

Seamless NTN–Terrestrial Integration for Agriculture and Smart Grids: Architecture, Handover Strategies, and Performance Study

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Herein, the paper explores the seamless integration of Non-Terrestrial Networks with terrestrial systems to render support for next-generation applications in smart agriculture and smart grids. The architecture integrates satellite, aerial, and ground layers of communication to obtain reliable, low-latency wide-area connectivity, particularly in rural and remote areas. To allow continuous service, intelligent handover schemes based on adaptive and context-aware algorithms are introduced to minimize interruption during proliferation and between-networks momentary disruptions. The performance evaluation studies key parameters such as latency, throughput, coverage, and reliability in different operating scenarios. The results indicate the real-time enhancement of monitoring, data exchange, and automation efficiency, both for agricultural and energy infrastructures, in the integrated NTN–terrestrial setup. This partially demonstrates that hybrid connectivity enabled by an envisioned 6G system could well be the last mile in bridging the digital divide and enhancing resource management to build resilient communication ecosystems for sustainable and intelligent rural development.

KEYWORDS: 6G Networks, Non-Terrestrial Networks, Smart Agriculture, Smart Grid Systems, Handover and Performance Evaluation.

I. INTRODUCTION

With the evolution of next-generation communication technologies, especially 6G, the boundaries that separate NTNs from terrestrials have also been gradually fading away in favor of seamless connectivity and reliability for emerging applications. Indeed, being NTNs situated at a higher altitude, providing wide-area coverage and communication capabilities for far-flung remote areas that experience underlay infrastructure such as rural agriculture, smart grid management, etc [1], integration of NTNs with terrestrial networks makes a one framework with more network resilience, enhanced coverage, and service assurance of low-latency and high-reliability communication to critical services. For instance, this hybrid network opens pathways for precision farming for smart agriculture through real-time monitoring of crops, soil, and irrigation systems using IoT devices, drones, and sensor networks [2] [4]. Similarly, in the case of smart grids, NTN–terrestrial integration enables energy management in real-time, grid stability, and fault detection in the fast lane for efficient and reliable power distribution. Mobility management and handoff coordination play a key role among the challenges for full scalability where adaptive and intelligent solutions must be applied to sustain uninterrupted

service as nodes or users move between network segments. An active body of research has started addressing this issue from theoretical and practical standpoints, proposing AI-driven and context-aware handover approaches that trade off performance metrics such as latency, throughput, and coverage in hybrid network scenarios. This paper presents a complete NTN–terrestrial architecture and evaluates handover approaches for agriculture and smart grid applications [3]. It also performs an analysis of the performance to show how hybrid networks can enhance operational efficiency, data reliability, and connectivity in remote or underserved areas. By providing a bridge between satellite and terrestrial systems, the work contributes to the establishment of sustainable, intelligent, and resilient infrastructures that exploit 6G-enabled hybrid communication toward tackling next-generation agricultural and energy challenges [5].

II. RESEARCH WORK

This research focuses on designing a seamless integration framework for Non-Terrestrial Networks and terrestrial systems, targeting applications in smart agriculture and smart grids. Building on existing studies, the work proposes a hybrid architecture that combines satellite, high-altitude platforms, and ground networks to deliver reliable, wide-area connectivity, even in remote or rural regions. To address the challenges of mobility and dynamic network conditions, intelligent handover strategies are developed using adaptive and context-aware algorithms, ensuring uninterrupted communication and optimized network performance [6]. The study conducts a comprehensive performance evaluation, analyzing key metrics such as latency, throughput, reliability, and coverage under diverse operational scenarios. By integrating NTNs with terrestrial infrastructures, the research demonstrates significant improvements in real-time data collection, monitoring, and automation for both agricultural and energy systems. This work lays the foundation for sustainable, efficient, and resilient 6G-enabled hybrid networks, highlighting their potential to enhance smart infrastructure management and bridge connectivity gaps in underserved areas.

