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A Comprehensive Review of Hybrid Radio Frequency (RF) and Free-Space Optics (FSO) Communication Systems

Abdikarim Ismail Abdi [1], Er. Amandeep Kaur Brar [2],

1 Student at Department of Electronics and communication Engineering, Punjabi University, Patiala, Punjab - 147002, India
cabdikariim025@gmail.com

2 Assistant Professor at Department of Electronics and communication Engineering, Punjabi University, Patiala, Punjab - 147002, India
amanbrar123@gmail.com

ABSTRACT

Radio frequency (RF) and free-space optics (FSO) communications are two important technologies. They can help fix each other's weaknesses. Hybrid RF/FSO systems combine the high data rates and low latencies offered by FSO with the resilience and vast coverage provided by RF. Therefore, they are suitable for various applications, including mobile networks and satellite communications. This study offers a comprehensive analysis of the advancements in hybrid RF/FSO communication systems, with a special emphasis on performance evaluation, system topologies, and optimisation approaches. The basic technologies involved include Alamouti coding, antenna and relay selection, connection adaptation, and security techniques. This survey examines hybrid systems within the context of 5G and future networks with advanced artificial intelligence and machine learning to enhance system performance.

Keywords**:** Hybrid Communication Systems, Radio Frequency (RF), Free-Space Optics (FSO), Alamouti Coding, Link Adaptation, Relay Selection, Antenna Diversity, 5G Networks, Machine Learning, Security, RF/FSO Integration, System Performance, Atmospheric Turbulence, Communication Networks, Next-Generation Networks, Wireless Communications.

INTRODUCTION

Due to the rising demand for high-data-rate, dependable, and energy-efficient communication systems, hybrid RF and FSO communication systems have garnered considerable interest in recent years. These systems seek to utilize the combined advantages of both RF and FSO technologies to improve performance regarding capacity, reliability, and coverage.

RF communication technologies give resilience to inclement weather and support for mobility, while FSO systems deliver elevated data speeds, enhanced security, and operating in a license-exempt spectrum. Nonetheless, each of these methods possesses intrinsic limitations. RF communication is limited by restricted spectrum availability and interference, whereas FSO is affected by atmospheric turbulence, misalignment, and pointing errors[1] [2][3] .

Hybrid RF-FSO systems have been suggested as an effective approach to address these limitations through the integration of both communication paradigms. This hybrid method offers adaptive switching and diversity strategies to guarantee uninterrupted data transmission over fluctuating channel conditions [4] [5] by dynamically allocating resources according to channel state information (CSI), these systems attain superior spectrum efficiency and reliability in comparison to independent RF or FSO systems [6]. Moreover, hybrid RF-FSO systems provide effective connection adaptation mechanisms, guaranteeing continuous communication despite unfavorable environmental conditions.

Dual-hop relaying methods, such as decode-and-forward (DF) and amplify-and-forward (AF), improve the performance of hybrid RF-FSO systems by extending their range and mitigating channel imperfections[7] [8]. Relay-assisted transmission bolsters system resilience by introducing path diversity, minimising the risk of outage probability, and enhancing signal quality. Furthermore, hybrid RF-FSO networks can employ multiple-input multiple-output (MIMO) and cooperative relaying strategies to further strengthen the link reliability and expand the transmission capacity [4] [5].

Recent research has extensively analysed the performance of hybrid RF-FSO systems under various channel conditions, including generalised fading models and pointing errors. These studies have explored diversity-combining techniques, such as selection combining and maximal ratio combining , to optimise system performance in different environments[9][10]. Additionally, advanced coding schemes, including Alamouti coding and space-time block coding , have been investigated to enhance link reliability in hybrid communication setups[11][12]. These strategies seek to reduce the detrimental impacts of fading, turbulence, and misalignment, thereby guaranteeing stable connectivity and throughput in hybrid networks. Additional advancements, including adaptive modulation, hybrid automatic repeat request protocols, and intelligent resource allocation, have been implemented to optimise spectrum efficiency and energy usage.

Despite extensive research on hybrid RF-FSO systems, several challenges remain unaddressed. The impact of adaptive relaying protocols, interference management, and energy efficiency optimisation requires further investigation. Moreover, realistic implementations and experimental validations are vital for turning theoretical developments into real-world applications[13] [14] Other major issues include integrating hybrid RF-FSO systems with upcoming wireless networks, developing efficient resource-allocation algorithms, and advancing machine-learning-based adaptive communication techniques to improve performance dynamically[5] [15].

