

Article

UAV-Assisted MOSI/SOMI MIMO-FSO Relay for Resilient Transport Communication Links

Ho Van Cuu ¹, Leminh Thien Huynh ¹ and Žarko Kobojević ^{2,*}

¹ Faculty of Engineering and Technology, Saigon University, 273 An Duong Vuong Street, Cho Quan Ward, Ho Chi Minh City 70000, Vietnam; cuuhovan@sgu.edu.vn (H.V.C.); leminhthien.huynh@sgu.edu.vn (L.T.H.)

² Faculty of Maritime Studies, University of Dubrovnik, Branitelja Dubrovnika 41, 20000 Dubrovnik, Croatia

* Correspondence: zarko.kobojevic@unidu.hr; Tel.: +385-98-428152

Abstract

Reliable communication infrastructure is a fundamental component of Intelligent Transport Systems (ITSs), particularly in scenarios involving maritime corridors and emergency traffic management. In locations where optical fiber deployment is geographically constrained, unmanned aerial vehicle (UAV)-assisted free-space optical (FSO) relay links provide a flexible and rapidly deployable alternative. However, atmospheric attenuation, turbulence-induced fading, and wind-induced UAV misalignment can severely degrade link reliability and disrupt real-time transport data streams. This study proposes a payload-efficient multiple-input multiple-output free-space optical (MIMO-FSO) relay architecture based on a multi-output/single-input (MOSI) uplink and a single-output/multi-input (SOMI) downlink. Here, MOSI denotes multiple ground-based transmit apertures directed toward a single UAV receiving aperture, whereas SOMI denotes one UAV transmitting aperture serving multiple ground-based receiving apertures. Unlike conventional symmetric UAV-assisted MIMO-FSO relays that may duplicate diversity hardware on the aerial node, the proposed design shifts the parallel optical branches to the ground stations and keeps only one optical receiver and one optical transmitter on board the UAV. Under the adopted 4×4 comparison assumption, this reduces the UAV-side optical branch count from eight to two, corresponding to a 75% branch-count reduction proxy. System performance is evaluated over a 1.54 km relay link. The analytical framework describes Beer–Lambert attenuation, log-normal/gamma–gamma turbulence, and statistical pointing errors; in the OptiSystem implementation, their combined effects are represented by equivalent aggregate losses of 25 dB/km for atmospheric absorption/scattering and 25.5 dB/km for turbulence- and pointing-related degradation. Comparative simulations for SISO, 2×2 , and 4×4 configurations show that the proposed 4×4 architecture increases the Q-factor from 8.38 to 18.25 and changes the OptiSystem-reported minimum BER from 2.73×10^{-17} to 9.95×10^{-75} . Because a finite simulation cannot statistically validate error probabilities of this magnitude through raw error counting, values far below 10^{-12} are interpreted primarily as comparative indicators of receiver decision margin. The findings provide simulation-based evidence that the proposed architecture is a scalable candidate for resilient optical wireless backhaul in smart transport corridors under adverse propagation conditions.

Keywords: UAV-assisted communication; transport infrastructure resilience; MIMO-FSO architecture; spatial diversity; intelligent transport systems; atmospheric turbulence

Academic Editors: Salvatore Rosario Bassolillo, Vito Antonio Nardi and Giuseppe Tricomi

Received: 25 May 2026

Revised: 26 June 2026

Accepted: 2 July 2026

Published: 10 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Free-space optical (FSO) communication has been widely recognized as a promising solution for high-capacity wireless transmission due to its license-free spectrum, high data rates, and immunity to electromagnetic interference [1,2]. In recent years, the integration of unmanned aerial vehicles (UAVs) as relay nodes has attracted increasing research interest, as UAV-assisted FSO systems enable rapid deployment, flexible topology, and extended coverage for emergency communications, disaster recovery, and temporary backhaul links. Hybrid optical fiber-wireless fronthaul and UAV-relay studies further demonstrate the relevance of optical wireless links for high-capacity backhaul applications [3,4]. General FSO references are also used as background for the device and channel assumptions [5,6].

A typical UAV-assisted FSO communication scenario is illustrated in Figure 1, where a UAV operates as an aerial relay between two ground stations, establishing an optical line-of-sight (LoS) link to overcome geographical obstacles and extend communication range. This relay-based architecture enables high-speed optical transmission across rivers, swamps, and large water bodies, where conventional fiber or radio-frequency infrastructure is difficult or costly to deploy.

Despite these advantages, the performance of UAV-assisted FSO links is severely affected by atmospheric attenuation, turbulence-induced fading, and transceiver misalignment [7,8]. In particular, UAV mobility can increase pointing errors, while fog/haze attenuation and ground-to-HAP optical-link modeling provide relevant propagation context for the adopted channel stress test [9,10]. The 40 Gbit/s optical-interface context is supported by ITU-T G.693 [11], while spatial diversity has been analyzed in earlier FSO links [12]. To address these impairments, multiple-input multiple-output free-space optical (MIMO-FSO) techniques have been investigated as an effective means of exploiting spatial diversity to enhance link robustness.

Existing studies on UAV-assisted MIMO-FSO systems typically employ multiple optical transmitters and receivers on the UAV platform to achieve spatial diversity gains [13,14]. However, such approaches substantially increase system complexity, payload weight, and power consumption, which directly limit UAV endurance and practical applicability [15]. Consequently, a fundamental trade-off exists between link performance enhancement and UAV payload constraints, which has not been sufficiently addressed in current MIMO-FSO relay designs.

To overcome this limitation, this study proposes an improved UAV-assisted MIMO-FSO architecture based on a multi-output/single-input (MOSI) uplink and a single-output/multi-input (SOMI) downlink. In this paper, MOSI means that multiple ground-based transmit apertures illuminate one UAV receiving aperture, whereas SOMI means that one UAV transmitting aperture illuminates multiple ground-based receiving apertures. These terms are used to describe the proposed hardware placement and should not be interpreted as a claim that standard MIMO-FSO theory is new. By shifting spatial diversity to the ground stations while maintaining only a single optical transmitter and receiver onboard the UAV, the proposed architecture preserves diversity gain without a proportional increase in airborne payload. Furthermore, a unified channel model incorporating atmospheric absorption, turbulence-induced fading, pointing-error statistics, geometric loss, coupling loss, and receiver noise is adopted to evaluate system performance [16,17]. Visibility-based attenuation studies are also relevant to interpreting atmospheric-loss assumptions in FSO links [18].

Comprehensive OptiSystem simulations are conducted to compare SISO, 2×2 MIMO-FSO, and 4×4 MIMO-FSO configurations under the same channel settings and identical per-branch optical hardware parameters. Each active laser branch uses a 10 dBm

launch power and an individual 32 dB optical amplifier. Therefore, the study is a controlled per-branch comparison rather than an equal-total-transmit-power comparison; this distinction is stated explicitly in the Methods, Results, and Limitations. Recent millimeter-wave and terahertz-over-fiber optical transport demonstrations provide additional context for high-capacity optical backhaul systems [19,20].

Novelty clarification. The novelty of the present work does not lie in introducing MIMO-FSO, UAV relaying, or spatial diversity as isolated concepts. Instead, the contribution is the asymmetric MOSI/SOMI relay architecture that relocates the parallel diversity apertures from the airborne relay to the ground infrastructure. In the uplink, several ground-based transmit apertures illuminate a single UAV receiver; in the downlink, one UAV transmitter serves several ground-based receive apertures. Thus, the ground-side diversity order can be increased without a proportional increase in UAV optical front ends. Under the comparison adopted in this study, a conventional symmetric 4×4 relay would use four receive and four transmit optical branches on the UAV, whereas the proposed relay uses one UAV receiver and one UAV transmitter. The UAV-side branch count is therefore reduced from eight to two (75%); for the 2×2 case, it is reduced from four to two (50%). These percentages quantify branch count only. Exact reductions in mass, volume, power consumption, and flight-endurance impact require prototype-level measurements.

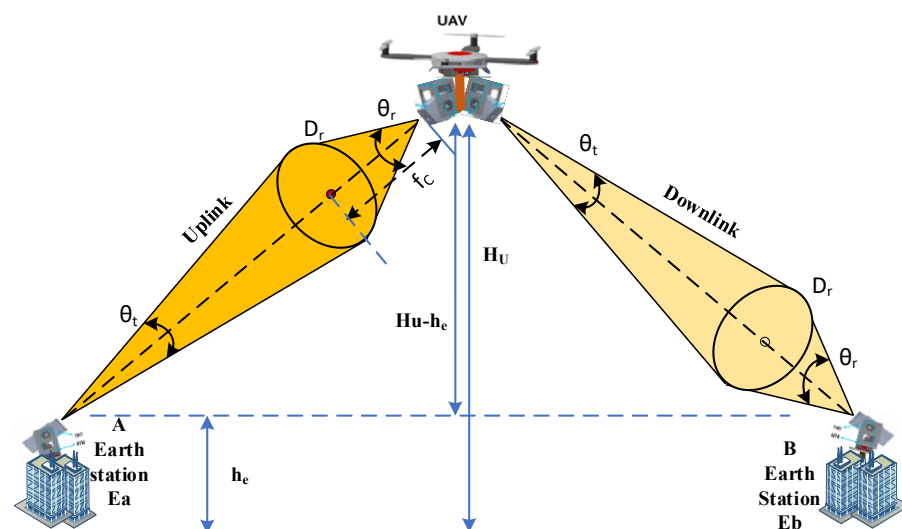


Figure 1. FSO communication channel between ground stations with relay UAVs.

The main contributions of this paper are summarized as follows:

- A payload-efficient asymmetric MOSI/SOMI MIMO-FSO relay architecture is proposed, in which the UAV carries only one optical receiver for the uplink and one optical transmitter for the downlink while the diversity apertures are implemented at the ground stations.
- The work sharply separates the proposed novelty from prior MIMO-FSO and UAV-FSO studies by emphasizing the ground-shifted diversity placement and the resulting reduction in UAV-side optical branches.
- A unified analytical channel framework is retained for atmospheric absorption/scattering, log-normal and gamma–gamma turbulence, pointing-error statistics, geometric loss, coupling loss, background noise, and receiver noise. In OptiSystem, the combined turbulence- and pointing-related effects are implemented through equivalent

aggregate loss parameters, thereby preserving the original high-loss comparison scenario without claiming separate calibration of Cn^2 , α , β , or pointing-jitter variance.