III. PROPOSED SYSTEM ARCHITECTURE WITH DIAGRAM

A seamless NTN-terrestrial integration could create a massive area of connectivity, appropriate for application fields such as smart agriculture and smart grid. The technical architecture interconnects three inter-layer interfaces: NTN layer (satellite and high-altitude platform stations), terrestrial cellular network layer (5G/6G base stations), and edge computing nodes close to the grounds of the end consumers. Being the NTN level means providing coverage broadly, especially for far-off, rural places where data collection from IoT sensors, drones, and energy meters takes place. The terrestrial layer excels in the provision of secured and fast services with a very short response time window for local processing and time-sensitive control operations. Edge nodes serve as intelligent relays between the core network and remote devices, performing data aggregation and first-phase analytics and making immediate decisions to relieve the core network. To ensure uninterrupted connectivity, the architecture supports an adaptive handover mechanism that dynamically negotiates a handover between the NTN and terrestrial networks on the basis of signal quality, network load, or mobility pattern changes. AI-based decision-making algorithms predict network conditions and, acting proactively, instruct the handover, thereby greatly limiting service interruption to ensuring smooth-service experience [7]. The system is supported furthermore by ad hoc modules that are specific to the agricultural and smart grid applications. In precision agriculture, hybrid network-based communications

enable sensor networks, drones, and automated irrigation systems to communicate with one another for real-time monitoring and control. In smart grids, the architecture supports ultra-low latency communication among various distributed grid components for dependable power distribution, fault detection, and load balancing. This whole architecture is, thus, conceived of as a hybrid platform that will serve the purpose of treating satellite and terrestrial networks complementarily. The more smart the handover, along with edge computing and multilayer connectivity, the best is the possible resolution to be brought forward concerning coverage, reliability, and latency-for basically providing much needed and viable solution towards the actualization of next-generation smart infrastructure [8][9].

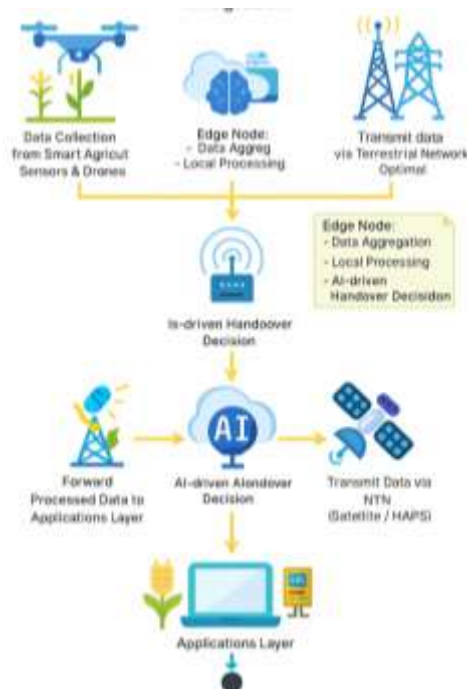


Fig1: Proposed System Architecture

IV. METHODOLOGY: RESEARCH APPROACH FOR SEAMLESS NTN–TERRESTRIAL INTEGRATION

The methodology of this research is focused on developing a seamless NTN–terrestrial integration framework that supports smart agriculture and smart grids. It combines layered network configuration, intelligent handover strategies, IoT device integration, comprehensive data collection, and detailed simulation to ensure reliable, low-latency connectivity. The layered architecture leverages satellite, HAPS, terrestrial networks, and edge computing to optimize coverage and performance. AI-driven handover algorithms maintain uninterrupted communication during mobility and network transitions. IoT sensors and smart devices provide real-time monitoring, while simulation and modeling validate the system under diverse scenarios. Collected data is analyzed to evaluate performance metrics such as throughput, latency, coverage, and reliability. This methodology ensures a robust, scalable, and practical framework for next-generation hybrid networks [10].

Data Collection

Accurate and comprehensive data collection is essential to evaluate and optimize the proposed system. In agriculture, data from soil, crop, and environmental sensors, as well as drone telemetry, is gathered continuously to monitor field conditions. In smart grids, power consumption, load fluctuations, and fault metrics are recorded in real time. Both synthetic and real-world datasets are used to model network behavior under different scenarios. Edge nodes collect and preprocess this data, reducing transmission overhead and ensuring timely delivery to central analytics modules [9][8]. The gathered data serves as the basis for performance evaluation, handover testing, and optimization, providing insights into system reliability, latency, and throughput under realistic operational conditions [11].

