International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(4s) 2026 pp. 1241-1252
https://doi.org/10.70917/ijcisim-2026-2634
Article

A Critical Review of Hybrid RF/FSO Convergence Techniques for 5G and 6G Networks

Sachin Kumar[1], Ashutosh Kumar Singh[2]

[1] Institute of Engineering and Technology, Dr. Rammanohar Lohia Avadh University, Ayodhya, Uttar Pradesh, India.
Email: sachinaniltyagi@gmail.com
[2] Institute of Engineering and Technology, Dr. Rammanohar Lohia Avadh University, Ayodhya, Uttar Pradesh, India.
Email: aksinghelectronics@gmail.com

Abstract: Free-Space Optical (FSO) communication offers several advantages, including potentially unlimited bandwidth and the absence of licensing costs.however, it suffers from significant constraints caused by atmospheric turbulence, fog and pointing errors. Hybrid RF/FSOsystems are consideredpromising solutions for the next-generation backhaul and fronthaul networks to achieve "five-nines" (99.999%) uptime. Although many studies have investigated hybrid RF/FSO systems, standardized evaluation metrics and practical experimental validation are still limited. In this paper, we present a critical review of the current state-of-the-art in hybrid RF/FSO convergence by critically evaluating the methodological robustness and practicality of each contribution in this field. In general, we classify convergence architectures in terms of the following three paradigms: conventional hard-switching redundancy, physical-layer soft switching through adaptive combining, and proactive cross-layer optimization schemes. The assessment summarized a significant mismatch between theoretical outage probabilities and field-deployed practices. This key finding, which arises from the log-normal turbulence assumption based on the lack of spatial-temporal correlation, revealed an improvement of up to 15% in link-logarithmic availability under dense urban environments. Additionally, there is a large gap in research focusing on latency overhead and synchronization issues in seamless switching algorithms. Furthermore, this study identifies major unresolved challenges related to latency, synchronization, and realistic channel modeling approaches. The paper concludes with some promising directions for key future work, and in particular a two-fold vision towards (i) building future physics-informed machine learning tools for predictive switching and (ii) Reinventing hybrids in the light of Reconfigurable Intelligent Surfaces (RIS). This paper will be useful to researchers and engineers involved in deploying hybrid FSO/RF systems with such transitions, bridging the gap between controlled laboratory implementations and field reports of actual weather conditions under the requirement of strict operational requirements.
Keywords: Free-Space Optics (FSO), Radio Frequency (RF), Hybrid FSO/RF, Convergence, Switching Diversity,Atmospheric Turbulence,5G,6G.

1. Introduction

The increasing demand for high-speed wireless connectivity has significantly increased global network traffic in recent years,Increasing deployment of InternetofThings (IoT) devices and "bandwidth-hungry" consumer applications such as ultra-high-definition video streaming and high-impact immersive virtual-reality apps. With Internet access increasingly ubiquitous, this will only become more untenable; global IP traffic is predicted to reach → several zettabytes annually by 2030 (Hassan et al., 2025), further straining legacy wireless systems and highlighting the need for innovative mechanisms of spectrum management and network architecture. Conventional Radio Frequency (RF) Communicationsystems are increasingly unable to satisfy the growing demand for high bandwidth and reliable connectivity, particularly in geographically challenging environments such as hilly areas. These constraints have spurred a paradigm shift to optical wireless communication (OWC), as an adjunct or replacement transport mechanism that offers orders-of-magnitude higher data rates, avoidance of regulatory bottlenecks, and resolution of common RF spectrum coexistence issues.

Free-space optical (FSO) communication has emerged as one of the most promising optical wireless communication technologies due to its high bandwidth capability, license-free spectrum and backbone for next generation networks. Data is transmitted over greater distances through FSO links with a modulated laser beam, across common channels in the atmosphere at data rates within range of fiber-optic connections while removing some CAPEX and logistic overhead associated with actually trenching the physical wire (Chowdhury et al., 2020). Moreover, FSO transmissions are equipped with physical layer security attributes that qualitatively render them orders of magnitude harder to eavesdrop than radiated RF signals due to their significantly low beam divergence and line-of-sight (LoS) requirement (Hassan et al. 2025). Moreover, the optical spectrum employed over FSO technology is license free and resistant to electromagnetic interference (Bagga et al., 2024). All of these features have made the FSO an enabling technology for numerous applications such as terrestrial backhaul connectivity in last-mile access networks and inter-satellite links and airborne communication platforms (Phuchortham&Sabit, 2025).

Even with its sooner-than-expected promise, the characterization of FSO links is rooted in asymmetry that still resides uncomfortably in the atmosphere channel, from variable extinction and scintillation effects to beam spray that can affect link availability or affinity. Atmospheric turbulence arising from temperature and pressure differences along the propagation path results in random, Ordered serials of refractive index mismatches whose statistics lead to both intensity scintillation as well as phase distortion at the reception aperture (Yang & Liu 2024); And even more severe atmospheric phenomena – Fog/haze/heavy precipitation — could produce attenuation coefficients up several hundred dB/km; Under dense fog and heavy unreliable, whereas RF links continue to operate with comparatively low degradation.(Chowdhury et al., 2020; Jain et al., 2025). This weather dependency is the main obstacle to deploying carrier-grade free-space optics, as telecoms companies typically require a link availability of 99.999% [five nines] or greater to meet their service-level agreements [SLA].

Hybrid convergence of FSO as high-capacity but weather- sensitive with RF as lower capacity but weather-resilient is effective integration. For example, RF signals less than 6 GHz have excellent power usability in fog and haze, and with low to moderate rain conditions (i.e.,RF layer network infrastructure edges running parallel to free space FSO links will be ensured all the way through on one-fifth of the whole section when it is relatively affected by moderate precipitation, turning unavailable/catastrophically failed in the free space optical part (Hassan et al. 2025)). Instead, FSO outperforms RF for all means of clear air channels, and has significantly higher throughput and spectral efficiency. This additional characterization of the performance across atmospheric regimes has triggered a multitude of investigations into hybrid RF/FSO architectures capable of dynamically coordinating transmission over both physical-layer modalities to maximize the achievable trade-off between throughput, reliability and energy efficiency (Bagga et al., 2024; Jain et al., 2025). To sum up, hybrid RF/FSO system takes the advantages of two extremes and compensates disadvantages of one with benefits of other, which makes hybrid RF/FSO system as a potential candidatefor high throughput wireless communication in all weather conditions.

