Revolutionizing 6G Networks: Deploying Free Space Optics for Aerial Base Stations

– Leveraging Enhanced Bandwidth for Massive Access and Ultra-Reliable Low-Latency Services

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The expected arrival of sixth generation (6G) mobile technology by 2030 aims to offer comprehensive three-dimensional coverage, ensuring connectivity for everyone, everywhere, at any time. Aerial base stations using Free-Space Optical (FSO) communication are key technologies that can connect terrestrial and non-terrestrial layers providing high-speed, low-latency, and reliable transmission capabilities. In this article, we propose an innovative aerial architectural swarm design to improve network performance via cooperative transmissions. We highlight the properties, types of formation, and transmission methods for aerial swarms. Next, we analyze the considerations and challenges of deploying aerial FSO base stations, with a focus on channel-induced fading and weather induced degradations. The simulation results show greater potential associated with the proposed vertical FSO architecture in overcoming channel induced fading losses and providing high data rates. Additionally, the article discusses self-sustainability and explores future research directions, including the application of AI/ML, intelligent reflecting surfaces, and quantum internet security to optimize and design next-generation FSO-based aerial base stations.

Aerial FSO Base Stations: Ushering in 6G Era

Terrestrial base stations are costly due to expenses related to power, backhaul, installation, maintenance, and security. Many regions also lack stable power sources, and challenging terrains further complicate their deployment. In remote areas and small islands, telecom infrastructure often relies on diesel generators, which are environmentally harmful and conflict with sustainability goals. As a result**,** sixth generation (6G) networks towards sustainable massive access and ultra-reliable and low latency services must integrate space-air-ground (SAG) architectures, offering lower costs and broader coverage. In such cases, aerial platforms, serving as on-demand base stations will play crucial roles in enabling dense small-cell deployment.[1]

Microwave RF bands currently support aerial wireless links, for example, the U.S. Department of Defense's Common Data Link (CDL) operating in the Ku (12–18 GHz) and Ka (26–40 GHz) bands for HAP-to-ground communication. However, CDL's 274 Mbps to 3 Gbps capacity is inadequate for high-speed demands. Hybrid RF/FSO systems, such as DARPA's FaRIA-C initiative, improve capacity by switching between FSO (10 Gbps) and RF (2 Gbps) links. Yet, these systems face scheduling, scalability, and RF capacity constraints. To overcome spectrum limitations and achieve terabit-per-second data rates, a shift to an 'All-Optical' vertical backhaul/fronthaul network is needed which is the focus of this article. The existing works on SAG architectures have primarily focused on hybrid RF/FSO links [2-3]**,** static relays [4-6], or layered aerial networks [7-9] with limited adaptability. For instance, [5-6] proposes a SAG FSO link by deploying HAPs as relay, but it mainly focuses on mitigating the effects of atmospheric turbulence rather than forming a fully cooperative aerial communication framework. Similarly, [7] explores single- and dual-layer FSO systems involving both HAPs and rotary-wing platforms, but the architecture remains constrained by predefined roles and limited adaptability. In [8], a decode-and-forward relay chain is studied for uplink transmission from a ground station to a LEO satellite via multiple HAPs, focusing on routing efficiency but not system coordination. [9] investigates a multi-layer FSO backhaul network employing HAPS and unmanned aerial vehicles but focuses primarily on deployment planning while [10-11] investigates HAPs performance in multi-layer airborne systems without considering real-time control across layers. While these studies contribute valuable insights into specific design aspects, they largely rely on fixed topologies and RF-assisted fallback mechanisms. A comparative summary of related works highlighting platform scope, communication technology, and HAP capabilities is provided in Table 1.

In this article we propose a novel multi-tier cooperative aerial swarm, where HAPs serve as both leaders and relay**s**, coordinating dynamically with MAPs, LAPs, and UAVs. Unlike the existing models, which are limited to fixed relay placements and two-layer cooperation, our architecture provides adaptive aerial coordination, scalable multi-layer FSO relays, and intelligent load balancing across multiple network layers. This highly flexible and resilient approach ensures superior coverage and reduced latency, supporting both massive access and ultra-

[1] In our recent work [1], we studied the possibility of providing fronthaul services with a terrestrial FSO link. In this article, we explore FSO based vertical links for fronthaul/backhaul services in the future 6G networks.

reliable and low latency services requirements, marking a significant advancement over state-of-the-art SAG architectures.

Contributions

1. We propose a multi-tier cooperative aerial swarm architecture that integrates multiple aerial platforms, enabling an adaptive, high-speed, long-range backhaul/fronthaul network using FSO links—a shift from conventional static relay-based models.
2. Unlike existing approaches, our architecture enables stratospheric platforms to function as both swarm leaders and relays, optimizing tropospheric swarm coordination while ensuring reliable satellite-ground connectivity.
3. We evaluate the practical challenges of aerial FSO base stations, focusing on channel-induced fading, turbulence effects, and weather-related degradation, providing key insights into real-world deployment feasibility.
4. To address network scalability and security challenges, we explore the integration of AI/ML-driven optimization, intelligent reflecting surfaces (IRS) for adaptive beam steering, and quantum-secured communications, ensuring a resilient and future-ready aerial communication framework.

