International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Intelligent Automation in Free-Space Optical Communications: Atmospheric Turbulence Mitigation Techniques and 6G Applications

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Abstract

Free-Space Optical (FSO) communications represent a transformative technology for next-generation telecommunications, offering ultra-high data rates, unlicensed spectrum, and inherent security advantages over conventional RF systems. However, system performance significantly degraded by atmospheric phenomena—particularly turbulence, fog, and rain—which pose fundamental challenges to widespread commercial deployment.

This paper presents a comprehensive and in-depth review of advanced mitigation techniques for atmospheric effects, with particular emphasis on artificial intelligence-supported adaptive optics, spatial and temporal diversity strategies, and hybrid RF/FSO systems. We examine recent breakthroughs in deep learning-based turbulence estimation and prediction, reconfigurable intelligent surface (RIS) technologies, and optical phase conjugation systems that have achieved qualitative improvements in response time to dynamic atmospheric conditions.

Furthermore, we explore emerging applications in space communications, underwater environments, and smart urban networks, highlighting the critical role of FSO systems in sixth-generation (6G) networks and space-air-ground integrated network (SAGIN) infrastructure. A comparative analysis of various mitigation techniques presented in terms of effectiveness, complexity, cost, and suitable applications.

Our results demonstrate that optimized systems achieve Bit Error Rates (BER) as low as 1.49×10−151.49×10−15 over 2500 meters even under strong atmospheric turbulence, with link availability exceeding 99.999% when employing hybrid systems. Furthermore, the integration of artificial intelligence with FSO systems reduces BER by up to 79% compared to conventional approaches.
The paper concludes by identifying key challenges hindering widespread FSO deployment and presenting a future vision for innovative solutions, including AI-enabled systems, integration with quantum communications, and the development of unified standards—paving the way for a new generation of ultra-high-speed, reliable wireless communications.

Keywords: Free-Space Optical Communications, Atmospheric Turbulence, Adaptive Optics, MIMO-FSO, Hybrid RF/FSO, Deep Learning, Underwater Optical Wireless Communication, Satellite Laser Communications, 6G Networks, Intelligent Reflecting Surfaces.

1. Introduction

Free-Space Optical communications have experienced accelerated development driven by escalating bandwidth demands, spectrum congestion in RF bands, and the need for rapidly deployable, cost-effective communication solutions. The global FSO communication market reached $2.09 billion in 2026, with projections for compound annual growth of 12.9% through 2033 [1]. This growth trajectory reflects the increasing recognition of FSO as a complementary technology to traditional wireless systems.

FSO systems find application across diverse domains: last-mile connectivity in dense urban environments, enterprise network backhaul, military communications requiring low probability of intercept, and post-disaster network recovery. Their ability to deliver fiber-like data rates without physical infrastructure makes them particularly attractive for bridging the digital divide in underserved regions.

The emergence of 6G networks, with requirements for terabit-per-second data rates and ubiquitous connectivity, has further elevated the importance of FSO technology. As radio frequency spectrum becomes increasingly congested, optical wireless communications offer a viable pathway to meet the capacity demands of next-generation networks [2]. Furthermore, the integration of FSO with unmanned aerial vehicles (UAVs) and satellite systems is creating new paradigms for space-air-ground integrated networks (SAGIN) [3, 4].

2. Literature Review and State of the Art

The study of atmospheric effects on optical propagation has been a subject of investigation for decades. Early work by Tatarski established the theoretical foundations for turbulence-induced scintillation, while subsequent research developed statistical models including the lognormal distribution for weak turbulence and the gamma-gamma model for moderate-to-strong turbulence conditions [5, 6].

Adaptive optics, initially developed for astronomical applications, was adapted for FSO communications in the early 2000s. Zhu and Kahn [7] provided a comprehensive analysis of FSO communication through atmospheric turbulence channels, establishing performance bounds and identifying key mitigation strategies. More recently, Gao et al. [8] proposed a hybrid deep learning-based modeling approach that separates high-frequency scintillation from low-frequency power drift, achieving 79% BER reduction compared to conventional methods.