Emerging technologies, such as 5G and beyond, necessitate ultra-reliable and low-latency communication, positioning hybrid RF-FSO systems as crucial for future wireless networks. These systems can markedly improve network performance in smart cities, disaster recovery systems, and deep-space communication. Future research should concentrate on novel modulation schemes, intelligent network management, and the seamless integration of RF-FSO systems with artificial intelligence-driven optimization techniques to enhance efficiency and reliability.

HYBRID SYSTEM ARCHITECTURE

A hybrid system combining RF and FSO communication enhances reliability by merging the high-speed capabilities of FSO with the consistent performance of RF. This system switches between optics and RF channels based on the prevailing conditions of the environment. In hard switching, data are transmitted solely through either the optics or RF link, depending on which is available, whereas soft switching allows simultaneous data transfer across both channels, improving speed and stability. FSO links are vulnerable to weather conditions such as rain, fog, and haze, which can scatter or absorb light, whereas RF links, particularly those operating above 10 GHz, suffer from signal degradation due to rain. Hybrid RF/FSO systems aim to maximise connection availability by leveraging the strengths and compensating for the weaknesses of each link, particularly in areas with adverse weather. These systems are beneficial for terrestrial applications, including mobile networks, remote control, and high-speed point-to-point communication over short distances. In tropical regions, where the weather often affects FSO reliability, predictive models use local climate data to evaluate atmospheric attenuation effects and determine link availability. RF channels at higher frequencies are typically chosen to maintain data rates similar to those of FSO links, although they are more susceptible to rain attenuation. By effectively managing environmental factors such as pointing errors and turbulence, which cause signal scattering, hybrid RF/FSO models deliver dependable and high-performance communication through efficient channel switching[16].

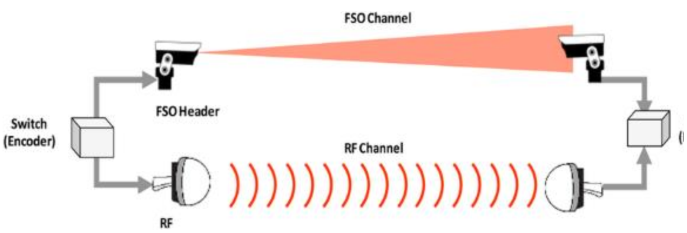

FIGURE 1 Hybrid RF/FSO system's architecture[16]

Hybrid RF-FSO communication systems have been extensively researched for their capacity to integrate the advantages of RF and FSO technologies while mitigating their respective shortcomings. The research regarding hybrid RF-FSO systems predominantly emphasizes system architecture, performance assessment, channel modeling, diversity methodologies, and optimization tactics. This section offers a comprehensive analysis of the current research, emphasizing significant contributions and discoveries.

SYSTEM ARCHITECTURE AND RELAYING STRATEGIES

Hybrid RF-FSO systems frequently utilize relay-assisted transmission to improve reliability and broaden coverage. Numerous research has examined various relaying methods, including amplify-and-forward (AF) and decode-and-forward (DF), to alleviate fading and turbulence effects.

[1]Examined mixed mm Wave RF/FSO relaying systems under generalised fading conditions, emphasising the influence of pointing errors and turbulence on system performance. The results indicate that hybrid systems surpass independent RF and FSO systems in challenging channel conditions by utilising adaptive switching methods.

[2] Performed a performance analysis of hybrid RF-FSO systems with AF selection relaying, demonstrating that the selection of the optimal relay markedly enhanced the outage probability and spectrum efficiency. They underscored the significance of relay positioning and selection in enhancing the system performance.

[3]Examined the performance trade-offs between reliability and energy efficiency in hybrid RF/FSO systems. The research indicated that hybrid systems employing intelligent relay selection and adaptive transmission can enhance energy efficiency while ensuring dependable connectivity, rendering them appropriate for energy-limited applications.

[17]A hybrid RF-FSO THz relay communication system was introduced to deliver high-speed, low-latency, and dependable data transmission. This system employs a hybrid RF-FSO communication approach, utilising an adaptive combining scheme for the backhaul network before reaching the relay node, and subsequently connecting to users via a THz link. The authors developed performance equations that consider atmospheric turbulence and pointing errors in the FSO link, as well as fading and pointing errors in the THz link. The simulation results indicate that the adaptive combining scheme in the initial hop of the relay system outperforms the single-threshold switching and single-link FSO systems. The research also assesses the system's performance under different fading conditions and pointing errors, concluding that both elements can negatively impact system performance.