- A controlled per-branch OptiSystem comparison of SISO, 2×2 , and 4×4 configurations is conducted under identical channel parameters. The minimum BER values are reported by the BER Analyzer and are interpreted together with the received power and Q-factor; values far below 10^{-12} are used as comparative link-margin indicators rather than evidence of experimentally verified error-free operation.

2. FSO Channel and Impairment Model

2.1. FSO Channel-Loss Model

Analyzing the upward (u) and downward (d) FSO channels in the atmosphere, the received signals at the UAV and ground station have the general formula:

$$r_{u/d}(t) = h_{u/d}(t)s_{u/d}(t) + n_{u/d}(t) \quad (1)$$

In this case, $s_{u/d}(t)$ is the transmitted optical signal, $h_{u/d}(t)$ is the channel attenuation characteristic function, and $n_{u/d}(t)$ is the noise. The radio optical signal attenuation in the atmosphere is due to absorption and scattering by free-space air particles such as smoke, fog, snowfall, rain, weather, pressure, weather changes, and windstorms, which are modeled in Figure 2. The general attenuation formula in one direction will be as follows:

$$h = h_{al} \cdot h_{at} \cdot h_{pl} \quad (2)$$

where h_{al} is the product of transmission losses due to absorption from smoke, fog, snow, and rain in the atmosphere; h_{at} is the loss due to weather changes; and h_{pl} is the loss due to misalignment of the transmitting and receiving mirrors. The main atmospheric attenuation mechanisms affecting the FSO channel, including absorption, scattering, and misalignment losses, are illustrated in Figure 2.

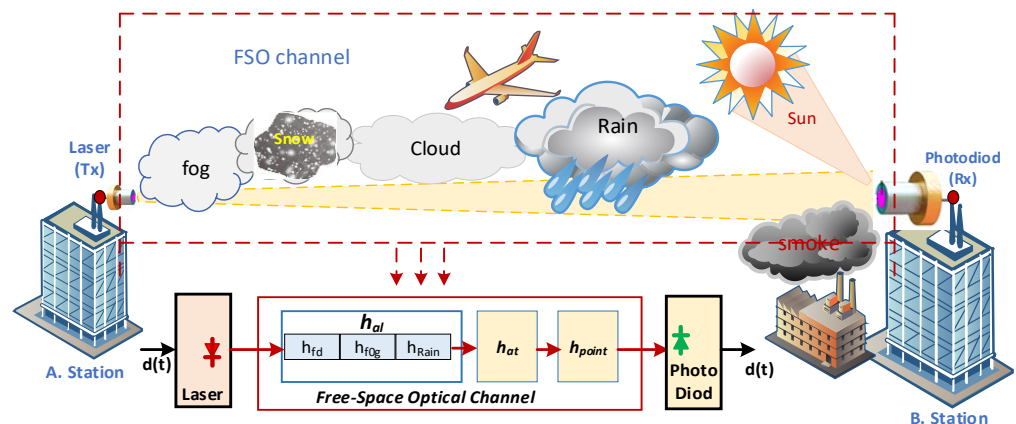


Figure 2. Model of a radio optical signal transmission channel in the atmosphere.

The optical signal power of the FSO channel in one direction is as follows [5,6]:

$$P_r = P_t \eta_t G_t \eta_r G_r \eta_\lambda (h_{al} \cdot h_{at} \cdot h_{pl}) \quad (3)$$

where G_t is the gain of the transmitting lens, G_r is the gain of the receiving lens, η_t is the additional loss due to coupling the optical signal source from the laser to the transmitting mirror, η_r is the coupling loss of the optical source from the receiving lens to the photodiode, and the optical filter loss at the received wavelength is η_λ . Let D_t be the diameter of the transmitting mirror and D_r be the diameter of the receiving mirror. Then, the beam pattern of the transmitted beam is $\theta_t \approx 2 \arctan \frac{D_r}{R_u}$; θ_r , the beam pattern of the light

source converging with the receiving mirror, is $\theta_r = 2\arctan\left(\frac{D_r}{2f_c}\right)$, where f_c is the focal length of the receiving mirror; the spherical surface of the optical wave at the receiving point is Ω_{FOV} , where $\Omega_{FOV} = 2\pi[1 - \cos(\theta_r/2)] \cong \left(\frac{\pi}{4}\right)\theta_r^2$; the gain of the receiving mirror is $G_r = \left(\frac{4\pi}{\lambda^2}\right)A_r$; and the gain of the transmitting mirror is $G_t = \left(\frac{4\pi}{\Omega_{FOV}}\right) \approx \left(\frac{4D_t}{\lambda^2}\right)^2$.

Symbol	Description
h_{at}	Atmospheric-turbulence fading coefficient
h_{pl}	Pointing-loss coefficient
h	Total FSO channel gain
Q	Q-factor
μ	Electrical signal-to-noise ratio

2.2. Atmospheric Absorption Loss

The absorption loss of air in free space as a function of the transmission distance R_z is expressed by the Beer–Lambert formula as follows [13,14]:

$$h_{al} = \exp(-R_z\xi) \quad (4)$$

where ξ is the attenuation coefficient. Hennes and Kim's study proposed the following formula for calculating attenuation due to fog, smoke, and clouds predicted by empirical models [5,6,14]:

$$L_{fog}(\lambda) = \frac{3.91}{V(\text{km})} \left(\frac{\lambda(\text{nm})}{550} \right)^{-p} \quad (5)$$

where $V(\text{km})$ is the observation distance, and p is the size distribution coefficient of the scattering area.

$$p = \begin{cases} 1.6 & V > 50 \\ 1.3 & 6 < V < 50 \\ 0.58 \cdot V^{1/2} & V < 6 \end{cases}$$

When the rain is 0.25 to 25 mm/h, the approximate formulas for calculating the rain attenuation and snow loss are as follows [9,10,14]:

$$L_{rain} = \frac{2.8}{V(\text{km})} \quad (6)$$

$$L_{snow} = \frac{58}{V} \quad (7)$$

2.3. Weather-Induced Atmospheric Turbulence Attenuation h_{at}

Atmospheric turbulence is a random phenomenon caused by changes in atmospheric temperature and pressure along the transmission line, forming turbulence cells, called vortices, with different sizes and refractive indices, causing interference between optical beams, resulting in a scintillation effect of the receiving beam. The scintillation index is a function of the air surface refractive index structure parameter C_n^2 . For weak to moderate turbulence conditions, turbulence is a random process that follows a log-normal distribution [9,21–24], while moderate to strong turbulence follows a gamma–gamma distribution function. The PDF of h_{at} based on the LN model is as follows:

$$f_{LN}(h_{at}) = \frac{1}{2 \cdot h_{at} \sqrt{2\pi \cdot \sigma_r^2}} \exp\left(-\frac{(\ln h_{at} + 2\sigma_r^2)^2}{8\sigma_r^2}\right) \quad (8)$$

where σ_r^2 is the Rytov variance of height $l(\text{m})$ with the following formula [14]:

$$\sigma_r^2 = 2.25 \left(\frac{2\pi}{\lambda} \right)^{\frac{7}{6}} (H - h_0)^{\frac{5}{6}} \sec(\theta_E)^{\frac{11}{6}} \times \int_{h_0}^H C_n^2(l) \left(1 - \frac{l - h_0}{H - h_0} \right)^{\frac{5}{6}} \cdot \left(\frac{l - h_0}{H - h_0} \right)^{\frac{5}{6}} dl \quad (9)$$

Similarly, the PDF of h —at according to the GG model is as follows:

$$f_{GG}(h_{at}) = \frac{2(\alpha.\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha).\Gamma(\beta)} \cdot h_{at}^{\frac{\alpha+\beta}{2}-1} \cdot K_{\alpha-\beta}(2\sqrt{\alpha.\beta.h_{at}}) \quad (10)$$

where $\Gamma(.)$ is the Gamma function and $K_v(.)$ is the Bessel function. The parameters α and β are represented as follows [14]:

$$\alpha = \left[\exp \left(0.49.\sigma_r^2 / (1 + 0.5.\sigma_r^{12/6})^{7/6} \right) - 1 \right]^{-1} \quad (11a)$$

$$\beta = \left[\exp \left(0.51.\sigma_{Bu}^2 / (1 + 0.69.\sigma_r^{12/6})^{5/6} \right) - 1 \right]^{-1} \quad (11b)$$

2.4. Transceiver Directional Offset Loss h_{pl}

Analyzing the spherical optical beam in 3D space of the FSO transmission channel from ground station A (A Earth station) at position $A(x_a, y_a, z_a)$ with height h_e to the UAV repeater station (UAV repeater station) at position Z_u , with coordinates $Z_u(x_u, y_u, z_u)$ and height H_u as shown in Figure 3, the transmission distance along the main axis is $R_z(m)$. The best transmission channel occurs when the optical beam travels from the laser to the center and converges at the focal point of the receiving mirror in series with the receiving photodiode. Figure 3 illustrates the geometric relationship between the ground station and the UAV relay, which is used to model the pointing error and axial deviation loss.

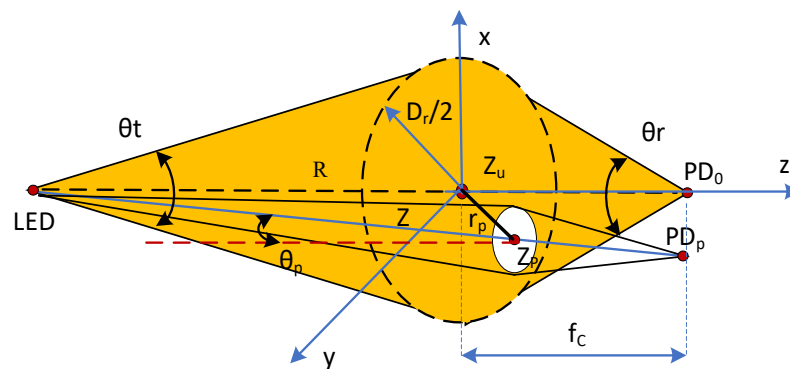


Figure 3. Diagram of the radio wave beam transmitted from station A to the UAV.

