A Review on FSO/RF based Satellite-Aerial-Ground Communication Systems

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***Abstract*—Thanks to its unique and fundamental characteristics, Free Space Optic (FSO) has emerged as a significant choice for both fronthaul and backhaul links in satellite-aerial-ground (SAG) communication systems. These features have rendered FSO a key player in recent and future network systems and use more feasible in the first-hop of communication channel i.e., from satellite-High Altitude Platform (HAP). However, ensuring a dependable FSO connection to subsequent HAP-Ground Station (GS) network becomes challenging due to the adverse impact of weather and atmospheric conditions. An optimal solution is implementing a hybrid FSO/RF approach for the second leg of HAP-to-GS communication. In this configuration, the Radio Frequency (RF) link acts as a contingency connection in the event of FSO link breakdown. However, a notable limitation of hybrid FSO and RF links lies in the constrained spectral capacity of the RF link, especially when the FSO link encounters obstruction due to cloud cover in the second hop. In order to address this challenge, a solution has been devised involving the deployment of an additional unmanned aerial vehicle (UAV) to diversify the path of FSO link from HAP-UAV-GS, thus preventing cloud blockages while preserving the high speed functionality of the FSO link. This approach incorporates a mirror array constructed using reconfigurable intelligent surface (RIS) technology, an emerging and adaptable solution. The RIS-UAV channel model takes into consideration turbulence-induced and pointing errors due to hovering, offering a comprehensive strategy to overcome the issues arising from adverse weather conditions. This work begins by presenting a taxonomy of single-hop, dual-hop, and multi-hop FSO/RF-based SAG networks. It then proceeds to provide an assessment, discussion, and review of prior research endeavors related to FSO/RF fronthaul and backhaul links. Furthermore, it identifies current open research problems and challenges, while presenting potential research directions for in-depth analysis and investigation.**

***Index Terms*—FSO/RF link, dual-hop, RIS-UAV, HAP**

I. Introduction

In the realm of 6G and beyond communication technology, there's a growing demand for achieving extremely high data access and transmission rates, reaching into the ultra-high Gbps and Terabytes, all while maintaining incredibly low latency and ensuring high-quality services (QoS). This requirement has become increasingly vital as Internet-of-Remote Things (IoRT) experiences significant growth and advancement, extending its support to non-urban and remote rural areas, including even oceanic regions [1].

The concerns about air-ground connection and coordination have gained widespread attention in academic circles and the technological industry [2]. As a result, the development of satellite communication systems has become a reality, not only to achieve seamless coverage of wireless communication but also to provide substantial support for economic development and social stability [3].

The integration of satellite networks with terrestrial communication systems has proven to be an effective solution, especially when it comes to the incorporation of satellite communication. Satellite communication networks and ground-based mobile communication systems complement each other in terms of coverage, capacity, speed, and various other aspects within the realm of 5G/6G communication [4]. In the study presented in [5], it is evident that direct links between space-ground communication networks face significant vulnerabilities, primarily due to factors such as atmospheric turbulence, signal fading, path loss resulting from long-distance travel, and masking effects. Atmospheric turbulence introduces notable differences between Free Space Optical (FSO) uplinks (ground-to-satellite connections) and FSO downlinks in satellite communications.

In the uplinks, laser beam signals immediately encounter atmospheric turbulence, leading to severe distortions owing to spatial and temporal changes in the refractive index of the atmosphere. Conversely, challenges also exist in downlinks, where signals experience beam divergence loss (geometric spreading loss) and encounter minor spreading due to atmospheric turbulence. Generally, the impact of atmospheric turbulence on downlink signal propagation is less pronounced than on uplink propagation. This is because the light beam signals swiftly traverse a non-atmospheric path until they reach an altitude of about 20 km above ground level, which is referred to as the troposphere.

To mitigate these challenges and address other issues, satellite-ground communication is enhanced through the use of an intermediate station cooperative model known as HAP. HAP serves as decode-and-forward (DF) and amplify-and-forward (AF) relaying point [5] and creates the single-hop (i.e., Satellite-ground) into dual-hop (i.e., satellite-HAP and HAP-ground). These networks are becoming increasingly essential for delivering effective and reliable multi-access applications and services to end users, regardless of their locations [2] [6] [7].

