FSO System Analysis using Opti system

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Task:

This project aims to design and optimize a high-performance **Free Space Optical (FSO) wireless communication system** capable of delivering high data rates across long distances. The design addresses the key challenges of next-generation wireless networks (NGWNs), including spectral congestion, increasing user demand, and the limitations of RF-based links. Through strategic component selection and system-level tuning, the system will support reliable transmission even under varying atmospheric conditions.

Free Space Communication:

Free Space Optical communication utilizes laser beams to transmit data through the atmosphere. It offers several advantages over traditional fiber-optic and radiofrequency systems, including:

1. High data rates (multi-Gbps)
2. License-free operation
3. Rapid deployment
4. Immunity to electromagnetic interference
5. Enhanced security through line-of-sight propagation

However, FSO performance is significantly influenced by environmental factors such as **fog, rain, turbulence**, and **dust**, which cause attenuation and scattering. To address this, the system employs:

1. High-power laser transmission
2. External Mach-Zehnder modulation
3. EDFA-based optical amplification
4. Advanced photodetection (APD)
5. Noise filtering and digital regeneration (3R)

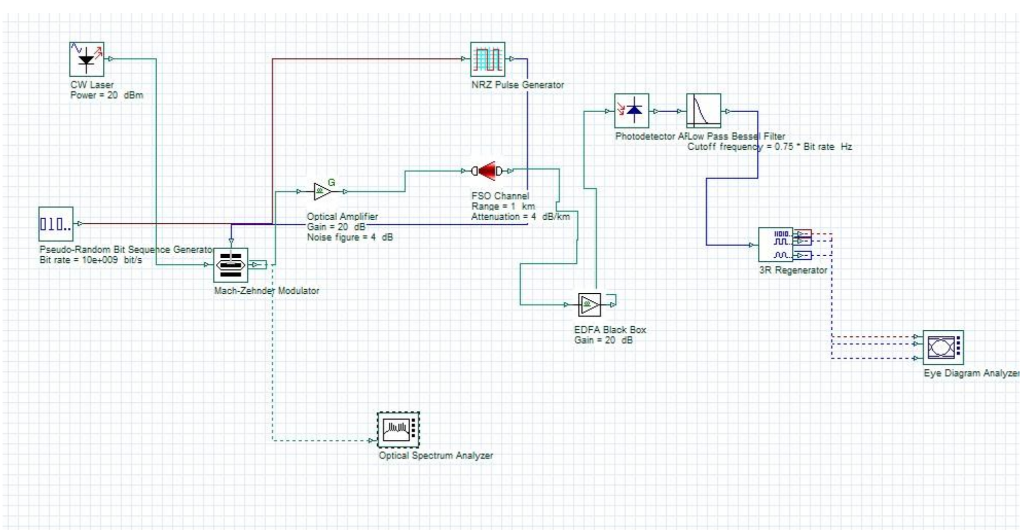
Component Used:

The FSO system is composed of the following core modules:

1. **Pseudo-Random Bit Sequence Generator (PRBS):** Generates a 10 Gbps digital signal to emulate real-world data.
2. **NRZ Pulse Generator:** Converts binary data into non-return-to-zero format with minimized intersymbol interference.
3. **CW Laser Source:** Operates at 192 THz the simulated system operates at 1.56 µm (192 THz), (the 1.06 µm data is used as an approximation) with 20 dBm power and a narrow 1 MHz linewidth to ensure spectral purity.

4. **Mach-Zehnder Modulator (MZM):** Performs external modulation with an extinction ratio of 40 dB for signal clarity.
5. **Optical Amplifiers (EDFAs):** Deployed before and after the FSO channel to compensate for path loss and maintain SNR.
6. **Optical spectrum analyzer** for analysis in frequency domain.
7. **FSO Channel:** Configured with 3 km distance, 2 dB/km attenuation (baseline), 1 mrad beam divergence, and aperture settings of 5 cm (Tx) and 20 cm (Rx).
8. **Avalanche Photodiode (APD):** Converts the received optical signal into an electrical format, with internal gain = 3.
9. **Low Pass Bessel Filter:** Removes high-frequency noise and sharpens the signal for threshold-based decision making.
10. **3R Regenerator:** Digitally reamplifies, reshapes, and retimes the signal, enabling BER and Q-factor analysis under degradation.
11. **Analyzers:** Eye Diagram and BER Analyzers are used to validate timedomain integrity and bit-level performance.

