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Quality Signal Degradation in Single-Channel Fiber Using 10 Gbps Bit Rate

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Abstract— **Reliable data transmission capacity is a crucial factor in supporting high-data-rate communication for smart cities by implementing the Internet of Things. Optical fiber has become the most favorable transmission media by taking advantage of optical signals. However, when optical signals propagate through optical fibers, disturbances occur as the transmission distance increases. These disturbances affect the system performance indicated by the deteriorating transmission data quality in terms of the quality factor (Q-factor) and bit error rate. These parameters are vulnerable to certain factors that can alter signal transmissions such as fiber attenuation, group velocity dispersion (GVD), and self-phase modulation (SPM) as a nonlinear effect. In this study, the effects of these factors on a single-channel, single-mode fiber are investigated using a bit rate of 10 Gbps at various transmission distances and source power levels. The parametric study of attenuation, GVD, and SPM with non-return-to-zero (NRZ) modulation format are considered at various transmission distances, from 10 to 100 km, and input powers of 5 and 10 dBm are simulated using OptiSystem to characterize the parameters of Q-factor and received power. The results indicate that the performance of the system deteriorates as the transmission distance increases, and the dominant effect that impacts the performance is GVD. This result is useful for designing effective and precise fiber optic transmission for high-data-rate transmission.**

Keywords— **Optic; fiber; transmission; quality; dispersion.**

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I. INTRODUCTION

Cities around the world have been transforming from traditional to smart cities. If a city considers becoming a smart city, it integrates information and communication technology (ICT) to manage the entire city more effectively and efficiently [1]. Public service, including surveillance systems for crime prevention, smart traffic control to tackle congestion, and smart buildings to support sustainable living, is a concept supported by a smart city's idea. In Indonesia, almost 100 cities are currently developing into smart cities, including Jakarta, the largest city in the country [2]. Jakarta initiated the smart city concept by launching the Jakarta Smart City (JSC) program in 2014. JSC's concept is to improve the quality of public services based on six aspects: smart governance, smart people, smart living, smart mobility, smart economy, and smart environment [3], [4].

One of the potential technologies that can facilitate the improvement of public services for the development of smart cities is the Internet of Things (IoT). IoT can monitor and manage environmental conditions and infrastructure across communities. It encompasses integrated sensors, network architecture, and human interface applications [5]. IoT devices generate volumes of data that are processed and transmitted in real-time via the Internet. Data transmission is a part of the communication between IoT devices. Interconnected technologies with high-speed, low-latency and ultra-reliable networks are crucial for ensuring real-time communication of data between IoT devices [6]. The upcoming 5G cellular mobile communications will support these technology demands.

5G network technology can significantly increase wireless data-transfer speeds and operate more reliably and stably than current LTE networks [7]. However, the successful implementation of IoT in cities depends not only on 5G network technology but also on the deployment of an adequate backhaul network [8]. Most 5G network deployments will use optical fiber as their backhaul network. Developing a fiber optic network is one of the means for transporting large amounts of data very quickly and reliably. In the form of a backhaul network, the optical fiber plays a crucial role in improving the quality of life in cities, facilitating their conversion into smart cities by supporting the IoT.

Optical fibers provide more advantages than other transmission line media, such as high data rate, low attenuation, free from electromagnetic interferences, and low cost [9]. However, when optical signals propagate through the fiber, some disturbances occur as the transmission distance increases [10]. These disturbances affect the performance of the system, leading to irretrievable data transmission quality in terms of the quality factor (Q-factor) and the bit error rate (BER) [11]. These parameters are vulnerable to certain factors that can alter signal transmission, such as fiber attenuation, group velocity dispersion (GVD), and nonlinear effects [10], [12]. Further, the transmission performance of a communication link, particularly data speed, also depends on the pulse width [13]. Most optical fiber systems use the on-off keying (OOK) modulation scheme, and the standard signal formats are non-return-to-zero (NRZ) and return-to-zero (RZ). Owing to the shorter pulse width, the RZ format may suffer more from dispersion. On the other hand, the NRZ format is more resilient toward dispersion but suffers to a larger extent from nonlinearities [14].

