps	100 km	16
[16]	2023	DCF and EDFA	80 Gbps	100 km	8
[17]	2022	Optical Amplifier	320 Gbps	500 km	8 & 16
[18]	2021	DCF and EDFA	1.28 Tbps	1000 km	32
This work	-	Optimized DCF and EDFA	1.28 Tbps	2000 km	32

4.CONCLUSIONS

To overcome the bottleneck problem occurring in the backbone of current and future communication systems, a 32-channel DWDM system with a data rate of 1.28 Tbps was proposed in this paper. An optimization algorithm is used to improve the efficiency of the system and increase SNR which is crucial for increasing the data rate and distance of the link between the transmitter and receiver. To compensate for the effects of dispersion and attenuation, three scenarios are used, namely SMF-EDFA-FBG, SMF-DCF-EDFA, and SMF-EDFA1-DCF-EDFA2, to obtain efficient long-distance communication. To ensure a fair comparison, the total optical fiber length is 50 km for all scenarios and farther distances are achieved by repeating these sequences. Optimizing multi-parameters including power, gain, and bandwidth of the entire system (transmitter, channel and receiver) has provided a significant improvement in the performance, where a minimum BER of 8.01 x 10^{-67} fulfilled higher performance in comparison to the minimum BER before the optimization 3.04 x10^{-7}. Regarding compensation for dispersion and attenuation, the scenario of SMF-EDFA1-DCF-EDFA2 gained high distances than SMF-EDFA-FBG and SMF-DCF-EDFA scenarios. In conclusion optimized proposed scheme, that can reach long distances with a data rate of 1.28 Tbps utilizing channel configuration of SMF-EDFA1-DCF-EDFA2, making it a promising candidate for high-speed backbone optical fiber link. Based on the results obtained, and by depicting the various options for actual improvement using the simulation program (OptiSystem), the research paves the way for promising work through the implementation of the proposed system in the real world in the future.

5.CONFLICTS OF INTEREST

"The authors affirm that they have no financial or other conflicts of interest to disclose about the current work".

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