Performance Analysis of FSO-Based Communications in Space-Air-Ground Integrated Networks: A Comprehensive Survey

Ayalneh Bitew Wondmagegn[a], Dongwook Won[a], Quang Tuan Do[a], Demeke Shumeye Lakew[b] and Sungrae Cho [a]

[a]School of Computer Science and Engineering, Chung-Ang University, Seoul, 06974, Republic of Korea
[b]Department of Computer Science, kiot, Wollo University, Dessie, Ethiopia

ARTICLE INFO

Keywords:
Free-space optics (FSO)
Satellite
Aerial
Space-air-ground integrated networks (SAGINs)
Performance metrics
Mitigation techniques

ABSTRACT

Integrating free-space optical (FSO) communication into space-air-ground integrated networks (SAGINs) provides a robust solution to the growing demand for high-capacity, low-latency connectivity in advanced wireless networks. FSO communication offers several advantages over traditional radio frequency (RF) systems, including high data rates, enhanced security, and immunity to electromagnetic interference, making it particularly effective in spectrally congested environments or regions with limited bandwidth. However, its performance is heavily influenced by environmental and geographical factors, such as atmospheric turbulence (AT), adverse weather conditions, alignment precision, interference, and physical obstacles, which can significantly affect reliability and efficiency. To address these challenges, various physical and upper layer mitigation techniques (e.g., TCP) are used, and the effectiveness of FSO communication is assessed using key performance metrics, including outage probability, bit error rate, latency, throughput, ergodic capacity, spectral efficiency, energy efficiency, and security. This study provides a comprehensive overview of FSO-based SAGINs, beginning with a background and an in-depth review of existing research, followed by an extensive survey of mitigation strategies aimed at optimizing these critical performance metrics. In addition, it highlights ongoing challenges and unresolved research questions related to FSO-specific issues, encouraging further investigation and advancements. Ultimately, the study aims to foster the development of more resilient and efficient FSO-integrated SAGINs, paving the way for their role in future 6G networks.

1. Introduction

1.1. Background

The rapid growth of human activities and the rising demand for environmental monitoring and space-based services have pushed terrestrial networks to their limits. Despite advances in network technologies, terrestrial systems face persistent practical, geographical, and financial limitations, restricting their ability to meet the complex requirements of modern society. In response, non-terrestrial networks (NTNs)—particularly satellite-based communications—are being explored to fill these gaps. Satellite communications now play a crucial role in the global communications ecosystem by extending coverage to remote and underserved areas where terrestrial infrastructure is unavailable or economically impractical [1]. Recent initiatives, such as the deployment of satellite constellations, aim to provide seamless broadband access worldwide, a significant step toward realizing the concept of a 'space-based Internet ' [2, 3]. Beyond global broadband, these networks support the growing demand for efficient data acquisition and dissemination for billions of devices across terrestrial and airborne networks, underscoring the evolving role of satellite communications in an increasingly interconnected world [4].

Satellite communications are classified into three main categories based on orbit altitude: geostationary (GEO), medium-earth orbit (MEO) and low-earth orbit (LEO) satellites. GEO satellites provide continuous regional coverage, but experience high latency due to their altitude [1]. MEO satellites cover broader areas with reduced latency. In contrast, LEO satellites, ideal for real-time applications such as the broadband internet, offer the lowest latency, advanced communication technologies, and lower launch costs. However, LEO systems require large constellations and complex infrastructure [1]. The increasing interest in LEO mega-constellations (e.g., Starlink and OneWeb) aligns with the objectives of advanced 6G networks, aiming to deliver low-latency, high-bandwidth capabilities [5].

Aerial platforms, including high-altitude platforms (HAPs) and low-altitude platforms (LAPs) such as unmanned aerial vehicles (UAVs), complement satellite systems by providing on-demand connectivity and extending network coverage in regions with limited infrastructure. HAPs, operating at high altitudes, act as relay stations for LEO satellites, maintaining quasi-stationary positions to ensure reliable line of sight (LoS) communication [6]. They use amplify-and-forward (AF) and decode-and-forward (DF) relaying protocols to reduce latency and improve signal-to-noise ratio (SNR) [7, 8]. DF relays are especially valuable for removing noise propagation and improving signal quality. Furthermore, the ability of HAPs to hover above ground stations (GSs) minimizes optical signal degradation, mitigating the adverse effects of turbulence and beam wander during transmission [9]. UAVs further strengthen the network by supporting emergency communications, remote sensing, environmental monitoring, smart agriculture, and IoT connectivity [10, 11].

*Corresponding author: Sungrae Cho
ayalneh@uclab.re.kr (A.B. Wondmagegn); dwwon@uclab.re.kr (D. Won); dqtuan@uclab.re.kr (Q.T. Do); demeke@uclab.re.kr (D.S. Lakew); srcho@cau.ac.kr (S.C.)

Table 1
DEFINITIONS OF ACRONYMS

Acronym	Definitions
AF	Amplify-and-forward
AL	Atmospheric loss
AoA	Angle-of-arrival
AT	Atmospheric Turbulence
ARQ	Automatic repeat request
BER	Bit error rate
DF	Decode-and-forward
EE	Energy efficiency
EC	Ergodic capacity
FEC	Forward error correction
FoV	Field of view
FSO	Free-space optics
GEO	Geostationary Earth orbit
GG	Gamma-Gamma
HAPs	High-altitude platforms
HARQ	Hybrid automatic repeat request
LEO	Low-Earth Orbit
LAPs	Low-altitude platforms
LoS	Line-of-sight
MEO	Medium Earth orbit
MIMO	Multiple input multiple output
OP	Outage probability
PEs	Pointing errors
PL	Path loss
QoS	Quality of service
RF	Radio frequency
SAGINs	space-air-ground integrated networks
SE	Spectral efficiency
SER	Symbol error rate
SIMO	Single-input multiple-output
SISO	Single-input single-output
SNR	Signal-to-noise ratio
UAV	Unmanned aerial vehicle

Their dynamic deployment capabilities and scalability make UAVs ideal for disaster zones, surveillance, traffic monitoring, and military operations, enabling agile and adaptable network solutions [12, 13].

The space-air-ground integrated network (SAGIN) architecture has emerged as a pivotal enabler of global connectivity, supporting a wide range of large-scale applications such as satellite remote sensing and Earth observation services [14]. To realize seamless integration across satellite, aerial, and terrestrial domains in fifth-generation (5G) and beyond, advanced wireless communication technologies are being adopted. Among these, free-space ptical (FSO) communication stands out due to its exceptional transmission characteristics. As detailed in [15], FSO offers ultra-high data rates, broad spectral availability, low power consumption, enhanced physical layer security, full-duplex transmission, and protocol transparency. These features make FSO particularly advantageous for enabling high-capacity and low-latency connectivity across the heterogeneous and hierarchical layers of SAGIN.

The emergence of data-intensive applications—such as ultrahigh-definition imaging, real-time video surveillance, and large-scale remote sensing—has introduced stringent bandwidth and latency requirements. For instance, a single high-resolution remote sensing image covering an area of 100×30 km² at 0.3-meter resolution can generate approximately 160 Gbits of raw data [16, 17]. When multiple such images are acquired and transmitted in real-time, the cumulative bandwidth requirement can exceed 100 Gbit/s. This level of performance is difficult to achieve using conventional radio frequency (RF) communication technologies, which are limited by narrower spectrum availability and susceptibility to interference and congestion [18].

FSO communication addresses these limitations by exploiting highly directional, line-of-sight optical beams, typically in the infrared spectrum—to achieve gigabit-level data transmission through free space. With its broader bandwidth and higher spectral efficiency, FSO enables the efficient transfer of massive data volumes across spatially distributed nodes in SAGIN [8, 19]. Its underlying optical physics, where modulated light beams act as carriers for digital signals, supports real-time and secure communication even in dense or remote environments. Fig. 1 illustrates an FSO-enabled SAGIN architecture that integrates geostationary (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) satellite constellations with HAPs, UAVs, and terrestrial networks. This hierarchical and layered configuration fosters dynamic resource allocation, end-to-end data transmission, and operational resilience. Ultimately, such an integrated framework lays the foundation for intelligent, scalable, and mission-critical communication infrastructures capable of supporting the evolving demands of next-generation networks.

The performance of this FSO links is evaluated using various key metrics such as the probability of outage (OP), the bit error rate (BER), latency, throughput, ergodic capacity, spectral efficiency, energy efficiency and security. These metrics provide a comprehensive understanding of the reliability and overall communication efficiency of the FSO link under varying atmospheric and network conditions. A comprehensive analysis of these performance indicators is presented in Section 4. However, the effectiveness of FSO communication in SAGIN is significantly challenged by factors such as atmospheric turbulence (AT), pointing errors (PEs), beam divergence, and weather-induced attenuation (for example, fog, rain, and clouds). These impairments degrade signal quality, reduce link availability, and increase error rates. To overcome these issues, several mitigation strategies have been proposed, including adaptive optics, spatial diversity, hybrid FSO/RF solutions, error correction coding, and relay-assisted transmission. A brief analysis of these challenges and their corresponding mitigation techniques is presented in Sections 3.1 and 3.2, respectively.

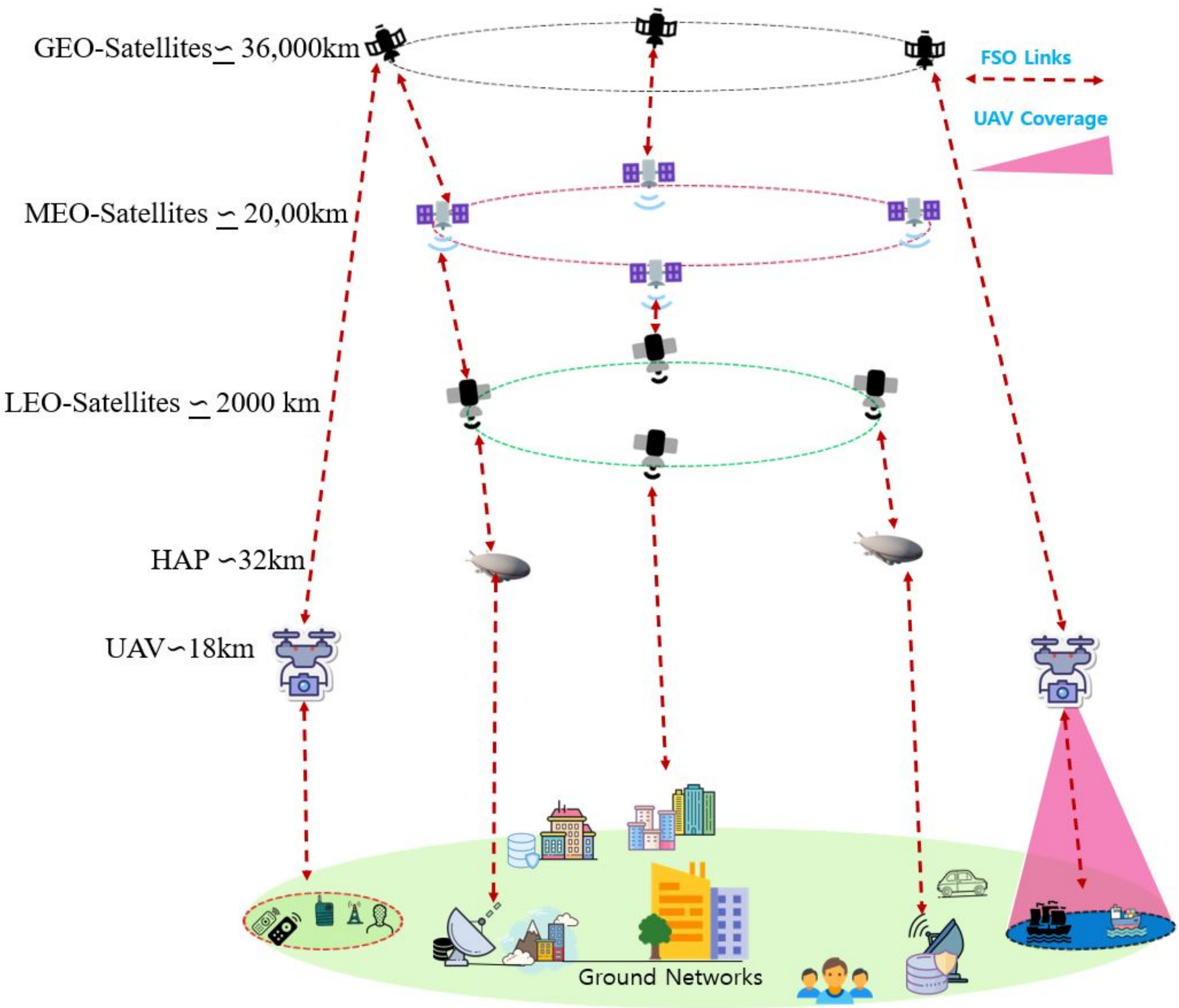

Fig. 1. SAGIN Architecture

1.2. Related Surveys

With recent advances and increased interest in FSO-based communication, several studies have explored various network architectures and themes. For example, [20] discussed the challenges of FSO communication, focusing on acquisition, tracking, and pointing (ATP) methods for mobile FSO, but without detailed performance evaluations. A similar study by [21] introduced a classification scheme for FSO link elements, although it lacks performance metric evaluation. [22] provided a historical overview of FSO links, tracing their evolution, while [23] highlighted FSO applications where fiber installation is impractical, such as in terrestrial and satellite networks, though it did not analyze performance metrics. [24] examined fundamental FSO concepts, including system architecture and weather effects, and proposed a hybrid FSO system for scalability, but did not focus on performance evaluation. The study in [25] addressed open challenges in FSO, including integration with illumination and communication, security, FSO transceiver design for 5G, and hybrid RF-FSO solutions. [26] explored critical FSO technologies such as spectrum reuse, architecture, and security, focusing on future applications in optical wireless technologies. In [27], error control solutions for FSO systems were discussed, including link-layer protocols such as ARQ and hybrid ARQ (HARQ), particularly for high-rate FSO networks. Lastly, [28] examined the impact of adverse weather on FSO, together with a survey of ongoing projects and the integration of FSO with 5G networks, focusing on hybrid FSO-RF systems and techniques to optimize performance metrics.

The extensive array of surveys available shows that they cover a wide range of focus areas within optical link technologies. Subsequent surveys expanded to include both ground-and satellite-based optical links [20, 23, 24]. The focus expanded to encompass ground- and water-based connections, eventually including ground-, aerial, satellite, and water-based systems [25]. In particular, the remaining surveys in Table 2, including ours, are primarily dedicated to

Table 2
Comparison of Existing Surveys With our Survey

Ref.	Year	SAGIN	Challenges	MT	PM
[20]	2018	×	×	✓	×
[21]	2019	✓	ϕ	ϕ	×
[22]	2019	✓	✓	✓	×
[24]	2020	×	✓	✓	×
[23]	2020	×	✓	ϕ	×
[25]	2021	✓	×	✓	×
[28]	2022	✓	✓	ϕ	×
[26]	2022	✓	ϕ	✓	×
[27]	2022	✓	×	ϕ	×
This Paper		✓	✓	✓	✓

MT-Mitigation Techniques, PM-Performance Metrics

exploring SAGIN systems. This reflects the multifaceted nature of optical link research, which spans various environments and configurations, and underscores the growing importance of SAGINs in contemporary research. Similarly, while surveys such as [21, 26] partially explored challenges related to FSO links, studies such as [21, 23, 27, 28] also addressed mitigation techniques to a limited extent. In addition, surveys such as [22, 23, 24] focused primarily on identifying the challenges in the FSO links and the corresponding mitigation strategies. In contrast, performance metrics received less attention, with studies like [23, 25, 26, 27, 28] only briefly mentioning them without in-depth discussions; furthermore, certain critical performance metrics needed to be addressed or included altogether.

This survey focuses on FSO-based SAGINs to address existing gaps, with an emphasis on key challenges, the current state of research, and recent developments in this field. We provide a comprehensive overview of the obstacles faced in space-air-ground FSO communication links and analyze key performance metrics along with the mitigation techniques employed to enhance their performance. Unlike previous surveys that address challenges and solutions in broad terms, our study specifically evaluates individual performance metrics and the tailored mitigation techniques designed to improve each metric. By enhancing each metric separately, we aim to achieve an overall improvement in FSO communication links. Our in-depth analysis offers new insight into the complexities of FSO communication systems, ultimately contributing to better performance and reliability in SAGINs. Table 2 provides a comparative analysis between our survey and existing related studies. Within this table, the symbol ✓ denotes comprehensive discussion, ϕ indicates partial coverage (meaning the issue is mentioned briefly without substantial elaboration or dedicated sections), and the symbol × signifies that the topic is not addressed in the reference work.

1.3. Motivation and Contribution

As the global demand for ubiquitous, high-capacity connectivity continues to accelerate, free-space optical (FSO) communication has emerged as a cornerstone technology for enabling high-speed, high-bandwidth links in next-generation satellite–aerial–ground integrated networks (SAGINs). While a growing body of research has explored various aspects of FSO performance, existing studies remain largely fragmented and domain-specific. Most investigations have either focused on isolated phenomena—such as pointing errors (PEs), atmospheric turbulence (AT), or cloud-induced attenuation—or addressed performance within a single network layer, such as UAV-assisted relaying under specific weather conditions or satellite-to-ground FSO propagation in ideal clear-sky scenarios. Consequently, the broader interoperability and performance evaluation of FSO systems across multiple SAGIN tiers remain insufficiently addressed.

Furthermore, the current literature often evaluates FSO performance using a narrow set of metrics, such as outage probability (OP), bit error rate (BER), latency, or energy efficiency (EE), typically analyzing only one or a few metrics in isolation. For instance, Kaur et al. [29] analyzed the BER and OP performance of FSO systems under different weather conditions, exploring the benefits of MIMO spatial diversity and aperture averaging. Ata et al. [30] investigated adaptive optics correction—an effective turbulence mitigation technique—using Zernike polynomial representations to enhance OP performance in high-altitude platform (HAP) FSO links. Elamassie et al. [31] evaluated BER performance in two deployment scenarios: a single-layer HAP–GS backhaul for rural connectivity and a dual-layer model involving rotary-wing UAVs for urban environments. Shang et al. [32] examined ergodic capacity, average BER, and outage probability in non-terrestrial networks, while Park et al. [33] introduced a cloud-aware UAV operation strategy aimed at minimizing OP through dynamic elevation angle optimization. Similarly, Mohsen et al. [34] focused on BER performance in 32-channel WDM-FSO systems under varying turbulence and launch power conditions. Other notable works, such as those by Wang et al. [35] and Guo et al. [36], explored the role of hovering UAVs in air–ground FSO integration.

Despite these contributions, there remains a critical lack of unified references that synthesize these fragmented findings into a cohesive framework. Specifically, the research community lacks a comprehensive study that (1) clearly delineates the interoperability among satellite, aerial, and terrestrial platforms in FSO-based SAGINs; (2) systematically categorizes the major physical and network-layer impairments along with corresponding mitigation strategies; (3) identifies essential performance metrics and associated optimization methodologies; (4) rigorously analyzes the trade-offs between multiple conflicting objectives (e.g., OP vs. EE, BER vs. latency); and (5) highlights open research gaps warranting further investigation.

This survey aims to bridge these deficiencies by integrating insights from diverse subdomains—ranging from satellite-ground optical links to UAV-assisted airborne FSO relays and terrestrial optical systems—into a unified, cross-layer analytical framework. The key contributions of this survey are as follows:

- **System Overview:** This survey offers a holistic view of how satellites, high-altitude platforms (HAPs), low-altitude platforms (UAVs), and terrestrial nodes synergistically form the FSO communication backbone of SAGINs. This comprehensive perspective elucidates the unique propagation geometries, platform mobility patterns, and service requirements at each network tier. Understanding these factors is critical for determining optimal deployment strategies for FSO links and identifying scenarios that require a return to radio frequency solutions.
- **Unified Treatment of Challenges and Mitigation Techniques:** FSO links are inherently sensitive to impairments such as atmospheric turbulence, pointing errors, cloud blockage, and background radiance—each varying in severity with altitude and environmental conditions. This survey categorizes these impairments by network layer and discusses associated countermeasures, including aperture averaging, relay placement strategies, diversity, techniques, advanced modulation/coding schemes, re-transmission techniques (ARQ/HARQ), and hybrid transmission solutions. This systematic treatment enables designers to tailor mitigation strategies to specific deployment environments.
- **Comprehensive Performance Metrics Analysis, Optimization Parameter Strategies, and Research Roadmap:** The survey presents a comprehensive analysis of key performance metrics—including outage probability (OP), bit error rate (BER), throughput, and energy efficiency (EE)—within dynamic, multi-hop FSO environments. It further explores a range of optimization strategies, including system parameter tuning and multi-objective optimization, with particular attention to the trade-offs among competing performance metrics. In addition, the survey highlights critical research directions that warrant further exploration, such as real-time digital twin-enabled FSO network control, the integration of non-orthogonal multiple access (NOMA), and the advancement of quantum-secured communication techniques, particularly quantum key distribution (QKD). Collectively, these insights aim to steer future research toward the development of more resilient, intelligent, and high-performance FSO systems within the broader SAGIN framework.

In summary, this survey paper significantly contributes by synthesizing fragmented insights across satellite, aerial, and terrestrial optical communication studies, thus offering a holistic, end-to-end framework for designing, evaluating, and optimizing FSO-enabled SAGINs. By clearly delineating both current knowledge and unresolved questions, this survey stands as an essential reference for researchers dedicated to enhancing link reliability, optimizing data throughput, and achieving the ambitious terabit-per-second connectivity envisioned for 6G-era heterogeneous networks.

1.4. Organization of the Paper

As shown in Fig. 2, this paper is structured as follows: Section I highlights the importance and motivation for studying key aspects of FSO communications within the context of SAGINs. Section 2 presents a general description of satellite, aerial, and ground networks and their integration with FSO communication systems. Section 3 discusses the main challenges FSO communication systems face and the key mitigation techniques used to address these challenges. Section 4 analyzes key metrics and explores optimization strategies to evaluate and improve the overall performance of FSO communication systems. Section 5 identifies gaps in the current literature and outlines open research problems, proposing several promising future research directions to advance the field. Section 6 concludes the paper. A list of common acronyms used throughout this survey is provided in Table 1.

2. Network Scenario and Communication Systems

2.1. Network Scenario

According to Internet World Stats [37], the estimated global internet penetration rate in July 2022 was around 69%, indicating that over 2.4 billion people still lack internet connectivity. Consequently, a primary goal for many organizations is to extend connectivity to remote and rural areas, effectively "connecting the unconnected". Beyond this objective, growing investments in SAGINs offer the potential to support a broader range of applications and use cases more efficiently. By integrating recent advancements in technologies such as networking, computing, caching, edge computing, sensing, and artificial intelligence (AI), SAGINs can facilitate numerous innovative applications, capitalizing on ubiquitous network availability. This integration is critical in achieving broad coverage, ubiquitous service availability, and scalability [38]. With high data rates, ultra-low latency, and enhanced reliability, SAGINs are well-suited for applications such as autonomous vehicles, IoT, and real-time services. Furthermore, by incorporating mobile edge computing (MEC), SAGINs enable efficient data processing closer to end-users, effectively meeting the diverse, high-mobility, and massive connectivity demands of 6G technology.

2.1.1. Ground Networks

Terrestrial communication networks face increasing pressure due to rising capacity demands and the need for widespread coverage, mainly as internet traffic doubles every two years. The rollout of 5G networks, designed for high-speed mobile broadband and connecting numerous smart devices, has placed additional burdens on these networks,

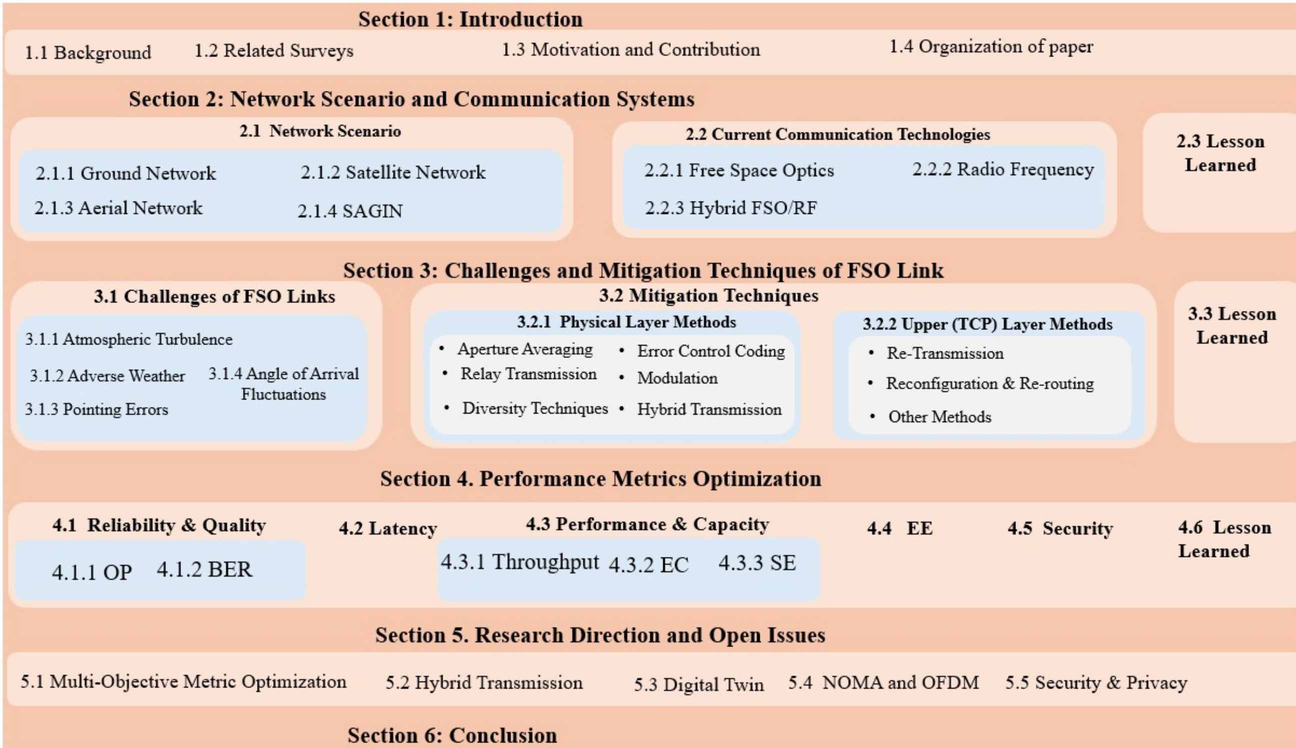

Fig. 2. Organization of the Paper

necessitating enhanced backhaul support for 5G and beyond [9]. Relying solely on ground networks to meet these demands, especially in remote areas, poses challenges and incurs substantial costs. Satellite communication (Satcom) systems offer an effective solution by providing universal coverage and augmenting the reach and capacity of terrestrial networks.

2.1.2. Satellite Networks

Satellite networks are a vital component of modern communication systems, enabling long-distance data transmission through Earth-orbiting satellites. They are increasingly regarded as a promising 6G wireless communications architecture due to their global coverage and high data transmission rates [39]. As illustrated in Fig. 3, the integration of terrestrial networks with LEO satellite constellations has garnered significant research attention, leading to innovations such as using satellites as edge nodes with computing resources and introducing virtual network function placement algorithms for delay-sensitive users [40]. Frameworks like satellite-terrestrial integration with double-edge intelligence and network function virtualization (NFV) for deploying next-generation NodeBs on satellites have further advanced these networks by enabling IoT traffic offloading and enhancing network efficiency [41].

