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

Independent Technical Study

ABSTRACT

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

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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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Remote and Rural Coverage Extension Using Integrated Terrestrial–NTN Architecture for 6G-Era Networks

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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.

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2. Key Performance Indicators (KPIs) and System Parameters

2.1 Rationale for KPI Selection

The selection of Key Performance Indicators (KPIs) in this study is driven by **operator-centric performance considerations** rather than detailed physical-layer implementation. The objective is to evaluate how the integration of Non-Terrestrial Networks (NTN) affects **end-to-end service quality, mobility, and network usability** in future 6G-era deployments.

The KPIs selected reflect:

- User experience impact
- Network design trade-offs
- Deployment feasibility for operators

2.2 Selected Key Performance Indicators

2.2.1 End-to-End Latency

Definition:

Total one-way propagation delay between User Equipment (UE) and the core network through the access network.

Why it matters:

Latency directly impacts:

- Interactive services
- Real-time applications
- Control-plane responsiveness

Relevance to NTN:

Propagation delay increases significantly with satellite altitude, making latency one of the most critical limitations for NTN-based connectivity.

2.2.2 Round Trip Time (RTT)

Definition:

Time taken for a signal to travel from UE to the network and back.

Why it matters:

RTT affects:

- TCP performance
- Signaling procedures
- Handover and mobility robustness

Relevance to NTN:

RTT penalties are particularly severe for GEO-based systems and must be carefully evaluated for service viability.

2.2.3 Doppler Shift

Definition:

Frequency shift caused by relative motion between the satellite and the UE.

Why it matters:

High Doppler shifts:

- Complicate synchronization
- Increase receiver complexity
- Impact scheduling and HARQ performance

Relevance to NTN:

LEO systems experience significant Doppler effects due to high orbital velocity, while MEO offers intermediate behavior.

2.2.4 Path Loss

Definition:

Free-space propagation loss between transmitter and receiver.

Why it matters:

Path loss impacts:

- Link budget
- Required transmit power
- Modulation and coding feasibility

Relevance to NTN:

Long transmission distances introduce substantial path loss, particularly for GEO systems.

2.2.5 Theoretical Throughput (Indicative)

Definition:

Estimated throughput based on available bandwidth and signal-to-noise conditions.

Why it matters:

Although simplified, throughput estimation helps:

- Compare relative performance across orbits
- Understand capacity limitations

Note:

This study uses throughput as a **relative indicator**, not as an absolute performance metric.

2.2.6 Mobility and Service Continuity (Qualitative)

Definition:

Ability to maintain service during UE movement and satellite handovers.

Why it matters:

Frequent satellite handovers and mixed terrestrial–NTN mobility introduce new challenges in session continuity.

Note:

This KPI is analyzed conceptually, supported by **widely reported simulation trends and behavior observed in existing 3GPP studies and published research**, rather than by full protocol-level modeling within this study.

2.2.7 Voice Delay Impact (Qualitative)

Although round-trip time (RTT) and propagation delay are network-level parameters, they directly affect **end-to-end voice delay**, which is a critical factor for conversational services.

From a satellite orbit perspective:

- **LEO-based NTN** can support acceptable voice delay for conversational services due to relatively low propagation latency.
- **MEO-based NTN** may introduce noticeable voice delay, impacting conversational quality but remaining usable for non-interactive voice scenarios.
- **GEO-based NTN** typically results in high end-to-end voice delay, making real-time conversational voice challenging and limiting its suitability primarily to emergency or non-interactive voice services.

Voice delay is therefore treated as a **derived service-level effect**, rather than an independently modeled KPI, consistent with the system-level scope of this study.

2.3 System Parameters and Assumptions

To ensure realistic and reproducible analysis, the following system parameters are assumed.

2.3.1 Satellite Orbit Parameters

Orbit	Approx. Altitude	Typical Use Case
LEO	600 km	Low latency, high mobility
MEO	10,000 km	Balanced trade-off
GEO	35,786 km	Wide coverage, stable position

2.3.2 Carrier Frequency Assumption

For the purpose of system-level analysis, the NTN access link between the satellite and the user equipment (UE) is assumed to operate at a carrier frequency of approximately **2 GHz**, representative of lower-frequency satellite bands suitable for direct handheld access.

This frequency assumption refers specifically to the **NTN radio access link** and not to terrestrial cellular carriers or satellite feeder links.

The choice of a 2 GHz carrier is motivated by the following considerations:

- Favorable propagation characteristics for long-distance satellite links
- Feasibility of integration with smartphone form-factor antennas
- Reduced transmission power requirements for handheld devices
- Alignment with frequency ranges commonly discussed in 3GPP NTN studies
- Simplification of comparative analysis across LEO, MEO, and GEO orbits

To maintain focus on system-level behavior, higher-frequency effects are not explicitly modeled in this study. However, future extensions may consider sensitivity analysis at moderately higher frequencies (e.g., upper S-band or L-band) to assess the impact of increased path loss, antenna constraints, and Doppler effects on NTN service performance.

2.3.3 Satellite Velocity (Approximate)

Orbit	Approx. Velocity
LEO	~7.5 km/s
MEO	~3.9 km/s
GEO	~3.1 km/s (relative motion ≈ 0)

2.3.4 User Equipment Assumptions

• UE mobility scenarios:

– Pedestrian: 3 km/h

– Vehicular: 60 km/h

• UE antenna: Omnidirectional, representing mass-market handheld devices

• UE connectivity: Single active access at a time (terrestrial or NTN), assuming break-before-make mobility

These assumptions enable evaluation across both static and mobility scenarios while remaining aligned with current commercial UE capabilities and early-phase NTN integration models.