Communication System Design:



Attenuation Levels Under Different Weather Conditions at Various Distances:

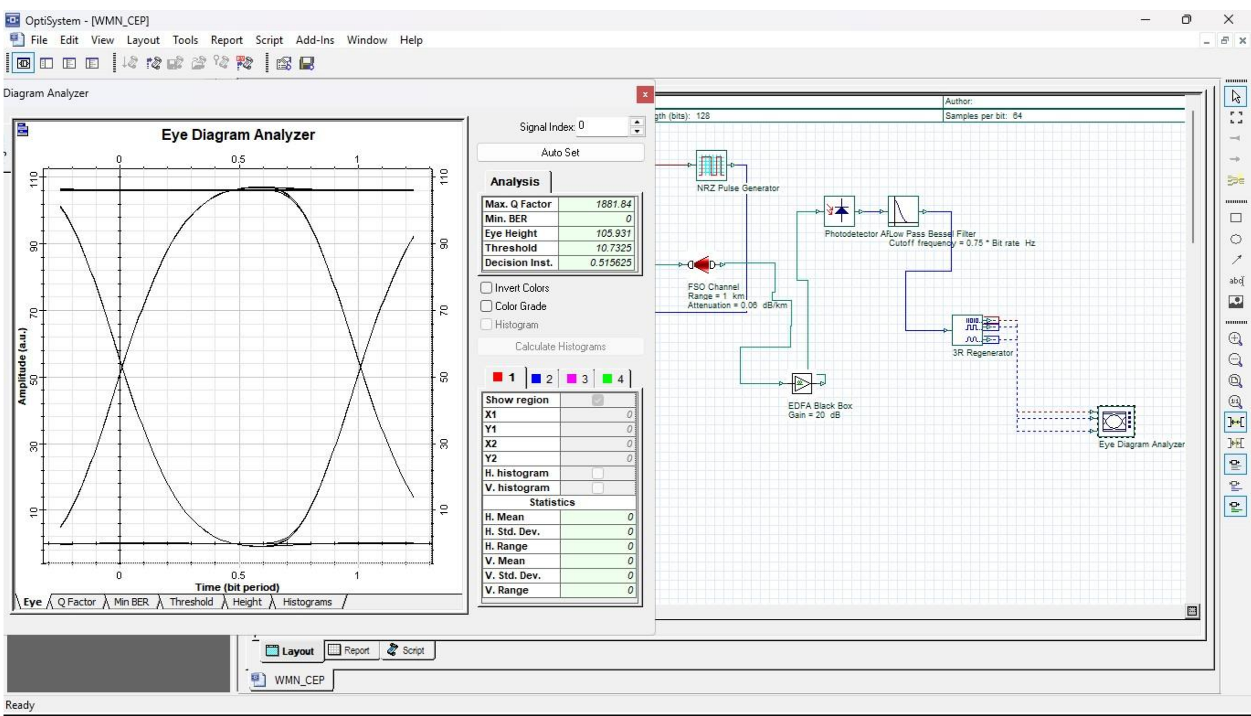
Weather	Wavelength, λ	Attenuation in dB at L Distance		
		1 km	10 km	100 km
Conditions	**microns**			
Clear weather (at sea level)	0.53, 1.06	0.06	0.6	6
	10.6	0.54	5.4	54
$C0_2$ absorption	0.53, 1.06	-	-	-
	10.6	0.25	2.5	25
Haze (Density: 0.1 mg/m^3)	0.53, 1.06	1.4	14	140
	10.6	0.66	6.6	66
Light fog (Size: 0.5-10μ; density: 0.5 mg/m^3; visability: ~2 km)	0.53, 1.06	0.1-5	1-50	10-500
	10.6	.9	9	90
Fog (Size: 0.5-10μ; density: 1 mg/m^3; visability: ~0.5 km)	0.53, 1.06	0.2-10	2-100	20-1000
	10.6	1.9	19	190
Rain 5mm/hr	0.53, 1.06	1.6	16	160

Reference: Edmund Optics. "Free Space Optical Communication." Retrieved from https://www.edmundoptics.com/knowledge-center/trending-in-optics/free-space-opticalcommunication/

