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Deployment Strategies for 5G Connectivity in Rural and Remote Regions

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***Abstract*—5G plays a central role in modern daily life by enabling faster internet speeds, ultra lower latency, and massive device connectivity, powering everything from streaming to smart homes. Non-Terrestrial Networks (NTN), particularly High-Altitude Platform Stations (HAPS), offer a transformative solution for delivering 5G connectivity to rural and remote regions where traditional terrestrial infrastructure is economically or logistically unfeasible. Positioned in the stratosphere at 18-22 km altitude, HAPS act as "towers in the sky," providing wide-area coverage with near-terrestrial latency, flexible repositioning, and seamless integration into 5G New Radio (NR) architectures. These solar-powered platforms enable ubiquitous broadband access, support IoT applications like smart agriculture, and enhance resilience during disasters by complementing ground networks without extensive cabling. Challenges such as weather sensitivity and energy constraints persist, but ongoing 3GPP standardization and trials demonstrate HAPS's potential to bridge the digital divide, achieving 5G targets for data rates and reliability in underserved areas.**

***Index Terms*— 5G in Rural Area, HAPS (High Altitude Platform Stations), Solar Powered**

I. INTRODUCTION

The fifth-generation (5G) mobile communication system has been designed to support high data rates, ultra-low latency, and massive device connectivity for a wide range of applications. While most commercial 5G deployments have focused on urban and suburban environments, extending reliable broadband connectivity to rural and remote areas remains a major global challenge. Rural and remote areas suffer from inadequate 5G connectivity due to high infrastructure costs, challenging terrain, sparse population density, and regulatory hurdles for deploying ground base stations, leaving billions without access to high-speed broadband, IoT services, and emergency communications. Challenges are Coverage Gaps in Traditional towers can't economically span large areas (e.g., farms, mountains) with low user density.

The very few issues which plays a rollback are **Deployment Barriers**: Fiber backhaul is impractical; wireless alternatives face propagation limits and high power needs. **Economic Viability:** Operators avoid investment where ROI is low, exacerbating the digital divide.

Despite its potential, deploying terrestrial 5G infrastructure in rural and remote locations is challenging due to several factors. Low population density, reducing economic incentives for operators. Large inter-site distances, requiring more coverage per base station. Limited fiber backhaul availability, restricting high-capacity connectivity. Difficult terrain, such as mountains, forests, and isolated islands. Unreliable power supply and high maintenance costs. High capital expenditure, making deployment less feasible. As a result, traditional ground-based (terrestrial) networks alone are often insufficient to achieve widespread rural 5G coverage.

To overcome these limitations, Non-Terrestrial Networks (NTN) have emerged as a promising approach. NTN extends communication beyond terrestrial infrastructure by incorporating aerial and space-based platforms. The NTN includes, high-Altitude Platform Stations (HAPS). Unmanned Aerial Vehicles (UAVs) or drones. These technologies enable connectivity in areas where building conventional towers and fiber networks is impractical or too expensive. The Role of HAPS in Rural 5G Connectivity, among NTN technologies, High-Altitude Platform Stations (HAPS) play a key role in providing rural broadband access. HAPS are aerial platforms positioned in the stratosphere at altitudes of approximately 18–22 km, functioning as “cell towers in the sky." Wide-area coverage, reaching large rural regions with fewer platforms. Near-terrestrial latency, offering better performance compared to satellites. Rapid deployment, especially in underserved or disaster-affected zones. Solar-powered operation, improving sustainability and reducing energy dependency.

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Seamless integration with 5G New Radio (NR) architectures. HAPS-enabled 5G networks can support critical rural applications such as smart farming through IoT sensors, remote education, telemedicine, emergency communications, and rural smart grid monitoring. The integration of 5G with NTN-HAPS represents a transformative solution for bridging the connectivity gap in rural and remote areas. This research focuses on exploring NTN-based architectures, identifying technical challenges such as weather sensitivity, spectrum coordination, and mobility management, and evaluating how hybrid terrestrial–non-terrestrial networks can deliver cost-effective.

II. METHODOLOGY

This work adopts a structured methodology to analyze the effectiveness of integrating Non-Terrestrial Networks (NTN) and High-Altitude Platform Stations (HAPS) for providing 5G connectivity in rural and remote areas. The methodology consists of system modeling, scenario definition, performance evaluation, and comparative analysis to assess the proposed hybrid architecture.

