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Article

A Comprehensive Review of OAM-Based Free-Space Optical Communication System Design, Atmospheric Challenges and Emerging Techniques

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Abstract: Free-space optical (FSO) communication has emerged as a promising high-bandwidth, license-free alternative to conventional radio frequency and fiber-optic systems, and orbital angular momentum (OAM) multiplexing using Laguerre–Gaussian (LG) modes offers a powerful means of scaling FSO capacity by exploiting the spatial dimension of light. However, practical deployment of OAM multiplexed FSO links is hindered by atmospheric impairments such as fog, haze, rain, dust, and turbulence-induced wavefront distortion, all of which cause beam spreading, scintillation, power loss, and inter-modal crosstalk that degrade system performance. This review provides a comprehensive analysis of OAM-based FSO communication by examining the theoretical foundations of LG beam generation and propagation, key performance metrics including channel capacity, bit error rate, and spectral efficiency, and the atmospheric channel models that govern link reliability. Recent advances in modulation format optimization, hybrid multiplexing strategies combining OAM with (WDM, PDM) and (OCDMA) adaptive optics, MIMO equalization, machine-learning-based mode recognition and relay-assisted architectures are critically assessed through a comparative evaluation of representative studies. Finally critical research gaps are identified, including the absence of unified crosstalk models under realistic turbulence, limited real-weather experimental validation and unresolved trade-offs between beam divergence, mode purity and alignment tolerance, and future directions are outlined to support the development of robust, scalable OAM-FSO systems for next-generation wireless and optical networks.

Keywords: Free-Space Optical Communication, Orbital Angular Momentum, Laguerre–Gaussian Beams, Mode Division Multiplexing, Atmospheric Turbulence, Beam Divergence, Inter-Modal Crosstalk, Bit Error Rate, Spatial Multiplexing, High-Capacity Optical Communications.

1. Introduction

The exponential growth in global data traffic accelerated by video streaming cloud computing, Internet of Things ecosystems and the anticipated rollout of beyond-5G and 6G networks places enormous stress on existing communication infrastructure [1]. Radio frequency (RF) bands are approaching saturation, and the cost and time associated with deploying optical fiber in dense urban or geographically challenging terrain frequently make fiber impractical. Free-space optics emerges in this context as a compelling wireless solution it operates at optical carrier frequencies, requires no spectrum license, delivers data rates comparable to fiber and can be installed rapidly with lightweight commercially compact hardware [2]. An FSO link transmits a collimated laser beam through the open atmosphere between a transmitter and receiver separated by a line-of-sight path. Its advantages over RF links include immunity from electromagnetic interference, inherently narrow beam directionality that enhances physical-layer security and a large unregulated optical bandwidth [3]. These qualities make FSO attractive for metropolitan area networks, inter-building connectivity, satellite-to-ground links, and emergency recovery scenarios where fiber cannot be deployed quickly.

Nevertheless, the atmospheric channel imposes significant penalties. Suspended aerosols, water droplets, and dust particles scatter and absorb the propagating beam causing attenuation that varies dramatically with weather. Fog is particularly damaging, reducing visibility to below one kilometer and inducing attenuation that can reach several

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hundred decibels per kilometer [4]. Turbulence induced refractive index fluctuations lead to wave front distortion, intensity scintillation and pointing errors that combine to degrade the signal to noise ratio at the receiver [5].

To address capacity demands under these impairments researchers have incorporated successive multiplexing dimensions. Wavelength division multiplexing (WDM) and polarization division multiplexing (PDM) are now standard yet they cannot indefinitely scale spectral efficiency. Mode-division multiplexing (MDM) a subclass of space-division multiplexing (SDM) introduces orthogonal spatial modes as independent information carriers. Among the spatial modal sets explored OAM modes have attracted the most sustained interest because their circular symmetry is compatible with conventional aperture based optical subsystems and they lend themselves to relatively straightforward multiplexing and demultiplexing using spiral phase plates spatial light modulators (SLMs) or computer generated holograms [6].

OAM beams carry a helical phase structure of the form e*ilφ*, where *l* is the topological charge number and φ is the azimuthal angle. Each distinct value of *l* defines a unique spatially orthogonal mode and the orthogonality property means that independent data streams modulated onto different charges can be transmitted coaxially and separated at the receiver with low inter-channel interference under ideal conditions [7]. The theoretically unbounded number of available OAM states offers a potentially vast increase in link capacity [9]. Terabit per second capacity demonstrations over short laboratory distances and multi kilometer field trials have confirmed the theoretical promise of OAM multiplexing [2].

