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Data-Rate Dependence of Launch-Power Sensitivity and Transmission Reach in Optical Fiber Communication Systems

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Abstract

This work investigates the response of optical fiber communication systems to variations of the launch power for data rates between 2.5 and 40 Gb/s. A simulation model with OptiSystem is developed, where launch power and transmission distance are varied systematically for each data rate. The Q-factor and bit error rate (BER) are used to evaluate the maximum QoS-qualified transmission distance and the first-failing distance. The sensitivity to launch power was quantified by the relative change in Q-factor with launch power. The results indicate that the maximum transmission reach is decreasing from 103 km at 2.5 Gb/s to 4 km at 40 Gb/s. In contrast, the relative Q-factor variation decreases from 89.94% to 2.69%, which means that the sensitivity of the transmission quality to the launch-power variation decreases significantly with the increase of the data rate. The study finds different sensitivity regions and shows the correlation between data rate, transmission reach and launch-power sensitivity. These results provide practical guidelines for launch-power adjustment in multi-rate optical networks, particularly showing that power tuning is most effective in the 2.5–10 Gb/s range.

Keywords

Optical fiber communication; launch power; data rate; relative Q-factor variations; maximum transmission distance.

1. Introduction

Continuous advances in optical transmitters, receivers, amplifiers, and signal-processing technologies have further increased the capacity of fiber-optic systems, enabling the transmission of increasingly high data rates over extended distances. Consequently, maintaining reliable transmission performance as the data rate increases remains an important consideration in the design and optimization of optical communication links [1, 2]. Despite the high capacity of optical fiber, transmission performance is constrained by several physical impairments that become increasingly important as the transmission rate and distance increase. Fiber attenuation reduces the received optical power with distance, while chromatic dispersion broadens optical pulses and can cause intersymbol interference (ISI), thereby degrading the quality of the detected signal [3]. Polarization-mode dispersion can further restrict the achievable bit-rate-distance product. These effects are particularly important in high-speed systems, where the shorter duration of transmitted symbols provides less tolerance to temporal pulse broadening [4]. Launch power is a parameter that can be controlled at the transmitter and is important for determining the quality and reach of an optical communication link. The launched optical power must be sufficiently high to maintain an adequate received signal level. However, increasing the power does not necessarily lead to continuous performance improvement, since excessive optical power can introduce power-dependent signal degradation [3, 5, 6]. Therefore, an appropriate launch-power operating point is generally required to balance the benefits of increased received power against power-related impairments. This raises an important question: to what extent does launch-power adjustment remain effective as the data rate increases?

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The optimization of launch power has been extensively studied as a key strategy for maximizing system performance. A study in [7] investigated the accuracy of nonlinear interference estimation in launch power optimization for short-reach systems. It is demonstrated that even the approximate Gaussian noise model provides sufficient accuracy for launch power optimization. The authors of [8] employed Pareto and particle swarm optimization algorithms to find the optimum launch power for minimum BER**.** It was observed that as data rate increases, the trade-off between launch power optimization benefits and computational complexity becomes more pronounced. It is confirmed that in [9] as data rate increases, transceiver design complexity increases, and the effectiveness of launch power optimization becomes more constrained. Petersen and Nielsen [6] experimentally demonstrated a method for optimizing launch power in single- and multispan optical transmission systems, using an in-band subcarrier to monitor fiber nonlinearities and correlate the monitor response with the bit error rate (BER) of a 10-Gb/s signal. Almeida et al. [10] developed a fast methodology for predicting optimum launch power in long-haul dispersion-managed links, predicting the correct launch parameters in few seconds through Q-factor evaluations. Adaptive optimization of transmitter parameters, including launch power and modulation format is investigated in [11]. It is demonstrated that launch-power adjustment can improve SNR and data throughput by accounting for nonlinear interference. The authors of [5] studied launch-power optimization together with transceiver noise in ultra-wideband transmission and showed that the gain obtained from launch-power optimization depends on the balance between nonlinear impairments and transceiver-noise limitations. In [12], the authors compared RZ and NRZ transmission for a 40-Gb/s fiber-optic system using standard single-mode fiber, showing that increasing launch power can enhance nonlinear effects and consequently degrade BER and maximum Q-factor. Moreover, the study in [13] investigated nonlinear impairments at different bit rates in single-channel dispersion-managed systems and demonstrating that nonlinear transmission behavior varies with data rate.