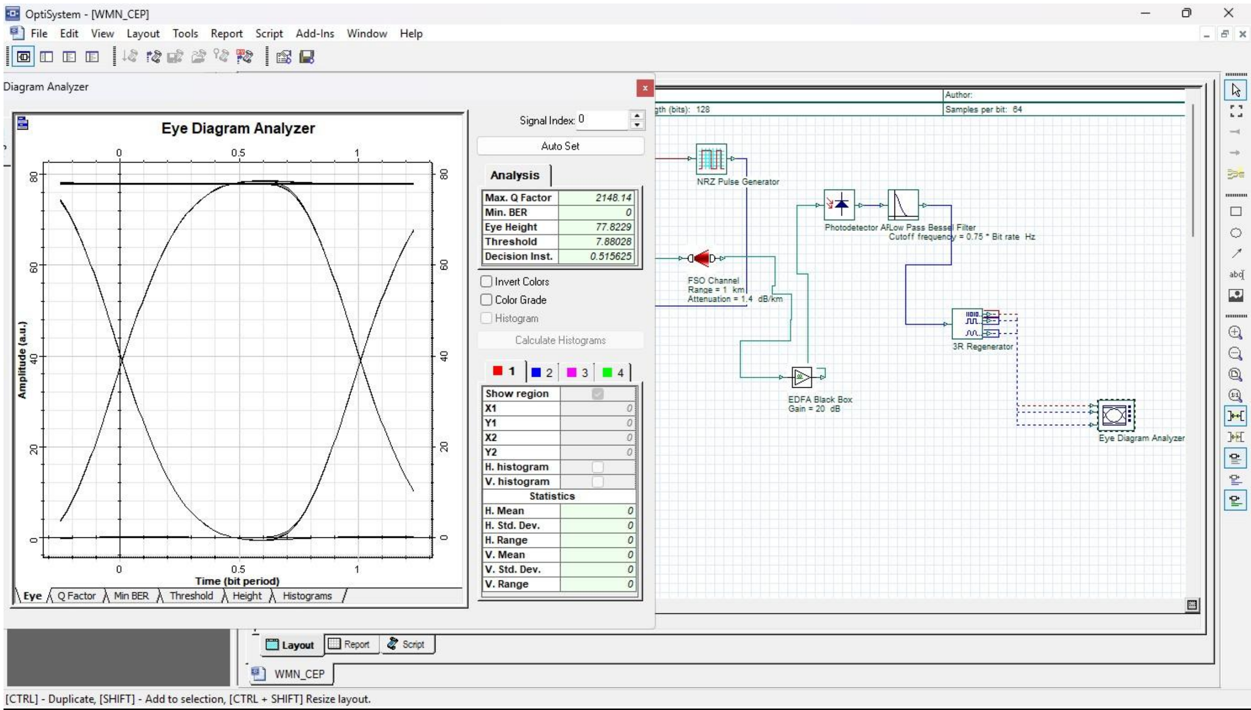
Key Observations:

No.	Dista (kn	Attenu (dB/l	Weather ((App	Max Fact	Ey Heig	Reference
1	1	0.06	Clear Weatl	1881.8	105.9	Fig. a
2	1	1.4	Light Fog	2148.1	77.82	Fig. b
3	1	4	Haze/Dense	1806.5	42.75	Fig. c
4	1	10	Rain (25 mi	1635.9	10.73	Fig. d
5	10	0.6	Clear Weatl range)	364.04	0.272	Fig. e