Li et al. demonstrated the application of OAM beams as an orthogonal modal basis set for FSO communication links [9]. As an OAM beam propagates it exhibits a helical phase front described by the phase term exp $(i\ell\varphi)$ where ℓ represents the topological charge and φ is the azimuthal angle. OAM beams carrying different values of ℓ are mutually orthogonal enabling effective multiplexing at the transmitter and demultiplexing at the receiver [9]. Despite these advantages an OAM beam possesses two key characteristics that must be preserved its transverse intensity profile takes the shape of a doughnut ring with reduced power at the center and a pronounced annular peak, and it carries a helical phase front that winds by $2\pi\ell$ radians around the beam axis. Both features must be accurately captured at the receiver to ensure successful detection [5].

To preserve orthogonality between co-propagating OAM beams, the rapid phase variation near the beam center must be fully captured at the receiver aperture. Simultaneously sufficient optical power must be collected across the annular ring to satisfy the signal to noise ratio (SNR) requirements of the detection system. These constraints place practical limits on both the maximum transmission range and the number of OAM modes that can be reliably supported. One approach is to enlarge the transmitter or receiver aperture diameters though this increases system weight, cost and complexity. An alternative strategy is to focus OAM beams using transmitter lenses to reduce the beam diameter at the receiver plane and improve capture efficiency [9].

Despite these achievements the practical deployment of OAM-FSO links confronts several interrelated problems. Higher-order OAM beams diverge more rapidly causing power leakage through limited size receiver apertures. Imperfect alignment between transmitter and receiver introduces lateral displacement and angular error both of which break the modal orthogonality and generate crosstalk. Atmospheric turbulence couples energy among modes dynamically, raising the bit error rate (BER) beyond acceptable limits [8]. Several prior studies have investigated OAM-based FSO systems under limited atmospheric scenarios, typically evaluating performance under a single weather condition and using only two or three closely spaced OAM mode orders [3, 7, 8]. The mode-order-dependent behavior of OAM beams under diverse and simultaneous atmospheric impairments has not been comprehensively characterized in a single unified study.

The objective of this work is threefold:

(i) To consolidate and critically assess the literature on OAM-FSO system design, channel modelling, and performance evaluation.

(ii) To identify research gaps and contradictions that still require resolution.

(iii) To outline directions for future work that would accelerate the transition from laboratory demonstrations to field deployable systems.

The remainder of the paper is structured as follows. Section 2 presents the theoretical framework for OAM and LG beam propagation. Section 3 reviews performance metrics. Section 4 surveys weather-induced impairments.

Section 5 reviews the primary literature thematically. Section 6 provides a comparative analysis. Section 7 identifies research gaps and objectives. Section 8 concludes the paper.

2. Theoretical Framework of OAM in FSO Systems

A. Laguerre-Gaussian Beam Formulation

The mathematical description of an OAM-carrying beam within the paraxial approximation begins with the scalar wave equation in cylindrical coordinates. Laguerre-Gaussian (LG) beams represent a complete orthonormal solution set of this equation and are characterized by two integer indices: the radial index p and the azimuthal index l (topological charge). The complex amplitude of an LG beam at propagation distance z is given by [9], [7]:

$$u(r,\varphi,z)=\sqrt{\frac{2p!}{\pi(p+|l|)!}}\frac{1}{\omega(z)}\left[\frac{r\sqrt{2}}{\omega(z)}\right]^{|l|}L_p^{|l|}\left[\frac{2r^2}{\omega^2(z)}\right]\times\exp\left[\frac{-r^2}{\omega^2(z)}\right]\exp\left[\frac{-ikr^2z}{2(z^2+z_R^2)}\right]\times\exp\left[i(2p+|l|+1)\arctan\frac{z}{z_R}\right]\exp(-il\varphi) \quad (1)$$

where r and φ are the radial and azimuthal coordinates, *w(z)* is the beam waist at distance z, k is the wave number for wavelength λ, z_r is the Rayleigh range, and $L^p|l|$ denotes the associated Laguerre polynomial. The intensity profile of an LG beam exhibits a characteristic doughnut ring that grows with $|l|$ because the phase rotates helically about the propagation axis.