In this study, the effects of the abovementioned factors are investigated in single-channel, single-mode fibers at various transmission distances and input powers. The variables considered are attenuation, GVD, and self-phase modulation (SPM) at bit rates of 10 Gbps using the NRZ modulation format. This format is typically used in most high-speed communication systems, with speeds ranging from 155 Mbps to 10 Gbps. A modulation format that is more resilient to dispersion is required to increase the transmission distance because the fiber used in this system has a high dispersion value, which limits the transmission distance. Further, because of the simplicity of the NRZ modulation format, upgrading the bit rate to higher than 10 Gbps is limited by polarisation-mode dispersion (PMD) [15], [16], which was not observed in this study. For comparison and analysis of signal degradation, various transmission distances from 10 to 100 km and two input powers of 5 and 10 dBm were considered. The performance parameters considered were the Q-factor and received power parameters obtained from an optical system simulation software, OptiSystem.

II. MATERIALS AND METHODS

The nonlinear Schrödinger equation (NLSE) describes the effect of pulse propagation in single-mode optical fiber, as displayed in Equation (1) [17]. Here, the first term represents the slowly varying amplitude of the pulse envelope along the *z*-axis, the second term represents the effect of fiber attenuation α, the third term represents the effect of group velocity dispersion β_2 concerning time *T*, and the fourth term is responsible for the nonlinear effect γ, which represents the effect of SPM. The equation comprises factors that can alter signal transmission, i.e., fiber attenuation, GVD, and SPM.

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \frac{i}{2}\frac{\beta_2 \partial^2 A}{\partial T^2} + i\gamma|A|^2 A = 0 \quad (1)$$

A. Attenuation

Fiber attenuation is defined as the ratio between an optical source's output and input powers emitting signals through an optical fiber at a certain length, usually observed every 1 km. Attenuation limits the maximum transmission distance because the pulse power through the fiber is attenuated or decreased [10], [16]. It is caused by material, structural, and modular imperfections in the fiber. Amplifiers, such as erbium-doped fiber amplifiers (EDFA), are additional components that compensate for fiber loss because of attenuation [18], [19]. This component plays an essential role in increasing the power of the signal.

Furthermore, the increase in input power can increase the achievable transmission distance. Equation 2 represents a basic calculation for the total loss between the transmitter and receiver [16]. The two variables α_f and *L* associated with the optical fiber are the fiber attenuation (dB/km) and the transmission distance. Insertion loss includes connector loss, splice loss, and loss from additional components such as from the modulator:

$$P_T = \alpha_f L + insertion\ loss \quad (2)$$

B. Group Velocity Dispersion

Group velocity dispersion arises because the fiber refractive index has a wavelength-dependent characteristic. Each spectral component has a different velocity; thus, it takes a different amount of time to propagate through the fiber. Therefore, there is a group delay τ_g that leads to pulses as well as intersymbol interference (ISI), which limits the bit rate and transmission distance [12], [16]. As displayed in Equation (3), the group delay τ_g depends on the distance *L* travelled by the pulse. The factor β_2 represents the GVD parameter or chromatic dispersion, which is related to the dispersion *D*. Further, the GVD determines how much a light pulse broadens in time as it travels along with an optical fiber [20]. Therefore, it is necessary to provide a dispersion compensation technique, such as a dispersion compensation fiber, fiber Bragg grating, optical phase conjugation, or electrical compensation methods [21], to remove the dispersion in the system:

$$D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 \quad (3)$$

C. Self-Phase Modulation

Fiber nonlinearities are another factor associated with the fiber refractive index depending on the input signal intensity. The most dominant fiber nonlinear effect in a single-channel fiber is SPM [10], which refers to a phase shift in pulses with the time that causes changes in frequency, also known as the chirping phenomenon. The chirping phenomenon from SPM leads to spectral broadening [22], which combines with the GVD and increases the pulse spreading, limiting the transmission rate [16], [23]. The interplay of GVD and SPM can lead to various results of pulse broadening in the anomalous and normal dispersion regimes [24].