2.3.5 Propagation Model

- Free-space path loss model is assumed for all satellite links
- Clear line-of-sight (LOS) conditions between UE and satellite
- Atmospheric losses (e.g., rain attenuation, scintillation) are neglected for baseline analysis

These assumptions allow isolation of system-level effects such as satellite altitude, propagation delay, and mobility, while avoiding detailed link-level modeling. Additional propagation impairments may be incorporated in future extensions of the study.

2.4 Key Performance Formulations (High-Level)

This study adopts a high-level, system-oriented view of key performance relationships relevant to NTN-assisted connectivity. Rather than introducing detailed mathematical formulations or protocol-level models, performance behavior is described using well-established physical and geometric relationships.

Key relationships considered include:

- Propagation delay increasing with satellite-to-UE distance
- Round-trip time (RTT) approximated as twice the one-way propagation delay
- Doppler shift increasing with relative velocity and carrier frequency
- Path loss increasing with free-space distance and operating frequency

These relationships are used **qualitatively** to compare terrestrial, LEO, MEO, and GEO access characteristics and to explain observed performance trends. Detailed equation-based modeling and numerical simulation are intentionally outside the scope of this study.

2.5 Summary of KPI Intent

The selected KPIs and parameters enable a **clear, fair, and operator-relevant comparison** between terrestrial-only, NTN-only, and hybrid terrestrial–NTN architectures across LEO, MEO, and GEO satellite systems.

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3. System Model & Architecture

3.1 Overview of System Model

This study considers a **hybrid access network architecture** combining **terrestrial cellular infrastructure** with **Non-Terrestrial Network (NTN) components**, in alignment with emerging **6G design principles**.

The system model is intentionally designed at a **system level**, focusing on **end-to-end performance behavior** rather than detailed protocol or physical-layer implementation. This approach reflects the perspective of **mobile network operators** evaluating the feasibility and performance implications of NTN integration for future deployments.

The core network in this study represents a **simplified, service-based core architecture aligned with 5G Standalone (SA) design principles**. The core is modeled as a **logical, access-agnostic network entity** providing session management, mobility anchoring, and data routing functions for both terrestrial and non-terrestrial access. Detailed control-plane and user-plane procedures are abstracted, as the focus of this study is on **system-level performance evaluation** rather than protocol-specific implementation.

Although the architecture supports LEO, MEO, and GEO integration, the actual set of enabled NTN orbits is determined by operator policy and deployment strategy.

3.2 Network Entities and Functional Blocks

The system model consists of the following key entities:

3.2.1 User Equipment (UE)

- Represents a standard mobile terminal
- Capable of connecting to:
    - Terrestrial base station (gNB)
    - NTN access node (satellite)
- Supports mobility across terrestrial and NTN coverage areas

Assumption:

At any given time, the UE maintains a **single active access connection**, while alternative access options are available for fallback or hybrid operation.

3.2.2 Terrestrial Radio Access Network (RAN)

- Modeled as a conventional cellular base station (gNB)
- Provides:
    - Low latency
    - High spectral efficiency
    - Localized coverage

Role in the model:

- Primary access in urban or semi-urban regions
- Baseline for performance comparison

3.2.3 Non-Terrestrial Network (NTN) Access

The NTN component is modeled using satellite-based access nodes operating in three orbital regimes:

- **LEO satellite**
- **MEO satellite**
- **GEO satellite**

Each satellite acts as an AP providing wide-area coverage to UEs beyond terrestrial reach.

Key characteristics modeled:

- Satellite altitude and velocity
- Propagation distance
- Doppler effects
- Coverage footprint (conceptual)

3.2.4 Core Network (Simplified Representation)

- Represents a centralized network entity
- Provides:
    - Session management
    - Data routing
    - Service anchoring

Assumption:

The same core network serves both terrestrial and NTN access, enabling seamless service continuity in hybrid scenarios.

3.3 Access Scenarios Considered

To evaluate performance trade-offs, three access scenarios are defined.

3.3.1 Scenario A: Terrestrial-Only Access

- UE connects exclusively to terrestrial gNB
- Used as **baseline reference**
- Represents current 4G/5G-like deployments

3.3.2 Scenario B: NTN-Only Access

- UE connects exclusively to satellite access
- Three sub-cases:
  - LEO-NTN
  - MEO-NTN
  - GEO-NTN

This scenario evaluates **pure NTN feasibility** for coverage extension.

3.3.3 Scenario C: Hybrid Terrestrial–NTN Access

- UE primarily served by terrestrial gNB
- NTN provides:
  - Coverage extension
  - Backup connectivity
  - Control-plane or resilience support

This scenario reflects **6G-era integration concepts**, where access selection is intelligent and adaptive.

3.4 Satellite Beam Coverage Model and Control Assumptions

In NTN-based systems, coverage is provided through satellite beams rather than fixed terrestrial cell sites. These beams create **spot-like coverage areas on the Earth's surface**, whose size, shape, and movement depend on the satellite orbit and antenna configuration.

Unlike terrestrial base station antennas, satellite beams:

- Are projected from space
- Form moving coverage footprints
- Do not rely on mechanical tilt or azimuth adjustment

From a planning perspective, the effective coverage area of a satellite beam is primarily determined by:

- Satellite orbit altitude (LEO, MEO, GEO)
- Beamwidth and antenna design
- Elevation angle relative to the UE
- Allocated transmission power per beam

Typical NTN deployments utilize **predefined spot beams**, whose approximate coverage ranges from:

- Hundreds of kilometers for LEO satellites.
- Up to continental-scale footprints for GEO satellites

While satellite beamwidth is not dynamically adjustable in the same manner as terrestrial antennas, **beam selection, activation, and power allocation can be controlled** through network configuration and satellite payload capabilities. This allows operators to:

- Limit service activation to specific geographic areas
- Reduce interference and border spillage
- Align NTN coverage with areas lacking terrestrial service

In comparison to terrestrial base stations, where coverage is shaped by fixed antenna patterns and terrain, satellite coverage is **geometry-driven and orbit-dependent**, requiring policy-based control rather than classical RF tuning.