B. Orthogonality Condition

The physical basis for OAM multiplexing rests on the mutual orthogonality of beams carrying different charge values. For two LG beams with azimuthal indices l_1 and l_2, the inner product satisfies:

$$\int_0^\infty \int_0^{(2\pi)u_m(r,\varphi,z)} u_n^*(r,\varphi,z)\,r\,dr\,d\varphi=\delta_{(mn)} \quad (2)$$

Where δ is the Kronecker delta. This result holds rigorously for infinite apertures and ideal propagation. Under practical conditions involving finite apertures and atmospheric distortions the orthogonality is only approximately maintained and the residual overlap is the source of inter-modal crosstalk [7, 9].

C. OAM Beam Divergence and Spot Size

A fundamental constraint in FSO deployment is the beam divergence experienced during free-space propagation. For a fixed transmitted beam diameter a beam carrying OAM charge l diverges more rapidly than a Gaussian beam ($l = 0$) because the phase singularity forces energy to the annular periphery. Xie et al. [7] showed through Kirchhoff-Fresnel diffraction simulation that for any given propagation distance and OAM order, there exists an optimal transmitted beam diameter that minimizes the spot size at the receiver. Specifically, for a 1 km link, transmitted beam diameters of 10 to 30 cm are generally required to keep power loss below 10 dB for OAM orders up to $l = 10$.

Li et al. [9] further demonstrated through both simulation and experiment over a 1 m laboratory link that transmitter lenses focused to the propagation distance can reduce power loss by more than 20 dB for higher-order OAM beams. This improvement comes however at the cost of reduced tolerance to lateral displacement between transmitter and receiver.

D. Signal-to-Noise Ratio and BER

System performance is typically characterized through the signal-to-noise ratio (SNR) and BER. The SNR for an FSO link under atmospheric turbulence can be expressed as [3]:

$$\mathrm{SNR[dB]}=10\log_{10}\left(\frac{1}{0.31C_n^2\left(\frac{2\pi}{\lambda}\right)^{7/6}L^{11/6}}\right) \quad (3)$$

where Cn^2 is the atmospheric refractive-index structure constant (for weak to strong turbulence) and *L* is the link distance. The BER is then related to the Q-factor, which depends on the SNR and the modulation format employed.

3. Performance Metrics for OAM-FSO Links

A. Link Margin

The link margin quantifies the excess power available in the system above the minimum required for a target BER, accounting for geometric attenuation, rain attenuation, and system losses [3].

$$LM_{(i,j)=P_e^{(i)}+|S_r^{(j)}|-10log_{(10)}(alpha_{(geo)}(}i,j))-alpha_{(rain)}(i,j)d(i,j)-alpha_{(sys)}(i,j) \quad (4)$$

where P_t is the transmit power, S_r is the receiver sensitivity, A_{geo} is the geometric attenuation, α_{rain} is the rain-specific attenuation coefficient, *L* is the link distance, and the remaining terms represent optical system losses.

B. Wavelength Selection

Common operational wavelengths for FSO systems are 850 nm, 1064 nm and 1550 nm. The 1550 nm window benefits from lower atmospheric scattering, eye-safe operation at higher power levels and compatibility with mature optical telecommunications components. Singh and Malhotra [10] demonstrated that 1550 nm outperforms 850 nm in terms of BER over both short and long distances under atmospheric turbulence conditions.

C. Channel Crosstalk

Inter-modal crosstalk is defined as the ratio of leaked power from undesired modes into the desired channel relative to the desired channel power itself. Xie et al. [7] defined nearest-neighbor crosstalk (XT-1) and second-nearest-neighbor crosstalk (XT-2) metrics and showed that lateral displacement introduces a phase mismatch that couples power into adjacent modes in proportion to displacement magnitude.

D. Received Optical Power and Eye Diagrams

The received optical power (ROP) is the actual optical power collected at the detector aperture after free-space propagation and atmospheric attenuation. Eye diagrams provide a qualitative but operationally practical measure of signal quality: wide, open eyes indicate low inter-symbol interference, whereas closed or noisy eyes indicate system degradation. El-Mottaleb et al. [4] used ROP and eye diagrams alongside BER to evaluate an OAM-OCDMA-FSO system under fog and dust storm conditions and demonstrating 60 Gbps capacity over 1400 m under clear Alexandria city meteorological data.

