A SYSTEM-LEVEL STUDY OF HYBRID TERRESTRIAL–NTN ARCHITECTURE FOR 6G-READY CELLULAR NETWORKS

An Operator-Centric Performance and KPI Perspective

ABSTRACT

Performance Trade-offs, Operational Considerations, and Deployment Insights for 6G ready cellular networks

Adeel Khan
Senior Telecom Professional

Adeel Naim Khan
Expert Telecom Optimizer / Network Performance / MSP / Cloud / AI / 6G / NTN

https://www.adeel-khan.com
https://www.adeelkhan77.com

About the Author

Adeel Naim Khan is a senior telecom professional with over 20 years of experience in radio access network optimization, performance management, and service assurance across 2G, 3G, 4G, and 5G networks.

His professional interests include 5G-Advanced, 6G system architecture, Non-Terrestrial Networks (NTN), and hybrid terrestrial–satellite integration from a mobile network operator perspective.

This study reflects independent learning and analysis conducted during a professional transition period.

LinkedIn: https://www.linkedin.com/in/adeel-naim-khan-6093122/

Disclaimer

About this Study

This study examines the integration of Non-Terrestrial Networks (NTN) into future 6G-ready cellular architectures from a system-level and operator-centric perspective.

Rather than focusing on physical-layer modeling or protocol-level implementation, the study evaluates end-to-end performance behavior, service continuity, and key performance indicators (KPIs) relevant to mobile network operators.

The work compares the characteristics of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) satellite systems and discusses their suitability for hybrid terrestrial–NTN deployment scenarios such as remote coverage, resilience, and service continuity.

This publication is intended for telecom engineers, network planners, researchers, and decision-makers seeking a practical understanding of NTN integration in future mobile networks.

Executive Summary

The evolution toward 6G networks is expected to extend mobile connectivity beyond traditional terrestrial boundaries, enabling seamless service availability in remote, rural, and infrastructure-challenged environments. Non-Terrestrial Networks (NTN), leveraging satellite-based access, are emerging as a key enabler of this vision.

This study presents a system-level analysis of a hybrid terrestrial–NTN cellular architecture aligned with 5G Standalone (SA) and future 6G design principles. The objective is to evaluate how Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) satellite systems can complement terrestrial cellular networks from an operator perspective.

The analysis focuses on operator-relevant performance indicators, including latency, round-trip time (RTT), throughput, voice service feasibility, mobility continuity, and service availability. Rather than detailed physical-layer modeling, the study emphasizes end-to-end system behavior, architectural trade-offs, and deployment considerations relevant to real-world cellular networks.

Key findings indicate that LEO satellites offer the most balanced performance for broadband and latency-sensitive services, while MEO and GEO satellites provide wider coverage and stability at the cost of increased latency. NTN is best positioned as a complementary access technology, supporting coverage extension, service continuity, and resilience, particularly in areas where deploying terrestrial infrastructure or VSAT-backed base stations is economically or operationally challenging.

The study also discusses regulatory, spectrum, cost, and scalability considerations, highlighting that while NTN adoption is progressing globally, deployment strategies must remain policy-driven, use-case-specific, and aligned with operator business models. Ongoing advancements in satellite technology are expected to further enhance NTN performance, reinforcing its role in future 6G ecosystems.

This work aims to provide practical insights for mobile network operators, researchers, and technology planners exploring NTN-enabled cellular architectures as part of the 6G evolution.

Summarizing:

- LEO-based NTN offers the best balance between latency and coverage extension
- NTN is most effective as a controlled fallback and resilience layer
- Hybrid terrestrial–NTN architectures align well with operator cost models

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1. Detailed Problem Statement

1.1 Background and Context

Mobile network operators worldwide face persistent challenges in providing reliable and cost-effective connectivity in **remote, rural, desert, mountainous, maritime, and sparsely populated regions**. In such areas, traditional terrestrial cellular deployments suffer from:

- High capital expenditure (CAPEX) due to long inter-site distances
- Low return on investment (ROI) because of limited user density
- Operational complexity and maintenance challenges
- Limited backhaul availability and resilience

Despite advances in 4G and 5G technologies, **terrestrial-only Radio Access Networks (RANs)** remain economically and technically constrained when extending coverage to these environments. Costs and structure feasibility both become a big hurdle to extend the coverage in these areas.

