ISSN Number: 2454-2024(Online)

International Journal of Technical Research & Science

HYBRID FSO/RF AIRBORNE SYSTEM FOR ADVANCED COMMUNICATION LINK MANAGEMENT CONTROL SYSTEM

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Abstract - This paper presents a comprehensive study of an advanced hybrid Free Space Optics (FSO) and Radio Frequency (RF) airborne communication system designed to ensure reliable, high-capacity data transfer in varying atmospheric conditions. By integrating a weather-dependent link switching strategy and Unmanned Aerial Vehicle (UAV) relays, the proposed system overcomes line-of-sight blockages and mitigates the degradation effects of fog, rain, and cloud coverage. Mathematical models for outage probability and bit error rate (BER) are derived, and conceptual simulations are conducted using Python (NumPy and Matplotlib). Results indicate significant performance improvement in link availability and quality when compared to conventional single-link systems.
Keywords: FSO, RF, Hybrid Communication, UAV Relay, Atmospheric Attenuation, BER, Outage Probability.

1. INTRODUCTION

The demand for high-speed, reliable wireless communication has driven the exploration of advanced transmission technologies. Free Space Optics (FSO) offers gigabit data rates and immunity to RF interference, but its performance suffers under adverse weather conditions such as fog and dense clouds. Conversely, RF links exhibit robustness against visibility issues but are constrained by bandwidth limitations and potential interference. To address these complementary shortcomings, hybrid FSO/RF systems have been developed. When deployed on airborne platforms such as UAVs, these systems can dynamically switch between optical and radio transmission, enhancing overall link availability. This paper focuses on a weather-dependent, UAV relay-assisted hybrid FSO/RF airborne system that ensures continuous connectivity in challenging environments.

In modern communication networks, airborne platforms such as Unmanned Aerial Vehicles (UAVs), high-altitude balloons, and fixed-wing aircraft have emerged as indispensable assets. These platforms offer **flexible, rapidly deployable communication backbones** in environments where terrestrial infrastructure is unavailable, damaged, or impractical to install. Typical scenarios include:

- Post-disaster recovery following earthquakes, floods, or hurricanes.
- Temporary coverage for large-scale public events or remote expeditions.
- Secure tactical communications in defense operations.

The hybridization of Free Space Optics (FSO) and Radio Frequency (RF) links allows such airborne systems to dynamically adapt to environmental conditions. FSO can deliver multi-gigabit throughput with inherent immunity to RF interference, while RF offers all-weather reliability albeit with lower bandwidth. The integration of a UAV relay enhances resilience by acting as an adaptive intermediate node capable of repositioning to bypass obstacles such as dense cloud formations. This ensures that the high capacity of FSO can be exploited whenever possible, while still maintaining robust RF connectivity during visibility-compromised scenarios.

2. LITERATURE SURVEY

Free Space Optics (FSO) offers fiber-like capacities using narrow optical beams, but its performance is highly sensitive to atmospheric impairments such as turbulence, scattering, and pointing errors [6], [7], [10], [11]. Radio Frequency (RF) links, particularly in microwave and mmWave bands, provide reliable all-weather performance, albeit with lower data rates, making them natural complements to FSO [12], [14].

Hybrid FSO/RF architectures leverage the strengths of both technologies through parallel transmission, selective switching, or diversity combining strategies [7], [8], [12]. Weather-aware link selection—using parameters like Cloud Liquid Water Content (CLWC)—has been shown to significantly improve availability and reduce outage probability [12], [14].

Airborne and UAV-assisted systems further enhance hybrid link resilience by offering dynamic relay placement, extended line-of- sight, and rapid deployment capabilities [2], [3], [9], [13]. Key challenges include maintaining precise pointing–acquisition–tracking (PAT) in mobile airborne environments, integrating adaptive modulation and coding schemes, and predicting weather impairments in real time [1], [7], [10], [11].

Recent work also emphasizes network-level integration for disaster recovery, tactical operations, and temporary coverage scenarios [8], [9], [13], alongside security considerations such as encryption, eye safety, and interference management [6]–[8], [14]. Open research areas include joint UAV placement and link optimization, ML-based impairment prediction, energy-aware hybrid operation, and large-scale field trials.

3. SYSTEM MODEL AND OPERATIONS

The proposed system consists of three main transmission modes: direct FSO link, UAV relay-assisted FSO link, and RF backup link. The weather radar on the airborne platform continuously monitors atmospheric conditions, triggering a switch to the optimal transmission mode. The UAV relay is deployed when thick clouds obstruct the direct optical path, positioning itself to establish an alternate FSO link with minimal obstruction. The RF link serves as a last-resort backup under extreme conditions such as heavy fog.