In the context of a satellite-aerial-terrestrial network, where ground users broadcast data to space communication (uplink), HAPs serve as relay points [7] and it provides several advantages; including deployment flexibility, ease of maintenance, cost-effectiveness, and the ability to cover large distances [8]. FSO as an optical carrier stands out as a prominent choice for fronthaul and backhaul networks, in conjunction with traditional RF. FSO communication systems offer the ability to transport high-speed data in the form of light signals over extended distances. They establish high-speed point-to-point communication links, boasting high bandwidth capacity, rapid data rates, reliable channel security, low electrical power consumption, freedom from licensing requirements for carrier frequency spectrum, and the potential for more compact system designs compared to their RF counterparts.

However, despite these advantages, it's important to note that FSO communication is not without its limitations. Indeed, FSO communications are subject to several challenges and limitations. Some of the problems associated with FSO include the impact of atmospheric factors such as absorption, scattering, and turbulence [9], as well as issues like pointing errors, beam scintillation, and beam wandering. Among these factors, atmospheric turbulence is a particularly significant challenge that can lead to substantial degradation in the performance of bit error rate (BER), rendering communication links infeasible.

To address these issues, the use of hybrid FSO/RF links to serve as a contingency measure in the event of FSO link failure is recommended [1] [6]. This is because RF is less affected by cloud coverage and atmospheric turbulence. However, RF links have their own limitations, including susceptibility to heavy rain, limited capacity, low bandwidth, spectrum congestion, and security concerns. Therefore, FSO communication is not intended to replace RF communication entirely but rather to coexist with it. Hybrid FSO/RF or both links are employed in a complementary manner when atmospheric turbulence and heavy rain are present in the environment.

In HAP-based aerial-ground communications, the use of a hybrid FSO/RF link, as opposed to an FSO link alone, can introduce challenges such as lower data rates and increased latency due to the need for conversion between optical and electrical signals, or vice versa, caused by the presence of atmospheric turbulence and/or cloud coverage between HAP) and GS, especially when the FSO link experiences blockages and the RF link is utilized as a backup more frequently [10]. To address these challenges, a new network scenario involving UAVs has been developed to function as relay nodes [6].

To address the issues related to pointing errors caused by the hovering nature of UAVs and atmospheric turbulence, the RIS-UAV channel model, as discussed in [6], is employed. A Reconfigurable Intelligent Surface (RIS) is utilized as a mirrored array device connected to a UAV. Its purpose is to reflect beam signals originating from the HAP down to GS, thereby solving the non-line of sight (NLoS) problem. This approach enables the establishment of a line of sight (LoS) link by deploying UAV relays between the HAP and GSs.In FSO communication, transmitter-receiver line-of-sight communication is essential. FSO typically employs narrow beams that lack the ability to penetrate obstacles or achieve permeability. As a result, communication can fail when non-line of sight (NLoS) conditions exist between the transmitter and receiver [11] [12].

