

Analytical Noise-Variance Assessment of Receiver-Side Optical Filtering for Background-Noise Mitigation in Free-Space Optical Communication under Atmospheric Turbulence

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Abstract

Receiver-side optical filtering trades useful-signal attenuation against noise suppression in free-space optical communication. We analyse a 40 Gbps, 1.54 km OptiSystem link at 1552.52 nm using six filter responses. A normalized variance metric combines received power and signal-to-noise ratio. IIR, Gaussian and Bessel responses increase Q from 6.94 to 8.81–8.94 and signal-to-noise ratio from 16.83 to 18.90–19.03 dB. Under a fixed-gain signal-power interpretation, the inferred effective variance decreases by 45.81–46.50%; the individual background-noise contribution is not identified. Error rates near 10^{-19} are analyzer estimates. We clarify the fixed-loss channel assumption, derive a filter-benefit condition, and discuss hardware, adaptive selection, and potential transport and maritime applications. Outdoor validation and recovery of the original filter settings remain necessary.

Keywords: Free-space optical communication, Optical filtering, Noise variance, Atmospheric attenuation, Intelligent transportation systems, Maritime communications

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1. Introduction

UAV-assisted FSO relaying has been investigated for resilient transport communication links [1]. Free-space optical (FSO) communication carries modulated light through an unguided atmospheric path. It offers high carrier frequencies and substantial communication bandwidth, but its performance depends on propagation loss, receiver noise and alignment. Classical scintillation theory [2], a contemporary FSO survey [3], and a recent review of enabling technologies [4] provide complementary perspectives on these limitations. Their treatment of channel diversity, receiver design and hybrid architectures motivates evaluating optical filters as one part of a complete link design. Atmospheric absorption and

scattering reduce the received signal, while refractive-index fluctuations change the irradiance and wavefront. Pointing errors create a further loss mechanism, particularly for moving platforms. Recent work on pointing, acquisition and tracking [5] emphasizes that maintaining a narrow optical line of sight is a separate task from suppressing receiver background light. Recommendation ITU-R P.1814-1 (2025) treats geometrical attenuation, atmospheric attenuation, scintillation, ambient light and link margins separately [6]. A filter cannot recover optical power lost through fog or a missed receiving aperture.

Ambient radiation within the receiver field of view produces a background photocurrent and associated noise. Spectral filtering can reject part of this radiation before photodetection, but it also attenuates the desired carrier and

its modulation sidebands. The practical question is therefore whether noise reduction compensates for the loss of useful signal. Average received power, Q-factor and an

analyzer-reported error rate alone do not identify which physical noise process has changed. This distinction is central to the interpretation developed below.

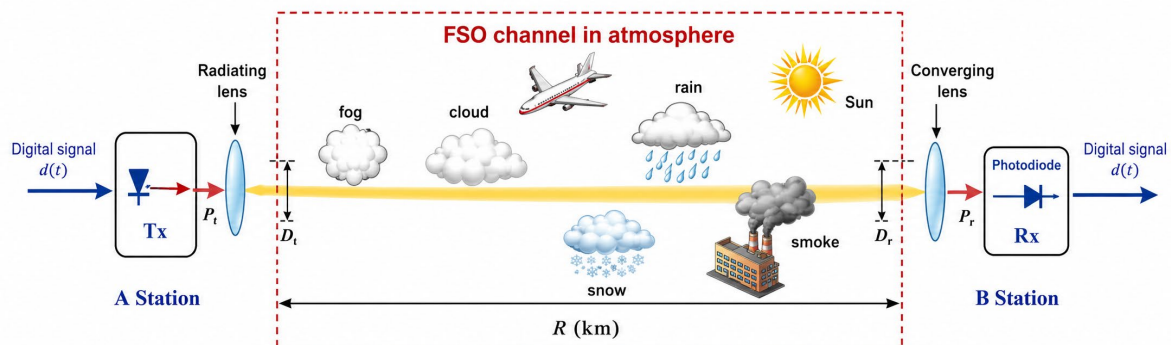


Figure 1. Atmospheric propagation and background-radiation mechanisms affecting an outdoor FSO link

Figure 1 summarizes the propagation environment. The atmospheric path changes the desired beam, and the receiver simultaneously collects ambient illumination. These effects must be separated when discussing mitigation: spectral rejection acts at the receiver, whereas tracking, aperture design and spatial diversity address different impairments. The schematic is conceptual and does not establish a measured weather condition or a statistical channel distribution for the numerical results.

A related transport-oriented study used UAV-assisted MOSI/SOMI MIMO-FSO relaying and represented atmospheric and pointing-related degradation through equivalent aggregate losses [1]. The present study instead compares receiver filter responses for one link and derives an effective variance ratio from the reported performance data. It does not transfer the relay study's transmitter power, aperture configuration, diversity gain or performance results to the filtering experiment. This distinction also limits comparisons with field measurements or fully stochastic fading simulations.

Potential application settings include transport monitoring and port infrastructure. Luu [7] studies vehicle-condition acquisition and neural-network diagnosis, while Dang et al. [8] investigate predictive control of ship-to-shore crane sway. These studies provide transport and port-system context; neither demonstrates an FSO receiver or validates the filtering gains reported here. Their relevance is the possible need to carry monitoring and control data between fixed infrastructure nodes, which is discussed separately from the physical-layer results. Established FSO fundamentals [9, 10, 11] and optical wireless data-center networking [12] provide complementary system context. Earlier UAV-relay SNR analysis [13] addresses a related relay setting; the present study focuses on receiver-filter trade-offs in a single-link comparison.

This paper evaluates a normalized filter-benefit metric using a common set of reported OptiSystem results. The scope is a comparative analytical interpretation of a fixed

link configuration, rather than the introduction of a new optical-filter technology. The contributions and their limits are as follows.