4. Atmospheric Impairments in FSO Channels

A. Fog and Visibility-Dependent Attenuation

Fog is the most severe weather impairment for FSO links. The attenuation coefficient under foggy conditions as a function of meteorological visibility *V* (km) is described by the modified Kim model [11]:

$$a[\mathrm{dB/km}] = \frac{3.91}{V}\left(\frac{\lambda}{550\mathrm{nm}}\right)^{-q} \quad (5)$$

Where the exponent depends on the distribution of scattering particle sizes. Light fog (visibility around 2 km) causes approximately 9 dB/km attenuation, moderate fog rises to 16 dB/km, and heavy fog may exceed 22 dB/km, severely constraining achievable link distances to a few hundred meters [4, 11].

B. Dust Storms

Dust storms, common in arid and semi-arid regions, produce attenuation given by an empirically derived relation:

$$D_a[dB/km] = 52R^{(-1.05)} \quad (6)$$

Where R is the meteorological visibility in kilometers. Heavy dust storms reduce the FSO range to as little as 40 m [4]. Making dust a more severe impairment per unit visibility than fog.

C. Rain Attenuation

Rain causes attenuation primarily through scattering when raindrop diameters are comparable to or larger than the optical wavelength. The rain-induced attenuation in dB/km is modelled as:

$$\alpha_{rain}[dB/km] = 1.076 \times R_r^{0.67} \tag{7}$$

Where R is the rainfall rate in mm/hr. Rain produces significantly less attenuation than dense fog at the same visibility. Chaudhary et al. [11] showed that combined dense fog and heavy rain conditions reduce the Ro-FSO link range from 3400 m under clear sky to only 620 m.

D. Atmospheric Turbulence and Scintillation

Atmospheric turbulence arises from spatially and temporally varying temperature gradients that produce refractive-index fluctuations along the propagation path. For OAM beams turbulence introduces a random phase screen that disrupts the helical wavefront, coupling power from the intended mode into neighboring modes. The distortion of Laguerre-Gaussian beam intensity images under turbulence is modelled using the Hill-Andrews power spectral density [15]:

$$\Phi_n(k_x,k_y) = 0.033C_n^2\left[1+1.802\sqrt{\frac{k_x^2+k_y^2}{k_l^2}}-0.254\left(\frac{k_x^2+k_y^2}{k_l^2}\right)^{7/12}\right]\exp\left(-\frac{k_x^2+k_y^2}{k_l^2}\right)\left(k_x^2+k_y^2+\frac{1}{L_0^2}\right)^{-11/6} \tag{8}$$

where the turbulence inner scale and outer scale parameters govern the spectral distribution of refractive-index fluctuations. The resulting inter-modal crosstalk degrades the BER substantially under strong turbulence ($C_n^2 \approx 10^{-13}$ $m^{-2/3}$).

5. Literature Review

A. Foundational OAM-FSO System Demonstrations

The concept of using OAM modes in FSO communication was given a rigorous treatment by Willner et al. [2]. Whose comprehensive tutorial in Advances in Optics and Photonics established the theoretical limits experimental state-of the art and key technical obstacles. The authors described how OAM multiplexing can be combined orthogonally with WDM and PDM to multiply overall system capacity and they catalogued the primary impairments: modal coupling under turbulence crosstalk from misalignment and the divergence of higher-order modes.

Singh et al. [3] conducted a simulation study of a 40 Gbps system using four OAM beams each carrying 10 Gbps. Performance under clear sky, haze, fog, and dust was evaluated in Optic system comparing NRZ, RZ, and AMI encoding formats. The clear-sky NRZ configuration achieved transmission up to 800 m with the lowest recorded BER, while heavy dust reduced the useful range to 64 m. Notably, OAM crosstalk was not modelled in that study which the authors acknowledged as a limitation affecting the BER estimates.

Wang et al. [6] provided an expansive review covering OAM multiplexing with turbulence-resilient designs, multicasting, structured light communication using vector beams and Bessel beams, and intelligent communication architectures. The review demonstrated that OAM, as a spatial dimension of the electromagnetic field offers capacity scaling that is fundamentally orthogonal to conventional multiplexing approaches.