Cooperative SAG network Architecture

Recently, there has been a remarkable increase in the deployment of aerial platforms and operators. However, this growth brings a significant challenge: rising interference. Without proper management, this interference could hinder network performance, resulting in minimal gains or even a decline in throughput. To address this, we propose cooperative aerial architecture aimed at enhancing network performance. This innovative framework primarily relies on two key technologies: free-space optics and integrated aerial nodes. We use the term aerial nodes broadly to include satellites, high-, medium-, and low-altitude platforms (HAPs, MAPs, LAPs), balloons and different kinds of aeronautical nodes like unmanned aerial vehicles and drones.

Stratospheric Layer as RELAY

FSO based communication system's performance significantly decreases with an increase in path lengths. Ideally, the zenith angle for FSO communication should be small, but this is generally not practical for terrestrial nodes trying to establish satellite connections because of the fixed zenith angles of geostationary (GEO) satellites and the varying zenith angles of low Earth orbit (LEO) satellites during a communication session. In contrast, an FSO communication via SAG network can achieve low zenith angles by strategically placing a HAP vertically above the desired terrestrial node. This setup reduces the propagation path over turbulence-prone locations, reducing geometric and scintillation losses in ground-to-HAP FSO transmissions. This short propagation length is independent of the zenith angle of the satellite, and thus particularly beneficial in case of LEO satellites. At altitudes above 20 km, the low aerosol density results in weak turbulence effects for HAP-to-satellite FSO transmissions, further reducing pointing errors and scintillation. Consequently, as depicted in Fig. 1, with the integration of stratospheric layer as a relay between ground and satellite link, the proposed SAG-FSO system maintains consistent performance regardless of the satellite zenith angle. Additionally, in a network with both LEO and GEO satellites, GEO satellites can handle tasks requiring low latency and throughput, while tasks with higher latency and throughput requirements can be offloaded to LEO satellites, which offer shorter latency and higher throughput. This load balancing optimizes resource use across the entire network.

Stratospheric Layer as LEADER

It is widely recognized that achieving extremely high data rates in 6G wireless networks largely depends on the dense deployment of small cells. However, effectively backhauling and fronthauling the small cell base stations (SBSs) presents a

Table 1: Comparison of related works based on platform scope, link type, and HAP capabilities

Reference	System Model	Satellite	HAP	UAV	Link Type	HAP Capabilities
[2]	Energy-efficient multi-HAPS FSO/RF system	✅	✅	❌	Hybrid	Relay only
[3]	Coverage area + HAPS deployment in SAGIN	✅	✅	❌	Hybrid	Relay + coverage control
[4]	Improving ground-HAPS MIMO-FSO performance	❌	✅	❌	FSO	Relay only
[6]	Multiple HAPS-based SAG network	✅	✅	❌	FSO	Relay only
[7]	Multi-layer airborne FSO systems	❌	✅	✅	FSO	Static multi-tier relay
[8]	Multiple HAPs-based hybrid FSO/RF	✅	✅	❌	Selective FSO/RF	Decode and forward relay
[9]	FSO-based multi-layer backhaul networks	❌	✅	✅	FSO	Layered backhaul relay
Our proposed model	6G-ready swarm architecture with leader-follower coordination	✅	✅	✅	FSO	Relay + leader (centralized swarm management)

