INTEGRATING LEO AND GEO SATELLITE NETWORKS FOR 6G AND BEYOND: THE ROLE OF SDN AND MEC

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AGENDA

THE EVOLUTION TOWARDS 6G AND THE ROLE OF NTN

The journey from 5G to 6G aims to achieve global, ultra-reliable, low-latency connectivity with integrated intelligence and sensing

- Terrestrial networks alone are insufficient to achieve this vision
- Especially in remote, rural, and underserved regions

Non-Terrestrial Networks (NTNs) are critical to bridging this gap

- Include LEO, MEO, and GEO satellite segments
- Offer broader reach, resiliency, and redundancy

LEO satellites bring ultra-low latency and high-throughput connectivity

- Ideal for real-time applications like autonomous systems and IoT
- However, they require large constellations and constant ground contact

GEO satellites provide wide-area coverage and persistent visibility

- Remain fixed relative to Earth's surface
- Operate longer with fewer orbital adjustments
- Highly suitable for coordination, control, and data relay roles

6G networks leverage Software-Defined Networking (SDN) and Multi-access Edge Computing (MEC)

- Enable real-time network reconfiguration and distributed intelligence
- GEO satellites can serve as SDN controllers and data relays for LEO-based MEC nodes

This approach is endorsed by global standards bodies

- Aligned with ITU Network 2030 (ITU-T, 2020)
- Informed by 3GPP NTN architecture in Release 17 and 18 (3GPP, 2023)

An integrated GEO-LEO NTN provides enhanced orchestration and resilience

- Enables seamless inter-orbital handovers and mission-critical communication
- Reduces reliance on extensive ground infrastructure
- Supports TT&C, spectrum management, and secure network control

This presentation explores the critical and underappreciated role of GEO satellites

- Highlights how GEO integration empowers intelligent, scalable 6G NTN connectivity

LIMITATIONS OF CURRENT LEO-ONLY ARCHITECTURES

LEO satellite constellations have revolutionized satellite communication

- Enable low-latency broadband with smaller, user-friendly terminals
- Support high-throughput and direct-to-device (D2D) services

However, LEO-only architectures face multiple limitations

- Require massive constellations for global coverage
- Continuously moving satellites necessitate constant handovers
- Ground stations must track and switch links rapidly

Dependence on numerous ground stations (GS) increases cost and complexity

- LEO satellites have short visibility windows with each GS
- Need dozens to hundreds of GS to ensure seamless global communication
- Limited uplink/downlink windows result in potential data delays

LEO-only systems face challenges with TT&C and regulatory compliance

- No centralized control leads to delays in reconfiguration and command updates
- Difficult to enforce national spectrum and orbital regulations without relay support

High traffic in LEO orbits increases congestion and collision risk

- Thousands of satellites increase SSA and deorbiting challenges
- Requires efficient, centralized control to manage orbital safety

Limited onboard processing and energy budgets constrain LEO satellites

- Restricts their ability to perform autonomous management functions
- Makes offloading to GEO-based SDN controllers more efficient

Spectrum efficiency is difficult to optimize without orchestration

- Overlapping footprints and uncoordinated beams may cause interference
- Needs centralized SDN-based spectrum and power management

These limitations underscore the need for integration with GEO satellites

- A hybrid approach can offload control, extend communication windows, and improve efficiency

THE ROLE OF GEO SATELLITES IN NTN

GEO satellites offer unique advantages in Non-Terrestrial Networks (NTNs)	Stationary position ensures continuous visibility over one-third of the Earth Provide persistent, reliable communication without handovers
Act as centralized SDN controllers for LEO constellations	Enable unified routing, switching, and resource orchestration Enhance network agility, scalability, and service provisioning
Extend communication windows with LEO satellites	Maintain near-continuous links with multiple LEOs in view Reduce dependency on dense ground station infrastructure
Support Telemetry, Tracking, and Command (TT&C) operations	Provide backup and emergency communication during GS outages Ensure secure control and configuration of LEO nodes
Enable data relay and inter-orbit connectivity	Facilitate uplink from LEO and downlink to GS via GEO Offload traffic from congested LEO-GS links
Improve compliance with national and regional regulations	Provide regional coverage control to avoid restricted airspace Coordinate beam shaping and dynamic access per regulatory zones
Support secure and resilient connectivity for critical use cases	Enhance performance for military, maritime, disaster recovery, and aviation sectors Allow intelligent routing during LEO service interruptions
GEOs play a pivotal role in 6G NTN architecture	Bridge gaps in LEO networks and act as space-based network orchestrators

GEO VS GROUND STATION FOR LEO COMMUNICATION

Comparing GEO satellites and Ground Stations (GS) for LEO communication

- GEO satellites provide global or continental coverage from a single orbital position
- Ground stations have limited line-of-sight, requiring large numbers for global LEO support