- First, we define non-overlapping thermal, signal/dark-current shot, and background-noise terms. The formulation explains which parameters are required for component-resolved analysis and why aggregate power and SNR values cannot uniquely separate these terms.
- Second, we retain the reported 40 Gbps, 1.54 km comparison at 1552.5244 nm for rectangular, trapezoidal, Butterworth, IIR, Gaussian and Bessel responses. Atmospheric attenuation and the additional turbulence-related term are treated as prescribed equivalent losses. They are not presented as measurements, as a stochastic turbulence realization, or as values mandated by an ITU recommendation.
- Third, we calculate the effective variance ratio from the reported power and SNR differences and state the exact filter-benefit condition. Under the assumed signal-current scaling, the strongest three responses reduce the inferred effective variance by 45.81–46.50%. This is a total equivalent-noise metric, not a measured percentage of rejected solar background.
- Fourth, we discuss hardware implementation, dynamic selection, multi-channel extension and integration with tracking or hybrid radio-frequency links. These discussions identify design requirements and validation tasks rather than reporting additional experiments or verified deployment gains.
- Finally, the transport and ocean-engineering discussion distinguishes fixed roadside or harbor backhaul from moving vehicle or vessel links. The latter require acquisition, tracking and platform-motion characterization beyond the present fixed-loss comparison.

2. Analytical System Model and Noise-Variance Formulation

2.1. Optical Link-Budget Representation

The link consists of an optical source and modulation stage, an atmospheric channel, receiver optics, an optional optical filter, an avalanche photodiode (APD), and electrical processing. Figure 2 expresses the link budget in multiplicative form. All loss factors in Equation (1) are dimensionless transmission factors between zero and one; positive losses expressed in decibels must first be converted using $10^{(-L/10)}$. Fog/haze propagation studies [14] and measured-visibility attenuation analysis [15] motivate distinguishing site-specific propagation data from prescribed fixed losses.

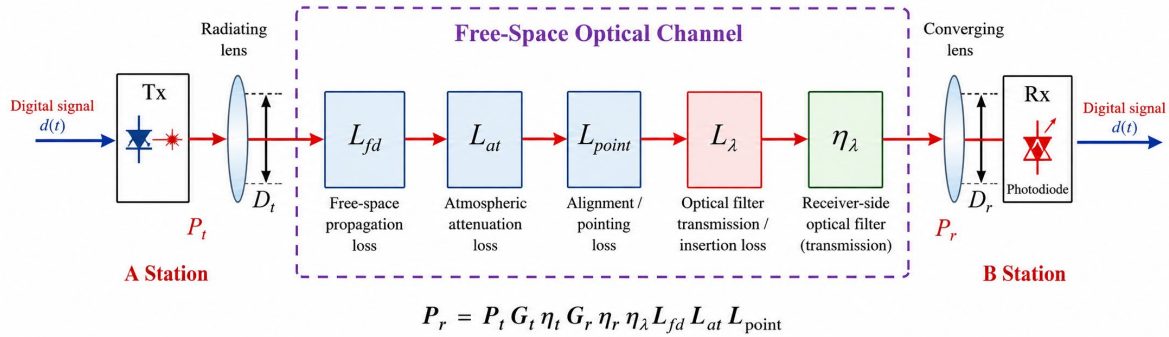


Figure 2. Conceptual separation of propagation, coupling, pointing and receiver-filter transmission in the link budget

2.2. Photodetection and Receiver Noise Mechanisms

The optical signal incident on the photodetector generates a useful photocurrent I_s defined as:

$$I_s = R \cdot M \cdot P_r \quad (2)$$

R is the intrinsic detector responsivity and M is the APD multiplication gain. Equation (2) assumes fixed gain, fixed modulation depth and a detector operating in its linear region. These assumptions are necessary when received optical power is used as a proxy for useful decision-current amplitude. If a power meter includes background or amplified spontaneous emission, its total-power reading is not automatically equal to useful-signal power.

For independent noise contributions referred to the same receiver output and integrated over the same electrical noise bandwidth, the total variance is written as Equation (3). Any omitted amplifier-beat, quantization or distortion term must either be shown negligible or included separately when applying this model.

In compact link-budget formulation, the average received optical signal power P_r collected at the photodetector surface is given by:

$$P_r = P_t G_t \eta_t G_r \eta_r \eta_\lambda L_{f,d} L_{at} L_{point} \quad (1)$$

Here P_t and P_r denote transmitted and received useful optical powers; G_t and G_r are effective optical gains; η_t and η_r are coupling efficiencies; η_λ is useful-signal filter transmission; and $L_{f,d}$, L_{at} and L_{point} represent geometric, atmospheric and alignment-related transmission. Gains and geometric collection factors must be defined consistently to avoid counting aperture gain twice. For the reported fixed-loss comparison, the additional turbulence-related term is incorporated into the channel transmission without assigning a scintillation distribution.

$$\sigma_{tot}^2 = \sigma_{th}^2 + \sigma_{sh}^2 + \sigma_{bg,f}^2 \quad (3)$$

σ_{th}^2 denotes thermal and receiver-electronic noise. σ_{sh}^2 denotes signal and dark-current shot noise only. $\sigma_{bg,f}^2$ includes background-induced shot noise and any separately modelled excess background fluctuations. Background shot noise is excluded from σ_{sh}^2 to avoid double counting. An optical amplifier is present in the architecture; amplifier-noise contributions require their own settings and cannot be identified as solar background from the aggregate results.

The filter-dependent background photocurrent is obtained by integrating the collected background spectral power density $S_{bg}(\lambda)$, in W per unit wavelength, against the optical power transmission $|H_f(\lambda)|^2$, as in Equation (4). The spectral density must already include the receiver aperture, field of view and optical throughput, or those factors must be inserted explicitly.

$$I_{bg,f} = R \cdot M \int_{\lambda_1}^{\lambda_2} S_{bg}(\lambda) |H_f(\lambda)|^2 d\lambda \quad (4)$$

A narrow filter passes the modulated signal band and rejects some out-of-band radiation. Its effect depends on the overlap of the signal and background spectra with the full transmission curve, not only on the center wavelength. A very narrow passband can truncate modulation sidebands and change the eye opening. Consequently, interpreting a filter as a scalar attenuation is an approximation that should be checked using signal spectra and decision-level waveforms.