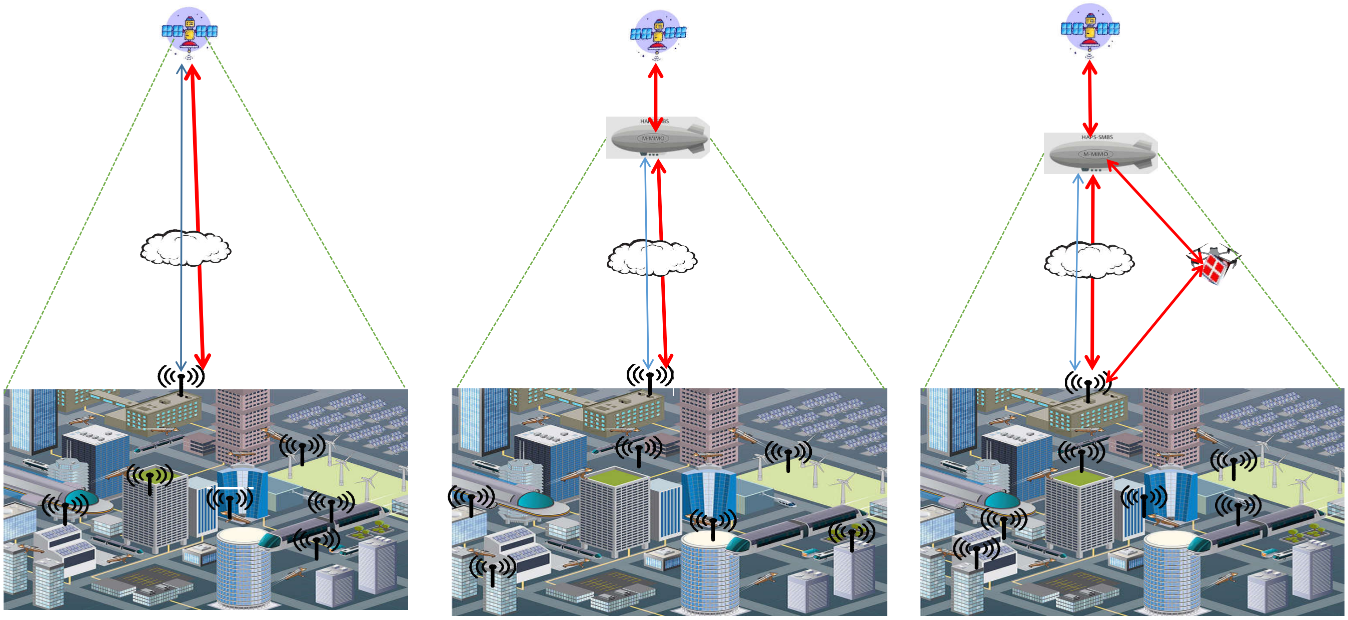
Using UAVs as intermediate relays can provide a solution to meet the requirements for massive access by remote smart devices, creating opportunities for improved connectivity in a broad spectrum of applications.

II. FSO/RF based Satellite-Aerial-Ground Communication

We can classify the research on hybrid FSO/RF link SAG communications into three distinct structures based on the layers between the source and the destination of signals [13] [14], as depicted by Fig.1. These classifications are: Single Hop Structure- a straightforward and a single hop architecture that signals are transmitted directly from source to destination without passing through an intermediate relay and the communication occurs in between satellite and ground station; Dual Hop Structure- a structure that involves the use of one intermediate node, such as a HAP or UAV, functioning as a relay. Lastly, Multi-Hop Structure- a structure having mostly two or more intermediate nodes or devices (i.e., HAP and UAV) employed as relays, to enhance communication between the satellite and ground station. This structure introduces additional hops to the communication process, leading to more complex but potentially more robust communication routes. These different structural classifications allow researchers to explore various approaches to FSO/RF based SAG communication, each with its unique advantages and challenges. In the subsequent sections, we will provide a detailed assessment and explanation of recent research in these categories to further elucidate the developments in FSO/RF based SAG communication and Fig. 2. shows the taxonomy of these recent works into different hops.

A. Single-hop FSO/RF based Satellite-Ground communications

In the Single-hop structure of transmission, as illustrated in Fig. 1(a), no intermediary networking device involved as the data packet travels directly from the source to the destination. The transmission signal travels from the source to the remote destination exclusively through a hybrid FSO/RF link. This architecture is characterized by significantly high data rates and is particularly effective when used over short distances between senders and receivers. The study presented in [15] highlights the importance of achieving seamless connections between satellites and ground stations, emphasizing the significance of maximizing site diversity by selecting the best ground stations with optimal channel conditions. Despite its advantages, the overall performance of hybrid FSO/RF communication systems is highly dependent on the atmospheric and weather conditions in the area where they are deployed. Such affecting factors are; cloud coverage, rain, fog, haze, and snow have huge impact on the performance of FSO communication. Especially atmospheric turbulence is a major degrading factor that can lead to the absorption, refraction, and weakening of transmission signals, causing fluctuations in the received optical signal's irradiance and this phenomenon is often referred to as the scintillation effect [15] [16] [17] [18]. The sensitivity of single-hop hybrid FSO/RF links to these atmospheric and weather conditions necessitates careful consideration and mitigation strategies when deploying such systems.



a) Single-hop FSO/RF Link b) Dual-hop FSO/RF Link C) Multi-hop FSO/RF Link

Fig. 1: Single, Dual and multi-hop FSO/RF based SAG

To end up this section, in the lower atmospheric layer (in troposphere) i.e., from the Earth's surface up to at the height of approximately 18-20 km, the impact of weather on this model is huge because of lengthy distance between the source and destination of signals. In such conditions, using the FSO link alone may not be feasible due to those factors and using the backup RF link absolutely essential. As a result, the development of High altitude platform station (HAPS) that provides a connectivity services between terrestrial and satellite technologies [6] solves some problems of this hop.