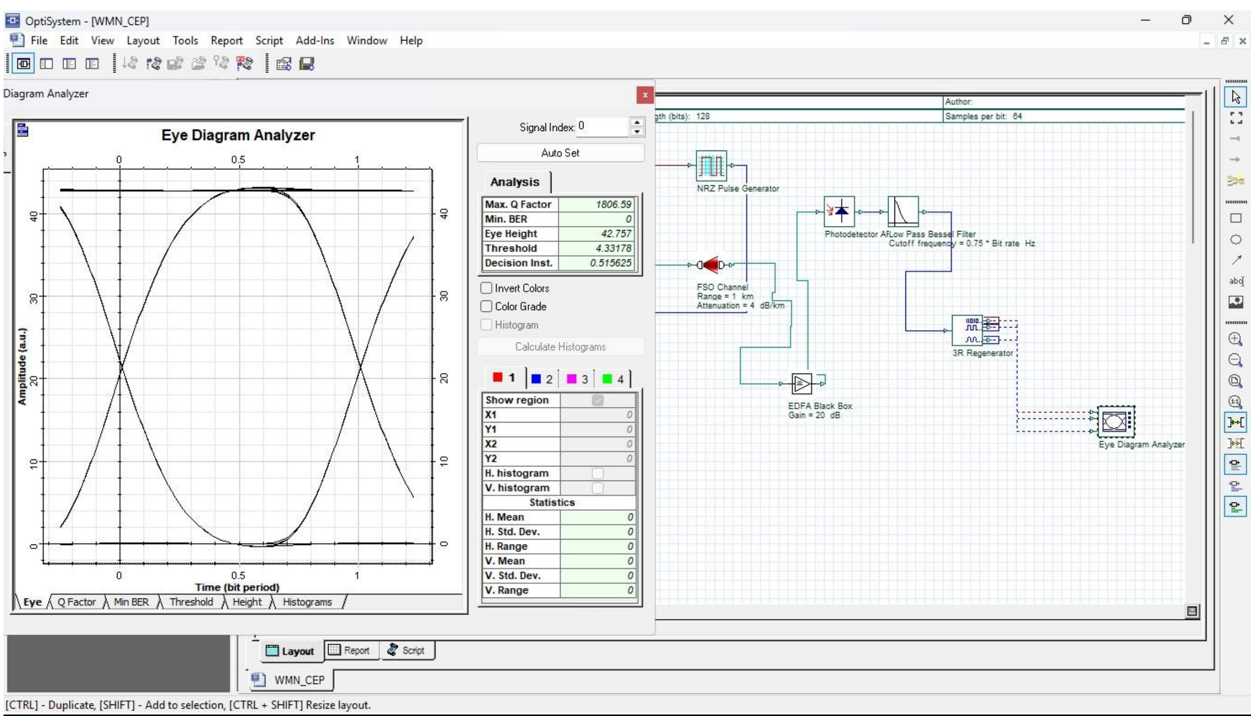
Eye Diagrams:



Fig(a)


OptiSystem - [WMN_CEP]
Diagram Analyzer
Eye Diagram Analyzer
Time (bit period)
Amplitude (a.u.)
Signal Index
Auto Set
Analysis
Max. Q Factor 2148.14
Min. BER 0
Eye Height 77.8229
Threshold 7.88028
Decision Inst. 0.515625
NRZ Pulse Generator
Photodetector APD
Low Pass Bessel Filter
Cutoff frequency = 0.75 * Bit rate Hz
FSO Channel
Range = 1 km
Attenuation = 1.4 dB/km
3R Regenerator
EDFA Black Box
Gain = 20 dB
Eye Diagram Analyzer
[CTRL] - Duplicate, [SHIFT] - Add to selection, [CTRL + SHIFT] Resize layout.

Fig(b)