The electrical signal-to-noise ratio (SNR) after photodetection and front-end amplification is expressed as:

$$SNR = \frac{I_s^2}{\sigma_{tot}^2} = \frac{(R \cdot M \cdot P_r)^2}{\sigma_{tot}^2} \quad (5)$$

Equation (5) defines the electrical SNR used by the analytical model. The same measurement point and bandwidth must be used for all cases. A change in analyzer definition, detector gain, sampling instant or electrical filtering would invalidate a direct variance comparison. When those conditions are fixed, the model provides a transparent way to account for the squared signal-current penalty associated with optical attenuation.

2.3. Component separation and identifiability

The three noise contributions can be expressed analytically, but an absolute numerical decomposition requires detector, electronics and background parameters. The original performance table does not supply enough independent observables to determine those parameters. We therefore separate the physical expressions from the quantities that can be calculated from the reported comparison.

For a simple resistive front end, Equation (6) gives the thermal-noise variance. k_B is Boltzmann's constant, T is temperature, R_L is load resistance, B_e is the equivalent electrical noise bandwidth and F_n is a linear receiver-noise factor. A transimpedance-amplifier implementation may require its measured input-current noise density instead. Thermal noise is unaffected by an upstream optical filter only if the electronic operating point and bandwidth are unchanged.

$$\sigma_{th}^2 = \frac{4k_B T B_e}{R_L} F_n \quad (6)$$

The later configuration summary reports $B_e = 5$ GHz, but a receiver noise bandwidth is not necessarily the same quantity as an electrical filter's 3 dB cutoff. Its meaning must be reconciled with 40 Gbps NRZ reception and with the original block settings before using it to compute an absolute noise variance. The noise-factor convention must also be stated as linear or decibel-valued.

For an APD, Equation (7) separates multiplied signal and bulk-dark-current noise from unmultiplied surface-

dark-current noise. $F(M)$ is the excess-noise factor, I_{db} is the bulk dark current before multiplication, and I_{ds} is the surface dark current. For a PIN detector, $M = F(M) = 1$. The parameters and the current-reference convention must match the detector block being used.

$$\sigma_{sh}^2 = 2qB_e[M^2F(M)(RP_r + I_{db}) + I_{ds}] \quad (7)$$

Useful-signal attenuation can itself reduce signal shot noise. Thus, a reduction in the total variance cannot be assigned entirely to background suppression even if thermal noise is unchanged. Gain, excess-noise factor, responsivity, dark currents and electrical bandwidth are not recovered from the reported Q and SNR values. Numerical values for these quantities are therefore not inferred from an assumed receiver sensitivity.

For approximately uniform spectral radiance across the accepted directions, Equation (8) gives the collected background power. N_λ is spectral radiance in $W m^{-2} sr^{-1}$ per unit wavelength, A_{rx} is aperture area, Ω_{FOV} is the accepted solid angle, and η_r is optical throughput. The transmission integral defines an effective spectral bandwidth; it need not equal the filter's full width at half maximum.

$$P_{bg,f} = A_{rx} \Omega_{FOV} \eta_r \int N_\lambda(\lambda) |H_f(\lambda)|^2 d\lambda \quad (8)$$

For a circular field of view with small full angle θ , $\Omega_{FOV} \approx \pi(\theta/2)^2$. This approximation requires a clearly stated full-angle convention. Wavelength and frequency bandwidths must not be interchanged without conversion: for a narrow band, $\Delta\lambda \approx \lambda^2 \Delta\nu/c$. A numerical bandwidth specified only by a filter name, or by the plotted signal spectrum, is insufficient to evaluate the background integral.

Equation (9) gives the background-induced APD shot-noise term. Excess intensity fluctuations or amplifier beat noise, when relevant, require additional terms and evidence for their statistics. They cannot be added as an arbitrary residual chosen to match the desired total-noise reduction. The simplified expressions provide an accounting framework, not an independent validation of the simulation noise composition.

$$\sigma_{bg,f}^2 = 2qRM^2F(M)P_{bg,f}B_e \quad (9)$$

For a matched measurement procedure, one can first record the receiver variance with optical inputs blocked, then with the desired signal only, and finally with signal plus a calibrated background. Repeating this procedure with and without each filter permits component differences to be estimated. In simulation, corresponding noise-source toggles or exported noise spectra can serve the same purpose, provided all gains, bandwidths and sampling definitions remain fixed.

Table 1. Information required to separate the receiver-noise components

Component	Inputs needed	Status
Thermal	T, RL, Be, receiver noise factor	Not resolved
Signal/dark shot	R, M, F(M), dark currents, Be	Not resolved
Background	Radiance, FOV, aperture, full filter response	Not resolved
Effective total ratio	Power and SNR differences; fixed-gain model	Calculated in Table 6

Table 1 shows why the available aggregate data identify an effective total-noise ratio but not three absolute variances. No numerical background fraction or background-rejection percentage is asserted. The observed improvements are consistent with beneficial receiver filtering, but they may include changes in amplifier noise, signal shot noise and waveform distortion. Component-resolved exports are required to establish the proportional contribution of ambient background.