This study assumes a simplified beam coverage model in which NTN service availability is governed by **beam presence and operator policy**, rather than dynamic beam shaping at the user level.

3.5 Mobility and Connectivity Assumptions

- UE mobility modeled as:
    - Static / pedestrian
    - Vehicular movement
- Satellite motion modeled based on orbital characteristics
- Frequent satellite handovers expected in LEO
- Minimal handover frequency in GEO
- Intermediate behavior in MEO

Note:

Handover performance is evaluated qualitatively, supported by latency and Doppler trends.

3.6 End-to-End Communication Path

The system model supports two mutually exclusive end-to-end communication paths depending on the selected access network.

• **Terrestrial access path:**

UE → gNB → Core Network

• **NTN access path:**

UE → Satellite (LEO / MEO / GEO) → NTN Gateway → Core Network

For modeling simplicity, the NTN gateway is abstracted as part of the NTN access network. At any given time, the UE maintains a single active end-to-end path, either terrestrial or NTN, consistent with the system-level assumptions of this study.

3.7 Architectural Representation

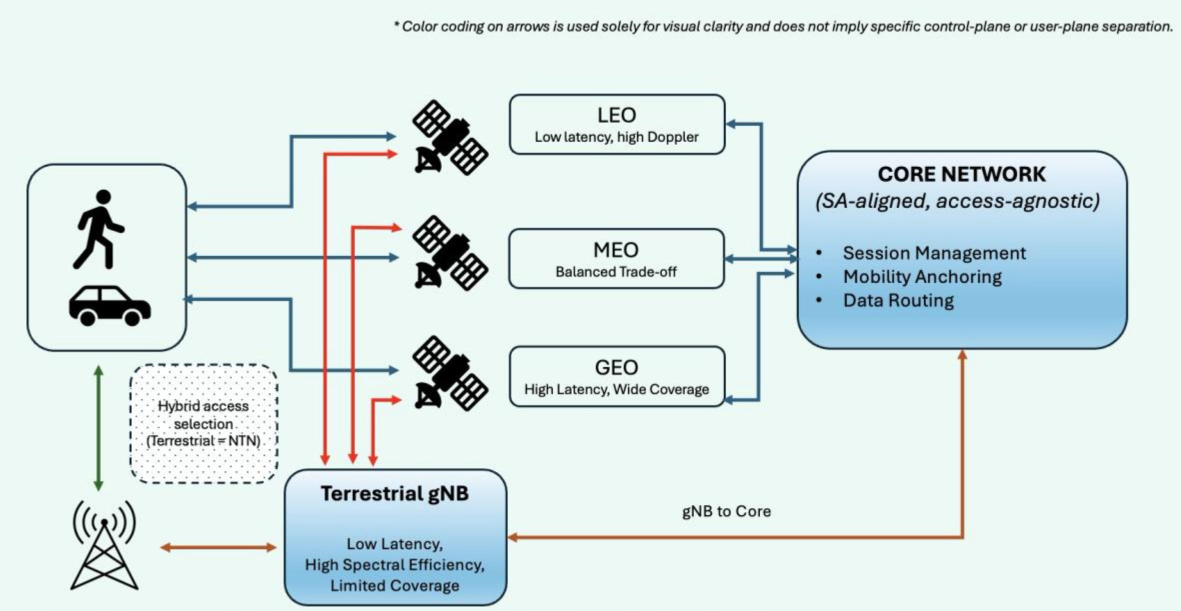

Figure: System-level architecture of a hybrid terrestrial–NTN network integrating terrestrial gNB and LEO/MEO/GEO satellite access with a 5G SA–aligned, access-agnostic core network.

Figure: High-level hybrid terrestrial–NTN system architecture

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3.8 Modeling Boundaries and Limitations

To maintain clarity and focus, the following aspects are **outside the scope** of this model:

- Detailed PHY/MAC procedures
- Beamforming and antenna array modeling
- Exact 3GPP signaling flows
- Traffic-level simulation

This ensures the study remains **accessible, explainable, and operator-relevant**.

3.9 Summary of System Model

The defined system model enables structured analysis of **performance trade-offs** between terrestrial and NTN access across LEO, MEO, and GEO satellite systems, while remaining aligned with future **6G hybrid connectivity principles**.

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4. Functional Description & Operational Flow

This section describes the end-to-end functional behavior of the proposed hybrid terrestrial–NTN system under different operational conditions. It explains how user equipment (UE) interacts with terrestrial and non-terrestrial access networks during initial access, mobility, service continuity, and coverage loss scenarios.

The objective of this section is to illustrate system behavior from an operator perspective, focusing on access selection, session continuity, and service handling rather than protocol-level signaling.

4.1 Initial Access and Session Establishment

1. **UE Power-On / Activation**
    - The UE supports both **terrestrial NR** and **NTN access** (LEO/MEO/GEO).
    - At power-on, the UE performs **radio measurements** across available access options:
        - Terrestrial gNB (if in coverage)
        - Visible NTN satellites (based on elevation, signal strength, Doppler conditions)
2. **Hybrid Access Selection**
    - A logical hybrid access selection function evaluates:
        - Radio link quality
        - Latency constraints
        - Service requirements (eMBB, emergency, IoT, mobility)
    - The function determines the **preferred access path**:
        - Terrestrial gNB when available
        - NTN access when terrestrial coverage is weak or unavailable
3. **Session Establishment via Selected Access**
    - The UE establishes a session through the selected access (gNB or NTN).
    - The **core network (SA-aligned)** handles:
        - Authentication
        - Session management
        - IP address allocation
    - From the core perspective, the access is **transparent** (terrestrial or NTN).

✓ Key point:

The **core network remains unchanged**, reinforcing access-agnostic design.