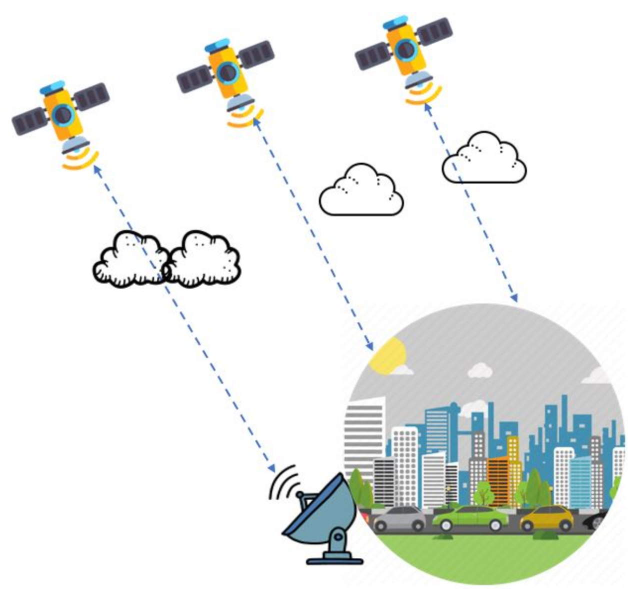

Fig. 3. Satellite-Ground Network

2.1.3. Aerial Networks

Aerial networks encompass a variety of airborne platforms—most notably UAVs and HAPs—which operate at distinct altitude regimes to furnish communication links, extend coverage, and deliver computational resources. By leveraging their inherent mobility and flexible deployment, these aerial nodes can rapidly establish or restore connectivity in exigent circumstances, such as wartime operations or post-disaster relief efforts [42]. Beyond mere connectivity, contemporary aerial networks increasingly incorporate distributed computing capabilities: on-board processors and edge servers aboard UAVs or HAPs can execute data-intensive tasks locally, reducing the reliance on distant ground facilities. Furthermore, the integration of AI techniques—such as federated learning and reinforcement learning—enables these platforms to make autonomous, context-aware decisions. For example, in a disaster scenario, an AI-enabled HAP might reconfigure its communication links in real time to prioritize critical rescue signals [43, 44].

Despite these advantages, aerial networks typically offer a more limited geographic footprint compared to satellite constellations; they excel at providing low-latency, line-of-sight links over a localized region rather than global coverage. In the context of 5G and emerging 6G architectures, UAV-based communications have garnered substantial interest: their ability to hover over or traverse challenging terrain—where traditional terrestrial infrastructure is nonexistent or damaged—makes them both cost-effective and adaptable [45]. UAVs can act as flying base stations, offloading data traffic from congested ground networks, supporting IoT deployments in remote areas, and ensuring secure, reliable data transfer for mission-critical applications.

However, orchestrating seamless communication among UAVs, HAPs, satellites, and GSs introduces significant routing and networking challenges. The highly dynamic topology—where UAVs may change speed, altitude, or mission objectives on the fly—renders traditional static routing schemes inadequate. Network designers must contend with unpredictable aerial mobility patterns, spectrum constraints, and the need to avoid mid-air collisions or physical obstacles. Key performance metrics such as throughput, end-to-end latency, and energy consumption must be carefully balanced against stringent security and reliability requirements to maintain data integrity [46, 47].

Recent research efforts have focused on categorizing various UAV routing protocols (e.g., proactive, reactive, and hybrid schemes), proposing architectures that combine terrestrial, aerial, and satellite segments, and addressing regulatory challenges surrounding spectrum allocation for UAV swarms [11]. By classifying these protocols and exploring new communication paradigms—such as multi-tiered network coordination and cross-layer optimization—scholars aim to overcome the inherent variability of aerial environments and unlock the full potential of UAV-enabled 5G/6G networks.

2.1.4. Satellite-Aerial-Ground Integrated Networks (SAGINs)

The architectural framework of SAGINs has emerged as a foundational component in the evolution of 5G and beyond communication systems. SAGINs provide a unified, hierarchical networking model that seamlessly integrates spaceborne (satellite), airborne (UAVs, HAPs), and terrestrial (ground-based) infrastructures into a cohesive, interoperable environment. This architecture enables ubiquitous connectivity, real-time data exchange, and intelligent resource coordination across diverse geographical regions and operational domains. Fig. 4 illustrates the satellite-aerial-ground integration network in two deployment scenarios: (a) a rural or remote environment where clear line-of-sight (LoS) conditions allow for satellite-to-HAP and HAP-to-ground communication, and (b) an urban setting where LoS is obstructed by buildings, necessitating a multi-hop architecture involving satellite-to-HAP, HAP-to-UAV, and UAV-to-ground links. The key goals of SAGINs include maintaining uninterrupted communication services, enhancing network resilience, and enabling efficient, adaptive resource utilization in an environmentally sustainable manner.

To address the challenges associated with dynamic topology and heterogeneous network components, recent research has introduced various AI-assisted control frameworks. In [48], the authors proposed a federated learning-enhanced deep reinforcement learning (DRL) framework to overcome the limitations of traditional deployment strategies, which often rely on manual configuration and lack scalability. This intelligent framework supports autonomous decision-making and adaptability across SAGIN layers. Similarly, [49] presented a hierarchical hybrid DRL model that integrates software-defined networking (SDN) principles to balance centralized and distributed control. By embedding DRL agents within network controllers, the architecture dynamically adapts to changing conditions while optimizing network control policies through learned interactions and incentive-based mechanisms. Meanwhile, the work in [50] addressed radio access network (RAN) slicing by jointly optimizing low-latency, high-throughput, and wide-coverage slices in SAGINs using a multi-agent deep deterministic policy gradient algorithm. This approach accounted for the distinct channel characteristics of terrestrial, aerial, and satellite links to ensure service-specific performance guarantees.

Further advancements include a priority-aware load balancing strategy introduced in [51], where a multi-agent DRL approach dynamically adjusts resource allocation based on network demands and service priorities, enhancing the flexibility and efficiency of RAN slicing in SAGINs. Additionally, [52] developed a multisided many-to-one matching game to enable reliable and distributed node association across heterogeneous network layers. Their randomized algorithm reduces signaling overhead while maintaining stable associations, ultimately improving end-to-end throughput. These innovations underscore the importance of intelligent coordination mechanisms for managing the complexity and dynamics of SAGINs.

The integration of FSO communication into SAGINs further amplifies their potential by enabling ultra-high data rate, low-latency, and interference-resistant links. However, such integration introduces new design challenges, including the need for sophisticated cross-layer optimization, dynamic topology control, and intelligent resource orchestration. The inherent mobility, heterogeneity, and volatility of SAGIN nodes require adaptive network management strategies that

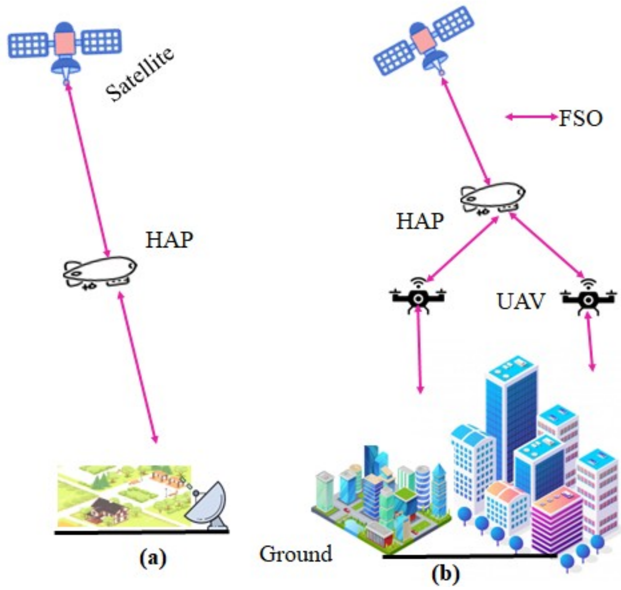

Fig. 4. Satellite-Aerial-Ground Network: (a) Rural and Remote Areas, and (b) Urban Areas (Multi-hop Required for LoS)

can respond to fluctuating link quality, node availability, and service demands in real time. In this context, digital twin frameworks, AI-driven control algorithms, and cooperative communication schemes are increasingly being adopted to facilitate coordinated, efficient network behavior. FSO-enabled SAGINs are expected to form the high-capacity backbone of future communication systems, supporting a wide range of emerging applications such as autonomous navigation, real-time Earth observation, immersive media delivery, and global broadband access.

2.2. Current Communication Technologies

In 6G and beyond, communication system technologies form the foundational infrastructure that allows seamless transmission of signals between the source and destination. A range of advanced wireless technologies have been proposed to meet the demanding requirements of next-generation networks. Each technology offers unique capabilities and trade-offs:

- FSO: Leverages light to transmit data through free space, such as air or vacuum. It supports ultra-high data rates and is highly energy-efficient, but is susceptible to atmospheric conditions like fog and turbulence, which can impact link reliability.

- RF: As a conventional medium for wireless communication, RF uses electromagnetic waves in the radio spectrum. It provides robust performance in diverse weather conditions and over long distances, but offers lower bandwidth and faces spectral congestion.

- mmWave: Operating within the 30–300 GHz range, mmWave enables gigabit per second data transmission, making it ideal for dense deployments and short-range high-capacity links. However, its performance degrades significantly under non-line-of-sight (NLoS) conditions due to high penetration loss.

- THz: Employing frequencies from 0.1 to 10 THz, THz communication supports ultra-high-capacity transmission, potentially reaching terabit-per-second rates. It is well-suited for inter-satellite links (ISLs) with minimal interference at high altitudes, yet suffers from severe path loss and limited range in NLoS environments.

- VLC: Using light sources, such as LEDs, to transmit data. It operates in license-free spectrum and offers high data rates at short distances, while being immune to RF interference. However, it requires LOS, is highly sensitive to ambient lighting, and lacks bidirectional communication due to its dependence on illumination.

- Hybrid FSO/RF: Combines the advantages of both FSO and RF, dynamically switching between them based on link conditions. This hybrid approach offers both high throughput and improved reliability, making it particularly suitable for SAGIN environments where atmospheric conditions are variable.

Among these, FSO, RF, and hybrid FSO/RF technologies are particularly promising for SAGIN applications due to their ability to support long-distance communication between heterogeneous segments of space, air, and ground. A comparative analysis of their respective strengths and limitations is provided in Table 3.

2.2.1. Free Space Optics (FSO)

Free-Space Optical communication has emerged as a key enabler for next-generation military and satellite networks due to its ability to deliver ultra-high data rates, typically up to 1.28 Tbps [53, 54], using frequencies several orders of magnitude higher than traditional RF systems [55, 56]. Operating in the 800–1700 nm wavelength range, FSO leverages narrow beam divergence and tight spatial confinement, allowing for high spectral efficiency, virtually unlimited frequency reuse, and reduced transmission power [15, 57]. As a Line-of-Sight (LoS) technology, it enables rapid deployment, low-cost installation, and secure communications—qualities particularly advantageous in tactical and emergency environments.

Unlike RF systems that are heavily regulated and subject to spectrum licensing, FSO operates in the unlicensed optical spectrum. This regulatory freedom, coupled with the minimal risk of signal interference due to high beam directionality, allows for greater deployment flexibility [15]. Moreover, the inherent spatial confinement of optical beams enhances physical layer security. Potential eavesdropping is significantly limited, as interception requires precise alignment within the narrow beam path—rendering unauthorized access both technically challenging and easily detectable [57].

Table 3
Strengths and Limitations of Common Communication Technologies in SAGINs

Communication Link	Strengths	Limitations
FSO	• High bandwidth • License-free spectrum • Low interference susceptibility • Small hardware size (≈ 0.1 of RF [23]) • High transmission security • Low power consumption (≈ 0.5 of RF [23]) • Ease of deployment	• Highly sensitive to atmospheric conditions (fog, haze, rain, snow) • Requires precise alignment (requires LoS); suffers from PEs • Beam scintillation and wander at long ranges
RF	• Robust in most weather conditions • Long-range NLoS communication supported • Mature and well-understood technology • Broad ecosystem and device support	• Limited bandwidth • Spectrum licensing and congestion • Larger hardware footprint • Higher power consumption compared to FSO • Susceptible to electromagnetic interference
Hybrid FSO/RF	• Combines FSO's capacity and RF's robustness • Maintains high availability under varying conditions • Adaptive to environmental conditions • Enhances reliability and continuity of service	• Increased system complexity • Higher implementation and maintenance cost • Requires efficient switching mechanisms • Synchronization and coordination challenges between subsystems

In the context of SAGINs, FSO plays a critical role in supporting high-throughput applications, such as real-time satellite remote sensing. The transmission of ultra-high-definition imagery from satellites demands link capacities exceeding 100 Gbps—levels that are unfeasible using conventional RF links alone [14, 18]. As demand for data rates in 6G and beyond approaches terabit-per-second (Tbps) scales, FSO offers a practical solution to overcome the spectral limitations of RF systems [9].

2.2.2. Radio Frequency (RF)

Radio frequency communication system is extensively utilized in terrestrial and non-terrestrial communication systems due to its reliability, obstacle penetration capability, and broad range. It is well-suited for connectivity across diverse environments, including urban settings and remote areas. In terrestrial networks, RF signals enable long-distance communication over ground-based infrastructure, while in non-terrestrial networks—such as those involving satellites and aerial platforms—they support effective data transmission across vast distances, even under adverse weather conditions. However, the use of RF bands in LEO satellite constellations faces significant limitations due to spectrum scarcity, high licensing costs, and constrained capacity [58]. These constraints hinder the scalability and cost-efficiency of high-throughput satellite communication systems. To reduce the cost per transmitted bit and improve system affordability, the deployment of SAGIN capable of supporting Tbps throughput becomes essential. Achieving such data rates with conventional RF communication is a highly challenging task. As a promising alternative, the use of the vast unlicensed optical spectrum presents a viable solution. In particular, FSO communication offers extremely high data rates and is well-suited for next-generation SAGIN architectures, providing a cost-effective means of overcoming RF spectrum limitations.

2.2.3. Hybrid FSO/RF

Hybrid FSO/F communication systems enhance robustness and availability of the link in SAGINs by leveraging the complementary strengths of both technologies. FSO links offer high data rates, but are highly sensitive to weather changes such as fog, haze, and clouds, whereas RF links, although smaller in capacity, perform more reliably in adverse conditions due to their resilience to turbulence and misalignment [15, 59].

In such systems, a high-capacity optical link can be backed by a lower-rate RF link that activates during FSO outages, enabling link availability up to 99.999% [59]. For example, a 100 Mbps optical link may switch to a 10 Mbps RF fallback during blockages [15]. However, hybrid systems also face challenges, including increased complexity, higher operational costs, and limited RF bandwidth, which can restrict throughput during fallback scenarios.

2.3. Lesson Learned

This section provides a comprehensive overview of SAGINs, highlighting their potential to meet the increasing demand for advanced communication infrastructure and seamless connectivity. SAGINs combine satellite, aerial, and terrestrial networks to deliver scalable, high-capacity communication systems essential for modern applications such as autonomous vehicles, the Internet of Things (IoT), and 6G services. This integration utilizes diverse technologies: FSO communication enhances performance by reducing latency and increasing reliability, while RF communication serves as a resilient backup during unfavorable atmospheric conditions. This section also underscores the limitations of terrestrial networks in handling the surge in data traffic, particularly with the rollout of 5G, and emphasizes the complementary role of satellite networks. LEO satellites, capable of providing global coverage and high data rates, substantially enhance network capacity. Additionally, aerial networks offering flexible communication solutions and bridging connectivity gaps. UAVs provide localized coverage and support real-time data processing, while HAPs function as stable relay nodes between ground and satellite networks, mitigating atmospheric disruptions. HAPs and UAVs enhance network reliability by reducing latency and enabling seamless communication.

3. Challenges and Mitigation Techniques of FSO Links in SAGIN

3.1. Challenges of FSO-Links

Satellite networks continue to encounter significant challenges, including signaling storms, transmission delays, and elevated energy consumption—primarily due to the rapid orbital movement of satellites and the dynamic, transient nature of user-satellite associations [60]. One of the most critical consequences of satellite mobility is the need for frequent handovers, which disrupt link continuity and degrade the overall quality of service [20]. Satellite-ground networks continue to face limitations, including high latency, bandwidth constraints, and susceptibility to weather conditions, which degrade signal quality [61]. Atmospheric turbulence, frequent handovers in LEO systems, and regulatory complexities further complicate their operations, alongside challenges of scalability, security, and energy efficiency. Similarly, aerial networks face operational challenges arising from the altitude variability and mobility of airborne platforms. These fluctuations necessitate continuous beam tracking and precise alignment of FSO links to ensure stable connectivity. Altitude changes can also disrupt the LoS with GSs, thereby impairing signal fidelity.

The integration of FSO technology into SAGINs (FSO-SAGINs) further intensifies these challenges. Although FSO offers high data rates and spectrum efficiency, its performance is highly sensitive to environmental factors such as AT, fog, and cloud coverage. These impairments can severely attenuate optical signals, leading to increased link outages and degraded system reliability [8].

To systematically address these issues, FSO-related challenges in SAGINs can be broadly categorized into internal and external factors [24]. Internal challenges are intrinsic to the system and include hardware limitations such as inefficient transmitter/receiver configurations, optical misalignments, and internal noise. These impairments primarily affect the structural and operational efficiency of the system. Conversely, external challenges arise from dynamic environmental and geographical conditions, which are generally more difficult to control. This study places particular emphasis on these external limitations, given their pronounced impact on the stability and quality of FSO communication. Major external impairments include AT, adverse weather conditions (e.g., fog, rain, clouds), PEs, and variations in angle of arrival (AoA) that collectively degrade link robustness and signal accuracy [9].

3.1.1. Atmospheric Turbulence (AT)

Atmospheric Turbulence refers to a naturally occurring phenomenon caused by fluctuations in air temperature, pressure, and density along the optical signal's propagation path. These variations give rise to turbulent eddies or cells of differing diameters and refractive indices, which in turn lead to beam wander, beam spreading, and scintillation effects [62, 63]. Such turbulence distorts the optical signal, resulting in signal fading and a degradation in communication quality. Sustaining stable, high-performance data transmission over long distances becomes especially challenging under these dynamic atmospheric conditions.

3.1.2. Adverse Weather Conditions

Atmospheric attenuation caused by weather plays a significant role in the degradation of the performance of the FSO link. Factors such as fog, rain, snow and cloud cover absorb and scatter the optical signal along its transmission path, leading to increased signal loss and potential link outages [21]. These effects are particularly severe in regions with unpredictable or extreme weather conditions, making FSO links highly vulnerable. Fog, in particular, is a critical limiting factor and is categorized according to visibility, wavelength, and attenuation in decibels per kilometer (dB/km) into four types: dense, thick, moderate and light fog [62, 63].

3.1.3. Pointing Errors (PEs)

This impairment arises from mechanical and environmental disturbances such as wind, structural vibrations, building sway, thermal expansion, and hovering instability of UAVs. These factors result in misalignment between the transmitter and receiver apertures, significantly reducing the received optical power and increasing the probability of link failure and bit errors [62, 63]. Precise beam alignment is especially challenging on mobile platforms such as UAVs

Table 4
Challenging Issues on FSO Links Across Different SAGIN Scenarios

Network Scenario	Challenging Issues on FSO Links
Building-to-Building	Turbulence (Weak, Medium, Strong), Fog, Rain, PEs, Scintillation, Alignment Loss, Building Spiral
Ground-to-UAVs	Turbulence (Weak to Strong), Beam Wander, PEs, UAV Instability, Link Intermittency
Ground-to-HAPs	Beam Divergence, Atmospheric Absorption, Weak to Strong Turbulence, PEs, Link Blockage
Ground-to-Satellite	Turbulence-induced Beam Wander, Geometric Loss, Clouds, Fog, Rain, PEs, Scintillation
Satellite-to-Ground	Clouds, Scintillation due to Strong Turbulence, PEs, Geometric Loss, Atmospheric Attenuation
UAV-to-UAV	Turbulence (Weak to Strong), PEs, AoA Fluctuations, UAV Jitter
UAV-to-HAP	Mobility-Induced Misalignment, Dynamic Link Stability, Turbulence, PEs
HAP-to-HAP	Weak Turbulence, Limited Beam Steering Precision, PEs, Propagation Delay
HAP-to-Satellite	Altitude-Induced Beam Dispersion, Weak Turbulence, PEs, Geometric Loss
Satellite-to-HAP	Geometric Loss, Beam Broadening, PEs, Atmospheric Entry Angle Effects
Inter-Satellite	Doppler Shift, Point Ahead Angle, Laser Beam Tracking, PEs, Link Switching Delay
Deep Space	Severe Path Loss, PEs, Space Dust Scattering, Coronal Solar Wind Turbulence, Delay, Power Constraints

and satellites, where even small deviations can lead to substantial signal degradation.

3.1.4. *Angle-of-Arrival (AoA) Fluctuations*

These occur due to unstable hovering of aerial platforms, such as drones, caused by high-speed winds or mechanical jitters. Such fluctuations disrupt the alignment between the FSO transmitter and receiver planes, causing intermittent link interruptions and further compromising the reliability of the communication system[62]. Table 4 presents a summary of the key challenges faced by FSO links between various network scenarios.

Furthermore, interference and physical obstructions present significant challenges to FSO communication systems. Given their reliance on strict LoS alignment, FSO links are particularly vulnerable to disruptions caused by obstacles such as buildings, uneven terrain, or temporary barriers [55]. This issue is especially acute in dense urban environments, where the likelihood of LoS blockages is high. In addition to structural obstructions, environmental particulates such as dust, smoke, and atmospheric scattering can attenuate optical signals, thereby reducing the effective communication range. Unlike RF systems, which can propagate through certain obstacles and over longer distances, FSO systems are highly susceptible to such impairments, limiting their scalability and reliability for extended-range applications. Moreover, security remains a critical concern in FSO communications. Although FSO inherently offers a level of physical security due to its narrow beam and confined transmission path, it is still susceptible to interception and jamming under certain conditions.

In summary, the implementation of robust mitigation strategies to address external challenges is essential to ensure the reliability, stability, and operational resilience of FSO systems in real-world deployment scenarios.

3.2. Mitigation Techniques

Recent studies have investigated several mitigation strategies to overcome the inherent challenges in SAGINs. For instance, Liu et al. [64] proposed a distributed and stateless Satellite Core Network (SCN) architecture incorporating reliable context management mechanisms to address signaling storms, latency, and inefficiencies in satellite networks. By decoupling the state from network instances, this architecture enables flexible function deployment and leverages Network Function Virtualization (NFV) to unify the satellite-terrestrial integration framework. As a result, it significantly reduces transmission delays, minimizes signaling overhead, and enhances overall reliability.

To mitigate the challenges specific to FSO links within SAGINs, various techniques have been proposed. These can broadly be categorized into two major classes: physical-layer approaches and upper-layer (e.g., TCP-layer) solutions, as illustrated in Fig. 5. Physical-layer strategies primarily aim to address impairments such as AT, PEs, and weather-induced attenuation, while upper-layer methods focus on protocol-level enhancements to ensure end-to-end reliability, congestion control, and dynamic routing under fluctuating link conditions. Together, these mitigation approaches form a comprehensive defense against the vulnerabilities affecting FSO-based SAGIN architectures.

3.2.1. *Physical Layer Methods*

Physical layer methods encompass various techniques to enhance signal quality and transmission efficiency at both the hardware and optical signal levels. Key methods include:

- ***Aperture Averaging:*** Aperture averaging is a widely used mitigation technique in FSO systems to reduce signal fluctuations. By employing a larger receiver aperture, fading effects are mitigated through intensity averaging. As illustrated in Fig. 6, incorporating a wider lens at the receiver reduces channel fading, improves SNR, and enhances link reliability. This figure demonstrates the concept of aperture averaging in FSO transceivers, where the receiver's aperture is intentionally wider than the transmitter's to minimize beam wandering losses. However, larger apertures can

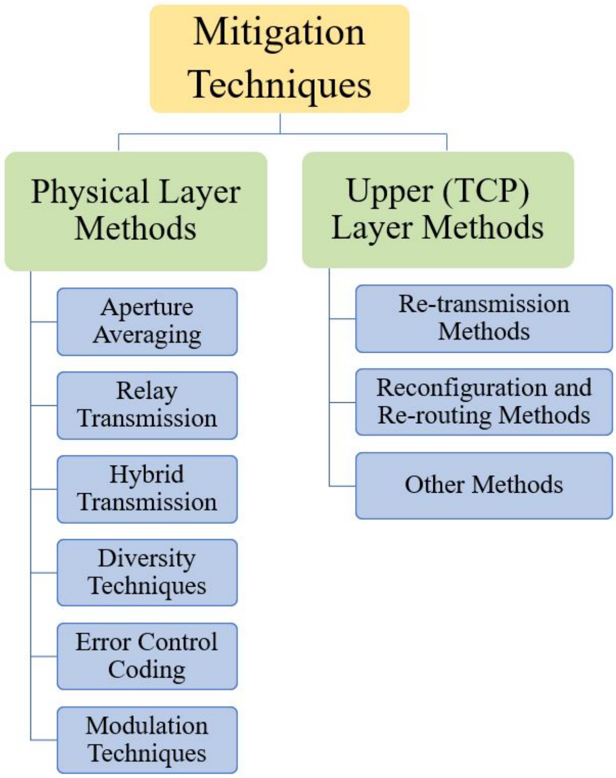

Fig. 5. Mitigation Techniques for AT, Signal Attenuation, Beam Wandering, and Link Instability.

also increase background noise and add weight to the system, creating challenges for mobile platforms such as UAVs and satellites. Recent studies have focused on optimizing aperture radius to balance power efficiency with system agility and alignment [65, 66, 67].These studies demonstrate that employing optimized aperture radius-based techniques is effective in mitigating the effects of various weather-induced impairments, including PEs, random fog, and scintillation, particularly under conditions of strong AT.

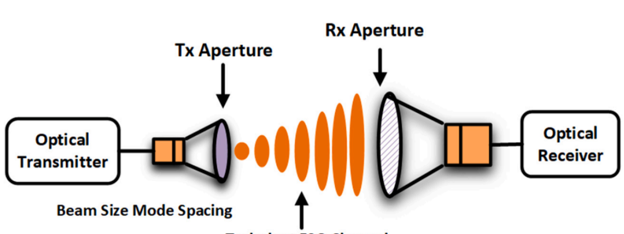

Fig. 6. Aperture Averaging of FSO Transceiver [68].

In [65], researchers analyzed the effect of aperture size on maintaining reliable FSO communication, examining various multi-receiver aperture diameters under clear rainy conditions to optimize outage performance and power consumption. Their findings underscored the importance of selecting an optimal aperture size for achieving robust outage performance. Likewise, [66] introduced multi-aperture FSO transmitters that served as a multi-aperture receiver through an optical reconfigurable intelligent surface (RIS). While multiple apertures improve performance under turbulent conditions, they add complexity in implementation, such as static skew mismatches and time-varying signal attributes like gain, phase, and polarization. To address these challenges, [67] proposed a complex-valued MIMO 2N $\times$ 2 adaptive equalizer that employs a constant modulus algorithm to calculate tap coefficients and electronically compensate for skew, thereby reducing hardware constraints associated with time alignment.

