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Enhancing Beyond-5G and 6G Network Backhaul through Hybrid RF-FSO Communication: An Examination of HAPS and LEO Satellite Integration

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Abstract- As data demands increase with the evolution toward beyond-5G and 6G communication systems, achieving efficient network backhaul is crucial to support high data rates, minimized latency, and broad geographic coverage. Traditional backhaul networks, reliant on radio frequency (RF) communications, face limitations in scalability and bandwidth, particularly in dense urban and rural remote areas. This paper explores a hybrid RF-Free-Space Optical (FSO) communication model, integrating Low Earth Orbit (LEO) satellites with High Altitude Platform Stations (HAPS) to enhance backhaul network efficiency. The proposed HAPS-LEO cooperative model mitigates atmospheric disruptions and offers scalable, high-bandwidth solutions. We further examine Contact Graph Routing (CGR) as a protocol for optimized data routing in variable connectivity conditions, presenting simulated performance results that demonstrate the advantages of this architecture.

Index Terms- Integration, Land mobile satellite system, Satellite, Satellite challenges

I. INTRODUCTION

As next-generation communication systems continue to evolve, the demand for high-speed data transfer in network backhaul infrastructures grows exponentially. Traditional RF-based backhaul networks struggle to keep up, facing congestion, limited bandwidth, and environmental vulnerabilities. A backhaul network serves as the critical link between cellular base stations and the core network, influencing the overall performance of cellular and satellite-based communication systems.

The emergence of Low Earth Orbit (LEO) satellite networks promises significant improvements in data rates, latency, and coverage. However, LEO satellites are susceptible to disruptions such as fading, atmospheric interference, and signal loss due to weather. Meanwhile, High Altitude Platform Stations (HAPS) offer stable, quasi-stationary positions in the stratosphere, providing broad coverage and low propagation delays. Leveraging HAPS as relay points within a LEO backhaul network can overcome many traditional network challenges, especially when coupled with Free-Space Optical (FSO) communication for high-bandwidth, line-of-sight (LOS) transmission. However, FSO is limited by weather sensitivity and signal degradation over distance.

This paper proposes a hybrid RF-FSO communication model to maximize the potential of HAPS-aided LEO satellite networks for beyond-5G and 6G backhaul solutions.

II. LITERATURE REVIEW

1. LEO Satellite Networks

LEO satellites orbit between 100 to 1,200 miles above Earth's surface, providing low-latency and global coverage. Their proximity allows for higher data rates compared to geostationary satellites, but they also experience issues such as atmospheric fading, path loss, and disruptions from obstacles like cloud formations and weather effects.

2. High Altitude Platform Stations (HAPS)

Operating at altitudes of 18-24 km, HAPS systems can cover wide areas and maintain consistent LOS with ground stations, making them ideal for bridging connections in rural and underserved regions. Unlike LEO satellites, HAPS experience minimal signal delays and are easier to deploy and maintain, though they face their own challenges, such as weather-induced attenuation in FSO links.

3. RF and FSO Communication Technologies

Radio frequency communication is well-suited for longer distances and non-LOS connections, but it suffers from spectrum congestion, low bandwidth, and rain fade, especially at frequencies above 11 GHz. In contrast, FSO communication offers high data rates in unlicensed spectrums with minimal interception risks. However, FSO links are highly sensitive to weather and environmental factors, often resulting in signal degradation during fog, rain, or snow.

4. Contact Graph Routing (CGR)
In today's evolving networking landscape, large-scale, dynamic, and heterogeneous networks are becoming increasingly common. These networks, including those in the domains of terrestrial networks, space communications, and the Internet of Things (IoT), present unique challenges in terms of scalability, efficiency, and reliability.

Traditional routing protocols, such as OSPF (Open Shortest Path First) and BGP (Border Gateway Protocol), often struggle to maintain performance in these environments due to factors such as high latency, intermittent connectivity, and large node counts.