Recent advances in wavefront-polarization joint correction represent a significant evolution in adaptive optics. Shangjun et al. [9] demonstrated that combining wavefront correction with polarization compensation using liquid crystal spatial light modulators improves relative power from 0.8869 to 0.9964 at 1 km transmission distance and increases polarization correlation from 0.5395 to 0.9491. This vectorial adaptive optics approach provides a theoretical foundation for next-generation FSO systems requiring both phase and polarization control.

Optical phase conjugation (OPC) has emerged as a particularly promising technique for automatic turbulence mitigation. Zhou et al. [10] experimentally demonstrated OPC-based automatic mitigation of dynamic turbulence in an 8-Gbit/s QPSK coherent FSO link using four-wave mixing in a GaAs crystal. Their approach achieved sub-millisecond response times suitable for practical deployment, representing a significant advancement over previous photorefractive crystal implementations that required seconds of stable illumination.

Hybrid RF/FSO systems have garnered substantial research attention as a pragmatic approach to overcoming weather-related link unavailability. The adaptive switching between RF and FSO channels based on real-time channel conditions enables reliable communication under diverse weather scenarios. Belmonte [11] proposed an adaptive-waist mode approach where the transmitter utilizes turbulence statistics (rather than instantaneous conditions) to optimize beam parameters, achieving significant performance gains over standard Gaussian beams without requiring wavefront correction.

The integration of FSO with reconfigurable intelligent surfaces (RIS) represents a frontier in optical wireless communications. Shakir and Charafeddine [12] developed an analytical framework for RIS-empowered MIMO-FSO systems, providing closed-form expressions for probability density functions and performance metrics under gamma-gamma turbulence with pointing errors. Their results confirm RIS technology is potential in mitigating turbulence-induced fading and misalignment, with computational efficiency suitable for practical applications.

Deep reinforcement learning (DRL) applied to optimize UAV trajectories in optical IRS-aided hybrid FSO/RF aerial access networks [13]. The DRL-based approach dynamically optimizes UAV placement and user association in real time, maximizing end-to-end throughput under turbulence and cloud-induced attenuation. This work highlights the potential of deploying OIRS-assisted architectures for robust 6G networks.

3. Free-Space Optical Communication System Architecture

3.1. Basic Components

A typical FSO system consists of an optical transmitter (laser diode or LED source), the atmospheric propagation channel, and an optical receiver (photodetector). The electrical information signal converted into optical pulses representing digital data (1s and 0s), transmitted through free space, received by the photodetector, and converted back into an electrical signal for processing.

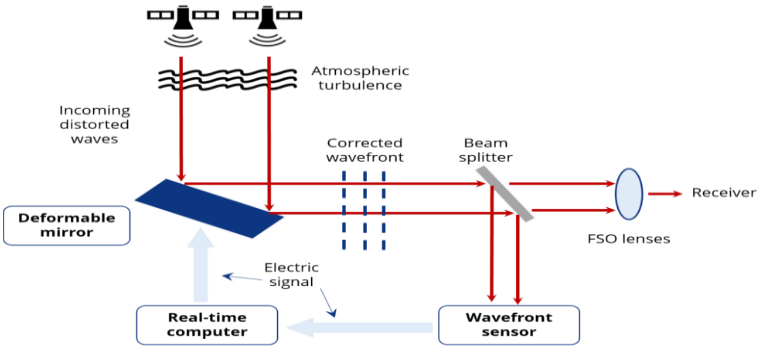

Figure 1: Basic FSO System Architecture

The transmitter section typically includes a laser source operating in the near-infrared window (780-1600 nm), where atmospheric attenuation is minimal, along with beam shaping optics. The receiver incorporates a photodetector (PIN or APD), optical filters, and signal processing electronics. Key performance parameters include optical power budget, link margin, and pointing/tracking requirements.

3.2. Atmospheric Effects on Free-Space Optical Communications

Atmospheric turbulence is the primary limiting factor for FSO system performance. Turbulence arises from temperature and pressure variations in the atmosphere, creating refractive index in homogeneities that distort propagating optical wave fronts. These distortions cause fluctuations in received signal intensity (scintillation) and phase distortions, leading to degradation of optical link performance [6].