4.2 User Plane Data Flow

Once a session is established, user-plane traffic is routed through the selected access network based on coverage availability and operator policy.

• **Terrestrial mode:**

UE ↔ gNB ↔ Core Network

• **NTN mode:**

UE ↔ Satellite (LEO / MEO / GEO) ↔ Core Network

User-plane traffic continues to flow through the selected access without modification to:

- Session anchor
- Application endpoint
- Service context

This abstraction enables fair comparison of performance metrics across terrestrial and NTN access modes without introducing protocol-level complexity.

4.3 Mobility and Access Switching

4.3.1 Terrestrial ↔ NTN Switching

As the UE moves across different coverage conditions, the serving access network may change based on signal quality, coverage availability, and operator-defined access selection policies.

• During UE mobility:

- Terrestrial signal quality may degrade (e.g., cell edge, rural areas, disaster scenarios)
- NTN access via LEO, MEO, or GEO satellites may become available

• Based on access selection criteria:

- The UE performs access reselection or handover between terrestrial and NTN access
- Session continuity is maintained through the core network

The access transition occurs without requiring application-layer re-establishment, enabling service continuity while the underlying access path changes.

4.3.2 NTN Orbit-Level Adaptation (LEO / MEO / GEO)

The proposed system model supports orbit-aware access behavior, enabling flexible integration of different satellite orbits based on operator deployment strategy and service requirements.

Depending on the selected NTN configuration, the system may utilize one or more satellite orbits with the following characteristics:

• **LEO-based NTN:**

- Preferred for latency-sensitive services
- Requires frequent mobility management due to satellite movement

• **MEO-based NTN:**

- Provides a balance between latency performance and link stability

• **GEO-based NTN:**

- Suitable for wide-area or fallback coverage scenarios
- Characterized by high latency but stable connectivity

Orbit-level adaptation, when supported by the operator's NTN deployment, allows the access selection logic to prioritize the most suitable orbit based on service continuity, mobility conditions, and coverage availability. This capability is considered optional and deployment-specific rather than a mandatory requirement.

4.4 Core Network Anchoring and Continuity

The core network acts as the logical mobility anchor for all access scenarios considered here.

Session continuity is preserved regardless of:

- Access domain transitions (terrestrial ↔ NTN)
- Satellite handovers within the same orbit
- Beam or footprint changes caused by satellite motion

These mobility events are handled within the access and transport layers, while the core network maintains a stable session anchor and service context.

As a result:

- Active sessions remain anchored during access changes
- Mobility complexity is hidden from applications
- Service continuity is maintained across terrestrial and non-terrestrial domains

This design aligns with 5G Standalone (SA) architecture principles and anticipates future 6G-native NTN integration, where non-terrestrial access is treated as a native component of the network rather than an external extension.

4.5 Failure and Fallback Scenarios

The proposed architecture supports controlled failure handling and service fallback mechanisms, aligned with operator deployment choices.

• **Terrestrial access failure:**

- UE may transition to an available NTN access, if enabled by the operator

• **NTN service interruption:**

- UE may reselect terrestrial access when coverage becomes available

• **Orbit-level fallback (optional):**

- In deployments where multiple satellite orbits are integrated, fallback between orbits (e.g., LEO to MEO or GEO) may be supported to enhance service continuity

These mechanisms improve service resilience while allowing operators to deploy NTN capabilities incrementally based on cost, coverage needs, and service objectives.

This flexibility makes the architecture applicable to:

- Remote and underserved regions
- Disaster recovery scenarios
- Maritime, highway, and desert coverage

4.6 Summary of Operational Behavior

In summary, the system:

- Supports **hybrid access selection**
- Maintains **core-anchored session continuity**
- Adapts dynamically across terrestrial and NTN domains
- Abstracts orbit complexity from applications

This operational model enables **fair performance evaluation** of hybrid terrestrial–NTN networks in a 6G-oriented context.

4.7 Operator-Driven NTN Orbit Selection Policy

While the system architecture supports connectivity to LEO, MEO, and GEO satellite systems, **simultaneous integration of all NTN orbits is neither mandatory nor economically optimal** for a mobile network operator.

In practical deployments, operators apply an **NTN orbit selection policy** based on technical, operational, and commercial considerations.

4.7.1 Orbit Enablement Configuration

The operator defines a **network-level configuration** that enables one or more NTN orbits:

- **LEO-only deployment**
  - Focus on low-latency broadband and mobility support
  - Higher handover complexity, higher constellation management cost
- **GEO-only deployment**
  - Focus on coverage extension and service availability
  - Simpler integration, higher latency, stable links
- **LEO + GEO hybrid deployment**
  - LEO for performance-critical services
  - GEO as fallback or wide-area coverage
- **MEO-enabled deployment (optional)**
  - Used when a balance between latency, coverage stability, and satellite count is desired

This configuration determines **which satellite systems are visible to the access selection function**.

- Non-enabled orbits are completely ignored by the system
- UE behavior adapts automatically to operator policy

4.7.2 Policy-Based Access Selection

The hybrid access selection function operates **within operator-defined constraints** and considers:

- **Service type** (latency-sensitive vs coverage-driven)
- **Cost weighting** per orbit (LEO > MEO > GEO, or operator-defined)
- **Geographical deployment scenario** (urban, rural, maritime, highway)
- **Regulatory and spectrum availability**

The access selection outcome is therefore:

- Technically feasible
- Economically viable
- Aligned with operator business strategy

4.7.3 Dynamic vs Static Orbit Policy

Two policy modes are supported:

- **Static Policy**
    - Orbit selection fixed per region or service
    - Simpler operational model
- **Dynamic Policy**
    - Orbit preference adjusted based on:
        - Network load
        - Service priority
        - Time-of-day or emergency conditions

This enables operators to gradually evolve their NTN strategy without architectural changes.