First, a hybrid 5G network architecture is modeled by combining terrestrial 5G gNodeBs with HAPS and satellite-based NTN components. Terrestrial base stations are assumed to provide localized coverage in accessible rural regions, while HAPS deployed at stratospheric altitudes (17–25 km) extend coverage over wide geographical areas. Satellite-based NTN, including LEO and GEO systems, is incorporated to ensure connectivity in extremely remote and hard-to-reach locations. The architecture is designed in accordance with 3GPP NTN specifications to enable seamless integration with the 5G core network.

Second, rural deployment scenarios are defined considering low user density, large inter-site distances, limited backhaul availability, and challenging terrain conditions.

Low-frequency spectrum bands are assumed to maximize coverage, and Fixed Wireless Access (FWA) is considered as the primary last-mile broadband solution. HAPS are modeled as quasi-stationary platforms, while NTN satellites are modeled with mobility and propagation delay characteristics appropriate to their orbital altitude.

Third, the performance of the proposed system is evaluated using key metrics relevant to rural connectivity, including coverage probability, end-to-end latency, throughput, packet delivery ratio, and energy efficiency. Appropriate propagation and channel models are applied to capture rural and non-terrestrial communication effects such as increased path loss, Doppler shift, and latency variations. Finally, a comparative analysis is conducted between the proposed hybrid NTN–HAPS-assisted 5G network and a conventional terrestrial-only 5G deployment. The comparison focuses on coverage extension, service reliability, and feasibility under rural constraints. The obtained results are further analyzed in the context of practical rural use cases such as telemedicine, distance education, precision agriculture, and emergency communication services.

Hybrid Optimization Algorithms (DLSFO): To tackle complex, multi-user, multi-beam environments, advanced optimization techniques like Dynamic Levysalp Fusion Optimization (DLSFO)—which combines the Lévy Flight Algorithm (LFA) for exploration and Improved Slap Swarm Optimization (ISSO) for exploitation—are used to optimize power and beam patterns, significantly improving system capacity and reducing latency.3D-Cell Control and Frequency Sharing: To facilitate coexistence with terrestrial networks (TNs), 3D-cell control techniques manage interference by not directing beams towards areas with heavy terrestrial base station (gNB) traffic, enabling shared spectrum usage (e.g., in the 2 GHz band).

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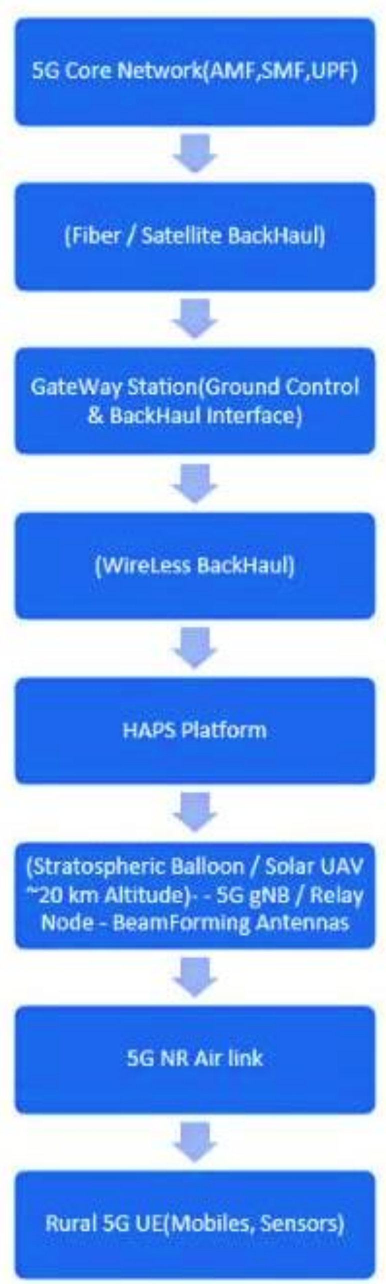

Fig 1: Flow Chart

5G Core Network: Manages core functions (AMF, SMF, UPF). Backhaul: Uses fiber/satellite links to a Gateway Station and wireless links to the HAPS Platform. HAPS Platform: A stratospheric balloon or solar UAV at 20 km altitude acting as a 5G gNB/Relay Node with beamforming antennas. 5G NR Air link: Connects the HAPS to rural 5G User.