B. Dual-hop FSO/RF based Satellite-Ground communications

In the dual-hop structure, as shown in Fig. 1(b), an intermediary device HAP is introduced and serving as a relay to extend network coverage and provide reliable transmission to underserved or uncovered regions. The deployment of this hop relay offers the benefits of system capacity enhancement and the reliability of transmitted signal and simultaneously, it can lead to a reduction in the overall power consumption [13]. An important consideration in here is the choice of relaying scheme and Decode-and-Forward (DF) relaying is preferred as it can provide better noise performance compared to Amplify-and-Forward (AF) relaying [18]. After receving satellite signals, the HAP detects the noise signals and amplify the source signals and send to the ground station. Recent works categorized under this class and uses A hybrid FSO/RF link are [5], [7], [18]–[28].

Since the HAP is positioned in the atmospheric zone of stratosphere, and which is less prone to turbulence and cloud cover, we utilize a FSO link for the high-speed connection from the satellite to the HAP. In the second hop, which involves communication between HAPs and GS, it's important to note that the impact of weather conditions on FSO and RF links differs [16]. These two types of links complement each other [29], as a result, a hybrid FSO/RF system that incorporates a switching mechanism, prioritizing FSO link as the primary option. RF link is designated as the backup solution for scenarios where the optical channel conditions do not support the required high data rate. When cloud obstructions impact the primary FSO link between HAP and GS, the system seamlessly transitions to an alternative strategy. This secondary approach involves RF transmission, facilitating a direct link between the HAP and GS. This dynamic switching system ensures robust and uninterrupted communication under varying conditions.

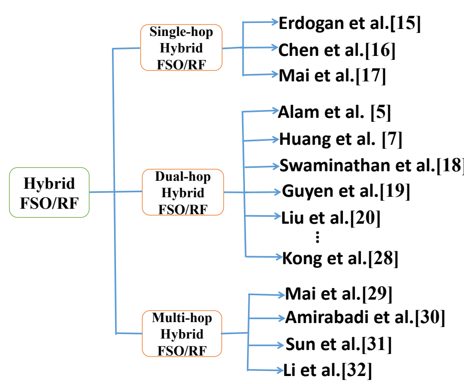


Fig. 2: Taxonomy of FSO/RF based SAG

C. Multi-hop FSO/RF basedSatellite-Ground communications

As shown in figure 1(c), the network structure has three levels; satellite-HAP, HAP-UAV, and UAV-GS [6]. This multi-hop structure employing hybrid FSO/RF schemes utilizes two or more relaying devices to establish communication between satellite and ground networks. These relaying devices operate using a detect-and-forward relay scheme [6], [30]–[33]. Hybrid FSO/RF scheme considering as the backhaul link between each hop ensure reliable and error-free signal transmission. However, HAP-based SAG employing the hybrid FSO and RF link faces significant challenges such as reduced data rates and an extra dalliance resulting from optical signal to electrical signal and vise versa conversions. This issue becomes especially apparent when there is cloud cover, which may obstruct the FSO scheme, leading to more frequent use of the backup RF link [10].