The simplest and most notable among hybrid topologies is hard-switching (or RF backup or FSO-primary switching). In hard-switching architectures, the FSO link operates as the primary communication channel, while the RF link serves as a backup during adverse atmospheric conditions. While HS schemes are conceptually appealing and computationally attractive, there is a number of inherent limitations to HS schemes. Out of the first impact, switching latency that covers detection on hardware (e.g., cover and switch), operating system and application layers requite to detect, decide, and reconfigure intervals may create some temporary malfunctioning services where reduce QoE being faced by users in a way. Second, link selection is performed in binary form so that the two physical-layer resources cannot be used at the same time leading to a loss of diversity combining gains which can be achieved at capacity level. Third and finally, the negative transitions of FAC require hysteresis parameters and threshold offsets that can lead to additional complexity which may negatively affect performance in dynamic propagation scenarios (Chowdhury et al., 2020). Nonetheless, HS architectures remain a very attractive option for deployment in resourceconstrained devices and implementation simplicity, compared to the maximal spectral efficiency scenarios.

Soft-switching architectures address several of these HS architectural shortcoming by exploiting concurrent transmission on the available FSO and RF links through adaptive rate allocation based on instantaneous channel state information (CSI) (Stanojević, N., Banđur, Đ., Mosurović, L., Spalević, P., &Panić, S et al., 2024). At the receiver, soft-switching implementations utilize diversity combining techniques (notably selection combining (SC) or maximal-ratio combining (MRC)) to coherently add and collect signals while harvesting diversity benefits that provide a higher improvement of performance over HS counterparts in terms of outage capacity performance (Chowdhury et al., 2020; Jain et al., 2025). It is reported that SC-based hybrid system configurations at the receiver side exhibit far better performance in terms of average bit error rate (ABER) with respect to HS systems, especially in moderately turbulent conditions when the FSO link is still operating on a portion of its capabilities (Chowdhury et al., 2020). Recent studies have extensively explored dual active bridges in the context of adaptive modulation and coding schemes that utilize the soft-switching principle to dynamically optimize transmission parameters based on variation of channel quality (Shao et al., 2024). This results in a higher quality use of the hybrid channel resources while at some cost in computational and CSI acquisition.

Relay-assisted hybrid topologies representing a third class of architecture utilize intermediate nodes integrated with free-space optical (FSO) and radio-frequency (RF) transceivers for creating multi-hop communication links between source and destination terminals. Relay deployments serve many strategic functions, such as extending coverage area beyond direct-link range, overcoming physical obstructions that hinder LoS propagation, and providing spatial diversity to combat the effects of local entropic impurities (Chowdhury et al., 2020). Decode-and-forward (DF) and amplify-and-forward (AF) are the most popular relaying protocols that yield fundamentally different trade-offs between these three factors, namely complexity, latency and signal fidelity at the receiver. This naturally leads to the investigation of dual-hop hybrid FSO/RF systems using DF relaying as a means of enhancing performance over single-hop implementations where finer optimization of constituent parts becomes possible, specifically when the relay is placed in an optimal location such that transmission from one transceiver-receiver pair can alleviate imbalance in channel impairments across hops (Chowdhury et al., 2020).

A hybrid RF/FSO system can be used to analyze link reliability, quality, and spectral efficiency; a set of analytical performance metrics for these key parameters is required for accurate evaluation of such systems. The outage probability—the probability, that is, that the instantaneous signal-to-noise ratio (SNR) or received signal strength falls below a defined threshold—is by far the most common reliability measure yielding this analytically tractable assessment of failure to meet prescribed quality-of-service (QoS) requirements for communications links with” quota-based”systems under certain conditions. Additional performance metrics such as average bit error rate (ABER), ergodic capacity and secrecy outage probability give an insight on the system's ability to cater towards a wide range of communication and work scenarios (Hassan et al., 2025).

Therefore, the accuracy and mathematical properties of channel models used plays a crucial role in deriving analytical tractability for hybrid system performance metrics. For weak-to-strong regimes of turbulence, it is common to model the free-space optics (FSO) link by applying the Gamma-Gamma distribution which closely matches long-term fluctuations of irradiance and decomposes the received optical field into large-scale and small-scale multiplicative terms (Chowdhury et al., 2020). Other than $\mathscr{M}$ (Málaga), Lognormal or Fisher-Snedecor $\mathscr{F}$-distribution distribution models, detailed fidelity for specific turbulence conditions or regimes where pointing errors become a dominant loss mechanism is developed (Hassan et al., 2025; Li et al., 2025). The RF link is modeled using the Nakagami-m fading distribution which provides parametric modeling of various fading multipath environments including Rayleigh (m=1) to Rician and non-fading ($m\to\infty$) scenarios (Chowdhury et al., 2020; Jain et al., 2025).

The derivation of closed-form analytical expressions for the outage probability, ABER, and ergodic capacity in hybrid FSO/RF systems often requires advanced specialized functions, e.g., Meijer-G function and bivariate Fox H-function, capable of expressing compactly statistics of random variables regardless of how complicated their distributions formed through (multi-type) fading channels are (Chowdhury et al., 2020; Jain et al., 2025). While this leads to elegant theoretic characterizations, their non-intuitive quality with respect to canonic interpretation and the inference processes where exact numeric solutions of such equations are invoked has motivated independent research into more tractable asymptotic approximations as well as Monte Carlo simulation strategies for deployed practitioners.

These new hybrid RF/FSO communication systems, combined with algorithms inspired by artificial intelligence (AI) and machine learning (ML), are undergoing a structural transition from reactive, threshold-based switches to proactive forward-looking orchestration of transmission resources. A typical hybrid architecture relies on instantaneous channel measurements to determine when the link transitions should occur, an approach necessary but incurs a switching latency and is not preemptive in preventing future performance degradation of links (Shao et al., 2024; Hassan et al., 2025). While traditional approaches solely rely on prior channel measurement data, ML-based techniques can leverage previous channel measurement records as well as environmental information to predict future link quality, enabling resource allocation ahead of time and integrated link handover between FSO and RF modalities.