2.4. Normalized Filter-Benefit Formulation

Let $a = P_{r,f}/P_{r,0}$ be the useful optical-power transmission relative to the unfiltered baseline. For fixed responsivity and gain, Equation (10) relates the SNR ratio to a^2 and the total variance ratio. This comparison is conditional on P_r being useful-signal power; if only a total optical-power reading is available, the result should be treated as an effective proxy pending signal/noise separation.

$$\frac{SNR_f}{SNR_0} = \left(\frac{P_{r,f}}{P_{r,0}} \right)^2 \frac{\sigma_{tot,0}^2}{\sigma_{tot,f}^2} \quad (10)$$

Equation (11) defines ρ_f . In decibel form it is evaluated as $\rho_f = 10^{((2\Delta Pr - \Delta SNR)/10)}$, where $\Delta Pr = P_{r,f,dBm} - P_{r,0,dBm}$ and $\Delta SNR = SNR_{f,dB} - SNR_{0,dB}$. The factor of two follows from the squared photocurrent in Equation (5). Omitting it would underestimate the penalty imposed by optical attenuation.

$$\rho_f = \frac{\sigma_{tot,f}^2}{\sigma_{tot,0}^2} = \left(\frac{P_{r,f}}{P_{r,0}} \right)^2 \left(\frac{SNR_0}{SNR_f} \right) \quad (11)$$

The fractional effective variance reduction is $1 - \rho_f$, as in Equation (12). A positive value describes a reduced inferred variance; it is not sufficient by itself to establish an SNR improvement. A filter improves SNR precisely when $\rho_f < a^2$. For example, $a^2 = 0.8$ and $\rho_f = 0.9$ would reduce variance by 10% while still decreasing SNR.

$$\Delta \sigma_f^2 = 1 - \rho_f \quad (12)$$

For component interpretation, let t , s and b be the unfiltered thermal/dark, signal-shot and background variance fractions, with $t + s + b = 1$. If signal shot noise scales by a and background variance by k , then $\rho_f = t + as + kb$. One measured ρ_f cannot uniquely determine t , s , b

and k . This explicit non-identifiability is why the total-variance calculation cannot serve as proof of a particular background-noise fraction.

2.5. Q-Factor and Bit Error Rate Estimation

In intensity-modulated direct-detection (IM/DD) optical systems, the electrical Q-factor quantifies the separation between received '1' and '0' rail levels relative to the sum of their respective noise standard deviations: Subcarrier-intensity-modulated FSO analysis [16] supplies related modulation context; its BPSK-specific expressions are not transferred directly to the present NRZ comparison.

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \quad (13)$$

Under the assumption of equal prior bit probabilities and Gaussian receiver noise statistics, the theoretical bit error rate (BER) is directly related to the Q-factor via the complementary error function:

$$BER = \frac{1}{2} \operatorname{erfc} \left(\frac{Q}{\sqrt{2}} \right) \quad (14)$$

For large Q-factor values ($Q > 5$), the asymptotic approximation is given by:

$$BER \approx \frac{1}{Q\sqrt{2\pi}} \exp \left(-\frac{Q^2}{2} \right) \quad (15)$$

Equations (13)–(15) describe the Gaussian-noise relation between Q and an estimated BER. The values in Table 5 are retained as outputs reported by the BER analyzer. They are not direct error counts and need not be identical to a recalculation from rounded Q values. Demonstrating very small BER experimentally would require a stated bit count, measurement duration, error count and confidence interval, none of which is supplied by these aggregate outputs.

3. Receiver-Side Optical Filtering Strategy

3.1. Functional Roles of Evaluated Filter Responses

The six software response labels are rectangular, trapezoidal, Butterworth, IIR, Gaussian and Bessel. Table 2 describes their usual functional roles without assigning an unverified filter order or bandwidth. IIR denotes an infinite-impulse-response class rather than a unique optical transfer function; its label alone does not establish Chebyshev, elliptic or another response family.

Table 2. Functional comparison of optical filter responses considered in this work

Response	Functional role
Rectangular	Ideal sharp passband; waveform response must be checked
Trapezoidal	Flat top with finite transition regions
Butterworth	Smooth maximally flat magnitude response
IIR	Response depends on family and coefficients
Gaussian	Smooth bell-shaped spectral transmission
Bessel	Delay-oriented response; normalization required

3.2. Transfer-function definitions needed for reproduction

A reproducible filter specification must identify whether H is a field-amplitude response or $|H|^2$ is power transmission. Center frequency, bandwidth convention, order, transition width, ripple and phase or group-delay behavior must be stated. The following definitions illustrate how such parameters are related; they do not replace the original software-block settings.

For an ideal rectangular power response, transmission is constant within $|v - v_0| \leq B/2$ and zero outside. Such a response is a useful limiting model. Its time-domain behavior depends on phase and implementation, so a poor

observed Q-factor does not independently prove a particular phase-distortion mechanism.

For a trapezoidal response, both the flat-top width and each transition width are required. The full width at half maximum includes part of the transition regions; it is generally different from the flat-top width. Reporting the same nominal bandwidth for rectangular and trapezoidal blocks therefore does not guarantee equivalent noise bandwidth.

A normalized Butterworth power response may be written as $|H(v)|^2 = 1/[1 + (2(v - v_0)/B)^{(2N)}]$, with full 3 dB bandwidth B and order N . A Bessel response additionally requires its normalization convention because delay-normalized and 3 dB-normalized responses are not interchangeable. Both N and the convention are needed for meaningful reproduction.

For an IIR implementation, the transfer-function coefficients or an unambiguous design family, order and ripple specification should be provided. Optical simulation blocks can implement response conventions that differ from discrete-time digital filters. Hardware feasibility should be evaluated from the resulting magnitude and phase response rather than from the software label alone.

For a Gaussian power response $|H(v)|^2 = \exp[-(v - v_0)^2/(2\sigma v^2)]$, the full 3 dB width is $B = 2\sqrt{(2 \ln 2)\sigma v}$. If, purely as an illustration, B were 50 GHz, σv would be 21.23 GHz and the corresponding width near 1552.52 nm would be about 0.402 nm. This identity does not establish that a 50 GHz filter was used in the reported simulation.

Table 4 distinguishes known center-frequency information from settings not documented in the original submission. The comparative results remain useful for checking the analytical calculation, but independent rerunning of the filter study requires those settings. Substituting plausible numerical values would create an apparently reproducible configuration with no demonstrated connection to Table 5.