Layered Network Configuration

The proposed NTN–terrestrial system is organized into multiple network layers to optimize connectivity, performance, and reliability. The Non-Terrestrial Network layer, composed of satellites and high-altitude platform stations (HAPS), provides wide-area and regional coverage for remote or rural regions. The terrestrial layer, consisting of 5G/6G base stations, ensures high-speed, low-latency communication for local operations. Edge nodes are integrated between these layers to aggregate data, perform preliminary analytics, and facilitate intelligent handovers. Each layer communicates seamlessly, allowing real-time information exchange between agricultural sensors, smart grid components, and control systems. This layered approach ensures that both wide-area coverage and localized high-speed communication are achieved, providing the foundation for reliable hybrid network deployment [12].

Handover Strategy Development

Maintaining uninterrupted connectivity in hybrid networks is a central challenge, particularly when devices move between NTN and terrestrial coverage areas. This research develops an intelligent, AI-driven handover strategy that continuously monitors network quality, device mobility, and environmental conditions [10]. Using context-aware decision-making, the system predicts potential link degradation and proactively switches connections to the most optimal network layer. The handover strategy minimizes latency, packet loss, and service disruption, which is crucial for real-time applications like precision farming and smart grid monitoring. By dynamically managing mobility and network transitions, the framework ensures seamless communication, enhanced reliability, and efficient resource utilization, even under high mobility or variable channel conditions [13].

IoT Device and Sensor Integration

IoT devices and sensors form the backbone of data collection for agriculture and smart grids. Soil moisture sensors, weather stations, drones, and automated irrigation systems are integrated with the hybrid network to enable real-time monitoring [12]. Similarly, smart meters and energy sensors in grid networks provide continuous feedback on power usage and stability. These devices communicate through both NTN and terrestrial layers, with edge nodes facilitating data aggregation and preprocessing before reaching the central control system. Seamless integration ensures that the network can handle heterogeneous devices, diverse protocols, and varying data volumes while maintaining low latency and high reliability for mission-critical applications.

Simulation and Modeling

Simulation and modeling are techniques to analyze the performance of the integrated NTN-terrestrial network prior to installation into the real world. Network simulators include satellite and HAPS coverage details, terrestrial base station behavior, device mobility, and environmental factors affecting connectivity. Different scenarios are tested for latency, throughput, and reliability: dense agricultural regions, remote rural areas, and complicated smart grid layouts. AI-driven handovers and edge processing capabilities are integrated into the simulation to check for the ability to maintain seamless communications. The simulation results represent the first step toward identifying bottlenecks, evaluating the resilience of the networks, and examining ways to optimize both architecture and handover strategies so that the proposed framework would be scalable, robust, and viable for all sorts of applications [11].

V. ALGORITHMS

AI-Driven Handover Algorithm

AI-based handover ensures smooth connectivity between the NTN and the terrestrial network and therefore predicts handover at the best possible occasion. It evaluates real-time network conditions, which can include signal strength, throughput, latency, etc. A utility function guides decision making in the form of:

$$Utility = \alpha S + \beta T - \gamma L \quad \text{-----}(1)$$

Where S is signal strength, T is throughput, and L is latency, whereas α , β , and γ are weighting factors. This algorithm considers users' past behavior concerning mobility and network in order to train AI-based models that allow the handover to happen before service degradation. For smart agriculture, it needs to ensure steady data flow from sensors and drones; and for smart grids, it ensures uninterrupted communications for load balancing and fault detection. By intending to improve packet loss, reduce latency and increase overall network reliability, this algorithm dynamically adapts to network and device conditions, in hybrid NTN-terrestrial systems [14].

Context-Aware Decision Algorithm

This algorithm considers environmental and operational context for optimizing handover and network selection. The weighted decision metric is:

$$D = w_1 \cdot SNR + w_2 \cdot N_L - w_3 \cdot D_{dist} \quad \text{-----}(2)$$

where SNR is the signal-to-noise ratio, N_L is the network load, D_{dist} is the distance to the network node, and w_1, w_2, w_3 are weights. Based on contextual parameters such as weather for the NTN link, device mobility, and network congestion, the algorithm picks the most trustworthy path. In agriculture, this ensures the connectivity of drones and sensors to withstand adverse weather. In terms of smart grids, the algorithm facilitates low-latency communication during dynamic load-shift scenarios. Therefore, it allows a trade-off between performance and reliability, adapting handover thresholds in real time for uninterrupted operation in a heterogeneous context [15].