Contact Graph Routing (CGR), initially designed for Delay-Tolerant Networks (DTNs) and space communications, offers a promising alternative.

CGR's design is rooted in managing contacts—periods during which communication between nodes is possible—and leveraging contact plans to determine optimal paths in environments with intermittent or disrupted connectivity.

CGR has been primarily used in space networks but shows potential for broader application in large-scale networks, such as global terrestrial networks and IoT systems. This paper investigates the scalability of CGR, particularly its ability to manage routing efficiently as the size of the network grows and the complexity of network dynamics increases.

CGR was first developed to support space-based networks, where the limitations of traditional Internet protocols became apparent due to the vast distances and the resulting high latency and frequent disconnections.

CGR builds a contact graph by mapping out potential communication opportunities between nodes based on scheduled contacts and propagates this information to route data in a manner that minimizes disruption.

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III. SYSTEM ARCHITECTURE OF THE PROPOSED HAPS-LEO COOPERATIVE MODEL

The hybrid HAPS-LEO network utilizes both RF and FSO links to leverage the strengths of each technology while compensating for their limitations. The core components of the architecture include:

1. LEO Satellites
Provide global coverage with high data rates and low latency. Data from LEO satellites is transmitted to HAPS via FSO links during clear weather and switches to RF during adverse conditions.

2. HAPS Nodes
Act as relay points in the stratosphere, connecting LEO satellites to ground stations. HAPS can utilize both RF and FSO, with RF links activated as backups during FSO disruptions.

3. Ground Stations
Serve as the final relay in the backhaul network, receiving data from HAPS and distributing it through terrestrial networks.

This architecture provides dual-channel redundancy, reducing the risk of signal loss by dynamically switching between RF and FSO based on environmental conditions.

IV. TECHNICAL EVALUATION OF RF-FSO COMMUNICATION IN HAPS-LEO NETWORKS

1. Challenges with RF and FSO Links
RF links, while versatile, are limited in bandwidth and susceptible to spectrum congestion and rain fade. FSO links, on the other hand, provide high data rates but are highly vulnerable to weather conditions like fog and snow, which can significantly degrade performance.

Incorporating both RF and FSO links allows the network to benefit from the bandwidth and data rate of FSO, with the reliability of RF as a backup.

2. Hybrid RF-FSO Communication Protocol
A hybrid protocol enables the dynamic selection of RF or FSO links based on real-time environmental monitoring. This approach maximizes data throughput and minimizes signal disruption, creating a more resilient network.

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V. SIMULATION AND RESULTS

1. Simulation Setup

This study evaluates the scalability of CGR through a combination of theoretical analysis and simulation-based experiments. The methodology includes:

Theoretical Analysis: We perform a detailed analysis of CGR's computational complexity as a function of network size, focusing on the growth of routing tables, the time required for contact plan computations, and the frequency of updates required for maintaining accurate routing information.

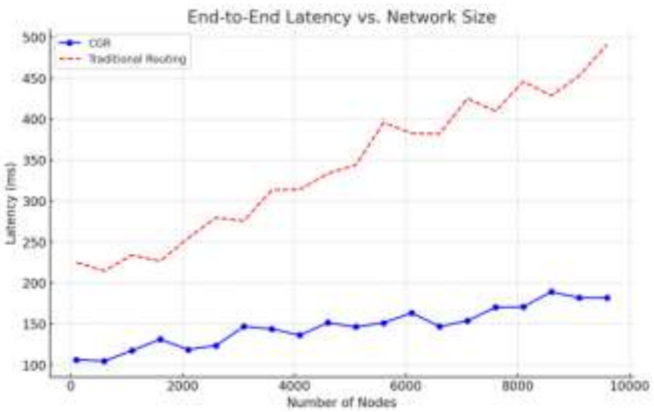
Simulation Based Evaluation: We simulate CGR in a variety of network environments, ranging from moderately sized DTNs to large-scale terrestrial networks with up to 10,000 nodes.