Suppose that the UAV moves off-axis from the main axis of the optical beam emitted from the center Z_u to point $Z_p(x_p, y_p, z_p)$. Let r_p be the eccentric distance between the center of the receiving mirror. The formula is as follows:

$$\|r_p\| = \sqrt{(x_u - x_p)^2 + (y_u - y_p)^2 + (z_u - z_p)^2} \quad (12)$$

When examining the change in the UAV's position in 3-dimensional space (x, y, z) , the variation along the z -axis is very low, so it can be disregarded. Thus, $\|r_p\| = \sqrt{(x_u - x_p)^2 + (y_u - y_p)^2}$. Similarly, the eccentricity angle along the x -axis is θ_{px} , and that along the y -axis is θ_{py} , so the general eccentricity angle will be as follows:

$$\theta_p = \sqrt{(\theta_{px})^2 + (\theta_{py})^2} \quad (13)$$

The change in UAV position in space is random, modeled according to a Gaussian normal distribution; thus, the eccentricity magnitude r_p and eccentricity angle θ_p are also calculated according to a normal distribution, with a mean of 0 and a variance of σ_0^2 , $N(0, \sigma_0^2)$, calculated using the following formula:

$$\sigma_0^2 = 2.07 \int_{h_e}^H C_n^2(l) \left(\frac{H_u - h_e}{\cos(\theta_E)} - l \right)^2 r_z^{-1/3} dl \quad (14)$$

where r_z is the radius of the beam sphere at point Z_u with height l , (θ_E) is the zenith angle of the UAV, and $C_n^2(l)$ is the refractive index structure parameter describing the intensity change of the optical signal beam disturbance with height l , with the following calculation formula [14]:

$$C_n^2(l) = 0.00594(V_\omega/27)^2(10^{-5}l)^{10}e^{-l/1000} + 2.7 \cdot 10^{-16} \cdot e^{-l/1500} + C_n^2(0)e^{-l/100} \quad (15)$$

where V_ω (m/s) is the average wind speed, and $C_n^2(0)$ is the refractive index structure at the ground calculated in $m^{-2/3}$. Consider a Gaussian distributed optical signal beam transmitted from the transmitter to the receiver with the optical signal source intensity as follows [9,22–24]:

$$I(p; Z) = \frac{2}{\pi \cdot \omega_z^2} \exp\left(-\frac{2 \cdot \|\rho\|^2}{\omega_z^2}\right) \quad (16)$$

where ρ is the main axis optical signal beam, and ω_z is the beam at a distance R_z received [9]:

$$\omega_z \approx \omega_0 \sqrt{1 + \varepsilon \left(\frac{\lambda R_z}{\pi \omega_0^2} \right)^2} \quad (17)$$

where ω_0 is the beam at $R_z = 0$. The formula for calculating the axial deviation loss according to the angle θ_p is as follows [9]:

$$h_{pl|\theta_d} = \int_{A_r} I(\rho - r_p; R_z) \cos(\theta_p) d\rho \quad (18)$$

Assuming that the radius of the optical beam cross-section at a distance R_z is $r_z \gg r_p$, Formula (18) is approximated as follows:

$$h_{pl|\theta_d} \approx 2 \cdot \left(\frac{1/2 \cdot D_r}{r_z^2} \right)^2 \exp\left(-\frac{2 \cdot \|r_p\|^2}{r_z^2}\right) \cos(\theta_p) \quad (19)$$

According to Figure 3, the axis deviation distance $r_p = \|r_p\|$ is a Rayleigh distributed random variable with the following PDF [9]:

$$f_{r_p}(r_p) = \frac{r_p}{\sigma_r^2} \exp\left(-\frac{r_p^2}{2 \cdot \sigma_r^2}\right); r_p \geq 0 \quad (20)$$

From (19) and (20), the PDF of h_{pl} can be deduced according to θ_p as follows:

$$f(h_{pl}|\theta_d)(h_{pl}) = C_1^{-C_2} \cdot C_3 \cdot h_{pl}^{C_3-1} \cdot \cos(\theta_d) \quad (21)$$

where $C_1 = 2 \cdot \left(\frac{r_d}{\omega_z^2} \right)^2$, $C_2 = \frac{2}{\omega_z^2}$, and $C_3 = \frac{1}{2 \cdot C_2 \omega_r^2}$. From Formula (10), considering the component h_{al} as a constant parameter, and h_{at} and h_{pl} as functions that change randomly according to the channel distribution, the distribution density function PDF of the channel loss product function FSO is $h = h_{al} \cdot h_{at} \cdot h_{pl}$ according to the axis deviation angle θ_p and is written as follows [9]:

$$f(h|\theta_d)(h) = \int \left(\frac{1}{h_{al}} \right) f(h_{pl}|\theta_d)(h_{pl}) f_{h_{at}}(h_{at}) dh_{at} \quad (22)$$

Replace (13), (11), and (20) with (21), the PDF of h according to both atmospheric turbulence models LN and GG in (22) and (23), respectively, where $C_4 = \frac{2.C_3(\alpha,\beta)^{\frac{\alpha+\beta}{2}}}{h_{at}^{C_3} \cdot \Gamma(\alpha) \cdot \Gamma(\beta)}$, $C_5 = \frac{\alpha+\beta-2C_2}{2}$

$$f_{(h|\theta_d)}^{LN}(h) = \frac{C_3 \cdot C_1^{-C_3} \cdot h_h^{C_3-1}}{2 \cdot h_{at}^{C_3} \sqrt{2\pi\sigma_r^2}} \sqrt{8\pi\sigma_r^2} \exp\left(8 \cdot \sigma_r^2 \left(\left(\frac{2 \cdot C_3 + 1}{4}\right)^2 - \frac{1}{16}\right)\right) \quad (23)$$

$$f_{(h|\theta_d)}^{GG}(h) = \frac{2^{2.C_5+1} \cdot C_1^{-C_3} \cdot h_h^{C_3-1} \cdot C_4 \cos(\theta_d)}{(4 \cdot \alpha \cdot \beta)^{C_5+1}} \Gamma\left(\frac{2C_5 + 2 + \alpha - \beta}{2}\right) \cdot \Gamma\left(\frac{2C_5 + 2 - \alpha + \beta}{2}\right) \quad (24)$$

3. Signal-to-Noise Ratio (SNR)

Notation convention: To avoid ambiguity, σ_r^2 denotes the Rytov-variance-related turbulence quantity in the analytical model, σ_n^2 denotes the total receiver-noise variance, and σ_B^2 denotes the background-radiation noise variance. The gamma–gamma shape parameters are denoted by α and β , whereas M and N denote the numbers of ground-side transmit and receive apertures. The symbols a and b are not used as substitutes for α and β . These analytical parameters establish the physical basis of the model; the OptiSystem implementation uses the aggregate loss values specified in Section 6.1 rather than independently calibrated Cn^2 , α , β , or pointing-jitter parameters.

Let us assume that the digital optical radio transmission channel after modulation is given by the following:

$$m(t) = A_k g(t - kT) d_k \cos(\omega_c t + \varphi_k) \quad (25)$$

where $d_k \in \{-1, +1\}$ gives the bit data $\{0,1\}$, $g(t - kT)$ is the rectangular pulse characteristic function, and T is the symbol duration. The laser generates the optical signal source after BPSK digital modulation, transmitting through the atmosphere to the receiver. The receiver uses a photodiode and a low-pass filter (LPF) to recover the digital signal stream d_k with minimal distortion as follows [12]:

$$i_r(t) = R_p \cdot I(1 + \xi m(t)) + n(t) \quad (26)$$

where ξ is the modulation index, R_p is the sensitivity of the photodetector, and $n(t)$ is the additive noise. The amplitude of the digital signal current can be modeled as follows [12]:

$$i_r(t) = \frac{d_k I \cdot R_p \cdot \xi [A \cdot h] g(t - kT)}{2} + n_r(t) \quad (27)$$

The AWGN channel noise, with a normal distribution, $n(t) \sim N(0, \sigma_t^2)$, affects the digital signal recovery current. The probability density function (PDF) of the received current I after the optical detector is given by the following [16]:

$$p_I(I) = \frac{1}{\sqrt{2\pi}\sigma} \frac{1}{I} \exp\left\{-\frac{(\ln(I/I_0) + 0.5\sigma_t^2)^2}{2 \cdot \sigma_t^2}\right\}; I \geq 0 \quad (28)$$

The signal-to-noise ratio (SNR) after the receiver demodulator will be as follows:

$$SNR = \frac{(I \cdot R_p \cdot \xi [A \cdot h])^2}{2\sigma^2} = \left(\frac{I R_p \xi \cdot [A \cdot h]}{\sqrt{2}\sigma}\right)^2 = (Q)^2 \quad (29)$$

Q is the ratio of the received signal amplitude to the noise amplitude. The average SNR will be denoted by $\bar{\mu} = \frac{(\eta \cdot E[I])^2}{N}$, where $E[\cdot]$ denotes the mathematical expectation. The PDF of the SNR can be written as follows:

$$f_{\mu}(\mu) = \frac{1}{2\mu\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln(\mu/\bar{\mu}) + \sigma^2)^2}{8\sigma^2}\right) \quad (30)$$

The result of calculating the integral $F_{\mu}(\mu) = \int_{-\infty}^{\mu} f_{\mu}(\mu) d\mu$ will be the cumulative distribution function (CDF) for μ as follows [18]:

$$F_{\mu}(\mu) = \frac{1}{2} \operatorname{erfc}\left(\frac{\ln(\bar{\mu}/\mu) - \sigma^2}{2\sqrt{2}\sigma}\right) \quad (31)$$

Equations (30) and (31) present the PDF and CDF of the log-normal distributed SNR of the disturbed channel.