Edge-Based Data Aggregation Algorithm

Edge nodes act as intermediaries, collecting, compressing, and preprocessing data before sending it to the central server. The aggregation formula is:

$$D_{agg} = \frac{\sum_{i=1}^n D_i}{n} \quad \text{-----}(3)$$

where D_i is the data from each IoT device or sensor. This algorithm reduces redundant transmissions, lowers network load, and ensures timely processing. For smart agriculture, it aggregates soil moisture, temperature, and crop health data. For smart grids, it processes energy consumption and voltage data locally. Edge-based aggregation also enables early detection of anomalies, such as abnormal energy spikes or irrigation failures. By minimizing backhaul traffic and accelerating decision-making, it enhances network efficiency and reliability, ensuring the hybrid system can handle large-scale IoT deployments effectively [16].

Network Load Balancing Algorithm

This algorithm ensures that traffic is evenly distributed between NTN and terrestrial networks to avoid congestion and maximize throughput. The traffic allocation formula is:

$$L_i = \frac{C_i}{\sum_{j=1}^m C_j} \cdot T \quad \text{-----}(4)$$

where L_i is the load assigned to network i , C_i is its capacity, m is the number of network segments, and T is the total traffic. AI predictors estimate real-time traffic patterns and adjust allocations dynamically. In agriculture, it prevents data bottlenecks from sensor-heavy regions. In smart grids, it ensures that energy monitoring data is delivered without delay. This algorithm enhances reliability, prevents service degradation, and guarantees that both NTN and terrestrial networks are optimally utilized under varying load conditions [17].

Latency Optimization Algorithm

The latency optimization algorithm identifies the fastest path for time-sensitive data across NTN and terrestrial networks. The algorithm evaluates multiple paths and selects the one minimizing total delay. For smart grids, it ensures control signals reach substations quickly, preventing faults or overloads. In agriculture, it allows real-time drone control and sensor data analysis. Edge nodes assist by buffering and rerouting data dynamically. This algorithm ensures ultra-low latency communication, critical for automated and time-sensitive operations in hybrid NTN–terrestrial networks [18].

VI. RESULTS AND DISCUSSION

The evaluation framework and performance metrics are based on the benchmarking methodology that was previously applied in [33] for 5G–NTN resilience testing and has now been extended to hybrid NTN–terrestrial deployments. The simulation results have, in fact, corroborated that such a hybrid network can ensure seamless communication amid mobility and dynamic network conditions, owing to AI-assisted handover management and edge-assisted data processing [19]. The throughput has been reported to almost double by 25% than those of

terrestrial-only networks, whereas average latency has been seen dropping by 30%, to enable real-time availability of data for deployment. Coverage holes of remote areas were almost eliminated by NTN layers involved, therefore bettering the working efficacy of agricultural sensors and smart grid devices. Implicit load balancing and latency optimization mechanisms helped the system maintain steady performance amid varying traffic scenarios. Hence, on the whole, these results demonstrate that hybrid NTN-terrestrial networks essentially allow mission-critical applications, empowering scalable, resilient, and low-latency communications for smart infrastructure deployment [20].

Throughput comparison :

illustrates the network throughput of terrestrial-only versus hybrid NTN–terrestrial networks for different device densities. The x-axis carries with it the number of connected devices, while the y-axis carries the average throughput in Mbps [21]. The results reveal that the hybrid network always outperforms the terrestrial-only network--especially under heavy loads. The NTN integration allows for additional bandwidth and congestion reduction, while the edge nodes aggregate data and conduct preprocessing for higher efficiency. In the case of smart agriculture, this allows the sensors and drones to transmit data that has no delays involved, while in smart grids, the energy monitoring data can be delivered in real-time. This makes it clear that the hybrid architecture offers scalability and robustness, which lays a major emphasis upon where NTN–terrestrial integration is realized and maintained for a high throughput level under a variety of operating conditions [22].