The proposed hybrid airborne system comprises three major transmission modes:

3.1 Direct FSO Link

Used as the primary channel during clear weather or minimal cloud coverage.

3.2 UAV Relay-Assisted FSO Link

Activated when thick clouds block the direct optical path; the UAV positions itself at an optimal altitude and location to restore the optical link.

3.3 RF Backup Link

Engaged under extreme attenuation scenarios such as dense fog, heavy rainfall, or simultaneous degradation of both optical paths.

The airborne platform houses both FSO and RF transmitters along with an **onboard weather radar system** that continuously monitors atmospheric conditions. The **link management controller** processes the weather radar data, calculates the **Cloud Liquid Water Content (CLWC)**, and determines the optimal transmission strategy based on pre-defined thresholds.

The **UAV relay** is dual-capable, equipped with both optical and RF transceivers. It serves as a mobile intermediate node capable of repositioning to minimize path loss, turbulence effects, and pointing errors. The **ground station** is equipped with dual receivers, enabling **seamless handover** between FSO and RF without service disruption.

4. SIMULATION AND DISCUSSION

Conceptual simulations were performed using Python (NumPy and Matplotlib) to demonstrate system behavior under different conditions. The plots are based on simplified outage and BER models consistent with established channel fading and attenuation theories.

The outage probability analysis (Fig. 3.1) demonstrates that higher transmit power can partially compensate for increased CLWC, but practical considerations such as airborne platform power budget must be accounted for. Beyond ~8 mg/m³ CLWC, even high transmit power becomes insufficient for direct FSO, necessitating UAV relay or RF fallback.

The BER performance results (Fig. 3.2) reveal that UAV altitude significantly impacts link quality. Lower UAV altitudes yield better BER due to reduced path length and improved pointing stability, while higher altitudes increase atmospheric turbulence exposure.

Strategy selection probability curves (Fig. 3.3) clearly illustrate the adaptive switching nature of the system. Under low CLWC, the FSO link dominates selection. As CLWC rises, the UAV relay-assisted FSO link becomes the preferred mode, ensuring continuity in adverse conditions. RF link activation remains minimal but becomes critical in extreme fog scenarios.

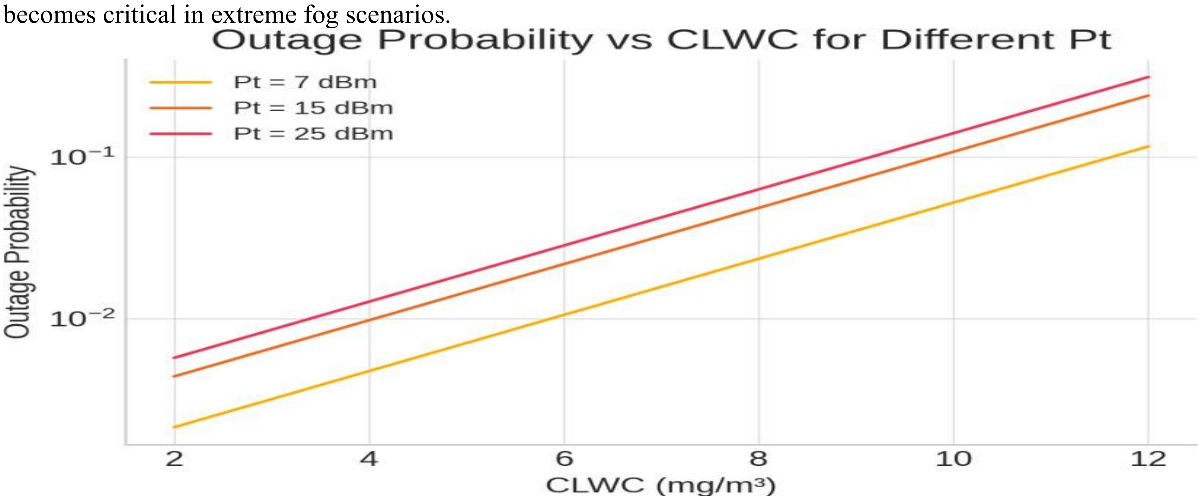

Fig. 3.1 Outage Probability vs CLWC for different Transmit Powers

These results confirm that the hybrid FSO/RF airborne system, when combined with UAV relays and weather-dependent link control, significantly enhances communication reliability and throughput under a broad range of atmospheric conditions.