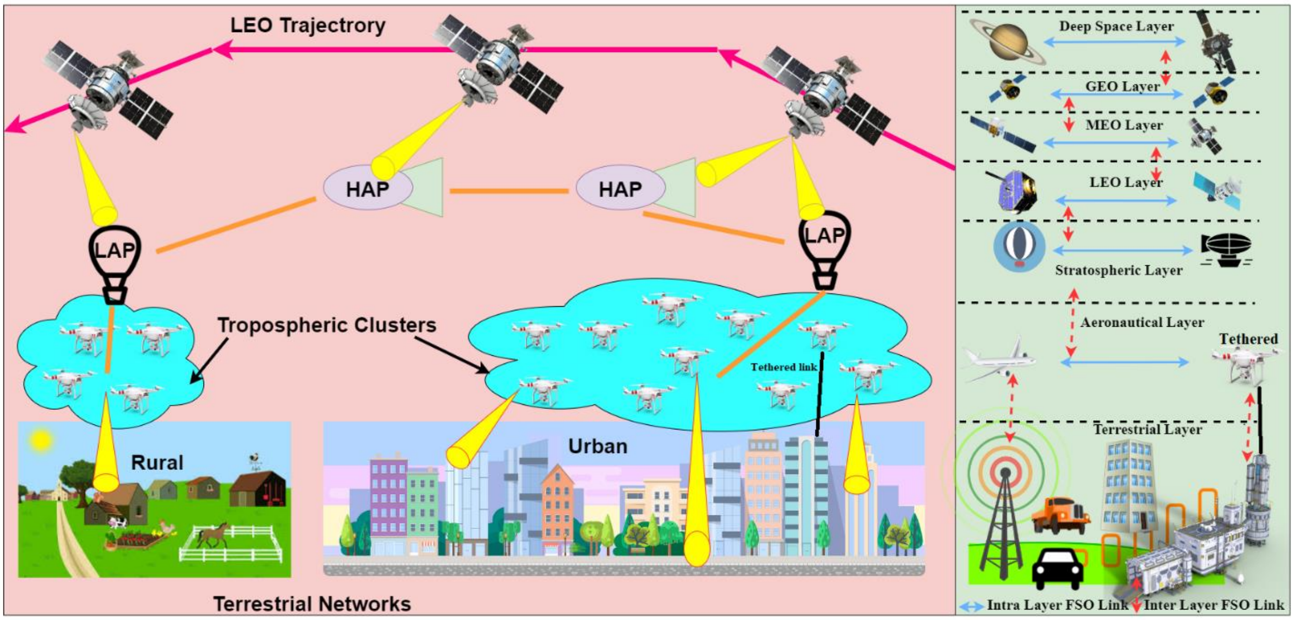

Figure 1: A generic SAGIN architecture, with layers at different altitudes: deep space (> 35,838 km), geosynchronous Earth orbit (GEO) (12,000-35,838 km), medium Earth orbit (MEO) (2,000- 12,000 km), low Earth orbit (LEO) (200-2,000 km), stratospheric (17-22 km), and aeronautical (0.15-17 km) layer. Stratospheric platforms help in mitigating zenith angle limitations for satellite-to-ground FSO links and managing coordinated tropospheric clusters.

major challenge. Current solutions involve directing traffic from SBSs to a central hub for aggregation, but placing these hubs is complex and has been identified as an NP-complete problem. Additionally, line-of-sight (LoS) hub placement can be impractical in areas where SBSs are deployed in inaccessible locations. Sky-based connectivity offers a solution to these challenges. The proposed novel framework includes HAPs/LAPs as a leader and a swarm of aeronautical platforms as followers as depicted in Fig. 2. In a multi-tier heterogeneous network (HetNet) with ultra-dense small cells overlaid with macro cells in a geographic area, this system can complement terrestrial backhaul/fronthaul networks, particularly in challenging environments. For instance, it can be deployed when terrestrial networks fail or during temporary high-demand events like sports games.

This system can also provide backhaul/fronthaul to SBSs in hard-to-reach areas where fiber or microwave links are unavailable or expensive, such as rural or remote regions, or urban areas below surrounding buildings where SBSs are mounted on street furniture like walls and lamp posts. A stratospheric aerial platform acts as the leader of the swarm, connecting the aeronautical platforms to the core ground network. All in-between layer and within the same layer connections use FSO links, and SBSs with a clear LoS to an aerial platform use FSO beams to deliver/receive traffic. SBSs without LoS can be served by a nearby SBS that has LoS to an aerial platform. Alternatively, rather than connecting each SBS to an aerial platform, traffic can be aggregated and relayed from SBSs to a designated SBS with LoS to an aerial platform, resulting in higher energy efficiency. SBSs connected to aerial platforms are equipped with tracking systems to maintain the beam alignment with the aerial platforms.

Swarm Formation: Regarding swarm formation, one method involves equidistant placement of follower platforms from the leader platform, forming a circular swarm. This configuration ensures comparable in-between layer link distances, aiding in transmission timing synchronization across the cluster and simplifying antenna or lens alignment. However, with many platforms, space limitations may necessitate a uniform swarm formation, where the leader is centrally located, and followers are uniformly distributed around it. Although this configuration complicates timing synchronization and transceiver alignment due to unequal within the same layer link distances, it efficiently uses the available area for dense deployment.

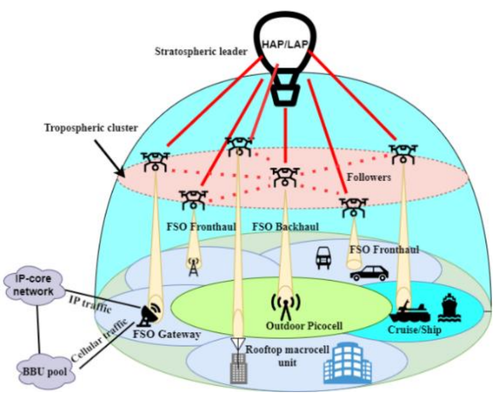

Figure 2: The conceptual topology of vertical fronthaul/backhaul FSO framework for 6G wireless networks.

Stratospheric Transmission Schemes

In stratospheric FSO communication, joint transmission and dynamic point selection are two fundamental techniques that significantly impact the system performance. The primary challenge in such a network is ensuring high-capacity and reliable connectivity, despite turbulence, beam misalignment, and varying channel conditions. By optimizing the selection and coordination of transmission points, the system can adaptively allocate resources, mitigate signal degradation, and enhance spectral efficiency.

Joint Transmission involves multiple transmission points cooperatively sending the same signal to improve reception quality. One approach to implementing this is Maximal ratio transmission (MRT), which offers superior signal gain by maximizing the received signal-to-noise ratio. However, MRT requires full knowledge of both the amplitude and phase of the channel coefficients. This demands accurate channel estimation and imposes strict synchronization and feedback requirements among the stratospheric platforms. The need for high-precision in-between layer's communication makes this technique computationally intensive and challenging in dynamic environments. As an alternative, *Equal gain transmission (EGT)* offers a more practical solution by equally distributing transmit power across multiple platforms. Unlike MRT, EGT requires only channel phase information, which simplifies implementation and reduces hardware complexity. This makes it possible to use less expensive power amplifiers, which is a crucial advantage since power amplifiers are vital for compensating FSO signal power loss. However, for effective operation, precise synchronization and cooperation among the platforms remain necessary, especially as the number of participating nodes increases.