Similarly, by integrating (15), the CDF of the gamma–gamma distributed strong-type disturbance model with respect to parameter I can be derived as follows [18]:

$$F_I(I) = \frac{(abI)^{(a+b)/2}}{\Gamma(a)\Gamma(b)} G_{1,3}^{2,1}\left(abI \left| \begin{matrix} 1 - \frac{a+b}{2} \\ \frac{a-b}{2}, \frac{b-a}{2}, -\frac{a+b}{2} \end{matrix} \right. \right) \quad (32)$$

where $G_{p,q}^{m,n}[\cdot]$ is the Meijer G function. The PDF of SNR μ is calculated as follows:

$$f_{\mu}(\mu) = \frac{(ab)^{(a+b)/2}}{\Gamma(a)\Gamma(b)} \cdot \frac{\mu^{\{(a+b)/4\}-1}}{\bar{\mu}^{(a+b)/4}} K_{a-b}\left(2\sqrt{ab\frac{\mu}{\bar{\mu}}}\right) \quad (33)$$

We express the Bessel function $K_{\nu}(\cdot)$ in terms of the Meijer function $G_{p,q}^{m,n}[\cdot]$ as the following formula:

$$\left(K_{\nu}(z) = \frac{1}{2} G_{0,2}^{2,0}\left(z \left| \begin{matrix} \nu \\ \frac{\nu}{2}, -\frac{\nu}{2} \end{matrix} \right. \right)\right) \quad (34)$$

The result of integrating according to (33) obtains the cumulative distribution function (CDF) of the SNR according to the gamma–gamma noise model as follows:

$$F_{\mu}(\mu) = \frac{(ab)^{(a+b)/2}}{\Gamma(a)\Gamma(b)} \left(\frac{\mu}{\bar{\mu}}\right)^{(a+b)/4} \times G_{1,3}^{2,1}\left(ab\sqrt{\frac{\mu}{\bar{\mu}}} \left| \begin{matrix} 1 - \frac{a+b}{2} \\ \frac{a-b}{2}, \frac{b-a}{2}, -\frac{a+b}{2} \end{matrix} \right. \right) \quad (35)$$

Therefore, according to (34) and (35), the PDF and CDFs of the ratio μ according to the gamma–gamma distribution are as above.

4. Discussion

According to Formula (3), the optical signal power increases when the transmit and receive aperture gains increase. According to the pointing-loss and received-power relationships, reducing the off-axis loss generally requires a larger receive aperture. However, increasing the receiving mirror area on the UAV also increases the mass, aerodynamic drag, alignment complexity, and background-radiation collection, which can reduce the effective SNR. Background noise is modeled as a Gaussian process with variance σ_B^2 as follows [14]:

$$\sigma_n^2 = 2 \cdot e \cdot B \cdot \eta \cdot P_{bg} \quad (36)$$

In this case, e is the electron charge, B represents the photodiode bandwidth, and P_{bg} is the background-light power collected by the receiver aperture. This payload–noise trade-off motivates the MOSI/SOMI structure: the larger and multiple diversity apertures are placed mainly at the ground stations, where size, mass, power, and stabilization constraints are less restrictive, while the UAV carries only one receiver and one transmitter.

The very small BER values reported later are therefore used together with the Q-factor and received power to compare the simulated decision margin after the practical 10^{-12} target has already been exceeded; they are not presented as field-validated error-free operation.

5. Proposed MOSI/SOMI MIMO-FSO Relay Architecture

The proposed MOSI/SOMI MIMO-FSO relay model has M optical transmit apertures at ground station A, N optical receive apertures at ground station B, and only one upward-facing receiver and one relay transmitter on the UAV. The terms MOSI and SOMI are used in this manuscript as hardware-placement descriptors: MOSI refers to M ground transmit outputs feeding one UAV input on the uplink, whereas SOMI refers to one UAV output feeding N ground receiving inputs on the downlink. Assuming statistically independent transmit and receive apertures, the combined optical signal current at the UAV and at ground station B, using equal-gain combining (EGC), is expressed as follows:

$$r_u(t) = \frac{\eta_r s_u(t)}{M_u} \sum_{m=1}^{M_u} I_m + n_u(t) \quad (37)$$

$$r_d(t) = \frac{\eta_r s_d(t)}{N_d} \sum_{n=1}^{N_d} I_n + n_d(t) \quad (38)$$

Here, the photodiode responsivity and the branch currents are defined consistently with the preceding receiver model, and equal-gain combining is applied to the recovered branch signals. The UAV-side optical branch count remains two—one receiving and one transmitting branch—when the ground-side diversity order is increased from 2×2 to 4×4 . Figure 4 illustrates the resulting MOSI/SOMI hardware placement.

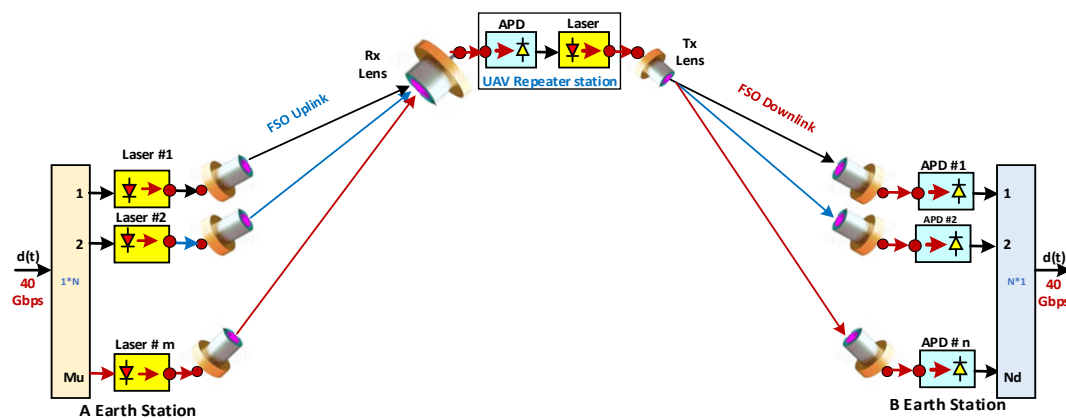


Figure 4. Proposed MOSI/SOMI MIMO-FSO relay architecture with ground-side diversity and a single receive/transmit optical chain on the UAV.

The received digital signal current intensity of the improved MIMO-FSO configuration will be as follows:

$$i_{r-EGC}(t) = \frac{d_k R_p \xi [A.h] g(t-kT)}{2.N_d} \left(\sum_{n=1}^{N_d} I_n \right) + n_d(t) \quad (39)$$

The ratio of received signal power to noise power (SNR) can be rewritten as follows:

$$SNR_{EGC-MIMO} = \frac{\left(\frac{d_k R_p \xi [A.h] g(t-kT)}{2.N_d} \left(\sum_{n=1}^{N_d} I_n \right) \right)^2}{(\sigma^2)} = \frac{(\eta_r I)^2}{N_d \cdot (2\sigma^2)} \quad (40)$$

6. Simulation

6.1. Simulation Parameters

Based on the analytical atmospheric-loss framework in Sections 2 and 3, propagation guidance for terrestrial FSO links [25], related UAV-FSO studies [9,17,22], and the device-level 40 Gbit/s interface context in ITU-T G.693 [11], the following parameters were adopted: laser launch power = 10 dBm per active branch; uplink optical carrier = 193.1 THz; downlink optical carrier = 193.2 THz; optical amplifier gain = 32 dB per active branch; bit rate = 40 Gbit/s; receiver-sensitivity reference = −21 dBm; practical BER target = 10^{-12} ; link length per hop = 1.54 km; atmospheric absorption/scattering loss = 25 dB/km; equivalent combined turbulence- and pointing-related loss = 25.5 dB/km; transmitter coupling loss = 0.3 dB; receiver coupling loss = 0.3 dB; device-aging margin = 1.0 dB; transmitter aperture diameter = 5 cm; and receiver aperture diameter = 20 cm. The same values were used in the SISO, 2×2 , and 4×4 OptiSystem cases. ITU-T G.693 is cited only as a device-level reference and is not used as an atmospheric UAV-FSO performance standard. Because 10 dBm and 32 dB are assigned to every active branch, the aggregate launched optical resources increase with diversity order; the comparison is therefore intentionally described as per-branch rather than equal-total-power.

Representation of adverse atmospheric conditions. The original analytical model describes Beer–Lambert attenuation, log-normal/gamma–gamma turbulence, and Gaussian/Rayleigh pointing-error statistics. In the OptiSystem implementation, these mechanisms are not entered through independently calibrated C_n^2 , α , β , beam-jitter variance, or angular-deviation parameters. Instead, their net effect is represented by the original equivalent loss settings: 25 dB/km atmospheric absorption/scattering and an additional 25.5 dB/km combined turbulence- and pointing-related loss over each 1.54 km hop, together with 0.3 dB coupling loss at each optical interface and a 1.0 dB aging margin. Accordingly, the phrase “adverse” or “severe” conditions refers to this repeatable high-loss stress-test scenario, not to a site-specific measured weather record. Identical loss settings are applied to all three architectures.

Physical model versus OptiSystem implementation. Sections 2–5 establish the physical relationships among atmospheric loss, turbulence, pointing error, receiver noise, and the proposed relay architecture. Section 6 implements the resulting link in OptiSystem using PRBS generation, optical carriers, branch amplifiers, FSO channel blocks, photodetectors, Bessel filters, equal-gain combining, optical spectrum analyzers, eye diagram analyzers, and BER analyzers. The simulation uses equivalent aggregate impairment settings and does not separately calibrate C_n^2 , α , β , pointing-jitter variance, long-duration weather variation, UAV vibration dynamics, or acquisition/tracking/control-loop transients. These assumptions delimit the interpretation of the results while keeping the implementation consistent with the original manuscript.

6.2. OptiSystem Simulation Diagram of the SISO-FSO Baseline Link

The simulation model represents a UAV-assisted free-space optical (FSO) communication link implemented in OptiSystem. A pseudo-random binary sequence (PRBS) is generated and directly modulates a laser source operating at an optical carrier frequency of 193.2 THz. The modulated optical signal is amplified and transmitted through an atmospheric FSO channel with a link distance of 1.54 km, incorporating absorption loss, geometric loss, atmospheric turbulence, and pointing error effects.