Statistical Models for Turbulence

Table 1: Multiple Statistical Models Atmospheric Turbulence Effects

Model	**Turbulence Range**	**Key Equation**
Log-normal	Weak	$\rho(\mathrm{I}) = \frac{1}{\mathrm{I}\sqrt{2\pi\sigma^2}}\exp(-\frac{(\ln\mathrm{I}-\mu)^2}{2\sigma^2})$
Gamma-gamma	Moderate to strong	$\rho(\mathrm{I}) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{r(\alpha)r(\beta)}\mathrm{I}^{(\alpha+\beta)/}2-1 \quad \kappa_{\alpha-\beta}(\sqrt[2]{\alpha\beta\mathrm{I}})$
Rytov variance	Strength measure	$\sigma^2\mathrm{R} = 1.23\mathrm{C}_n^2\ \mathrm{K}^{7/6}\,\mathrm{L}^{11/6}$

The lognormal model applies to weak turbulence conditions where scintillation is relatively small. The gamma-gamma model, parameterized by α and β representing effective numbers of large-scale and small-scale eddies, is widely used for moderate to strong turbulence. The Rytov variance σR2σR2 provides a measure of turbulence strength, with values less than one indicating weak turbulence and values greater than one indicating strong turbulence [5].

Contemporary studies have since moved past these foundational models, evolving to account for the full complexity of atmospheric behavior. Belmonte [11] proposed the use of adaptive-waist modes statistically matched to turbulence conditions, where the transmitter leverages turbulence statistics (but not instantaneous conditions) to optimize beam parameters. This approach offers significant gains over standard Gaussian beams.

Weather Effects

In addition to turbulence, fog and rain significantly affect FSO propagation. Fog causes Mie scattering of light, severely attenuating optical signals and potentially causing complete link failure [14]. Studies in subtropical monsoon climates (e.g., Bangladesh) have shown atmospheric attenuation up to 12.46 dB/km for light fog and 23.11 dB/km for heavy rain [15]. Rain causes both scattering and absorption, with attenuation increasing with rainfall rate.

The Málaga (M) distribution has emerged as a unifying statistical model for atmospheric optical channels, encompassing lognormal, gamma-gamma, and negative exponential distributions as special cases. This model provides a comprehensive framework for analyzing FSO performance under diverse turbulence and pointing error conditions [16, 17].

4. Advanced Mitigation Techniques

4.1. Adaptive Optics

Adaptive optics represent the fundamental technology for compensating atmospheric effects. These systems measure wavefront distortions and correct them in real-time using deformable mirrors, spatial light modulators, and wavefront sensors.

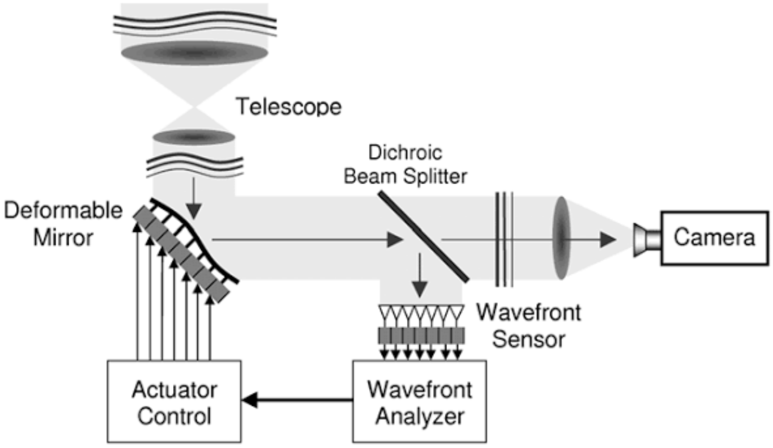

Figure 2: Adaptive Optics System

Traditional adaptive optics systems use a wavefront sensor (e.g., Shack-Hartmann) to measure distortions, a controller to compute correction signals, and a deformable mirror to apply phase correction. However, the complexity and cost of wavefront sensors have motivated the development of sensorless adaptive optics approaches.