Aperture averaging, while useful for mitigating turbulence-induced scintillation in FSO links, has several unresolved limitations in SAGINs. Its effectiveness is limited in addressing pointing errors, beam wander, and alignment issues, which are prevalent in mobile platforms like UAVs and satellites. Additionally, the technique becomes less effective under severe weather conditions (e.g., fog, clouds) and at extreme link distances. Implementing large apertures also adds size and weight—constraints that conflict with the payload limits of aerial and space platforms—making widespread deployment in SAGINs challenging.

- ***Relay Transmission:*** Relay transmission is a fundamental physical-layer technique in SAGINs, enhancing communication reliability and signal strength by leveraging aerial platforms such as HAPs and UAVs. These aerial relays serve as intermediary nodes between satellites and GSs, effectively reducing signal path lengths, lowering latency, and extending coverage to remote or obstructed regions.

  HAP offer wide-area coverage with long endurance, acting as stable intermediaries in satellite-ground communication. It operates at altitudes between 18–20 km [12], function as effective relay nodes in SAGINs, enhancing signal coverage and mitigating attenuation effects [69]. Positioned in the stratosphere—an environment largely free from atmospheric impairments such as turbulence, rain, and fog—HAPs provide robust LoS links to satellites, improving the reliability of ground-to-satellite FSO communication [9, 70].

  The relay capability of HAPs has attracted growing interest due to their potential for rapid deployment, ease of maintenance, and cost-effectiveness, as demonstrated by initiatives like Google's Project Loon. In SAG-FSO architectures, a typical deployment involves placing an HAP between GS and a satellite, where the FSO signal is first transmitted from the GS to the HAP and then relayed to the satellite [7, 42, 71]. This multi-hop approach effectively reduces the propagation distance of each FSO segment, thereby mitigating beam-wandering-induced PEs. For instance, the dual-hop design in [42] achieves a 4 dB

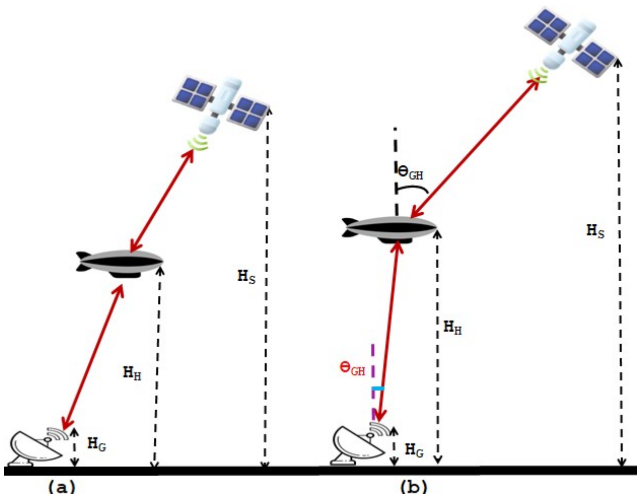

Fig. 7. SAGIN–FSO Link (a) Without Considering Zenith-Angle θ, and (b) With Zenith-Angle θ Consideration.

performance gain over single-hop transmission at an average symbol error probability (ASEP) of 10^{-2}.

AT, driven by wind-blown aerosol particles and solar heating, predominantly affects altitudes below 2 km and diminishes above 17 km. While a dual-hop configuration using a HAP relay reduces the impact of PEs, it cannot fully overcome the limitations imposed by AT on the GS-HAP link, especially at high zenith angles, where longer optical paths intensify turbulence-related impairments.

To mitigate these effects, recent studies advocate for strategic HAP placement directly above the GS to maintain a low zenith angle (typically $\theta_{GH} \leq 5°$) [9]. This alignment shortens the FSO beam's path through turbulent layers, reducing scintillation and beam wander in the GS-HAP segment and enhancing the overall reliability and performance of the SAG-FSO network, as illustrated in Fig. 7(b). Fig. 7(a) depicts the SAGIN-FSO links without accounting for the zenith angle between the HAP and the GS, whereas Fig. 7(b) illustrates the configuration with an optimized zenith angle, resulting in enhanced link performance.

In contrast, UAVs offer distinct advantages for communication networks due to their rapid deployment capability, mobility, and localized service support. These features make UAVs particularly effective in dynamic and mission-critical scenarios such as disaster response [43, 44]. Operating at lower altitudes than satellites, UAVs enable lower latency communication while providing connectivity in regions where terrestrial infrastructure is limited or unavailable, thus supporting the high data demands of the 5G and future 6G networks [45]. Furthermore, aerial networks based on UAVs are increasingly integrated with artificial intelligence technologies, enabling distributed computing, real-time data analytics, and autonomous decision making.

Nevertheless, achieving robust communication among UAVs, satellites, and ground nodes poses significant challenges. The dynamic nature of UAV topologies, frequent link changes, potential network congestion, end-to-end latency constraints, limited on-board energy, and the need to preserve data security and integrity all complicate the design of efficient routing protocols [11, 46, 47].

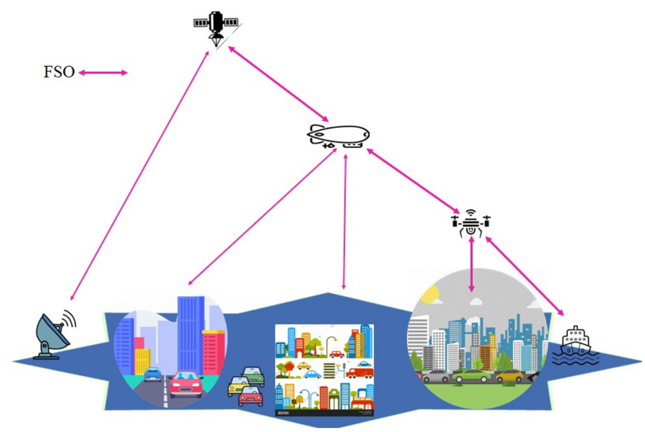

Fig. 8. Using UAV and HAP as relays in SAGINs Architecture.

Fig. 8 illustrates the integration of HAPs and UAVs within SAGINs, where they function as relay nodes to shorten the optical path between satellites and GSs. This design is particularly effective in mitigating challenges such as AT, PEs, and NLoS conditions. However, cloud coverage between the HAP and UAV can obstruct FSO links. In such cases, a practical solution is the rapid deployment of an additional UAV acting as a relay node to circumvent the cloud-blocked segment of the HAP-to-ground FSO link.

To enhance this capability, RIS technology has been proposed [72, 73]. By equipping UAVs with RIS arrays, the incoming optical beam from the HAP can be redirected toward the GS, thereby maintaining the optical link even in the presence of obstructive clouds. The combination of UAV mobility and adaptability to RIS presents a low-complexity and cost-effective alternative to conventional AF or DF relays.

Fig. 9 presents a HAP-based SAGIN scenario where a RIS-equipped UAV is temporarily deployed in a region with minimal or no cloud coverage. This setup ensures reliable FSO communication continuity by dynamically redirecting the light beam toward the intended ground target. It is noteworthy that the study of FSO-based RIS–UAV relaying remains in its early stages. Recent efforts [74, 75] have begun exploring the potential of RIS-equipped UAVs as relay stations in terrestrial FSO networks, particularly for establishing links between buildings in environments where direct line-of-sight is obstructed. These preliminary investigations highlight the promise of integrating RIS-UAVs within SAGINs for robust, flexible, and adaptive optical communication.

Two primary relay protocols are commonly used: DF and AF [62]. In the DF protocol, the relay node enhances signal integrity by first decoding the received transmission to extract the original message and eliminate accumulated noise. The relay then re-encodes and forwards a clean version of the signal to the destination, thereby improving link robustness and communication quality. At relay R, the received signal is given by:

$$R_R = \sqrt{P_1} h_R \epsilon_c s + n_R \tag{1}$$

where P_1 denotes the transmit power from the source to the relay, h_R represents the channel gain of the source-to-relay link, ϵ_c is the optical-to-electrical conversion efficiency, s is the original transmitted signal, and n_R is the additive white Gaussian noise (AWGN) at the relay with variance σ_R^2. The relay decodes the signal $\hat{s}$ from the received signal R_R. At destination D (Satellite/GS):

$$R_D = \sqrt{P_2} h_D \epsilon_c \hat{s} + n_D \tag{2}$$

where P_2 denotes the transmit power from the relay to the destination, h_D represents the channel gain of the relay-to-destination link, $\hat{s}$ is the signal decoded and re-encoded at the relay, and n_D is AWGN at the destination with variance σ_D^2.

In contrast, AF protocol offers a simpler relay strategy. Instead of decoding the received signal, the relay directly amplifies the entire received waveform, including both the desired signal and any accompanying noise, and forwards it to the destination. Although AF enables faster processing and lower complexity, it can also amplify noise, which can degrade the overall system performance. At the relay node R, the received signal is expressed as:

$$R_R = \sqrt{P_1} h_R \epsilon_c s + n_R \tag{3}$$

where P_1 is the transmit power from the source to the relay, h_R is the channel gain for the source-to-relay link, ϵ_c denotes the optical-to-electrical conversion efficiency, s is the original transmitted signal, and n_R represents AWGN at the relay with variance σ_R^2. The relay amplifies this signal using a fixed gain G, yielding:

$$R_R^{\text{amp}} = G r_R = G\left(\sqrt{P_1} h_R \epsilon_c s + n_R\right) \tag{4}$$

This amplified signal is then transmitted to the destination (e.g., satellite or ground station). The signal

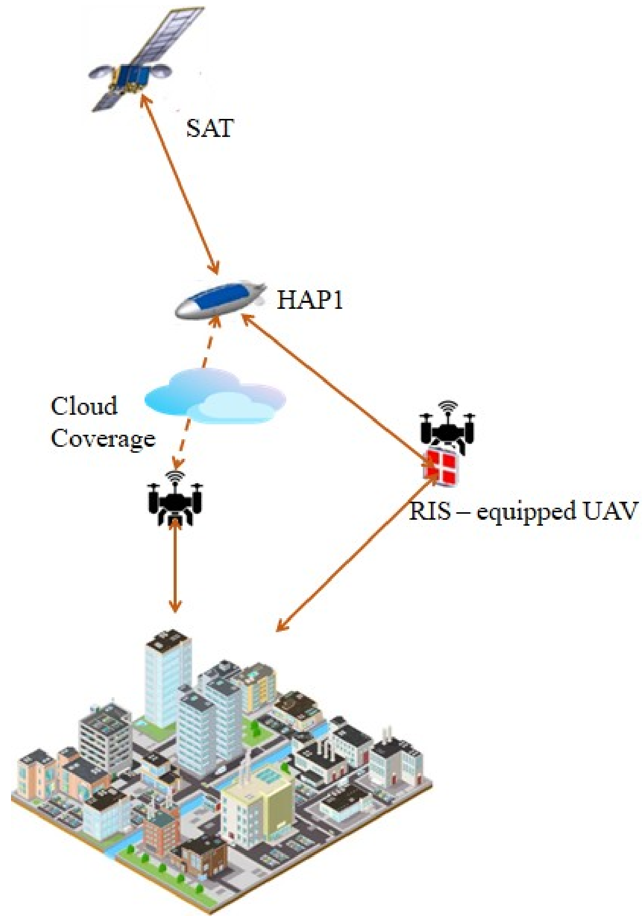

Fig. 9. HAP-based SAGIN using FSO with optical RIS–UAV relay solution.

received at the destination node D is given by:

$$R_D = G\sqrt{P_1} h_R h_D \epsilon_c s + G h_D n_R + n_D \tag{5}$$

where h_D is the channel gain for the relay-to-destination link and n_D is the AWGN at the destination with variance σ_D^2.

Despite its advantages, relay transmission in FSO-based SAGINs faces several unresolved limitations. Misalignment due to platform mobility and environmental disturbances remains a critical issue, as it can severely degrade signal quality. UAV-based relays are constrained by limited energy capacity, reducing operational time. Additionally, dual-hop configurations introduce latency and overhead, which are unsuitable for real-time applications. Atmospheric impairments such as fog and turbulence still affect ground-to-relay segments, and limited payload capacity restricts the deployment of advanced optical hardware. These unresolved challenges limit the scalability and reliability of relay-assisted FSO systems in dynamic SAGIN environments.

- ***Diversity Techniques:*** Diversity techniques in FSO communication systems are essential for mitigating the effects of AT, PEs, and angle-of-arrival (AoA) fluctuations by utilizing time, frequency, space, and polarization domains. Spatial diversity, for example, involves using multiple antennas at the transmitter, receiver, or both to improve signal reception and reliability. In SIMO systems, diversity is achieved on the receiver side using methods like selection combining (SC), equal gain combining (EGC), or MRC, with MRC providing the highest signal-to-interference-plus-noise ratio (SINR). A study on Earth-to-HAP FSO systems highlighted the effectiveness of spatial diversity in mitigating AoA fluctuations, especially through a SIMO FSO uplink over long distances, ensuring reliable data transmission [76]. MIMO systems in FSO networks perform optimally when independent or uncorrelated beams are used [77].

Additionally, time diversity enhances performance by transmitting redundant symbols across different coherence times, reducing OP and improving reliability [78]. Frequency diversity transmits signals over multiple frequency channels to minimize interference, and polarization diversity improves signal integrity by using different signal polarizations, ensuring communication remains robust in varying environmental conditions [79]. These diverse techniques collectively enhance communication reliability and performance, ensuring continuous, high-quality data transmission.

Despite of their effectiveness in mitigating turbulence, fading, and pointing errors, diversity techniques in FSO-based SAGINs still face unresolved challenges that limit their practical deployment. One major issue is the difficulty in achieving uncorrelated channels for spatial diversity, especially in size- and weight-constrained platforms like UAVs and small satellites, where sufficient aperture separation is impractical. Additionally, dynamic network topologies and frequent link disruptions in SAGINs reduce the effectiveness of time and path diversity methods. Implementing diversity schemes also introduces synchronization and processing overhead, which is problematic for delay-sensitive applications. Furthermore, there is no adaptive framework to dynamically select the optimal diversity method based on changing atmospheric and mobility conditions. These challenges highlight the need for intelligent, resource-aware, and context-adaptive diversity mechanisms that can operate reliably under the non-stationary and highly variable conditions of SAGINs.

- ***Error Control Coding:*** Error control coding (ECC) substantially improves communication reliability by enabling the detection and correction of errors during data transmission. ECC techniques are primarily divided into two categories: error detection codes, such as parity checks and cyclic redundancy checks (CRC), and error correction codes, including forward error correction (FEC) methods. Prominent FEC codes, such as reed-solomon (RS), LDPC, polar, and turbo codes, introduce redundancy that helps the receiver correct errors caused by channel impairments, thereby enhancing data integrity, reliability, and overall performance of FSO communication systems. By incorporating redundancy into transmitted messages, these codes enable receivers to detect and correct errors from channel fading, enhancing performance in fading channels [80, 81, 82, 83, 84].

  For instance, in [80], the authors analyzed FEC-coded 32QAM signals with a rate-flexible hybrid constellation shaping (HCS) scheme for FSO, achieving a Q^2 factor improvement of 1.84–3.40 dB over conventional methods, even under weak turbulence. Optimizing FEC overhead is crucial, especially for wavelength-division multiplexing (WDM) systems. In [82], researchers evaluated FEC performance across WDM channels, underscoring the importance of balancing FEC overhead in single- and multi-channel systems to improve bit-rate efficiency.

  In addition, LDPC codes are increasingly utilized in hybrid RF/FSO systems; [81] examines deep learning-based LDPC decoders, which demonstrate substantial performance gains over traditional methods and are particularly effective for efficient terminal-side decoders in 5G systems. Polar codes have made notable advancements in FSO systems due to their flexibility. In [83], a rate-flexible HCS scheme for polar-coded 32QAM signals exhibited enhanced receiver sensitivity and resilience against turbulence.

  Furthermore, [84] demonstrates polar codes' effectiveness in reducing fading due to scintillation, improving BER performance in FSO channels. These advancements in ECC collectively provide robust solutions for optimizing FSO communication under varied atmospheric conditions. While these codes strengthen FSO systems against signal degradation, they also increase computational complexity and bandwidth demands, making adaptive strategies essential for efficiency under dynamic atmospheric conditions.

  Despite the demonstrated benefits of ECC in enhancing FSO link robustness, several unresolved issues hinder its full potential in SAGINs. First, conventional ECC schemes, such as LDPC and Turbo codes, often require long block lengths and iterative decoding, leading to high latency and computational complexity—factors unsuitable for real-time, delay-sensitive SAGIN applications. Second, the effectiveness of ECC degrades under rapidly varying channel conditions caused by atmospheric turbulence and platform mobility, for which most existing schemes are not optimized. Additionally, selecting appropriate coding rates and modulation schemes in response to unpredictable link quality remains a challenge, as current adaptive coding techniques lack precision and responsiveness in dynamic FSO environments.

Moreover, energy constraints on aerial platforms (e.g., UAVs) limit the feasibility of computationally intensive ECC decoders. Lastly, there is a lack of joint design frameworks that integrate ECC with other physical-layer mitigation techniques, such as diversity or aperture averaging, to holistically address multi-faceted impairments. These issues underscore the need for lightweight, adaptive, and cross-layer ECC designs tailored for the unique constraints and variability of FSO-SAGIN systems.

- ***Modulation:*** Modulation in optical signals involves modifying amplitude, phase, or frequency to encode information for transmission. In FSO communication, modulation techniques are essential for efficient data transmission over optical beams, particularly in outdoor environments. These methods help maintain signal quality over long distances, where factors like AT, fog, and other disturbances can degrade performance. Various modulation formats are available, such as on-off keying (OOK), return-to-zero (RZ), non-return-to-zero (NRZ), advanced variants of NRZ, phase-shift keying (PSK) and its variants, pulse position modulation (PPM), quadrature amplitude modulation (QAM), and others. Details of these modulations are explained in [21, 24, 26].

  The choice of modulation technique directly influences FSO system performance, enabling extended link ranges, higher data rates, and reduced interference under challenging atmospheric conditions. For instance, RZ modulation performs optimally in single-channel systems, whereas NRZ is more effective in multi-channel systems under turbulent conditions [85]. Carrier-suppressed RZ (CSRZ) modulation outperforms multi-level differential RZ (MDRZ) and differential RZ (DRZ) regarding BER and Q-factor under various atmospheric conditions, including clear weather, rain, haze, and fog [86]. Other promising techniques for FSO systems include PPM, which operates in the time domain, and orthogonal frequency division multiplexing (OFDM), which mitigates multipath fading [87, 88]. Binary PSK (BPSK) is valued for its simplicity, noise resistance, and low power requirements [89], while differential PSK (DPSK) offers robustness against phase noise and AT [90]. A comparison of OOK and DPSK [91] shows that OOK performs better in low SNR conditions, whereas DPSK excels in high SNR environments. QAM is notable for its high data rates and SE [92], with quadrature PSK (QPSK) being particularly effective due to its noise immunity and ease of demodulation. These modulation strategies collectively provide diverse solutions for optimizing FSO communication across various operational scenarios, ensuring robust and efficient data transfer under different atmospheric conditions.

  Current unresolved issues with modulation techniques for FSO links in SAGINs highlight several critical limitations that hinder optimal system performance. Firstly, conventional modulation schemes like OOK, PPM, and their variants often exhibit poor resilience under severe atmospheric turbulence and pointing errors, leading to signal degradation and increased BER. Secondly, many advanced modulation formats require high SNR and precise synchronization, which are difficult to maintain in dynamic satellite-aerial-ground environments where mobility and channel variability are prominent. Thirdly, there is a lack of adaptive modulation techniques that can rapidly respond to channel fluctuations in real time, particularly under varying weather and zenith angle conditions. Moreover, high-order modulation schemes, while spectrally efficient, often demand complex receiver designs and tight power control, which are not always feasible on resource-constrained platforms like UAVs or HAPs. Lastly, the joint optimization of modulation with coding, power allocation, and beam parameters remains an open problem, especially for scalable, low-complexity solutions compatible with the latency and energy constraints in SAGIN-based FSO systems. These gaps call for the development of robust, adaptive, and lightweight modulation strategies tailored to the harsh and heterogeneous conditions of FSO-enabled SAGINs.

- ***Hybrid Transmission:*** Although hybrid FSO/RF transmission in SAGINs introduces higher costs, lower bit rates for backup RF links, and system complexity, it remains a viable solution for enhancing communication reliability and availability. FSO links offer exceptionally high data rates and large bandwidth, making them ideal for ultra-fast transmissions under favorable conditions. However, their susceptibility to atmospheric impairments—such as fog, rain, and turbulence—limits their reliability. To compensate, RF links serve as resilient backups, maintaining stable communication during adverse weather conditions. By integrating both technologies, hybrid FSO/RF systems provide a robust end-to-end communication architecture that ensures continuity across varying environmental scenarios [93]. They mitigate atmospheric impairments such as fog, rain, and turbulence, compensate for pointing errors and NLoS scenarios, and enhance link availability through adaptive switching and signal combining techniques. This integration ensures stable throughput and high system availability, even when environmental conditions fluctuate, making hybrid transmission a resilient solution.

  These systems employ intelligent switching mechanisms to adaptively toggle between FSO and RF links based on real-time channel conditions. Hard switching involves a full transition to RF when FSO

Table 5
Overview of Switching Schemes Employed in Recent Research.

Switching Scheme	Downlinks	Uplinks	Performance Metrics	References
Hard-Switching	✓		Latency	[94]
	✓		Throughput	[95]
Single Threshold-Based Switching		✓	OP and ASER	[42]
	-	-	BER	[96]
Adaptive combining	✓	✓	OP and ASER	[7]
	✓	✓	OP	[97]
Rate Adaptation Switching	✓		OP and SE	[71]
	✓		OP	[98]

quality deteriorates, while soft switching enables concurrent or partial use of both links, reducing service interruptions. Adaptive rate control further optimizes throughput by adjusting data rates in response to link quality—utilizing high rates during clear conditions and falling back to RF at lower rates when optical links degrade. Additionally, techniques like Maximum Ratio Combining (MRC) enhance reliability by aggregating signals from both FSO and RF channels. Table 5 presents a summary of the switching schemes used in recent research on hybrid FSO-RF transmission systems. Signal-combining methods such as MRC further enhance robustness by leveraging RF as a backup during FSO fluctuations.

Recent studies emphasize the growing importance of hybrid FSO/RF systems in maintaining high link availability under dynamically changing environmental conditions. Advanced strategies, including channel state information (CSI) monitoring and real-time dynamic rate adaptation, further improve resilience and performance, highlighting the practical advantages of hybrid communication architectures in SAGIN deployments [71].

On the other hand there are several unresolved issues that persist in hybrid FSO/RF systems. One major challenge lies in the design of efficient and low-latency switching mechanisms between FSO and RF links. Current schemes, such as hard-switching and soft-switching, often suffer from suboptimal performance during rapid environmental changes, leading to interruptions or throughput degradation. Additionally, integrating CSI from two vastly different mediums (optical and RF) remains complex, especially under mobility and turbulence. Hybrid systems also increase hardware complexity, size, and energy consumption—issues that are particularly problematic for aerial platforms like UAVs with limited payload and power. These limitations necessitate further research into joint resource allocation, AI-based link adaptation, and lightweight hardware integration to make hybrid FSO/RF systems scalable and efficient for next-generation SAGINs.

3.2.2. *Upper-Layer (TCP) Methods*

Upper-layer methods, such as those at the TCP or application level, focus on managing data protocols to handle errors and disruptions in FSO systems. Techniques include:

- ***Re-transmission:*** Error control mechanisms in FSO systems are essential for mitigating transmission errors caused by AT, adverse weather, and misalignments in the points, addressing both physical and link-layer problems. Link-layer solutions, such as Automatic Repeat reQuest (ARQ) and Hybrid ARQ (HARQ), have been extensively studied to enhance the reliability and efficiency of FSO communication [99, 100, 101].

  ARQ protocols enable the retransmission of erroneous frames based on feedback from the receiver. Common variations include Stop-and-Wait (SW), Go-Back-N (GBN), and Selective Repeat (SR), each offering different levels of retransmission efficiency. Recent advancements, such as Cooperative ARQ (C-ARQ), leverage cooperative diversity in systems like HAPs, improving performance under challenging conditions [99, 100, 101]. Adaptive switching schemes using SW-ARQ also facilitate smoother transitions in hybrid FSO/RF systems, addressing disparities in data rates and channel coherence times, particularly in mmWave links and adaptive multi-rate systems [102].

  Fading channel models, such as the Gamma-Gamma and Malaga distributions, have improved the accuracy of performance predictions in FSO systems [100]. These models are particularly useful in time-varying channels like inter-HAP and satellite links, where long distances introduce high latency. For example, SR-ARQ has achieved near-error-free communication at rates close to 100 Gbps in LEO satellite links by optimizing frame sizes to align with channel coherence times [103].

  HARQ protocols integrate FEC with retransmission requests, making them highly effective in satellite-based FSO systems prone to fading [104, 105]. Fig. 10 illustrates the comparison of the three error control methods for data transmission: ARQ, FEC, and HARQ. In ARQ, the receiver detects errors, discards the erroneous packet, and requests retransmission.

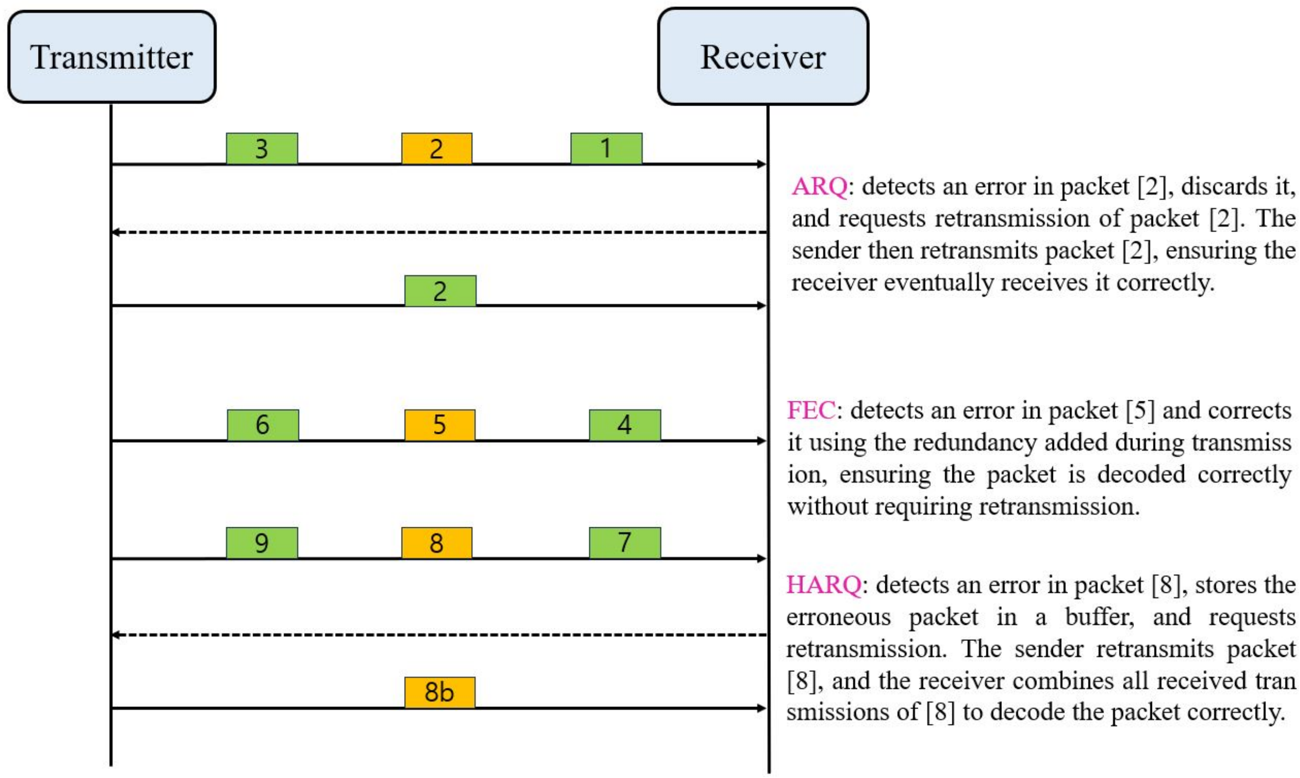

Fig. 10. Graphical Comparison of the Three Error Control Methods for Data Transmission: ARQ, FEC, and HARQ.