III. WORKING PRINCIPLE

High-Altitude Platform Stations (HAPS) enable 5G connectivity in rural areas by positioning lightweight aircraft or balloons in the stratosphere at 20 km altitude, acting as airborne base stations to cover vast underserved regions cost-effectively. HAPS Positioning HAPS operate in a "sweet spot" between terrestrial towers and satellites, providing line-of-sight (LoS) coverage over 15,000 square kilometers per platform equivalent to 450 ground masts using low-emission hydrogen or solar power for weeks-long endurance.

This avoids expensive rural infrastructure builds while enabling quick deployment for remote agriculture, disaster recovery, or monitoring. 5G Antenna Technology Phased array antennas on HAPS generate 500 steerable beams for 5G non-terrestrial networks (NTN), delivering up to 150 Mbps downlink speeds via open RAN integration. Trials by BT with Stratospheric Platforms Ltd simulate this from high buildings, testing multi-user 4G/5G scenarios before full stratospheric flights.

Coverage Mechanism HAPS create circular cells up to 60 km in diameter using co-located transceivers for synchronized resource allocation and interference reduction, often leveraging TVWS spectrum for better propagation in rural gaps. Channel bonding and high-order modulation (e.g., 64QAM/256QAM achieve 27-145 Mbps per cell, meeting rural 5G KPIs like 30-50 Mbps user throughput.

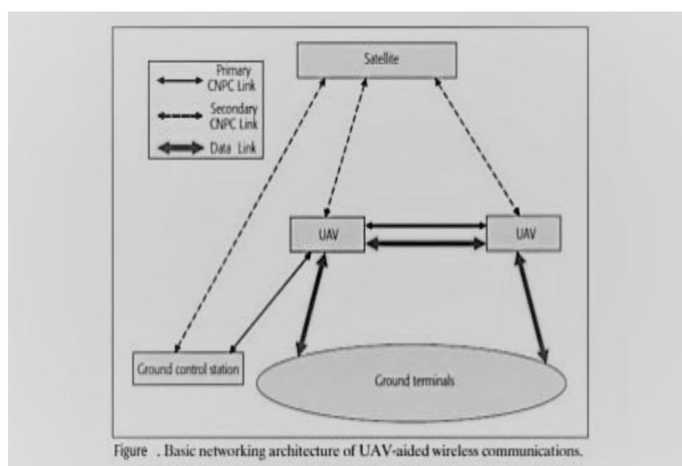

Fig 2 : Basic Networking Architecture

Hardware Core: The platform relies on physical airborne systems like solar-powered drones or balloons stationed at 20 km altitude, equipped with phased array antennas, gNB base stations (or ng-eNB for hybrid 4G/5G), RF amplifiers, mixers, and transceivers for beamforming and signal relay.

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These enable line-of- sight coverages over large areas without ground infrastructure. Software Role On board processing runs 5G NR protocols, resource allocation, interference management, and open RAN integration, often with dual-connectivity to ground networks via NG interfaces. Firmware handles beam steering (up to 500 beams) and modulation like 64QAM, but it's secondary to the hardware platform.

The below diagram illustrates a communication network architecture that utilizes High Altitude Platform Stations (HAPS). HAPS Role: HAPS are positioned at high altitudes (often on aircraft or balloons) and act as airborne base stations, providing cost-effective coverage over a wide area.

Connectivity: HAPS can provide coverage to ground-based user equipment (UE) or base stations (BS). They also connect to the Core Network (CN), likely via a gateway or other link. The diagram shows line-of-sight (LoS) links between the HAPS and ground components. CSI Delivery: Channel State Information (CSI) is delivered via a control channel, as indicated in the diagram. This system aims to bridge the gap between terrestrial and satellite networks, offering extended coverage and flexibility. HAPS (High Altitude Platform Stations) serve as airborne base stations on aircraft or balloons, delivering cost-effective, wide-area coverage. They connect via line-of-sight (LoS) links to ground user equipment (UE), base stations (BS), and the Core Network (CN) through gateways. Channel State Information (CSI) flows to users over a control channel. This architecture bridges terrestrial and satellite networks for enhanced flexibility and extended reach.