Recent studies have further emphasized the interaction between launch power, data rate, and transmission performance. For example, in [14] the authors evaluate BER, Q-factor, and maximum transmission reach under different bit rates and launch powers for coherent WDM systems. Their results showed that the optimum launch power varies with system configuration and that increase in transmission rate can reduce the achievable distance because of nonlinear effect. Mohammed and Hadi [15] analyzed the effect of different launch-power levels and transmission distances on BER. The study considered 60 Gb/s per wavelength and reported degradation beyond suitable power and distance conditions due to nonlinear effects. Finally, the study conducted in [16] experimentally demonstrated 112.5-Gb/s transmission over 50 km of standard single-mode fiber using high launch power. Although the study focuses on a much higher data rate and a different PON architecture, it provides recent experimental evidence that high-speed transmission requires careful management of launch power, nonlinear distortion, and transmission reach.

The recent studies have also highlighted the increasingly complex interaction among launch power, transmission impairments, system architecture, and achievable performance in modern optical links [17-22]. These works include experimental and numerical investigations of nonlinear transmission behavior, advanced high-capacity optical systems, and performance optimization under different physical-layer constraints. Collectively, they demonstrate that optical-power effects cannot be considered independently of the transmission regime, since the relative contributions of noise, dispersion, nonlinear propagation, modulation/detection configuration, and other system limitations vary with operating conditions [17-22]. These recent developments provide important context for the present study. However, they primarily address specific advanced architectures, transmission conditions, or optimization problems rather than a systematic comparison of the magnitude of launch-power-induced Q-factor variation across several data rates using the same transmission configuration and QoS criterion. The present work addresses this complementary question for an NRZ-OOK/PIN system by evaluating launch-power responsiveness at the data-rate-specific transmission boundary.

Although previous studies have established the importance of launch-power selection and have investigated its effects under specific transmission conditions, a systematic characterization of how the Q-factor response to launch-power variation changes with data rate under a common QoS-based framework remains limited. This issue is important because the practical benefit of launch-power adjustment may not remain the same as the data rate increases and rate-dependent transmission impairments become more significant. Therefore, a clearer understanding of the relationship among data rate, launch-power response, and transmission reach is needed to determine the operating regions in which launch-power adjustment can provide meaningful performance improvement.

Motivated by this gap, the main goal of this study is to systematically characterize the dependence of launch-power response and QoS-qualified transmission reach on

data rate in an NRZ-OOK optical fiber communication system. Specifically, the study aims to: (i) determine the maximum QoS-qualified transmission distance and first-failing distance for data rates from 2.5 to 40 Gb/s using Q-factor and BER criteria; (ii) evaluate the Q-factor and corresponding BER response to launch-power variation from −5 to +10 dBm at the transmission boundary; (iii) quantify the relative Q-factor variation as a normalized comparative index for assessing launch-power response across different data rates; and (iv) identify the data-rate regions in which the response to launch-power adjustment is relatively high or low. Through this analysis, the study seeks to clarify how increasing data rate affects the usefulness of launch-power adjustment under the investigated system configuration and operating conditions.

The contribution of this work is therefore not the use of Q-factor or BER as individual performance metrics, which are well established, but the systematic application of a common QoS-based evaluation framework across a broad data-rate range and at the corresponding rate-specific transmission boundary. This framework enables a direct comparison of launch-power response, transmission reach, and data rate under consistent system conditions.

The rest of the paper is organized as follows. Section 2 presents the methodology of this work. The obtained results of simulation are presented and discussed indetails in the Section 3. Finally, section 4 concludes the paper by summarizing the main findings and implications of the study.

2. Methodology

2.1. System Module

The simulated optical communication system is built in OptiSystem as shown in Figure 1. The transmitter consists of a pseudo-random bit sequence generator, NRZ pulse generator, CW laser, and Mach-Zehnder modulator (MZM). The modulated optical signal is launched in one single-mode fiber and detected by a PIN photodetector. At the receiver, a Butterworth low pass filter is used before the signal is fed to the BER Analyzer. Optical power meters are provided on the transmitter and receiver sides for measuring the launched and received optical power. The system operates at 1550 nm wavelength. The fiber length (L) and the launch power (P_L) are considered variable parameters and they are varied systematically according to the simulation conditions described in the following section. In this study, launch-power refers to the optical output power setting of the CW laser. Because the MZM has negligible insertion loss under the adopted simulation settings, the CW laser output power and the actual optical power entering the fiber are effectively the same and their difference is almost negligible.

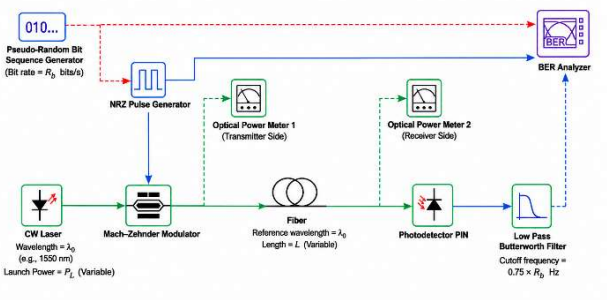


Figure 1: Design of simulated optical communication system implemented in OptiSystem.