FEC, on the other hand, adds redundancy to the data, enabling the receiver to detect and correct errors without needing retransmission. HARQ combines both approaches by storing the erroneous packet, requesting retransmission, and using the combined data to correctly decode the packet. This integration of ARQ and FEC makes HARQ more efficient and reliable, especially in scenarios with high error rates. Incremental redundancy HARQ (IR-HARQ) is particularly efficient, transmitting parity bits incrementally to optimize power usage and reliability under fading conditions. For example, IR-HARQ using rate-compatible punctured convolutional codes has improved power efficiency and reliability in LEO links [106, 107, 108]. In FSO-based backhaul networks with LEO and HAP nodes, Cooperative HARQ mechanisms have been developed to ensure latency fairness among GSs experiencing variable turbulence [109]. These mechanisms, combined with rate adaptation, improve throughput, energy efficiency, and resilience against imperfect channel state information (CSI). Rate-compatible low-density parity check codes (RC-LDPC) offer a scalable solution to manage rate adaptation without degradation at high rates [110, 111].

Although retransmission techniques are effective in enhancing the reliability of FSO communications, several unresolved issues continue to limit their full potential within SAGIN environments. First, ARQ and HARQ inherently introduce additional latency due to repeated transmissions, which is problematic for delay-sensitive applications such as real-time video streaming or emergency response. In high-mobility and dynamic scenarios typical of SAGINs, maintaining reliable acknowledgment and feedback channels becomes difficult, leading to feedback delays or losses that further degrade performance. Moreover, excessive retransmissions can significantly increase energy consumption, particularly on power-constrained platforms like UAVs or LEO satellites. The performance of ARQ/HARQ is also severely impacted under deep fades or bursty errors caused by atmospheric turbulence or pointing errors, where repeated retransmissions may still fail to recover the original data. Additionally, the integration of retransmission protocols into optical links requires complex buffer management and synchronization mechanisms, especially in dual-hop or relay-based FSO systems. Current ARQ/HARQ schemes are not well-optimized for joint operation with adaptive modulation, coding, and hybrid RF/FSO systems. Therefore, developing intelligent retransmission strategies that balance reliability, delay, and energy efficiency under dynamic SAGIN conditions remains an important open challenge.

- ***Path Reconfiguration and Data Rerouting:*** Path reconfiguration and data routing are essential to maintain the availability and reliability of FSO networks, particularly in scenarios involving LoS loss, adverse weather, or device failures. Dynamic node reconfiguration through physical and logical control mechanisms significantly enhances link availability, as explored in [63]. At the physical layer, automated pointing techniques (ATP) are employed to dynamically adjust beam directions, while the logical layer relies on autonomous reconfiguration algorithms to manage network paths. Data packets are rerouted through alternative optical or low-data-rate RF links to ensure continuous communication. This approach is widely used in optical satellite networks, where dynamic path switching compensates for link disruptions [112].

  Optical RIS (ORIS) further enhance FSO network adaptability by enabling real-time path reconfiguration and reducing the reliance on rerouting under challenging conditions. ORIS can be categorized into mirror-based systems, which use mechanical adjustments for signal reflection, and metasurface-based systems, which employ electronically controlled subwavelength elements to manipulate light's phase and direction [66, 113]. Metasurface-based ORIS, with their superior spatial resolution, provide stronger signal reception, reduced interference, and improved adaptability, making them particularly suitable for applications like vehicular FSO communications. These systems improve coverage by alleviating LoS constraints, enhance signal quality by mitigating AT and fading, and offer dynamic reconfigurability for better performance in complex environments.

- ***Other Approaches:*** When direct transmission or rerouting is infeasible in FSO systems, alternative techniques like replaying and Delay Tolerant Networking (DTN) enhance reliability and resilience. Replaying, implemented in protocols like ARQ, retransmits lost or corrupted packets to maintain data integrity, effectively addressing temporary disruptions or interference. However, it may introduce delays, making it less ideal for real-time applications. On the other hand, DTN is designed for environments with long delays or intermittent connectivity, such as space communications or remote regions. Using a store-and-forward approach, DTN temporarily stores data at intermediate nodes and forwards it when links become available, ensuring delivery despite disruptions. This method is especially suited for FSO systems in challenging atmospheric conditions, offering a robust solution for maintaining connectivity and ensuring reliable communication.

3.3. Lesson Learned

This section summarizes key mitigation techniques to address challenges in FSO links, particularly within SAGINs. At the physical layer, techniques such as aperture averaging are highlighted for reducing signal fluctuations by collecting light over larger surfaces, thereby improving the SNR. Relay transmission, primarily through HAPs, extends coverage and maintains signal quality in hybrid FSO/RF systems, ensuring continuous communication during adverse weather conditions. Additionally, we emphasize the role of hybrid transmission techniques, where dynamic switching between FSO and RF links is employed to maintain connectivity and optimize system performance. Integration of spatial, time, and frequency diversity further mitigates the impact of turbulence and enhances communication robustness. In the upper layers, this study examines retransmission protocols, including ARQ and HARQ, which facilitate the retransmission of lost data to ensure data integrity despite channel impairments. Reconfiguration and rerouting methods are also discussed, enabling networks to dynamically adapt to link failures by switching to alternative paths or protocols. Advanced technologies, such as optical ORIS and DTN, are introduced to improve the adaptability and resilience of FSO systems, ensuring uninterrupted communication even under challenging environmental conditions. These comprehensive mitigation strategies position FSO-based SAGIN systems as viable solutions for reliable and efficient communication, particularly for future 6G networks and beyond.

4. Performance Metrics Optimization

Optimization in FSO-based SAGINs is the systematic tuning of system parameters to maximize or minimize key performance metrics, such as maximizing throughput, minimizing OP, BER, and latency, while enhancing reliability, SE, EE, and security. The goal is to ensure that the communication system operates with high efficiency, robustness, and security in dynamic space, air, and ground environments. Within the FSO communication systems deployed in SAGINs, optimization plays a key role in addressing environmental impairments, such as AT, PEs and weather disturbances, and system-level challenges, including resource constraints, mobility, and link heterogeneity.

Several parameters are vital to the performance of FSO links and thus subject to optimization. One such parameter is the **FoV**, which defines the angular span over which the receiver can detect incoming optical signals. A wider FoV allows for better signal capture under misalignment and atmospheric fluctuations but also increases susceptibility to background noise. Conversely, a narrower FoV reduces noise intrusion, but may lead to signal loss. Hence, determining the optimal FoV is essential to strike a balance between signal reception and noise suppression, particularly under varying SNR conditions [62, 114].

Another critical parameter is the **AoA**, which refers to the direction from which the optical beam reaches the receiver [114, 115]. In aerial networks involving UAVs or HAPs, dynamic movement introduces AoA fluctuations, potentially degrading alignment and signal strength. Adaptive tracking mechanisms or beam-steering strategies can be employed to compensate for such variations and maintain link stability. Furthermore, **average SNR** is a pivotal metric, as higher SNR typically corresponds to lower bit or symbol error rates and higher communication capacity. This can be optimized through power control strategies, efficient receiver design, and diversity techniques [114].

The **beam divergence angle** is a critical parameter influencing the performance of FSO communication systems. A larger divergence angle enhances robustness against PEs by increasing the beam's tolerance to misalignment, but it also reduces beam intensity at the receiver. Conversely, a narrower divergence angle concentrates optical power, improving energy efficiency but requiring highly precise alignment. Therefore, optimizing the beam divergence angle is essential to achieve a favorable trade-off between signal strength and alignment sensitivity, ultimately enhancing link reliability.

Similarly, the **beam width**—the spatial extent of the beam at a given distance—affects the balance between pointing error resilience and received signal strength. A wider beam can alleviate the effects of PEs, yet it diffuses the optical power, weakening the received signal strength. Hence, careful optimization of beam width is also vital for sustaining robust communication performance under varying channel conditions [35]. This paper aims to minimize the **end-to-end OP** P_{out} in air-ground FSO-based network. To achieve this, it formulates an optimization problem that jointly adjusts FoV angles $\theta_{\text{FoV},i}$ for each link $i = 1, \ldots, N + 1$. The optimization objective is:

$$\min_{\theta_{\text{FoV},1},\ldots,\theta_{\text{FoV},N+1}} P_{\text{out}} \tag{6}$$

Subject to the constraint that the **beam divergence angle** $\omega_{z,i}$ at each hop must meet or exceed a **minimum required divergence** $\omega_{z,i}^{\min}$, ensuring reliable link performance:

$$\text{s.t.} \quad \omega_{z,i} \geq \omega_{z,i}^{\min}, \quad i = 1, \ldots, N + 1.$$

This formulation balances **FoV optimization** to capture sufficient signal strength while mitigating background noise and PEs, and **beam divergence constraints** to ensure alignment tolerance and robustness. The solution effectively reduces the overall OP across all links, thereby enhancing the **reliability and efficiency** of FSO links.

In addition to beam parameters, the optimal placement of relay nodes, such as HAPs or UAVs, is fundamental in mitigating AT and minimizing propagation losses. Strategic positioning of these relays can reduce the zenith angle—the angular distance between the transmitter and receiver LoS and the vertical—thus shortening the path through turbulence-prone atmospheric layers. This improves link quality by reducing signal degradation and enhancing transmission stability.

In sum, optimizing these interrelated parameters—FoV, AoA, average SNR, divergence angle, relay placement and beam width forms the foundation for realizing high performance, adaptive, and resilient FSO communication links in SAGINs. These efforts are indispensable to meet ever-growing demands of next-generation communication systems in terms of speed, reliability, and global coverage. Table 6 provides a comprehensive summary of recent studies that employ various parameter optimization strategies within different system models to improve the performance of FSO links in SAGINs. It highlights key impairments addressed, the corresponding performance metrics analyzed, and the specific parameters optimized to mitigate challenges and improve overall link reliability and efficiency.

The performance of FSO communication links within SAGINs is typically evaluated using a structured taxonomy of key performance metrics, broadly classified into five categories: reliability and quality, latency, capacity, energy, and security. Reliability and quality metrics, such as OP and BER, assess the system's ability to maintain robust connectivity and mitigate signal degradation induced by atmospheric turbulence and alignment errors. Latency metrics are essential for time-sensitive applications, aiming to reduce end-to-end transmission delays and enhance handover responsiveness across the network layers.

Capacity metrics—including Throughput, EC, and SE —focus on optimizing data transfer rates and maximizing spectrum utilization, which are crucial for high-bandwidth applications. Energy metrics, particularly relevant for energy-constrained nodes like UAVs and small satellites, evaluate EE to ensure sustainable operations. Lastly, security metrics evaluate the system's resilience against eavesdropping, jamming, and other cyber threats, capitalizing on the inherent directionality and low probability of interception in FSO links.

Fig. 11 illustrates this performance taxonomy, underscoring the criticality of each metric in ensuring the overall reliability and efficiency of FSO-based SAGINs. In recent literature, performance evaluations often isolate specific metrics. For instance, the study in [117] emphasizes OP and Average BER, while [118] expands the analysis to include SER and EC. Each of these metrics provides a unique lens on the system's behavior under varying channel and mobility conditions. For example, OP quantifies the likelihood of link failure under severe attenuation, while BER and SER offer insights into the fidelity of data transmission. Latency and throughput metrics capture responsiveness and channel utilization efficiency, respectively—both critical for real-time services.

4.1. Reliability and Quality Metrics Optimization

The reliability and quality of the signal are essential metrics for assessing the performance of FSO communication links in SAGINs. These metrics are critical for evaluating the system's ability to consistently deliver accurate, error-free data, particularly in challenging environments. Two primary indicators of reliability are OP and BER. Reducing these metrics substantially enhances the dependability of FSO communication links, ensuring optimal performance even under variable or adverse operational conditions.

Table 6
Summary of Recent Works Employing Various Parameter Optimization to Enhance the Performance of FSO Links in SAGINs

Ref.	System Model	Considered Impairments	Performance Analysis	Parameter Optimization
[9]	Space-Air-Ground FSO Links	- AT - Pointing Error - Beam scintillation	ASER	- Average SNR - Zenith Angle
[35]	Hovering UAV-Based FSO Communications	- Atmospheric loss - AT - Pointing error - AoA fluctuation	End-to-end OP	- Beam Width - FoV - UAVs' Locations
[36]	Hovering UAV-assisted FSO Links	- AT - PEs - AOA Fluctuations - Link Attenuation	OP, EC, BER	- Angle of FoV - Size of receiving Aperture - Beam Divergence Angle
[62]	Ground-air UAV assisted hybrid PLC/FSO	- AT - Pointing Error - Fog - AoA Fluctuations	ASER and OP	- FoV - Average SNR
[77]	UAV-based FSO links with CV-QKD	- AT - Attenuation - PEs	QBER, OP and SKR	- Transmit Power - Beam Divergence Angle - FoV
[114]	Ground-to-HAP FSO Link	- Attenuation Loss - AT - PEs - AOA Fluctuations	OP	- FoV - Beam width
[115]	Ground-Air-Space FSO Links	- Atmospheric Attenuation - Pointing Error - AOA Fluctuations - AT	OP	- HAPs Altitude - Zenith Angle
[116]	FSO-MIMO Communication System	- AT - PEs	BER, OP	- Beam Width - Average SNRs

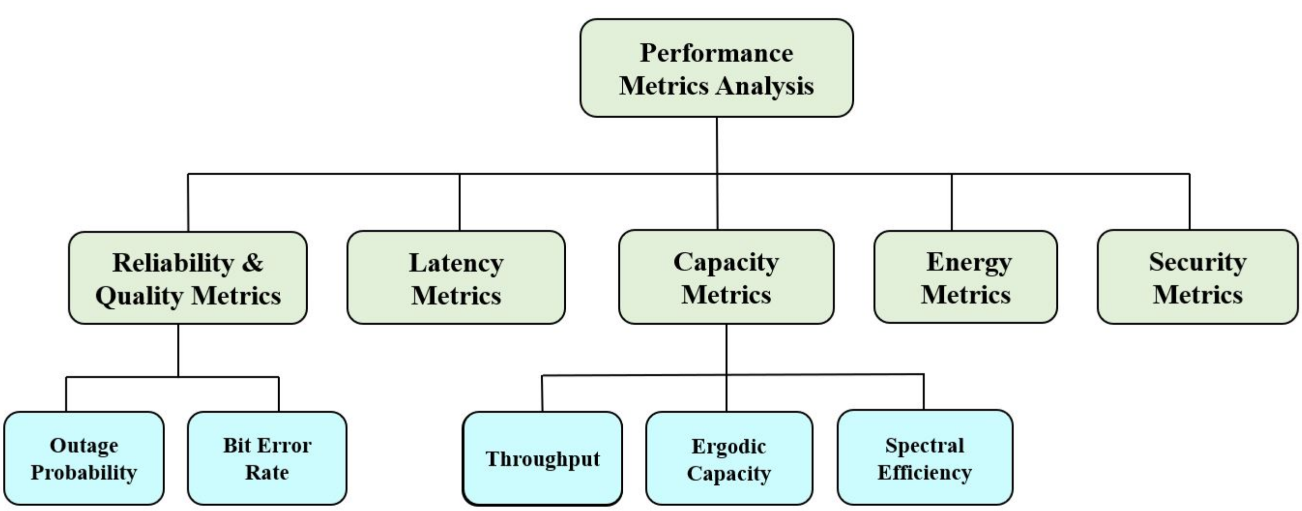

Fig. 11. Taxonomy of Performance Optimization Strategies for FSO Links.

4.1.1. Outage Probability (OP)

Outage probability is one of those key metrics for evaluating the performance of FSO communication systems. It quantifies the likelihood of a communication link failing or its signal quality dropping below acceptable performance thresholds due to adverse weather or physical obstructions. In FSO communication systems, the transmitted optical signals are received by a photodetector (PD), which captures and converts the incoming light, focused through a lens, into electrical signals [114]. The received optical signal $I[t]$ at the PD at time t is modeled as follows:

$$I[t] = \lambda g[t] T_x[t] + n, \tag{7}$$

where λ denotes the responsivity of the PD, $H[t]$ represents the channel gain coefficient, $T_x[t]$ is the transmitted symbol with power $P[t]$, and n is the additive signal-independent white Gaussian noise with variance σ_n^2. The instantaneous electrical SNR $\gamma[t]$ in the FSO system is therefore given by:

$$\gamma[t] = \frac{\lambda^2 g^2[t] P^2[t]}{\sigma_n^2}. \tag{8}$$

P_{out} is the probability (p_r) that the instantaneous SNR falls below a predefined threshold γ_{th}, which denotes the minimum acceptable communication quality [119, 120]. Mathematically, it can be expressed as:

$$P_{\text{out}} = P_r\{\gamma[t] < \gamma_{\text{th}}\}. \tag{9}$$

where the likelihood of the instantaneous SNR (γ) is less than or equal to the predefined threshold γ_{th}. By rearranging the SNR expression, the corresponding threshold for the channel gain coefficient g_{th} can be derived as:

$$g_{\text{th}} = \frac{\sqrt{\gamma_{\text{th}} \sigma_n^2}}{\lambda P[t]}. \tag{10}$$

Since γ_{th} is a monotonically increasing function of g_{th}, the OP can equivalently be expressed in terms of the probability density function (PDF) of the channel gain g:

$$P_{\text{out}} = \int_0^{g_{\text{th}}} f_g(g)\, dg, \tag{11}$$

Or in terms of SNR:

$$P_{\text{out}} = \int_0^{\gamma_{\text{th}}} f_\gamma(\gamma)\, d\gamma \tag{12}$$

where $f_\gamma(\gamma)$ and $f_g(g)$ denote PDF of γ and g, respectively.

A lower OP indicates a more reliable and resilient communication link, making it essential for ensuring system reliability, especially under varying atmospheric conditions [10, 121]. FSO system designers establish the OP threshold to define the maximum permissible failure probability, ensuring the communication system maintains satisfactory performance even under adverse conditions. Minimizing OP is essential for reliable communication.

The study in [33] introduces an optimization framework to enhance the reliability of FSO backhaul links in non-terrestrial networks by minimizing the probability of simultaneous link outages caused by cloud blockage. Focusing on a multi-HAP deployment scenario, the framework models the slant distance d_l between HAPs and GS as a function of the horizontal distance d_u and average node altitudes. By incorporating cloud statistics—such as spatial correlation and attenuation—the authors use a bivariate Gaussian model to capture the joint outage probability $P_{out,c}$ across multiple links. The optimization problem aims to find the optimal d_u that minimizes $P_{out,c}$, subject to $d_l \geq 0$, and is solved using a generalized Lagrange multiplier method:

$$\text{(P1)} \quad \min_{d_u} P_{out,c}, \tag{13}$$

$$\text{subject to} \quad d_l \geq 0 \tag{C1}$$

This cloud-aware HAP positioning strategy significantly enhances system robustness in dynamic atmospheric conditions. As shown in Fig. 12, the model captures key geometrical relationships among slant distance, elevation angle θ, cloud height, and HAP altitude. The figure highlights how cloud layers obstruct LoS paths, reinforcing the importance of optimizing HAP placement to reduce link outages.

Results confirm that adjusting d_u effectively modifies the elevation angle, thereby lowering the likelihood of simultaneous cloud-induced link failures—a critical factor for 6G FSO backhaul reliability. The dynamic HAP positioning scheme consistently outperforms fixed-placement strategies, especially under varying cloud conditions and transmit power levels. However, the study does not explore the impact of a broader altitude range for HAPs or the potential integration of UAVs as LAPs. Additionally, a key limitation is the absence of joint optimization involving OP, transmit power, or EE, which is essential for energy-constrained aerial platforms. Future work addressing these aspects could further enhance system adaptability, sustainability, and performance.

Similarly, the study in [122] introduces a dual-hop SAG-FSO transmission scheme. This scheme employs either multiple HAP relays, as shown in Fig. 13(a), or site diversity techniques, illustrated in Fig. 13(b), with the aim of reducing OP and enhancing the reliability of FSO links in SAGINs. However, the analysis does not account for the impact of zenith angles between the HAP and the ground station, which can critically influence link performance due to geometric alignment and atmospheric path length. In contrast, studies such as [9] and [115] incorporate the effect of zenith angles and report improved OP performance, thereby demonstrating the importance of angular optimization in enhancing the overall efficiency of FSO links. Nevertheless, these studies operate under the assumption that the HAP can always be deployed at a fixed, low zenith angle (e.g., $0° or \leq 5°$) relative to the ground station. In practice, such assumptions may not hold due to geographic constraints, airspace

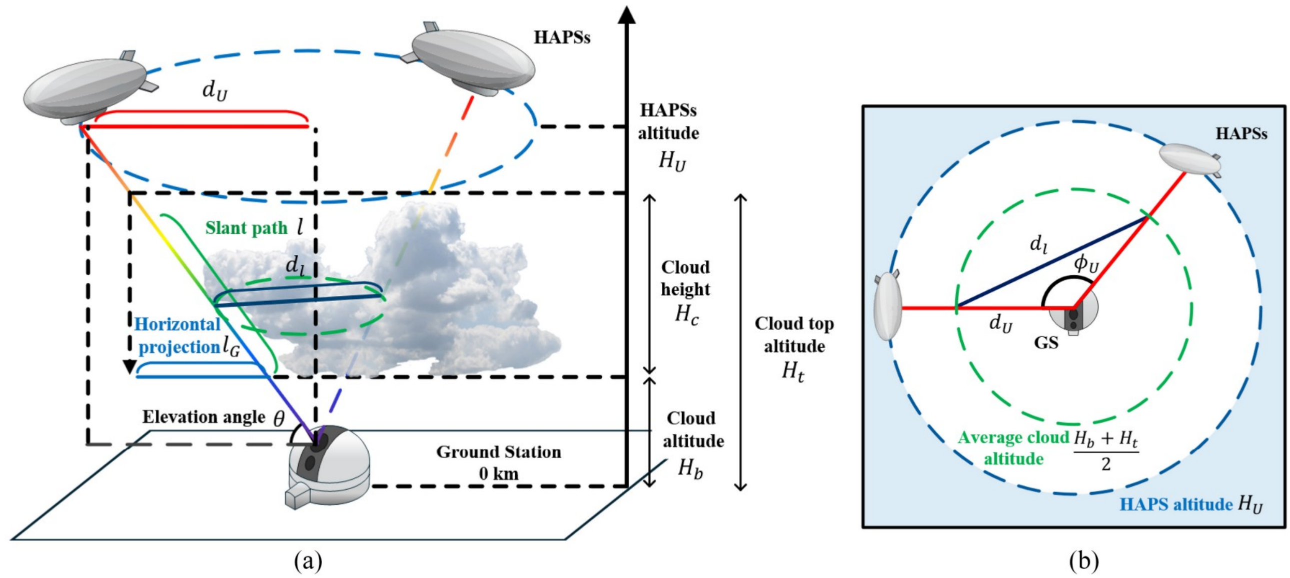

Fig. 12. Geometrical representation of the SAGIN-FSO communication model: (a) vertical system geometry illustrating slant path, elevation angle, and cloud layers between a HAP and ground station, and (b) horizontal projection showing the angular separation and link distances between the ground station and multiple HAPs [33].

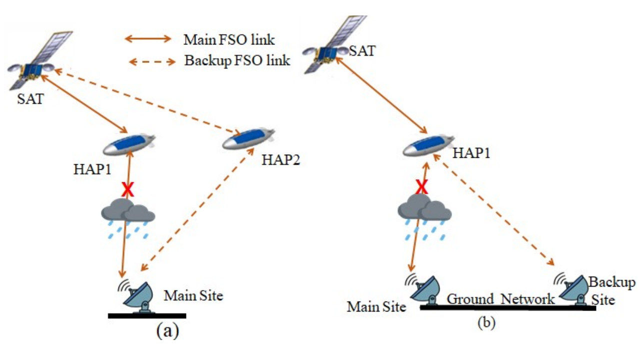

Fig. 13. SAG-FSO Transmission (a) With Multiple HAP Relays and (b) With Site Diversity.

regulations, or deployment feasibility, limiting the practicality of fixed-angle configurations. Additionally, the proposed SAG-FSO systems effectively mitigate atmospheric turbulence and weather-induced attenuation, they rely on a fixed transmission strategy with hard switching and do not optimize energy efficiency or transmit power. To improve adaptability under dynamic weather and network conditions, future research should investigate the joint optimization of OP and EE. Leveraging techniques such as multi-objective optimization, deep reinforcement learning, or model predictive control (MPC) could enable intelligent power control and switching strategies for enhanced performance in 6G satellite networks.

Furthermore, studies have found that HAP-assisted links improve reliability compared to direct ground-to-satellite connections [115], and UAV multi-hop relaying systems reduce OP, particularly with optimization of beamwidth and FoV [123, 124]. Additional research, such as in [125], explored UAV-based dual-hop FSO systems and opportunistic relay selection models, further improving performance under turbulence.

Another recent study in [65] demonstrated that larger apertures improve performance in adverse weather by increasing the SNR and mitigating scintillation and fading. However, practical considerations, such as system weight and alignment challenges, particularly for mobile platforms like satellites and UAVs, must also be addressed. Despite the advantages demonstrated, the study overlooks critical factors such as the impact of transmit power and EE on overall system performance. These omissions highlight a broader research gap in the literature—namely, the lack of comprehensive analyses that jointly consider reliability, power consumption, and energy constraints. Future research should aim to bridge this gap by incorporating holistic performance evaluations that account for the intricate trade-offs between link quality, power budget, system weight, and operational sustainability. In contrast, the shape of the aperture, such as elliptical-apertures, can also have a significant impact OP by influencing beam collection efficiency and diffraction effects [126].

In [127], the performance of FSO links using various HARQ protocols, such as at least once (ALO), chase combining (CC), and incremental redundancy (INR) - is analyzed under GG AT and PEs. The study adopts information-theoretic outage probability formulations, where an outage occurs if mutual information does not exceed the target transmission rate R after N transmission rounds. In the ALO protocol, the receiver decodes only the most recent packet, and the mutual information in the i-th round is:

$$I_{\mathrm{ALO}}(i) = \log_2(1 + \gamma_i), \tag{14}$$

leading to the OP:

$$P_{\text{out,CC}}(N) = \Pr\left\{\log_2\left(1+\sum_{i=1}^{N}\gamma_i\right) \le R\right\} \tag{15}$$

$$= \Pr\left\{\sum_{i=1}^{N}\gamma_i \le 2^R - 1\right\}. \tag{16}$$

In CC, the transmitter repeats the same packet, and the receiver combines received signals via maximum ratio combining (MRC). The accumulated mutual information is:

$$I_{\text{CC}}(N) = \log_2\left(1+\sum_{i=1}^{N}\gamma_i\right), \tag{17}$$

with outage probability:

$$P_{\text{out,CC}}(N) = \Pr\left\{\log_2\left(1+\sum_{i=1}^{N}\gamma_i\right) \le R\right\} \tag{18}$$

$$= \Pr\left\{\sum_{i=1}^{N}\gamma_i \le 2^R - 1\right\}. \tag{19}$$

In INR, each retransmission adds new parity bits, and mutual information accumulates as:

$$I_{\text{INR}}(N) = \sum_{i=1}^{N}\log_2(1+\gamma_i), \tag{20}$$

yielding outage probability:

$$P_{\text{out,INR}}(N) = \Pr\left\{I_{\text{INR}}(N) \le R\right\}. \tag{21}$$

While ALO evaluates only the latest packet, CC and INR protocols aggregate information across rounds. Among these, INR shows superior reliability by effectively accumulating mutual information, making it well-suited for turbulence- and PE-impaired FSO environments. However, the analysis is limited by its focus on only two conventional detection methods and does not consider advanced detection techniques or account for OP under the joint impact of atmospheric turbulence and nonzero boresight pointing jitter.