The basic networking architecture of UAV-assisted wireless communications in a 5G network. It shows how Unmanned Aerial Vehicles (UAVs) work together with ground networks and satellites to provide reliable and flexible communication.

Ground Control Station (GCS)

The Ground Control Station is responsible for: Monitoring UAV operations, Sending control commands, Receiving flight status and network data, It maintains control and coordination of UAVs using wireless links, Communication with satellites and UAVs ensures continuous connectivity,

Ground Terminals

Ground terminals represent: Mobile users, IoT devices, Base stations in remote or disaster-affected areas. These terminals connect to UAVs when: Terrestrial infrastructure is unavailable, Network coverage needs enhancement, UAVs act as aerial base stations or relays.

UAVs (Unmanned Aerial Vehicles)

UAVs play a key role in 5G networks by providing :On-demand coverage, High data rates, Low-latency communication, Multiple UAVs can communicate with each other using UAV-to-UAV links, enabling: Cooperative networking, Load balancing, Extended coverage

Satellite

The satellite provides wide-area connectivity, especially for:

Remote regions, Rural areas, Emergency and disaster scenarios UAVs and ground control stations can connect to satellites to ensure backhaul communication when terrestrial networks fail.

Ground users send data to nearby UAVs. UAVs relay data to: Other UAVs, Ground control stations Satellites, Satellites provide long-distance backhaul connectivity.

IV. Experimental Result

High-Altitude Platform Stations (HAPS) can deliver promising 5G-like connectivity in rural areas, often outperforming traditional ground infrastructure in coverage and cost. Key Simulation Study: A 2022 study simulated HAPS at 17 km altitude using TV White Spaces (TVWS) spectrum for rural broadband. It covered a 100 km radius with 121 cells (each 10.5 km radius), achieving per-cell data rates of 27-40 Mbps via 64QAM/256QAM modulation. Channel bonding boosted peak throughput to 145.45 Mbps, meeting some rural 5G key performance indicators like uplink speeds of 33.3 Mbps with QPSK.BT Group TrialsBT trialed Stratospheric Platforms ' phased-array antenna simulating HAPS for 4G/5G rural coverage. Mounted on a building at Adastral Park (UK), it targeted 150 Mbps speeds over 15,000 sq km using 500 steerable beams, equivalent to 450 terrestrial masts.

Tests integrated with BT's Open RAN testbed for multi-user scenarios. Capacity Evaluations: A 2025 evaluation of 5G NR on HAPS noted higher-order modulation boosts rural data rates but reduces robustness in poor channels. Coverage emphasized line-of-sight advantages, with costs around 5 million euros for unmanned solar platforms serving large rural zones. Broader Insights HAPS enable 60 km diameter LoS coverage per platform, ideal for bridging urban-rural gaps. Trials highlight scalability for agriculture and remote use cases, though full 5G KPIs require denser stations or spectrum tweaks.

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V. Conclusion

This paper examined the feasibility of extending 5G connectivity to rural and remote regions through the integration of Non-Terrestrial Networks (NTN) and High-Altitude Platform Stations (HAPS). The study demonstrates that relying solely on terrestrial infrastructure is insufficient for achieving ubiquitous coverage in sparsely populated and geographically challenging areas. By incorporating aerial and satellite-based communication layers, wide-area coverage can be achieved with improved service availability and reduced dependence on dense ground deployments. The proposed multi-layer architecture highlights the ability of HAPS to provide low-latency, high-capacity regional coverage, while NTN satellites ensure connectivity in extremely isolated locations.

The results indicate that intelligent access selection and seamless integration with the 5G core network can effectively manage latency, mobility, and resource allocation challenges associated with non-terrestrial links. Furthermore, the use of energy-efficient platforms and renewable power sources enhances the sustainability and long-term viability of rural deployments.

Overall, the findings suggest that NTN- and HAPS-assisted 5G networks offer a practical and scalable solution for bridging the digital divide in rural and remote areas.

With continued standardization, supportive regulatory frameworks, and advancements in aerial and satellite technologies, such hybrid architectures can play a crucial role in enabling inclusive digital services and socio-economic development.

Future work will focus on large-scale field trials, advanced interference mitigation techniques, and optimization of cross-layer resource management to further improve system performance.

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