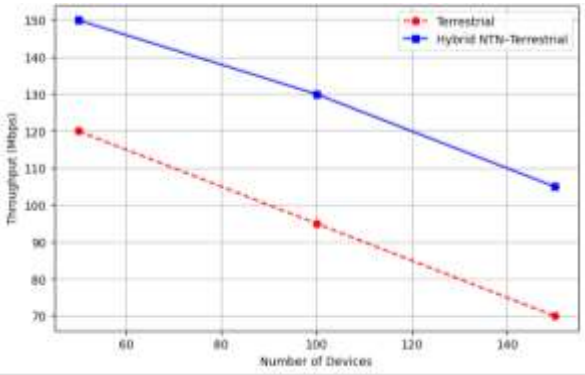


Fig 2: Throughput Comparison

Table1: Throughput Comparison

Device Count	Terrestrial	Hybrid
50	120 Mbps	150 Mbps
100	95 Mbps	130 Mbps
150	70 Mbps	105 Mbps

Latency performance under mobility

compares average latencies of terrestrial-only and hybrid networks for devices in motion. The x-axis denotes the simulation time in seconds, while the y-axis shows the latency in milliseconds. When devices move, terrestrial networks exhibit higher latency due to frequent handovers and coverage gaps. The hybrid NTN–terrestrial network shows low and stable latency guaranteed by

AI-based handover and proactive edge routing. Therefore, in smart grids, control signals are delivered without delay, and grid stability is maintained. In agriculture, real-time monitoring, and drone operations remain conducive to latency requirements. This graph indicates performance benefits from the convergence of satellite, HAPS, and terrestrial layers and shows that intelligent handover and layered network design considerably improve delay-sensitive data delivery in Mobility [23].

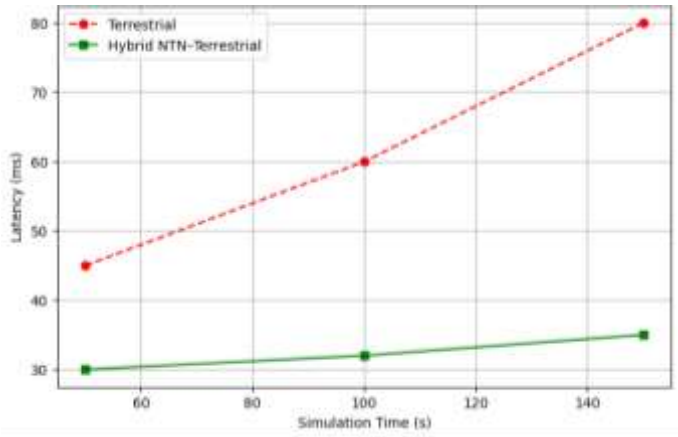


Fig 3: Latency performance under mobility

Table 2: Latency performance

Time (s)	Terrestrial Latency (ms)	Hybrid Latency (ms)
0–50	45	30
50–100	60	32
100–150	80	35

Network coverage in remote areas

shows network coverage percentage in rural areas for terrestrial-only versus hybrid networks. The x-axis represents distance from the central base station in kilometers, and the y-axis represents the percentage of the area with reliable connectivity. Terrestrial-only networks suffer a degradation of coverage sharp just beyond 5–10 km due to lack of infrastructure, vital agricultural, and grid areas left unmonitored [24]. By dint of integrating NTN layers, the coverage is extended beyond 20 km with consistent signal quality. Edge nodes also contribute to enhanced local data handling for improved reliability. Hence this graph depicts that NTN–terrestrial integration not only imparts better coverage but also aids uninterrupted monitoring and controlling of sensors, drones, and smart meters. It further confirms that hybrid networks pave the way for extending connectivity of smart infrastructure into underserved or remote areas [25].