Another potential transmission scheme is *Dynamic Point Selection (DPS)* which is a beamforming technique that optimizes transmission by selecting the transmission point with the best channel conditions. This approach helps minimize inter-cell interference by deactivating other transmission points [12]. This method is particularly suitable for clustered aeronautical networks with many platforms. The leader platform only needs to inform the follower with the best channel condition, reducing the need for more capacity and synchronization. However, DPS requires low-latency in-between-layer switching due to frequent changes in the selected transmission point. A major advantage of DPS is its lower requirement for in-between-layer capacity and synchronization compared to MRT-based joint transmission. Since only the best transmission point is selected at any given moment, the system avoids unnecessary power consumption and reduces co-channel interference.

Moreover, in practical deployments, multiple co-existing FSO links must be considered to assess the system-level performance of the proposed approach. While the performance evaluation in this study focuses on a single FSO link, the principles can be extended to larger, more dynamic networks. In a multi-link scenario, interference management, resource allocation, and link diversity become critical factors affecting throughput and reliability. The integration of multiple FSO links enables adaptive routing strategies, allowing the system to dynamically select the most favorable transmission paths based on real-time atmospheric conditions and network demand. Moreover, different network topologies, such as centralized and decentralized architectures, impact scalability and communication robustness. A centralized topology, where a leader platform coordinates transmission among follower platforms, facilitates efficient resource allocation but may introduce bottlenecks in high-density deployments. In contrast, a decentralized topology enhances flexibility and resilience by enabling independent decision-making among platforms, albeit at the cost of increased coordination complexity.

Channel Induced Optical Losses Faced by Vertical Backhaul / Fronthaul Framework

As shown in Fig. 3, turbulence-induced fading, geometric loss, air attenuation, and pointing errors are some of the factors that can affect the quality of an FSO signal.

- *Atmospheric Attenuation:* Optical signal loss due to absorption by air particles and scattering, exacerbated by fog, rain, and snow.

- ***Turbulence:*** Random air motion causing intensity fluctuations, categorized by the Rytov parameter (σ_I^2) into weak $\sigma_I^2 \leq 1$, moderate ($\sigma_I^2 \leq 5$), and strong ($5 \leq \sigma_I^2 \leq 25$) turbulence.

- *Geometric Loss:* Beam spreading over distance reduces received optical power.

- *Pointing Errors:* Misalignment due to platform instability, tracking inaccuracies, and beam divergence, more severe in lower-altitude rotary-wing platforms.

- ***Low Visibility:*** In conditions where visibility is extremely low, such as less than 1 km, fog can cause significant attenuation losses that surpass all other types of losses.

- ***Clear Weather:*** In clear weather, the losses are a few dBs, comparable to those caused by atmospheric turbulence, rain, and weak pointing errors.

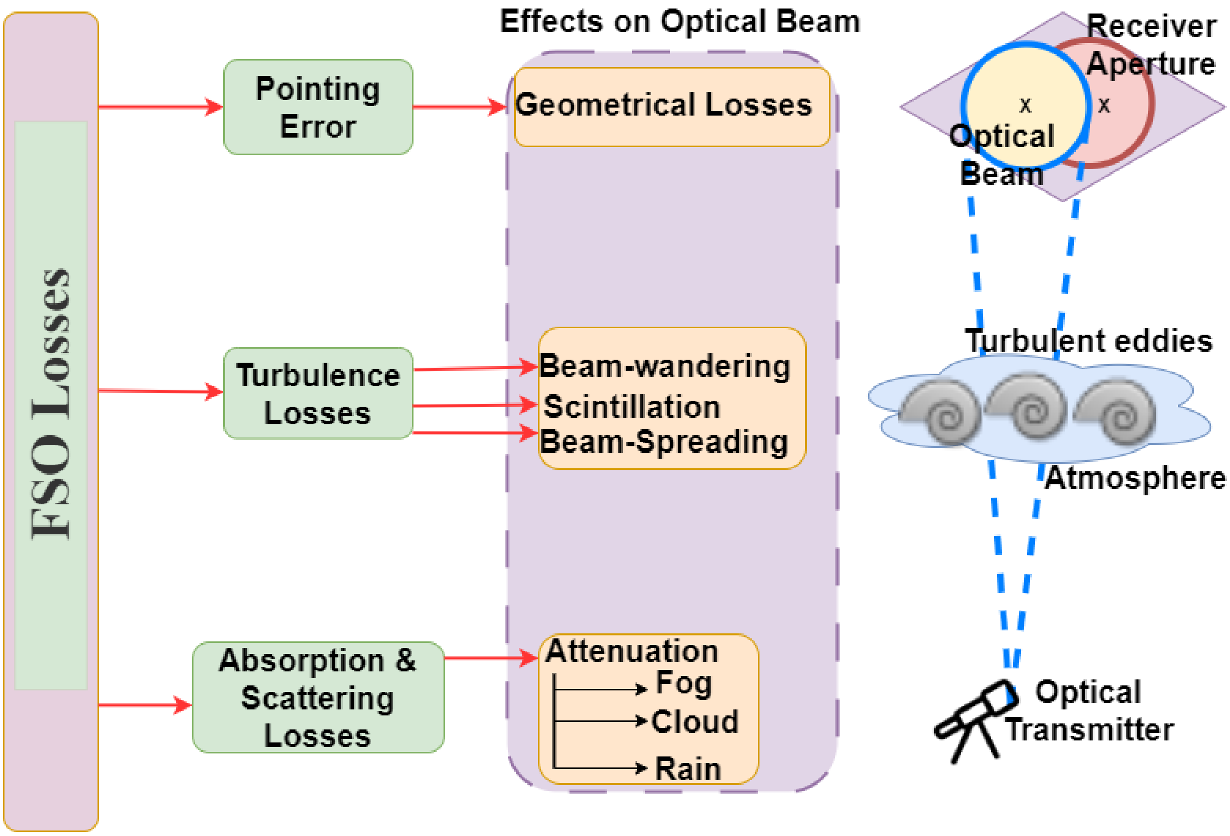

Figure 3: Free-space optical channel induced losses faced by optical beam. Turbulence induced beam-spreading and beam-wander dominate in good weather conditions.