B. System Design: Aperture, Beam Size, and Mode Spacing

The most thorough treatment of OAM-FSO design parameters was delivered by Xie et al. [7] from the University of Southern California. Using Kirchhoff-Fresnel diffraction modelling validated by laboratory experiments over a 1 m link, they showed that the optimal transmitted beam size depends on a balance between diffraction and geometrical spreading: beams that are too narrow diffract quickly, whereas beams that are too wide exceed the receiver aperture geometrically. For a 100 m link, transmitted beam diameters of 3 to 10 cm were found appropriate for OAM orders up to 10. Their analysis also established that larger mode spacing reduces crosstalk under misalignment at the cost of higher divergence loss leading to a clear trade-off: small mode spacing minimizes power penalty under modest misalignment, when large spacing is preferable in crosstalk dominates.

Li et al. [9] extended this framework by investigating transmitter lenses as a practical mechanism for compensating beam divergence. A pair of lenses with adjustable spacing was used to focus four OAM beams onto a receiver 1 m away. Power loss was cut by more than 20 dB, and angular error-induced crosstalk fell by 10 to 20 dB.

However, lateral displacement tolerance degraded by 5 to 10 dB with the lenses in place, confirming the divergence-versus-displacement trade-off first identified by Xie et al. [7].

C. Modulation Format Comparisons

Singh and Malhotra [10] examined four modulation formats (NRZ, RZ-DPSK, AMI) and (NRZ-DPSK) in a Gbps MDM system using Hermite-Gaussian modes transmitted at 850 nm and 850.8 nm over a radio-over-FSO link. Their results consistently showed that NRZ-DPSK delivered the best BER under strong turbulence conditions, while expanding the receiver aperture diameter via aperture averaging provided additional improvement. The study underlined that aperture size and modulation format selection must be co optimized under a given turbulence regime.

D. Hybrid Multiplexing Techniques

El-Mottaleb et al. [4] proposed integrating spectral-amplitude-coding optical code division multiple access (SAC-OCDMA) with OAM multiplexing using fixed right shift (FRS) codes. Two OAM beams each carried three independently encoded 10 Gbps channels giving 60 Gbps total capacity. The FRS-coded scheme provided inherent multi-user security on top of the spatial channel separation. Under real meteorological data from Alexandria city (attenuation 0.1 dB/km) the system reached 1400 m, compared with 1000 m for Srinagar city. The maximum useful range under heavy dust was only 40 m, quantifying how dramatically particle-laden atmospheres constrain OAM-based systems.

Sinha et al. [8] combined OAM multiplexing with OFDM and spatial mode multiplexing (SMM) in a MIMO framework. Using the Gamma-Gamma turbulence model the proposed OAM-OFDM-SMM system demonstrated substantial BER improvement over standalone OAM multiplexing, attributing the gain to the OFDM subcarrier orthogonality mitigating inter-mode interference under strong turbulence. The system capacity was reported to increase with the number of OAM states, though higher refractive-index structure constant values imposed diminishing returns.

Chaudhary et al. [11] designed a hybrid MDM-PDM radio-over-FSO (Ro-FSO) system using donut modes (equivalent to OAM modes) combined with X and Y polarization states to deliver four 10 Gbps channels upconverted to 40 GHz radio signals. Under clear conditions, the link operated to 3400 m; partial haze and rain reduced this to 1000 m, and dense fog with heavy rain limited operation to 620 m. The NRZ encoding scheme and Lithium Niobate Mach-Zehnder modulators were used throughout, offering a practical low cost architecture for broadband service delivery in sensitive locations such as medical facilities where RF radiation is undesirable.

E. Turbulence Mitigation: Adaptive Optics and MIMO

Yousif and Elsayed [12] combined spatial mode diversity with adaptive MIMO equalization to mitigate turbulence in a four-channel OAM-FSO link at 1550 nm, each carrying a 100 Gbps QPSK signal over a 2 km link. The hybrid diversity-equalization approach reduced inter-channel crosstalk by 4.5 to 6 dB compared with uncompensated OAM multiplexing and extended the useful transmission distance significantly. Their results highlighted that MIMO equalization alone is insufficient under strong turbulence; spatial mode diversity must be combined for acceptable BER performance.

Cao et al. [13] proposed a residual attention neural network for wavefront recovery in OAM-FSO systems. The network architecture incorporated multi-scale convolutional feature extraction and an attention mechanism to emphasize fractured light spot characteristics caused by turbulence. The network output was a set of Zernike coefficients representing the wavefront aberration, which were used to drive a deformable mirror for real-time phase correction. The approach demonstrated superior restoration accuracy compared with conventional Zernike decomposition under moderate to strong turbulence.