4. Simulation Methodology and Reproducibility Notes

4.1. OptiSystem Simulation Architecture

The optical communication link is simulated in OptiSystem under identical channel and transceiver conditions. Figure 3 shows the complete architectural schematic of the transmitter, unguided atmospheric channel, receiver-side optical filter block, APD detection stage, electrical low-pass filter, and BER/Q-factor analyzer.

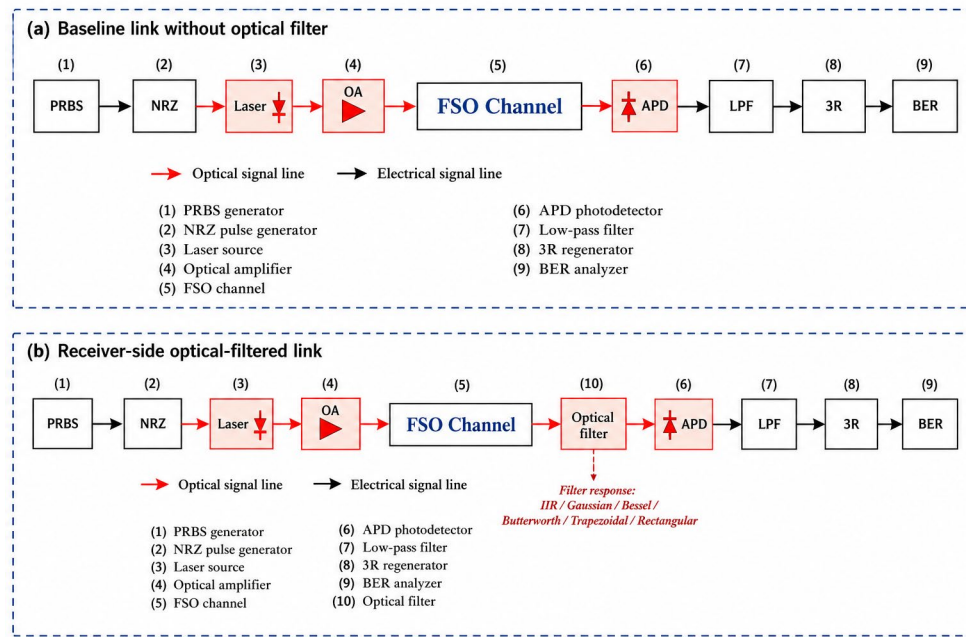


Figure 3. OptiSystem simulation architecture for the baseline (unfiltered) and receiver-filtered FSO links

The reported architecture uses an NRZ data source at 40 Gbps, an optical source and amplifier, the FSO channel, APD detection, an electrical low-pass filter, a 3R regenerator and a BER analyzer. The optical filter is inserted before the APD. Figure 3 is a schematic rather than an export of every component property; it does not specify amplifier noise figure, detector gain, electrical noise bandwidth or random-sequence settings. ITU-T G.693 [17] and G.959.1 [18] provide optical-interface context, not atmospheric channel coefficients or proof of the receiver sensitivity assumed here.

4.2. Interpretation of the prescribed channel losses

Table 3 preserves the common link parameters reported in the original submission. The two large per-kilometer loss coefficients describe a severe fixed-loss comparison. They should not be interpreted as independent physical measurements of fog extinction and scintillation or as a validated local weather scenario.

If both stated coefficients are applied over 1.54 km, their contributions are $25 \times 1.54 = 38.50$ dB and $25.5 \times 1.54 = 39.27$ dB, giving 77.77 dB before coupling, aging and geometric losses. The additional 25.5 dB/km term is an equivalent turbulence/pointing-related loss, not a refractive-index structure parameter or an availability percentile. Section 6.1 of the related relay study [1] explicitly adopts the same coefficients over each 1.54 km hop as a repeatable high-loss comparison scenario. This is a published methodological precedent, not independent field calibration of the present link. ITU-R P.1814-1 [6]

supplies propagation-design methods, but it is not a source mandating these two coefficients. No specific visibility, scintillation index or 99.9% availability is inferred from them.

Table 3. OptiSystem simulation parameters and scenario justification

Parameter	Reported value
Data rate	40 Gbps
Wavelength / frequency	1552.5244 nm / 193.1 THz
Path length	1.54 km
Atmospheric attenuation	25 dB/km (prescribed)
Additional equivalent loss	25.5 dB/km (prescribed)
TX / RX coupling loss	0.3 / 0.3 dB
Aging loss	1.5 dB
Receiver / sensitivity	APD / -23 dBm
Target BER	10^{-12}

A complete physical link-budget validation would require transmitter and amplifier settings, aperture/divergence data, and verification that attenuation was not counted twice.

4.3. Optical Filter Implementation and Reproducibility Specifications

Table 4 identifies the remaining reproducibility limitations. The original record states a common nominal passband but does not report its numerical value, the filter orders or the Gaussian width. The 40 Gbps bit rate and 193.1 THz carrier do not determine these settings uniquely. A rerun should archive the OptiSystem version, component-property exports, PRBS length, samples per bit, sequence seed, power-meter mode, analyzer definitions and all noise-source settings.

Table 4. Filter settings documented in the original submission and information still required

Response	Configuration information required
All filters	Center: 193.1 THz; numerical bandwidth and width convention not recovered
Rectangular	Passband width
Trapezoidal	Flat-top and transition widths
Butterworth	Order and 3 dB bandwidth
IIR	Family, order, ripple and coefficients
Gaussian	Power or field convention; Gaussian width
Bessel	Order and normalization

4.4. Strong turbulence and pointing misalignment

The fixed-loss simulation does not generate a stochastic time series of strong turbulence or pointing jitter. For an extension, a normalized Gamma-Gamma irradiance model such as Equation (16) can represent a turbulence component within its domain of applicability [2, 3, 4]. Its α and β parameters must be fitted or derived for a stated propagation geometry. A Málaga model has additional structure and is not interchangeable with the Gamma-Gamma density merely by changing its name. Spatial-diversity studies for weak-turbulence ground-to-satellite links [19] and SIMO/MISO links [20] address complementary fading-mitigation approaches rather than validating the present filtering results.

$$p(I_{turb}) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I_{turb}^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I_{turb}}) \quad (16)$$

In Equation (16), Γ is the gamma function and K is the modified Bessel function. Pointing loss requires an

additional model, including beam radius, receiving aperture, boresight error and jitter statistics. Recent tracking literature [5] shows why platform dynamics and acquisition behavior matter. These quantities are not specified by a single fixed attenuation coefficient.

