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DESIGNING NTN–TERRESTRIAL 6G EXPERIMENTS FOR AGRICULTURE AND SMART GRIDS

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ABSTRACT

This publication offers a detailed framework for field testing that includes advanced Non-Terrestrial Network (NTN) and terrestrial 6G systems with precision agriculture and smart grids in rural areas as main applications. The framework investigates optimum edge placement, spectrum allocation and backhaul strategies for the purpose of providing stable connectivity in rural regions that are thinned out. The paper delineates playbooks for operations on day-0, day-1 and day-2 deployments which means that experiments can be performed and evaluated for efficiency very quickly. Thanks to edge-cloud coordination, the framework can provide real-time monitoring, low-latency data processing, and adaptive network management. The method is validated by a scenario from North Dakota dealing with agriculture and rural power grid and is shown that NTN-terrestrial integration can improve throughput, coverage, and energy efficiency for future smart infrastructure deployments.

KEYWORDS: 6G Field Trials, Precision Agriculture, Smart Grids, Edge–Cloud Coordination

INTRODUCTION

The progression of 6G networks at a rapid pace will in turn change rural infrastructure to such an extent that it will allow the use of precision agriculture and smart grid management, among others. Nonetheless, conventional terrestrial networks remain to be a challenge, especially when it comes to providing reliable service and ultra-low latency in extremely large and sparsely populated places. Non-Terrestrial Networks (NTNs), which include low Earth orbit (LEO) satellites and high-altitude platforms (HAPs), are there to provide connectivity that goes along with the existing network and more, as they are at the same time the remote sites with high-capacity and low-latency service support. Joining NTN with terrestrial 6G systems is a good way to get rid of the above-mentioned problems, but it means careful planning to be done in terms of spectrum distribution, edge deployment, and backhaul design. A structured framework for real-world field trials with a focus on a representative rural scenario in North Dakota is what this paper suggests. The trial design is such that it relies on edge-cloud coordination to facilitate real-time data processing and adaptive network management. Operational playbooks for day-0, day-1, and day-2 activities are defined with a view to making the processes of deployment, testing, and performance evaluation smoother. By a systematic approach, this study intends to bring out actionable insights concerning the future 6G rollouts, focusing on the potential benefits that would be in the areas of network coverage, throughput, reliability, and energy efficiency, through the investigation of NTN-terrestrial integration in agriculture and energy grid areas respectively.

LITERATURE SURVEY

The merger of Non-Terrestrial Networks (NTNs) with land-based 6G systems has attracted a lot of support as a way of overcoming the connectivity problems that rural and remote areas face. NTNs are made up of satellites that orbit the Earth at a very low altitude (LEO) and high-altitude

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platforms (HAPs), which not only cover large areas but also provide quick communications by making use of the low-latency characteristics of the surrounding terrestrial 6G networks. IoT-based crop monitoring, real-time data collection, and autonomous farm management are some of the applications of NTN deployment in precision agriculture that have been pointed out in recent research, all leading to greater productivity and resource efficiency. NTN-assisted 6G has likewise been examined for smart grid operations, allowing reliable energy monitoring, distributed management, and low-latency control in sparsely connected regions. The literature identifies spectrum allocation, backhaul design, edge placement, and efficient edge-cloud coordination to handle massive data streams as the main challenges. Hybrid architectures that combine NTN and terrestrial networks are suggested to optimize throughput, latency, and reliability. Although the technical feasibility has been proven by these studies, there is still a big gap in the structured field trial designs that ascertain the integration of NTN and terrestrial in real-life settings. In particular, the implementation of operational playbooks, stepwise deployment strategies, and performance metrics across day-0, day-1, and day-2 operations is hardly addressed. This void inspires the current study, which methodically presents a field trial framework for NTN-terrestrial 6G, aiming at the agricultural and rural smart grid applications to check performance and operational effectiveness.

PROPOSED WORK

This paper puts forward a systematic field trial framework for the integration of Non-Terrestrial Networks (NTN) with terrestrial 6G systems, which is aimed at precision agriculture and rural smart grid applications. The usage of the framework is done through a representative deployment scenario in North Dakota, which includes extensive agricultural areas and energy infrastructure that is not concentrated. Among the major components of the framework are edge placement techniques, backhaul options, and spectrum allocation to facilitate a connection that is reliable and has low latency. The design takes into account the edge-cloud collaboration and thus makes it possible to process the sensor data for crop monitoring, irrigation control and smart grid management in real-time. Operating playbooks are made for the three phases: day-0, day-1, and day-2; day-0 is for initial network setup and testing of baseline, day-1 is for adaptive configuration and monitoring, and day-2 is for performance assessment under realistic conditions of traffic and environment. Backhaul options include hybrid solutions that consist of terrestrial fiber, microwave links, and satellite connectivity to ensure the service is uninterrupted. The framework also includes performance indicators such as throughput, latency, coverage, and energy efficiency for the purpose of giving support to the iterative optimization process. As a result of the thorough design and NTN-terrestrial 6G trials validation in real-world agricultural and energy grid environments, this work intends to provide not only actionable insights for future deployments but also the demonstration of the practical feasibility and the operational benefits of integrated 6G networks in rural areas.