Table 1 lists the primarily simulation parameters and operating conditions used in this study. The launch-power and transmission distance were taken as variable parameters, while the other system conditions were kept constant for the selected data rate values.

Table 1: Simulation parameters

Parameter	Setting / Condition
Simulation platform	OptiSystem
Modulation format	NRZ-OOK
Transmission wavelength	1550 nm
Data rates	2.5, 5, 10, 20, 30, and 40 Gb/s
CW laser output power	−5 to +10 dBm
Transmission distance	Variable according to data rate and QoS condition
Receiver	PIN photodetector
Receiver filter	Low-pass Butterworth filter
Filter cutoff frequency	0.75 × bit rate
Performance metrics	Q-factor and BER
Effective area	80 um^2
PMD coefficient	0.5 ps/sqrt(km)
Laser linewidth	10 MHz
MZM extinction ratio	40 dB
Receiver responsivity	1 A/W
Noise bandwidth	1 THz
Butterworth filter order	1
Sequence length	32 bits

Samples per bit	64
Number of samples	2048
Simulation window	Set Bit Rate
Fiber attenuation	Vary depending on the operating wavelength (from .dat file)
Chromatic-dispersion coefficient	Vary depending on the operating wavelength (from .dat file)

2.2. Performance Evaluation and Sensitivity Analysis

A transmission condition was considered QoS-qualified when both $Q \geq 6$ and $BER < 10^{-9}$ were satisfied. For the initial transmission-distance evaluation, a reference launch-power of 0 dBm was used for all investigated data rates. At this fixed reference power, the distance was progressively increased until the Q-factor fell below the adopted threshold.

The last distance satisfying was defined as the maximum QoS-qualified transmission distance, (L_{max}), while the next tested distance was defined as the first-failing distance, (L_{fail}).

To maintain a controlled comparison, all transmitter, fiber, and receiver parameters were kept unchanged across the investigated data rates unless otherwise stated. The primary objective of this study is to quantify the response of Q-factor and BER to launch-power variation under a common system configuration. Therefore, parameters such as receiver bandwidth, fiber dispersion characteristics, and nonlinear coefficients were not independently varied; as such analyses constitute separate parametric investigations beyond the scope of the present study. The transmission distance in the baseline search was increased in 1-km increments; consequently, the reported L_{max} and L_{fail} values have a distance resolution of 1 km.

The threshold of $Q \geq 6$ was selected as it corresponds to BER $< 10^{-9}$, which represents acceptable telecommunication transmission. These parameters, that are used by OptiSystem, can be mathematically represented as follows [23]:

$$Q = \frac{(\mu_1 - \mu_0)}{(\sigma_1 + \sigma_0)}, \quad (1)$$

where μ_1 and μ_0 denote the mean amplitudes of the received logical '1' and '0' levels, respectively, while σ_1 and σ_0 represent their corresponding standard deviations.

In this study, the Q-factor values reported in the results were obtained directly from the OptiSystem BER Analyzer. Eq. (1) is provided to define the conventional Q-factor based on the received eye statistics and was not used as a separate numerical calculation to generate the reported Q-factor results.

The Q-factor is used as the primary performance metric, and the corresponding BER is calculated from Eq. (2) as its equivalent error-probability representation. Thus, the QoS condition $Q \geq 6$ corresponds to BER $< 10^{-9}$ under the Gaussian approximation.

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

where $erfc(\cdot)$ denotes the complementary error function. This relationship demonstrates that increasing the Q-factor results in an exponential reduction in the bit error probability.

$$\text{QoS} - \text{qualified: } (Q \geq 6) \text{ and } BER < 10^{-9} \quad (3)$$

$$L_{max} = \max\{ L : \quad Q(L) \geq 6 , BER < 10^{-9} \} \quad (4)$$

$$L_{fail} = \min\{L : L > L_{max}\} \quad (5)$$

where:

- L_{max} is the maximum QoS-qualified transmission distance;
- L_{fail} denotes the first tested distance after L_{max} at which the QoS condition is no longer satisfied.

At (L_{fail}), the launch power was varied from −5 to +10 dBm, and the corresponding Q-factor and BER were recorded. The relative Q-factor variation was calculated as:

$$\Delta Q_{rel} = \frac{Q_{max} - Q_{min}}{Q_{max}} \times 100\%, \quad (6)$$

where Q_{max} and Q_{min} denote the maximum and minimum Q-factor values obtained over the investigated launch-power range.