Continuous communication with LEO satellites

- GEO maintains longer and more stable communication windows with LEO satellites
- Ground stations experience frequent handovers due to short LEO passes (typically 10–15 minutes)

Reduction in infrastructure complexity

- Introducing GEO can significantly reduce the number of required ground stations
- Fewer handovers lower signaling overhead and management complexity

Centralized management and network control

- GEO satellites serve as central SDN controllers, orchestrating multiple LEO satellites
- Ground station-based control is fragmented and region-specific

Cost, reliability, and scalability

- GEO integration lowers long-term operational costs by minimizing terrestrial infrastructure
- Reduces susceptibility to regional outages or geopolitical disruptions

Enhanced TT&C and data relay capabilities

- GEO provides robust TT&C backup and global network visibility
- Efficient data relay from LEO to GEO to ground enables flexible routing and rapid response

Support for regulatory and mission-specific needs

- GEO facilitates dynamic coverage and beam shaping for compliance with international boundaries
- Simplifies cross-border service delivery compared to distributed ground stations

Strategic importance for 6G NTN networks

- Combining GEO with GS creates a resilient, flexible, and efficient hybrid satellite-ground architecture

6G NTN VISION AND INTERNATIONAL STANDARDS

Global vision for 6G-enabled Non-Terrestrial Networks (NTNs)	6G envisions seamless integration of terrestrial, aerial, and satellite networks
	Aims to deliver ultra-reliable, low-latency, high-throughput connectivity globally
Role of satellite systems in 6G architecture	Satellites extend 6G services to underserved and remote regions
	LEO constellations support low-latency applications, while GEO satellites enable global backbone and orchestration
ITU Network 2030 framework	Defines future network capabilities including dynamic topology, ultra-low latency, and time-sensitive networking
	Highlights space segment as a critical layer for mission-critical and real-time services
3GPP Non-Terrestrial Network standards	3GPP Release 17 and beyond introduces NTN support for 5G and 6G NR
	Defines satellite radio access integration, link adaptation, handovers, and beam management
Software-Defined Networking (SDN) and MEC alignment	GEO satellites function as SDN controllers managing distributed LEO-based MEC nodes
	Enables intelligent routing, traffic optimization, and network slicing across the NTN
Regulatory and spectrum coordination	ITU and national agencies coordinate spectrum sharing and orbital resource usage
	Standards address coexistence, handover, and interference mitigation between TN and NTN
Industry-wide adoption and momentum	Supported by ETSI, IEEE, 5G Americas, and regional policy frameworks
	Major players like ESA, NASA, and commercial operators contribute to standardization and trials

CHALLENGES IN CURRENT LEO-ONLY ARCHITECTURE

Scalability and constellation size	LEO systems require thousands of satellites for global coverage Managing large constellations increases operational and regulatory complexity
Ground station proliferation	Multiple LEO satellites need numerous ground stations for continuous coverage High infrastructure cost and limited regional deployment in remote areas
Limited satellite visibility	LEO satellites offer short visibility windows with fast orbital passes Requires seamless handover and frequent tracking updates
High Doppler shift and beam steering	LEO motion leads to frequent Doppler changes and beam realignment Impacts link stability and increases antenna system complexity
Spectrum allocation and interference	Shared spectrum between constellations leads to potential cross-link interference Coexistence with GEO and terrestrial systems needs dynamic coordination
Lack of global routing and synchronization	LEO-only systems lack centralized SDN control Global synchronization and session continuity remain challenging
Operational limitations	LEO satellites have shorter lifespans (5–7 years) Frequent replenishment increases maintenance and environmental burden

INTRODUCING GEO INTO INTEGRATED NTN

Global coverage from fixed location	GEO satellites maintain constant position relative to Earth
	Enable persistent visibility of entire hemisphere without tracking
Centralized network control	Ideal for SDN controller roles in NTN architectures
	Can manage routing, spectrum, and handovers across LEO constellations
Reduced dependency on ground stations	GEO relay allows fewer GS to communicate with LEO networks
	Improves accessibility in remote or geopolitically sensitive regions
High-capacity data relay and aggregation	GEOs act as relay hubs for uplink/downlink aggregation
	Facilitate data offloading and content caching in edge-enabled networks
Extended TT&C capabilities	Ensure always-on telemetry and control for LEO satellites
	Support health checks, emergency commands, and coordination
Support for cross-constellation communication	Bridge traffic between independent LEO networks
	Enable inter-network collaboration and satellite data exchange
Spectrum and policy compliance	Oversee spectrum access and regulatory enforcement
	Apply regional restrictions and licensing compliance remotely

BENEFITS OF GEO-LEO INTEGRATION

Enhanced global service continuity

- Seamless communication even in underserved or remote regions
- Complementary coverage between GEO (broad) and LEO (dense)