At the UAV relay node, the received optical signal is detected using a photodetector filtered by a low-pass Bessel filter, and re-amplified by an optical amplifier before being retransmitted over the downlink FSO channel. The downlink employs similar atmospheric parameters and optical components. At the ground receiving station, the signal is

photodetected, filtered, and regenerated for performance evaluation. Optical spectrum analyzers and optical power meters are used to monitor signal characteristics along the link. In contrast, an eye diagram analyzer and a BER analyzer are employed to evaluate signal quality in terms of Q-factor and bit error rate. This simulation framework is used to compare the performance of SISO and improved MIMO-FSO configurations under identical channel conditions. Figure 5 presents the SISO-FSO simulation model, which is used as a baseline for comparison with the proposed MIMO-FSO configurations.

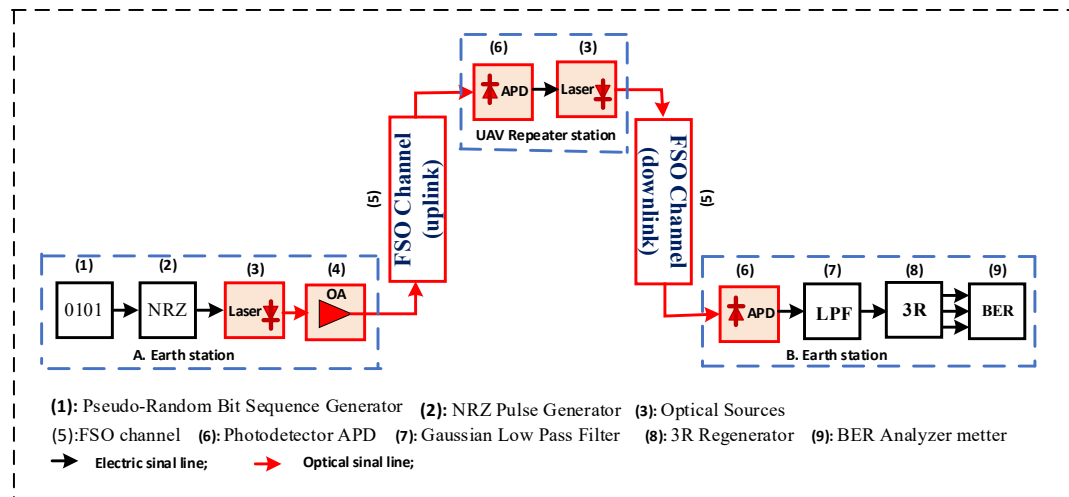


Figure 5. Simulation diagram of a SISO-FSO wireless optical transmission channel.

6.3. Simulation Results

Figure 6 presents the uplink optical signal characteristics at the ground transmitting station and at the UAV receiver. At the ground station, the transmitted optical signal exhibits a stable output power with a broadened spectrum centered on the carrier frequency (≈ 193.1 THz), mainly due to direct intensity modulation and amplifier noise. After propagating through the atmospheric FSO channel, the received optical power at the UAV is significantly attenuated due to absorption loss, geometric spreading, atmospheric turbulence, and pointing error. This attenuation is reflected by a noticeable reduction in total received power and a narrower, noise-suppressed spectrum at the UAV receiver. Nevertheless, the main spectral component remains clearly distinguishable from the noise floor, indicating that the uplink maintains sufficient signal integrity for reliable detection and relay amplification.

These results show that, under the high-loss setup defined in Section 6.1—25 dB/km atmospheric absorption/scattering plus 25.5 dB/km equivalent turbulence- and pointing-related loss over the 1.54 km uplink—the principal optical component remains distinguishable from the noise floor and retains a sufficient simulated margin for relay detection and regeneration.

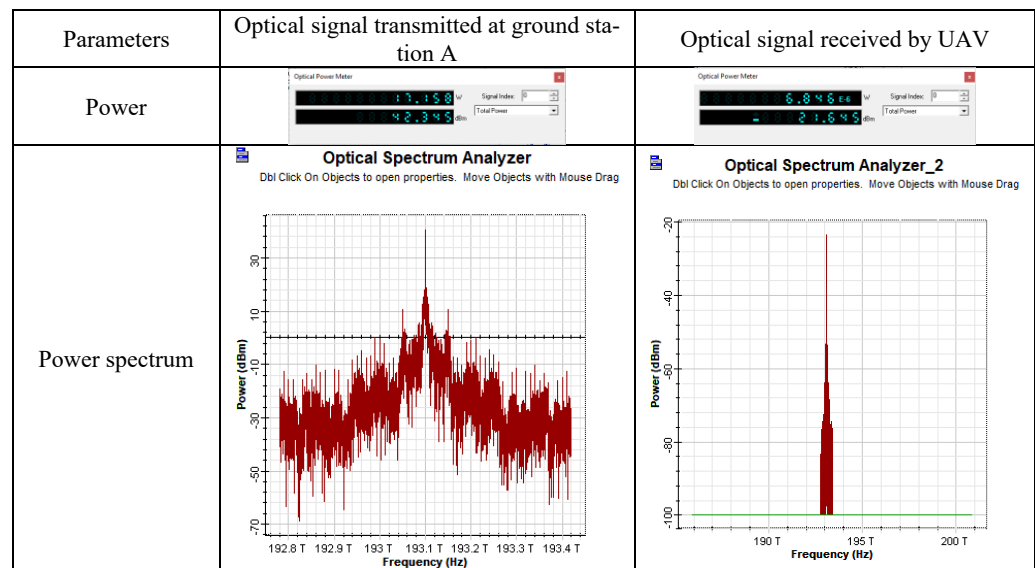


Figure 6. Optical signal on the uplink.

Figure 7 illustrates the downlink optical signal at the UAV transmitter and at ground station B. The same 1.54 km high-loss settings used for the uplink are applied to the downlink: 25 dB/km atmospheric absorption/scattering, 25.5 dB/km equivalent combined turbulence- and pointing-related loss, interface coupling losses, and the device-aging margin. Although the received power is attenuated, the dominant spectral component remains distinguishable from the simulated noise floor, indicating that the downlink can support photodetection and signal recovery under the adopted stress-test assumptions.

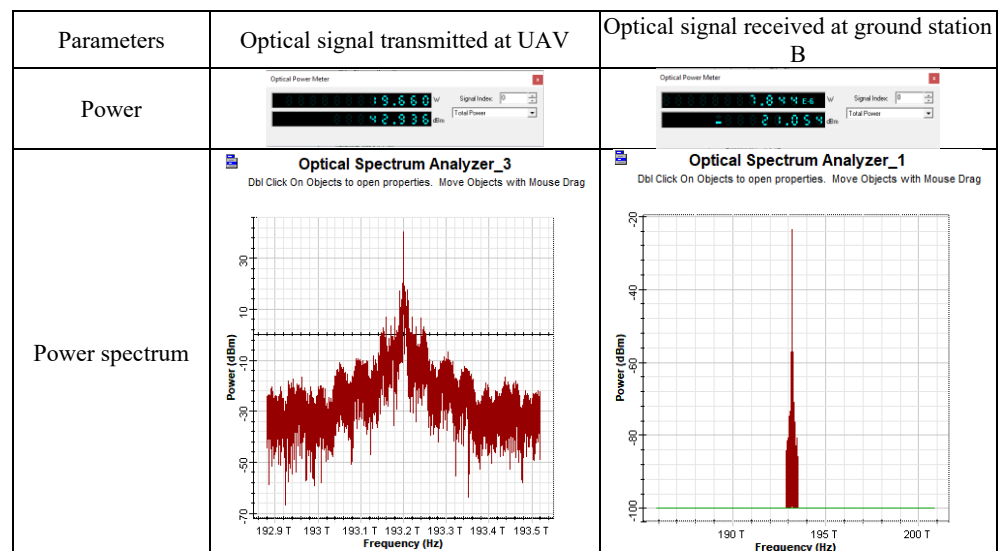


Figure 7. Optical signal on the downlink.

Digital signal quality received at ground station B

Figure 8 presents the Q-factor evolution and the corresponding eye diagram of the received signal at ground station B. The Q-factor reaches its maximum near the optimal sampling instant, indicating a favorable signal-to-noise ratio and stable decision threshold at the receiver.

The eye diagram exhibits a clearly open eye with distinct separation between logical '1' and '0' levels, demonstrating limited intersymbol interference and moderate noise influence. Although amplitude fluctuations are observable due to atmospheric turbulence

and pointing errors, the eye opening remains sufficiently wide to ensure reliable symbol detection.

These results indicate that the baseline SISO FSO link maintains acceptable signal quality after UAV-assisted relay transmission within the idealized OptiSystem setup. Figure 8 illustrates the Q-factor and eye diagram of the SISO configuration, serving as a reference for subsequent MIMO-FSO performance evaluation.

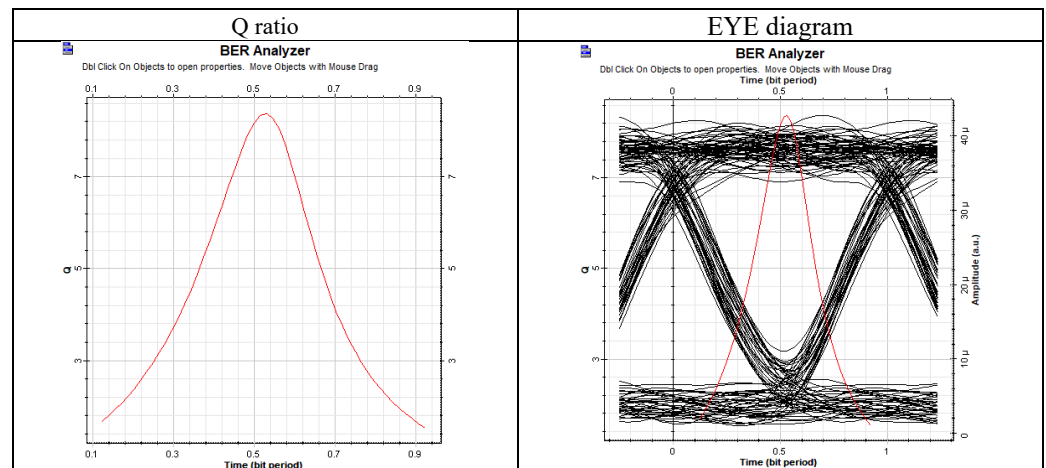


Figure 8. Q-factor and eye diagram for the SISO baseline.