In this study, ΔQ_{rel} is used as a normalized, range-based indicator of launch-power sensitivity. A larger ΔQ_{rel} indicates a stronger Q-factor response to launch-power variation, whereas a smaller value indicates weaker sensitivity. The normalization enables comparison among

data rates having different absolute Q-factor levels. It should be noted that ΔQ_{rel} represents the overall response across the investigated −5 to +10 dBm range and is not a local differential sensitivity coefficient. The resulting ΔQ_{rel} values were used to quantify and compare launch-power sensitivity across the investigated data rates, while the corresponding BER variations were used to confirm the associated error-performance trends. The performance evaluation procedure is summarized in the following flowchart. BER values reported by the OptiSystem BER analyzer are Gaussian-derived estimates from the Q-factor and are not obtained by direct error counting. The overall simulation procedure used to determine the maximum QoS-qualified transmission distance, first-failing distance, and launch-power sensitivity is summarized in Fig. 2

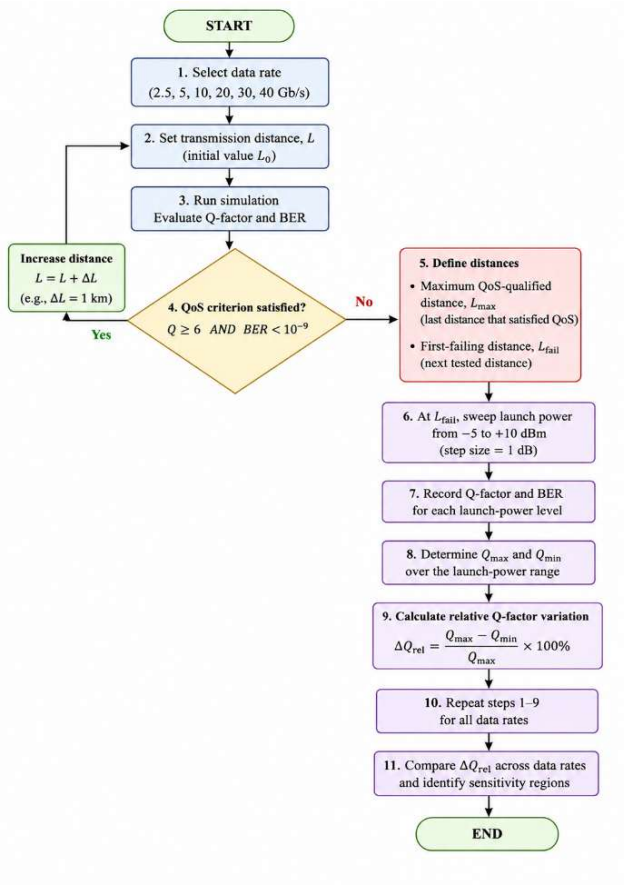


Figure 2: Flowchart of the simulation procedure used to determine the maximum QoS-qualified transmission distance, first-failing distance, and launch-power sensitivity.

3. Results and Discussion

3.1. Maximum Transmission Distance

The maximum transmission distance was first evaluated for each investigated data rate. Table 2 summarizes the maximum QoS-qualified distance, Q-factor, BER, and first-failing distance. The first-failing distance is one step beyond the maximum qualified distance and is subsequently used as the common operating boundary for evaluating launch-power sensitivity.

Table 2: Baseline maximum QoS reach and boundary distances for the investigated data rates at 0 dBm reference launch power.

Data rate (Gb/s)	Maximum transmission distance (L_{max})	Q at maximum distance	BER	First-failing distance (L_{fail})
2.5	103 km	6.06972	6.3×10^{-10}	104 km
5	94 km	6.25977	1.8×10^{-10}	95 km
10	72 km	6.05386	7.0×10^{-10}	73 km
20	18 km	7.02340	1.0×10^{-12}	19 km
30	8 km	7.04717	9.1×10^{-13}	9 km
40	4 km	7.82605	2.4×10^{-15}	5 km

Figure 3 illustrates the resulting dependence of transmission reach on data rate.

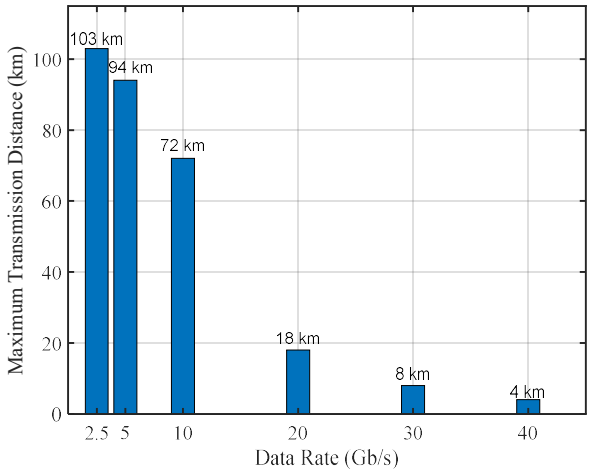


Figure 3: Maximum QoS-qualified transmission distance versus data rate at 0 dBm reference launch power.