4.8 Satellite Selection, Service Capability & UE Compatibility (NTN Access)

4.8.1 Operator-Driven Satellite Selection Logic

Although the reference architecture includes **LEO, MEO, and GEO satellites**, an operator is **not required to enable all satellite layers simultaneously**.

Satellite utilization is **operator-controlled and policy-driven**, based on:

- Service requirements (messaging, voice, data)
- Latency tolerance
- Cost per session / per bit
- Coverage objectives (remote, maritime, disaster scenarios)
- Regulatory approvals and satellite partnerships

The **5G Core (PCF/SMF)** applies selection policies to determine **which satellite layer is used for a given service**, user category, or geographic condition.

This approach enables **cost-efficient, use-case-specific NTN deployment**, rather than a one-size-fits-all satellite strategy.

4.8.2 Service Capability Across Satellite

Different satellite orbits provide **different service levels**, mainly due to latency and link budget constraints.

Service Type	LEO	MEO	GEO
Emergency messaging (SMS / SOS)	✅	✅	✅
Voice services	✅	⚠️	❌ / ⚠️
Packet data (IP)	✅	⚠️	⚠️
Latency-sensitive applications	✅	⚠️	❌

Notes:

- **LEO satellites** are best suited for **voice and broadband data** due to low latency.
- **GEO satellites** are mainly used for **messaging, IoT, and emergency services**.
- **MEO satellites** offer intermediate performance and are scenario-dependent.

4.8.3 UE Compatibility

Do All Mobile Phones Support NTN?

No. NTN connectivity requires specific UE capabilities.

Even if an operator enables NTN in its network, **only NTN-capable devices can access satellite connectivity**.

NTN support requires:

- Specialized RF and antenna design
- Support for extended timing advance
- Doppler shift compensation
- 3GPP NTN features (Release-17 and beyond)

Legacy smartphones **cannot gain NTN support via software updates alone**.

4.8.4 Commercial Smartphones Supporting NTN (Current Status)

As of today, NTN support in smartphones is **limited and vendor-specific**.

Apple

- **iPhone 14 and later**
- Supports **satellite messaging and emergency services**

- Uses **Globalstar (LEO)**
- Service availability is **operator and region dependent**
- Messaging only (no voice/data)

Samsung

- Selected **Galaxy S23 and later series**
- NTN capability aligned with **3GPP Rel-17**
- Intended for operator-enabled NTN services (LEO focus)
- Commercial availability depends on operator partnerships

Qualcomm Ecosystem

- Snapdragon **X70 / X75 modems** support NTN. More latest modems are coming with NTN support as of today
- Enables NTN functionality for Android OEMs
- Requires operator and satellite provider integration

Important: NTN capability does not automatically mean service availability.
The operator must enable NTN and partner with a satellite provider.

4.8.5 NTN Smartphones vs Dedicated Satellite Phones (e.g., Thuraya)

NTN smartphones are **not designed to replace dedicated satellite phones**.

Aspect	NTN Smartphones	Dedicated Satellite Phones
Device	Standard smartphone	Specialized handset
Network	Integrated with mobile operator	Standalone satellite network
SIM	Same operator SIM	Separate satellite subscription
Use case	Fallback / resilience	Primary satellite connectivity
Cost	Lower, bundled	High device and airtime cost

NTN targets **mass-market connectivity continuity**, while satellite phones remain preferred for **extreme and mission-critical environments**.

4.8.6 Network Selection & Mobility Behavior

NTN access is activated primarily when terrestrial coverage becomes unavailable or degraded, based on operator policy

• Transition between terrestrial and NTN access is treated as an access reselection at the radio level, while session continuity is preserved at the core network level

• The final access decision depends on:

- UE NTN capability
- Operator policy and service configuration
- Satellite availability

Users do not manually select satellite access. Network selection and access transitions are automatically controlled by the network, ensuring service continuity without user intervention.

4.8.7 Service-Level Comparison Across Satellite Orbits

The study includes a service capability comparison across LEO, MEO, and GEO satellite orbits to highlight their respective strengths and limitations for different service types.

This comparison:

- Clarifies performance trade-offs across satellite orbits
- Supports operator decision-making for NTN deployment
- Improves understanding for both technical and non-technical stakeholders

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4.9 VSAT and NTN – Architectural Deployment Models

Satellite-based connectivity in mobile networks can be realized using multiple architectural approaches. This section distinguishes between **VSAT used as cellular transmission**, **VSAT used as a direct service**, and **3GPP NTN-based direct access**, which are often incorrectly grouped together.

4.9.1 VSAT for Cellular Backhaul (Operator Transmission Model

In this model, the mobile network operator deploys **VSAT terminals as transmission links** to connect remote or hard-to-reach base stations to the core network.

Key characteristics:

- VSAT dish installed at the **base station site**
- Satellite link used for **backhaul or transport**
- Base station operates as a **standard terrestrial cell**
- User devices connect via **normal LTE/5G radio**
- Satellite link is **transparent to the UE**

This model is widely used for:

- Rural and remote coverage
- Temporary or rapid deployments
- Disaster recovery scenarios

Satellite orbits used:

- Primarily **GEO**
- Limited use of **MEO**
- Emerging use of **LEO** for latency-sensitive backhaul

From a user perspective, this is **not satellite access**; it is conventional cellular service with satellite-based transmission.

4.9.2 VSAT as an End-User Service Model

In this approach, VSAT provides **direct connectivity to end users** through dedicated satellite terminals.

Characteristics:

- Dedicated VSAT terminal and antenna
- Separate satellite subscription
- No integration with mobile core networks
- Limited mobility
- Typically, high latency (especially GEO)

Typical use cases:

- Enterprise broadband
- Maritime and aviation connectivity
- Industrial sites

This model operates **outside the cellular ecosystem**.