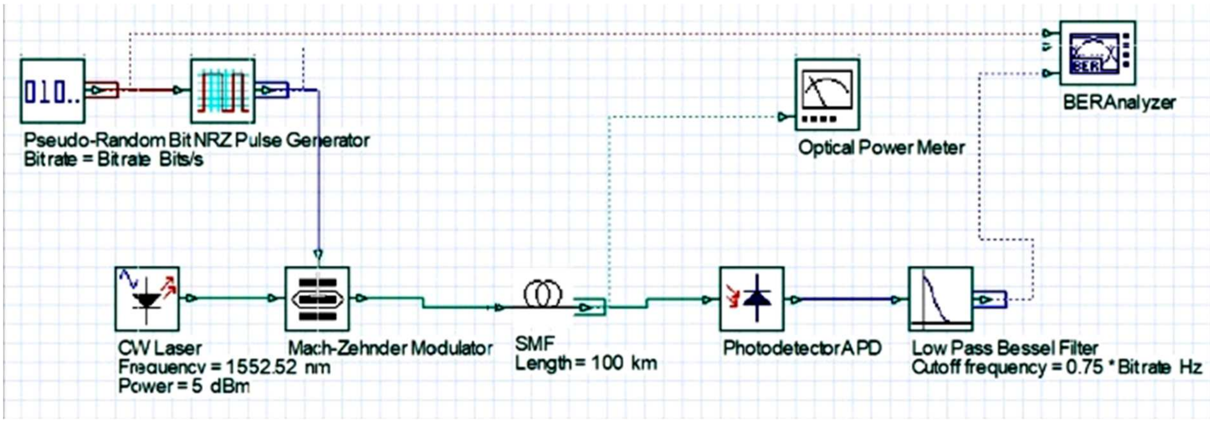


Fig. 1 Schematic of the optical fiber line system

In the anomalous dispersion regime, the combined effect can support solitons. In the normal dispersion regime, the combined effect can be used to modify the effect of pulse spreading from GVD [25]. Moreover, the pulse profile and power can be selected such that they compensate for each other precisely [26].

D. Bit Error Rate, Q-factor, and Eye Diagram

In digital communication, the BER is a common parameter used to represent the quality of the network. It represents the ratio between the bits of an error to the bits sent throughout. The BER value predicts the number of errors that occur in the receiver. The maximum BER value for an optical fiber system usually lies in the range 10^{-9} to 10^{-12} [16]. It means an allowance of not more than 1-bit error in 10^{-9} bits sent. Equation 4 expresses the relationship between the Q-factor and BER. The better the Q-factor value, the smaller the BER:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \quad (4)$$

The eye diagram is another method that can represent the signal quality and is also useful in analyzing it. It can diagnose problems such as attenuation, noise, jitter, and dispersion that appear in the system. The eye-opening indicates that the received signal was obtained without error from ISI because of the dispersion effect. The eye height is a measure of the vertical opening of an eye diagram, and it determines the noise that occurs during the signal propagation and causes the eye to close.

E. Setup of Simulation

The simulation setup used in this study is depicted in Figure 1. The optical fiber line system's schematic consists of three sections—a transmitter, optical fiber, and receiver. The optical transmitter's role is to modulate the output from the optical source using an electrical signal and produce an optical signal that is launched into the optical fiber. Before the optical signal reaches the optical receiver, an optical power meter is used to measure the optical power output by placing the meter right at the optical fiber's end and before the photodetector. When optical signals arrive at the optical receiver, it converts the optical fiber's distorted signals into electrical signals. The result is measured using a BER analyzer to study the performance of the entire system. In this study, we assess the system performance based on the BER analyzer's Q-factor parameter. To achieve an optimal communication system, the Q-factor's maximum value is 6 or equivalent with a BER of 10^{-9} [16], [27].

Table I lists the specifications of the transmitter components used in the transmitter section considered in this study. Pseudorandom bit sequences (PRBS) generate binary signals to the NRZ generator and an electrical signal at the bit rate of 10 Gbps. The optical source used is a continuous optical wave (CW) laser due to a single-mode fiber that requires a narrow spectral width and higher output. Further, it can provide high bandwidth for long-distance transmission [28]. In this study, we assume that the CW laser's launch powers are 5 and 10 dBm. A Mach–Zehnder modulator (MZM) is used to connect the optical signal generated from the CW laser and the electrical signal generated from the NRZ generator. The MZM produces an external modulation. It provides the advantages of high speed, high extinction, and low insertion loss [29]. External modulation is necessary to minimize the undesirable nonlinear effects in a high-bit-rate system (>2.5 Gbps) [16]. The nonlinear effect, such as SPM, is impacted by the chirping effect. When using direct modulation, the wavelength of a laser can shift due to the laser's instability and lead to chirping. The MZM combines and modulates the optical signal from the CW laser and the electrical signal from the NRZ generator. The MZM's output signal can minimize the wavelength shift and reduce the chirping effect [12]. As chirping impacts nonlinear effects such as SPM, this modulation technique can reduce the system's nonlinear effects. The MZM modulated optical signals are launched into an optical fiber using C-band frequency at 1555.52 nm. This frequency has a low loss value, which can be below 0.2 dB/km, and fiber amplifiers work efficiently at approximately this frequency [12].