Figure 3 illustrates that the data rate is increased and the transmission reach is clearly reduced. The maximum distance decreases from 103 km at 2.5 Gb/s to 94 and 72 km at 5 and 10 Gb/s, respectively, and then drops sharply to 18 km at 20 Gb/s. Increasing further to 30 and 40 Gb/s reduces the reach to only 8 and 4 km, respectively. In general, the maximum QoS qualified distance is reduced by approximately 96.1% from 2.5 to 40 Gb/s, and the most significant degradation occurs above 10 Gb/s. These boundary distances are then used in the subsequent.

The nonlinear reduction in the transmission reach with increasing data rate can be associated with the reduced temporal tolerance of higher-rate NRZ signals. As the bit period decreases, pulse broadening and receiver-bandwidth limitations occupy a larger fraction of the bit interval, increasing ISI and causing the QoS threshold to be reached over a shorter distance. This effect becomes particularly evident between 10 and 20 Gb/s, where the qualified reach-distance decreases from 72 to 18 km. The result therefore indicates that the reach-distance penalty is not simply proportional to data rate, but becomes substantially stronger once rate-dependent impairments dominate under the investigated system conditions analysis to investigate the effect of launch-power on the system performance.

3.2. Launch-Power Dependence at the Transmission Boundary

Transmission limits dependent on the data rate was set, and the influence of the launch-power on the first-failing distance (L_{fail}) was investigated for each data rate. This operating point was chosen since it is the boundary just beyond the maximum QoS-qualified reach and thus presents a sensitive condition for assessing the capability of launch-power adjustment to recover system performance. Figures 4 and 5 present the corresponding Q-factor and BER responses, respectively, over the investigated launch-power range.

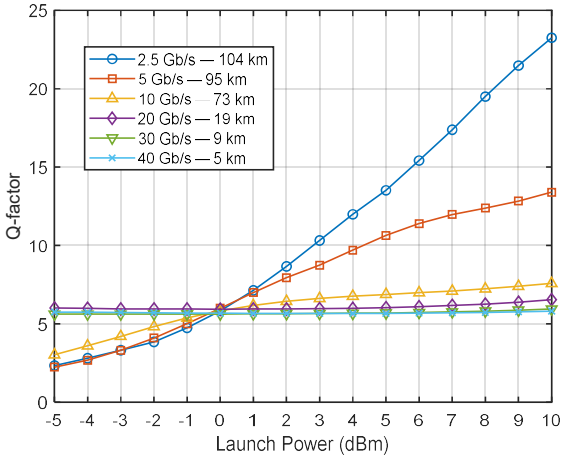


Figure 4: Q-factor variation with launch power at the first-failing distance for different data rates.

Figure 4 shows that the influence of launch power on Q-factor depends strongly on data rate. At 2.5 Gb/s, the Q-factor changes dramatically with launch-power, indicating a strong sensitivity to the available optical power. This sensitivity progressively decreases at 5 and 10 Gb/s, while the 20 Gb/s case represents an intermediate behavior. At 30 and 40 Gb/s, the Q-factor remains within a relatively narrow range despite the 15 dBm (-5 dBm to 10 dBm) launch-power variation, indicating that launch-power adjustment provides substantially less performance improvement at the higher data rates. These results demonstrate that the effectiveness of launch-power adjustment is strongly dependent on the data-rate operating regions.

The corresponding BER behavior is presented in Figure 5 to determine whether the launch-power-dependent Q-factor changes are also reflected in the bit-error performance. Since Q-factor and BER provide complementary measures of system quality, their combined behavior provides a more reliable assessment of the practical benefit of launch-power adjustment.

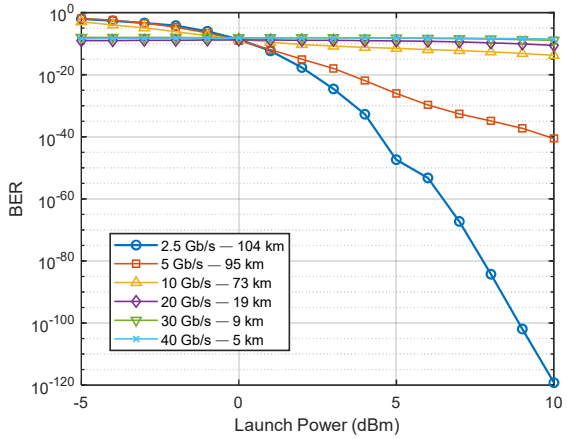


Figure 5: BER variation with launch power at the first-failing distance for different data rates.