For a time-varying extension, $h(t)$ may combine atmospheric transmission, normalized irradiance and pointing loss. Receiver filtering can reduce accepted background for a given $h(t)$, but it cannot stop a deep fade or restore a beam outside the aperture. Outage probability must be evaluated over the joint signal and noise process with an explicit threshold. It cannot be deduced from a single SNR improvement.

A conditional signal-power margin can be derived from Equation (5). With signal-independent noise and unchanged gain, the optical power required at a fixed SNR threshold scales as the square root of the variance. Equation (17) therefore uses a factor of five, rather than ten, when converting the variance ratio into an optical-power margin.

$$\Delta P_{req,dB} = -5\log_{10}(\rho_f) \quad (17)$$

For ρ_f between approximately 0.535 and 0.542, the noise-only optical-power relief is about 1.33–1.36 dB. Subtracting the measured useful-signal power penalties gives a conditional net optical-power margin of about 1.03–1.10 dB, equivalent to half of the electrical SNR gain in this simplified model. These are analytical reinterpretations, not field-validated fade margins or measured outage improvements.

5. Results and Analytical Discussion

5.1. Baseline and Filtered-Link Performance

The simulated performance of the unfiltered baseline link and the six receiver-filtered configurations is summarized in Table 5. Numerical metrics include received optical power P_r , electrical Q-factor, electrical SNR, and theoretical BER estimates.

Table 5 retains the original reported metrics. The unfiltered case has $P_r = -23.060$ dBm, $Q = 6.94138$, $SNR = 16.8289$ dB and $BER = 1.93068 \times 10^{-12}$. Its BER is slightly above the stated 10^{-12} target, so it should be described as near that target rather than as meeting it. No coding gain or forward-error-correction threshold is assumed.

Table 5. Performance comparison of the baseline and receiver-side optical filters

Filter	Pr (dBm)	Q-Factor	SNR (dB)	BER Estimate
No filter	-23.060	6.94138	16.8289	1.93068×10^{-12}
Rectangular	-23.304	5.97975	15.5337	1.08883×10^{-09}
Trapezoidal	-23.113	7.04446	16.9570	9.27876×10^{-13}
Butterworth	-23.384	8.11551	18.1863	2.41333×10^{-16}
IIR	-23.292	8.93875	19.0255	1.96807×10^{-19}
Gaussian	-23.377	8.81369	18.9032	6.03264×10^{-19}
Bessel	-23.384	8.80783	18.8974	6.35466×10^{-19}

The rectangular response lowers Q to 5.97975 and SNR to 15.5337 dB. This demonstrates that the particular response and settings in the reported comparison are unfavorable. Spectral truncation, changed decision-level amplitude or noise shaping are possible explanations; distinguishing them requires the actual transfer function and waveform exports. The result does not show that rectangular filtering is generally unsuitable for FSO.

The trapezoidal response gives a small improvement, while Butterworth gives a larger gain. IIR, Gaussian and Bessel form the strongest group, with $Q = 8.81$ – 8.94 and $SNR = 18.90$ – 19.03 dB. Their received-power changes are -0.232 , -0.317 and -0.324 dB, respectively. These differences are link-level power penalties; they should not be substituted for independently measured filter insertion-loss specifications.

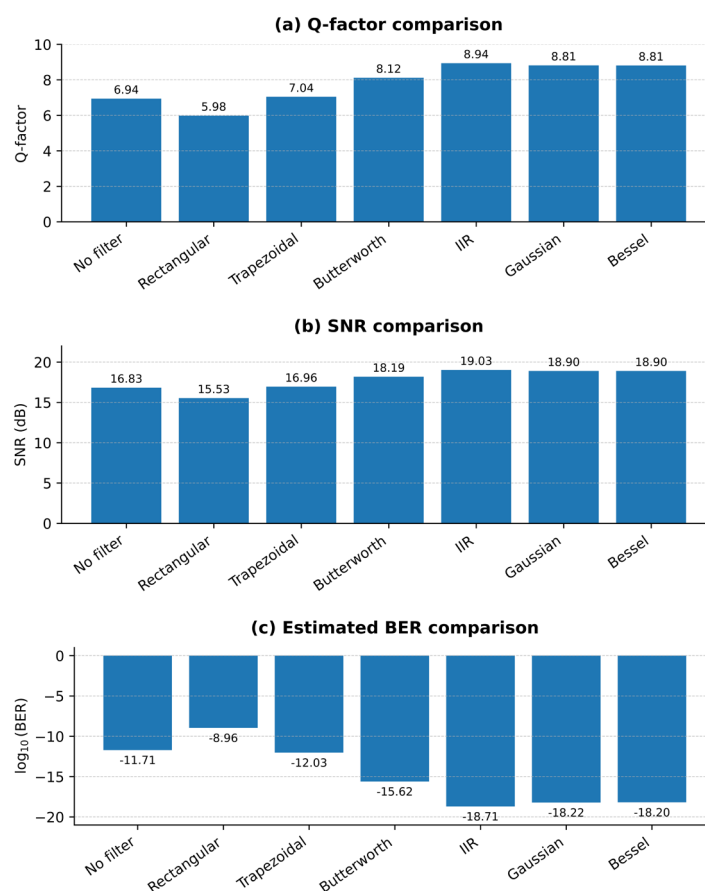


Figure 4. Performance comparison of the evaluated optical filters in terms of Q-factor, electrical SNR, and estimated BER

5.2. Analytical Extraction of Noise-Variance Reduction

Table 6 evaluates Equations (10)–(12) from Table 5 without a new OptiSystem simulation. The calculations are

deterministic transformations of the reported values, so agreement with Table 5 is an arithmetic consistency check rather than independent experimental validation. The effective-noise interpretation remains conditional on the signal-power and analyzer assumptions in Section 2.