TABLE I
SPECIFICATIONS OF TRANSMITTER COMPONENTS

Specifications	Value
Bit rate	10 Gbps
Modulation format	NRZ
Frequency	193.1 THz (C-band)
Optical CW launch power	5 and 10 dBm
Optical modulator	Mach–Zehnder modulator
Photodetector	APD

The optical section considers a single-mode fiber as the transmission medium. The single-mode fiber provides minimum pulse broadening and is capable of the highest transmission bandwidths, which currently lie in the gigahertz range [28]. Table II presents the simulated fiber specifications considered Corning SMF-28 Ultra Optical Fiber following ITU-T-REC-G.652-201611 standard working at 1550 nm [30], [31]. The single-mode fiber length varies within the range 10–100 km at intervals of 10 km. The attenuation and dispersion are 0.17 dB/km and 16.5 ps/nm/km, respectively—an optical power meter connected to the fiber before the photodetector measures the optical power output.

TABLE II
SPECIFICATIONS OF RECEIVER COMPONENTS

Specifications	Value
Length (*L*)	10, 20, 30, 40, 50, 60, 70, 80, 90,100 km
Attenuation (α_f)	0.17 dB/km
Dispersion (*D*)	16.5 ps/nm/km

Table III presents the specifications of the components of the receiver section used in this system. In this study, an ideal avalanched photodetector (APD) is used because it has higher sensitivity than PIN detectors to detect and convert optical signals into electrical signals. Higher sensitivity implies less power needed for a photodetector to detect optical signals so that the optical signal can travel longer along with the optical fiber; thus, the transmission distance is increased. Further, it provides high bandwidth and low noise [32]. The electrical signal outputs from the APD flow into a low-pass Bessel filter, which plays a crucial role in filtering the noise and minimizing the ISI [12]. The BER analyzer, connected directly to a low-pass Bessel filter, measures the filtered electrical signal, and generates data representing the performance of parameters such as the eye diagram, BER, and Q-factor. In this study, the parameters considered are the Q-factor and power received at the receiver section to analyze the dominant effect that impacts signal degradation.

TABLE III
SPECIFICATIONS OF RECEIVER COMPONENTS

Specifications	Value
Photodetector	APD
Photodetector responsivity	1 A/W
Electrical filter	Low-pass Bessel filter
Frequency cutoff	0.75 × bit rate

III. RESULTS AND DISCUSSION

This section describes the effects of attenuation, GVD, and SPM at a bit rate of 10 Gbps with the NRZ modulation format at transmission distances of 10–100 km at intervals of 10 km and input powers of 5 and 10 dBm.

A. Attenuation Effect

Figure 2 presents the effect of attenuation on the Q-factor and received power as functions of distance. The attenuation effect represents a loss in decibels per kilometer of the fiber. When the optical signals propagate in the fiber, loss in the fiber increases because of the attenuation effect corresponding to the transmission distance. Thus, the attenuation effect degrades the received power gradually due to the transmission distance [17]. The Q-factor is a parameter that determines the system performance and is related to the minimum power requirement of the receiver [12]. Therefore, when the received power decreases as the transmission distance increases, it reduces the value of the Q-factor. Therefore, a higher value of the Q-factor can be achieved by increasing the input power to meet the minimum requirement of received power [33]. As a comparison, it should be noted that the Q-factor at 100 km using an input power of 5 dBm is 57.37, whereas the value increases to 117.012 when the input power is 10 dBm. Thus, it is clear that the Q-factor is far above the standard value of Q > 6 [16], [27]. Based on the Q-factor, this result indicates that the attenuation effect does not seem to be the dominant factor affecting signal quality degradation.