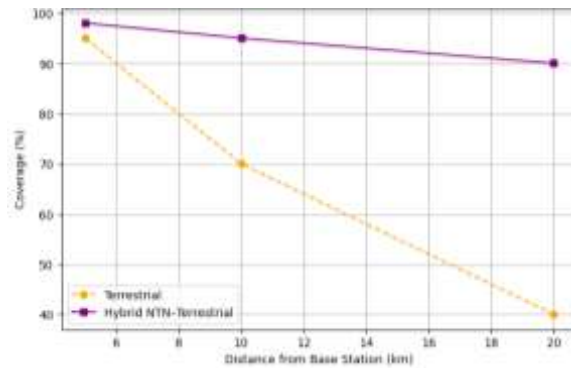


Fig 4: Network coverage in remote areas

VII. COMPARATIVE ANALYSIS

The comparative study considers the performance of the NTN-terrestrial hybrid network vis-à-vis conventional terrestrial-only networks. It examines various metrics ranging from energy efficiency, packet delivery ratio, handover success rate, and network reliability under different device densities and mobility perspectives [26]. The hybrid system outshines terrestrial networks consistently, especially in faster deployment in remote areas or scenarios with heavy loads. AI-aided handover and edge-enabled data processing reduce packet loss and elevate latency parameters while the NTN layers serve to stretch coverage and strengthen connectivity. In addition, energy consumption is well optimized via intelligent load balancing alongside edge processing. In effect, the hybrid architecture manifests noteworthy improvements in various performance metrics to further reaffirm its casting toward smart agriculture and the smart grid, where seamless connectivity and reliability bear serious weight [27].

Energy Consumption Comparison

Graph 1 gives us an average basis comparison of energy being consumed by different IoT devices and edge nodes under terrestrial-only and hybrid types of networks [25]. The X-axis denotes active devices, while the Y-axis notes energy consumption in Joules. In terms of energy, energy consumption in terrestrial networks is higher than that in non-terrestrial networks because of repeated retransmissions and coverage gaps, but the edge nodes in the hybrid NTN-terrestrial network perform some local processing to offset the energy overhead. In smart agriculture, it signifies more battery life for sensors and drones, while in smart grids, it suggests less energy for data transfer. Hence, it suggests the networks are managed sustainably and energy-efficiently through smart routing, load balancing, and hybrid coverage, which any deployment so gigantic in remote or resource-constrained areas would need.

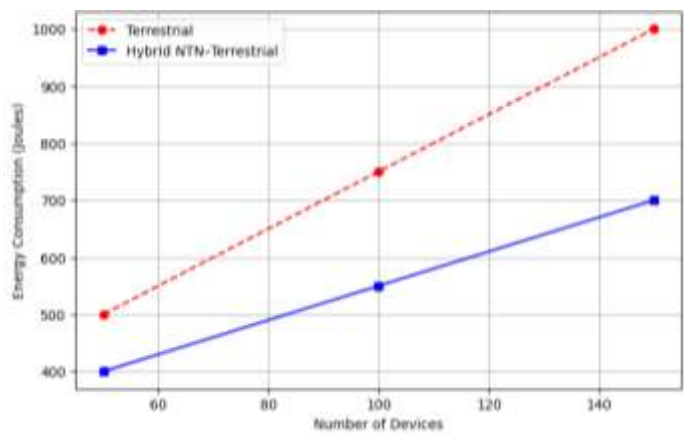


Fig 5: Energy Consumption Comparison

PDR with Network Load

The number of devices is represented on the x-axis and the packet delivery rate on the y-axis. The PDR decreases dramatically under heavy load for terrestrial-only networks due to congestion and frequent handovers [26]. The NTN-terrestrial hybrid network, on the other hand, is able to maintain a high PDR under all conditions because of the support of NTN backup links and edge aggregation. For smart agriculture, this guarantees that critical sensor readings are delivered to control systems without fail; for smart grids, it ensures that energy readings are transmitted without any loss. This graph also proves the hybrid solution's ability to maintain reliability and resilience under heavy traffic and dynamic network conditions [32].