Figure 9 shows the BER variation and the corresponding quality-analysis output at ground station B. The BER Analyzer directly reports the minimum BER metric from the simulated receiver waveform, and the minimum occurs near the optimum sampling instant. However, a finite simulation does not transmit the 10^{43} – 10^{75} bits that would be required to validate such probabilities by raw error counting. Therefore, BER values far below 10^{-12} are retained as software-reported indicators of decision margin and are interpreted together with the received power, Q-factor, and the eye diagram.

The quality analysis further reports a maximum Q-factor of 8.38 and a well-defined eye height, which together reflect a sufficient noise margin and clear separation between logical levels. The stable decision instant close to the center of the bit period indicates low intersymbol interference in the simulated receiver chain.

These results validate that the baseline SISO FSO link maintains detectable signal integrity after UAV-assisted relay transmission under the stated stress-test channel parameters. The minimum simulated BER reaches approximately 2.73×10^{-17} , which is already below the practical 10^{-12} target and therefore indicates a sufficient numerical link margin for the considered SISO case rather than a directly field-measured long-term error probability.

The two modulated branches propagate through independently instantiated FSO channel blocks with identical equivalent loss settings. At the UAV, the optical branches are combined and detected by a single photodetector. Thus, the 2×2 implementation preserves the original signal-flow concept while avoiding the duplication of UAV-side optical receiver hardware.

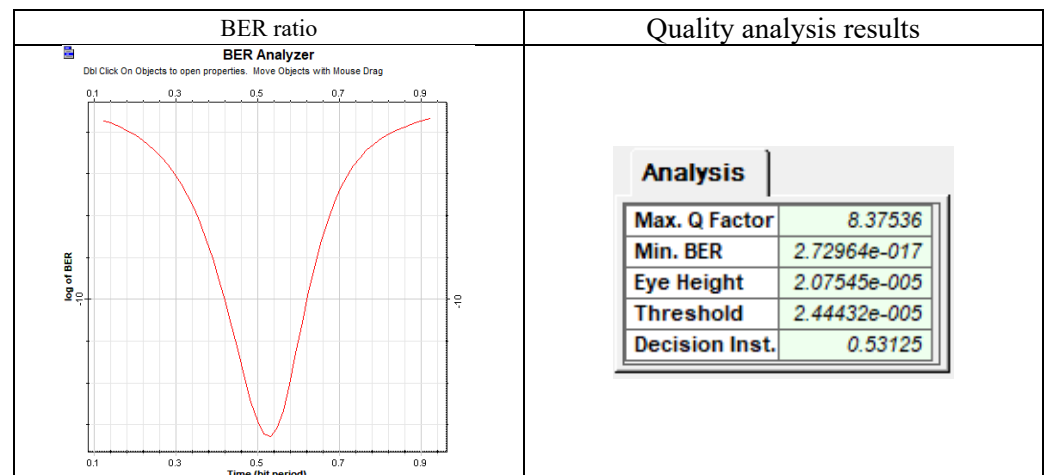


Figure 9. BER ratio and quality analysis results for the SISO baseline.

6.4. Simulation Results of the Proposed 2×2 MIMO-FSO Configuration in OptiSystem

Figure 10 illustrates a clean schematic of the proposed 2×2 MOSI/SOMI MIMO-FSO relay implementation in OptiSystem. At ground station A, a PRBS generator drives two parallel optical transmitters through a power splitter, forming the MOSI uplink. The two optical branches propagate through independent FSO channel blocks toward a single UAV receiver. At the UAV, the branches are combined, detected, regenerated, amplified, and retransmitted using one relay transmitter. On the downlink, the single UAV transmitter illuminates two ground receiving branches, forming the SOMI downlink, and the recovered electrical branches are combined at ground station B.

The two optical signals are transmitted through independent uplink FSO channels toward the UAV relay. These channels incorporate atmospheric attenuation, geometric loss, turbulence effects, and pointing errors under identical propagation conditions. At the UAV, the received optical signals are combined using an optical power combiner and detected by a single photodetector, thereby reducing the number of optical components and minimizing the payload on the UAV platform.

This improved 2×2 configuration enhances received optical power and link robustness while maintaining a lightweight UAV relay architecture. The simplified high-resolution schematic in Figure 10 replaces a small software screenshot to improve readability, while preserving the same OptiSystem signal-flow logic.

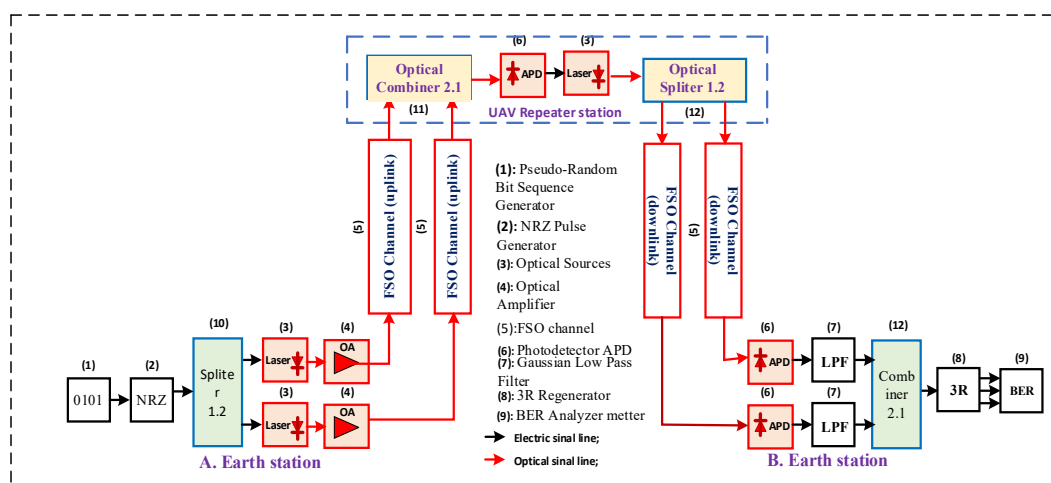


Figure 10. Clean high-resolution schematic of the proposed 2×2 MOSI/SOMI MIMO-FSO relay implementation in OptiSystem.

Simulation results of the received signal stream quality at ground station B

Figures 11 and 12 present the signal quality performance of the improved MIMO-FSO (2×2) configuration at the ground receiving station. As shown in Figure 11, the Q-factor reaches a peak value of approximately 13.79 at the optimal sampling instant, indicating a substantial improvement in signal-to-noise ratio compared to the SISO case. The corresponding eye diagram exhibits a wide eye opening with clear separation between logical levels, reflecting reduced intersymbol interference and enhanced noise tolerance.

Figure 12 further confirms the 2×2 performance improvement. The OptiSystem BER Analyzer reports a minimum BER of approximately 1.53×10^{-43} . Because this value is far below the range that can be validated by finite raw error counting, it is interpreted as a comparative link-margin indicator rather than as a field-measured probability. The Q-factor, eye opening, and received-power improvement provide the accompanying engineering evidence of improved receiver margin.

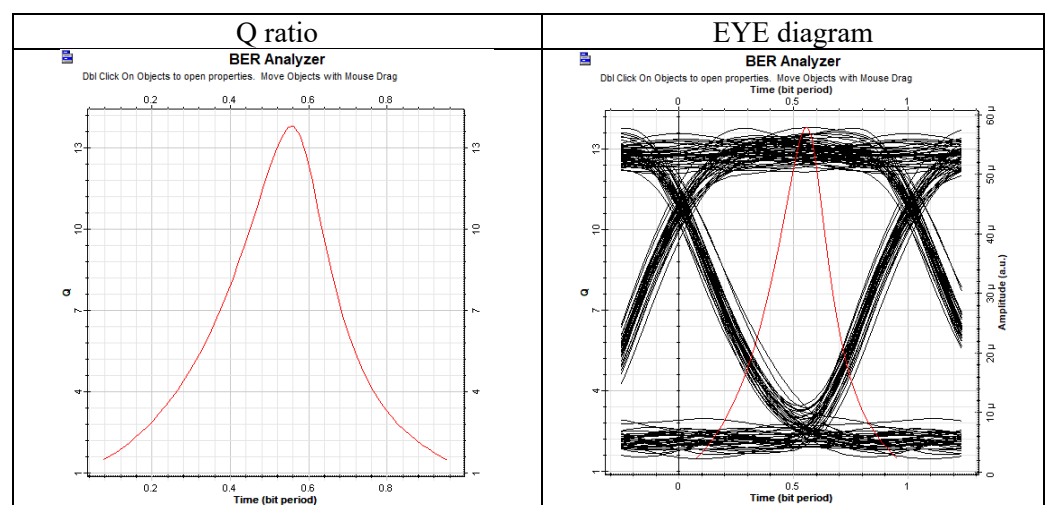


Figure 11. Q-factor and eye diagram for the 2×2 configuration.

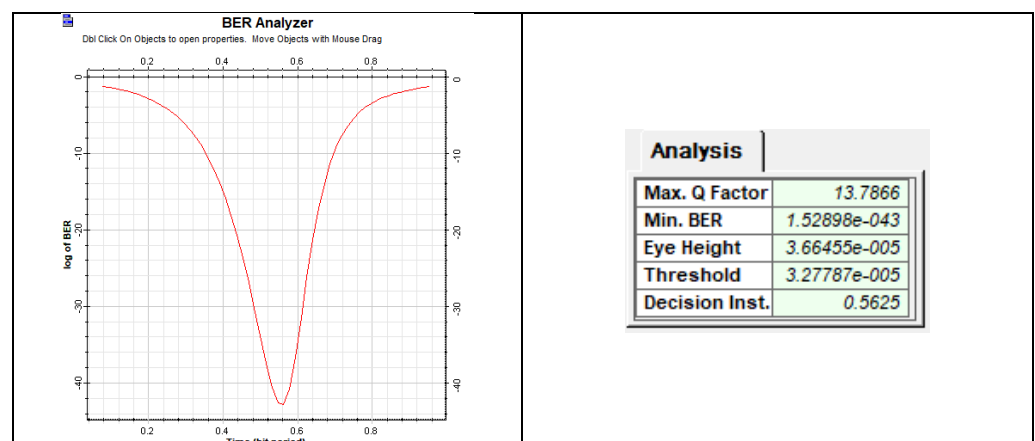


Figure 12. BER ratio and quality analysis results for the 2×2 configuration.