Hybrid FSO/RF systems employing adaptive combining techniques have demonstrated significant potential in enhancing link reliability by dynamically switching between FSO and RF links based on SNR, thereby reducing OP and improving overall performance [128]. Building on this concept, satellite-terrestrial mixed FSO/RF systems with AF and DF relaying, as examined in [118], further illustrate the effectiveness of cooperative transmission in mitigating link degradation and boosting system robustness.

A more advanced hybrid FSO/RF SAGIN system is proposed in [69], aiming to improve OP under adverse conditions such as cloud-induced attenuation, outdated CSI, and co-channel interference. Even with the application of site diversity techniques—such as utilizing backup ground stations (Fig. 14(a)) or deploying additional HAPs (Fig. 14(b))—FSO links may still suffer from intermittent blockages. In such scenarios, integrating RF links as a fallback path enhances the system's resilience and ensures uninterrupted communication. This study relies on outdated CSI for both FSO and RF links, which may not capture the dynamic nature of real-world SAGIN environments, potentially leading to suboptimal performance and reduced diversity gain. Additionally, the analysis is limited to OP and EC, lacking evaluation of critical performance dimensions such as latency, EE, and QoS, which are vital for mission-critical applications in SAGINs.

Furthermore, the integration of non-orthogonal multiple access (NOMA) and dual energy harvesting (EH) mechanisms into hybrid FSO/RF communication systems has demonstrated notable improvements in OP and throughput, as highlighted in [129]. These advancements enhance the viability of hybrid FSO/RF architectures for next-generation SAGIN deployments, where reliability, efficiency, and adaptability are critical. However, the study is constrained by its reliance on a single-hop communication model, without exploring multi-hop or cooperative relaying extensions. Although interference is considered, essential aspects such as physical layer security and active interference cancellation are overlooked—an important limitation in shared-spectrum environments. Moreover, the dual-mode EH system operates under fixed power-splitting and time-switching parameters, without dynamic adaptation to varying channel conditions, thereby restricting the system's responsiveness and real-world applicability.

4.1.2. Bit Error Rate (BER)

Bit error rate is another critical metric for evaluating the performance of FSO communication systems in SAGINs. It measures the reliability and accuracy of a communication system by quantifying the ratio of erroneous bits received to the total number of bits transmitted [120]. BER serves as a direct indicator of signal integrity and reflects the overall quality of the communication link, which is especially important in systems like FSO communication and SAGINs, where maintaining high-quality data transmission is essential. IT can be expressed as [120, 130]:

$$P = P(0)P(e|0) + P(1)P(e|1) \tag{22}$$

where $P(0)$ and $P(1)$ represent the probability of transmitting a bit of "0" and "1," respectively, and P(e|1) and P(e|0) denote the conditional bit error probabilities for transmitting bits of "0" and "1". Precise bit detection is essential for successful data transmission, and controlling fluctuations in received signal intensity is key to achieving a lower BER. A lower BER indicates higher accuracy and data integrity, substantially enhancing communication effectiveness, especially in dynamic and challenging environments.

Another version of BER is average BER (ABER), which represents the mean value of the BER over time or across different communication conditions. This metric is essential for evaluating long-term reliability and robustness, providing a clearer picture of how the communication link performs

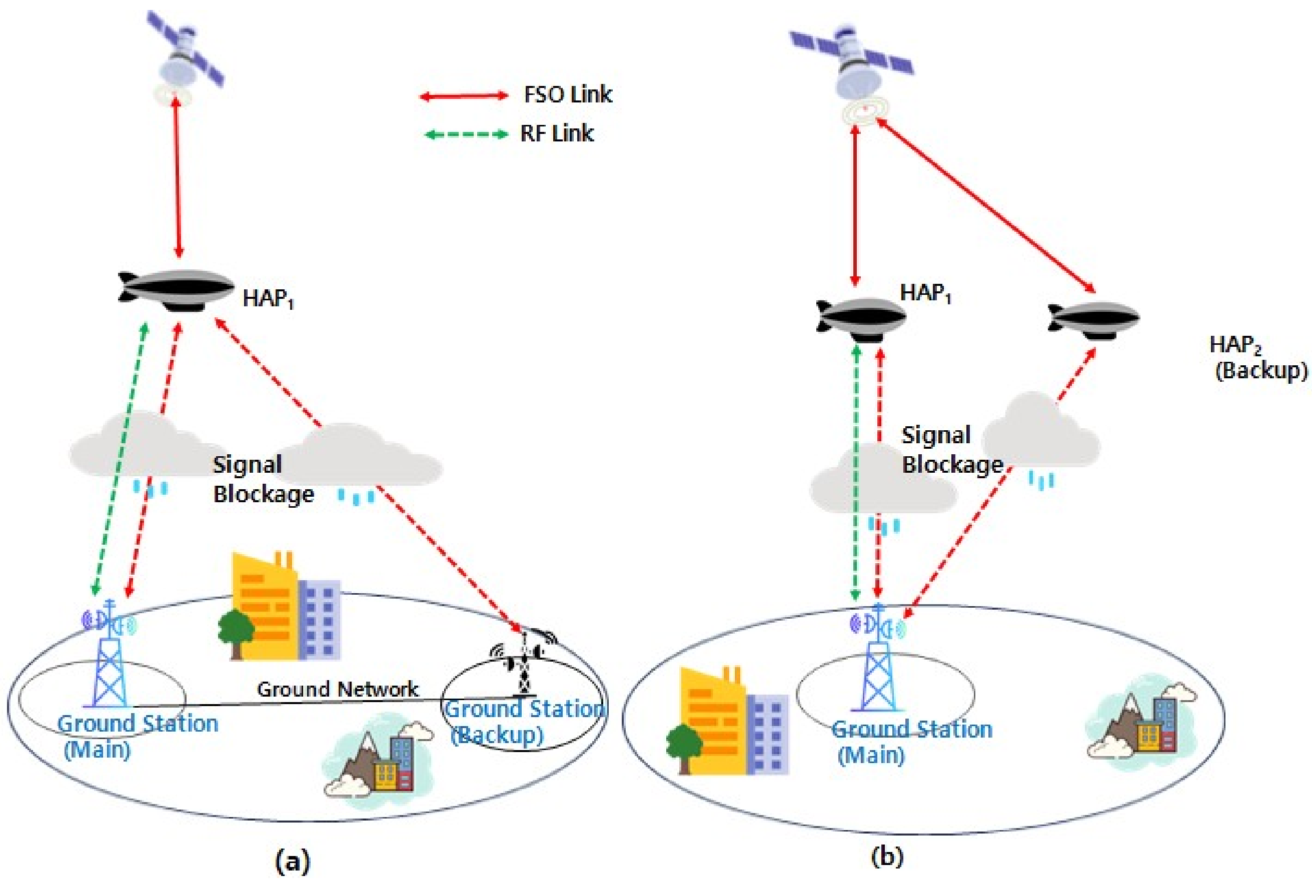

Fig. 14. Hybrid FSO/RF Systems (a) Employing a Relay Scheme with Site Diversity and Multiple HAPs and (b) a Relay Scheme with Multiple HAPs.

under varying conditions. In FSO communication systems, ABER is crucial for assessing communication reliability and effectiveness [131]. Unlike instantaneous BER, which measures bit errors at specific points in time, ABER offers a more stable and comprehensive view of error performance over time. This helps system designers evaluate overall performance, identify areas for improvement, and optimize network parameters to ensure reliable data transmission while smoothing out the impact of transient fluctuations. The ABER for each wavelength link within a diversity scheme can be expressed by averaging the received signal intensity (I_r) as follows [130]:

$$\int_0^\infty P_r(I_r) f_{I_r}(I_r) dI_r \tag{23}$$

where $f_{I_r}(I_r)$ represents PDF of the received signal intensity modeled by the GG distribution, and dI_r-denotes the differential in the received signal intensity (I_r).

Similarly, SER is another critical metric closely related to BER. It measures the probability that a transmitted symbol—representing multiple bits—is incorrectly received. While BER focuses on bit-level accuracy, SER operates at the symbol level, making it particularly relevant for systems using modulation schemes such as QPSK and QAM, where each symbol carries multiple bits. SER thus provides a broader view of system performance in modulated systems, complementing the insights from BER. In summary, BER provides a snapshot of bit-level transmission accuracy, ABER gives a long-term performance perspective, and SER extends the analysis to symbol-level accuracy. These metrics are fundamental for evaluating communication system effectiveness. Several factors impact BER, ABER, and SER in FSO systems, including AT, PEs, scattering and absorption from fog, rain, or dust, multipath interference in hybrid systems, hardware imperfections, and channel fading. These challenges degrade signal quality, increase error rates, and reduce communication reliability. Addressing these challenges is essential for performance enhancement, and various studies have developed strategies to optimize BER, ABER, and SER in FSO systems.

Recent studies have highlighted several techniques for minimizing BER and improving the reliability of FSO communication systems, particularly under challenging conditions. In [80] and [83], ECC techniques like FEC-coded and polar-coded 32QAM systems were shown to reduce BER and enhance performance by optimizing constellation shaping.

However, both are limited by assumptions of ideal channel conditions, excluding critical real-world impairments such as pointing errors, beam misalignment, and moderate-to-strong atmospheric turbulence. Their evaluations are confined to short-range, controlled environments and fixed transmission settings, lacking consideration for dynamic link adaptation, mobility, and scalability. Moreover, neither study addresses higher-layer integration challenges essential for deployment in complex or mobile FSO-SAGIN environments. Similarly, in [132], a multilevel polar-coded PAM-8 system demonstrated significant shaping gains, improving transmission efficiency in turbulent FSO channels. Advanced coding techniques, such as GC-LDPC codes and MRC, were employed in a mixed MIMO-FSO/MIMO-RF relaying system to improve BER under high turbulence [96]. Deep learning-enhanced LDPC codes, studied in [81], reduced BER in a mixed RF-FSO DF relay system, while BCH codes, especially when combined with repetition codes, improved BER in GG-faded FSO links [105]. Additionally, in [133], LDPC-coded multi-hop FSO systems using a DF strategy improved system reliability by addressing ABER over Gamma fading channels. These studies share several limitations, notably their focus on BER performance under idealized conditions while neglecting practical challenges such as pointing errors, hardware imperfections, and environmental variability. The GC-LDPC-based system overlooks decoding complexity and real-time implementation concerns, whereas the LDPC-coded multi-hop FSO model does not address energy efficiency or relay selection. Likewise, the study on BCH and repetition codes is restricted to basic coding schemes and single-hop scenarios, without considering adaptive coding, beam misalignment, or cooperative relaying. Collectively, these works lack attention to system-level adaptability, hybrid architecture integration, and scalability—factors that are critical for deploying reliable and efficient RF/FSO and SAGIN systems in dynamic, real-world environments.

Modulation schemes, diversity techniques, and adaptive strategies are critical for enhancing the bit error rate (BER) performance in FSO systems. Studies such as [131] and [134] demonstrate that approaches like spatial shift keying (SSK) with switch-and-examine combining (SEC), and BPSK-modulated MISO links with optimal combining (OC) or equal gain combining (EGC), can significantly improve BER under Gamma-Gamma turbulence. BPSK, in particular, is widely used for ground-to-satellite and UAV-to-satellite optical links due to its strong sensitivity and resilience. The BER for BPSK depends on the received optical intensity and detector noise, with average BER computed by integrating over the intensity distribution of the received signal for both uplink and downlink scenarios. Analytical and experimental evaluations highlight several key insights: higher UAV altitudes mitigate turbulence effects; optimal beam divergence angles exist for fixed transmit power and receiver aperture; and design trade-offs must consider payload constraints on receiver aperture sizes and power limitations, especially on UAVs. These findings provide practical guidance for designing robust and efficient FSO links in UAV-satellite communication systems.

Studies such as [135] explored multiple transmitters in gain-saturated FSO systems to improve BER in strong AT and PEs. Hybrid modulation schemes, such as PPM with BPSK-SIM and spatial diversity techniques such as EGC and MRC, were shown to reduce BER, especially in adverse weather conditions [136]. The time diversity schemes, explored in [130], transmitted redundant data across multiple time intervals, applying MRC to lower BER in turbulent channels.

An intelligent reflecting surface (IRS)-assisted FSO communication system is investigated in [137] to address the performance degradation resulting from random beam misalignment. The authors develop a comprehensive mathematical framework that models the effects of random PEs, specifically incorporating displacement uncertainties at both the IRS and the PD receiver. To quantify system performance, PDF of the received optical irradiance is derived, enabling the evaluation of critical metrics such as BER and OP. The analysis reveals that random beam non-orthogonality, when the reflected laser beam deviates from the optimal incident angle, significantly degrades the received power and BER, particularly when the beam exits the receiver's FoV. To mitigate these effects, the study proposes an optimization strategy to determine the optimal placement and orientation of the IRS, aimed at minimizing BER and OP in various misalignment and channel scenarios. Although the proposed IRS-assisted architecture shows notable improvements in link robustness under static misalignment conditions, the model assumes ideal reflection characteristics and does not incorporate dynamic considerations such as platform mobility, IRS control in real-time, or hardware constraints. These limitations highlight promising directions for future research, including the development of adaptive IRS control strategies, robust deployment in mobile environments, and the integration of machine learning-based optimization techniques.

Furthermore, wavelength division multiplexing (WDM) was assessed in [138]and [139], showing that it maximizes bandwidth, enhances throughput, and supports error correction in challenging conditions. BER can be further enhanced by applying various modulation techniques [140], which have been explored and analyzed in existing studies. Some of these modulation techniques are summarized in Table 7. Adaptive modulation and coding (AMC) techniques, as discussed in [141], dynamically adjust modulation schemes and coding to optimize data transmission and minimize BER under varying channel conditions. This adaptability allows for efficient communication and reduced BER, ensuring reliable performance across diverse environments.

In [62], the performance of FSO links is analyzed in terms of ASER, OP, and average channel capacity (ACC) for an AAV-assisted hybrid PLC–FSO communication system employing DF and AF relaying schemes. The study considers a dual-phase hybrid architecture that integrates power line communication (PLC) and FSO technologies. In the first phase, the source (S) transmits data to the relay (R) over a PLC link. In the second phase, the relay converts the received data into an optical signal and forwards it to an autonomous aerial vehicle (AAV) via an FSO link using either a DF or AF protocol. To enhance system performance, the analysis

Table 7
Summary of Modulation Techniques used for Optimizing BER

Ref.	Year	Modulation Type	Remarks
[85]	2020	NRZ, RZ variants	chirped NRZ and CSRZ-67% improve BER performance.
[89]	2020	BPSK, DPSK, QPSK	BPSK modulation outperforms (BER of 10^{-9}).
[140]	2023	NRZ-MSK-PSK	Hybrid modulation combining NRZ, MSK, and PSK investigated.
[142]	2023	Full-duplex OFDM	Full-duplex 40/40Gbps OFDM-based FSO-fiber used.
[143]	2023	DP-QPSK	DP-QPSK-based FSO outperforms than NRZ binary modulation.
[144]	2023	DPSK, PSK, CSRZ, NRZ	DPSK has better performance over a specified distance.
[145]	2023	NRZ and RZ	RZ modulation technique outperforms NRZ in FSO systems.
[146]	2024	RZ-DQPSK	RZ-DQPSK has better performance.
[147]	2024	Modified Hierarchical	High-priority data stream is sent via RF & low-priority sent via FSO.

incorporates strategic optimization of parameters such as the FoV angle and average SNR, targeting objectives such as minimizing ASER and maximizing channel capacity. For the DF relaying protocol, the ASER of the system is expressed as:

$$p_{aser}^{\mathrm{DF}} = p_{aser}^{\mathrm{SR}} + p_{aser}^{\mathrm{RD}} - 2p_{aser}^{\mathrm{SR}} p_{aser}^{\mathrm{RD}}, \tag{24}$$

where p_{aser}^{SR} and p_{aser}^{RD} denote the ASERs of the PLC and FSO links, respectively. The ASER for M-PSK modulation over the FSO link is calculated as:

$$p_{aser}^{\text{M-PSK}} = \int_0^\infty p_{aser}^{\text{M-PSK}}(\gamma) f_\gamma(\gamma)\, d\gamma, \tag{25}$$

where for $M > 2$, $p_{aser}^{\text{M-PSK}}(\gamma) \approx \operatorname{erfc}(\sin(\pi/M)\sqrt{\gamma})$. The conditional SER can also be expressed using Meijer's G-function as:

$$p_{aser}^{\text{M-PSK}}(\gamma) = \frac{1}{\sqrt{\pi}} G_{2,1}^{1,2}\left(\sin^2(\pi/M)\gamma \,\middle|\, \begin{matrix} 1 \\ 0.5, 1 \end{matrix}\right). \tag{26}$$

The OP analysis under the DF scheme is obtained by setting $\gamma = \gamma_{\mathrm{th}}$, such that:

$$P_{\mathrm{out}}^{\mathrm{DF}} = F_\gamma(\gamma_{\mathrm{th}}). \tag{27}$$

For the AF relaying scheme with fixed gain, the ASER is:

$$p_{aser}^{\mathrm{AF}} = \int_0^\infty p_{aser}^{\text{M-PSK}}(\gamma) f_{\gamma_{\mathrm{AF}}}(\gamma) d\gamma, \tag{28}$$

and the corresponding OP is given by:

$$P_{\mathrm{out}}^{\mathrm{AF}} = F_{\gamma_{\mathrm{AF}}}(\gamma_{\mathrm{th}}). \tag{29}$$

Results indicate that in the AF scheme, ASER and OP performance improve in low-SNR conditions using the IM/DD technique, while the HD technique performs better at high SNR. Compared to DF, the AF scheme yields better ASER, OP, and ACC performance, though it degrades under high impulsive noise levels. The analysis also shows that while the diversity gain of DF relies only on the detection technique, the diversity order of AF depends on both the detection technique and the PLC link's shaping parameters. Optimal values of FoV and average SNR were determined to minimize ASER in DF relaying. Despite these contributions, the proposed model does not consider Doppler shifts induced by AAV mobility, it assumes ideal synchronization between the PLC and FSO components, and does not incorporate dynamic adaptation mechanisms. Addressing these limitations would enhance the adaptability, robustness, and overall efficiency of the hybrid communication architecture.

In conclusion, the application of advanced coding schemes, modulation techniques, and adaptive strategies is crucial for minimizing BER and enhancing the reliability of FSO communication systems, especially in challenging environments. The integration of methods such as adaptive modulation and coding, LDPC codes, and hybrid FSO-RF systems is vital for improving overall system performance, ensuring efficient, and reliable communication in next-generation networks.

4.2. Latency Metrics

Latency is a key metric for assessing the performance of FSO communication in SAGINs, as it measures the delay in data transmission and the system's ability to adapt swiftly to changing network conditions. Defined as the time interval between sending and receiving a signal, latency is influenced primarily by the travel time of optical signals through the atmosphere, which depends on distance and atmospheric conditions. Low latency ensures real-time communication and system efficiency, particularly in dynamic environments where rapid adaptation is necessary for reliable performance. While FSO communication offers high data transfer rates, AT, and scintillation can cause latency fluctuations. This metric is essential for evaluating communication efficiency in SAGINs, especially for low-latency applications such as high-frequency trading, military operations [148], and real-time communications like video conferencing and voice calls. Latency can be categorized into four main types of delay, defined as follows:

1. ***Propagation delay:*** Also known as link latency, this is the time it takes for a signal to travel through the transmission medium, such as air or space, from one point to another. It depends on the medium's characteristics and the distance traveled. In FSO satellite networks, the propagation delay of a link can be calculated using

the formula [119]:

$$T_{\text{Prop}}^{(l)} = \frac{d_l}{C_l} \tag{30}$$

where d_l is the distance of propagation between the transmitter and receiver satellites, and C_l represents the speed of light. This formula provides a quantitative means of calculating propagation delay based on distance and the constant speed of light.

2. ***Transmission delay:*** This occurs during the transmission of data packets across the network and includes the time taken by the source node to prepare and send the data and the propagation time through the optical link. In FSO satellite networks, transmission delay can be computed using the following formula [119]:

$$T_{\text{tra}}^{(l)} = \frac{D_l}{R_l} \tag{31}$$

where D_l represents the packet length or transmitted data size and R_l denotes the transmission rate of the laser connection. Transmission delay decreases substantially with an exceedingly high link data rate.

3. ***Queuing delay:*** The queuing latency is the time spent by a packet in the output buffer, waiting (queuing) before being transmitted over the link [149, 150, 151]. This delay depends on the number of packets queued for transmission and is directly influenced by the traffic load and the average packet arrival rate. Using the M/M/1 queuing model [152], the queuing latency is expressed as [149]:

$$T_{Que}^{(l)} = \sum_{l=1}^{N} \omega_l T_l, \tag{32}$$

where $\omega_l = \frac{\lambda_l}{c_l}$ represents the load on the l^{th} link, T_l is the average system (link or node) delay for the l^{th} hop, λ_l denotes the average external packet arrival rate (in packets per second) on the l^{th} link, and c_l is the service capacity or link throughput of the l^{th} hop. N is the total number of links or nodes (hops) along the data transmission path.

4. ***Processing delay:*** Processing latency refers to the time required for hardware and software components—such as network interfaces, applications, and protocol stacks—to inspect and process packets [149, 150, 151]. This delay arises from layer-wise interactions within the network stack during packet-switching operations. Although generally minimal due to the high processing capabilities of modern devices, this latency can still contribute to overall transmission delay, especially in resource-constrained environments. The processing latency is mathematically defined as the ratio of the buffer size B_s (in bits) to the device's processing speed C_P (in bits per second), given by:

$$T_{\text{Proc}} = \frac{B_s}{C_P} \tag{33}$$

This equation quantifies the delay incurred while parsing and handling each packet prior to its transmission.

Network latency refers to the end-to-end delay experienced between the transmitter and receiver GSs within a given time slot [119]. It encompasses the cumulative effect of multiple latency components, including propagation delays across the downlink, uplink, and inter-satellite links (ISLs), as well as node delays associated with each satellite along the optimal routing path. The total network latency can be expressed as:

$$T_{\text{total}} = \sum_{l \in \mathcal{L}} \left(T_{\text{prop}}^{(l)} + T_{\text{tra}}^{(l)} + T_{\text{que}}^{(l)} + T_{\text{proc}}^{(l)} \right) \tag{34}$$

where $\mathcal{L}$ denotes the set of all links (uplink, downlink, and ISL) along the path.

Minimizing the total latency is vital for enabling reliable, low-latency communications, particularly in delay-sensitive applications such as autonomous control, remote surgery, and real-time surveillance. The latency minimization objective can be formulated as:

$$\min_{\text{path}} \quad T_{\text{total}} = \sum_{l \in \text{path}} \left(\frac{d_l}{C_l} + \frac{D_l}{R_l} + T_{\text{que}}^{(l)} + \frac{B_S}{C_P} \right) \tag{35}$$

Achieving low-latency performance while preserving the inherent advantages of FSO communication—such as ultra-high data rates, enhanced security, and resistance to electromagnetic interference—is essential for the future of SAGIN-enabled next-generation networks.

Numerous studies have explored latency minimization in network performance. For instance, in [153], the latency of optical wireless satellite networks (OWSNs) was compared to optical fiber terrestrial networks (OFTNs) using the Starlink Phase 1 constellation, showing that OWSNs outperformed OFTNs in latency, particularly over long distances. Similarly, [154] introduced the concept of crossover distance, determining when switching from OFTN to OWSN results in lower latency. The authors found that the crossover distance is influenced by factors like optical refractive index, propagation distance, and satellite altitude. In [149], various latency models for end-to-end networks were discussed, proposing a model for ISLs and uplink/downlink connections. Strategies for minimizing latency in multi-hop satellite links were explored in [155], where a nearest-neighbor search algorithm was proposed, achieving near-optimal latency.

Additionally, [156] demonstrated that the Starlink Phase 1 constellation offers reduced latency compared to terrestrial optical fiber networks over distances greater than 3,000 km. Studies like [157] and [158] focused on improving latency by managing satellite network topologies and addressing queuing and processing delays in ISLs, respectively. The impact of LISL range on latency was analyzed in [159], and a mathematical model was presented in [160] to minimize latency in FSO satellite networks, considering constraints like satellite transmit power. Furthermore, in [161], the use of drone base stations (DBS) was explored to reduce latency for ground users by offloading traffic from macro base stations, optimizing user association, bandwidth allocation, and DBS placement.

Finally, [162] examined the collaboration between wireless edge caching and rate splitting multiple access (RSMA) to minimize average latency by reducing redundant interference. These studies underscore the importance of optimizing system parameters such as link design, satellite altitude, and coding techniques to improve efficiency and meet quality-of-service requirements.

4.3. Performance and Capacity Metrics

Performance and capacity metrics in FSO-based networks are essential for evaluating the system's data transmission efficiency and ability to meet user demands. These metrics focus on assessing overall throughput, data-carrying capacity, and resource utilization efficiency within the network. The metrics in this category include throughput, EC, and SE.

4.3.1. Throughput

Throughput in FSO-based networks refers to the total amount of data successfully transmitted over the communication link within a specified time frame, typically measured in bits per second (bps). It is a critical performance metric for determining the network's capacity to handle data traffic, with higher throughput indicating the ability to process and deliver large volumes of data efficiently. This is particularly important for supporting bandwidth-intensive applications like video streaming, cloud services, and real-time communication.

The performance of FSO communication systems is evaluated in terms of throughput under GG atmospheric turbulence and the impact of PEs, considering various HARQ protocols, as discussed in [127]. Throughput is the average rate at which data is successfully delivered to the receiver, serving as a key metric for assessing the effectiveness and reliability of the communication link. The throughput for an H-ARQ protocol is mathematically defined as:

$$\alpha = \frac{R(1 - P_{\text{out}}(N))}{\left(1 + \sum_{n=1}^{N-1} P_{\text{out}}(n)\right)}, \tag{36}$$

where R is the raw data rate, $P_{\text{out}}(n)$ represents the outage probability after n transmission rounds, and N is the maximum number of allowed retransmissions. This formulation captures the trade-off between reliability and efficiency, as it accounts for the degradation in throughput due to multiple retransmission attempts. The maximum throughput can be achieved by maintaining an optimal balance between the transmission rate and the SNR for a given number of transmission rounds.

Throughput in FSO systems can be impacted by several factors, including atmospheric conditions such as fog and turbulence, link alignment, and the availability of alternative communication pathways. Optimizing throughput ensures that networks maintain robust data transmission rates and meet user demands despite these environmental challenges.

Several studies have focused on maximizing throughput in FSO systems. In [163], throughput maximization was explored in a mixed FSO/RF UAV-assisted mobile relaying system, where buffer limitations and delay constraints were considered. The study employed a successive optimization algorithm to address transmission rate imbalances under varying weather conditions. In [9] and [122], the authors combined SAG FSO transmission with site diversity to enhance throughput capacity, deploying FSO relays on HAPs positioned above GSs to mitigate AT and weather-related disruptions. A hybrid SAG-FSO/RF transmission system with multiple HAP relays was also proposed to optimize throughput by switching between HAPs based on channel quality.