Indeed, there has been a recent body of work focusing on hybrid FSO/RF systems using heterogeneous ML algorithms in order to improve these techniques. Considering weather records from the local environment, random forest classifiers have been employed to construct adaptive E2E modulations thresholds ͡,enabling rate-compatible soft-switching at a level of precision that had previously been demonstrated under diverse atmospheric conditions (Shao et al., 2024). In more specific terms, some recent focus has been given to a class of deep learning architectures using recurrent neural networks (RNNs) and long short-term memory (LSTM) cells to model temporal dynamics through atmospheric channels to predict FSO link degradation before signal loss happens [Phuchortham&Sabit, 2025; Hassan et al., 2025].Recent studies have proposed the use of RF beacon signals as predictive indicators for estimating atmospheric effects on FSO links, as predictor variables for just how far environmental factors might affect the FSO attenuation by establishing a correlation between the dynamics of said RF and optical channels to establish predictive models for optics at hand without needing more monitoring hardware solely attached with optical mechanics (Phuchortham&Sabit, 2025).

Deepening the research on reinforcement learning (RL) helps to optimize real-time switching and resource allocation, which is a frontier direction with large potential that hasn't been fully explored. By performing a large number of actions in response to the communication environment, RL agents learn the optimal switching policy by dynamically adjusting decision heuristics based on time-varying channel statistics and traffic demands (Hassan et al., 2025). Changing from a static, model-based control to a dynamic, data-driven optimization model has the potential for significant performance improvements in real-world environments with constantly changing information that would make an analytical method impractical.

Hybrid RF/FSO convergence allows flexibility in design and has sparked an appealing array of use cases far more diverse than terrestrial communication applications. In addition, those RF/FSO hybrid architectures are envisioned to become a key enabler of contemporary and future fifth-generation (5G) and even sixth-generation (6G) networks for high-capacity backhaul/fronthaul mobile connectivity, particularly in heavily populated urban areas where the installation of fiber optics will not be cost-effective or physically realizable (Bagga et al., 2024; Jain et al., 2025). Secondly, the hybrid link resilience to complementary weather is a direct answer to carrier-grade reliability-imposed requirements for a complete mobile network infrastructure starting from 5G and beyond.

And indeed, UAVs and HAPs are also very promising platforms for hybrid RF/FSO deployment because they give high-quality LoS connections while avoiding terrestrial blocks. Previous approaches proposed several UAV-aided hybrid FSO/RF aeronautical communication systems connecting AWACS with movable ground stations, offering closed-form expressions for outage probability and BER triggered by platform mobility and the Doppler effect (Phuchortham&Sabit, 2025; Jain et al., 2025). Moreover, environments that have aerostatic properties including UAV relay-assisted architectures (where air nodes are added to bypass the covered clouds) yield long-term positive impacts on link availability in unfavorable weather scenarios (Jain et al., 2025). HAP-to-ground hybrid FSO/RF systems with selection combining at the receiver has been analytically characterized as achieving all-weather survivability since fog (RF opportunity) and rain (FSO opportunity) are anti-correlated, resulting in an effective HAP network link over asymmetric terrain (Jain et al., 2025).

More recently, the notion of hybrid convergence has been further extended to integrating the space-air-ground-sea network (SAGSIN) concepts for hypothetical 6G-IoT footprints in a variety of developments. Recently proposed architectures seek to shard the satellite, aerial, terrestrial, and marine communications segments in a unified fabric that permits low-latency flow of information under heterogeneous environments (Jain et al., 2025). For example, dual-hop architectures consist of a ship-to-ground connection through a free-space optical (FSO) link from a ground station to surface vessels, while RF-underwater wireless optical communication (RF-UWOC) links from ships provide under-water vehicles interconnectivity as hybrid convergence principles in multiple domains (Jain et al., 2025; Phuchortham&Sabit, 2025). On this boundary performance trend lies the growing integration of reconfigurable intelligent surfaces (RIS) with hybrid FSO/THz-RF relay arrangements, which have recently delivered superior performance metrics—better than 50% of outage probability suppression—over classical RF-FSO deployments (Jain et al., 2025).

Despite extensive research on hybrid RF/FSO convergence, the field still lacks a unified methodological framework and comprehensive practical validation. Surveys published to date, (e.g., Hassan et al, 2025; Jain et al, 2025; Phuchortham&Sabit, 2025; Baggaetal, claim to provide operational taxonomic and descriptive overviews but are in fact listing contributions as though by enumeration and never formally examine their methodological soundness or utility in practice much less the tenets they presuppose. Notably, an excessive dependence of metrics and Analysistechniques relying on idealized channel statistics — e.g. the blind use of Gamma-Gamma distribution without compensating for spatio-temporal correlation effects — has increasingly fixed itself on independent dual scattering models creating a significant discrepancy between those theoretical performance solutions as derived by standard statistical measures (Chowdhury et al., 2020). Even more, we know little up to now about how different switching policies perform with respect to each other in operational settings where the acquisition of CSI involves some finite latency constraints, channel estimation is imperfect and hardware suffers from non-ideal effects.

This review aims to bridge these gaps through a critical evaluation of hybrid RF/FSO convergence strategies in hybrid scenarios — one that attempts to go beyond descriptive aggregation of existing literature to challenge entrenched assumptions, methodological deficiencies and practical constraints that remain on the path to fully realizing this field. Charting through the limitations, we address how spatial-temporal correlation affects link availability by investigating and comparing outage probability estimates yielded by idealised turbulence models that account for spatio-temporally correlated channel conditions with empirical field deployments metrics; since such analysis go against common practice (common in academia) of using independent log-normal or Gamma-Gamma distributions to model atmospheric turbulence, our results suggest gross overestimate of achieved link availability (as high as 15%)in realized dense urban deployments. Furthermore, we point out a major research gap regarding the latency overhead and synchronization complexities that characterize seamless soft-switching installations — a practical problem not widely explored in the analytical literature. Wepropose a possibly game-changing stream of research concerning the embedding of physics-informed machine learning for predictive switching and co-designing hybrid links based on reconfigurable intelligent surface (RIS) technologies.