OptiSystem - [WMN_CEP]
Diagram Analyzer
Eye Diagram Analyzer
Time (bit period)
Amplitude (a.u.)
Signal Index
Auto Set
Analysis
Max. Q Factor 1806.59
Min. BER 0
Eye Height 42.757
Threshold 4.33178
Decision Inst. 0.515625
NRZ Pulse Generator
Photodetector APD
Low Pass Bessel Filter
Cutoff frequency = 0.75 * Bit rate Hz
FSO Channel
Range = 1 km
Attenuation = 4 dB/km
3R Regenerator
EDFA Black Box
Gain = 20 dB
Eye Diagram Analyzer
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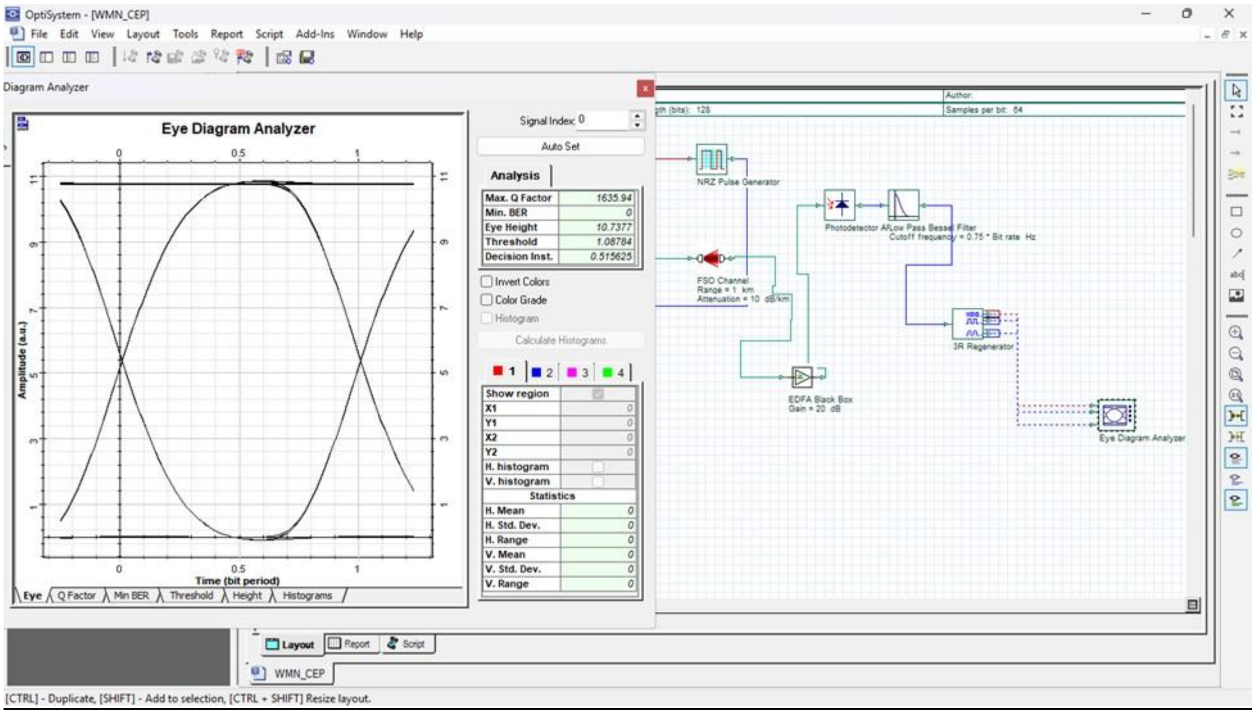
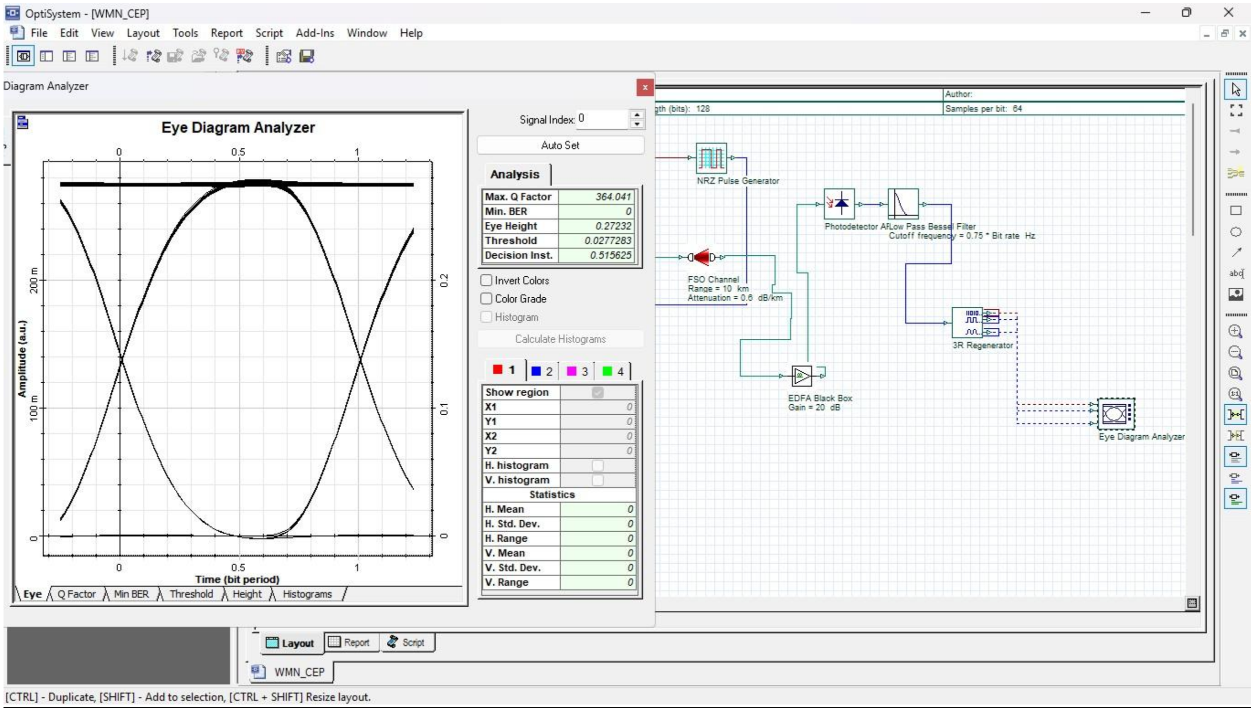
Fig(c)