Additionally, in [164], a framework was developed to assess the performance of TCP throughput on satellite-to-vehicle links under congestion losses and transmission errors. The use of the link-layer IR-HARQ protocol helped enhance TCP throughput in satellite-to-UAV channels. Similarly, in [106], the authors explored link-layer error-control solutions for HAP-aided relaying in satellite FSO systems, proposing a cooperative IR-HARQ protocol to improve throughput and frame delay in turbulence-fading channels, further optimizing network performance in the context of the Internet of Vehicles.

In conclusion, optimizing throughput in FSO-based networks is essential for supporting high-bandwidth applications, and several techniques, such as site diversity, hybrid systems, and error-control protocols, have proven effective in enhancing throughput performance under varying conditions. These advances contribute to more efficient and reliable FSO systems, vital for future communication infrastructures.

4.3.2. Ergodic Capacity (EC)

Ergodic capacity is a fundamental metric in FSO-based SAGINs that provides an average view of the data rate attainable over time under varying channel conditions. Unlike instantaneous metrics, EC incorporates statistical variations in the channel, offering a comprehensive system performance assessment. This is especially valuable in dynamic FSO environments where atmospheric conditions fluctuate constantly. By accounting for factors such as AT and fading, EC helps optimize system parameters and modulation techniques. System engineers use EC to ensure reliable and consistent data transmission, which is essential for remote sensing and surveillance applications. Asymptotic expressions for EC are often derived based on SNR and channel characteristics, with high and low SNR asymptotic analyses being commonly used. In the high SNR asymptotic, the received signal power substantially surpasses the noise power. Given a channel bandwidth B, the ergodic capacity C, expressed in bits per second, can be calculated using the expression [165, 166]:

$$C = B\log_2(1 + \mathrm{SNR}) \tag{37}$$

where SNR denotes the signal-to-noise ratio. This formula captures the fundamental relationship between channel capacity, bandwidth, and signal quality.

Several recent studies have explored strategies for optimizing EC, as detailed in [74, 165, 167, 168, 169]. In [165], the authors analyzed EC upper bounds and asymptotic approximations for UAV-based FSO links, considering two detection methods—IM/DD and HD—across high and low SNR regimes. Their findings revealed that stronger PEs (greater jitter) and heavier fog conditions significantly degrade performance, while shorter link lengths and reduced PEs enhance the system's ergodic capacity. Similar study in [74], a UAV-carried IRS was proposed for a laser path-controllable FSO system to enhance the performance of EC under different turbulence conditions.

Expanding the study of hybrid systems, [167] evaluated EC in a dual-hop RF/FSO communication system, modeling the RF channel with a mixture gamma distribution and the FSO channel with a double generalized gamma distribution. The study found that EC increases with higher average SNR under various turbulence conditions. Transmit diversity was explored in [168], where the authors applied Alamouti space-time block coding to mitigate AT in the feeder link. The authors complemented this with a beamforming algorithm using one-bit feedback and average virtual SINR to maximize EC in the user link. Lastly, [169] offered a comprehensive analysis of EC for an integrated satellite communication system. The authors derived exact and asymptotic EC expressions for IM/DD and HD schemes using GG and Rician distributions. They also provided an exact expression for the EC of the RF link under Rician fading and identified the optimal switching threshold to maximize EC for the Satcom system. In these studies, integrating advanced detection techniques, hybrid models, and diverse turbulence modeling has greatly enhanced EC in FSO and hybrid communication systems, addressing challenges such as PEs, turbulence, and fading.

4.3.3. *Spectral Efficiency (SE)*

Spectral efficiency is a crucial metric in FSO-based SAGINs, as it measures the system's ability to transmit data efficiently within a given frequency range. SE, typically expressed in bits per second per Hertz (bps/Hz), provides insight into how well the available bandwidth is utilized, and it is influenced by various factors such as atmospheric conditions, link distance, transmitter-receiver alignment, interference, channel capacity, and network topology [170]. These factors directly affect signal quality, error rates, and overall resource utilization, which in turn impact system efficiency. Recent research has focused on optimizing SE in FSO systems through various techniques. For instance, [171] explored long-wave infrared (LWIR) FSO systems using multilevel modulation signals to enhance SE, with the study finding that 8-level pulse amplitude modulation (PAM) achieved the highest SE. Similarly, [172] introduced a multi-level polarization shift keying (MLPolSK) scheme, which, paired with polarization-dependent gain optical amplification, counteracted scintillation effects to improve SE. Adaptive modulation techniques in [173] for MISO and SIMO systems dynamically adjusted modulation size and type based on channel conditions, ensuring SE was maintained under varying turbulence.

Further advancements in SE optimization are seen in research that employs adaptive modulation techniques and real-time channel adjustments. For example, [174] demonstrated the effectiveness of adaptive layered multipulse position modulation (LMPPM) for UAV-based FSO channels, which modified the modulation scheme in real time to optimize spectral utilization, outperforming traditional methods at high power levels. [175] presented an adaptive transmission modulation (ATM) technique that adjusted the modulation order based on channel state and target BER, employing a SIMO configuration with MRC to mitigate turbulence and PEs. In [176], the focus was on optimizing SE through ASER adaptation across different SNR values, addressing atmospheric challenges such as beam wandering and scintillation in vertical FSO channels. By selecting an optimal FoV angle for the HAP PD, the study maintained system reliability at a target average symbol error rate (SER).

Similarly, in [53], both SE and EE were analyzed in a UAV-enabled mobile relaying system. This study jointly optimized SE and EE by adjusting the UAV's trajectory, height, and speed. The FSO link was used as the backhaul for communication between the ground base station and UAV, enabling simultaneous data transfer and UAV charging via an optical beam, ultimately enhancing the overall system efficiency. SE measures how efficiently the UAV uses the available bandwidth to transmit data. It is defined as:

$$\eta_{\mathrm{SE}} \triangleq \frac{r^C_{\mathrm{sum}}}{b_u}, \tag{38}$$

where r^C_{sum} represents the total sum-rate of all users served by the UAV during a flying cycle C, and b_u denotes the average bandwidth utilized by the UAV during the cycle C from its available bandwidth resources. The EE of the UAV is defined as the ratio of the total achievable sum-rate of all users served by the UAV to its net power consumption during a flying cycle T. Mathematically, it is expressed as:

$$\eta_{\mathrm{EE}} \triangleq \frac{r^C_{\mathrm{tot}}}{p_u - C\hat{p}_{u,c}}, \tag{39}$$

where p_u denotes the total power consumption of the UAV, and $\hat{p}_{u,c}$ represents the rate of energy harvesting (or charging) of the UAV's portable battery. The joint optimization of EE and SE introduces a unified and adaptive metric called resource efficiency (RE). This metric balances the trade-off between EE and SE, taking into account power consumption and bandwidth utilization [53, 177, 178]. The RE is defined as:

$$\eta_{\mathrm{RE}} = \beta\gamma\eta_{\mathrm{EE}} + (1-\gamma)\eta_{\mathrm{SE}}, \tag{40}$$

where β is the ratio of the maximum available power that the UAV can utilize during a flying cycle C to its total available bandwidth. The parameter $\gamma \in [0, 1]$ is a tunable weight that governs the trade-off between energy efficiency and spectral efficiency.

Collectively, these studies emphasize the importance of advanced modulation schemes, adaptive techniques, and real-time adjustments in optimizing SE in FSO-based SAGINs, contributing to more efficient, reliable, and adaptable communication systems essential for future 6G networks.

4.4. Energy Metrics (EE)

Energy efficiency is a key parameter in communication systems, indicating how efficiently transmitted energy maintains reliable data transmission. This is particularly vital for FSO-based SAGIN systems with limited energy resources. EE emphasizes maximizing data rates while minimizing power consumption. Given system capacity and total power, EE can be calculated straightforwardly using the formula provided in [166].

$$EE[bit/joule] = \frac{CH_{capacity}[bit/s]}{T_p[joule/s]} \tag{41}$$

where, $CH_{cpacity}$ represents the channel capacity or data rate, and T_p denotes the total power (energy) consumption. This metric functions as a benefit-cost ratio, with the cost component encompassing transmit power and energy dissipated in both the transceiver hardware and baseband processing [179]. The relationship between SE and EE in communication systems is complex. Initially, increasing SE can enhance EE due to factors such as denser cell site deployment and more efficient spectrum utilization. However, further increases in SE may yield diminishing returns in EE [180] as higher energy consumption begins to outweigh the benefits. Striking a balance between SE and EE requires careful consideration of trade-offs influenced by network topology, transmission protocols, and environmental conditions EE [53, 177, 178, 179]. In FSO-based SAGIN communications, EE is essential for balancing high data rates with minimal energy consumption. Nonetheless, AT and alignment errors pose substantial obstacles to EE optimization. Various mitigation strategies have been explored to address these challenges and maximize the EE of FSO communication systems.

Recent studies have focused on improving EE in communication systems, particularly in FSO and hybrid FSO-RF networks, addressing various strategies and techniques. In [181], a sustainable UAV multicasting system was proposed, combining FSO backhaul and power transfer to optimize EE by balancing power-rate tradeoffs in UAV altitude and transmission modes. Similarly, [182] examined EE in UAV communication through trajectory optimization, revealing that unconstrained trajectory optimization led to suboptimal EE, while an optimized circular trajectory maximized EE. In [183], an EE cross-layer design framework for cooperative relaying networks was introduced, incorporating adaptive modulation and coding and formulating a power and time allocation problem to optimize EE in relay-assisted transmissions. The IR-HARQ protocol was shown to outperform other HARQ variants in EE and throughput in [107], with additional findings in [108] and [184]. In [166], the EE and EC of NOMA in FSO-backhauled uplink communication were analyzed, showing that NOMA improved EE by 37% to 60% compared to OMA.

Further advancements in EE were achieved by employing advanced digital signal processing techniques in a MIMO-OFDM-FSO system [185], which minimized power consumption and improved EE through the use of concatenated FEC codes. Energy harvesting (EH), which collects energy from ambient sources such as solar and wind, has also been integrated into FSO-RF networks to enhance EE. In [186], a solar-powered EH model was proposed, where satellites harvest energy from optical signals transmitted via laser. Similarly, in [187], a dual-hop FSO-RF system optimized EH efficiency and transmission performance, enhancing overall EE. The integration of EH into UAV-based systems was explored in [188], where UAVs harvested energy from optical signals, ensuring continuous power transmission even during logical '0' states, which helped optimize energy usage. These studies highlight the significant potential of EH in enhancing the EE of hybrid FSO-RF networks, supporting sustainable and optimized performance in various operational environments.

4.5. Security Metrics

In FSO communication systems within SAGINs, security metrics are crucial for evaluating and improving protection against eavesdropping and attacks. Key security metrics include: Secrecy capacity: which measures the maximum secure data transmission rate. Secrecy outage probability (SOP): assesses the risk of the secrecy capacity dropping below a secure threshold. Probability of positive secrecy capacity (PPSC): indicates the likelihood of secure communication. Secrecy rate: quantifies how effectively confidential information is transmitted, ensuring a gap between legitimate receivers and eavesdroppers. BER of the eavesdropper: measures the ease with which an eavesdropper can intercept messages, with higher BER signifying stronger security. Together, these metrics provide a comprehensive assessment of security performance in FSO-based SAGINs.

Various techniques are employed to enhance these security metrics in FSO communications. These include: Quantum key distribution (QKD): ensures secure key exchange using quantum mechanics. Physical layer security (PLS): leverages the inherent properties of FSO channels to resist interception. Artificial noise injection, beamforming, and directional transmission: reduce eavesdropping opportunities by focusing communication on specific paths. Traditional encryption and authentication methods: ensure only authorized users can access the communication. Diversity and switching techniques: provide alternative paths if an attack is detected. These security metrics and techniques collectively bolster the confidentiality, integrity, and resilience of FSO-based communications in dynamic environments.

Recent studies have made significant advancements in improving the security and reliability of satellite-based QKD systems, particularly in FSO communication networks. In [189], entanglement-based QKD using the E91 protocol was integrated into FSO systems between GSs and UAVs, addressing challenges such as AT, PEs, and link misalignment, while employing time-bin encoding and M-ary PPM for secure key distribution. This approach improved system security and reliability, with performance metrics like the ASER and OP evaluated under photon number splitting attacks. However, this study is limited in scope as it only considers basic eavesdropping attacks, without addressing more advanced threats such as coherent, collective, or active quantum attacks. Moreover, the analysis is confined to a single ground-to-UAV link, without extending to multi-hop or UAV-to-UAV quantum communication scenarios, thereby restricting its applicability to broader, networked quantum communication environments. Similarly, in [77], continuous variable QKD (CV-QKD) with dual polarization QPSK and coherent detection was used in UAV-enabled FSO systems to enhance security against collective attacks, achieving high security levels despite UAV positional deviations. However, The analysis here is focused on CV-QKD protocols; comparison with DV-QKD implementations under similar conditions is lacking. Studies in [190] and [191] focused on eavesdropping scenarios in optical networks, proposing parameter optimization strategies for enhancing security in FSO networks involving LEO satellites, HAPS, and UAVs.

Furthermore, [192] introduced secrecy throughput as a metric to balance reliability and security in CARQ systems. In addition, recent research has explored hybrid systems combining FSO, RF, and QKD technologies for secure communication, such as [193], which proposed a HAP-assisted satellite FSO system with QKD for vehicular networks, and [194], which analyzed the secrecy performance of a dual-hop RF-FSO system. Other studies like [195] and [196] optimized secrecy rates using energy-harvesting relays and UAV trajectory optimization, with [197] exploring RIS technology to enhance signal strength and reduce vulnerabilities. Machine learning techniques have also been increasingly applied to enhance security against jamming and eavesdropping, with [198] employing a convolutional neural network (CNN) to classify light modes in FSO systems and [199] using support vector machines and artificial neural networks for mode classification and signal-to-jammer ratio (SJR) estimation. These innovations, coupled with hybrid FSO/RF systems, UAV optimization, and machine learning applications, highlight a comprehensive approach to improving security and performance in communication systems, which is crucial for the development of secure 6G networks and beyond.

4.6. Lesson learned

In Section 4, we analyzed the critical performance metrics that influence FSO communication in SAGINs, alongside their corresponding mitigation strategies. As illustrated in Fig. 15, our assessment reveals a pressing need for joint multi-metric optimization to ensure resilient, efficient, and adaptable FSO links across heterogeneous and dynamic network layers. Nonetheless, a considerable limitation in existing research is the predominant focus on optimizing single performance metrics—such as OP, BER, or EE—often under idealized assumptions. This narrow perspective fails to capture the complex interdependencies and trade-offs among various metrics that critically impact system-wide performance.

For instance, reducing transmission power may improve EE but compromise link reliability and increase latency. Conversely, maximizing SE may result in elevated power consumption or higher vulnerability to channel impairments. Enhancing BER through sophisticated error correction techniques may increase computational overhead and processing delays, thereby degrading latency and throughput. Similarly, minimizing latency often necessitates tighter beam alignment or higher transmission power, inadvertently escalating pointing errors or energy demands. Improving security—through encryption or jamming-resilient protocols—introduces additional delay and processing cost, creating a trade-off with latency and energy efficiency. Maximizing throughput using broader bandwidth or higher-order modulation can also lead to increased BER under turbulent conditions. Despite some recent efforts to jointly optimize two or more metrics, as outlined in Table 8, comprehensive frameworks that capture holistic trade-offs across all critical metrics remain largely absent.

Furthermore, many studies approach system parameter optimization in disjointed isolation. For example, beam divergence, receiver FoV, and relay placement are often optimized separately. This approach neglects their interactive dynamics: increasing beam width may mitigate pointing errors but reduce received power and SE; optimal relay placement may minimize propagation loss yet increase handover complexity or UAV energy burden. The lack of integrated parameter tuning undermines the potential for system-level improvements under real-time mobility and atmospheric fluctuations.

Additionally, enabling technologies remain underutilized in this context. Digital Twin (DT) frameworks offer tremendous potential for real-time monitoring, predictive modeling, and adaptive control across SAGIN layers, yet their adoption in FSO systems is minimal. NOMA, while theoretically promising in terms of SE and EE, is underexplored in mobile SAGIN scenarios, particularly under the influence of imperfect SIC, Doppler effects, and dynamic user scheduling. Security solutions also remain traditional, relying predominantly on cryptographic methods without leveraging QKD or other quantum-secure mechanisms that are essential for the security demands of future 6G systems.

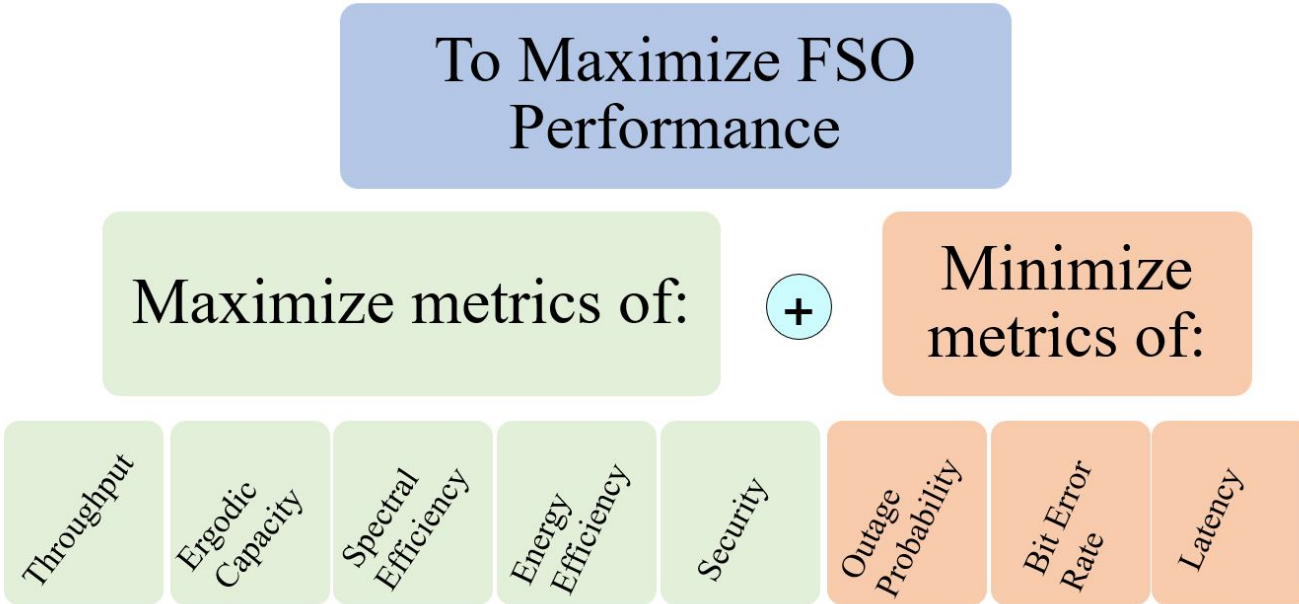

Fig. 15. Graphical Representation of Enhanced FSO Performance Achieved through the Optimization of Various Metrics, Including Reduced Outage Probability, Bit Error Rate, and Latency, Alongside Increased Throughput, Ergodic Capacity, Spectral Efficiency, Energy Efficiency, and Security.

Table 8
Summary of Multiple Metrics Optimization and their Mitigation Techniques.

Ref.	Year	Metrics Analyzed	HT	RT	SD	ReT	Description
[48]	2024	Throughput and EE		✓			RIS-assisted utilizing DRL technique.
[76]	2023	OP and BER			✓		Spatial diversity to improve FSO performance.
[109]	2023	Throughput, latency, & EE				✓	C-HARQ aided multi UAVs guarantee latency.
[118]	2024	OP and ASER	✓		✓		FSO/RF SAGINs with Adaptive Combining
[128]	2024	OP, ABER, and EC	✓	✓			Hybrid FSO/RF with satellite-terrestrial DF relay
[135]	2023	Latency, throughput, and EE				✓	IR-HARQ is analyzed with Markov model.
[200]	2023	EE and latency	✓				FSO/RF system with decentralized DQN- RL.
[201]	2023	OP and Throughput				✓	Power-Optimal HARQ for Reliable FSO.
[202]	2018	OP and throughput				✓	Compared ALO &IR, HARQ-IR outperforms.
[203]	2024	OP, ABER, and EC		✓			Use ORS to select the optimal UAV.
[204]	2024	OP and ABER		✓			UAV used as a relay RIS.
[205]	2024	OP, ASER and EC		✓			UAV-as a relay to enable LoS.
[206]	2023	OP, ABER, and EC		✓			Dual-hop FSO link using UAV as a relay.

Notation: *HT- Hybrid Transmission, RT- Relay Transmission, SD- Spatial Diversity, and ReT- Retransmission.*

In conclusion, addressing these research gaps requires a holistic, cross-layer optimization paradigm—one that concurrently considers OP, BER, SE, EE, latency, throughput, and security, while dynamically adapting system parameters in response to evolving network and environmental conditions. Moreover, integrating advanced control mechanisms, DT-driven adaptation, and quantum-secure communication will be pivotal in realizing resilient, intelligent, and high-capacity FSO communication infrastructures for next-generation SAGIN deployments.

5. Future Research Direction and Open Issues

The growing demand for Internet of Everything (IoE)-based smart services is driving the need for enhanced wireless networks that surpass the capabilities of 5G. While 5G can accommodate various services, it falls short of meeting the stringent requirements posed by emerging smart applications [207]. Consequently, developing 6G systems has become essential, with FSO links playing a significant role in addressing these advanced communication demands. However, optimizing FSO links for 6G presents substantial research challenges, particularly in mitigating the detrimental effects of atmospheric conditions on FSO performance. This necessitates robust channel models and adaptive modulation schemes, which are key areas for future research.

Ensuring the reliability and security of FSO links in 6G requires the development of advanced error correction methods and secure communication protocols. Integrating FSO with RF, and other technologies to establish seamless end-to-end connections introduces further challenges, including efficient handover processes, resource allocation, and effective interference management. Additionally, the scalability and EE of 6G networks demand innovative strategies for EE transmission and intelligent network management. Addressing these challenges is essential to harnessing the full potential of FSO communications, paving the way for optimized, resilient, and high-performance connectivity in next-generation 6G networks.

5.1. Joint Metric Optimization

Joint metric optimization, or multi-objective optimization, is essential for improving the overall performance of FSO systems in SAGINs, as it enables the simultaneous consideration of multiple, often conflicting metrics such as OP, EE, SE, and latency. However, many existing studies focus on isolated metrics under idealized conditions, which limits adaptability and can lead to suboptimal system performance when viewed holistically. For instance, works optimizing OP [35, 115], BER [9, 81], latency [161], EE [166], or SE [171] often yield conflicting outcomes, revealing the need for balanced, system-level designs [208].

Although a few recent efforts [209, 210, 211] have explored EE-SE trade-offs in UAV-assisted communications, they typically overlook critical constraints like GS-UAV backhaul capacity or dynamic topological changes. These studies employ multi-objective optimization problems to guide resource allocation and trajectory planning, but often rely on heuristics and evolutionary algorithms, which may not scale efficiently in real-time or large-scale applications [212].

Therefore, advancing joint optimization in FSO-based SAGINs requires the development of more sophisticated, scalable algorithms capable of balancing performance trade-offs dynamically. This includes optimizing transmit power, beam alignment, and routing to maintain robust, energy-efficient links, especially in mobile or resource-constrained environments. By systematically addressing these interdependencies, multi-objective optimization can enable FSO systems to deliver high-throughput, low-latency, and secure communication tailored to the complex demands of future 6G SAGIN architectures.

5.2. System Parameter Optimization

The system parameters significantly influence the optimization of key performance metrics, affecting the overall performance of FSO links within SAGINs. Existing research has primarily focused on optimizing only a limited subset of these parameters. For instance, recent studies have considered parameters such as average SNR and zenith angle [9], beam width, FoV, and UAV locations [35], and FoV and beam width [114]. However, an integrated approach that simultaneously considers multiple critical system parameters remains insufficiently explored.

Future research should emphasize comprehensive optimization frameworks that concurrently address multiple system parameters, including but not limited to beam width, FoV, zenith angle, UAV and satellite positioning, optical power, modulation schemes, and environmental conditions. Investigating these parameters collectively will provide deeper insights into their interdependencies and trade-offs, ultimately facilitating more robust, efficient, and adaptive SAGIN deployments. Open issues also include developing sophisticated optimization algorithms capable of real-time adjustment to dynamic network conditions, ensuring sustained performance even in rapidly changing scenarios. Additionally, research efforts should aim to integrate advanced predictive and adaptive techniques, such as machine learning and digital twin technologies, to anticipate and mitigate impairments proactively, further enhancing the resilience and reliability of FSO links.

5.3. Digital Twin (DT)

The integration of Digital Twin (DT) technology into FSO-enabled SAGINs offers a transformative means for enhancing real-time performance monitoring, predictive analytics, and system optimization. A DT functions as a virtual counterpart to physical network elements, maintaining real-time synchronization between digital and physical entities via continuous data exchange [213, 214]. In the context of FSO-based SAGINs, DTs can replicate and simulate the operational behavior of satellites, UAVs, and ground nodes, capturing parameters such as node mobility, link conditions, atmospheric influences, and hardware configurations. This virtualized mirror enables high-fidelity simulations that provide proactive control strategies and facilitate efficient performance management in dynamically changing environments.

The use of DTs addresses several limitations inherent in static or reactive FSO control frameworks. With DT-driven modeling, it becomes feasible to monitor link quality metrics such as SNR, BER, and pointing accuracy in real time. Additionally, DTs support the predictive modeling of environmental factors like turbulence or cloud blockage by leveraging sensory data, enabling early adjustments to system parameters such as beam divergence, transmit power, and alignment. This adaptability enhances link robustness and continuity. Furthermore, the DT framework enables simulation-based optimization strategies for resource allocation, network topology reconfiguration, and fault recovery, all of which are essential in maintaining service quality in dynamic SAGIN environments.

Future research should focus on developing hierarchical DT architectures capable of reflecting the multi-layered structure of SAGINs, including both centralized DTs at control hubs and distributed DTs on edge platforms such as UAVs and GSs. However, several challenges remain unresolved, including achieving real-time synchronization with minimal latency, maintaining the fidelity and integrity of data across the system, and designing scalable DT frameworks compatible with constrained bandwidth and energy resources. Open issues that warrant further exploration include the development of standardized DT modeling approaches suited to FSO-based networks, the integration of AI and machine learning techniques for real-time adaptive decision-making, and lightweight DT solutions for deployment on power- and computation-limited aerial or satellite platforms. In addition, cross-layer co-simulation mechanisms and dynamic feedback loops must be established to enable coordinated and intelligent system behavior throughout the SAGIN hierarchy.

5.4. NOMA

NOMA-based FSO systems have demonstrated promising improvements in system performance, particularly with respect to OP, throughput, SE, and EE, as shown in [129] and [166]. The study in [129] evaluates power-domain NOMA for FSO channels but does not address practical concerns such as channel estimation errors, imperfect successive interference cancellation (SIC), or adaptive user grouping—factors essential for real-world deployments. Similarly, [166] investigates a fixed NOMA-based uplink FSO backhaul system, reporting a 10% gain in ergodic capacity and a 37–60% improvement in EE compared to OMA systems. However, it assumes ideal SIC and overlooks the impact of dynamic environmental conditions, beam misalignment, and turbulence, which significantly affect mobile SAGIN applications. Notably, the integration of NOMA into FSO links within SAGIN architectures remains largely unexplored.