Figure 5 confirms the Q-factor trends observed in Figure 4 through the corresponding BER response. At the lower data rates, changing the launch-power produces a pronounced change in BER, demonstrating that power adjustment can substantially affect the system error performance. The response becomes progressively less pronounced as the data rate increases, with the 30 and 40 Gb/s cases showing very limited improvement across the launch-power range. The 20 Gb/s case again appears as a transition condition, showing a stronger response than the higher-rate cases but considerably less sensitivity than the 2.5–10 Gb/s cases. Thus, the common trends observed in Figures 4 and 5 confirm that the reduction in launch-power sensitivity with increasing data rate is not limited to the Q-factor metric but also reflected in the BER performance.

A comparison of Figures 4 and 5 further shows that the Q-factor and BER responses are internally consistent. For the 2.5 and 5 Gb/s cases, increasing launch power produces a large improvement in Q-factor and a corresponding orders-of-magnitude reduction in BER. At 30 and 40 Gb/s, however, a 15 dBm launch-power change produces only a small Q-factor variation and consequently a comparatively limited BER response. This indicates that the high-rate boundary is not primarily controlled by insufficient optical power within the investigated range; instead, rate-dependent pulse distortion and bandwidth limitations restrict the benefit obtained by increasing launch power. The approximately flat high-rate responses should therefore be interpreted as reduced power responsiveness, rather than superior transmission performance.

3.3. Quantification and Regions of Launch-Power Sensitivity

The above results reveal that the impact of launch-power on the system performance is very different for different data rates. In an effort to express this behavior in a single comparable metric, the relative Q-factor (ΔQ_{rel}) variation was calculated over the investigated launch-power range of −5 dBm to 10 dBm.

This metric is used as a normalized comparative index rather than as a conventional differential sensitivity coefficient. Normalization by Q_{max} allows the relative magnitude of Q-factor variation to be compared across different data rates. Since the same launch-power interval of −5 to +10 dBm is applied to all data rates, the index provides a consistent basis for comparing the Q-factor response to launch-power variation at the corresponding first-failing distance. The value of this index is conditional on the investigated launch-power range and operating condition.

It is worth mentioned that that ΔQ_{rel} is evaluated at different distances because L_{fail} is rate-specific (Table 2). Since L_{fail} is the QoS boundary determined for each rate, not an independently varied distance, the comparison reflects the combined influence of data rate and the rate-specific impairment state at that boundary.

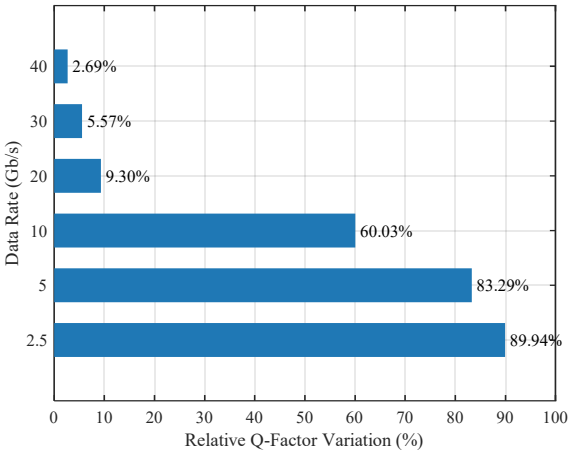


Figure 6: The variation of relative Q-factor with data rate for launch-power changes from −5 to 10 dBm.

Figure 6 quantitatively verifies the strong reduction of the launch-power sensitivity with increasing data rate. The relative Q-factor variation decreases from 89.94% at 2.5 Gb/s to 83.29% at 5 Gb/s and 60.03% at 10 Gb/s, indicating that launch-power adjustment has a substantial influence on Q-factor performance in the low-data-rate range. A pronounced reduction occurs at 20 Gb/s, where the variation falls to 9.30%, followed by only 5.57% and 2.69% at 30 and 40 Gb/s, respectively. Thus, increasing the data rate from 2.5 to 40 Gb/s reduces the relative Q-factor variation by approximately 97%, demonstrating that the effectiveness of launch-power optimization becomes progressively limited at higher data rates.

The decrease in ΔQ_{rel} with increasing data rate should not be interpreted as improved transmission performance at higher data rates. Rather, it indicates that, at the corresponding first-failing distance, the Q-factor becomes less responsive to launch-power adjustment. This distinction is important because the transmission reach simultaneously decreases with increasing data rate, as shown in Figure 3.