Lower total system cost

- Reduced number of required ground stations
- Optimized infrastructure for TT&C and data relay

Improved latency and throughput

- LEO ensures low-latency access
- GEO enables high-capacity backhaul and traffic aggregation

Scalability and flexibility

- GEO-based SDN enables real-time orchestration of LEO networks
- Facilitates dynamic network slicing and load balancing

Reduced complexity in LEO operations

- Centralized GEO control simplifies LEO fleet management
- Handles ISL coordination, routing, and spacecraft traffic management

Resilience and redundancy

- GEO provides backup communication paths
- Ensures failover options during LEO link outages

Future-readiness for 6G and beyond

- Supports AI/ML-based orchestration, MEC, and space-based SDN
- Aligns with ITU and 3GPP NTN integration frameworks

USE CASES ENABLED BY GEO INTEGRATION

Global Telemetry, Tracking & Command (TT&C)

- Centralized TT&C for LEO constellations via GEO
- Reduced latency and improved control coverage

Software-Defined Networking (SDN) Orchestration

- GEO as master controller for dynamic routing in LEO mesh
- Real-time network reconfiguration across NTN

Data Relay for Remote and Maritime Regions

- GEO relays high-throughput data from LEOs to centralized hubs
- Enables broadband services in hard-to-reach areas

Space Traffic Management (STM) and SSA

- GEO supports continuous monitoring of LEO assets
- Facilitates coordinated deorbiting and collision avoidance

Disaster Response and Emergency Connectivity

- Rapid-deploy connectivity via LEO
- GEO handles command and control with resilient downlinks

Cross-Border Regulation and Access Control

- GEO enables region-based routing and frequency governance
- Supports remote configuration to comply with national laws

Military and Government Secure Links

- Dedicated GEO-controlled LEO paths for defense networks
- Supports redundancy and encrypted space links

REGULATORY AND POLICY CONSIDERATIONS

ITU Spectrum Coordination

GEO plays a key role in harmonizing spectrum across regions

Supports avoidance of inter-satellite interference

3GPP NTN Standard Alignment

Ensures compatibility of LEO-GEO integrated architecture

Facilitates adoption of Release 17 and beyond for NTN

National Sovereignty and Licensing

GEO enables enforcement of regional satellite service boundaries

Supports dynamic activation/deactivation of LEOs over restricted airspace

Orbital Debris and End-of-Life Compliance

GEO can coordinate deorbit procedures for LEO fleets

Enables centralized compliance monitoring for SSA

Cross-Border Data Governance

Supports regulation-compliant routing for international data flow

Facilitates adherence to GDPR, HIPAA, and other frameworks

Emergency & Priority Access

GEO can manage emergency spectrum access policies

Supports first responders and governmental override

Space Traffic Management (STM) Standards

Coordinates collision avoidance alerts and satellite maneuvering

Interfaces with international STM frameworks

SUMMARY AND FUTURE DIRECTIONS

GEO-LEO Synergy is Key for 6G NTN

- GEO enhances control, stability, and coverage
- LEO enables low-latency and high-throughput delivery

GEO as Strategic Orchestration Layer

- Central hub for TT&C, SDN, and spectrum regulation
- Reduces reliance on expansive ground station networks

Scalability for Massive LEO Deployments

- Supports thousands of LEO satellites with fewer regulatory bottlenecks
- Manages space traffic, routing, and beamforming at scale

Performance Metrics Validated

- Simulation results confirm visibility, FSPL, Eb/No feasibility
- C-band exceeds 10 dB thresholds for TT&C; Ka-band challenges noted

ITU and 3GPP Support the Vision

- Endorsed in ITU Network 2030 and 3GPP Release 17
- Framework aligns with SDN-MEC edge compute paradigms

Future Research Directions

- Integration with AI for dynamic resource management
- Optical and mmWave ISLs between GEO and LEO
- Security, redundancy, and regulatory automation

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- International Telecommunication Union (ITU) – NTN and Network 2030 frameworks
- 3rd Generation Partnership Project (3GPP) – NTN integration in 5G/6G releases

Industry Observations Informing the Work

- FCC, NASA, ESA, and JAXA data and regulatory documentation
- Real-world insights from Iridium, OneWeb, and Starlink deployments

Presentation Context and Audience

- Thanks to c21-virtual and Paul Stahl for the opportunity
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Closing Note

- GEO-LEO integration is not just a concept but a necessity
- Together, we can architect a truly global, intelligent, and resilient 6G ecosystem

Q&A AND CONTACT INFORMATION

Questions and Discussion

Thank you for your attention

Open to questions, insights, or shared experiences

Looking forward to engaging conversations

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Let’s Connect and Collaborate

Open for joint research, industrial pilots, or academic outreach

Always keen to support innovation in 6G NTN networks