- ***Moderate Visibility:*** Under moderate visibility conditions, the losses are generally several dBs, similar to the losses caused by severe pointing errors.

In clear weather, geometric loss is comparable to losses from rain and air attenuation over tens of kilometres. Geometric losses for satellite links can be as high as tens of decibels, which is much higher than losses due to rain. The combined effects of geometric loss and significant pointing mistakes need to be considered at such great distances. While fog- and turbulence-induced losses change with wavelength, rain-induced losses do not rely on wavelength. Turbulence-induced losses are generally smaller at longer wavelengths than at shorter ones. Turbulence loss averages a few dBs in all cases.

Performance Evaluation and Numerical Results

The first part of this section begins with an overview of the simulation setup that considers various atmospheric turbulence and weather conditions for the proposed vertical FSO link. We then discuss the simulation results, focusing on outage probability and data rate for the proposed architecture.

Simulation Setup

Several statistical models have been developed to characterize the atmospheric channel accurately. This article employs simulation settings outlined in references [13-14]. We start with an outage probability analysis to assess the reliability of the received signal under different conditions [14]. Following this, we proceed to examine the data rate. To evaluate the outage probability of the FSO link under different atmospheric conditions, our simulation incorporates key physical impairments and system characteristics that impact link reliability. Atmospheric turbulence is modeled using the gamma-gamma distribution, capturing scintillation effects across weak, moderate, and strong turbulence regimes. Beam wander due to large-scale eddies is also considered, as it affects the received optical signal by causing lateral displacement from the optimal path. Weather-induced attenuation is accounted for using empirical extinction coefficients for fog, rain, and snow, following established models such as the Kruse model for fog and ITU recommendations for rain and snow. Pointing errors, which arise from platform motion and tracking inaccuracies, are modeled as Gaussian-distributed random variations affecting beam misalignment, leading to additional signal degradation.

Table 2: Summary of simulation parameters

LEO Height (H_{sat})	500 km
LEO Zenith Angle (θ_{sat})	15 µrad
LEO Divergence Angle (ξ_{sat})	10˚
HAP	
Height (H_{HAP})	25 km
Aperture radius (D_{HAP})	0.1 m
HAP-Ground beam (θ_{HG})	3 mrad
HAP-UAV beam (θ_{HU})	4 mrad
HAP-Ground beam (ξ_{HG})	15˚
HAP-UAV beam (ξ_{HU})	20˚
UAV	
Height (H_{UAV})	1 km -20 km
Zenith Angle (θ_{UAV})	60˚
Ground	
Height (H_{ground})	50 m
Ground aperture radius	0.1 m
Other Parameters	**Value**
Transmit power (P_t)	200 mWatt
Pointing losses (L_{poi})	3 dB
Optical losses (L_{opt})	3 dB
Weak turbulence (C_n^2)	1×10^{-17} $m^{-2/3}$
Moderate turbulence (C_n^2)	1×10^{-15} $m^{-2/3}$
Strong turbulence (C_n^2)	1×10^{-13} $m^{-2/3}$
Transmission wavelength (λ)	1550 nm
Wind speed (v)	21 m/s
Receiver sensitivity (N_b)	150 photons/b
Targeted BER	$< 10^{-5}$
Fog visibility (V_{fog})	100 m
Thickness of Fog layer (Δd_{fog})	100 m
Attenuation due to cloud (L_{cloud})	As proposed in [15]
Rain rate (R_{rain})	50 mm/h
Thickness of Rain layer (Δd_{rain})	1000 m

The achievable data rate for an FSO link is described by the equation provided in [18]:

$$R = \frac{P_t \eta_t \eta_r 10^{\frac{-L_{poi}}{10}} 10^{\frac{-L_{atm}}{10}} A_r}{A_B E_p N_b} \ [b/s].$$

P_t is transmitting power, the optical efficiencies η_t and η_r are of the transmitter and receiver, respectively, L_{poi} represents the pointing loss in dB, $L_{atm} = L_{rain} + L_{fog} + L_{cloud} + L_{sci}$ is the atmospheric attenuation due to rain, fog, clouds, or turbulence, measured in dB. E_p denotes the photon energy, given by $E = h_p c/\lambda$, with h_p being Planck's constant, c the speed of light, and λ the transmission wavelength. N_b represents the receiver sensitivity in number of photons/b. Table 2 summarizes the simulation parameters used in this article.