To effectively address this network scenario, a viable solution involves the rapid deployment of an additional UAV as a relay node [6]. This UAV can diversify the FSO link from HAP-ground in case of blockage from cloud. Furthermore, this solution incorporates an emerging technology called a reconfigurable intelligent surface (RIS) array [6]. The purpose of RIS array is to redirect the incoming light signal emitted by the HAP, ensuring precise alignment and direction of the transmitted light signal toward GS. In this analysis, we designate the FSO-based SAG network, which utilizes FSO transmissions as the primary link for both hops (Satellite-HAP and HAP-GS). However, in scenarios where cloud coverage obstructs the primary FSO-based link from the HAP-GS, a system transitions to transmission strategy 2 i.e., from HAP-UAV [6]. In accordance with the information presented in this paper, FSO link originating from the HAP via the UAV is manipulated through a process of reversal and forwarding by the UAV's RIS, ultimately facilitating the transmission of the optical signal to GS. So, If the the mentioned two transmission mechanisms become unavailable, such as when there is weather attenuation and/or blocked by cloud on the primary link (FSO) and strong turbulence in transmission strategy 2 (the RIS-UAV) relay link, the third transmission mechanism(RF) is activated. In this case, RF link is used for the network link between HAP-GS. This approach ensures reliable communication even in challenging conditions, with a seamless transition between FSO and RF transmission methods based on the prevailing environmental factors.

To determine whether to switch from FSO to RF, [6] [18] utilize the instantaneous thresholds of average bit error rate(average BER) of the FSO link, compare it with a predefined minimum threshold of FSO average BER, and make the decision based on these values. If the former exceeds the later, the system switches from FSO to RF; otherwise, FSO continues to operate as the backhaul link. Channel State Information (CSI) plays a crucial role for switching strategy. CSI plays a pivotal role in the communication system, as it conveys essential information for making informed decisions regarding data rate selection and link utilization. This information is based on the estimated Signal-to-Noise Ratios (SNRs) of received signals [10]. To optimize data rates over wireless channels while adhering to predefined Quality of Service (QoS) standards, an adaptive multi-rate scheme is employed [10]).

To enable the selection of appropriate data rates and links, a channel estimator is implemented at the destination, particularly on UAVs. This channel estimator is responsible for estimating CSI for both FSO and RF links. These CSI estimations are critical for guiding the selection of transmission rates and links based on the received SNRs. This process ensures that the communication network operates efficiently while meeting the predefined QoS standards.

It's worth noting that this study assumes the reliability of the feedback channel, which is responsible for carrying CSI information. The temporal coherence times of the FSO and RF links considered in this context are relatively long compared to the time slot duration. This extended duration ensures that CSIs remain up-to-date. Leveraging these up-to-date CSIs, the satellite's rate-adaptive controller and HAP's switching controller dictate the selection of data rates and transmission links, respectively, ensuring efficient communication network performance [10].

To end up the section, Multi-hop FSO/RF based Satellite-Ground communications is an efficient communication system even if it has complex nature and relatively high cost of deployment.

III. Challenges and Future Research Directions

Hybrid communication systems integrating FSO and RF technologies for satellite and aerial networks present a frontier of research with inherent challenges. One significant challenge lies in achieving seamless coordination and efficient switching mechanisms between FSO and RF links. The dynamic nature of aerial platforms and varying atmospheric conditions necessitates the development of adaptive protocols to ensure smooth transitions between the two communication modalities, optimizing for both reliability and data rates. Additionally, addressing security concerns related to the coexistence of FSO and RF signals is imperative. The integration of robust encryption methods and interference mitigation strategies becomes paramount to safeguarding communication channels and ensuring the integrity of data transmitted across the hybrid network.

Efficient resource management represents another critical area of investigation. Balancing power control, bandwidth allocation, and spectral efficiency between FSO and RF links requires advanced algorithms and intelligent networking solutions. Moreover, scalability and energy efficiency are pressing research issues, particularly in the context of aerial networks where power constraints are prevalent. Developing scalable architectures that can seamlessly handle the increasing demand for connectivity while minimizing energy consumption is pivotal for the sustainable deployment of hybrid FSO/RF-based satellite and aerial networks. Addressing these multi-faceted challenges is crucial to unlocking the full potential of hybrid communication systems, offering resilient and high-performance connectivity in diverse and dynamic environments.

IV. Conclusion

This paper provides an overview and discussion of FSO and RF based SAG communication systems. Specifically, the paper starts by presenting a taxonomy of recent research studies related to the single-hop, dual-hop, and multi-hop structure of hybrid FSO/RF links in satellite-terrestrial communication networks. It then conducts a comprehensive review and discussion of existing works categorized under these structures.

In conclusion, the paper highlights current research challenges and identifies open research issues that warrant further investigation and analysis in the field of FSO/RF based SAG communication systems.

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