CHANNEL MODELING AND PROPAGATION CHARACTERISTICS

Hybrid RF-FSO communication connections encounter many limitations, including atmospheric turbulence, fading, and aiming inaccuracies. Researchers have suggested multiple approaches to delineate these deficiencies and assess the system performance.

[6]Investigated dual-hop free-space optics transmission systems affected by gamma-gamma turbulence. Their investigation elucidated the impact of turbulence-induced fading on the signal quality and

presented diversification strategies to alleviate these impacts.

[8] Introduced an adaptive hybrid RF-FSO communication system that alternates between RF and FSO links according to real-time channel state information. Their research illustrated how adaptive switching diminishes the chance of an outage and guarantees dependable data transfer amid fluctuating weather conditions. [18]Examined mixed RF and multi-hop FSO systems under κ–μ shadowed and Exponentiated Weibull fading circumstances. They conducted an extensive statistical analysis of the effectiveness of hybrid systems and suggested ideal relay placements to reduce the impact of severe fading.

[14] This study focused on an asymmetric dual-hop RF-FSO communication system that employs Nakagami-m fading for RF links and Malaga turbulence fading for FSO channels. Detailed expressions for the outage probability and ergodic channel capacity were derived, including asymptotic analyses at high signal-to-noise ratios. This study provides insights into the performance of FSO communication systems in multiplexing RF signals for high data rate transmission.

This method involves analysing the system using specific channel models, deriving closed-form equations for both the outage probability and ergodic channel capacity, and performing numerical simulations in MATLAB. Furthermore, the effects of the heterodyne and IM/DD detection techniques on the system performance were evaluated by comparing them. The discourse emphasised the study's contributions to RF-FSO system analysis and stated that the Malaga-distribution serves as a generic channel model for FSO systems. It highlighted the importance of the derived expressions in comprehending system behaviour under varying settings and enhancing the effectiveness of FSO communication.

DIVERSITY COMBINING AND MODULATION TECHNIQUES

Diversity approaches are essential for enhancing the reliability and performance of hybrid RF-FSO systems. Researchers have investigated selection combining, maximal ratio combining, and equal-gain combining to alleviate fading and turbulence effects.

[4] examined link adaptation strategies for hybrid RF-FSO systems and suggested adaptive modulation schemes to enhance spectral efficiency. Their research revealed that hybrid systems may dynamically modify modulation levels according to channel circumstances to enhance throughput and reduce the average bit error rate.

[7] investigated hybrid RF-FSO systems utilising Alamouti coding and antenna selection methodologies. Their research demonstrated that space-time coding improves link dependability and guarantees resilient communication under variable channel conditions.

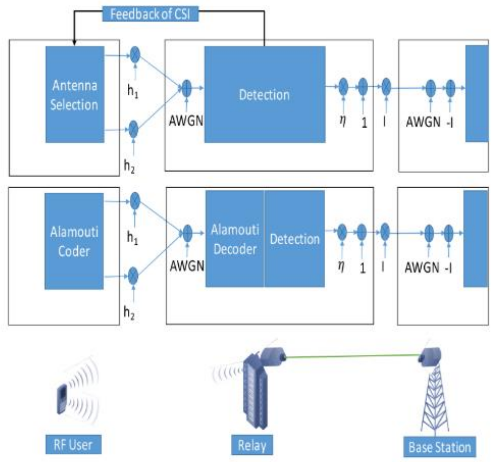

Figure 2 Hybrid RF/FSO structure of antenna selection and Alamouti coding scheme[7]

[9] and [10] Examined diversity integration methods, including MRC and SC, to enhance system performance. Their research validated that hybrid RF-FSO systems utilizing MRC attain substantial

enhancements in outage probability and signal quality relative to SC.

[12]Investigated hybrid RF-FSO systems utilizing STBC (Space-Time Block Coding) users, demonstrating that STBC-based hybrid systems surpass traditional hybrid systems regarding ABER and spectrum efficiency. Their research underscored the significance of coding methodologies in hybrid networks.