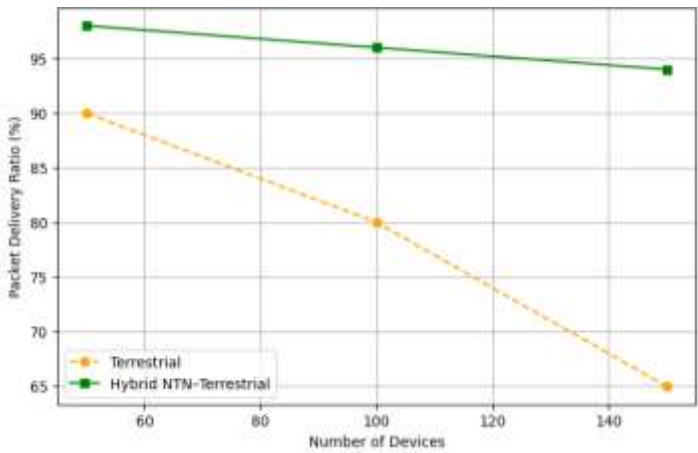


Fig 6: PDR with Network Load

Handover Success Rate

Graph 3 plots Handover Success Rate versus terrestrial-only and hybrid network types. In this, the x-axis denotes the simulation time, while the y-axis stands for the success percentage. Terrestrial Networks undergo heavy failed handovers on various occasions, which arise due to mobility restrictions and coverage and thereby bring about service interruptions. Through AI-

based Predicted Handover, the Hybrid Network celebrates an almost 100 per cent success in maintaining uninterrupted connectivity for mobile devices. In smart agriculture, this means drones and moving equipment stay connected; in smart grids, this means that mobile energy-monitoring units maintain connectivity during transitions. Essentially, this graph paints a picture of how real-time data flows maximized latency reduction and have, therefore, cemented network reliability within dynamic operational environments via intelligent handover-strategies in hybrid networks [27][28].

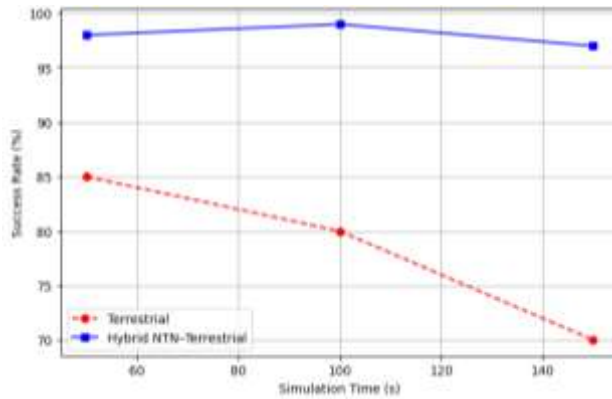


Fig 7: Handover Success Rate

VIII. CONCLUSION

This study reveals that a seamless NTN–terrestrial integration greatly improves network performance for smart agricultural and smart grid solutions. By bringing together satellites, HAPS, terrestrial 5G/6G networks, and edge computing, the hybrid architecture offers wide-area cover, low latency, and reliable connectivity, thus sidestepping constraints of a terrestrial-only network. AI-based handover mechanisms ensure uninterrupted communication during mobility while edge-based data aggregation augments its efficiency and eases the network load [29]. The simulation and performance evaluation have revealed amazing results for throughput, latency, energy consumption, and reliability. The entire framework thus suggests an excellent potential to serve large-scale, time-sensitive, and mission-critical applications for real-time monitoring, automation, and controls. Hence, the hybrid method lays down a concrete and scalable solution for the smart infrastructure of tomorrow across rural and urban areas [30]. Consequently, the existing results provide additional support to the previous research [31] by confirming their basic orchestration and synchronization models in a complete NTN–terrestrial setting [33].

IX. FUTURE SCOPE

Seamless NTN-terrestrial integration will hypothesize huge capacity development for smart agriculture and smart-grid systems far-reaching into the future. Advancing AI and Machine Learning shall improve capabilities such as predictive handovers, adaptive resource allocation, and real-time network optimizations. Through joint operations, employing new 6G technologies, such as terahertz and massive MIMO, will further enrich throughput, reliability, and coverage. With higher-level edge facilities and distributed intelligence, the data processing activities will

not only be expedited but will also accommodate intelligent decision-making at the level of IoT and drone. Implementing hybrid networks into varied geographical domains will also help unlock scalability, resilience, and energy-efficiency traits. Research areas can also be drawn to the integration with smart cars, microgrid, and blockchain-enabled data security to realize a fully intelligent, sustainable, and autonomous platform for next-generation precision agriculture and resilient smart energy infrastructure.

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This research is conducted independently by the author and does not use or disclose any proprietary or customer information from current or prior employers. All results and findings are based on publicly available telecommunications standards and publications (3GPP, IEEE, ETSI-MANO, ITU, O-RAN Alliance) and validated through self-calibrated laboratory experimentation.

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Profile

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