Simulation Results

In Fig. 4, we show the outage probability for the vertical FSO link architecture illustrated in Fig. 2. The optical channel between HAP-to-tropospheric layer is modeled as weak turbulence channel. UAV-to-ground FSO channel is modeled facing severe atmospheric turbulence and weather conditions. In the presence of weak turbulence, the impact on SNR is minimal, leading to only slight variations in outage performance. However, moderate turbulence introduces more fluctuations in the optical signal, increasing the likelihood of signal fading and outage. Strong turbulence causes severe signal distortion and beam wander, leading to frequent outages and significantly degrading performance even at higher SNR levels. Additionally, weather conditions such as fog, clouds, and rain further exacerbate the situation. Fog, with its dense water droplets, heavily attenuates the optical signal, leading to poor SNR and frequent outages. Clouds can scatter and absorb the optical signal, reducing SNR and causing higher outage rates. Rain causes scattering and absorption of optical beam causing degradation of received SNR and performance. The combined presence of clouds and fog poses the most severe challenge, causing drastic signal attenuation and very high outage rates, resulting in unreliable communication links regardless of even at very high SNR.

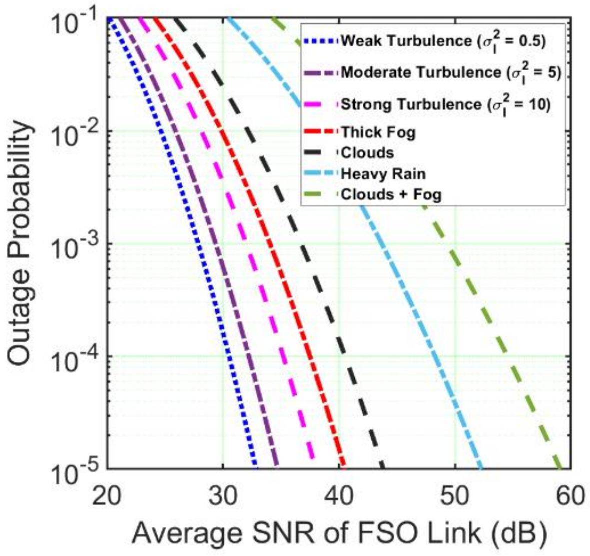

Figure 4: Outage Probability versus Average SNR.

In Fig. 5 we illustrate the data rate by varying the deployment altitude of the UAV swarm under different turbulence and weather conditions. The data rate tends to decrease as the altitude increases, primarily due to increased geometrical loss.

This effect is depicted in Figure 5, where higher altitudes lead to more significant beam spreading, thus reducing signal strength.

Clouds have a particularly detrimental impact on the vertical FSO link, primarily due to Mie scattering. Here, the scattering particles are about the same size as the wavelength of the light being transmitted, causing significant signal degradation. While fog also causes Mie scattering, it poses a less severe threat to FSO links traveling in vertical paths compared to horizontal paths in terrestrial communication scenarios. This is because in the vertical path, the FSO beam passes through the fog layer over a relatively shorter distance (the thickness of the fog layer), whereas terrestrial FSO links must contend with fog along the entire communication path. Other weather conditions, such as rain and snow, also contribute to atmospheric attenuation but to a lesser extent than clouds. Rain primarily causes absorption and scattering of the FSO signal, while snow, depending on its density and the size of snowflakes, can have varying impacts on signal quality. The atmospheric turbulence further impacts the data rate, as the random fluctuations of refractive index parameter values (C_n^2) causes beam wandering and broadening of the received signal. These effects have been categorized into weak, moderate, and strong based on the rytov parameter value (σ_I^2) to study their impact on the data rate as shown in Fig. 5.

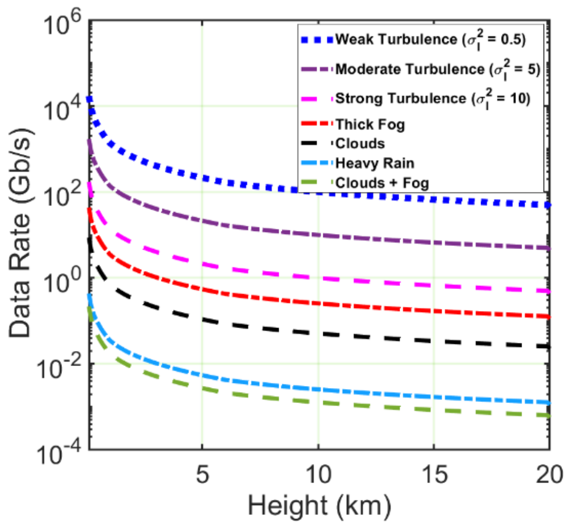

Figure 5: Data rate versus aerial platforms height.

In Fig. 6, we analyze the impact of transmit power on achievable data rates across different weather conditions. The results highlight how various atmospheric impairments, such as clouds, rain, and fog, significantly impact FSO link performance. The key observations include data rate increases with transmit power across all scenarios; the improvement is exponential in the lower power range but gradual at higher power levels due to physical limits in combating attenuation. Severe weather conditions (e.g., clouds + fog, thick fog) experience a much slower increase in data rate compared to clear sky conditions. Also, the proposed model consistently achieves higher data rates than the benchmark model [11]. This improvement is due to the optimized aerial swarm architecture, which enhances signal reliability by mitigating atmospheric impairments. The data rate improvement is more pronounced in severe conditions, such as clouds, fog, and rain, suggesting that the proposed system effectively compensates for extreme atmospheric disturbances. Moreover, the separation between the benchmark model [11] and the proposed model widens as transmit power increases, demonstrating greater efficiency of the proposed system in utilizing power for improved performance.