[19]This study presented a comprehensive performance analysis of a hybrid (RF/FSO) communication system, considering a single-threshold-based switching strategy for both terrestrial and satellite communication scenarios. The authors derive closed-form expressions for outage probability, average symbol error rate (SER), and ergodic capacity, assuming generalized Malaga distribution for the FSO link and α-η-κ-μ distribution for the RF link. This study also provides asymptotic expressions for obtaining the diversity and coding gains. Additionally, the authors determined the optimum switching threshold and beam waist values for optimal performance. The results, verified through Monte Carlo simulations, show that the hybrid RF/FSO system significantly outperforms the single-link FSO system, particularly in the presence of strong turbulence, high pointing errors, and adverse weather conditions.

[20]Explored affordable backhaul options for future wireless networks, with particular emphasis on small cell installations. This makes a case for using non-line-of-sight (NLOS) RF backhaul within sub-6 GHz licenced spectrum bands, emphasising its cost benefits compared to other backhaul options. Despite the limitations in data speed and latency associated with RF backhauls, this study suggests an innovative hybrid RF/FSO backhaul solution. This hybrid model merges the benefits of RF backhauls, such as low cost and NLOS capabilities, with the high speed and low latency of the FSO backhauls. This study tackles the challenge of reducing backhaul planning expenses while meeting reliability, connectivity, and data rate requirements, and proposes a heuristic algorithm based on graph theory to select the most cost-effective backhaul link between base stations.

MACHINE LEARNING AND INTELLIGENT RESOURCE ALLOCATION

With the increasing complexity of hybrid RF-FSO systems, there is a growing focus on leveraging machine learning and artificial intelligence to boost their performance and streamline decision-making processes.
[15]Examined the physical-layer security of hybrid RF-FSO systems using simultaneous wireless information and power transfer. Their research presented AI-based resource allocation strategies to enhance power efficiency and security while ensuring communication reliability.

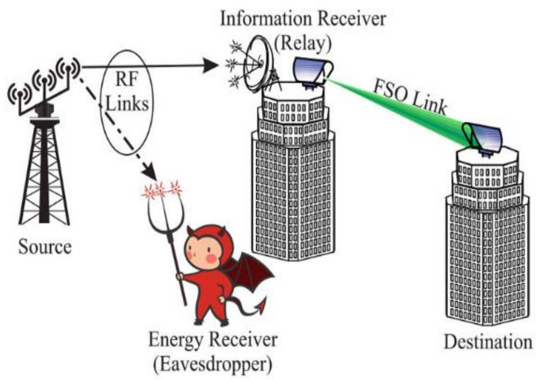

Figure 3 Mixed SIMO SWIPT RF and FSO cooperative communication system.[15]

[5] The study focused on hybrid RF-FSO systems for 5G C-RAN applications, suggesting that adaptive resource allocation using machine learning could improve link selection and boost network performance. The research highlighted the promise of AI-driven solutions in sophisticated hybrid networks.

[11] Introduced a relay-based hybrid RF-FSO architecture employing AI-driven link adaption methods. Their research indicated that effective

resource management markedly decreases delays and enhances data throughput.

[21]They introduced and evaluated two models for uplink satellite communication (SATCOM) a single-hop hybrid system combining RF/FSO technologies and a dual-hop space-air-ground integrated network (SAGIN) that employs high-altitude platform stations (HAPS) as relays. The researchers presented closed-form expressions for the average symbol error probability (SEP) and outage probability, considering gamma-gamma fading with pointing errors for FSO links and shadowed-Rician fading for RF links. The main conclusions are that hybrid RF/FSO systems surpass FSO-only systems in performance, and the dual-hop SAGIN model with HAPS relays notably enhances uplink SATCOM performance compared with single-hop systems, particularly in challenging scenarios, such as high pointing errors, large zenith angles, and strong wind conditions.

[22]This study evaluated the performance of a hybrid system that integrates RF-Reconfigurable Intelligent surfaces (RIS) with FSO communication. Their analysis incorporated physical models of RIS, RF channels, atmospheric turbulence, and pointing errors. The numerical findings confirm the accuracy of these derivations, revealing that RF-FSO links with RIS exhibit slightly inferior performance compared with conventional RF-FSO links. Nonetheless, this slight decline in performance is compensated for by the enhanced flexibility in beam adjustment offered by the RIS within the FSO link. Additionally, this study explores the system design and the impact of various parameters, drawing on both theoretical analysis and simulation outcomes.