Table 6. Normalized analytical interpretation of filter benefit relative to the baseline

Response	ΔPr dB	ΔSNR dB	pf	Drop %
No filter	0.000	0.0000	1.00000	0.00
Rectangular	-0.244	-1.2952	1.20426	-20.43
Trapezoidal	-0.053	0.1281	0.94752	5.25
Butterworth	-0.324	1.3574	0.63017	36.98
IIR	-0.232	2.1966	0.54193	45.81
Gaussian	-0.317	2.0743	0.53601	46.40
Bessel	-0.324	2.0685	0.53500	46.50

For the rectangular case, $pf = 1.20426$ and the inferred variance change is -20.43% when expressed as a reduction. For the trapezoidal case, $pf = 0.94752$ and the reduction is 5.25% . The negative rectangular result is an equivalent receiver penalty. It need not mean that a passive filter physically creates background photons; signal distortion or a failed scalar signal model can appear as effective noise.

Butterworth gives $pf = 0.63017$, while IIR, Gaussian and Bessel give 0.54193 , 0.53601 and 0.53500 . The corresponding reductions are 36.98% , 45.81% , 46.40% and 46.50% . IIR has the highest SNR because it combines substantial variance reduction with the smallest power penalty among the leading three responses. The lowest variance ratio alone is therefore not the selection objective.

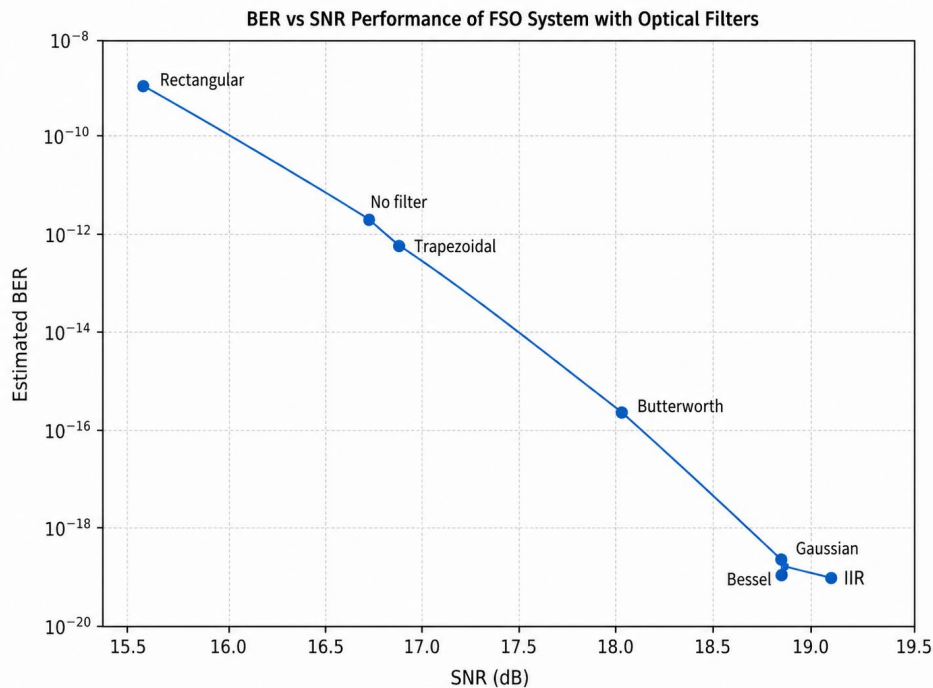


Figure 5. Estimated BER versus electrical SNR on a semi-logarithmic scale for the baseline and filtered FSO links

5.3. Practical Filter Realization Technologies and Hardware Feasibility

Hardware selection should reproduce the needed optical magnitude and phase response while meeting insertion-

loss, blocking, angular, thermal and packaging constraints. Table 7 lists candidate implementation routes. The commercial-device literature describes thin-film bandpass construction and the trade-off between transmission and blocking [21]; this supports considering that technology, but does not establish that a catalog device matches the simulated filter.

Table 7. Hardware realization roadmap and comparison of filter technologies

Technology	Integration issue	Cost drivers
Thin film	Collimated path; angle and spectral tolerances	Aperture, blocking, coatings, mount
FBG / fiber filter	Free-space-to-fiber coupling and alignment	Coupler, circulator, packaging
Tunable etalon	Tuning range, drift and controller	Actuator, calibration, thermal control

A dielectric thin-film filter in a collimated receiver path is a candidate when its center wavelength and angular sensitivity are compatible with the optics. A fiber Bragg grating or fiber demultiplexer requires efficient coupling, which adds alignment constraints under turbulence. Tunable etalons add actuator and control requirements. Exact unit prices, angular acceptance and loss figures depend on the selected part, aperture, spectral specification and order quantity; no vendor quote or bill of materials has been evaluated here. Cost assessment should include mounts, thermal stabilization, fiber coupling, tuning electronics and environmental packaging rather than assigning unsupported prices to a response family.