By analyzing the outage probability and data rate under these extreme conditions, we gain insights into the need for optimizing the deployment and operation of FSO links. Strategies such as adaptive transmission, beam steering, and real-time environmental monitoring can be implemented to mitigate these impairments and enhance the overall performance of FSO communication systems.

In the next section we lay down a forward-looking vision of our proposed cooperative aerial architecture for 6G wireless communication networks. We will delve into the integration of AI/ML with aerial platforms, the use of reconfigurable intelligent surfaces, and the enhancement of global security through the quantum internet. These advancements aim to develop more robust and reliable 6G networks based on FSO systems.

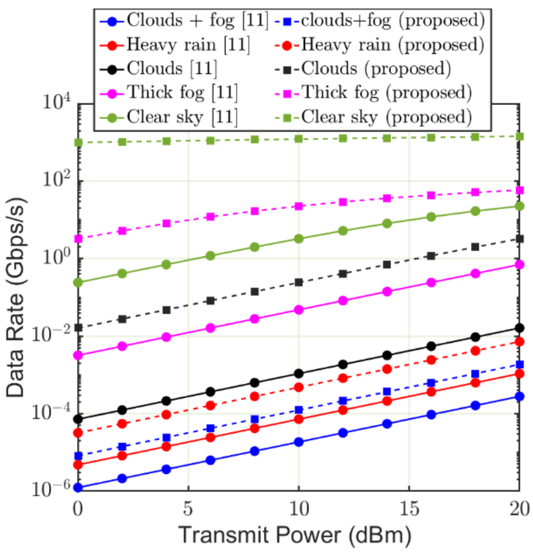

Figure 6: Data rate versus transmit power.

Integration of Proposed Cooperative Aerial Architecture with cutting-edge 6G Technologies

In the following, we outline solutions to address the losses encountered by FSO-based aerial base stations. Additionally, we discuss methods to enhance the security of the proposed cooperative aerial architecture, a crucial requirement for future 6G networks.

1. Integration of AI/ML with aerial platforms: Artificial intelligence (AI) and machine learning (ML) can significantly enhance airborne FSO communication by dynamically adjusting link parameters in response to real-time atmospheric conditions and system performance metrics. By leveraging real-time data, AI/ML can also optimize path and trajectory planning in non-terrestrial networks, considering factors like terrain, weather, and energy consumption. Moreover, as shown in Fig. 3, turbulence causes beam wandering and broadening, disrupting FSO links. AI/ML-enhanced adaptive optics can mitigate these effects using deformable mirrors and wavefront sensors. AI/ML techniques can analyze turbulence patterns and adjust optical components to correct phase distortions in real-time, guaranteeing reliable link performance. Additionally, AI/ML can predict and manage other atmospheric disturbances, such as clouds, rain, and snow, by analyzing weather data and enabling dynamic routing to avoid adverse situations.

Another application of integrating AI/ML to the proposed architecture for optimizing trajectory planning lies in energy efficiency. AI/ML models within FSO-based non-terrestrial networks can enhance energy efficiency while trajectory planning by prioritizing factors like network quality, topographical features, weather, and scalability. AI/ML can optimize energy efficiency in non-terrestrial networks by monitoring energy generation and consumption patterns. These models can dynamically adjust UAV paths to maximize energy harvesting, such as from solar panels, and minimize energy use. Additionally, AI/ML can integrate alternative energy sources, like ground-based laser-powered systems, into the network. For instance, AI/ML can coordinate the use of solar-powered balloons in the stratosphere to maintain energy-efficient operation of fixed-wing HAPS.

2. Utilizing Reconfigurable Intelligent Surfaces: The key feature of the proposed cooperative aerial architecture is its three-dimensional mobility and adjustable height, enabling it to establish backhaul/fronthaul services with ground base stations. This agility makes it ideal for integrating Reconfigurable Intelligent Surfaces (RIS). RIS can be incorporated in various ways depending on the aerial platform's shape and altitude. One way is to place them horizontally on the top/bottom of the flying/ aerial node such as LAP/HAP/UAV. Other way is to coat the RIS layers on the sides if the platform’s shape allows. An on board control unit manages the RIS configuration, adjusting the elements based on optimized parameters.

Also, as the distance between ground nodes and aerial platforms grows, path loss increases, requiring high-power emitters and very well responsive receivers, which results in greater hardware and power demands. Integration of RIS into the proposed aerial architecture can help in manipulating the propagating optical beam in a controlled manner. By dynamically adjusting the phase, amplitude, and direction of the incident waves, RIS can optimize signal propagation and improve the overall performance of FSO links.

3. Global Quantum Internet: The emergence of space-based quantum communications is a significant breakthrough in the development of the worldwide "Quantum Internet." This innovative network will link a wide array of devices, from mobile phones to the highly anticipated quantum computers, enabling them to transfer quantum information and communicate securely. Cooperative SAG networks play a crucial role in facilitating this global Quantum Internet. The proposed architecture offers significant benefits for facilitating entanglement distribution between distant ground stations, a crucial component for the quantum internet. By incorporating satellite connections to various aerial platforms at different altitudes, this architecture can employ free-space optics to transmit entangled photons across long distances. This capability enables the establishment of interconnected quantum communication links, essential for the development of a global quantum internet.