Vectorial Adaptive Optics and Polarization Control

Recent advances have extended adaptive optics beyond wavefront correction to include polarization compensation. Shangjun et al. [9] demonstrated a joint wavefront-polarization correction strategy for radially polarized vortex beams. Their approach uses:

1. Polarization multiplexing and demultiplexing for wavefront correction.
2. Gauss-Newton iterative algorithm for polarization compensation using two serial liquid crystal spatial light modulators.

Experimental results showed remarkable improvement: after wavefront correction, relative power increased from 0.9927 to 0.9962 at 100 m, from 0.8869 to 0.9964 at 1 km, and from 0.7751 to 0.9944 at 5 km. Subsequently, polarization compensation increased polarization correlation from 0.6444 to 0.8585 at 100 m, and from 0.4393 to 0.9408 at 5 km. This demonstrates that polarization effects ignored in anisotropic atmospheric turbulence and that joint control significantly improves performance [9].

Sensorless Adaptive Optics with Deep Learning

In a recent study, a model-free adaptive optics system developed using deep learning to estimate and correct distortions without traditional wavefront sensors. This approach uses deep neural networks to estimate phase distortions from the received signal intensity alone, simplifying the system and reducing cost while maintaining excellent performance under rapidly changing turbulence conditions [8].

4.2. Spatial and Temporal Diversity

Diversity techniques are effective solutions for mitigating fading caused by atmospheric turbulence.

Temporal Diversity

Temporal diversity uses a single receiver with knowledge of temporal fading statistics. Maximum Likelihood Sequence Detection (MLSD) can improve performance by exploiting the temporal correlation of fading. However, this approach requires knowledge of the joint fading distribution over time and may be limited by the fading coherence time.

Spatial Diversity

Spatial diversity uses multiple receivers at different locations (SIMO) or multiple transmitters (MISO). For effective diversity gain, the distance between receivers must exceed the fading correlation length. Spatial diversity reduces correlation between received signals and improves diversity order. Configurations include:

- SISO (Single-Input Single-Output): Basic FSO link.
- SIMO (Single-Input Multiple-Output): Multiple receivers at spatially separated locations.
- MISO (Multiple-Input Single-Output): Multiple transmitters, typically using aperture averaging.
- MIMO (Multiple-Input Multiple-Output): Multiple transmitters and receivers.

4.3. Hybrid RF/FSO Systems

Hybrid systems combining Radio Frequency (RF) and Free-Space Optical communications represent an optimal solution to overcome the limitations of each technology individually.

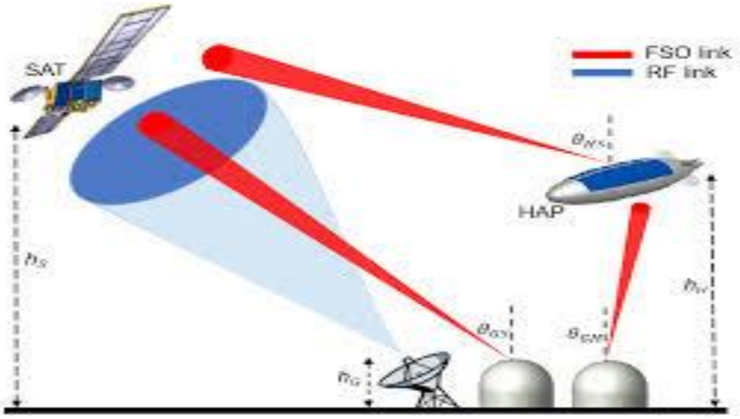

Figure 3: Hybrid RF/FSO System and HAPS Network Architecture

Key Advantages

- High reliability under all weather conditions: FSO provides high data rates in clear conditions; RF serves as backup during adverse weather.
- Redundant link architecture: Both FSO and RF links operate simultaneously or in switchable modes.

- Significant improvement in link availability: Can achieve 99.999% availability even in regions with frequent fog or rain.

In 2026, experimental projects in Europe reported a 25% reduction in atmospheric fading issues using hybrid RF/FSO solutions [18].