To address these gaps and improve FSO link performance in future SAGIN environments, NOMA should be dynamically integrated with adaptive beam alignment techniques and SIC-aware receiver architectures that consider user mobility, pointing errors, and the heterogeneous nature of inter-layer links. Furthermore, cross-layer optimization frameworks involving user scheduling, power control, and link adaptation—potentially supported by deep reinforcement learning or model predictive control—are essential to enhance robustness and scalability. Such an approach would enable hybrid SAGIN-FSO-NOMA systems to efficiently support a large number of concurrent users while maintaining high spectral and energy efficiency under diverse and dynamic operating conditions.

5.5. Security and Privacy issues

Despite the inherent advantages of FSO technology—such as narrow beam divergence, high bandwidth, and immunity to electromagnetic interference—security and privacy remain critical challenges, especially in dynamic and heterogeneous SAGINs. These concerns are further exacerbated in mobile and multi-domain settings, where FSO links span between GSs, UAVs, HAPs, and LEO satellites. In such environments, varying and evolving threat models, including advanced eavesdropping (e.g., collective and coherent attacks), jamming, spoofing, and device-level side-channel vulnerabilities must be systematically addressed.

To overcome these limitations, future research should integrate quantum-secured communication, particularly QKD, into the FSO-enabled SAGIN architecture. Quantum technologies provide information-theoretic security grounded in the fundamental principles of quantum mechanics, such as the no-cloning theorem and Heisenberg's uncertainty principle. This makes QKD particularly suitable for mitigating the vulnerabilities of conventional cryptographic systems in the face of quantum computing.

Quantum-enhanced FSO links can enable long-distance, low-latency secure key distribution between LEO satellites, HAPs, and mobile UAVs, forming the backbone of a quantum-secure overlay network across SAGIN tiers. These links can operate either as standalone secure FSO channels or in hybrid FSO-RF configurations, where quantum keys are distributed via the FSO path while data transmission utilizes the more robust RF spectrum [193]. This hybrid model enhances both security and resilience in dynamic atmospheric and mobility conditions.

Key concepts essential for integrating quantum security into SAGINs include a variety of advanced quantum communication techniques. Discrete-variable and continuous-variable QKD protocols, tailored for mobile and turbulence-prone FSO environments, form the foundation for secure key distribution. Entanglement-based QKD enables the establishment of highly secure correlations between geographically dispersed SAGIN nodes, enhancing the robustness of inter-domain communication [189]. Measurement-device-independent QKD serves as an effective countermeasure against practical side-channel attacks, ensuring device-level security. In parallel, post-quantum cryptography offers a classical layer of protection that remains resilient in the face of quantum computing threats. Additionally, quantum-secure identity management mechanisms—such as quantum tokens and authenticated key exchanges—facilitate trusted interaction across heterogeneous SAGIN layers.

Despite these promising advances, several open research issues remain. The development of scalable and adaptive quantum communication architectures that can operate efficiently across multi-tier, mobile SAGIN environments is a critical priority. Equally important is the design of lightweight and low-complexity QKD protocols that can be deployed on resource-constrained platforms like UAVs, without compromising security. Ensuring stability in mobile FSO-based quantum links will require mobility-aware and turbulence-resilient beam tracking systems capable of operating under real-time conditions. Furthermore, comprehensive cross-layer security frameworks are needed to integrate quantum physical layer protections with upper-layer functionalities such as routing, authentication, and secure handover processes. To bridge the gap between theoretical advancements and practical deployments, experimental testbeds and digital twin platforms should be developed to evaluate performance under realistic mobility, atmospheric, and adversarial conditions.

Finally, fundamental challenges such as photon loss, beam misalignment, UAV flight instability, and atmospheric decoherence must be addressed to enable the practical, robust, and scalable deployment of quantum-secured FSO links in next-generation SAGIN infrastructures.

6. Conclusion

This study provides a comprehensive review of FSO communication performance within SAGINs, thoroughly examining primary challenges and various mitigation techniques. It delves into key performance metrics, including OP, BER, latency, throughput, EC, SE, EE, and security, analyzing their impacts on FSO systems in depth. The analysis explores the trade-offs among these metrics, such as balancing EE with OP, BER, latency, and security, as well as the interactions between EE, SE, and other metrics, highlighting the complexity of optimizing multiple factors simultaneously. The study reviews existing mitigation strategies, including optimized aperture sizes, beam shaping, relay-assisted transmissions, hybrid FSO/RF systems, and advanced protocols like NOMA with energy harvesting and HARQ. Additionally, it evaluates the effectiveness of error control coding, adaptive modulation methods (e.g., multi-level pulse amplitude modulation (PAM) and multi-level polarization shift keying (MLPolSK)), quantum key distribution (QKD), and machine learning-based jamming detection in enhancing system performance. Furthermore, this survey identifies fundamental research challenges that require further investigation, particularly in integrating these mitigation techniques within future 6G wireless communication networks. Finally, the study outlines unresolved research questions that hinder the advancement of FSO communication performance in SAGINs, offering a roadmap for future research aimed at addressing these challenges and fostering innovation in FSO-based 6G communication systems.

References

[1] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, et al., Satellite communications in the new space era: A survey and future challenges, IEEE Communications Surveys & Tutorials 23 (1) (2020) 70–109.

[2] S. Liu, Z. Gao, Y. Wu, D. W. K. Ng, X. Gao, K.-K. Wong, S. Chatzinotas, B. Ottersten, Leo satellite constellations for 5g and beyond: How will they reshape vertical domains?, IEEE Communications Magazine 59 (7) (2021) 30–36.

[3] T. K. Nguyen, C. T. Nguyen, H. D. Le, A. T. Pham, Tcp performance over satellite-based hybrid fso/rf vehicular networks: Modeling and analysis, IEEE Access 9 (2021) 108426–108440.

[4] K. Guo, M. Lin, B. Zhang, J.-B. Wang, Y. Wu, W.-P. Zhu, J. Cheng, Performance analysis of hybrid satellite-terrestrial cooperative networks with relay selection, IEEE Transactions on Vehicular Technology 69 (8) (2020) 9053–9067.

[5] C.-Q. Dai, M. Zhang, C. Li, J. Zhao, Q. Chen, Qoe-aware intelligent satellite constellation design in satellite internet of things, IEEE Internet of Things Journal 8 (6) (2020) 4855–4867.

[6] G. K. Kurt, M. G. Khoshkholgh, S. Alfattani, A. Ibrahim, T. S. Darwish, M. S. Alam, H. Yanikomeroglu, A. Yongacoglu, A vision and framework for the high altitude platform station (haps) networks of the future, IEEE Communications Surveys & Tutorials 23 (2) (2021) 729–779.

[7] S. Shah, M. Siddharth, N. Vishwakarma, R. Swaminathan, A. Madhukumar, Adaptive-combining-based hybrid fso/rf satellite communication with and without haps, IEEE Access 9 (2021) 81492–81511.

[8] O. B. Yahia, E. Erdogan, G. K. Kurt, I. Altunbas, H. Yanikomeroglu, Haps selection for hybrid rf/fso satellite networks, IEEE Transactions on Aerospace and Electronic Systems 58 (4) (2022) 2855–2867.

[9] R. Samy, H.-C. Yang, T. Rakia, M.-S. Alouini, Space-air-ground fso networks for high-throughput satellite communications, IEEE Communications Magazine 60 (12) (2022) 82–87.

[10] P. Bhardwaj, V. Bansal, N. Biyani, S. Shukla, S. Zafaruddin, Performance of integrated iot network with hybrid mmwave/fso/thz backhaul link, arXiv preprint arXiv:2304.01178 (2023).

[11] D. S. Lakew, U. Sa'ad, N.-N. Dao, W. Na, S. Cho, Routing in flying ad hoc networks: A comprehensive survey, IEEE Communications Surveys & Tutorials 22 (2) (2020) 1071–1120.

[12] M. S. Alam, G. K. Kurt, H. Yanikomeroglu, P. Zhu, N. D. Đào, High altitude platform station based super macro base station constellations, IEEE Communications Magazine 59 (1) (2021) 103–109.

[13] W. J. Yun, S. Park, J. Kim, M. Shin, S. Jung, D. A. Mohaisen, J.-H. Kim, Cooperative multiagent deep reinforcement learning for reliable surveillance via autonomous multi-uav control, IEEE Transactions on Industrial Informatics 18 (10) (2022) 7086–7096.

[14] Z. Niu, H. Yang, Q. Yao, A. Yu, S. Yin, S. Shen, B. Wei, J. Zhang, A. V. Vasilakos, Hap networking enables highly reliable space-air-ground optical interconnect: an integrated network perspective, IEEE Network (2024).

[15] F. Demers, H. Yanikomeroglu, M. St-Hilaire, A survey of opportunities for free space optics in next generation cellular networks, in: 2011 Ninth annual communication networks and services research conference, IEEE, 2011, pp. 210–216.

[16] L. Chen, F. Tang, X. Li, J. Liu, Y. Yang, J. Yu, Y. Zhu, Delay-optimal cooperation transmission in remote sensing satellite networks, IEEE Transactions on Mobile Computing 22 (9) (2022) 5109–5123.

[17] H. Yang, J. Yuan, C. Li, G. Zhao, Z. Sun, Q. Yao, B. Bao, A. V. Vasilakos, J. Zhang, Brainiot: Brain-like productive services provisioning with federated learning in industrial iot, IEEE Internet of Things Journal 9 (3) (2021) 2014–2024.

[18] A. Yu, H. Yang, C. Feng, Y. Li, Y. Zhao, M. Cheriet, A. V. Vasilakos, Socially-aware traffic scheduling for edge-assisted metaverse by deep reinforcement learning, IEEE Network (2023).

[19] T. Yu, H. Yang, J. Nie, Q. Yao, W. Liu, J. Zhang, M. Cheriet, Bias-compensation augmentation learning for semantic segmentation in uav networks, IEEE Internet of Things Journal (2024).

[20] Y. Kaymak, R. Rojas-Cessa, J. Feng, N. Ansari, M. Zhou, T. Zhang, A survey on acquisition, tracking, and pointing mechanisms for mobile free-space optical communications, IEEE Communications Surveys & Tutorials 20 (2) (2018) 1104–1123.

[21] A. S. Hamza, J. S. Deogun, D. R. Alexander, Classification framework for free space optical communication links and systems, IEEE Communications Surveys & Tutorials 21 (2) (2018) 1346–1382.

[22] A. B. Raj, A. K. Majumder, Historical perspective of free space optical communications: from the early dates to today's developments, Iet Communications 13 (16) (2019) 2405–2419.

[23] A. Trichili, M. A. Cox, B. S. Ooi, M.-S. Alouini, Roadmap to free space optics, JOSA B 37 (11) (2020) A184–A201.

[24] S. A. Al-Gailani, M. F. M. Salleh, A. A. Salem, R. Q. Shaddad, U. U. Sheikh, N. A. Algeelani, T. A. Almohamad, A survey of free space optics (fso) communication systems, links, and networks, IEEE Access 9 (2020) 7353–7373.

[25] S. Zafar, H. Khalid, Free space optical networks: applications, challenges and research directions, Wireless Personal Communications 121 (1) (2021) 429–457.

[26] A. Jahid, M. H. Alsharif, T. J. Hall, A contemporary survey on free space optical communication: Potentials, technical challenges, recent advances and research direction, Journal of Network and Computer Applications 200 (2022) 103311.

[27] H. D. Le, A. T. Pham, Link-layer retransmission-based error-control protocols in fso communications: A survey, IEEE Communications Surveys & Tutorials 24 (3) (2022) 1602–1633.

[28] O. Aboelala, I. E. Lee, G. C. Chung, A survey of hybrid free space optics (fso) communication networks to achieve 5g connectivity for backhauling, Entropy 24 (11) (2022) 1573.

[29] P. Kaur, V. K. Jain, S. Kar, Performance analysis of free space optical links using multi-input multi-output and aperture averaging in presence of turbulence and various weather conditions, IET Communications 9 (8) (2015) 1104–1109.

[30] Y. Ata, M.-S. Alouini, Haps based fso links performance analysis and improvement with adaptive optics correction, IEEE Transactions on Wireless Communications 22 (7) (2022) 4916–4929.

[31] M. Elamassie, M. Uysal, Multi-layer airborne fso systems: Performance analysis and optimization, IEEE Transactions on Communications (2024).

[32] S. Shang, E. Zedini, M.-S. Alouini, Enhancing non-terrestrial network performance with free space optical links and intelligent reflecting surfaces, IEEE Transactions on Wireless Communications (2024).

[33] M. Park, M. Choi, J.-M. Chung, Cloud aware dynamic uav operation for 6g fso backhaul network performance improvement, IEEE Open Journal of the Communications Society (2024).

[34] D. E. Mohsen, E. M. Abbas, M. M. Abdulwahid, Performance evaluation of 32 wdm-fso systems with different weather turbulence under variance launch power values, in: 2024 IEEE 1st International Conference on Communication Engineering and Emerging Technologies (ICoCET), IEEE, 2024, pp. 1–4.

[35] J.-Y. Wang, Y. Ma, R.-R. Lu, J.-B. Wang, M. Lin, J. Cheng, Hovering uav-based fso communications: Channel modelling, performance analysis, and parameter optimization, IEEE Journal on Selected Areas in Communications 39 (10) (2021) 2946–2959.

[36] W. Guo, Y. Zhan, T. A. Tsiftsis, L. Yang, Performance and channel modeling optimization for hovering uav-assisted fso links, Journal of Lightwave Technology 40 (15) (2022) 4999–5012.

[37] M. Y. Abdelsadek, A. U. Chaudhry, T. Darwish, E. Erdogan, G. Karabulut-Kurt, P. G. Madoery, O. B. Yahia, H. Yanikomeroglu, Future space networks: Toward the next giant leap for humankind, IEEE Transactions on Communications 71 (2) (2022) 949–1007.

[38] J.-g. Seo, I.-H. Lee, H. Jung, D. B. da Costa, H. Shin, Doppler characterization in leo satellite-aided uav swarm networks, IEEE Wireless Communications Letters (2024).

[39] N. Saeed, H. Almorad, H. Dahrouj, T. Y. Al-Naffouri, J. S. Shamma, M.-S. Alouini, Point-to-point communication in integrated satellite-aerial 6g networks: State-of-the-art and future challenges, IEEE Open Journal of the Communications Society 2 (2021) 1505–1525.

[40] X. Gao, R. Liu, A. Kaushik, H. Zhang, Dynamic resource allocation for virtual network function placement in satellite edge clouds, IEEE Transactions on Network Science and Engineering 9 (4) (2022) 2252–2265.

[41] G. Giambene, S. Kota, P. Pillai, Satellite-5g integration: A network perspective, Ieee Network 32 (5) (2018) 25–31.

[42] R. Swaminathan, S. Sharma, N. Vishwakarma, A. Madhukumar, Haps-based relaying for integrated space–air–ground networks with hybrid fso/rf communication: A performance analysis, IEEE Transactions on Aerospace and Electronic Systems 57 (3) (2021) 1581–1599.

[43] P. Wang, Y. Yang, W. Sun, Q. Wang, B. Guo, J. He, Y. Bi, Federated learning with privacy-preserving incentives for aerial computing networks, IEEE Transactions on Network Science and Engineering (2023).

[44] S. Park, C. Park, J. Kim, Learning-based cooperative mobility control for autonomous drone-delivery, IEEE Transactions on Vehicular Technology (2023).

[45] C. M. Ho, D. S. Lakew, A.-T. Tran, C. Lee, D. T. Hua, S. Cho, A review on unmanned aerial vehicle-based networks and satellite-based networks with rsma: Research challenges and future trends, in: 2023 International Conference on Artificial Intelligence in Information and Communication (ICAIIC), IEEE, 2023, pp. 139–142.

[46] I. Bekmezci, O. K. Sahingoz, Ş. Temel, Flying ad-hoc networks (fanets): A survey, Ad Hoc Networks 11 (3) (2013) 1254–1270.

[47] K. Haseeb, A. Rehman, T. Saba, S. A. Bahaj, H. Wang, H. Song, Efficient and trusted autonomous vehicle routing protocol for 6g networks with computational intelligence, ISA transactions 132 (2023) 61–68.

[48] S. Wu, N. Chen, A. Xiao, H. Jia, C. Jiang, P. Zhang, Ai-enabled deployment automation for 6g space-air-ground integrated networks: Challenges, design, and outlook, IEEE Network (2024).

[49] P. Zhang, N. Chen, S. Shen, S. Yu, N. Kumar, C.-H. Hsu, Ai-enabled space-air-ground integrated networks: Management and optimization, IEEE Network (2023).

[50] G. Zhou, L. Zhao, G. Zheng, S. Song, J. Zhang, L. Hanzo, Multi-objective optimization of space-air-ground integrated network slicing relying on a pair of central and distributed learning algorithms, IEEE Internet of Things Journal (2023).

[51] H. Tu, P. Bellavista, L. Zhao, G. Zheng, K. Liang, K.-K. Wong, Priority-based load balancing with multi-agent deep reinforcement learning for space-air-ground integrated network slicing, IEEE Internet of Things Journal (2024).

[52] D. Hamza, H. E. Hammouti, J. S. Shamma, M.-S. Alouini, Multi-sided matching for the association of space-air-ground integrated systems, arXiv preprint arXiv:2111.09411 (2021).

[53] F. H. Panahi, F. H. Panahi, Cellular coverage extension using an intelligent fso-based uav: An energy and spectral efficient approach, IEEE Transactions on Cognitive Communications and Networking (2024).

[54] E. Ciaramella, Y. Arimoto, G. Contestabile, M. Presi, A. D'Errico, V. Guarino, M. Matsumoto, 1.28 terabit/s (32x40 gbit/s) wdm transmission system for free space optical communications, IEEE Journal on selected areas in communications 27 (9) (2009) 1639–1645.

[55] Y. Tumma, V. K. Kappala, A review on deployment of uav-fso system for high-speed communication, IEEE Access (2024).

[56] M. A. Khalighi, M. Uysal, Survey on free space optical communication: A communication theory perspective, IEEE communications surveys & tutorials 16 (4) (2014) 2231–2258.

[57] J. C. Juarez, A. Dwivedi, A. R. Hammons, S. D. Jones, V. Weerackody, R. A. Nichols, Free-space optical communications for next-generation military networks, IEEE Communications Magazine 44 (11) (2006) 46–51.

[58] E. Zedini, A. Kammoun, M.-S. Alouini, Performance of multibeam very high throughput satellite systems based on fso feeder links with hpa nonlinearity, IEEE Transactions on Wireless Communications 19 (9) (2020) 5908–5923.

[59] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, Y. M. Jang, Optical wireless hybrid networks: Trends, opportunities, challenges, and research directions, IEEE Communications Surveys & Tutorials 22 (2) (2020) 930–966.

[60] Y. Li, H. Li, W. Liu, L. Liu, Y. Chen, J. Wu, Q. Wu, J. Liu, Z. Lai, A case for stateless mobile core network functions in space, in: Proceedings of the ACM SIGCOMM 2022 Conference, 2022, pp. 298–313.

[61] Z. Han, C. Xu, K. Liu, L. Yu, G. Zhao, S. Yu, A novel mobile core network architecture for satellite-terrestrial integrated network, in: 2021 IEEE Global Communications Conference (GLOBECOM), IEEE, 2021, pp. 01–06.

[62] V. Mohan, D. Bhaskar, A. Mathur, Ground-aerial uav-assisted hybrid plc-fso integrated communication networks: A performance analysis, IEEE Internet of Things Journal (2024).

[63] H. Kaushal, G. Kaddoum, Optical communication in space: Challenges and mitigation techniques, IEEE communications surveys & tutorials 19 (1) (2017) 57–96.

[64] Y. Liu, L. Wang, Z. Lu, K. Du, G. Shou, A stateless design of satellite-terrestrial integrated core network and its deployment strategy, IEEE Transactions on Network and Service Management (2023).

[65] R. Ara, I. E. Lee, Z. Ghassemlooy, G. C. Chung, Outage performance of free-space optical links over turbulence channels with pointing errors, in: 2024 14th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), IEEE, 2024, pp. 1–6.

[66] A. Girdher, A. Bansal, Ris-assisted multi-aperture fso communication network for high-speed train: Second-order statistical analysis, IEEE Transactions on Intelligent Transportation Systems (2024).

[67] N. Liu, C. Ju, D. Wang, D. Wang, P. Xie, Multi-aperture coherent digital combining based on complex-valued mimo 2n× 2 adaptive equalizer for fso communication, Journal of Lightwave Technology 41 (18) (2023) 5983–5990.

[68] A. K. Majumdar, Free-space optical (fso) platforms: Unmanned aerial vehicle (uav) and mobile, in: Advanced Free Space Optics (FSO) A Systems Approach, Springer, 2014, pp. 203–225.

[69] X. Li, Y. Li, Diversity scheme based fso/rf hybrid systems in sagin with interference and outdated csi, in: 2023 3rd International Conference on Electronic Information Engineering and Computer Communication (EIECC), IEEE, 2023, pp. 22–27.

[70] S. C. Arum, D. Grace, P. D. Mitchell, A review of wireless communication using high-altitude platforms for extended coverage and capacity, Computer Communications 157 (2020) 232–256.

[71] T. V. Nguyen, H. D. Le, N. T. Dang, A. T. Pham, On the design of rate adaptation for relay-assisted satellite hybrid fso/rf systems, IEEE Photonics Journal 14 (1) (2021) 1–11.

[72] T. V. Nguyen, H. D. Le, A. T. Pham, On the design of ris–uav relay-assisted hybrid fso/rf satellite–aerial–ground integrated network, IEEE Transactions on Aerospace and Electronic Systems 59 (2) (2022) 757–771.

[73] K. Guo, M. Wu, X. Li, S. Mumtaz, T. Charalampos, Joint optimization for ris-aided hybrid fso sagins with deep reinforcement learning, in: GLOBECOM 2023-2023 IEEE Global Communications Conference, IEEE, 2023, pp. 431–436.

[74] H. Jia, J. Zhong, M. N. Janardhanan, G. Chen, Ergodic capacity analysis for fso communications with uav-equipped irs in the presence of pointing error, in: 2020 IEEE 20th International Conference on Communication Technology (ICCT), IEEE, 2020, pp. 949–954.

[75] P. Saxena, Y. H. Chung, On the performance of all-optical roris dual hop uav based fso systems, ICT Express 9 (3) (2023) 466–472.

[76] R. Priyadarshani, M.-S. Alouini, Earth-to-hap fso communication with spatial diversity and channel correlation, IEEE Transactions on Aerospace and Electronic Systems (2023).

[77] N. Alshaer, T. Ismail, Performance evaluation and security analysis of uav-based fso/cv-qkd system employing dp-qpsk/cd, IEEE Photonics Journal 14 (3) (2022) 1–11.

[78] H. E. Nistazakis, A time-diversity scheme for wireless optical links over exponentially modeled turbulence channels, Optik 124 (13) (2013) 1386–1391.

[79] K. Prabu, S. Cheepalli, D. S. Kumar, Analysis of polsk based fso system using wavelength and time diversity over strong atmospheric turbulence with pointing errors, Optics Communications 324 (2014) 318–323.

[80] X. Liu, W. Yang, Z. Liu, S. Xiao, Performance enhancement of fec-coded 32qam dmt signals with rate-flexible hcs in fso systems, IEEE Photonics Technology Letters (2024).

[81] I. Gueye, I. Diop, I. Dioum, D. Dione, Performance analysis of mixed rf/fso df relay based on low density parity check (ldpc) codes using deep learning techniques, in: 2023 9th International Conference on Computer and Communications (ICCC), IEEE, 2023, pp. 706–712.

[82] M. A. Fernandes, G. M. Fernandes, B. T. Brandão, M. M. Freitas, N. Kaai, A. Tomeeva, B. van Der Wielen, J. Reid, D. Raiteri, P. P. Monteiro, et al., 4 tbps+ fso field trial over 1.8 km with turbulence mitigation and fec optimization, Journal of Lightwave Technology (2024).

[83] X. Liu, Z. Liu, S. Xiao, W. Yang, W. Hu, Rate-flexible hybrid constellation shaping for polar-coded 32qam in fso systems, in: Optical Fiber Communication Conference, Optica Publishing Group, 2024, pp. W4G–7.

[84] Y. S. Rohmah, A. Kurniawan, M. S. Arifianto, K. Anwar, Investigating the performances of polar codes under atmospheric turbulence log-normal distributed channels for free space optical (fso) communications, in: 2022 IEEE Symposium on Future Telecommunication Technologies (SOFTT), IEEE, 2022, pp. 35–39.

[85] N. Sadiq, A. Hussain, F. Qamar, R. Shahzadi, M. Ali, N. Qamar, M. F. Nadeem, U. Masud, Performance analysis of nrz and rz variants for fso communication system under different weather conditions, Journal of Optical Communications 44 (s1) (2024) s1197–s1204.

[86] R. Baiwa, P. Verma, Performance analysis of fso system for advanced modulation formats under different weather conditions, in: 2018 Second International Conference on Intelligent Computing and Control Systems (ICICCS), IEEE, 2018, pp. 1490–1495.

[87] G. Kaur, D. Srivastava, P. Singh, Y. Parasher, Development of a novel hybrid pdm/ofdm technique for fso system and its performance analysis, Optics & Laser Technology 109 (2019) 256–262.

[88] N. Yu, P. Wang, Z. Zhuang, Design of digital pulse-position modulation system, in: Journal of Physics: Conference Series, Vol. 2093, IOP Publishing, 2021, p. 012030.

[89] A. Sharoar Jahan Choyon, R. Chowdhury, Performance comparison of free-space optical (fso) communication link under ook, bpsk, dpsk, qpsk and 8-psk modulation formats in the presence of strong atmospheric turbulence, Journal of Optical Communications 44 (s1) (2024) s763–s769.

[90] H. Singh, M. Arora, Comparison of bit error rate performance of different modulation techniques over turbulent fso link, International Journal of Computer Applications 109 (12) (2015) 20–24.

[91] Z. Xu, G. Xu, Z. Zheng, Ber and channel capacity performance of an fso communication system over atmospheric turbulence with different types of noise, Sensors 21 (10) (2021) 3454.

[92] F. Qamar, M. K. Islam, R. Farhan, M. Ali, S. Z. Ali Shah, Secure optical qam transmission using chaos message masking, Journal of Optical Communications 43 (3) (2022) 421–428.

[93] J.-Y. Lee, B. Lim, Y.-C. Ko, Performance analysis of multi-hop low earth orbit satellite network over mixed rf/fso links, ICT Express (2024).

[94] K. D. Dang, H. D. Le, C. T. Nguyen, A. T. Pham, Resource allocation for hybrid fso/rf satellite-assisted multiple backhauled uavs over starlink networks, IEICE Communications Express 13 (3) (2024) 52–55.

[95] T. K. Nguyen, C. T. Nguyen, H. D. Le, A. T. Pham, Tcp over hybrid fso/rf-based satellite networks in the presence of cloud coverage, IEICE Communications Express 11 (10) (2022) 649–654.

[96] I. Gueye, I. Diop, I. Dioum, K. W. Keita, P. Ndiaye, M. Diallo, S. M. Farssi, Performance analysis of mixed mimo rf/fso df relaying based on globally coupled low density parity check (gc-ldpc) codes, in: 2021 23rd International Conference on Advanced Communication Technology (ICACT), IEEE, 2021, pp. 14–22.