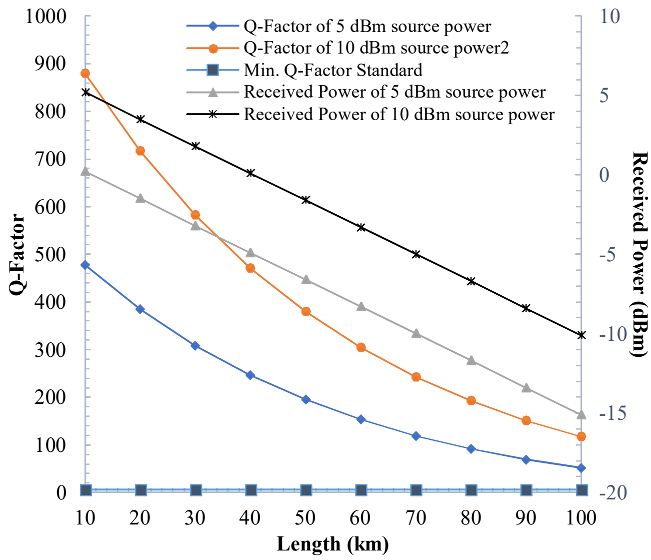


Fig. 2 Effect of attenuation on Q-factor and received power

B. GVD Effect

Figure 3 presents the impact of GVD on the Q-factor and received power. When optical signals propagate, its spectral components take different amounts of time to travel within the fiber. Thus, increasing the transmission distance increases the time required by the signals to travel along with the fiber. Therefore, the spectral components broaden, overlap strongly, and are indistinguishable, affecting the Q-factor [16]. Thus, the GVD effect degrades the Q-factor gradually owing to increased transmission distance. However, it does not degrade received power because the pulse shape and spectrum are normalized concerning the input signal [34]. Therefore, increasing the transmission distance does not affect the pulse power. Figure 3 indicates that the obtained Q-factor decreases and reaches its minimum (Q > 6) at 70 km. However, after this distance, the Q-factor does not meet the minimum standard. The Q-factors for a length of 70 km at input powers of 5 and 10 dBm are 5.567 and 5.676, respectively. Furthermore, Figure 3 indicates that increasing the input power does not lead to a better Q-factor. Thus, these results indicate that the GVD dominantly effects signal quality degradation based on the Q-factor and limits the transmission distance.

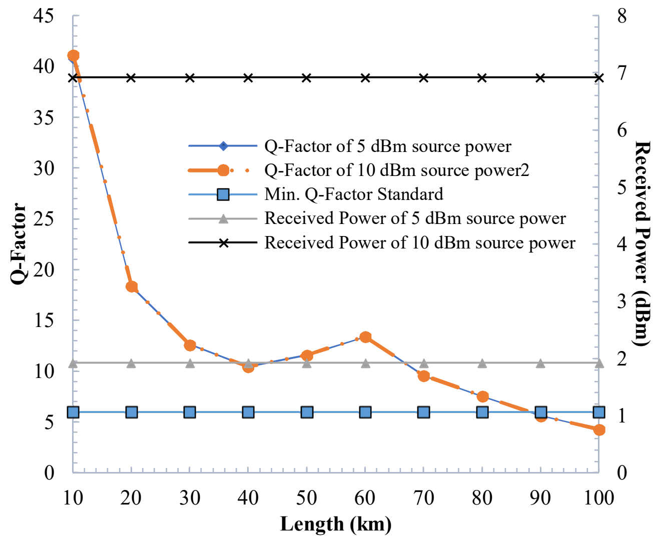


Fig. 3 Effect of GVD on Q-factor and received power

C. SPM and GVD Effect

Figure 4 presents the combined nonlinear effect of GVD and SPM on the Q-factor and received power. As described in the preceding section, increasing the input power does not affect the Q-factor. However, it can be seen in Figure 4 that the interplay of SPM and GVD has a different effect on the Q-factor value. This is so because the SPM depends on the input power value [17]. In consequence, a higher input power affects signal quality degradation owing to the SPM effect. As depicted in Figure 4, the Q-factors at a distance of 100 km at input powers of 5 and 10 dBm are 4.237 and 4.794, respectively. A comparison with Figure 3 indicates that the Q-factor is 3.297 and 3.312 at the same distance for 5 and 10 dBm input powers, respectively. This indicates that the SPM effect produces a better Q-factor than the GVD effect, as described in the preceding section. Figure 4 also indicates that the obtained Q-factor decreases and reaches the minimum Q-factor standard (Q > 6) at 80 km. These results illustrate that SPM and GVD compensate for each other's effects and increase the transmission distance further by 10 km when compared with the distance effected by GVD. Moreover, the results indicate that SPM and GVD dominantly affect signal quality degradation based on the Q-factor and limit the transmission distance.