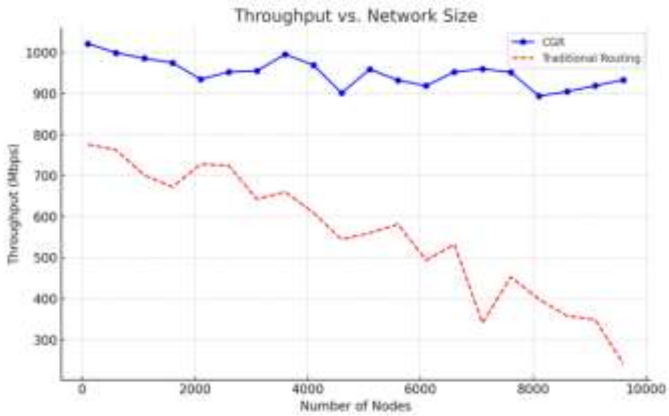
We use network simulation tools to model the network's topology, node mobility, contact opportunities, and traffic patterns. The simulation scenarios include varying levels of network heterogeneity and dynamic behaviour.

The performance of CGR is measured using the following key metrics:

- **Latency:** The end-to-end delay in delivering data packets.
- **Throughput:** The total amount of successfully delivered data.
- **Resilience to Failures:** The protocol's ability to maintain communication in the presence of node failures or disruptions in connectivity.
- **Resource Efficiency:** The amount of computational and network resources required to maintain the routing process.

2. Results





The simulation results provide insights into CGR's performance across different network scenarios. Key findings include:

Latency and Throughput: CGR performs well in managing latency in large-scale networks, particularly when intermittent connectivity is present. It can reduce delays by selecting optimal paths based on predicted contact opportunities, though its performance degrades in highly dynamic topologies with frequent topology changes.

Scalability: As network size increases, CGR shows a moderate increase in computational overhead for routing table management and path computation. However, it maintains scalability better than many traditional routing protocols, especially in networks with predictable or semi-predictable contact patterns.

Resilience: CGR exhibits strong resilience to node failures, as its contact-based routing decisions are made with redundancy and alternative paths in mind. However, in highly unpredictable environments, CGR's reliance on predefined contact plans can become a limitation, requiring more adaptive mechanisms.

Resource Efficiency: CGR shows resource efficiency in networks with scheduled contacts, as it does not require continuous communication overhead for routing updates. However, in more dynamic or unstructured networks, the need for frequent updates can increase resource consumption.

Challenges and Future Directions

While the proposed HAPS-LEO hybrid RF-FSO architecture shows significant promise, challenges remain:

- Scalability: Expanding HAPS coverage over large regions requires substantial investment in infrastructure and maintenance.
- Protocol Complexity: Implementing adaptive routing protocols that account for weather and atmospheric

conditions in real-time adds to system complexity and cost.

- Hardware Limitations: FSO links require precise alignment, and RF links must be resilient to rain fade and other atmospheric effects.

Future research could explore the integration of machine learning for predictive weather analysis, allowing proactive link switching, and the development of low-cost, high-durability HAPS units.

Building upon this study, future work could investigate the integration of CGR with machine learning techniques to predict contact patterns in dynamic environments. Additionally, exploring hybrid routing protocols that combine the strengths of CGR with more adaptive, reactive routing strategies could provide further scalability improvements for large-scale heterogeneous networks.

VI. CONCLUSION

CGR's scalability makes it a viable routing solution for large-scale networks, particularly those characterized by intermittent connectivity and dynamic topologies. It offers advantages in terms of resilience and latency reduction in environments where contact opportunities can be predicted.

However, its performance can degrade in highly unpredictable networks, where dynamic topology changes outpace the ability to update contact plans. Future research should focus on hybrid approaches that combine CGR with more adaptive routing mechanisms to address these limitations..

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