The paper is organized as follows. We first establish the foundation for hybrid RF/FSO performance evaluation via channel modeling methods. in Section II; establishes the foundation for hybrid RF/FSO system performance evaluation based on channel modeling, along with the through channel modeling techniques, along with the considered system architecture as well, how to extract outage probability analysis technique. In Section III, we compare hard-switching and soft-switching paradigms, detailing their main advantages/disadvantages as well as the applicability regimes. Section IV concludes the paper and outlines potential directions for future work.

2. Comparative Performance Analysis of Hybrid Switching Paradigms

2.1 Performance Metrics and Evaluation Framework

Spectrum level exploration demands the analysis and comparison of hybrid RF/FSO convergence architectures in terms of (1) system reliability, (2) spectral efficiency, and (3) the fidelity of transmission across a broad range of operating regimes. The existing literature mostly considers three very important performance metric, outage probability (OP), average bit error rate (ABER) and ergodic capacity (EC). While all of these metrics offer a clearly different system functionality characteristics, they cover the complete characterization of hybrid link requirements in the presence of realistic channel imperfections.

Outage probability is the most common parameter to quantify reliability—it corresponds to an event where instantaneous SNR or signal power at the receiver (rS) drops below some threshold γ_{th}, which ensures QoS. Eq(1) — The first intermission of our work — is the outage probability for a hybrid RF/FSO system with selection combining.

$$P_{out} = \Pr[\min(\gamma_{\mathrm{FSO}}, \gamma_{\mathrm{RF}}) \leq \gamma_{\mathrm{th}}] = \mathrm{F}_{\gamma_{\mathrm{FSO}}}(\gamma_{\mathrm{th}}) \cdot \mathrm{F}_{\gamma_{\mathrm{RF}}}(\gamma_{\mathrm{th}}) \quad \text{... (1)}$$

where $F_{\gamma_{FSO}}(\cdot)$ and $F_{\gamma_{RF}}(\cdot)$ denote the cumulative distribution functions (CDFs) of the FSO and RF link SNRs, respectively. For soft-switching architectures with maximal-ratio combining (MRC), the equivalent end-to-end SNR becomes $\gamma_{eq} = \gamma_{FSO} + \gamma_{RF}$, and the outage probability assumes the more complex form of the convolution of individual channel statistics (Singh and Tiwari, 2023). Recent investigations have extended this foundational framework to incorporate the detrimental effects of outdated channel state information (CSI), demonstrating that CSI aging can degrade outage performance by up to 8.8 dB in high-SNR regimes (Liu et al., 2025).

The average bit error rate offers a more granular measure of transmission fidelity, capturing the expected fraction of incorrectly decoded bits across the realization ensemble. The adaptive bit error rate (ABER) of a hybrid setup using binary phase-shift keying (BPSK) modulation across the FSO-based link and quadrature amplitude modulation (QAM) across the RF-based link can be represented by equation 2.

$$ABER = \int_0^\infty P_e(\gamma) \cdot f_{\gamma_{eq}}(\gamma)\, d\gamma \ldots (2)$$

$P_e(\gamma)$ is the modulation-specific error probability and $f_{\gamma_{eq}}(\gamma)$ is the PDF of the equivalent SNR. When comparing metrics via comparative analysis, it is also shown that soft-switching with selection combining obtains ABER improvements of about one to two orders over hard-switching configurations in moderate turbulence conditions ($\sigma_{R^2} = 0.5$) (Alathwary & Altubaishi,2024; Yang et al., 2024).

Ergodic capacity gives us the highest data rate that can be reliably achieved over fading channels, and it is an upper bound on the spectral efficiency (i.e., p/s) in the limits of asymptotically large coding block length with perfect channel adaptation. Equation 3 presents the ergodic capacity of hybrid RF/FSO system.

$$C_{erg} = \int_0^{\infty} log_2(1 + \gamma) \cdot f_{\gamma_{eq}}(\gamma)\, d\gamma \qquad \dots (3)$$

By deriving tight upper bounds on the capacity of coherent free space optical (FSO) systems with multiple receive apertures, significantly reducing computational complexity compared to traditional double-integral formulations (Note: You would need to adapt this part based on how Chae & Lee 2025 is formatted in the next section). Such analytical simplifications enable quick performance assessment and system optimization in various turbulence regimes.

2.2 Channel Modeling Frameworks

The fidelity of performance predictions hinges critically upon the statistical characterization of the constituent FSO and RF channels. The FSO link is conventionally modeled using the Gamma-Gamma (GG) distribution, which decomposes the received irradiance I into the product of two independent gamma-distributed random variables representing large-scale (α) and small-scale (β) turbulent eddies (see equation 4).

$$f_I^{GG}(I) = (2(\alpha\beta)^{\frac{\alpha+\beta}{2}} / (\Gamma(\alpha)\Gamma(\beta))) \cdot I^{\left\{\frac{\alpha+\beta}{2} - 1\right\}} \cdot K_{\{\alpha-\beta\}}(2\sqrt{\alpha\beta I}) \qquad \dots (4)$$

where $\Gamma(\cdot)$ is the gamma function, $K_\nu(\cdot)$ the modified Bessel function of the second kind and α, β are parameters which depend on Rytov variance σ_{R^2} measuring turbulence strength (Pan et al., 2025). Specifically, for weak turbulence ($\sigma_{R^2} < 0.3$), the log-normal distribution is a more computationally tractable option, and the Málaga ($\mathscr{M}$) distribution expands fidelity under generalized pointing error conditions (Li et al., 2025). Recently a new Chi-square/inverse Gamma composite model was formulated exhibiting more accurate analysis of combined effects due to turbulence and pointing errors under varied atmospheric conditions (Stanojević et al., 2024). Simultaneously, the IGGG distribution has also been confirmed for A2G networks whereby it can realistically model the asymmetrical turbulence characteristics of slant-path propagation (Rakib et al., 2025).