D. Combined Effect of Attenuation, GVD, and SPM

In this section, we discuss the simulation results to examine how the combined effects of attenuation, GVD, and SPM degrade the signal quality. Figure 5 presents the impact of these combined effects with increasing transmission distance on the Q-factor and received power. The maximum quality value of the Q-factor occurs at a distance of 10 km, whereas the minimum quality value occurs at 100 km. This means that the Q-factor meets the minimum standard (Q > 6) at the range of distance 10–80 km. As displayed in Figure 5, the Q-factor obtained from the system at 80 km using an input power of 5 dBm is 6.032, and it increases to 7.299 at an input power of 10 dBm. Therefore, a higher Q-factor can be achieved by increasing the input power from 5 to 10 dBm. However, when the simulation enters a distance greater than 80 km, the system performance degrades to the worst quality. It does not meet the minimum standard of the Q-factor, which is not recommended for designing effective optical fiber transmission. Therefore, this scheme is effective for propagation only up to 80 km based on the Q-factor's minimum standard to maintain the quality of information.

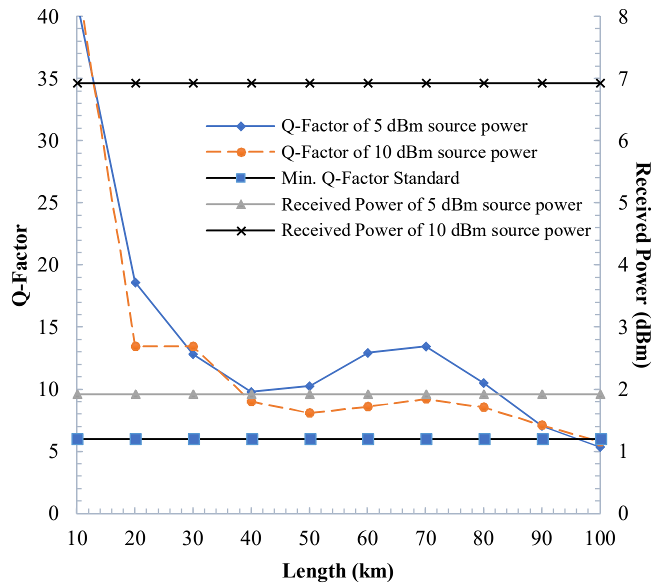


Fig. 4 Effect of GVD and SPM on Q-factor and received power

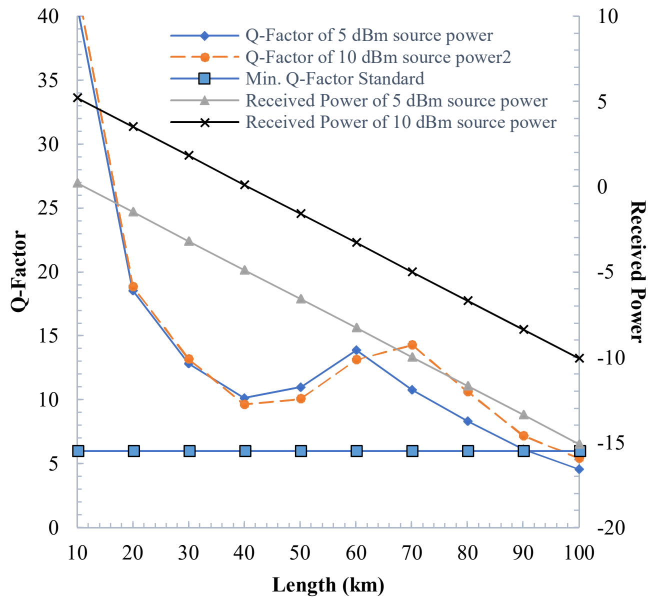


Fig. 5 Q-factor and received power for input powers of 5 and 10 dBm

The simulation results presented in Figure 5 indicate that the received power decreases with increasing transmission distance. The results presented in Figures 2–4 suggest that the most dominant effect that degrades the received power is the attenuation effect. As the transmission distance increases, the total power loss owing to attenuation (α_f) in the cable increases and gradually degrades the received power. However, based on Equation 2, the decrease in the received power is affected by loss from additional components. For comparison, Table IV presents various results of received power in simulation and calculation using 5 and 10 dBm input powers. In the calculation, we only consider the attenuation caused by increasing the transmission distance. The difference between the simulation and calculation is approximately 3 dB. This additional loss is caused using the MZM, which also contributes to decreasing the transmitted optical signals.