[97] M. Siddharth, S. Shah, R. Swaminathan, Outage analysis of adaptive combining scheme for hybrid fso/rf communication, in: 2020 National Conference on Communications (NCC), IEEE, 2020, pp. 1–6.

[98] T. V. Nguyen, H. D. Le, N. T. Dang, A. T. Pham, Average transmission rate and outage performance of relay-assisted satellite hybrid fso/rf systems, in: 2021 International Conference on Advanced Technologies for Communications (ATC), IEEE, 2021, pp. 1–6.

[99] B. Makki, T. Svensson, T. Eriksson, M.-S. Alouini, Performance analysis of arq-based rf-fso links, IEEE Communications Letters 21 (6) (2017) 1253–1256.

[100] M. R. Aghaei, A. A. Hemmatyar, A. Chamanmotlagh, M. Fouladian, Analysis of adaptive multi-rate fso/rf hybrid systems using málaga-$\mathcal{M}$ distribution model in turbulent channels, Journal of Modern Optics 67 (13) (2020) 1159–1169.

[101] H. Hemmati, Near-earth laser communications, in: Near-Earth Laser Communications, Second Edition, CRC press, 2020, pp. 1–40.

[102] S. Rangan, T. S. Rappaport, E. Erkip, Millimeter-wave cellular wireless networks: Potentials and challenges, Proceedings of the

IEEE 102 (3) (2014) 366–385.
[103] C. M. Schieler, A. S. Garg, B. C. Bilyeu, J. P. Wang, B. S. Robinson, Demonstration of reliable high-rate optical communication over an atmospheric link using arq, in: 2019 IEEE International Conference on Space Optical Systems and Applications (ICSOS), IEEE, 2019, pp. 1–6.
[104] N. Gupta, A. Dixit, V. K. Jain, et al., Ber analysis of bch codes in slow fading channel with l-ppm and dppm scheme, in: 2018 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), IEEE, 2018, pp. 1–6.
[105] N. Gupta, A. Dixit, V. K. Jain, et al., Performance analysis of bch and repetition codes in gamma-gamma faded fso link, in: 2019 National Conference on Communications (NCC), IEEE, 2019, pp. 1–5.
[106] H. D. Nguyen, H. D. Let, C. T. Nguyen, A. T. Pham, Throughput and delay performance of cooperative harq in satellite-hap-vehicle fso systems, in: 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), IEEE, 2021, pp. 01–06.
[107] H. D. Le, H. D. Nguyen, C. T. Nguyen, A. T. Pham, Fso-based space-air-ground integrated vehicular networks: Cooperative harq with rate adaptation, IEEE Transactions on Aerospace and Electronic Systems 59 (4) (2023) 4076–4091.
[108] T. T. Kapsis, A. D. Panagopoulos, Power allocation for reliable and energy-efficient optical leo-to-ground downlinks with hybrid arq schemes, in: Photonics, Vol. 9, MDPI, 2022, p. 92.
[109] K. D. Dang, H. D. Le, C. T. Nguyen, A. T. Pham, Cooperative harq-based frame allocation for optical satellite/hap-assisted backhaul networks, in: 2023 IEEE Globecom Workshops (GC Wkshps), IEEE, 2023, pp. 221–226.
[110] T.-Y. Chen, K. Vakilinia, D. Divsalar, R. D. Wesel, Protograph-based raptor-like ldpc codes, IEEE Transactions on Communications 63 (5) (2015) 1522–1532.
[111] A. A. Farid, S. Hranilovic, Outage capacity optimization for free-space optical links with pointing errors, Journal of Lightwave technology 25 (7) (2007) 1702–1710.
[112] I. K. Son, Design and optimization of free space optical networks, Auburn University, 2010.
[113] M. Najafi, B. Schmauss, R. Schober, Intelligent reflecting surfaces for free space optical communication systems, IEEE transactions on communications 69 (9) (2021) 6134–6151.
[114] H. Safi, A. Dargahi, J. Cheng, M. Safari, Analytical channel model and link design optimization for ground-to-hap free-space optical communications, Journal of Lightwave Technology 38 (18) (2020) 5036–5047.
[115] Y. Ata, M.-S. Alouini, Performance of integrated ground-air-space fso links over various turbulent environments, IEEE Photonics Journal 14 (6) (2022) 1–16.
[116] M. A. Amirabadi, V. T. Vakili, A new optimization problem in fso communication system, IEEE Communications Letters 22 (7) (2018) 1442–1445.
[117] G. Xu, N. Zhang, M. Xu, Z. Xu, Q. Zhang, Z. Song, Outage probability and average ber of uav-assisted dual-hop fso communication with amplify-and-forward relaying, IEEE Transactions on Vehicular Technology 72 (7) (2023) 8287–8302.
[118] G. Xu, M. Xu, Q. Zhang, Z. Song, Cooperative fso/rf space-air-ground integrated network system with adaptive combining: A performance analysis, IEEE Transactions on Wireless Communications (2024).
[119] J. Liang, A. U. Chaudhry, E. Erdogan, H. Yanikomeroglu, G. K. Kurt, P. Hu, K. Ahmed, S. Martel, Free-space optical (fso) satellite networks performance analysis: Transmission power, latency, and outage probability, IEEE Open Journal of Vehicular Technology (2023).
[120] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis, M. Uysal, Optical wireless links with spatial diversity over strong atmospheric turbulence channels, IEEE transactions on wireless communications 8 (2) (2009) 951–957.
[121] R. Samy, H.-C. Yang, T. Rakia, M.-S. Alouini, Hybrid sag-fso/sh-fso/rf transmission for next-generation satellite communication systems, IEEE Transactions on Vehicular Technology (2023).
[122] R. Samy, H.-C. Yang, T. Rakia, M.-S. Alouini, Reliable terabits feeder link for very high-throughput satellite systems with sag-fso transmission, IEEE Wireless Communications (2023).
[123] M. T. Dabiri, S. M. S. Sadough, M. A. Khalighi, Channel modeling and parameter optimization for hovering uav-based free-space optical links, IEEE Journal on Selected Areas in Communications 36 (9) (2018) 2104–2113.
[124] Y. Ma, J.-Y. Wang, J.-B. Wang, M. Lin, H. Zhang, C. Chang, Outage performance analysis and parameter optimization of hovering uav-based fso system, in: ICC 2020-2020 IEEE International Conference on Communications (ICC), IEEE, 2020, pp. 1–6.
[125] D. Singh, R. Swaminathan, Multiple uav-based fso system with opportunistic relay selection over malaga turbulence channel, in: 2024 IEEE 99th Vehicular Technology Conference (VTC2024-Spring), IEEE, 2024, pp. 1–6.
[126] Y. Huang, H. Huang, H. Chen, J. C. Alvarado, N. K. Fontaine, M. Mazur, Q. Zhang, R. Ryf, R. Amezcua-Correa, Y. Song, et al., Free-space optics communications employing elliptical-aperture multimode diversity reception under anisotropic turbulence, Journal of Lightwave Technology 40 (5) (2021) 1502–1508.
[127] G. D. Verma, A. Mathur, Performance improvement of fso communication systems using hybrid-arq protocols, Applied optics 60 (19) (2021) 5553–5563.
[128] Q. Sun, Q. Hu, Y. Wu, X. Chen, J. Zhang, M. López-Benítez, Performance analysis of mixed fso/rf system for satellite-terrestrial relay network, IEEE Transactions on Vehicular Technology (2024).
[129] J. Zhang, L. Zhang, G. Pan, Outage performance for noma-based fso-rf systems with a dual energy harvesting mode, IEEE Internet of Things Journal (2023).
[130] V. Srivastava, A. Mandloi, G. G. Soni, Outage probability and average ber estimation of fso system employing wavelength diversity, Optical and Quantum Electronics 51 (2019) 1–15.
[131] A. Das, B. Bag, C. Bose, A. Chandra, Aber of an fso link in gamma-gamma turbulence with ssk and sec, in: 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), IEEE, 2021, pp. 1–5.
[132] W. Yang, X. Liu, Z. Liu, S. Xiao, Multilevel polar-coded pam-8 with msb shaping over turbulent fso communication link, in: 2023 Asia Communications and Photonics Conference/2023 International Photonics and Optoelectronics Meetings (ACP/POEM), IEEE, 2023, pp. 1–4.
[133] C. Jia, P. Wang, Y. Li, C. Huang, H. Fu, W. Pang, Abers of ldpc-coded multi-hop fso over double gg fading channels with pointing error and path loss, IEEE Photonics Technology Letters 30 (15) (2018) 1357–1360.
[134] R. Miglani, J. S. Malhotra, Statistical analysis of fso links employing multiple transmitter/receiver strategy over double-generalized and gamma–gamma fading channel using different modulation techniques, Journal of Optical Communications 40 (3) (2019) 295–305.
[135] J. O. Bandele, A. O. Salau, M. Mangwala, A. M. Zungeru, Multiple transmitters for gain saturated pre-amplified fso communication systems limited by strong atmospheric turbulence and pointing error, IEEE Access (2023).
[136] R. Kumar Giri, B. Patnaik, Bit error rate performance analysis of hybrid subcarrier intensity modulation-based fso with spatial diversity in various weather conditions, Journal of Optical Communications 40 (3) (2019) 307–314.
[137] J. Sipani, P. Sharda, M. R. Bhatnagar, Modeling and design of irs-assisted fso system under random misalignment, IEEE Photonics Journal 15 (4) (2023) 1–13.
[138] H. A. Fadhil, A. Amphawan, H. A. Shamsuddin, T. H. Abd, H. M. Al-Khafaji, S. Aljunid, N. Ahmed, Optimization of free space optics parameters: An optimum solution for bad weather conditions, Optik 124 (19) (2013) 3969–3973.
[139] J.-M. Kim, J.-H. Lee, Y. Lee, Y.-C. Ko, Wdm-rofso transmission: Demonstration based on ieee 802.11 wlan standard, ICT Express

9 (6) (2023) 1110–1115.
[140] S. Srivastava, H. Singh, Performance analysis of fso communication system using nrz-msk-psk hybrid modulation techniques, in: 2023 International Conference on IoT, Communication and Automation Technology (ICICAT), IEEE, 2023, pp. 1–4.
[141] Q. Zhang, B. Liu, G. Chen, S. Zhan, Z. Li, J. Zhang, N. Jiang, B. Cao, Z. Li, An improved adaptive coding and modulation scheme with hybrid switching standard for uav–to–ground free space optical communication, IEEE Photonics Journal (2023).
[142] V. Arya, M. Kumari, R. Chauhan, N. Sharma, Full-duplex ofdm modulation based fso-fiber system for 5g scenario, in: 2023 6th International Conference on Contemporary Computing and Informatics (IC3I), Vol. 6, IEEE, 2023, pp. 838–841.
[143] S. Sharma, N. Sharma, S. Agrawal, et al., Performance analysis of dp-qpsk based fso systems under different weather conditions, in: 2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT), IEEE, 2023, pp. 1–7.
[144] M. Qasim, H. J. Abd, Performance improvement of hybrid fso/fiber optic communication system under different modulation schemes, in: 2023 Al-Sadiq International Conference on Communication and Information Technology (AICCIT), IEEE, 2023, pp. 258–262.
[145] N. Mubarakah, R. Afdila, R. N. L. Gaol, Weather variations influence on nrz and rz modulation in free space optical systems, in: 2023 7th International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM), IEEE, 2023, pp. 105–110.
[146] T. Amar, D. Samia, F. Benattou, K. Mahadjoubi, Impact of rz-dqpsk modulation generation method on fso link performance in turbulent environments, in: 2024 8th International Conference on Image and Signal Processing and their Applications (ISPA), IEEE, 2024, pp. 1–4.
[147] M. M. Amay, J. Bas, M. Á. Vázquez, A. Pérez-Neira, Modified hierarchical modulation for hybrid rf-fso satellite communication, in: 2024 27th International Workshop on Smart Antennas (WSA), IEEE, 2024, pp. 1–7.
[148] C. Drubin, Blackjack focuses on risk reduction flights and simulations to prepare for full demonstration, "[Online].Available: https://www.darpa.mil/news-events/2020-05-11, Accessed:January 16, 2024." (2020).
[149] A. A. Bisu, A. Purvis, K. Brigham, H. Sun, A framework for end-to-end latency measurements in a satellite network environment, in: 2018 IEEE International Conference on Communications (ICC), IEEE, 2018, pp. 1–6.
[150] P. Hinton, E. Baker, C. Hill, Latency–time for lawyers to get up to speed?, Computer Law & Security Review 28 (3) (2012) 340–346.
[151] T. Eylen, C. F. Bazlamaçcı, One-way active delay measurement with error bounds, IEEE Transactions on Instrumentation and Measurement 64 (12) (2015) 3476–3489.
[152] J. W. Stahlhut, T. J. Browne, G. T. Heydt, V. Vittal, Latency viewed as a stochastic process and its impact on wide area power system control signals, IEEE transactions on power systems 23 (1) (2008) 84–91.
[153] A. U. Chaudhry, H. Yanikomeroglu, Optical wireless satellite networks versus optical fiber terrestrial networks: The latency perspective: Invited chapter, in: 30th Biennial Symposium on Communications 2021, Springer, 2022, pp. 225–234.
[154] A. U. Chaudhry, H. Yanikomeroglu, When to crossover from earth to space for lower latency data communications?, IEEE Transactions on Aerospace and Electronic Systems 58 (5) (2022) 3962–3978.
[155] R. Wang, M. A. Kishk, M.-S. Alouini, Stochastic geometry-based low latency routing in massive leo satellite networks, IEEE Transactions on Aerospace and Electronic Systems 58 (5) (2022) 3881–3894.
[156] M. Handley, Delay is not an option: Low latency routing in space, in: Proceedings of the 17th ACM Workshop on Hot Topics in Networks, 2018, pp. 85–91.
[157] D. Bhattacherjee, A. Singla, Network topology design at 27,000 km/hour, in: Proceedings of the 15th International Conference on Emerging Networking Experiments And Technologies, 2019, pp. 341–354.
[158] Z. Guo, J. Liang, N. Xiao, J. Chen, B. Xie, Reliability analysis of software-defined satellite network based on control delay, in: Journal of Physics: Conference Series, Vol. 1693, IOP Publishing, 2020, p. 012145.
[159] A. U. Chaudhry, G. Lamontagne, H. Yanikomeroglu, Laser inter-satellite link range in free-space optical satellite networks: Impact on latency, IEEE Aerospace and Electronic Systems Magazine 38 (4) (2023) 4–13.
[160] J. Liang, A. U. Chaudhry, J. W. Chinneck, H. Yanikomeroglu, G. K. Kurt, P. Hu, K. Ahmed, S. Martel, Latency versus transmission power trade-off in free-space optical (fso) satellite networks with multiple inter-continental connections, IEEE Open Journal of the Communications Society (2023).
[161] S. Zhang, N. Ansari, Latency aware 3d placement and user association in drone-assisted heterogeneous networks with fso-based backhaul, IEEE Transactions on Vehicular Technology 70 (11) (2021) 11991–12000.
[162] Y. Hua, Y. Fu, Q. Zhu, Latency minimization for advanced rsma-enabled wireless caching networks, IEEE Wireless Communications Letters (2023).
[163] J.-H. Lee, K.-H. Park, Y.-C. Ko, M.-S. Alouini, Throughput maximization of mixed fso/rf uav-aided mobile relaying with a buffer, IEEE Transactions on Wireless Communications 20 (1) (2020) 683–694.
[164] H. D. Le, P. V. Trinh, T. V. Pham, D. R. Kolev, A. Carrasco-Casado, T. Kubo-Oka, M. Toyoshima, A. T. Pham, Throughput analysis for tcp over the fso-based satellite-assisted internet of vehicles, IEEE Transactions on Vehicular Technology 71 (2) (2021) 1875–1890.
[165] K.-J. Jung, S. S. Nam, M.-S. Alouini, Y.-C. Ko, Ergodic capacity analysis of uav-based fso links over foggy channels, IEEE Wireless Communications Letters 11 (7) (2022) 1483–1487.
[166] D. M. S. Islam, N. Das, M. F. Uddin, Energy efficiency analysis of fso backhauled uplink noma system, in: 2022 25th International Conference on Computer and Information Technology (ICCIT), IEEE, 2022, pp. 159–163.
[167] P. Jain, N. Javanthi, M. Lakshmanan, Ergodic capacity of mixture gamma and double generalized gamma distribution in dual hop rf/fso transmission system, in: 2023 2nd International Conference on Vision Towards Emerging Trends in Communication and Networking Technologies (ViTECoN), IEEE, 2023, pp. 1–5.
[168] H. Kong, M. Lin, Z. Wang, J. Ouyang, J. Cheng, Ergodic capacity of high throughput satellite systems with mixed fso-rf transmission, IEEE Wireless Communications Letters 10 (8) (2021) 1732–1736.
[169] R. Samy, H.-C. Yang, T. Rakia, M.-S. Alouini, Ergodic capacity analysis of satellite communication systems with sag-fso/sh-fso/rf transmission, IEEE Photonics Journal 14 (5) (2022) 1–9.
[170] T. Y. Elganimi, Performance comparison between ook, ppm and pam modulation schemes for free space optical (fso) communication systems: Analytical study, International Journal of Computer Applications 79 (11) (2013).
[171] M. Han, M. Joharifar, M. Wang, R. Schatz, R. Puerta, Y.-T. Sun, Y. Fan, G. Maisons, J. Abautret, L. Zhang, et al., High spectral efficiency long-wave infrared free-space optical transmission with multilevel signals, Journal of Lightwave Technology (2023).
[172] Y.-Q. Hong, W.-H. Shin, D.-H. Kwon, S.-K. Han, High pdg-oa-based mlpolsk modulation for spectral efficient free-space optical communication, IEEE Photonics Technology Letters 32 (1) (2019) 35–38.
[173] H. Nouri, S. M. Sait, M. Uysal, Adaptive modulation for fso im/dd systems with multiple transmitters and receivers, IEEE Communications Letters 27 (2) (2022) 586–590.
[174] H. S. Khallaf, S. Hashima, M. Rihan, E. M. Mohamed, H. M. Kasem, Quantifying impact of pointing errors on secrecy performance of uav-based relay assisted fso links, IEEE Internet of Things Journal (2023).
[175] M. Al-Nahhal, T. Ismail, Enhancing spectral efficiency of fso system using adaptive sim/m-psk and simo in the presence of atmospheric

turbulence and pointing errors, International Journal of Communication Systems 32 (9) (2019) e3942.
[176] S. Adel, N. Alshaer, T. Ismail, Enhancing spectral efficiency of ground-to-hap fso system with adaptive mask in presence of beam-wander and aoa fluctuation, in: 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), IEEE, 2022, pp. 65–70.
[177] J. Tang, D. K. So, E. Alsusa, K. A. Hamdi, Resource efficiency: A new paradigm on energy efficiency and spectral efficiency tradeoff, IEEE Transactions on Wireless Communications 13 (8) (2014) 4656–4669.
[178] F. H. Panahi, F. H. Panahi, T. Ohtsuki, Intelligent cellular offloading with vlc-enabled unmanned aerial vehicles, IEEE Internet of Things Journal 10 (20) (2023) 17718–17733.
[179] A. Mammela, A. Anttonen, Why will computing power need particular attention in future wireless devices?, IEEE Circuits and Systems Magazine 17 (1) (2017) 12–26.
[180] E. Björnson, L. Sanguinetti, J. Hoydis, M. Debbah, Optimal design of energy-efficient multi-user mimo systems: Is massive mimo the answer?, IEEE Transactions on wireless communications 14 (6) (2015) 3059–3075.
[181] Y. L. Che, W. Long, S. Luo, K. Wu, R. Zhang, Energy-efficient uav multicasting with simultaneous fso backhaul and power transfer, IEEE Wireless Communications Letters 10 (7) (2021) 1537–1541.
[182] Y. Zeng, R. Zhang, Energy-efficient uav communication with trajectory optimization, IEEE Transactions on wireless communications 16 (6) (2017) 3747–3760.
[183] K. Wang, Q. Wu, W. Chen, Y. Yang, D. W. K. Ng, Energy-efficient buffer-aided relaying systems with opportunistic spectrum access, IEEE Transactions on Green Communications and Networking 4 (3) (2020) 731–744.
[184] H. D. Le, V. V. Mai, C. T. Nguyen, A. T. Pham, Throughput analysis of incremental redundancy hybrid arq for fso-based satellite systems, in: 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), IEEE, 2019, pp. 1–5.
[185] C. Panda, U. Bhanja, Energy efficiency and ber analysis of concatenated fec coded mimo-ofdm-fso system, in: 2022 IEEE Fourth International Conference on Advances in Electronics, Computers and Communications (ICAECC), IEEE, 2022, pp. 1–5.
[186] B. Donmez, I. Azam, G. K. Kurt, Mitigation of misalignment error over inter-satellite fso energy harvesting, arXiv preprint arXiv:2306.05570 (2023).
[187] J. Zhang, H. Ran, X. Pan, G. Pan, Y. Xie, Outage analysis of wireless-powered relaying fso-rf systems with nonlinear energy harvesting, Optics Communications 477 (2020) 126309.
[188] C. Álvarez-Roa, M. Álvarez-Roa, F. J. Martín-Vega, M. Castillo-Vázquez, T. Raddo, A. Jurado-Navas, Performance analysis of a vertical fso link with energy harvesting strategy, Sensors 22 (15) (2022) 5684.
[189] N. Alshaer, A. Moawad, T. Ismail, Reliability and security analysis of an entanglement-based qkd protocol in a dynamic ground-to-uav fso communications system, IEEE Access 9 (2021) 168052–168067.
[190] V. Bankey, S. Sharma, R. Swaminathan, A. Madhukumar, Physical layer security of haps-based space–air–ground-integrated network with hybrid fso/rf communication, IEEE Transactions on Aerospace and Electronic Systems 59 (4) (2022) 4680–4688.
[191] O. B. Yahia, E. Erdogan, G. K. Kurt, I. Altunbas, H. Yanikomeroglu, Physical layer security framework for optical non-terrestrial networks, in: 2021 28th International Conference on Telecommunications (ICT), IEEE, 2021, pp. 162–166.
[192] X. Guan, Y. Cai, W. Yang, On the reliability-security tradeoff and secrecy throughput in cooperative arq, IEEE Communications Letters 18 (3) (2014) 479–482.
[193] M. Q. Vu, N. T. Dang, A. T. Pham, Hap-aided relaying satellite fso/qkd systems for secure vehicular networks, in: 2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring), IEEE, 2019, pp. 1–6.
[194] X. Pan, H. Ran, G. Pan, Y. Xie, J. Zhang, On secrecy analysis of df based dual hop mixed rf-fso systems, IEEE Access 7 (2019) 66725–66730.
[195] Y. Wang, Z. Zhan, Z. Shen, On secrecy performance of swipt energy-harvesting relay jamming based mixed rf-fso systems, in: Photonics, Vol. 9, MDPI, 2022, p. 374.
[196] Y. Zhang, X. Gao, H. Yuan, K. Yang, J. Kang, P. Wang, D. Niyato, Joint uav trajectory and power allocation with hybrid fso/rf for secure space-air-ground communications, IEEE Internet of Things Journal (2024).
[197] Y. Sim, S. Sin, J. Ma, S. Moon, Y.-H. You, C. H. Kim, I. Hwang, Ris-aided double beamforming optimization algorithm for improving secrecy rate in space-ground integrated networks, ICT Express (2024).
[198] A. M. Ragheb, W. S. Saif, S. A. Alshebeili, Ml-based identification of structured light schemes under free space jamming threats for secure fso-based applications, in: Photonics, Vol. 8, MDPI, 2021, p. 129.
[199] A. B. Ibrahim, A. M. Ragheb, W. S. Saif, S. A. Alshebeili, Structured light transmission under free space jamming: an enhanced mode identification and signal-to-jamming ratio estimation using machine learning, in: Photonics, Vol. 9, MDPI, 2022, p. 200.
[200] Q. Guo, N. Kato, F. Tang, Energy efficient routing for fso-rf space-air-ground integrated network: A deep reinforcement learning approach, in: 2023 8th IEEE International Conference on Network Intelligence and Digital Content (IC-NIDC), IEEE, 2023, pp. 254–258.
[201] G. D. Chondrogiannis, N. A. Mitsiou, N. D. Chatzidiamantis, A.-A. A. Boulogeorgos, G. K. Karagiannidis, Power-optimal harq protocol for reliable free space optical communication, in: 2023 IEEE International Conference on Communications Workshops (ICC Workshops), IEEE, 2023, pp. 1765–1770.
[202] A. Touati, M. O. Hasna, F. Touati, Harq performance over fso channels with atmospheric fading and pointing errors, in: 2018 14th International Wireless Communications & Mobile Computing Conference (IWCMC), IEEE, 2018, pp. 158–163.
[203] D. Singh, R. Swaminathan, A. Marrapu, A. Madhukumar, Performance analysis of multiple haps-based hybrid fso/rf space-air-ground network, in: 2024 16th International Conference on COMmunication Systems & NETworkS (COMSNETS), IEEE, 2024, pp. 920–926.
[204] J.-Y. Wang, P. Feng, L.-H. Hong, H.-N. Yang, N. Liu, Performance evaluation and optimization of uav-based hybrid dual-hop fso/uowc systems, IEEE Systems Journal (2024).
[205] P. Sharma, D. Singh, R. Swaminathan, Performance analysis of uav-based fso communication over doubly inverted gamma-gamma turbulence channel, in: 2024 National Conference on Communications (NCC), IEEE, 2024, pp. 1–6.
[206] X. Yu, Y. Dong, J. Wang, G. Xu, J. Chen, X. Liu, Z. Song, Dual-hop optical communication for space-air-ground integrated network over foggy channel under málaga turbulence, in: 2023 IEEE 23rd International Conference on Communication Technology (ICCT), IEEE, 2023, pp. 96–101.
[207] Z. Qadir, K. N. Le, N. Saeed, H. S. Munawar, Towards 6g internet of things: Recent advances, use cases, and open challenges, ICT express 9 (3) (2023) 296–312.
[208] F. H. Panahi, F. H. Panahi, T. Ohtsuki, Energy efficiency analysis in cache-enabled d2d-aided heterogeneous cellular networks, IEEE Access 8 (2020) 19540–19554.
[209] J. Zhang, Y. Zeng, R. Zhang, Spectrum and energy efficiency maximization in uav-enabled mobile relaying, in: 2017 IEEE International Conference on Communications (ICC), IEEE, 2017, pp. 1–6.
[210] H. Hu, X. Da, Y. Huang, H. Zhang, L. Ni, Y. Pan, Se and ee optimization for cognitive uav network based on location information, IEEE Access 7 (2019) 162115–162126.
[211] K. Li, X. Zhu, Y. Jiang, F.-C. Zheng, Closed-form beamforming aided joint optimization for spectrum-and energy-efficient uav-bs networks, in: 2019 IEEE Global Communications Conference

(GLOBECOM), IEEE, 2019, pp. 1–6.
[212] K. Li, T. Zhang, R. Wang, Deep reinforcement learning for multiobjective optimization, IEEE transactions on cybernetics 51 (6) (2020) 3103–3114.
[213] L. Zhao, C. Wang, K. Zhao, D. Tarchi, S. Wan, N. Kumar, Interlink: A digital twin-assisted storage strategy for satellite-terrestrial networks, IEEE Transactions on Aerospace and Electronic Systems 58 (5) (2022) 3746–3759.
[214] Y. Zhou, R. Zhang, J. Liu, T. Huang, Q. Tang, F. R. Yu, A hierarchical digital twin network for satellite communication networks, IEEE Communications Magazine 61 (11) (2023) 104–110.