Recent Advances in Hybrid Networks

The integration of UAVs with hybrid FSO/RF systems has created new possibilities for aerial access networks. A deep reinforcement learning (DRL)-based approach has been developed to optimize UAV placement and user association in real time, maximizing end-to-end throughput while adhering to backhaul capacity constraints [13]. The dynamic multi-UAV configuration, trained under realistic cloudy conditions, significantly outperforms single-UAV and static deployment strategies.

Hybrid FSO/RF is also playing a crucial role in space-air-ground integrated networks (SAGIN). A novel RIS-assisted downlink hybrid FSO/RF SAGIN architecture proposed where high-altitude platforms (HAPS) convert satellite optical signals for distribution to ground users [3]. This architecture addresses communication challenges caused by RF link blockages from clouds or buildings, achieving 39.7% improvement in sum secrecy rate compared to NOMA schemes.

A reinforcement learning-based algorithm for optimizing HAPS trajectory in hybrid RF/FSO networks introduced by [19], enabling dynamic switching between RF and FSO modes based on propagation channel conditions to maximize achievable capacity. This approach adapts to dynamic cloud formations and atmospheric conditions.

5. Advanced MIMO-FSO Systems

5.1. Architecture and Principle

Multiple-Input Multiple-Output (MIMO) systems represent an effective solution for mitigating atmospheric turbulence. These systems use arrays of transmitters and receivers to improve reliability and capacity through spatial diversity and multiplexing.

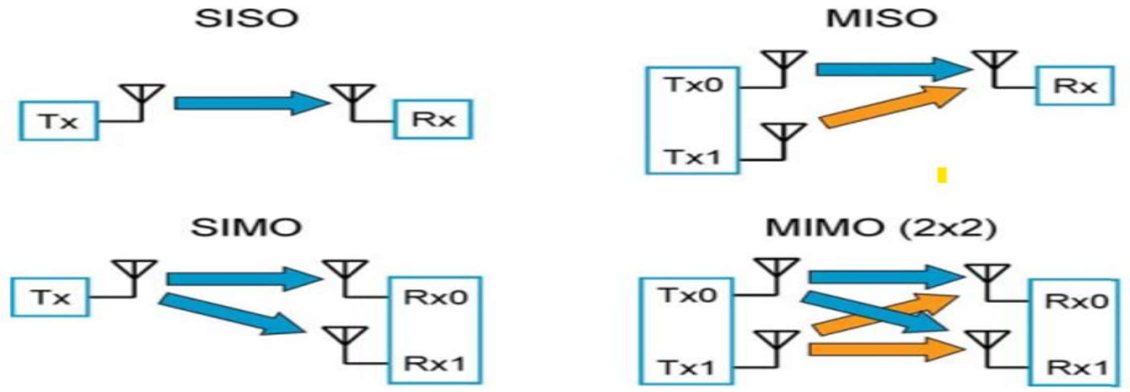

Figure 4: MIMO System Configurations

The MIMO channel represented by a matrix H where each element hij represents the complex gain between transmitters i and receiver j. MIMO systems exploit the spatial degrees of freedom to achieve:

- Diversity gain: Multiple independent fading paths reduce signal outage probability.
- Multiplexing gain: Multiple spatial channels increase data rate.
- Array gain: Coherent combining of signals improves SNR.

5.2. Recent Advances in MIMO-FSO

Recent research has focused on integrating MIMO-FSO with advanced modulation techniques. A hybrid system combining adaptive spatial modulation (N-SM), spatial pulse position modulation (SPPM), dense wavelength division multiplexing (DWDM), and orbital angular momentum (OAM) achieved BER as low as 10−910−9 over 2 km using 2×12×1 MISO configuration and over 200 m using 4×44×4 MIMO configuration.