4.9.3 3GPP NTN (Direct-to-UE Model)

3GPP Non-Terrestrial Networks (NTN) enable **direct satellite access to standard mobile user equipment**, integrated with the operator's cellular core network.

Characteristics:

- No external satellite terminal
- Uses standard SIM and mobile core
- UE connects directly to satellite radio access
- Supports mobility and service continuity

- Access controlled by operator policies

Satellite orbits used:

- **LEO** (primary)
- **MEO** (optional)
- **GEO** (limited to non-latency-sensitive services)

NTN is designed as a **complement to terrestrial networks**, not a replacement.

4.9.4 Comparative Summary

Aspect	VSAT Backhaul (Operator)	VSAT Service	NTN
Satellite link terminates at	Base station	User terminal	UE
UE satellite awareness	❌	❌	✅
SIM-based services	✅	❌	✅
Mobility support	Terrestrial only	Limited	Native
Core network	Mobile core	Satellite provider	Mobile core
Typical orbit	GEO	GEO	LEO / MEO / GEO
Use case	Coverage extension	Enterprise broadband	Service continuity

4.9.5 Why NTN Is Not a Replacement for VSAT Backhaul

NTN does **not eliminate the need for VSAT backhaul**:

- VSAT backhaul supports **full-capacity terrestrial cells**
- NTN provides **basic service continuity**
- VSAT backhaul remains critical for high traffic sites

Operators will continue to deploy **both architectures in parallel**, depending on capacity and cost considerations.

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5. Performance Evaluation Framework & Key Metrics

5.1 Evaluation Objectives

The objective of the performance evaluation in this study is to assess the **system-level behavior** of a hybrid terrestrial–NTN network under different coverage and service conditions.

Rather than focusing on detailed physical-layer or protocol-level performance, the evaluation emphasizes **end-to-end service feasibility**, **latency behavior**, and **service continuity**, which are critical from a mobile operator perspective.

Specifically, the evaluation aims to:

- Compare terrestrial-only, NTN-only, and hybrid access scenarios
- Understand the impact of satellite orbit selection on service performance
- Assess the feasibility of voice, messaging, and data services over NTN
- Identify trade-offs between latency, coverage, and cost
- Evaluate the role of NTN as a fallback mechanism rather than a primary access network

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5.2 Reference Deployment Scenarios

To evaluate the proposed system model, the following representative deployment scenarios are considered:

Scenario 1: Terrestrial Coverage Available

- UE is served by terrestrial gNB
- NTN access is inactive
- Represents normal urban or suburban operation

Scenario 2: Terrestrial Coverage Unavailable

- No gNB coverage
- UE attempts NTN access
- Satellite selection governed by operator policy
- Represents remote or rural environments

Scenario 3: Degraded Terrestrial Coverage

- Weak or intermittent gNB signal
- UE evaluates NTN as fallback

- Represents disaster recovery or edge-of-coverage scenarios

Scenario 4: Mobility Across Coverage Zones

- UE transitions between terrestrial and NTN coverage
- Focus on service continuity and reselection behavior

These scenarios reflect realistic operational conditions faced by mobile network operators.

5.3 Key Performance Indicators (KPIs)

The following KPIs are considered to evaluate system performance across terrestrial and NTN access, with particular emphasis on service continuity in remote and underserved areas:

- **End-to-End Latency**
  - Measured from UE to application server
  - Strongly influenced by satellite orbit and propagation delay
- **Service Availability**
  - Probability of maintaining basic network connectivity
  - Especially critical for emergency and rural services
- **Session Setup Time**
  - Time required to establish initial network access
  - Relevant for NTN access activation and reselection
- **Voice Setup Success Rate (VSSR)**
  - Probability of successfully establishing a voice call
  - Includes access setup, signaling completion, and media path establishment
  - Considered a key KPI for remote and emergency communication scenarios
- **Packet Loss Rate**
  - Indicator of link reliability
  - Affected by satellite movement, fading, and propagation conditions
- **Throughput (Uplink / Downlink)**
  - Evaluated at a system level
  - Used to differentiate broadband versus basic service feasibility
- **Service Continuity**
  - Ability to maintain ongoing services during access transitions
  - Includes avoidance of call drops and session interruption

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5.4 Performance Comparison Across Access Types

Metric	Terrestrial	LEO NTN	MEO NTN	GEO NTN
Latency	Low	Low–Medium	Medium	High
Voice feasibility	High	High	Medium	Low
Messaging	High	High	High	High
Broadband data	High	Medium	Limited	Limited
Mobility support	Native	Supported	Supported	Limited

This comparison highlights that **NTN is not intended to match terrestrial performance**, but rather to **extend service availability beyond terrestrial coverage**.

Voice setup success rate is expected to be highest for terrestrial and LEO-based NTN access, while MEO and GEO orbits may experience reduced success rates due to increased signaling latency.

5.5 Discussion on Trade-offs and Practical Considerations

The performance evaluation indicates that NTN provides **coverage and resilience benefits** at the expense of **increased latency and reduced throughput**, particularly for higher satellite orbits.

From an operator perspective:

- NTN is best positioned as a **fallback and continuity solution**
- LEO satellites offer the most balanced performance
- GEO satellites remain suitable for messaging and emergency services
- Hybrid access provides the highest overall service availability

These trade-offs reinforce the importance of **policy-driven satellite selection** and **service-aware access control**.

It is also important to note that NTN performance characteristics are evolving. Ongoing deployment of next-generation LEO satellite constellations with lower orbital altitudes, improved inter-satellite coordination, and advanced antenna technologies is expected to reduce latency and improve overall service performance over time. While NTN is unlikely to fully match terrestrial network KPIs, these advancements strengthen its role as a complementary access technology within future 6G systems.