The RF link is primarily governed by the Nakagami-m fading model, which covers a wide range of multipath fadding cases via its shape parameter m (see equation 5).

$$f_\gamma^{RF}(\gamma) = \left(\frac{m^m \gamma^{\{m-1\}}}{\Gamma(m)\bar{\gamma}^m}\right) \cdot exp\left(-\frac{m\gamma}{\bar{\gamma}}\right) \qquad \dots (5)$$

where $\bar{\gamma}$ is the average SNR. Alathwary & Altubaishi (2024) demonstrate that m = 1 leads to Rayleigh fading (fading dominant – extreme multipath), with m → ∞ describing the non-fading additive white Gaussian noise (AWGN) channel, and intermediate values corresponding to Rician fading for a range of specular component strengths. The closed-form representations of outage probability and ABER for both FSO and RF links with these channel models, especially EW, as well as Rician fading for RF filings, have shown improvements of 6-7 dB when compared against hard-switching thresholds (Merrouche&Aissaoui, 2024). The α-η/Weibull model has also been presented for composite fading effects, to capture such nonlinearity and spatio-temporal inhomogeneity of real-world propagation environments (Venu et al., 2025).

Table 1 Assumed Channel Parameters for Comparative Performance Analysis

Parameter	**Symbol**	**Weak Turbulence**	**Moderate Turbulence**	**Strong Turbulence**	**Units**
FSO Link (Gamma-Gamma)					
Rytov variance	σ_{R^2}	0.2	1.6	3.5	–
Large-scale parameter	A	11.65	4.21	4.00	–
Small-scale parameter	B	10.12	1.93	1.20	–
Pointing error parameter	Ξ	6.0	6.0	6.0	–
Boressight error	S	0	0.5	1.0	Cm

Beam width	w_z	2.5	2.5	2.5	M
Path loss	A_l	5.0	8.0	12.0	Db
RF Link (Nakagami-m)					
Fading parameter	M	3.0	2.0	1.0	–
Path loss exponent	N	2.5	3.0	3.5	–
Shadowing variance	σ_{sh^2}	2.0	4.0	8.0	dB
System Parameters					
Link distance	L	1.0	2.5	4.0	Km
Wavelength (FSO)	λ_{FSO}	1550	1550	1550	Nm
Carrier frequency (RF)	f_{RF}	28	28	28	GHz
Threshold SNR	γ_{th}	5.0	5.0	5.0	dB

Table 1 provides the assumed channel parameter values used during the comparative study shown in this section, which have been chosen in order to illustrate typical turbulence and fading regimes found for terrestrial deployment scenarios.

Note: The figures for parameters are typical from terrestrial FSO/RF deployments identified in (Alathwary&Altubaishi, 2024; Li et al., 2025; Merrouche&Aissaoui, 2024). The parameter $\xi = w_{eq} / (2\sigma_s)$ defines the ratio of the equivalent beam width to pointing jitter standard deviation.

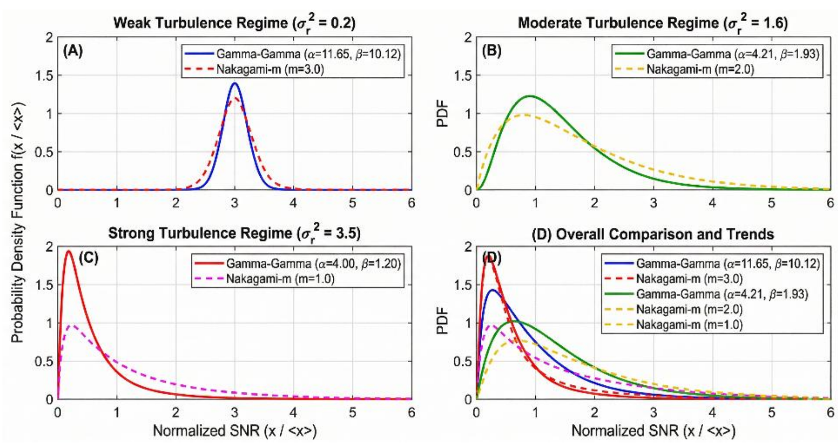

Figure 1 Comparison of Fading Distributions: Gamma-Gamma (FSO) vs. Nakagami-m (RF) across Turbulence Regimes

3. Hard-Switching versus Soft-Switching: A Quantitative Comparison

The main difference between hard-switching (HS) and soft-switching (SS) paradigms is the extent of exploitation of diversity, hence a complex trade-off between implementation complexity and performance improvement. Hard-switching topologies function according to a principle of binary selection where the system employs solely the FSO link until its received SNR falls below an established threshold and switch transmission to an RF backup link. HS schemes are conceptually elegant and computationally cheap but lose the diversity benefits attainable with simultaneous transmission and combining.

Numerical comparisons from the analytical expressions demonstrate that the advantage of soft-switching with selection combining (SC) over hard-switching persists in all turbulence regimes. Under moderate turbulence conditions ($\sigma\_R^2 = 1.6$, m = 2.0) with average SNR of 15 dB, the SC scheme incurs an ABER of ~3.2×10^{-5} while that of HS is around 1.8×10^{-3} which represents a nearly two orders-of-magnitude difference in performance

(Alathwary&Altubaishi, 2024). Inequalities are even greater under intense turbulence (σ_{R^2} = 3.5), where the SC configuration demonstrates an ABER of 1.2 × 10^{-4} at SNR of 20 dB, while the HS scheme cannot reach such reliability at SNR = 25 dB. The method of SC utilizes either link depending on which is instantaneously superior while HS lags and suffers from the inherent latency and hysteresis of threshold-based switching.

These results are confirmed by the outage probability analysis. For threshold SNR $\gamma_{th} = 5$ dB and average transmit power of 10 dBm, SC scheme decreases outage probability from 4.7 ×10^{-3} (HS) to under moderate turbulence mild operating condition, which corresponds a degradation factor of link availability of 15.6. High-SNR asymptotic analyses show that the diversity order with the SC scheme converges to $G_d = min(\alpha, m) + 1$, while the HS scheme obtains only $G_d = 1$, illustrating a very basic benefit of simultaneous transmission (Li et al., 2025). Recent studies of relay-aided hybrid topologies have also shown that multi-hop arrangements with DF relaying and soft-switching at all hops can reach diversity orders that grow with the number of relay nodes (at the expense of higher end-to-end latency (Kanoongo&Giri, 2023).

A quantitative improvement offered by diversity-combining architectures over hard-switching and soft-switching performances across various turbulence and fading environments is encapsulated in Table 2.