RIS-Enabled MIMO-FSO

The integration of reconfigurable intelligent surfaces (RIS) with MIMO-FSO represents a significant advancement. Shakir and Charafeddine [12] developed an analytical framework for RIS-empowered MIMO-FSO systems, providing the first closed-form expressions for probability density functions and cumulative distribution functions of end-to-end channels considering gamma-gamma turbulence, generalized Rician pointing errors, and RIS size-related constraints.
Key findings include:

- RIS placement optimization reduces outage probability even under challenging atmospheric conditions.
- The framework provides closed-form performance metrics including outage probability, average BER, ergodic capacity, and energy efficiency.
- Computational efficiency makes the approach feasible for practical, large-scale applications.

RIS technology offers a transformative potential for next-generation optical networks by enabling beam manipulation, improving link reliability, and increasing network scalability without requiring active signal processing at the RIS nodes [13].

Adaptive Mode Switching

Chen et al. [17] analyzed MIMO FSO adaptive mode switching in Malaga turbulent channels with pointing errors. Their work demonstrated that adaptive switching between spatial modes based on channel conditions significantly improve spectral efficiency while maintaining reliability. This approach dynamically selects between diversity and multiplexing modes depending on instantaneous channel quality, representing a practical implementation of the diversity-multiplexing tradeoff.

6. Deep Learning in FSO Systems

6.1. Deep Learning Models for Turbulence Mitigation

Deep learning has revolutionized atmospheric turbulence mitigation. A hybrid deep learning framework proposed that separates high-frequency scintillation from low-frequency power drift using a conditional variation auto encoder with bidirectional LSTM architecture and adaptive gate mechanism [8].
Key Results

- Average reduction of 79% in Bit Error Rate (BER) compared to traditional methods.
- Compensated BER approaching zero in practical experiments.
- Successful performance under rapidly changing turbulence conditions.

6.2. Optical Phase Conjugation with AI

Optical phase conjugation (OPC) has emerged as a powerful technique for automatic turbulence mitigation. Zhou et al. [10] demonstrated automatic mitigation of dynamic turbulence in coherent FSO links using four-wave mixing (FWM)-based OPC in a GaAs crystal. Their approach achieved both high data rates (8 Gbit/s QPSK) and rapid response times (sub-millisecond).

Key achievements:

- Significant reduction in SMF-coupling loss fluctuation range.
- Demonstrated "automatic" mitigation without electronic signal processing.
- Suitable for dynamic turbulence with Greenwood frequency up to several hundred Hz.
- Practical response time of less than 1 ms using GaAs semiconductor crystal [10].

6.3. Sensorless Adaptive Optics

Neural network-based phase compensation without wave front sensors represents another important development. This approach uses deep neural networks to estimate phase distortions from the received signal alone, simplifying system architecture and reducing cost. The neural networks trained to map intensity patterns to phase corrections, enabling effective compensation without complex wave front sensing hardware.

6.4. AI-Enabled Resource Management

Deep reinforcement learning (DRL) applied to optimize resource allocation in hybrid FSO/RF networks. Kaur et al. [13] demonstrated a DRL-based approach for UAV trajectory optimization in optical IRS-aided hybrid FSO/RF aerial access networks. The approach:

- Dynamically optimizes UAV placement and user association in real time.
- Maximizes end-to-end throughput under turbulence and cloud-induced attenuation.
- Achieves higher data rates and stable user connectivity compared to static deployment strategies.

Reinforcement learning applied to optimize HAPS trajectory in hybrid RF/FSO links, enabling maneuvering around cloudy areas and seamless switching between communication modes to maximize achievable capacity [19].

7. Emerging Applications

7.1. Satellite Optical Communications

Laser communications in space are experiencing increasing technological maturity. Companies including SpaceX and Google, along with space agencies (NASA and ESA), are actively developing laser communication technologies for space applications.

Figure 5: Satellite Laser Communications

Key Applications

- Aircraft-to-geostationary satellite links: High-capacity data relay from airborne platforms.
- Inter-satellite communications: Laser links between satellites in constellations.
- Ground-to-space communications: High-speed uplink/downlink through the atmosphere.

The Earth's atmosphere remains a limiting factor for space-to-ground communication efficiency, requiring adaptive optics and predictive turbulence models.