At the same time, emerging **6G visions** identify **ubiquitous connectivity** as a fundamental requirement, aiming to deliver seamless service continuity across remote desert, Mountainous trails, deep sea rigs, and air. This vision inherently requires the **integration of Non-**

Terrestrial Networks (NTN) — including satellite systems — with terrestrial cellular infrastructure.

1.2 Motivation for NTN Integration

Non-Terrestrial Networks, particularly satellite-based systems, offer unique advantages for coverage extension:

- Wide-area coverage with minimal ground infrastructure
- Rapid service availability in hard-to-reach regions
- Enhanced resilience for disaster recovery and emergency communication
- Support for mobility scenarios beyond terrestrial reach

However, **integrating NTN into future 6G networks introduces significant technical challenges**, especially when viewed from an operator and system-performance perspective. These challenges include:

- **High propagation latency**, particularly for GEO satellite systems
- **Doppler effects** caused by high satellite velocities (especially in LEO orbits)
- **Increased path loss** due to long transmission distances
- **Mobility and handover complexity** across terrestrial and non-terrestrial links
- **Service continuity issues** when switching between terrestrial and NTN access

In addition to Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) satellite systems, **Medium Earth Orbit (MEO)** satellites represent an important intermediate solution, offering a **balance** between coverage footprint, latency, Doppler effects, and constellation complexity. MEO-based NTN systems have the potential to mitigate some of the extreme trade-offs observed in LEO and GEO systems, making them a compelling candidate for future integrated 6G architectures.

Without careful system-level design and performance analysis, these impairments can severely degrade user experience and network efficiency.

1.3 Gap in Current Research and Practice

While significant research efforts exist on **satellite communications** and **5G-NTN standardization**, much of the available literature:

- Focuses on **link-level or physical-layer performance**
- Is **technology-centric rather than operator-centric**
- Lacks practical comparison between **terrestrial, NTN-only, and hybrid architectures**
- Does not sufficiently analyze **end-to-end performance trade-offs** relevant to mobile operators

Furthermore, current deployments and trials primarily address **5G-NTN**, while **6G-era integration principles** — such as intelligent access selection, hybrid connectivity, and system-level optimization — remain largely conceptual.

This creates a clear need for **operator-focused, system-level performance analysis** that bridges theoretical 6G concepts with realistic deployment constraints.

1.4 Problem Definition

The core problem addressed in this project is:

How can integrated terrestrial and non-terrestrial network architectures support reliable and acceptable service quality in remote and rural environments in the 6G era, and what are the key performance (KPI) trade-offs compared to terrestrial-only networks?

Specifically, this project investigates:

- The impact of different satellite orbits (**LEO, MEO, and GEO**) on latency, Doppler shift, and link performance within integrated terrestrial–NTN architectures.
- The comparative behavior of:
  - Terrestrial-only access
  - NTN-only access
  - Hybrid terrestrial-NTN access
- The feasibility of using NTN as:
  - A coverage extension layer
  - A resilience and fallback mechanism
  - A complementary component in future 6G network architectures

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1.5 Objectives of the Study

This project aims to:

- **Model and analyze** key performance indicators (KPIs) relevant to integrated terrestrial–NTN networks
- Quantify performance differences between terrestrial access and NTN access using **LEO, MEO, and GEO satellite systems**, highlighting their respective trade-offs.
- **Identify system-level limitations** that impact service quality in NTN-assisted connectivity
- **Propose optimization strategies** aligned with 6G design principles and operator requirements
- **Provide practical insights** that can guide future research, standardization, and deployment strategies

"While numerical simulation is outside the scope of this study, the comparative framework establishes a clear basis for future quantitative evaluation."

1.6 Scope and Assumptions

To maintain practical relevance, this study adopts the following scope:

- Focus on **system-level performance**, not detailed physical-layer implementation
- Consider **downlink-centric analysis**, with uplink discussed conceptually
- Use simplified but realistic high-level propagation and mobility models
- Emphasize **operator-relevant KPIs** rather than theoretical limit

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1.7 Expected Contribution

The expected contribution of this work is a **clear, operator-oriented evaluation** of integrated terrestrial–NTN architectures for future 6G networks, highlighting:

- When and where NTN integration is beneficial
- Which satellite orbits are more suitable for specific use cases
- What performance penalties must be managed
- How hybrid architectures can mitigate inherent NTN limitations
- The study also provides a **comparative evaluation of LEO, MEO, and GEO-based NTN architectures**, offering insights into their suitability for different deployment scenarios in the 6G era.