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6. Challenges, Limitations, and Open Research Issues

This section discusses the **key challenges and unresolved issues** associated with integrating Non-Terrestrial Networks (NTN) into future 6G systems from a practical deployment perspective.

6.1 Latency and Service Quality Constraints

Despite advancements in satellite technology, **propagation delay remains a fundamental limitation**, particularly for MEO and GEO satellite orbits.

Challenges include:

- Increased end-to-end latency affecting voice setup and real-time services
- Higher signaling delay impacting session establishment and mobility procedures
- Reduced user experience for latency-sensitive applications

While LEO satellites mitigate some latency concerns, maintaining consistent service quality across all orbits remains a challenge.

6.2 Mobility Management and Satellite Dynamics

Unlike terrestrial cells, satellites—especially in LEO constellations—are in constant motion.

Key challenges:

- Frequent cell reselection events
- Rapidly changing link geometry
- Doppler shift compensation
- Maintaining service continuity during satellite transitions

Efficient mobility management for NTN remains an active research area, particularly for supporting voice services without call drops.

6.3 UE Capability and Power Constraints

NTN-capable user equipment must support:

- Extended timing advance
- Higher transmission power
- Advanced antenna designs
- NTN-specific signaling procedures

These requirements introduce:

- Increased battery consumption
- Hardware complexity
- Limited backward compatibility with legacy devices

Balancing NTN capability with smartphone form-factor constraints is a significant challenge.

6.4 Spectrum Regulation and Interference Management

NTN operation introduces regulatory and spectrum-sharing challenges that must be addressed as deployments scale across regions:

- Coordination between terrestrial and satellite spectrum usage
- Cross-border regulatory alignment for non-terrestrial services
- Interference management between adjacent satellite beams and terrestrial cells

While several countries have already initiated commercial and pilot NTN deployments, global harmonization of spectrum policies and coordination mechanisms is still evolving. These factors influence deployment complexity and timelines, particularly for large-scale, multi-region NTN integration, rather than limiting the overall viability of NTN solutions.

6.5 Cost, Scalability, and Business Viability

Deploying NTN-enabled cellular services introduces new cost and business considerations that differ from traditional terrestrial expansion models:

- Satellite integration involves capital and operational expenditures, primarily driven by satellite capacity leasing and gateway integration• Deployment models depend on partnerships between mobile network operators and satellite service providers

From an operator perspective:

- NTN economics must be evaluated against alternative solutions, such as deploying VSAT-based backhaul for remote base stations
- In sparsely populated or hard-to-reach areas, direct NTN access may offer a more cost-effective and faster-to-deploy solution compared to building and maintaining terrestrial infrastructure
- Service demand may be location- and event-specific, encouraging flexible and usage-based monetization models

Ensuring scalability while maintaining cost efficiency requires careful alignment of service offerings, deployment scope, and partnership models rather than uniform nationwide rollout.

As satellite capacity increases and integration matures, NTN is expected to further improve its cost competitiveness for targeted coverage and resilience use cases.

6.6 Service-Level Limitations and User Expectations

NTN cannot replicate terrestrial network performance.

Challenges include:

- Limited throughput
- Variable latency
- Reduced voice quality under certain conditions

Managing user expectations and clearly positioning NTN as a **service continuity solution**, rather than a full replacement, is essential.

6.7 Integration Complexity and Network Management

Hybrid terrestrial–NTN networks introduce additional complexity in:

- Network orchestration
- Policy management
- Monitoring and optimization

Operators require:

- Unified management frameworks
- New KPIs and optimization strategies
- Enhanced fault and performance monitoring tools

6.8 Open Research Directions Toward 6G

Several research areas remain open and critical for 6G evolution:

- AI-driven access and satellite selection
- Semantic-aware service prioritization
- Predictive mobility management using satellite trajectories
- Energy-efficient NTN protocols
- Native integration of NTN in 6G core architectures

These directions highlight the role of NTN as a **key enabler for global 6G connectivity**.

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7. Practical NTN–Cellular Collaboration Framework for Near-Term Deployment

7.1 Deployment Philosophy: NTN as a Controlled Extension

For near-term deployment, NTN should be positioned as a **controlled extension of terrestrial cellular networks**, rather than a parallel access network.

Key principles:

- NTN activated **only when terrestrial coverage is unavailable or degraded**
- Operator maintains **full control** over access, policies, and charging
- Services limited to **voice, messaging, and essential data**
- Clear service differentiation from terrestrial broadband

This philosophy minimizes cost, complexity, and regulatory risk.

7.2 Practical Collaboration Models Between MNOs and Satellite Operators

Rather than owning satellite infrastructure, mobile network operators can adopt **partnership-based models**, such as:

- Managed NTN access from satellite providers
- Service-level agreements (SLAs) for coverage and availability
- Integration of satellite access into existing 5G Core
- Roaming-like commercial agreements for NTN usage

This approach reduces CAPEX and enables rapid service introduction.

7.3 Spectrum Strategy Using Existing Assets

Near-term NTN deployment is primarily intended for **areas where the mobile network operator does not have existing terrestrial coverage**, such as remote, desert, offshore, mountainously trails or sparsely populated regions.

As a result, the reuse of existing licensed cellular spectrum for NTN access can have **minimal impact on the operational terrestrial network**.

However, special attention is required in **transition and border areas** where terrestrial coverage may partially overlap with NTN service availability.

Key spectrum strategy considerations include:

- **Selective Spectrum Reuse**

  Only a limited portion of existing licensed spectrum should be allocated for NTN, focused on low to moderate bandwidth services such as voice, messaging, and essential data.

- **Avoidance of Terrestrial Border Frequencies**

  Frequency blocks used for NTN should not overlap with terrestrial carriers deployed in border or edge-of-coverage areas.

  This reduces the risk of co-channel interference and minimizes service degradation during access transitions.