[23]Evaluated the efficiency of a satellite-terrestrial FSO/millimetre-wave (mmw) radio frequency (RF) relaying system employing amplify-and-forward (AF) and decode-and-forward (DF) relaying methods. The FSO link is characterised by the Málaga (M) distribution, which accounts for pointing error impairments, whereas the MMW link is described by the multi-cluster fluctuating two-ray (MFTR) fading model. The authors derived closed-form solutions for several performance metrics, such as the outage probability, average bit error rate, ergodic capacity, and effective capacity. They also conducted an asymptotic analysis at a high SNR and confirmed their analytical findings through Monte Carlo simulations. This study explored both heterodyne detection and IM/DD techniques for the FSO link and investigated how different system parameters affect performance.

[24] A reinforcement learning-based algorithm was developed to optimise the flight path of high-altitude pseudo-satellites (HAPS) within a hybrid RF/FSO space-air-ground communication network. This algorithm allows HAPS to manoeuvre around cloud formations and dynamically alternate between RF and FSO links to enhance the overall link capacity. The proposed method utilises an advantage actor-critic (A2C) algorithm and is evaluated against an algorithm. The simulation results indicate an increase in link capacity compared to systems using only RF, highlighting the methods effectiveness in adapting to varying atmospheric conditions and improving communication performance.

[25] Their study introduced an innovative hybrid RF/FSO system designed for satellite communications that utilises RF signals to forecast FSO link availability up to τ seconds ahead. The system incorporates RF beacons positioned around an FSO station and leverages a machine learning model to correlate RF data with future FSO link attenuation. Various RF beacon configurations were examined through simulations using a simulated cloud model, revealing a balance between the duration of the predictions and their accuracy. The research achieved up to 80% accuracy with a 250m beacon radius, surpassing conventional forecasting techniques. A routing case study illustrated average availability improvements ranging from 1.12 to 1.2 across different steering speeds, underscoring the potential of this predictive system to boost FSO link availability in satellite communications.

FUTURE RESEARCH DIRECTIONS

Some difficulties persist in the comprehensive investigation of hybrid RF-FSO systems. Subsequent research should focus on the following aspects:

- Enhanced AI-driven optimisation: Machine learning methodologies for adaptive relay selection and intelligent network management require further investigation.
- Optimised resource allocation: Creating advanced algorithms for the dynamic distribution of power, bandwidth, and transmission modes will enhance the performance of hybrid systems.
- Integration with 6G and beyond: Future hybrid systems must be engineered for smooth integration with next-generation networks to facilitate ultra-reliable low-latency communication.
- Experimental validation: The practical implementation and testing of hybrid RF-FSO networks reconciles theoretical models with real-world deployment.

RESEARCH GAPS

Although hybrid RF-FSO communication systems have been extensively researched, there are still considerable research gaps and challenges that must be addressed for their successful deployment in future wireless networks. This section outlines the major limitations of current studies and suggests possible ways to overcome these challenges.

1. NEED FOR MORE COMPARATIVE STUDIES IN HYBRID RF/FSO COMMUNICATION SYSTEM:

Many studies have been conducted on hybrid RF-FSO systems. However, there are few detailed studies comparing different system designs, relaying methods, modulation types, and diversity techniques. Most studies focus on one part of the system or specific situations, making it difficult to compare the overall performance. A detailed comparison, including real-world testing and applications, is required to fill this gap

2. MECHANISMS FOR ADAPTIVE RELAY SELECTION AND LINK SWITCHING:

Hybrid RF-FSO systems depend on relay-assisted transmission to guarantee reliable communication. Current research mostly concentrates on static or semi-adaptive relay selection, when relay nodes are selected according to predetermined criteria. Machine learning-based real-time dynamic relay-selection algorithms are still in their early stages. Developing AI-powered relay selection techniques that can adapt to changing channel conditions has the potential to significantly improve the system performance.

3. TECHNIQUES TO MINIMIZE INTERFERENCE IN HIGH-TRAFFIC NETWORKS

Hybrid RF-FSO systems are often used in crowded cities. Here, many RF sources and FSO link misalignments can cause problems. While many studies look at interference in isolated settings, there is a need for better models. These models should consider real-world issues like movement, interference from multiple users, and changing power control methods.

4. EFFECTS OF ADVANCED MODULATION AND CODING TECHNIQUES:

Various modulation and coding strategies, including adaptive modulation, Alamouti coding, and STBC, have been suggested to enhance the performance of hybrid RF-FSO systems. Nonetheless, a direct comparison of these approaches under uniform channel conditions is absent in the current literature. Additionally, research is required on the joint optimization of modulation and coding methods to improve spectral efficiency and reduce ABER.