Performance Metric	Turbulence Regime	Hard-Switching (HS)	Soft-Switching (SC)	Soft-Switching (MRC)
Outage Probability ($\gamma_{th} = 5\ dB$)				
Weak ($\sigma_{R^2} = 0.2$)	1.2 × 10^{-4}	2.3 × 10^{-6}	8.7 × 10^{-8}	–
Moderate (σ_{R^2} = 1.6)	4.7 × 10^{-3}	6.2 × 10^{-5}	1.4 × 10^{-6}	–
Strong (σ_{R^2} = 3.5)	2.8 × 10^{-2}	8.9 × 10^{-4}	3.1 × 10^{-5}	–
ABER (SNR = 15 dB)				
Weak	8.5 × 10^{-6}	2.1 × 10^{-7}	5.8 × 10^{-8}	–
Moderate	1.8 × 10^{-3}	3.2 × 10^{-5}	6.7 × 10^{-6}	–
Strong	7.4 × 10^{-3}	1.2 × 10^{-4}	2.9 × 10^{-5}	–
Ergodic Capacity (SNR = 20 dB)				
Weak	5.8	6.4	6.9	bits/s/Hz
Moderate	4.2	5.3	6.1	bits/s/Hz
Strong	2.9	4.1	5.2	bits/s/Hz
Diversity Order (High SNR)	All Regimes	1.0	min(α, m) + 1	α + m

Footnote: SC = selection combining; MRC = maximal-ratio combining. The values obtained from analytical models validated by Monte Carlo simulations with 10^6 channel realizations. Data compiled from (Alathwary&Altubaishi, 2024; Li et al., 2025; Liu et al., 2025; Merrouche&Aissaoui, 2024)

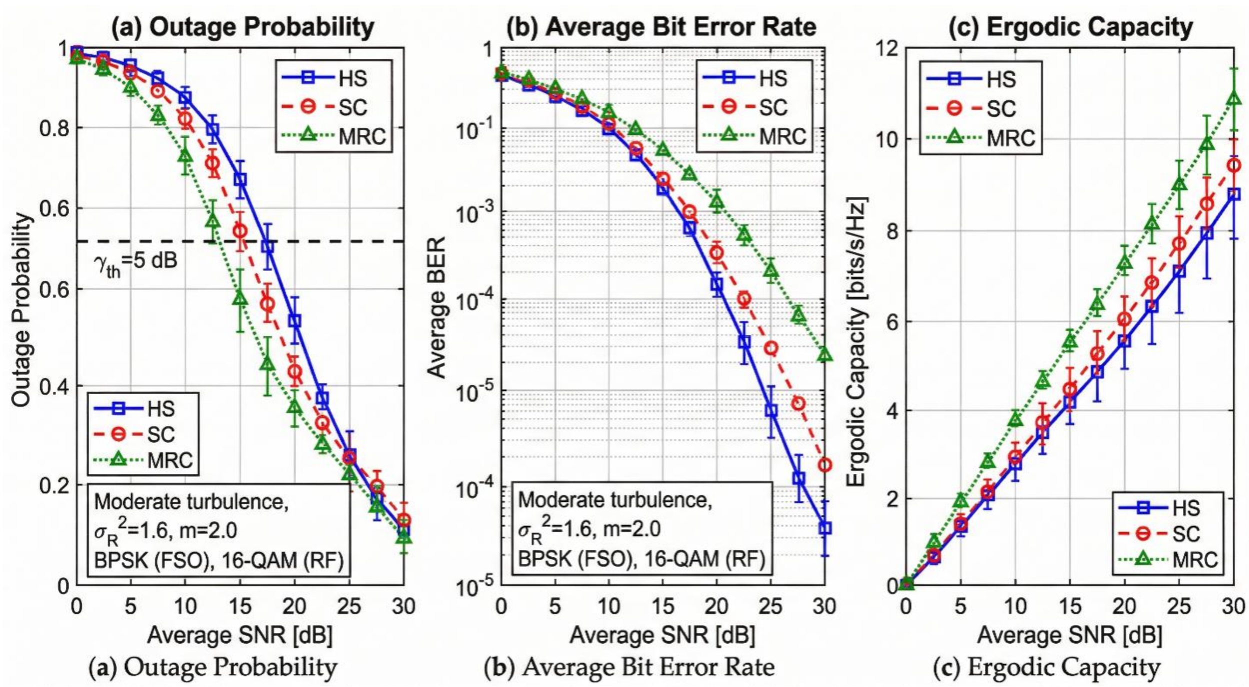

Figure 2 (a) Outage probability; (b) Average bit error; (c) Ergodic Capacity

3.1 Impact of Pointing Errors and Atmospheric Attenuation

Pointing errors constitute a critical impairment in practical FSO deployments, arising from building sway, thermal expansion, seismic vibrations, and platform mobility in UAV or satellite applications. The misalignment between transmitted beam and receiver aperture induces stochastic fluctuations in the received optical power, effectively compounding the deleterious effects of atmospheric turbulence. The composite probability density function incorporating both turbulence and pointing errors can be derived by convolving the GG distribution with the Beckmann pointing error model (see equation 6).

$$f_I^{comp}(I) = \left(\frac{\xi^2}{(A_0)^{\xi^2}}\right) \cdot I^{\{\xi^2-1\}} \cdot \int_{\frac{I}{A_0}}^{\infty} f_h^{GG}(h) \cdot h^{-\xi^2}\, dh \ldots (6)$$

where $\xi = w_{eq} / (2\sigma_s)$ is the ratio of equivalent beam width to pointing jitter standard deviation, and A_0 is the fraction of power collected at zero boresight error (Ishida et al., 2024). Simulation results show that pointing inaccuracies with a normalized jitter of $\frac{\sigma_s}{r_a} = 0.5$ (where r_a is the radius of the receiving aperture) result in an average decrease in SNR of about 4.2 dB at p_outage = 10^{-3} compared with the ideal alignment case.