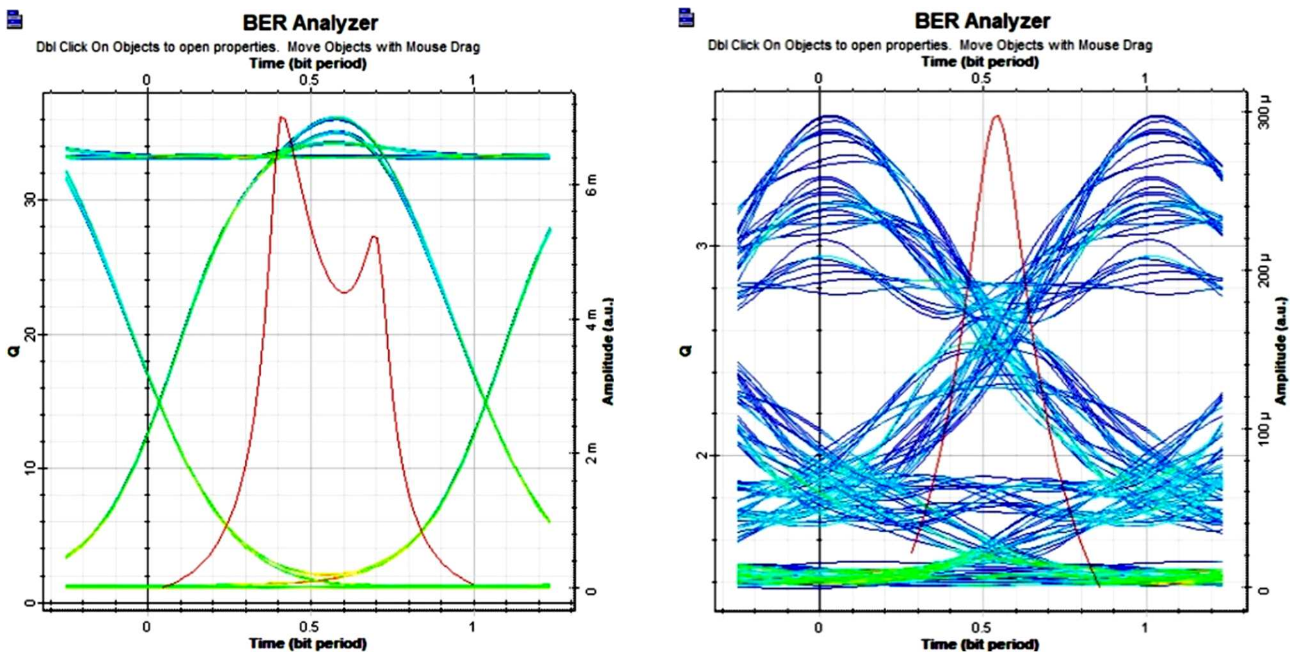
TABLE IV
COMPARISON OF SIMULATION AND CALCULATION OF RECEIVED POWER FOR INPUT POWER OF 5 AND 10 DBM

Distance (km)	Received power (dBm) for input power of 5 dBm		Received power (dBm) for input power of 10 dBm	
	Simulation	Calculation	Simulation	Calculation
10	0.152	3.3	5.082	8.3
20	-1.548	1.6	3.382	6.6
30	-3.248	-0.1	1.682	4.9
40	-4.948	-1.8	-0.018	3.2
50	-6.648	-3.5	-1.718	1.5
60	-8.348	-5.2	-3.418	-0.2
70	-10.048	-6.9	-5.118	-1.9
80	-11.748	-8.6	-6.818	-3.6
90	-13.448	-10.3	-8.518	-5.3
100	-15.148	-12	-10.218	-7

As presented in Figures 2-5, the simulation results indicate that the degradation in the received power is affected by attenuation. Meanwhile, the GVD effect is the most dominant effect that impacts signal degradation, and it is not affected by changes in the input power. Moreover, the existence of SPM as a nonlinear effect that interacts with the GVD effect produces a different result. The SPM effect depends on power; therefore, when GVD induces the SPM effect, changing the input power to a higher level will increase the Q-factor. As presented in Figures 2–5, this scheme can propagate up to 70 km to maintain the Q-factor's optimum value. Therefore, dispersion compensation schemes are necessary to compensate for the signal degradation effect, which is mostly caused by the GVD effect.