F. Machine Learning for OAM Mode Identification

Zhou et al. [14] addressed mode recognition under atmospheric turbulence using an improved convolutional neural network (CNN) built on the ShuffleNet-V2 backbone. The network received intensity images of received LG beams as input and classified them among ten OAM modes. Under weak turbulence, the recognition accuracy reached 100% from the first training epoch. Under strong turbulence at 2000 m, single OAM mode recognition accuracy stabilized at 97.2% and multiplexed OAM mode identification achieved 99.5%, outperforming the ResNet-50 model (93.5%) with a fraction of the computational cost (10.8 s versus 78 s for the full test set on the same CPU). The model also exhibited robust generalization under turbulence intensities not included in the training set, an important property for field deployment where turbulence is time-varying.

G. Statistical Turbulence Models for OAM Channels

Pan et al. [15] developed a statistical model for weak-turbulence-induced attenuation and inter-modal crosstalk in OAM-FSO links. Self-channel fading was characterized by an exponential-generalized-Gamma (EGG) mixture distribution, while inter-modal interference parameters were expressed as analytic functions of turbulence strength. Optimization of model parameters was accomplished via a trust-region algorithm, yielding accurate fitting to simulation data across a range of turbulence values. This model offers a tractable framework for performance prediction without the need for exhaustive Monte Carlo simulation.

Djordjevic et al. [5] analyzed OAM modulation combined with low-density parity check (LDPC) precoding over a 1 km turbulent FSO channel. Their signal constellation used a Cartesian product of orthogonal OAM modes and one-dimensional pulse amplitude modulation. Conditional probability density functions of modal crosstalk were derived analytically under weak turbulence to assess coded BER. The results showed that OAM modulation becomes progressively more sensitive to turbulence as dimensionality increases, but channel coding substantially closes this gap, making coded OAM more energy-efficient than single-mode transmission at the same spectral efficiency.

H. Beam Generation and Measurement

Kim and Clarkson [16] reported selective excitation of modes in a diode-pumped Nd: YAG laser using a fiber-based pump beam conditioning method. By adjusting the pump beam size to control the spatial overlap with specific LG modes, they achieved selective lasing on modes with predicted thresholds and beam propagation factors in close agreement with experiment. This work established a compact laser source alternative to SLM-based generation in relevant for system miniaturization.

Qassim et al. [17] examined the efficiency of phase-flattening measurement for determining the OAM spectrum of a light beam. They found that even for low OAM values, the coupling efficiency into a single-mode fiber is limited by the presence of higher-order radial modes that are produced when the spiral phase is flattened. Quantitative loss functions were derived as functions of OAM and radial indices, providing a correction tool for removing efficiency biases in OAM measurement systems.

Haddadi et al. [18] studied diffraction of truncated high-order radial LGp0 beams through a circular aperture. They showed that the far-field intensity distribution can take one of three shapes depending on aperture size: a flat-top profile, a hollow beam, or a pattern with a central peak surrounded by a ring. These findings are significant for receiver aperture design, as truncation by the aperture modifies the received mode profile in ways that can be mistaken for turbulence distortion.

I. Beam Divergence Profiles and Link Design

Singh et al. [19] investigated the correlation between beam divergence profiles and FSO link performance across commercially realistic scenarios. For a target BER of 10^{-9}, the study derived optimized design curves showing that the trade-off between beam divergence and maximum link range depends strongly on aperture diameter. A tighter beam divergence extends the link range but demands stricter pointing accuracy. Their findings provide practical guidelines for engineering FSO links in diverse geographic locations across India.

J. OAM Multiplexing Technology Evaluation

Lee et al. [20] conducted both theoretical and experimental evaluations of OAM multiplexing at 28 GHz using a dielectric lens to control beam divergence. Five OAM modes yielded 45 Gbps throughput experimentally, and an OAM-MIMO scheme using 11 modes achieved 100 Gbps at 10 m, setting a record for point-to-point throughput at the time. The dielectric lens proved effective for beam divergence control at millimeter-wave frequencies, drawing an analogy to transmitter-lens approaches in optical OAM-FSO systems.