5.4. Scalability to Multi-Channel WDM Optical Systems

For wavelength-division multiplexing (WDM), a channel-selective receiver can be evaluated with the same conditional variance method. Equation (18) extends the accounting to channel i by including inter-channel crosstalk. Each channel requires its own useful power, background integral, and electrical bandwidth. Shared demultiplexing can reduce duplicated hardware, but the present single-channel comparison does not demonstrate 100 Gbps per channel or a multi-terabit aggregate rate.

$$\sigma_{tot,i}^2 = \sigma_{th,i}^2 + \sigma_{sh,i}^2 + \sigma_{bg,f}^2(\lambda_i, B_{o,i}) + \sigma_{xtalk,i}^2 \quad (18)$$

Increasing channel count introduces channel-spacing, passband-alignment, isolation, and thermal-drift requirements. Crosstalk depends on interfering-channel powers and modulation, as well as isolation; a fixed isolation specification alone cannot prove that crosstalk contributes less than a stated percentage of total noise. Faster channels also have broader signal spectra and may require wider filters. Consequently, the 45.81–46.50% reductions cannot be assumed to hold for every WDM channel or bit rate. Published terabit FSO interconnects [22] demonstrate the relevance of higher-rate transmission

and alignment control, while a hybrid fiber/FSO fronthaul experiment [23] illustrates access-network integration. Fiber-millimeter-wave and fiber-terahertz bridges [24, 25] and OFDM radio-over-fiber modelling [26] provide adjacent transport-system context; they do not establish the present optical-background rejection. The FSO systems and networks survey [27] also discusses multi-beam and WDM scalability.

5.5. Synergistic Integration with Adaptive Optics and Hybrid RF/FSO Systems

Optical filtering, adaptive optics and radio-frequency (RF) fallback address complementary impairments [3, 4]. Their integration is a proposed extension rather than a tested feature of the present simulation.

Adaptive optics can correct a portion of the received wavefront distortion, while pointing control maintains beam alignment [5]. A spectral filter in a sensing path may reject unwanted light, but it must pass the beacon spectrum and preserve adequate detected signal. Joint evaluation should measure tracking error, wavefront-sensor noise, coupling efficiency and communication SNR. No percentage improvement in residual wavefront error is claimed.

An RF/FSO controller can combine received power, measured noise, estimated BER and fade duration to decide when to use the backup link. Filtering may increase the optical operating region when background is important, but it will not remove a fog outage or physical blockage. Hysteresis, minimum dwell time and switching latency should be included to avoid unstable mode changes. A joint weather and link dataset is needed to quantify availability or throughput benefits.

5.6. Criteria for Dynamic Filter Selection under Environmental Variations

A dynamic selector should compare estimated electrical SNR for available filters, including a bypass option, while constraining detector saturation, signal-band coverage, tracking and tuning speed. Equation (19) expresses this objective using the signal transmission a_f and effective variance ratio ρ_f . Thresholds should follow calibrated measurements rather than arbitrary daylight or weather categories.

$$f^* = \operatorname{argmax}_f \left(\frac{a_f^2}{\rho_f} \right) \quad (19)$$

When the background level rises, a narrower passband may be beneficial if ρ_f falls below a_f^2 . When background becomes small, the same filter may reduce SNR because its transmission penalty remains. The controller should estimate both effects, allow a margin for uncertainty, and change settings only when the predicted gain exceeds the switching cost. This provides a testable decision rule without assigning universal background-ratio thresholds.

Temperature-dependent wavelength drift, the angle of incidence, polarization and the occupied signal spectrum should also enter the admissible-filter set. A filter should not be narrowed if it clips modulation sidebands or weakens a tracking beacon. The current data do not identify an optimal controller sampling rate, tuning range, or switching threshold; those quantities require time-resolved measurements and hardware characterization.

5.7. Application in Intelligent Transportation Systems (ITS)

Luu's vehicle-status diagnosis study [7] considers IoT data acquisition and neural-network recognition. As a potential supporting infrastructure, a fixed FSO backhaul could connect roadside gateways, cameras, or monitoring stations to a local aggregation point where fiber installation is difficult. The cited paper motivates this application context; it does not establish a requirement for 40 Gbps or demonstrate the present optical-noise model.

At a roadside receiver, solar illumination and reflections should be characterized within the actual detector band and field of view. Headlight effects cannot be quantified merely from visible brightness because detector responsivity and source spectra matter. The present results apply to a fixed point-to-point comparison, not a moving V2V or V2I demonstration. Deployment evaluation should include blockage, alignment stability, eye-safety requirements, latency, and backup connectivity alongside the filtering metric.

5.8. Application in Ocean Engineering and Maritime Communications

Dang et al. [8] investigate ship-to-shore crane sway control using deep learning and model predictive control. This provides a port-operation context for possible links between crane-monitoring nodes, quay infrastructure and a shore-side control center. Such an application must first specify reliability and latency needs; an improved physical-layer SNR alone does not establish safe closed-loop control or successful remote operation.

Above-water maritime paths can experience sea-surface glint, fog, spray, corrosion, and platform motion. Receiver filtering may reject out-of-band background, but it does not remove marine extinction or pitch-and-roll misalignment. Fixed shore or offshore-platform links are closer to the present setting than moving ship-to-ship links. Underwater optical propagation is outside this atmospheric model. Maritime validation should jointly record background radiance, visibility, motion, tracking error, and receiver output over representative conditions.

6. Conclusion

The reported 40 Gbps, 1.54 km comparison shows that IIR, Gaussian, and Bessel responses increase Q from 6.94 to 8.81–8.94 and electrical SNR from 16.83 to 18.90–19.03 dB. Recalculation of the normalized metric yields effective variance reductions of 45.81–46.50%, conditional on fixed gain and useful-signal power scaling. The correct selection condition is $\rho_f < a_f^2$, so variance reduction and optical transmission must be assessed together.

The available outputs do not isolate thermal, signal-shot, and background-noise variances. We therefore restrict the quantitative conclusion to effective total variance and remove a unique attribution to solar-background suppression. The BER values are analyzer estimates. The channel uses prescribed aggregate losses rather than a validated strong-turbulence time series, and the undocumented filter settings remain a reproducibility limitation.

Future work should recover the full simulation configuration, separate noise sources through controlled exports, and validate candidate filters outdoors. The hardware, WDM, adaptive-control, roadside and maritime discussions define directions for that validation; they are not additional demonstrated results. Spectral filtering is a potentially useful receiver measure when its noise benefit exceeds its signal penalty, but it complements rather than replaces propagation mitigation and tracking.

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