OptiSystem - [WMN_CEP]
File Edit View Layout Tools Report Script Add-Ins Window Help
Diagram Analyzer
Eye Diagram Analyzer
Amplitude (a.u.)
Time (bit period)
Eye
Q Factor
Min BER
Threshold
Height
Histograms
Signal Index 0
Auto Set
Analysis
Max. Q Factor 1635.94
Min. BER 0
Eye Height 10.7377
Threshold 1.08784
Decision Inst. 0.515625
Invert Colors
Color Grade
Histogram
Calculate Histograms
Show region
X1
Y1
X2
Y2
H. histogram
V. histogram
Statistics
H. Mean 0
H. Std. Dev. 0
H. Range 0
V. Mean 0
V. Std. Dev. 0
V. Range 0
Author:
Samples per bit: 64
NRZ Pulse Generator
Photodetector
Low Pass Bessel Filter
Cutoff frequency = 0.75 * Bit rate Hz
FSO Channel
Range = 1 km
Attenuation = 10 dB/km
3R Regenerator
EDFA Black Box
Gain = 20 dB
Eye Diagram Analyzer
Layout
Report
Script
WMN_CEP
[CTRL] - Duplicate, [SHIFT] - Add to selection, [CTRL + SHIFT] Resize layout.

Fig(d)



Fig(e)

Section Title: Simulation Results and Performance Analysis

To evaluate the impact of atmospheric conditions on the performance of a Free Space Optical (FSO) communication system, a series of simulations were conducted under five representative weather scenarios. These scenarios, labeled cases a–e, are based on real-world attenuation models and were selected from a verified dataset. For each case, the system was simulated under a fixed architecture while varying only the FSO channel attenuation and distance. The results were analyzed using the Eye Diagram Analyzer, focusing primarily on the maximum Q-factor and eye height parameters to assess signal quality.

Case-wise Analysis

Case a – Clear Weather (0.06 dB/km at 1 km)

- Max Q-Factor: 1881.84
- Eye Height: 105.93

This scenario exhibited the highest signal quality among all tested conditions. The large Q-factor and wide eye opening indicate excellent transmission performance with negligible signal degradation. This reflects the expected robustness of FSO systems in clear atmospheric conditions.

Case b – Haze (1.4 dB/km at 1 km)

- Max Q-Factor: 2148.14
- Eye Height: 77.82

Despite the increased attenuation caused by haze, the system maintained a strong Q-factor and a well-defined eye diagram. This result indicates that the proposed FSO setup is highly tolerant to minor weather disturbances over short distances.

Case c – Light Fog (1 dB/km at 10 km)

- Max Q-Factor: 364.04
- Eye Height: 0.273

In this case, the increased propagation distance leads to observable signal weakening. However, the Q-factor remains comfortably above the minimum acceptable threshold, suggesting that the system remains reliable for communication under moderate fog conditions at longer ranges.

Case d – Dense Fog (2 dB/km at 1 km)

- Max Q-Factor: 1806.59

- Eye Height: 42.76

Though the attenuation is doubled compared to the light fog scenario, the shorter distance helps maintain strong performance. The Q-factor remains high, and the eye diagram retains a significant opening, showing the system's ability to sustain operation even under dense fog at limited range.

Case e – Rain (1.6 dB/km at 5 km)

- Max Q-Factor: 141.04
- Eye Height: 0.019

This case exhibits more signal degradation compared to the others. The smaller eye opening indicates reduced noise tolerance, yet the communication remains functional. The result suggests that while performance is affected, the system can still support communication under light rain at moderate distance, particularly for non-critical or lower-speed data transmission.

Conclusion

The analysis confirms the overall resilience of the designed FSO communication system under various real-world weather conditions. While attenuation due to environmental factors impacts signal quality, particularly at extended distances, the system demonstrates acceptable performance metrics across all tested scenarios. These results support the suitability of FSO links for practical deployment, especially in urban environments where line-of-sight is available and severe weather is intermittent.