Integration with Space-Air-Ground Networks (SAGIN)

Recent research has focused on integrating FSO into SAGIN architectures. A RIS-assisted downlink hybrid FSO/RF SAGIN architecture proposed where high-altitude platforms (HAPS) convert satellite optical signals for distribution to ground users [3]. This approach addresses:

- Communication challenges caused by RF link blockages from clouds or buildings.
- Security concerns through physical layer security (PLS).
- Large-scale user access scenarios using rate splitting multiple access (RSMA).

The hybrid FSO/RF approach for satellite-to-ground links combines the high bandwidth of FSO with the reliability of RF, providing robust communication even under challenging atmospheric conditions.

7.2. Underwater Optical Wireless Communication (UWOC)

In November 2025, Kyocera Corporation achieved a historic milestone in underwater wireless optical communications, successfully demonstrating UWOC technology capable of data transmission at 5.2 Gbps over short distances [20].

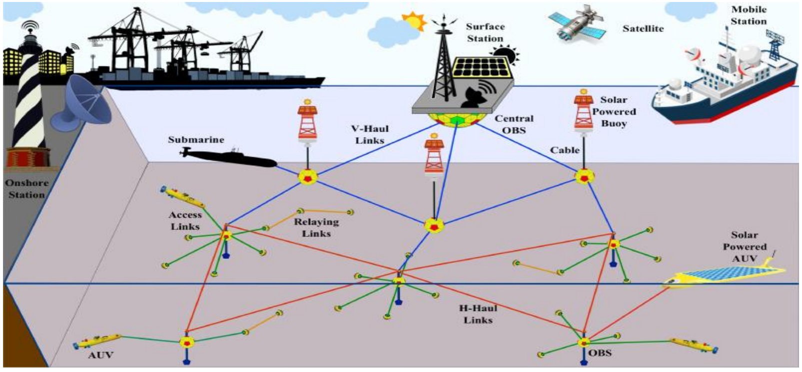

Figure 6: Underwater Optical Wireless Communication System

Technology Features

- Proprietary PHY layer dedicated to underwater environments.
- Underwater bandwidth expansion to 1 GHz using Kyocera's original communication specifications.
- Data transmission speeds 2.5 times higher than conventional underwater optical communications.
- Optical front-end circuit with wide bandwidth exceeding 1 GHz.

Applications

- Ocean exploration and scientific research.
- Underwater robot operations (AUVs and drones).
- Inspection of underwater structures.
- Real-time data collection from marine sensors.
- Live underwater video streaming.

This technology is particularly significant for enabling real-time, high-volume data transmission for ocean exploration and underwater robot operations, providing immediate access to high-resolution images, video feeds, and sensor data [20].

7.3. Urban Communications and Smart Networks

FSO systems increasingly used in urban networks as last-mile solutions and backhaul for 5G/6G networks. In 2025, urban deployments in the United States showed a 36% improvement in data transmission speeds using FSO compared to traditional microwave links [18].

FSO is particularly attractive in dense urban environments where:

- RF spectrum is congested and costly.
- Fiber deployment is expensive and disruptive.
- Quick deployment is required for temporary or emergency networks.

Role in 6G Networks

The unique advantages of FSO—ultra-high bandwidth, low latency, and enhanced security—position it as a key enabling technology for 6G networks. Key roles include:

- Backhaul and fronthaul for dense small-cell deployments.
- Last-mile connectivity for high-bandwidth users.
- Mobile fronthaul for UAV-based communication platforms.
- Space-air-ground integrated networks for ubiquitous coverage [2].

7.4. UAV-Based FSO Networks

UAV-based hybrid FSO/RF communication networks (UHCNs) have gained significant research attention. A scientometric analysis by [4] revealed:

- Research on UHCNs is expanding rapidly, with China, USA, and KSA as major contributors.
- Key research hotspots include RIS, UAV path design, wireless power transfer, and secure links.
- DRL, ML, and RIS are emerging trends.
- Testbeds and real-world validation needed.

UAV-based FSO communication provides comprehensive coverage, high bandwidths, network densification, and seamless connectivity in urban, rural, or disaster-affected areas, making it crucial for 6G communication [4].