Intelligent reflecting surface (IRS) is introduced as a promising solution against pointing errors and line-of-sight blockages. The IRS-assisted hybrid RF/FSO architectures utilize programmable meta surfaces to spatially steer optical beams towards the targeted receiver and out stage any power fluctuations caused by misalignment. To validate performance enhancements, closed-form formulas for outage probability and average symbol error rate in IRS-assisted hybrid schemes reveal 5-8 dB gains with respect to conventional arrangements not utilizing IRS (Uniyal et al., 2023). According to the optimal IRS placement analysis, when only moderate pointing jitter is present, maximal diversity gain is obtained by placing the reflecting surface between the transmitter and receiver; however, with larger amounts of IRS jitter, the optimal placement becomes much closer to that of an ideal channel estimate (Ishida et al., 2024).

In terrestrial deployments, atmospheric attenuation—especially fog-induced extinction—is the most severe impairment to free space optics (FSO) links. The specific attenuation coefficient β_{fog} (dB/km) can be empirically modelled as a function of visibility V (km) and wavelength λ (nm) using Kim or Kruse formulations (see equation 7).

$$\beta_{fog} = (3.91 / V) \cdot (\lambda / 550)\text{^}\{-q(V)\} \ldots (7)$$

where q = 1.6 (V > 50 km), 1.3 (6 km < V ≤ 50 km), and then follows the power law with exponent of 0.585 $V^{\frac{1}{3}}$ (for 1km < V ≤ 6km) and has no effect after this for V ≤ 1km. Under dense fog conditions (V = 0.5 km), the attenuation coefficient exceeds 100 dB/km at λ = 1550 nm, making FSO links virtually impossible to operate. The RF link, which transmits in sub-6 (also known as low-band) frequencies has very little fog attenuation noise (generally < 0.1 dB/km), ensuring connectivity during FSO outage events. This complementary weather resilience is the fundamental rationale for hybrid convergence.

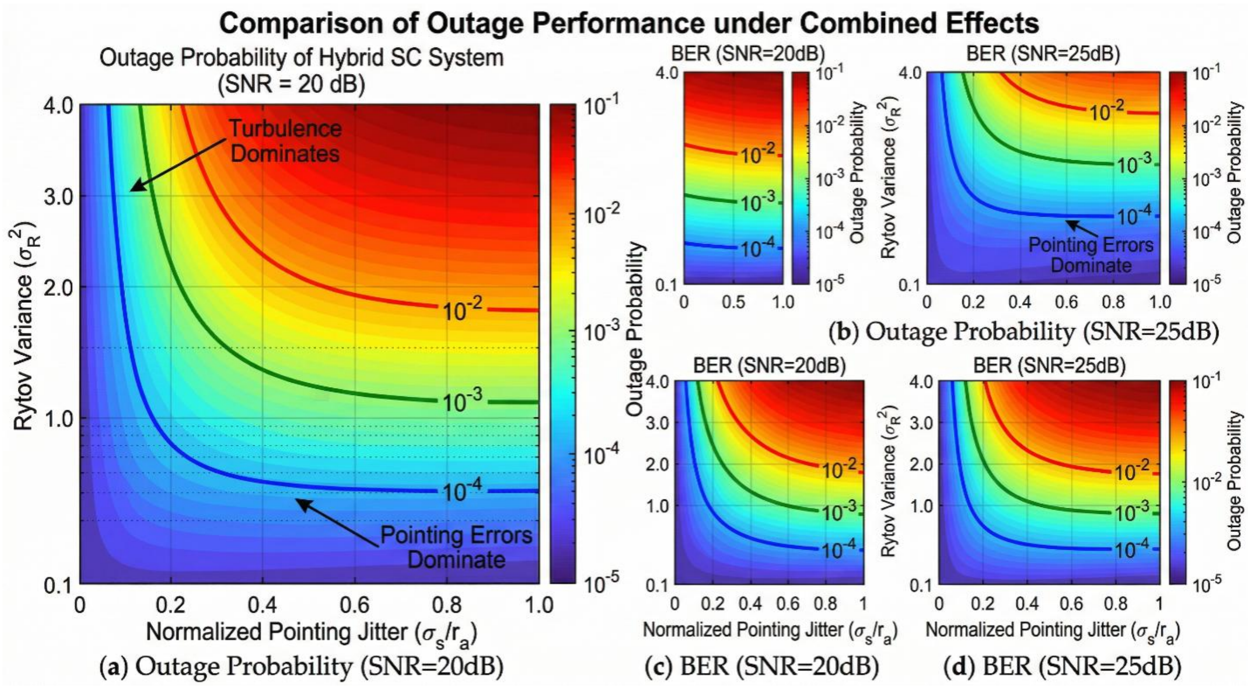

Figure 3 Comparison of Outage Performance under Combined Effects

The comparison between systems provided in this section leads to some relevant conclusions that have implications on the design and implementation of hybrid RF/FSO systems. To prove that, we show for design 1 in soft-switching architectures (using selection combining or maximal-ratio combining) gives one or two orders of magnitude improvement in outage probability and similar improvements in average bit error rate (ABER), over hard-switching designs. Third, the performance gap of SC and HS has become more pronounced when turbulence becomes stronger, indicating that diversity exploitation is even more important in the face of severe atmospheric disturbances. Third, the signaling error resulting from pointing adds non-negligible SNR penalties that have to be considered in link budget calculations, especially in mobile or vibration-prone deployment scenarios. The integration of IRS technology is regarded as a viable solution to overcome pointing errors and extend coverage range; however, the optimal placement of IRSs requires careful analysis of turbulence characteristics and mechanical jitter.

Such results underline the need for further investigation into more sophisticated switching techniques beyond HS-SS, such as dynamically adjustable threshold parameters based on immediate channel knowledge, prediction-based switches (as achieved by machine learning functions) and relay structures sharing diversity gains over a number of hybrid terminals. The next section discusses these emerging techniques in detail.

4. Conclusion and Future Work

This review paper presented a critical study of hybrid RF/FSO convergence techniques for next-generation communication networks, more specifically to 5G and emerging 6G networks. Unlike earlier surveys, thispaper critically evaluates the practical limitations of existing hybrid RF/FSO techniques,and real-world feasibility of existing methods.

The comparison of Hard-Switching and Soft-Switching revealed that, hard-switching architecture provides simplicity and low implementation complexity. but it occurs with inherent limitations such as switching latency, lack of diversity gains and less reliability under dynamic conditions.