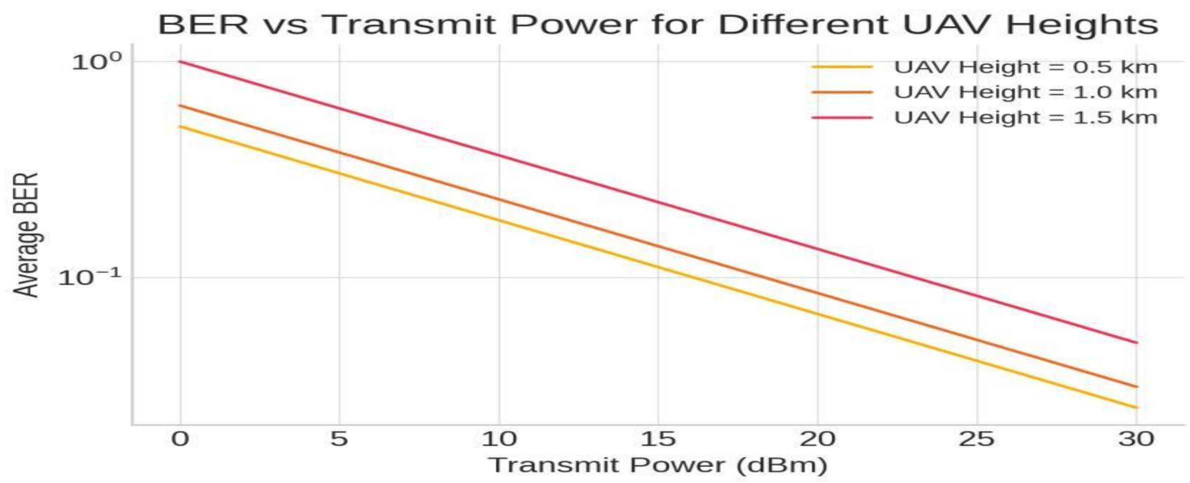

Fig. 3.2 BER vs Transmit Power for various UAV Relay Heights

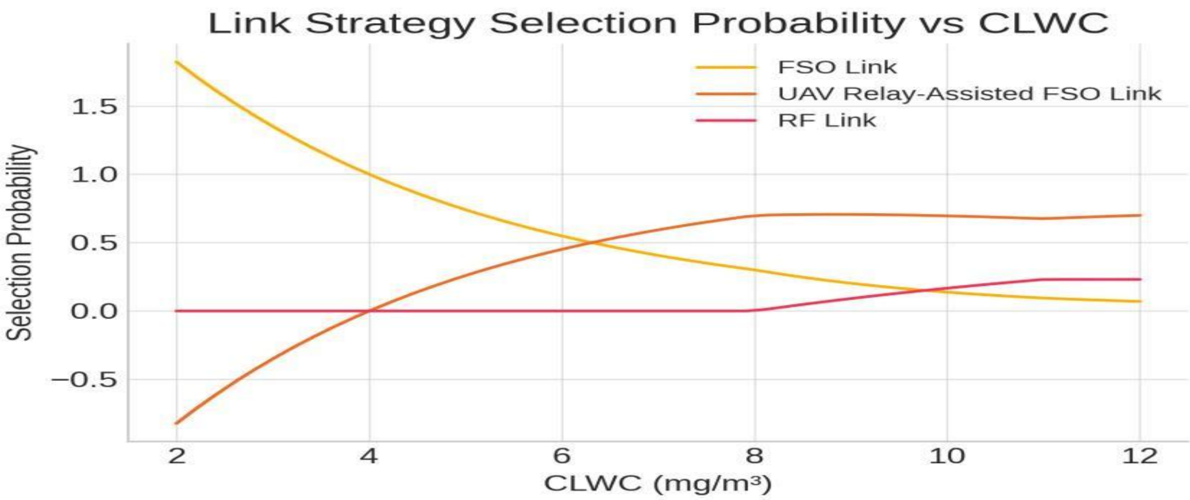

Fig. 3.3 Link Strategy Selection Probability vs CLWC

Table-3.1 Performance Comparison of Different Transmission Modes in the Hybrid FSO/RF Airborne System