- **Dedicated NTN Bandwidth Segmentation**

  NTN bandwidth should be logically separated from high-capacity terrestrial carriers, even if operating within the same frequency band.

- **Controlled NTN Activation Zones**

  NTN spectrum usage can be restricted to predefined geographic zones where terrestrial coverage is absent, using core-network-based policy control.

- **Conservative Bandwidth Selection**

  Narrower bandwidth allocation for NTN helps limit interference exposure and simplifies coordination with existing terrestrial deployments.

By carefully selecting frequency bandwidth and avoiding terrestrial border carriers, operators can integrate NTN access while preserving terrestrial network performance and regulatory compliance.

7.4 Border Spillage Mitigation in Satellite-Assisted Coverage

Border spillage is a key concern in satellite-based systems, particularly in geographically compact regions such as the GCC.

Mitigation strategies include:

- Geo-fencing of NTN service areas
- Location-based access control at the core network
- Country-specific PLMN and policy enforcement
- Satellite beam shaping and power control
- Time-limited-service activation for emergency or fallback use

These measures allow operators to retain regulatory compliance and avoid unintended cross-border service exposure.

7.5 Why the GCC Market Is a Strong Candidate for NTN–Cellular Collaboration

The GCC region presents several unique characteristics that make it a strong candidate for near-term NTN–cellular collaboration.

Firstly, large areas of the region include **remote oil fields, desert infrastructure, offshore installations, and pipeline corridors**, where extending terrestrial cellular coverage is technically challenging and economically inefficient. Reliable connectivity in these areas is critical for operational safety and coordination.

Secondly, the region is home to **mountainous and remote natural landscapes**, including popular trekking and tourism destinations, where terrestrial coverage is often limited or unavailable. Ensuring basic voice and messaging connectivity in such areas supports public safety and emergency response.

Additionally, the GCC market exhibits:

- High smartphone penetration
- Continuous adoption of **latest-generation mobile devices**
- Strong consumer willingness to upgrade handsets

This creates a favorable environment for NTN adoption, as a growing portion of the population will naturally own **NTN-capable smartphones** without requiring dedicated satellite devices.

Combined with strong regulatory frameworks and national interest in connectivity resilience, these factors position the GCC as an ideal region for controlled NTN deployment.

7.6 Operator Value Proposition and Business Enablement Model

From a commercial perspective, NTN services can be introduced as a **value-added, on-demand capability**, rather than a default access mode.

A practical business model is to offer NTN connectivity as:

- An **optional add-on service**
- Available only to **NTN-capable smartphones**
- Activated for specific scenarios such as desert travel, long-distance trekking, offshore work, or emergency use

This model is conceptually similar to international roaming:

- NTN access is dormant by default
- Activated when the user enters an area without terrestrial coverage
- Charged based on usage, duration, or service type

Such an approach allows operators to:

- Monetize NTN without impacting mass-market tariffs
- Limit network load and operational cost
- Align service usage with genuine coverage gaps
- Clearly position NTN as a **resilience and safety feature**, not a broadband replacement

By targeting users who already own NTN-supported devices, operators can introduce satellite connectivity **without requiring customers to purchase separate satellite phones**, while still preserving the role of dedicated satellite terminals for extreme or professional use cases.

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8. Conclusion and Future Outlook Toward 6G

This study has examined the integration of Non-Terrestrial Networks (NTN) with terrestrial cellular systems as a practical pathway toward future 6G connectivity. By focusing on system-level architecture, performance evaluation, and operator-driven deployment strategies, the work highlights how satellite-assisted cellular access can be realistically introduced using today's technologies.

The proposed hybrid architecture demonstrates that NTN is not intended to replace terrestrial networks, but rather to **extend coverage, enhance resilience, and ensure service continuity** in areas where terrestrial deployment is limited or impractical. By leveraging LEO, MEO, and GEO satellites in a policy-controlled manner, operators can selectively support essential services such as voice, messaging, and basic data while managing latency, cost, and spectrum constraints.

Through performance evaluation and comparison, the study confirms that **LEO-based NTN provides the most balanced trade-off** between latency and service feasibility, while higher orbits remain suitable for non-latency-sensitive applications. The inclusion of operator-relevant KPIs, such as voice setup success rate and service availability, further aligns the analysis with real-world deployment considerations.

Importantly, the study distinguishes NTN from traditional VSAT-based solutions and demonstrates how **NTN-cellular collaboration can coexist with existing transmission architectures**, including VSAT backhaul. Practical spectrum strategies, border spillage mitigation techniques, and region-specific considerations—particularly for the GCC market—illustrate how NTN can be deployed incrementally without disrupting existing networks or regulatory frameworks.

Looking ahead, NTN is expected to play a **foundational role in 6G**, enabling truly ubiquitous connectivity across land, sea, and air. Future evolution toward 6G will likely incorporate:

- AI-driven access and satellite selection
- Intelligent service-aware and context-aware connectivity
- Deeper integration of NTN into native 6G core architectures
- Energy-efficient protocols and advanced mobility prediction

By positioning NTN as a controlled, operator-managed extension of cellular networks today, mobile operators can gain valuable experience, establish partnerships, and prepare their networks for the **fully integrated terrestrial–non-terrestrial vision of 6G**.

This study represents a foundation for further applied research and prototyping toward AI-assisted hybrid terrestrial–NTN systems in the 6G era.

9. How to Cite This Study

Khan, A. (2026). A System-Level Study of Hybrid Terrestrial–NTN Architecture for 6G-Ready Cellular Networks. Independent Technical Study.

10. Author's Note

This study is an independent, system-level technical analysis developed from a mobile network operator perspective. It is intended to bridge practical cellular network experience with emerging research directions in 6G and Non-Terrestrial Networks (NTN). The work emphasizes architectural clarity, operational feasibility, and deployment realism rather than protocol-level or physical-layer optimization.