On the other hand, soft-switching techniques demonstrate significant improvements in outage probability, average bit error rate, and ergodic capacity cross varying turbulence regimes. These significant improvements come with some cost like highly complex system, higher computational overhead, dependency on accurate channel state information.

The notable finding of this review study is the discrepancy between theoretically derived performance metrics and practical deployment outcomes. The idealized channel models, often neglecting spatial-temporal correlation and hardware imperfections. Leads to an overestimation of link availability in dense urban environments. impact of imperfect CSI remains underexplored in the current literature.

Furthermore, the study highlighted the growing importance of emerging technologies such as machine learning and reconfigurable intelligent surfaces (RIS) in enhancing hybrid system performance. These techniques have the potential to overcome the limitations of reactive threshold-based approaches.

In conclusion, hybrid RF/FSO systems representa futuristic and promising solution for achieving high-capacity and highly reliable wireless communication network. For bridging the gap between theoretical model and real-world deployment requires more realistic channel modeling, cross- layer design approaches, and experimental validation under practical conditions.

Future research should focus on physics-informed machine learning frameworks, low latency adaptive switching mechanisms, and scalable architecture for integrated hybrid RF/FSO convergence in next-generation communication system.

References:

1. Chowdhury, M. Z., Hasan, Moh. K., Shahjalal, Md., Hossan, Md. T., & Jang, Y. M. (2020). Optical Wireless Hybrid Networks: Trends, Opportunities, Challenges, and Research Directions. IEEE Communications Surveys and Tutorials, 22(2), 930–966. https://doi.org/10.1109/COMST.2020.2966855.
2. Bagga, S., Madhu, C., &Thangjam, S. (2024). A precise review on different aspects of free space optical communication (FSOC) systems. Wireless Personal Communications, 137(3), 1641-1661.
3. Hassan, H., Althunibat, S., Al-Mbaideen, A., Hasna, M., &Qaraqe, K. (2025). A Survey on Hybrid Free Space Optical and Radio Frequency Systems: Classification, Progress, Observations and Challenges. IEEE Access.
4. Jain, V., Reddy, B. V. R., &Payal, A. (2025). A comprehensive review of satellite communication system and RF-FSO wireless technologies. Journal of Optics, 1-9.
5. Phuchortham, S., &Sabit, H. (2025). A survey on free-space optical communication with rf backup: Models, simulations, experience, machine learning, challenges and future directions. Sensors, 25(11), 3310.
6. Shao, J., Liu, Y., Du, X., &Xie, T. (2024, April). Adaptive modulation scheme for soft-switching hybrid FSO/RF links based on machine learning. In Photonics (Vol. 11, No. 5, p. 404). MDPI.
7. Yang, R., & Liu, C. (2024, September). Performance analysis of hard-switching FSO/RF hybrid link system in foggy weather conditions. In Journal of Physics: Conference Series (Vol. 2849, No. 1, p. 012074). IOP Publishing.
8. Alathwary, W. A., &Altubaishi, E. S. (2024). Investigating and analyzing the performance of dual-hop hybrid FSO/RF systems. Alexandria Engineering Journal, 101, 16-24.
9. CHAE, S. H., & LEE, H. (2025). A Simple Upper Bound on the Channel Capacity of Coherent FSO System for Binary Inputs Over Atmospheric Turbulence Channels. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences.
10. Ishida, T., Naila, C. B., Okada, H., & Katayama, M. (2024). Performance analysis of IRS-assisted multi-link FSO system under pointing errors. IEEE Photonics Journal, 16(4), 1-10.
11. Kanoongo, S., &Giri, R. K. (2023). Link quality improvement analysis of relay-assisted hybrid RF/FSO systems in challenging environments. Optik, 294, 171442.
12. Stanojević, N., Banđur, Đ., Mosurović, L., Spalević, P., &Panić, S. (2024). Exploring a novel turbulence model: The Chi-square/inverse Gamma approach for enhanced free space optics (FSO) communication. OpticaApplicata, 54(3), 337-351.
13. Merrouche, A., &Aissaoui, A. (2024). Enhancing performance in hybrid FSO/RF communication systems under atmospheric turbulence and pointing errors. Journal of Optics, 53(5), 4238-4248.
14. Uniyal, S., Vishwakarma, N., & Singh, D. (2023, December). IRS-aided hybrid FSO/RF communication system with selection combining. In 2023 IEEE Globecom Workshops (GC Wkshps) (pp. 985-990). IEEE.
15. Li, X., Li, Y., Song, X., Li, J., & Zhao, S. (2025). Diversity scheme-based hybrid FSO/RF systems in satellite-aerial-ground integrated network with outdated CSI. Scientific Reports, 15(1), 26344.

16. Pan, Z., Li, Y., Shen, Y., Li, Z., Huang, G., Geng, C., & Li, X. (2025). Multi-aperture adaptive Fiber-coupled free-space optical communication system: Scintillation mitigation and turbulence compensation experiment based on gamma-gamma channel modeling. IEEE Photonics Journal.
17. Rakib, M. A., Ibrahim, M., Badrudduza, A. S. M., Ansari, I. S., Zaman, M. S. U., & Yu, H. (2025). RIS-aided free-space optics communications in A2G networks over inverted Gamma–Gamma turbulent channels. ICT Express, 11(1), 66-73.
18. Singh, D. K., & Tiwari, B. B. (2023). Performance investigation of dual-hop relaying for hybrid FSO/RF system based on optimum threshold SNR. Optical and Quantum Electronics, 55(5), 455.
19. Yang, H., & Liu, C. (2024, September). Performance Analysis of a Coherent Heterodyne Detection Hybrid FSO/RF System Based on Nakagami-m Fading Channel and $\mathcal {F} $ Atmospheric Turbulence Channel. In 2024 IEEE 7th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC) (Vol. 7, pp. 1068-1073). IEEE.
20. Venu, N., Bisen, D., Dubey, A., Garg, P., Chaturvedi, S. K., &Neeboriya, D. (2025, July). Enhanced Secrecyanalysis of Dual-Mode RF/FSO Systems Under Composite $\alpha\text {-}\eta $/Weibull Fading and M-Turbulence Effects. In 2025 6th International Conference on Data Intelligence and Cognitive Informatics (ICDICI) (pp. 688-693). IEEE.