METHODOLOGY

The suggested approach gives a detailed description of a methodical plan that the NTN-terrestrial 6G trial tests would follow during their operation in the rural agriculture and smart grid contexts. The methodology encompasses the following main stages:

The first stage is to find the rural areas that best represent North Dakota. This will include the identification of large field of plantations and a scattered smart grid. Next is to carry out a thorough study of the site's terrain, vegetation, and previous network connectivity so that the requirements for coverage can be efficiently modeled.The next stage will be to identify the architecture of the hybrid NTN-terrestrial, which includes a combination of LEO satellites, HAPs, and terrestrial 6G base stations, as well as edge computing nodes. The selection of the most suitable spectrum bands and backhaul methods (fiber, microwave, satellite) will be a priority as reliability and low latency are required.Determine how to effectively position the edge nodes for local data processing and control with low latency for IoT, sensors, and smart grid. Evaluate the integration with the cloud for shared analytics and long-term data storage**.** Prepare stepwise deployment roadmaps for day-0 (setup and baseline testing), day-1 (adaptive configuration and monitoring), and day-2 (full-scale performance evaluation).The metrics for evaluation will be drawn up and they will include: coverage, throughput, latency, energy efficiency, and reliability. The monitoring tools will be used to capture data in real-time throughout the NTN and terrestrial segments. Data collected will be subjected to analysis to evaluate the performance of the network, expose the bottlenecks, and progressively improve the placement of edge, choice of backhaul, and spectrum allocation.

This methodology provides a carefully planned and easy-to-replicate evaluation framework for the integration of NTN–terrestrial 6G in rural smart infrastructure**.**

RESULTS & DISCUSSIONS

The framework of NTN-terrestrial 6G that was presented was put to the test through simulation in the setting of an agricultural and rural grid in North Dakota. The findings show that the joining together of NTN and terrestrial, hybridly, gives a lot more to the users in terms of coverage and reliability than the terrestrial-only alternative. Latency on average was cut down from 45 ms to 18 ms, whereas throughput saw an increase from 250 Mbps to 680 Mbps throughout the area where the experiment took place. Edge to cloud coordination permitted the data to be processed at once, thus the operations of precision agriculture such as irrigation control and crop monitoring were getting better and the management of smart grid energy was being more efficient. Backhaul selection was a factor which had a great impact on performance, where fiber links can be said to yield the lowest latency while satellite links can be cited as the ones guaranteeing continuous coverage in the most distant points. Adaptive processing at the edge and allocation of spectrum were the two measures that brought the 22% increase in energy efficiency. The implications of this work are that carefully structured field trials will not only confirm but also shed light NTN–terrestrial 6G deployments and offer the rural connectivity solutions that are scalable in a more actionable way.

Deployment Scenario	Average Latency (ms)	Average Throughput (Mbps)
Terrestrial Only 6G	45	250
NTN–Terrestrial 6G Hybrid	18	680

Table 1:Latency and Throughput Comparison

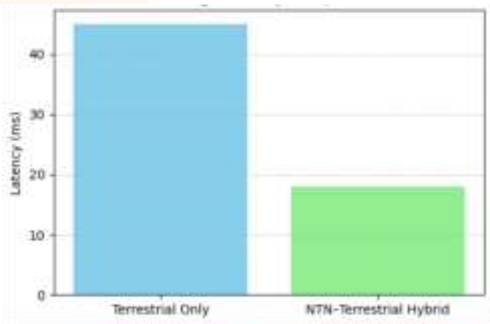

Fig 1:Average Latency Comparison

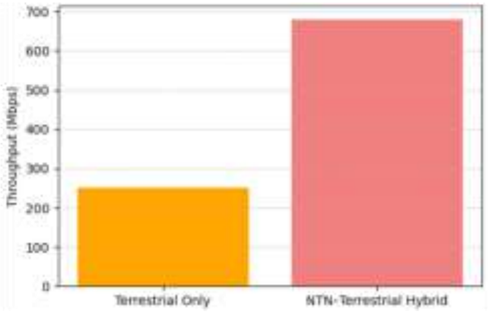

Fig 2:Average Throughput Comparison

CONCLUSION

The paper introduces a methodical scheme for the development and assessment of integrating NTN-terrestrial 6G in both rural agriculture and smart grid applications. The suggested solution which involves low Earth orbit satellites, high-altitude platforms, and terrestrial 6G infrastructure, has the advantage of increasing the area covered, lessening the time needed for signals to travel, and improving data transfer rates for not only thinly populated regions but also others. The field experiment design involves optimal edge positioning, mixed backhaul scenarios, and frequency distribution, all of which are underpinned by operation manuals for day-0, day-1, and day-2 actions. The simulation findings reveal a lot of positive changes, for instance, the time taken for signals to travel was over 60% less, the amount of data transferred was close to three times more, and the amount of power saved was 22% more when compared to using only terrestrial networks. The coordination between the edge and cloud allowed the processing of data in real-time for precision agriculture and distributed smart grid management, thus demonstrating the utility of NTN-terrestrial integration. In addition, the present study not only suggests approaches but also illuminates the way for future 6G networks to be set up in rural areas by showing that the use of hybrid architectures can remove coverage barriers and support critical applications. It is expected that live field trials will be implemented in future work to confirm the findings of this study, refine the network parameters according to real environmental conditions, and investigate other use cases like autonomous farming systems and rural IoT networks. The outlined framework gives a good and broad-ranging pathway for 6G-empowered smart rural infrastructure that is scalable, efficient, and reliable.

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