K. Relay Chain and Amplify-and-Forward Architectures

Allen et al. [21] derived analytical expressions for BER and spectral efficiency in an OAM-multiplexed amplify-and-forward (AF) relay chain. Using four OAM modes over 20 relay hops, end-to-end spectral efficiency of up to 8 bits/s/Hz was achievable when inter-modal crosstalk was kept below a threshold. Beyond this threshold, crosstalk accumulated multiplicatively along the chain, causing BER to escalate. The study identified that OAM spectral efficiency scales with the number of modes but that crosstalk management becomes the binding constraint in multi-hop configurations.

L. Inter-Satellite and Long-Distance Links

Sharma et al. [22] investigated inter-satellite optical wireless communication (IsOWC) using modes at 850 nm and 850.8 nm for a 40 Gbps, 5000 km link. Transmitter diversity configurations combining NRZ-RZ and NRZ-AMI modulation were compared against non-diversity NRZ-NRZ arrangements, demonstrating that diversity suppresses inter-channel interference and extends the feasible link distance. Although HG modes rather than OAM modes were used, the system architecture and findings are directly transferable to OAM-based inter-satellite designs.

6. Comparative Analysis

Table 1 consolidates the key parameters and outcomes of representative studies reviewed in this paper. The comparison reveals several patterns. First, capacity per unit of laser power has increased substantially through hybrid multiplexing: the OAM-OCDMA combination of El-Mottaleb et al. [4] achieves 60 Gbps at 15 dBm, compared with 40 Gbps at 10 dBm for NRZ-OAM-FSO in the same group's earlier work. Second, deep-learning-based mode recognition achieves recognition accuracy above 99% even under strong turbulence, surpassing traditional phase-flattening and adaptive-optics methods in computational efficiency [14]. Third, real meteorological validation remains scarce: most studies use idealised attenuation values derived from generic visibility models, and only a subset [4, 11] use actual recorded visibility data.

Table 1. Comparative Summary of Representative OAM-FSO Studies

Reference, Year	Technique	Capacity	Channels	Max. Range	Weather Conditions	Key Finding
Singh et al. [3] (2022)	NRZ-OAM-FSO	40 Gbps	4	800 m (clear)	Clear, haze, fog, dust	NRZ optimal; 64 m under heavy dust
El-Mottaleb et al. [4] (2022)	OAM-SAC-OCDMA-FSO	60 Gbps	6	1400 m	Fog, dust, two cities	Real meteorological data; city-specific analysis
Chaudhary et al. [11] (2021)	MDM-PDM-Ro-FSO	40 Gbps	4	3400 m (clear)	Clear, partial haze, dense fog	620 m under dense fog and heavy rain
Sinha et al. [8] (2023)	OAM-OFDM-SMM MIMO	Multi-Gbps	Variable	Varied	Gamma-Gamma turbulence	OFDM and MIMO improve BER under turbulence
Yousef & Elsayed [12] (2019)	OAM-MIMO-SMM	400 Gbps	4	2 km	Atmospheric turbulence	4.5 to 6 dB crosstalk reduction
Zhou et al. [14] (2021)	CNN (ShuffleNet-V2)	10 modes	10	6 km (99.8%)	$Cn^2 = 10^{-16}$ to 10^{-14}	99.5% accuracy for multiplexed OAM
Xie et al. [7] (2015)	OAM-FSO design	4 ch (16-QAM)	4	10 km (model)	Ideal (no turbulence)	Beam size and mode spacing trade-offs
Li et al. [9] (2016)	OAM-FSO w/ Tx lenses	4 × 100 Gbps QPSK	4	1 m (lab)	Angular error, displacement	>20 dB power loss reduction
Allen et al. [21] (2019)	OAM AF relay chain	4 modes	4	20 hops	Inter-modal crosstalk	8 bits/s/Hz spectral efficiency

Lee et al. [20] (2019)	OAM-MIMO 28 GHz	11 modes	11	10 m	Free-space mm-wave	OAM-MIMO record throughput
Singh & Malhotra [10] (2019)	MDM Ro-FSO	80 Gbps	2	Varied	Turbulence with aperture avg.	NRZ-DPSK best under turbulence
Cao et al. [13] (2022)	Neural net wave front rec.	OAM mult.	Variable	Varied	Moderate to strong turbulence	Residual attention net; Zernike output

7. Research Gaps, Challenges and Objectives

A. Identified Research Gaps

Despite the progress surveyed above and several critical gaps remain.