Table 2: Comparison of Mitigation Techniques

Technique	Effectiveness	Complexity	Cost	Application
Adaptive Optics	Very High	High	High	Long links
Spatial Diversity	Medium	Medium	Medium	Short links
Temporal Diversity	Medium	Low	Low	All links
MIMO-FSO	High	High	High	High-capacity links
Hybrid RF/FSO	High	Medium	Medium	Critical applications
Deep Learning	Very High	High	Medium	Adaptive systems
RIS-Enabled FSO	High	Medium	Medium	Deployable networks
Optical Phase Conjugation	Very High	High	High	Coherent systems

8. Challenges and Future Solutions

8.1. Key Challenges

1. Reliability in severe weather: Dense fog and heavy rain can completely sever the optical link. Fog-induced attenuation in tropical climates can reach up to 23.11 dB/km, making FSO links impractical during severe fog events [15].
2. Alignment complexity: FSO systems require precise alignment between transmitter and receiver. UAV-based FSO links face additional challenges due to orientation changes and angle-of-arrival fluctuations [4].
3. Eye safety: High-power lasers require strict safety considerations and regulatory compliance.
4. Cost: Advanced technologies such as adaptive optics and MIMO systems increase system cost, though sensor less approaches and integrated photonics are reducing this barrier.
5. Security: While FSO inherently offers low probability of intercept, eavesdropping in SAGIN environments remains a concern, particularly in military and sensitive applications [3].

8.2. Future Solutions

- AI-enabled systems: Deep learning and reinforcement learning models will continue to improve adaptive performance. The integration of AI for real-time channel estimation, resource allocation, and beam optimization will be critical for 6G systems. DRL has already demonstrated significant potential in optimizing UAV trajectories and hybrid switching decisions [13, 19].
- Advanced hybrid systems: Integration of FSO with Li-Fi, quantum communications, and RIS technology. RIS-enabled MIMO-FSO systems expected to play a significant role in next-generation optical networks [12].

- Integrated optical transceivers: Reducing size and cost using Silicon Photonics and photonic integrated circuits (PICs).
- New standards: Development of standards such as IEEE 802.11bb for indoor wireless optical communications and protocols for space-to-ground FSO links.
- RIS-assisted architectures: Optical intelligent reflecting surfaces (OIRS) mounted on HAPS or UAVs can enhance FSO signal distribution by enabling precise beam manipulation, improving link reliability, and increasing network scalability [13].
- Quantum-secure FSO: Integration with quantum key distribution (QKD) for enhanced security in critical applications.
- Testbeds and real-world validation: Growing emphasis on building open testbeds for validating hybrid FSO/RF networks in realistic conditions [4].

9. Conclusion

Free-Space Optical communications represent a pivotal technology for next-generation telecommunications, offering unique advantages in speed, security, and spectrum availability. While atmospheric effects pose a significant challenge, advanced mitigation techniques—from AI-supported adaptive optics and vectorial wave front-polarization correction to hybrid RF/FSO systems and RIS-enabled MIMO configurations—are opening new horizons for improving reliability and performance.

Recent advances in deep learning-based turbulence prediction and sensor less adaptive optics demonstrate the transformative potential of artificial intelligence in optical communications. The development of optical phase conjugation for automatic turbulence mitigation with sub-millisecond response times [10] and adaptive-waist mode optimization [11] represent significant breakthroughs toward practical, high-performance FSO systems.

The integration of FSO with RIS technology, UAV platforms, and space-air-ground networks is creating new paradigms for ubiquitous connectivity. Reinforcement learning-based approaches for resource allocation and trajectory optimization are enabling dynamic adaptation to changing atmospheric conditions [13, 19].

With market growth at 12.9% annually and emerging applications in space, oceans, and urban networks, the future of free-space optical communications appears very promising. The future requires continued collaboration between researchers and industry to develop innovative solutions that overcome current challenges—particularly in severe weather conditions and security—and open the door to a new generation of high-speed wireless communications. The convergence of FSO with AI, RIS technology, and 6G will be essential for realizing the full potential of optical wireless communications in the coming decade.

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