6.5. Simulation Results of the Proposed 4×4 MIMO-FSO Configuration in OptiSystem

Figure 13 illustrates a clean schematic of the proposed 4×4 MOSI/SOMI MIMO-FSO relay implementation in OptiSystem. At ground station A, a PRBS generator drives four parallel optical transmitters through a power splitter, forming the MOSI uplink. The four optical branches propagate through independent FSO channel blocks toward a single UAV receiver. At the UAV, the received branches are combined, detected, regenerated, amplified, and retransmitted using one relay transmitter. On the downlink, the single

UAV transmitter illuminates four ground receiving branches, forming the SOMI downlink, and the recovered electrical branches are combined at ground station B.

The four modulated branches propagate through independently instantiated FSO channel blocks with the same equivalent atmospheric and misalignment-loss settings. At the UAV, the branches are combined and detected using a single optical receiver, thereby keeping the UAV-side optical architecture unchanged while the ground-side diversity order is increased.

This improved 4×4 configuration further enhances the received optical power, Q-factor, and link margin compared with the 2×2 and SISO configurations, while keeping the UAV-side optical branch count fixed at two. The simplified high-resolution schematic in Figure 13 replaces a small software screenshot to improve readability and to emphasize the hardware-placement principle of the proposed MOSI/SOMI relay.

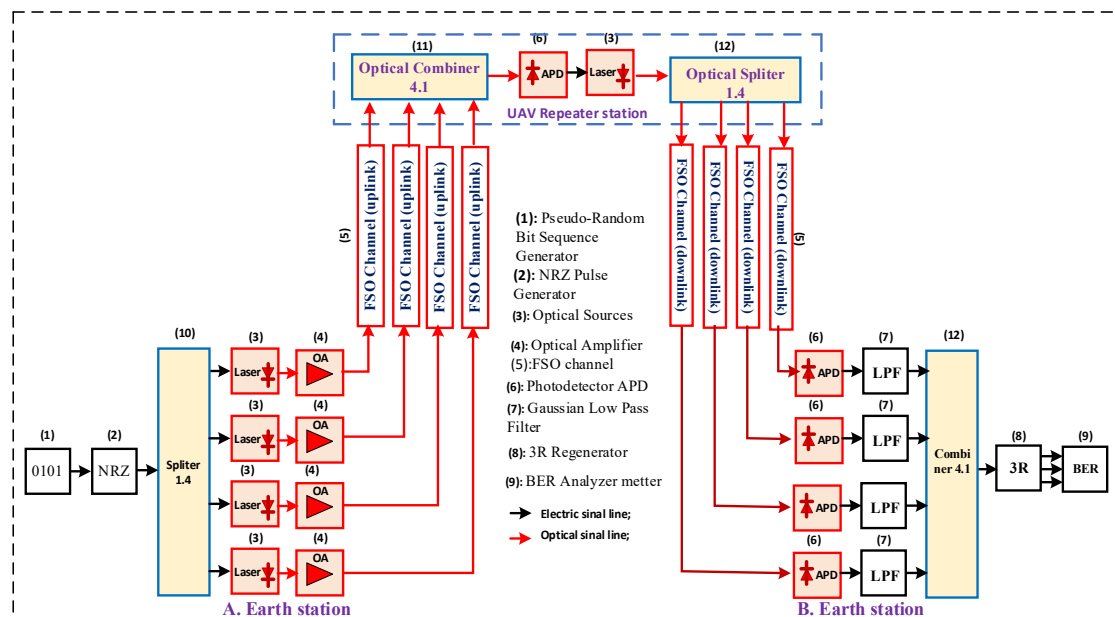


Figure 13. Clean high-resolution schematic of the proposed 4×4 MOSI/SOMI MIMO-FSO relay implementation in OptiSystem.

6.6. Received-Signal Quality at Ground Station B

Figures 14 and 15 illustrate the signal quality performance of the improved MIMO-FSO (4×4) configuration at the ground receiving station. As shown in Figure 14, the Q-factor reaches a maximum value of approximately 18.25 at the optimal sampling instant, indicating a substantial enhancement in signal-to-noise ratio compared with both the SISO and 2×2 MIMO-FSO configurations. The corresponding eye diagram exhibits a significantly wider eye opening and improved vertical eye height, reflecting strong immunity to intersymbol interference and atmospheric noise.

Figure 15 further confirms the performance improvement through the BER analysis. The OptiSystem BER Analyzer reports a minimum value of approximately 9.95×10^{-75} for the 4×4 case. This value is retained exactly as reported by the software, but it cannot be interpreted as an empirically counted field BER over a finite data sequence. Its practical meaning is that the simulated receiver has a substantially larger decision margin than the 10^{-12} design target and then the SISO and 2×2 cases. The received-power, Q-factor, and eye diagram results provide the more directly interpretable engineering comparison.

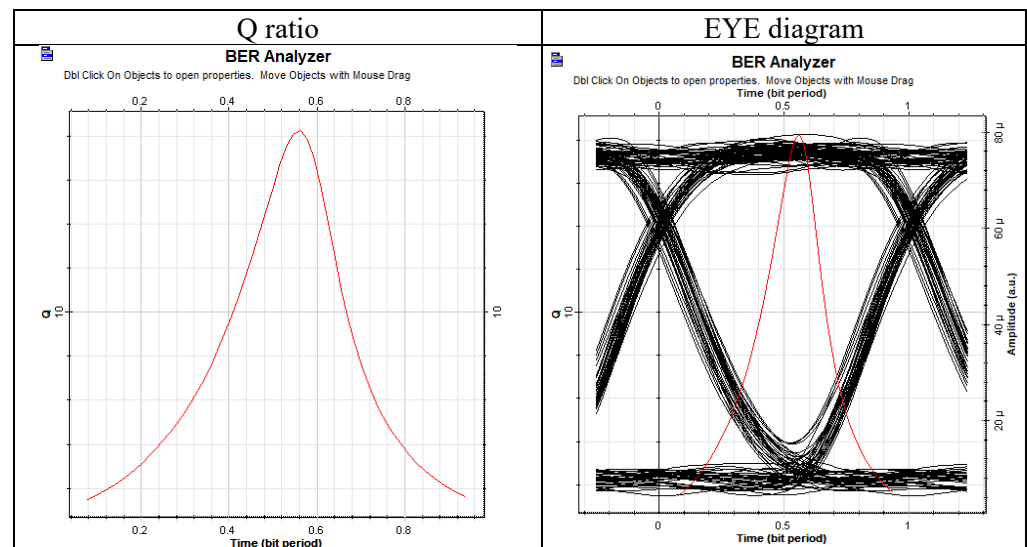


Figure 14. Q-factor and eye diagram for the 4×4 configuration.

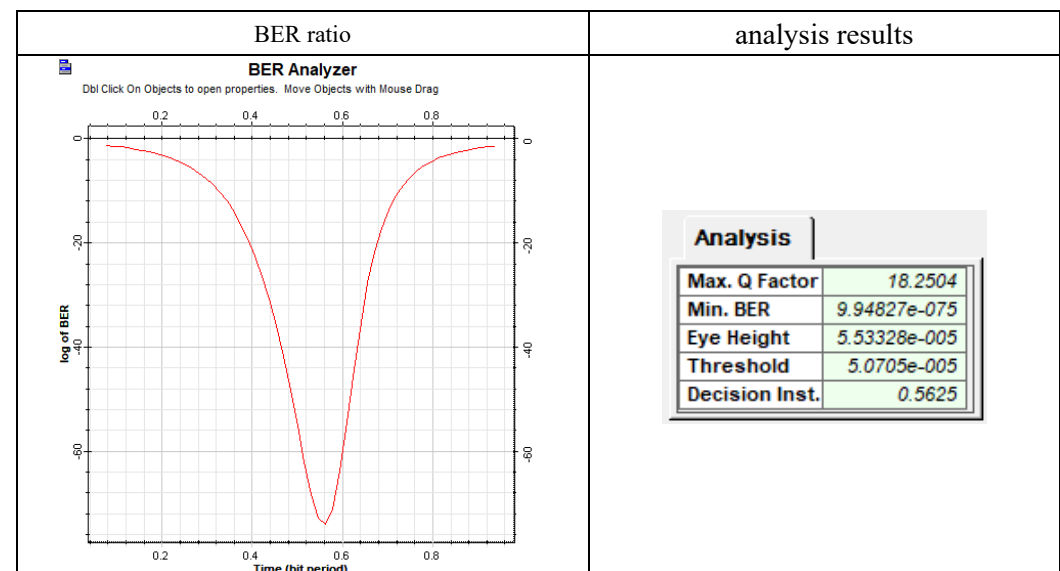


Figure 15. BER ratio and analysis results for the 4×4 configuration.

6.7. Analysis and Comparison of Results

Simulation results show that the received optical power at ground station B increases from -21.054 dBm (SISO) to -18.810 dBm (2×2) and -16.194 dBm (4×4). The maximum Q-factor increases from 8.37536 to 13.7866 and 18.2504, respectively. The OptiSystem BER Analyzer reports minimum values of 2.72964×10^{-17} , 1.52898×10^{-43} , and 9.94827×10^{-75} . Because all values already exceed the practical 10^{-12} reliability target by a wide margin, the very small BER outputs are used primarily to indicate the relative receiver decision margin; the received power, Q-factor, and eye opening remain the more directly interpretable engineering metrics. Table 1 also reports the per-branch laser and amplifier settings so that the power-comparison basis is explicit.

Table 1. OptiSystem results and per-branch optical settings for the SISO, 2×2 , and 4×4 configurations.