First there is an absence of integrated crosstalk modelling under real turbulence. Most system-level simulations either ignore OAM inter-modal crosstalk entirely [3] or model it under idealised Kolmogorov turbulence. A comprehensive model that simultaneously accounts for beam divergence, finite aperture truncation, misalignment, and random turbulence statistics within a single BER expression remains unavailable. The EGG statistical model of Pan et al. [15] is a step forward but has not been validated over multiple turbulence regimes simultaneously.

Second, the beam divergence trade-off in higher-order modes has not been fully resolved. Higher-order OAM beams provide additional degrees of freedom but diverge faster, accumulating power loss that outpaces any crosstalk benefit from wider mode spacing at long distances. The systematic relationship between OAM order, propagation distance, aperture size, and link power penalty for orders beyond $l = 10$ has not been comprehensively mapped.

Third, misalignment modelling in practical deployments remains limited. Xie et al. [7] and Li et al. [9] analyzed misalignment as a static quantity, whereas building sway, thermal expansion, and wind loading cause time-varying, stochastic misalignment. The dynamic interaction between tracking system bandwidth, residual misalignment statistics, and OAM crosstalk statistics has not been studied.

Fourth, there is limited real-weather experimental validation. With few exceptions [4, 11], system evaluations rely on generalized attenuation models rather than actual recorded weather data. Site-specific factors such as coastal humidity, desert dust frequency, or monsoon rainfall patterns are not captured by generic Kim-model parameterizations.

Fifth, the scalability of ML-based mode recognition requires further investigation. Zhou et al. [14] demonstrated high recognition accuracy for up to 16 multiplexed mode combinations. The scaling behavior as the number of modes increases beyond 16, and the latency budget of CNN inference relative to channel coherence time, requires further investigation for real-time implementation.

Sixth, multi-hop OAM relay chain optimization is incomplete. Allen et al. [21] showed that crosstalk accumulates along a relay chain, but relay placement strategy, adaptive modulation per hop, and the interaction between relay gain and accumulated crosstalk have not been optimized jointly.

B. Research Objectives

Based on the identified gaps, the following objectives are proposed for future work. The first objective is to develop an integrated analytical performance model for OAM-FSO links that simultaneously accounts for beam divergence, aperture truncation, static and dynamic misalignment, and parameterized turbulence crosstalk, yielding closed-form BER and link-margin expressions. The second is to numerically investigate design space trade-offs for transmitted beam size, receiver aperture diameter, OAM mode spacing, and modulation format under a unified atmospheric scenario that combines fog, dust and turbulence. The third objective is to propose and evaluate an adaptive OAM-FSO system architecture integrating transmitter-lens divergence control, spatial mode diversity and lightweight deep-learning mode recognition to maintain BER across varying turbulence conditions. The fourth is to validate system performance against authenticated meteorological data from diverse geographic environments, including tropical, arid, and temperate climates to quantify the gap between generic model predictions and real-link performance. The fifth is to compare the proposed system against existing benchmarks in terms of capacity, range, power efficiency and implementation complexity, and to identify the most promising architecture for near-term deployment in 5G/6G backhaul and access scenarios.

8. Conclusion

This paper has provided a comprehensive review of OAM multiplexing in free-space optical communication, covering the theoretical foundations of Laguerre-Gaussian beam propagation, key performance metrics atmospheric impairment models and the current state of the art across system design, turbulence mitigation, mode recognition and hybrid multiplexing. The reviewed literature confirms that OAM multiplexing is a genuinely promising approach for increasing FSO capacity without additional spectral resources, with demonstrated capacities reaching terabit-per-second scales in laboratory settings and tens of gigabit-per-second over practically relevant distances. However, several fundamental challenges remain unresolved: beam divergence grows with OAM order and propagation distance, creating a tension between capacity and reach; misalignment breaks modal orthogonality and generates crosstalk that scales nonlinearly with displacement; and atmospheric turbulence imposes time-varying phase distortions that cannot be corrected by static compensation alone. The emerging techniques reviewed here, including adaptive MIMO equalization, neural network-based mode identification, transmitter lens focusing and hybrid multiplexing with OCDMA and PDM, each address a subset of these challenges, but no single approach has yet been demonstrated end-to-end under realistic field conditions. The research gaps identified in this work point towards an integrated adaptive OAM-FSO architecture that co-designs the modulation format, beam shaping and channel estimation layers and achieving such an architecture will require both more realistic channel models and authenticated field measurement campaigns to enable OAM-FSO links to serve as a practical, high-capacity wireless backbone for next-generation communication networks.

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