The observed reduction in launch-power sensitivity with increasing data rate can be interpreted in terms of the changing relative influence of system impairments. At the lower data rates investigated in this study (2.5–10 Gb/s), changes in launch-power produce relatively pronounced variations in the measured Q-factor and BER. At the higher data rates (20–40 Gb/s), the transmitted optical pulses are more susceptible to dispersion and bandwidth-related limitations, which may reduce the additional performance improvement obtained through launch-power adjustment. However, the present simulations evaluate the combined system response and do not separately quantify the contributions of chromatic dispersion, receiver bandwidth, nonlinear effects, and noise. Therefore, this physical explanation should be regarded as an interpretation of the observed trend rather than as a separately validated attribution of the individual impairment contributions. The observed sensitivity dependence is specific to the system configuration and parameter range investigated.

The present observations are qualitatively consistent with the broader literature showing that the impact of optical power depends on its interaction with the dominant impairments of the particular transmission regime [14-22]. However, a direct numerical comparison of Q-factor or optimum-power values is not appropriate because these studies employ different link architectures, modulation and detection schemes, data rates, transmission distances, and impairment conditions. In the present NRZ-OOK/PIN configuration, the important observation is that the relative response to the same −5 to +10 dBm power sweep decreases with data rate, from ΔQ_{rel} = 89.94% at 2.5 Gb/s to 2.69% at 40 Gb/s. Thus, the present results complement earlier studies by quantifying how launch-power responsiveness changes with data rate under a common simulation framework.

The relative Q-factor variations obtained in Figure 6 reveal distinct changes in launch-power sensitivity across the investigated data-rate range. To visualize these differences more clearly, the data rates are classified according to the magnitude of their relative Q-factor variation under the same launch-power sweep. Figure 7 therefore provides a sensitivity map that distinguishes the high-, intermediate-, and low-sensitivity regions observed in the investigated operating range.

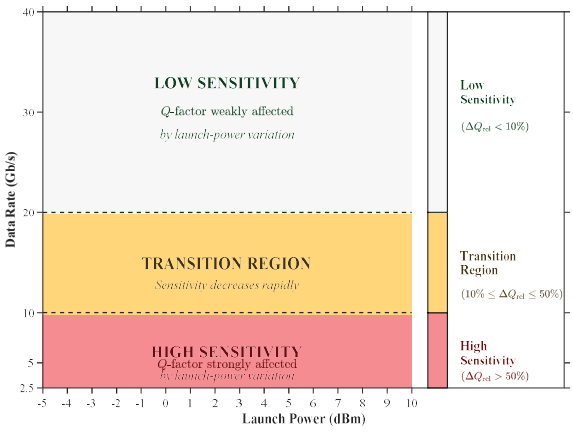


Figure 7: Launch-power sensitivity regions identified from the relative Q-factor variation across the investigated data-rate range.

As illustrated in Figure 7, for interpretation, the calculated responses are grouped into three operational sensitivity classes: high sensitivity ($\Delta Q_{rel} > 50\%$), intermediate sensitivity ($10\% \leq \Delta Q_{rel} \leq 50\%$), and low sensitivity ($\Delta Q_{rel} < 10\%$). These thresholds are used as descriptive classification criteria for the present dataset rather than universal physical boundaries. They provide a convenient means of visualizing the marked separation be-

tween the strongly power-responsive 2.5–10 Gb/s cases and the weakly responsive 20–40 Gb/s cases.

Figure 7 also shows a clear transition from a high-sensitivity region at lower data rates toward a low-sensitivity region at higher data rates. The 2.5, 5, and 10 Gb/s cases exhibit relative Q-factor variations of 89.94%, 83.29%, and 60.03%, respectively, and therefore fall within the high-sensitivity category according to the adopted classification. At 20 Gb/s, the relative variation decreases sharply to 9.30%, placing this operating point in the low-sensitivity category. The 30 and 40 Gb/s cases also remain within the low-sensitivity category, with relative variations of 5.57% and 2.69%, respectively. Therefore, the principal transition in launch-power sensitivity occurs between the 10 and 20 Gb/s operating points, where the normalized Q-factor variation decreases from 60.03% to 9.30%. Within the investigated system and launch-power range, this result indicates that the influence of launch-power adjustment changes substantially across this data-rate interval.

Taken together, Figures 3–7 reveal two simultaneous trends. Increasing data rate substantially reduces the achievable QoS-qualified reach, while also reducing the extent to which performance at the transmission boundary can be modified through launch-power adjustment. Thus, reduced launch-power sensitivity at high data rates should not be interpreted as increased robustness in an absolute sense: the 30–40 Gb/s cases have much shorter reaches, but their boundary performance changes relatively little with launch power. Conversely, the lower-rate systems provide longer reach and considerably greater performance leverage through launch-power adjustment. This combined interpretation links the reach and sensitivity results and constitutes the main practical observation of the study.