5. INTEGRATION WITH 5G AND SUBSEQUENT TECHNOLOGIES (6G, IOT, SMART CITIES)

Hybrid RF-FSO systems are anticipated to be crucial in 5G and subsequent technologies (6G, IOT, smart city applications, and satellite networks). Nevertheless, the majority of studies concentrate on independent hybrid RF-FSO lines, neglecting their integration within multi-tier heterogeneous networks. Future research should investigate the seamless integration of hybrid RF-FSO systems with next-generation wireless architectures, encompassing multi-hop networks, edge computing, and blockchain-based security.

6. EMPIRICAL VALIDATION AND PRACTICAL IMPLEMENTATION

Most studies on hybrid RF-FSO systems are predominantly based on theoretical models and simulations, with limited empirical testing in actual environments. Conducting field trials and developing testbeds are essential for addressing practical challenges like misalignment, environmental effects, and hardware limitations. Future research should prioritize the creation and deployment of comprehensive hybrid RF-FSO testbeds to assess performance in real-world conditions.

SIGNIFICANCE OF THE STUDY

The growing demand for high-speed, dependable, and energy-efficient communication has established hybrid RF-FSO systems as a crucial facilitator for next-generation wireless networks. This research is important for multiple reasons:

1) FIXING THE PERFORMANCE GAP:

Hybrid RF-FSO systems integrate the advantages of both RF and FSO technologies, offering a resilient communication architecture capable of functioning under many environmental circumstances. This study examines diverse relaying mechanisms, modulation schemes, and adaptive strategies to bridge the performance disparity between standalone RF and FSO systems.

2) IMPROVING NETWORK DEPENDABILITY AND EFFECTIVENESS:

This study examines alternative relay-assisted designs and diversity techniques to enhance network resilience and spectrum efficiency. The results enhance the advancement of intelligent relay selection, adaptive link switching, and resource allocation methodologies.

3) DIRECTING SUBSEQUENT RESEARCH AND EXECUTION:

This paper offers a thorough comparative analysis of current hybrid RF-FSO technologies, focusing on critical concerns including interference management, energy efficiency, and seamless integration with 5G and beyond. Researchers and engineers can utilize these insights to develop efficient hybrid RF-FSO systems for practical applications.

4) FACILITATING NEXT-GENERATION WIRELESS TECHNOLOGIES:

As wireless networks progress towards 6G, IoT, and smart city applications, hybrid RF-FSO systems will be essential for facilitating URLLC. The study's results endorse the advancement of AI-driven optimization methods, improving network flexibility and efficiency.

5) PROMOTING PRACTICAL IMPLEMENTATION:

This study emphasizes the necessity for experimental validation and practical implementation, in contrast to the predominant focus of most studies on theoretical modeling. This establishes a basis for subsequent research focused on the practical application of hybrid RF-FSO communication systems in urban, rural, and satellite communication contexts.

CONCLUSION

Hybrid RF-FSO communication systems present a viable option to address the constraints of independent RF and FSO technology. By utilizing the resilience of RF and the elevated data rate potential of FSO, these systems guarantee improved network reliability, spectral efficiency, and energy conservation. This study offers an extensive analysis of hybrid RF-FSO topologies, emphasizing performance measures, relaying mechanisms, and adaptive methodologies. Despite significant research progress, other obstacles persist, including adaptive relay selection, interference management, energy efficiency, and the absence of thorough comparative analysis. The combination of machine learning optimization, AI-facilitated resource allocation, and uninterrupted connectivity through 5G and subsequent technologies offers substantial research prospects. Confronting these problems will be essential for the effective implementation of hybrid RF-FSO networks in practical applications.

Future investigations should focus on creating adaptive algorithms for relay selection, enhancing modulation and coding methods, and performing practical experiments in real-world settings. Moreover, integrating hybrid RF-FSO systems with new technologies like 6G, IoT, and smart cities is crucial for the progression of next-generation wireless networks.

This study establishes a basis for future improvements in hybrid RF-FSO communication by explaining recent advancements and pinpointing significant research deficiencies. The ongoing advancement and refinement of these systems will be crucial in determining the future of high-speed, energy-efficient, and ultra-reliable wireless communication networks.

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