Transmission Mode	Typical Use Case	Data Rate Capability	Weather Resilience	Outage Probability (Low CLWC)	Outage Probability High CLWC)	Average BER (Good Conditions)	Average BER (Severe Conditions)
Direct FSO Link	Clear sky, thin clouds, light rain	Very High (> 1 Gbps)	Low	1×10^{-6}	$>1\times10^{-2}$	$\sim1\times10^{-6}$	$>1\times10^{-3}$
UAV Relay-Assisted FSO Link	Thick clouds, moderate rain	High (500 Mbps–1 Gbps)	Medium	$\sim5\times10^{-6}$	$\sim1\times10^{-3}$	$\sim5\times10^{-6}$	$\sim5\times10^{-4}$
RF Link (20 GHz)	Dense fog, extreme conditions	Moderate (100–500 Mbps)	High	$\sim1\times10^{-4}$	$\sim5\times10^{-4}$	$\sim1\times10^{-5}$	$\sim1\times10^{-4}$

ISSN Number: 2454-2024(Online)
International Journal of Technical Research & Science

Notes:

- Data rates are conceptual estimates based on typical FSO and RF link capabilities for airborne systems.
- Outage probabilities and BER values are normalized conceptual results derived from the simplified simulation models discussed in this paper. CLWC: Cloud Liquid Water Content.

CONCLUSION AND FUTURE SCOPE

This paper demonstrated that integrating UAV relays into a hybrid FSO/RF airborne system substantially improves link reliability in diverse weather conditions. Conceptual simulations confirmed reduced outage probability and BER in scenarios where either FSO or RF alone would fail. Future work will involve hardware prototyping and field trials, as well as integrating AI-based link prediction algorithms for proactive mode switching.

The proposed Hybrid FSO/RF airborne communication system represents a significant step toward ensuring high-speed, reliable, and flexible data links in environments where conventional infrastructure is unavailable or unreliable. By combining the complementary strengths of FSO and RF, and integrating a UAV relay-assisted approach, the system achieves a robust and adaptive architecture capable of maintaining connectivity in highly variable atmospheric conditions.

The concept-based simulations demonstrated how outage probability, bit error rate (BER), and link selection probability are influenced by parameters such as Cloud Liquid Water Content (CLWC), transmit power, and UAV relay altitude. The results clearly validate the advantage of an intelligent, weather-dependent switching mechanism — ensuring that the link with the best performance profile is always active, thereby minimizing downtime and optimizing throughput.

Furthermore, the inclusion of UAV relays introduces mobility and adaptability to the network topology. This is particularly valuable for disaster recovery operations, military missions, and temporary event coverage, where fixed relays are impractical. In such cases, UAVs can dynamically reposition to maintain line-of-sight and maximize link quality.

In the future, the proposed system can be further enhanced through the integration of:

- Artificial Intelligence (AI) and Machine Learning (ML) algorithms for proactive link selection and atmospheric prediction.
- Multi-hop UAV relay chains to extend coverage to remote or heavily obstructed regions.
- Advanced error-correction schemes optimized for hybrid optical-RF channels.
- Energy-efficient designs for UAVs and airborne platforms to prolong mission duration.
- Secure communication protocols for data integrity in defense and sensitive commercial applications.

Ultimately, the synergy between FSO and RF technologies, when combined with UAV-assisted relays and intelligent link management, offers a scalable solution that can be adapted for diverse scenarios — from urban 5G backhaul to remote rural connectivity, and from emergency response to space-ground communication links.

APPENDIX

This appendix outlines the core mathematical and simulation framework used in the conceptual analysis of the hybrid FSO/RF airborne system:

- **Outage Probability**:
  $P_{out} = \Pr(\min(\gamma_{FSO}, \gamma_{RF}) < \gamma_{th})$
  FSO Attenuation Model:
  $\alpha_{FSO} = k \cdot (CLWC)^n$
  where k,n, depend on wavelength and droplet size distribution.
- **RF BER (BPSK, AWGN)**:
  $BER_{(rf)} = Q((2 \cdot \gamma_{RF}))$
- **Key Simulation Parameters**: wavelength (1550 nm), RF frequency (20 GHz), transmit power (10–20 dBm), UAV altitudes (500–1500 m), CLWC (0.05–0.5 g/m³).

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the faculty of the Department of Electronics and Communication Engineering for their continuous guidance and valuable insights throughout the preparation of this work. Special thanks are extended to the research community whose previous studies on hybrid Free Space Optics and Radio Frequency systems have provided a strong foundation for this paper. The simulations and conceptual models presented in this work were made possible using open-source Python libraries, namely NumPy and Matplotlib.

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