4. Conclusions

This study investigated the effect of launch-power variation on optical fiber transmission performance across data rates from 2.5 to 40 Gb/s. The results demonstrate a clear relationship among data rate, transmission reach, and launch-power sensitivity. The maximum QoS-qualified transmission reach decreased from 103 km at 2.5 Gb/s to 4 km at 40 Gb/s, with intermediate values of 94, 72, 18, and 8 km at 5, 10, 20, and 30, Gb/s, respectively. At the same time, the normalized Q-factor variation decreased from 89.94% at 2.5 Gb/s to 2.69% at 40 Gb/s, with a pronounced transition between 10 and 20 Gb/s, where the variation decreased from 60.03% to 9.30%. Under the classification adopted in this study, the 2.5–10 Gb/s cases exhibit relatively high launch-power sensitivity, whereas the 20–40 Gb/s cases exhibit relatively low sensitivity. These results show that higher data rates are associated with both reduced transmission reach and a substantially smaller relative response of the Q-factor to launch-power adjustment within the investigated power range.

This behavior is consistent with a changing relative influence of launch-power-dependent effects and rate-dependent impairments; however, the individual contributions of dispersion, bandwidth limitations, nonlinear effects, and noise were not separately isolated in the present study. In a practical sense, these results suggest that the launch-power adjustment is most beneficial in the 2.5-10 Gb/s range, where significant performance improvement is possible.

For the 20–40 Gb/s range, the observed performance limitations indicate the need for further investigation of additional system-level approaches. Techniques such as dispersion compensation and advanced modulation may be considered in future studies; however, their effectiveness is not evaluated in the present work. The novelty of this study is the systematic comparison of launch-power sensitivity across a wide data-rate range at the rate-specific QoS boundary, which reveals distinct high-, transition-, and low-sensitivity regions. The formalism used is standard, but its application in this comparative framework provides new practical insight for multi-rate optical network design

The present work intentionally focuses on characterizing launch-power sensitivity across different data rates under a common system configuration rather than independently investigating the effects of individual fiber and receiver parameters. Future work can therefore extend the analysis by exploring a broader range of launch powers and data rates, assessing the influence of additional fiber and system parameters, and evaluating the robustness of the observed sensitivity behavior under different transmission setups and impairment scenarios. Lastly, a common-distance comparison, particularly for Q-factor variation, would be required to isolate the data-rate effect and is recommended for future work.

List of abbreviations

Abbreviation	Meaning
BER	Bit Error Rate
QoS	Quality of Service
Q	Q-factor / Quality Factor
$Q_{(rel)}$	Relative Q-factor
NRZ	Non-Return-to-Zero
OOK	On-Off Keying
NRZ-OOK	Non-Return-to-Zero On-Off Keying
CW	Continuous Wave
MZM	Mach–Zehnder Modulator
PIN	Positive-Intrinsic-Negative Photodetector
WDM	Wavelength Division Multiplexing
RZ	Return-to-Zero
SNR	Signal-to-Noise Ratio
PON	Passive Optical Network
NG-PON2	Next-Generation Passive Optical Network 2
f-OFDM	Filtered Orthogonal Frequency-Division Multiplexing
ECOC	European Conference on Optical Communication
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
IEEE	Institute of Electrical and Electronics Engineers
Gb/s	Gigabits per second
dBm	Decibels relative to 1 milliwatt
nm	Nanometre
km	Kilometre
L_{max}	Maximum QoS-qualified transmission distance
$L_{(fail)}$	First-failing transmission distance
erfc	Complementary Error Function

Author Contributions

Conceptualization, methodology, software, investigation, formal analysis, visualization, writing—original draft preparation, and supervision: Bakhtiar Ali Karim. Validation, writing—review and editing : Zhwan Rashid. Both authors read and approved the final manuscript.

Availability of Data and Materials

The data generated and analyzed during this study are available from the corresponding author upon reasonable request. The simulation model was developed using OptiSystem and the corresponding simulation parameters are provided in the manuscript to allow reproducibility. This study did not utilize any publicly archived datasets.

Consent for Publication

Not applicable. This manuscript does not contain any identifiable personal data, images, videos, or other information relating to individual participants that would require consent for publication.

Conflict of Interest

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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AI Declaration

OpenAI ChatGPT and Anthropic Claude were used to assist with proofreading and improving the language, grammar, and readability of the manuscript. These tools were also used to assist in preparing the graphical ab-

stract based on the study's methodology, simulation results, and principal findings. The authors reviewed and verified the AI-assisted text and graphical content to ensure their accuracy and consistency with the research. The AI tools were not used to generate the simulation data or to perform the scientific analysis. The authors take full responsibility for the content, accuracy, and integrity of the manuscript.

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