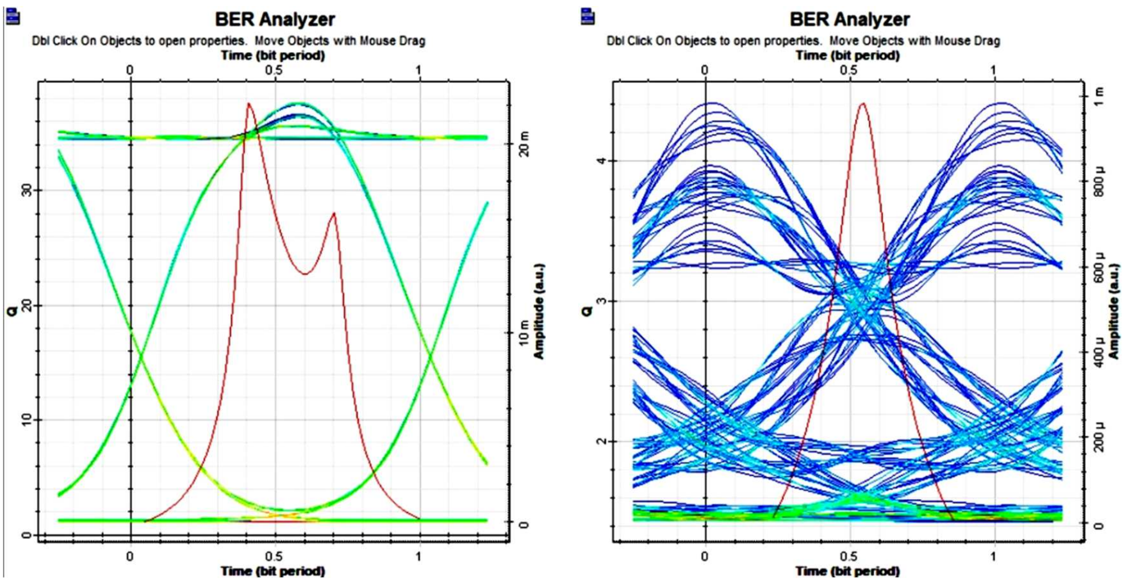
Figures 6 and 7 present eye diagrams used to evaluate the system's signal quality as displayed by the BER analyzer. Figures 6 (a) and 7 (b) present the eye-opening patterns, which are very clear because of minimum noise reflection. The minimum noise between the transition of "0" and "1" is represented by the green line. This condition reflects that the eye-opening pattern corresponds to minimum signal distortion during propagation up to 10 km. However, this pattern changes when the optical signal propagates up to a distance of 100 km, as depicted in Figures 6 (b) and 7 (b). Figures 6 (b) and 7 (b) exhibit the closure of the eye pattern because of ISI and noise. The noise and ISI that occurs between the transition of "0" and "1" are represented by the blue lines, which are not as clear as the red lines in Figures 6 (a) and 7 (a).

Moreover, the overlapping of the blue line is caused by ISI owing to the dispersion effect. Therefore, changing the propagation distance increases the channel noise and produces ISI, as depicted in Figures 6 and 7. The eye diagram pattern presented in Figure 7 is like that in Figure 6. However, the Q-factors depicted in Figures 6 and 7 are slightly different. As a comparison, it should be noted that the values of the Q-factor depicted in Figures 6 (a) and 7 (a) are 36.15 and 37.617, respectively, as represented by the red lines. Further, the values of the Q-factor depicted in Figures 6 (b) and 7 (b) are 3.617 and 4.11, respectively, which are also represented by the red line. Thus, increasing the power input produces a higher value of the Q-factor.



(a) (b)

Fig. 6 Eye diagram of the signal at an input power of 5 dBm for (a) 10 and (b) 100 km



(a)

(b)

Fig. 7 Eye diagram of signal at input power of 10 dBm for (a) 10 and (b) 100 km

IV. CONCLUSION

This study investigated the effects of attenuation, GVD, and SPM on the propagation pulses in an optical transmission system by varying the transmission distance and input power. Based on the Q-factor, the most dominant effect that impacts signal degradation is GVD. However, the interplay of GVD and SPM produces a better value of the Q-factor. Further, attenuation is the most dominant effect leading to the degradation of received power as the transmission distance increases. Further techniques are necessary to compensate for the signal quality and degradation of received power to increase the transmission distance. These results are useful for designing effective and accurate optical fiber transmission for high-data-rate transmission.

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