Parameter	SISO	MIMO (2×2)	MIMO (4×4)
Received power at ground station B, Pr (dBm)	−21.054	−18.810	−16.194

Maximum Q-factor	8.37536	13.7866	18.2504
OptiSystem-reported minimum BER	2.72964×10^{-17}	1.52898×10^{-43}	9.94827×10^{-75}
Laser launch power per active branch (dBm)	10	10	10
Optical amplifier gain per active branch (dB)	32	32	32
Aggregate laser launch power before amplification (dBm)	10.00	13.01	16.02
Equal-total-power normalized	Baseline	No	No

The comparison between the 2×2 and 4×4 MIMO-FSO configurations highlights the performance gains achievable by increasing the ground-side spatial diversity in UAV-assisted FSO links. While the 2×2 configuration already provides a significant improvement over the conventional SISO system in terms of the received power, Q-factor, and BER, further enhancement is observed when extending the ground-side diversity order to 4×4 .

Specifically, the 4×4 configuration exhibits a higher received optical power and Q-factor than the 2×2 and SISO cases, together with a smaller software-reported minimum BER. The improvement results from the combined effects of additional ground-side optical branches, equal-gain combining, and increased aggregate launched optical resources; it should not be attributed to diversity gain alone under an equal-total-power constraint.

Power-comparison interpretation. Each active laser emits 10 dBm, and each active branch uses an individual 32 dB optical amplifier. Before amplification, the aggregate laser launch power is therefore 10 dBm for SISO, approximately 13.01 dBm for two active branches, and approximately 16.02 dBm for four active branches. The 2×2 and 4×4 cases thus use approximately 3 dB and 6 dB more aggregate launch power than the SISO case, respectively. The present results quantify the benefit available when additional ground-side branch hardware and optical power are permitted; they are not an equal-total-energy diversity comparison. An equal-total-power study is identified as future work.

Overall, the 2×2 configuration provides a moderate improvement with fewer additional ground-side branches, whereas the 4×4 configuration provides the largest simulated receiver margin at the cost of greater ground-station hardware and aggregate optical power. These findings are intentionally framed as simulation-based evidence and do not constitute the field validation of ultra-reliable or error-free operation.

7. Conclusions

This study presented a payload-efficient MOSI/SOMI MIMO-FSO architecture for UAV-assisted relay links. The proposed hardware placement shifts the parallel optical branches to the ground stations while retaining one optical receiver and one optical transmitter on the UAV. Under the adopted symmetric-relay comparison assumption, the UAV-side branch count is reduced from eight to two in the 4×4 case, corresponding to a 75% branch-count reduction proxy; the exact mass and power savings require hardware validation. Under the high-loss OptiSystem settings defined in Section 6.1, the 4×4 configuration increases the received optical power from -21.054 dBm to -16.194 dBm and the Q-factor from 8.38 to 18.25 relative to SISO. The BER Analyzer also reports progressively smaller minimum BER values, but outputs far below 10^{-12} are interpreted as comparative decision-margin indicators rather than finite-length field measurements. The results therefore provide simulation-based evidence that the proposed ground-shifted diversity architecture can improve the link margin in transport-oriented FSO backhaul scenarios when additional ground-side optical branches and aggregate launch power are available.

Limitations and future work. This study used equivalent aggregate atmospheric and pointing-related loss coefficients rather than independently calibrated C_n^2 , α , β , beam-divergence, or pointing-jitter parameters. It also assumed ideal synchronization, ideal branch combining, fixed channel settings, and identical per-branch laser/amplifier parameters. Because the total launch power was not normalized across SISO, 2×2 , and 4×4 , the numerical improvement combined diversity, combining, and additional optical-power effects. The model does not yet include measured weather time series, finite-aperture tracking tolerances, UAV vibration and attitude dynamics, acquisition/tracking/control-loop transients, hardware nonlinearities, optical-safety constraints, or prototype-level mass and energy measurements. Future work should include equal-total-power simulations, explicit stochastic turbulence and pointing parameters, closed-loop UAV stabilization, and hardware or field validation.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, visualization, H.V.C.; writing, supervision, project administration, funding acquisition, L.T.H.; review and editing, Ž.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: During the preparation of this manuscript, the authors used Grammarly for the purposes of English grammar checking, spelling correction, punctuation checking, and language polishing. The authors reviewed and edited all suggested corrections, and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kumar, A.; Dhiman, A.; Kumar, D.; Kumar, N. Free space optical communication systems under different weather conditions. *IOSR J. Eng.* **2013**, *3*, 52–58.
2. Celik, A.; Shihada, B.; Alouini, M.S. Optical wireless center networks: Potentials, limitations, and prospects. In *Broadband Access Communication Technology XIII*; Dingel, B., Tsukamoto, K., Mikroulis, S., Eds.; SPIE: Bellingham, WA, USA, 2019.
3. Mufutau, A.O.; Guimar, F.P.; Fernandes, M.A.; Lorences-Riesgo, A.; Oliveira, A.; Monteiro, P.P. Demonstration of a hybrid optical fiber-wireless 5G fronthaul coexisting with en-to-en 4G network. *J. Opt. Commun. Netw.* **2020**, *12*, 72.
4. Van, C.H.; Nhat, T.N. A proposed method “Proposed Method Determination of the Total Signal to Noise Ratio for Free-Space Optical Communication Using Uav Relaying”. In Proceedings of the International Conference on Advanced Technologies for Communications (ATC), Ho Chi Minh City, Vietnam, 17–19 October 2024; ISBN 979-8-3503-5398-3.
5. Sallami, F.A.L.; Rajbhandari, S.; Ata, Y. Free space optics FSO communication. In *Handbook of Radio and Optical Networks Convergence*; Springer Nature Singapore Pte Ltd.: Singapore, 2024. https://doi.org/10.1007/978-981-97-2282-2_54.
6. Kaushal, H.; Jain, V.; Kar, S. *Free Space Optical Communications Systems-Optical Network*; Springer India Pvt Ltd.: Singapore, 2017. <https://doi.org/10.1007/978-81-322-3691-7>.
7. Henniger, H.; Wilfert, O. An introduction to Free space optical communications. *Radioengineering* **2010**, *19*, 203–212.
8. Nistazakis, H.E.; Tsiftsis, T.A.; Tombras, G.S. Performance analysis of free space optical communication systems over atmospheric turbulence channels. *IET Commun. J.* **2009**, *3*, 1402–1409. <https://doi.org/10.1049/iet-com.2008.0212>.
9. Kim, I.T.; McArthur, B.; Korevaar, E. *Comparison of Laser Beam Preparation at 785 nm and 1550 nm in Fog and Haze for Optical Wireless Communications*; Optical Access Incorporated: Chatsworth, CA, USA, 2021.
10. Safi, H.; Dargahi, A.; Cheng, J. Analytical Channel Model and Link Design Optimization for Ground-to-HAP Free-Space Optical Communications. *J. Light. Technol.* **2020**, *38*, 5036–5047.
11. *ITU-T Recommendation G.693; Optical Interfaces for Intra-Office Systems*. International Telecommunication Union: Geneva, Switzerland, 2009.

12. Kaushal, H.; Jain, V.K.; Kar, S. Ground-to-Satellite Optical Communication Link Performance with Spatial Diversity in Weak Atmospheric Turbulence. *Fiber Integr. Opt.* **2010**, *29*, 315–340.
13. Andrews, L.C.; Philips, R.L.; Hopen, C.Y. *Laser Beam Scintillation with Applications*; SPIE Press: Bellingham, WA, USA, 2005.
14. Andrews, L.C.; Phillips, R.L. *Laser Beam Propagation through Random Media*; SPIE Press: Bellingham, WA, USA, 2005.
15. Fernandes, M.A.; Montciro, P.P.; Guiomar, F.P. Free-Space Terabit Optical Interconnects. *J. Light. Technol.* **2022**, *40*, 1519–1526.
16. Mofidi, M.; Chaman-motlagh, A. Error and Channel Capacity Analysis of SISO and MISO Free-Space Optical Communications. In Proceedings of the 20th Iranian Conference on Electrical Engineering (ICEE2012), Tehran, Iran, 15–17 May 2012.
17. Dabiri, M.T.; Sadough, S.M.S.; Khalighi, M.A. Channel modeling and parameter optimization for hovering UAV-based free-space optical links. *IEEE J. Sel. Areas Commun.* **2018**, *36*, 2104–2113.
18. Khan, R.; Khattak, R.W.; Khan, M.S.; Mushtaq, M.T. Analysis of optical attenuation from measured visibility data in Islamabad, Pakistan. *Mehran Univ. Res. J. Eng. Technol.*, **2018**, *37*, 269–278.
19. Dat, P.T.; Yamaguchi, Y.; Motoya, M.; Oikawa, S.; Ichikawa, J.; Kanno, A.; Yamamoto, N.; Kawanishi, T. Transparent fiber millimeter wave fiber systems in 100 GHz band using optical modulation and photonic down converter. *J. Light. Technol.* **2022**, *40*, 1483–1493.
20. Dat, P.T.; Morohashi, I.; Sekine, N.; Kanno, A.; Yamamoto, N.; Akahane, K. Fiber-terahertz-fiber bridge systems in the 355 GHz band using simple frequency comb and photonic-enabled receiver. *Opt. Lett.* **2023**, *48*, 2190–2193.
21. Wong, Y.K.; Idrus, S.M.; Ghani, I.A. Performance analysis of the OFDM scheme for wireless over optical fiber communications link. *Int. J. Comput. Theory Eng.* **2012**, *4*, 807.
22. Kaymak, Y.; Rojas-Cessa, R.; Feng, J.; Ansari, N.; Zhou, M.; Zhang, T. A survey on acquisition, tracking, and pointing mechanisms for mobile free-space optical communications. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 1104–1123.
23. Popola, W.O.; Ghassemlooy, Z. BPSK Subcarrier Intensity Modulated Free-Space Optical Communications in Atmospheric Turbulence. *J. Light. Technol.* **2009**, *27*, 967–973.
24. Ghassemlooy, Z.; Popoola, W.O. MIMO free space optical communication employing subcarrier intensity modulation in atmospheric turbulence channels. *Opt. Commun. J.* **2015**, *343*, 188–194.
25. ITU-R Recommendation P.1814-1; Prediction Methods Required for the Design of Terrestrial Free-Space Optical Links. International Telecommunication Union: Geneva, Switzerland, 2025.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.