By incorporating multiple aerial nodes, the proposed cooperative architecture introduces redundancy and alternative routes for transmitting qubits, reducing the risks linked to potential disruptions in conventional non-cooperative communication channels. However, a key challenge in implementing a global quantum internet using the proposed architecture is achieving seamless integration and interoperability between quantum optical links and existing classical communication infrastructures. This integration demands advanced technologies and protocols to enable secure and adaptable connections that can effectively interface with traditional networks.

Conclusion

Integration of networked aerial platforms offers significant potential for enhancing network performance, particularly in scenarios demanding rapid deployment and flexible coverage. This article has highlighted key advancements, including the use of FSO technology to create efficient vertical backhaul and fronthaul links between aerial and ground nodes. FSO technology provides high data rates and low latency, which are essential for the future of 6G wireless networks.

The study has also addressed the impact of atmospheric conditions on FSO performance, examining how factors like turbulence, atmospheric attenuation, and scattering from clouds and fog affect outage probability and data rates. Simulation results have demonstrated the substantial influence of these environmental factors on network reliability. Furthermore, the integration of cutting-edge 6G technologies, such as AI/ML-driven solutions, intelligent reflecting surfaces, and the quantum internet, has been explored. These advancements promise to significantly improve network performance, energy efficiency, security, and adaptability, thus paving the way for robust and sustainable future 6G communication systems.

References

[1] N. Tiwari, S. De, and S. Dharmaraja, "Energy-efficient, turbulence-regime-based adaptive FSO broadcast systems," in *Proc. IEEE Veh. Technol. Conf. (VTC-Fall)*, Hong Kong, Sep. 2023, pp. 1–5.

[2] S. E. Turk, E. S. Ahrazoglu, E. Erdogan, and I. Altunbas, "Design of Energy Efficient Multi-HAPS Assisted Hybrid RF/FSO Satellite Communication Systems with Optimal Placement," *IEEE Trans. Green Commun. Netw.*, early access, Sep. 2024.

[3] K. Mashiko, Y. Kawamoto, N. Kato, K. Yoshida, and M. Ariyoshi, "Combined Control of Coverage Area and HAPS Deployment in Hybrid FSO/RF SAGIN," *IEEE Trans. Veh. Technol.*, early access, Feb. 2025.

[4] E. Zedini, Y. Ata, and M. -S. Alouini, "Improving Performance of Integrated Ground-HAPS FSO Communication Links with MIMO Application," *IEEE Photon. J.*, vol. 16, no. 2, pp. 1-14, April 2024.

[5] R. Samy, H. -C. Yang, T. Rakia, and M. -S. Alouini, "Space-Air-Ground FSO Networks for High-Throughput Satellite Communications," *IEEE Commun. Mag.*, vol. 60, no. 12, pp. 82-87, Dec 2022.

[6] D. Singh, R. Swaminathan, and A. T. Pham, "Multiple HAPS-based space-air-ground network with FSO communication: a performance analysis," *Appl. Opt.*, vol. 63, pp. 2362-2375, Mar. 2024.

[7] M. Elamassie and M. Uysal, "Multi-Layer Airborne FSO Systems: Performance Analysis and Optimization," *IEEE Trans. Commun.*, vol. 73, no. 4, pp. 2522-2537, April 2025.

[8] D. Singh, R. Swaminathan, A. Marrapu, and A. S. Madhukumar, ‘‘Per formance analysis of multiple HAPS-based hybrid FSO/RF space-air ground network,’’ in *Proc. COMSNETS conf.*, Bengaluru, India, Jan. 2024, pp. 920–926.

[9] M. Elamassie and M. Uysal, "FSO-Based Multi-Layer Airborne Backhaul Networks," *IEEE Trans. Veh. Technol.*, vol. 73, no. 10, pp. 15004-15019, Oct. 2024.

[10] R. Swaminathan, S. Sharma, N. Vishwakarma, and A. S. Madhukumar, ‘‘HAPS-based relaying for integrated space–air–ground networks with hybrid FSO/RF communication: A performance analysis,’’ *IEEE Trans. Aerosp. Electron. Syst*., vol. 57, no. 3, pp. 1581–1599, Jun. 2021.

[11] M. S. Alam, G. K. Kurt, H. Yanikomeroglu, P. Zhu, and N. D. Đào, "High altitude platform station-based super macro base station constellations," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 103–109, Jan. 2021.

[12] D.-H. Jung, G. Im, J.-G. Ryu, S. Park, H. Yu, and J. Choi, "Satellite clustering for non-terrestrial networks: Concept, architectures, and applications," *IEEE Veh. Technol. Mag.*, vol. 18, no. 3, pp. 29–37, Sep. 2023.

[13] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M. -S. Alouini, "FSO-Based Vertical Backhaul/Fronthaul Framework for 5G+ Wireless Networks," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 218-224, Jan. 2018.

[14] A.K. Majumdar, "Free-Space Laser Communication Performance in the Atmospheric Channel," *J. Opt. Fiber Commun. Rep.*, vol. 2, no. 4, pp. 345-96, Oct. 2005.

[15] M. S. Awan, M. E. Leitgeb, B. Hillbrand, F. Nadeem, and M. S. Khan, “Cloud attenuations for free-space optical links,” in *Proc. Int. Workshop Satell. Space Commun.*, Siena, Italy, pp. 274–278, 2009.