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INTEGRATION OF SATELLITE AND TERRESTRIAL COMMUNICATION NETWORKS IN THE CONTEXT OF GLOBAL INTERNET ACCESS

Fedor Shagzheev
Telecommunication Expert, USA

A B S T R A C T

This article examines the current state of standardization, architectural integration models, and key technical challenges, including spectrum management, high latency variability, and inter-segment roaming. Implementation recommendations and practical scenarios are provided, demonstrating the importance of hybrid networks for universal connectivity.

K E Y W O R D S

Satellite communications, non-terrestrial networks (NTN), 5G, LEO constellations, global Internet access, network integration, communications redundancy, 3GPP Release 17/18.

Introduction

The scientific novelty of the article lies in the generalization and analysis of modern models for the integration of satellite and terrestrial communication networks in accordance with current 3GPP and ITU standards, as well as in identifying the key technological challenges of such hybrid systems for providing global Internet access.

Despite the rapid development of terrestrial telecommunications infrastructure, more than 2.6 billion people, primarily in rural and remote areas, lack stable access to broadband internet [1]. Deploying traditional networks (fiber, cellular) in such regions is often economically impractical due to difficult terrain and low population density.

In response to this challenge, satellite communications systems are recognized as a vital solution for ensuring global access. The development of low-orbit (LEO) satellite constellations (e.g., Starlink, OneWeb, Kuiper) has significantly reduced latency and increased throughput compared to traditional geostationary-orbit (GEO) systems. The satellite communications network market is projected to exceed $100 billion by 2030, confirming their strategic importance [2].

Within 3GPP, the concept of Non-Terrestrial was developed in Releases 17 and 18 Networks (NTN). NTN provides direct integration of satellite systems with 5G architecture, providing mobile broadband access and IoT services globally.

Hybrid integration of terrestrial and satellite networks offers a promising foundation for a sustainable, scalable, and fault-tolerant communications infrastructure. It is particularly important for ensuring universal access within the global "connect everyone" vision, as well as in critical situations (natural disasters, power outages, attacks) when terrestrial networks fail [3].

Implementing full integration faces a number of complex technical challenges:
- high variability of delays and Doppler shifts;
- the need for adaptive spectrum distribution;
- ensuring seamless mobility management in a heterogeneous environment [4].

Successful implementation of hybrid networks requires a multidisciplinary approach, including the development of new protocols, radio planning methods and international coordination of radio frequency spectrum.

The integration of satellite systems into mobile communications has become a key area of standardization thanks to the organization of 3 GPP (3 rd Generation Partnership Project), which officially included the concept of Non-Terrestrial Networks (NTN) into the family 5G New Radio (NR) standards:

1. In Release 17 (2022), 3 GPP approved for the first time specifications supporting NR - NTN and IoT - over - NTN (NB - IoT / LTE - M via satellites). Mechanisms for Doppler shift compensation, delay management, and mobility in the satellite environment have been introduced (TR 38.821, TR 38.811). The goal is to ensure protocol unification and interoperability between satellite and terrestrial networks.
2. Release 18 (2024) - 5G - Advanced includes seamless handover improvements, IoT-over-NTN expansion, and QoS optimization in dynamic satellite channels.

Release 19 is expected to lay the groundwork for 6G NTN, including the use of inter-satellite laser links and orbital edge data processing [4].

The International Telecommunication Union (ITU) plays a key role in the global coordination of satellite systems:
- regulates the distribution of radio frequency spectrum and prevents mutual interference between satellite and terrestrial systems;
- carries out licensing of large LEO constellations.

ITU emphasizes that NTN integration is important for the implementation of the Connect 2030 strategy aimed at eliminating the digital divide [5].

The European Telecommunications Standards Institute (ETSI) is developing specifications for hybrid network architectures and shared resource management. IEEE is actively engaged in standardization of PHY/MAC protocols for LEO systems [6]. Technologies have already moved beyond theory. Commercial pilots include: direct integration of LEO satellites (Starlink) with cellular operators (T - Mobile), the launch of IoT - over - NTN services NB - IoT (Lynk Global, Sateliot), as well as successful testing of NR - NTN communications between standard smartphones and satellites (Qualcomm + Iridium). These projects confirm the high maturity of the technology and bring closer the full integration of satellite systems into global mobile communications.

Literature and standards distinguish several practical models for integrating satellite (NTN) and terrestrial (TN) segments: from simple "overlay" solutions to deep integration at the RAN / Core level and distributed (edge/on - orbit) computing. The choice of architecture is determined by objectives (coverage, redundancy, backhaul, IoT), the type of satellite payload (transparent/adjustable/regenerative), latency requirements, and deployment economics.

Main models:

1. Overlay (parallel/additional connection). The satellite network acts as an independent access channel or backup path: traffic is routed via satellite when terrestrial access is unavailable or for areas not covered by terrestrial infrastructure. Requires minimal changes to the operators' existing infrastructure (often implemented at the VPN / IP level. routing or through separate APN).

Advantages: ease of implementation, rapid expansion of coverage, weak dependence on changes in the PLMN architecture.

Limitations: lack of close RAN / Core cooperation, possible limitations on QoS and spectrum optimization [7].

2. Integration at the RAN / Core level (tight integration). Satellite segments (satellite gateways, on-board processing, ground gateways) act as full-fledged elements of a single 5G architecture - satellites can function as remote DU / CU or even perform part of the functions of the network core (edge in orbit). 3 GPP studied the architectural aspects of the use of satellite access in 5 GS (TR 23.737 and TR 38.821).

Advantages: unified management policy, improved handover/roaming support, more predictable QoS.

Limitations: high synchronization complexity, need for interface adaptation (fronthaul/midhaul), latency and computing resource requirements on board/on the ground side [8].

3. Satellite as Backhaul / Integrated Access and Backhaul (IAB over Satellite). The satellite is used primarily as a backhaul for terrestrial base stations (including IAB nodes). In this model, the satellite provides transport between the ODU/ OCU and the core / edge. This approach is widely considered an intermediate stage of integration.

Advantages: the RAN architecture of ground nodes is preserved, relatively simple scaling.

Limitations: Feeder bandwidth and latency affect some functions (eg fronthaul is delay sensitive), there may be difficulties with F 1/ eCPRI synchronization [9].

4. Multi - connectivity (Multi - Path). UE or CPE simultaneously support multiple radio interfaces : terrestrial and one or more satellite channels. Traffic is aggregated or dynamically switched according to policy (link) aggregation, flow Split, reliability). This is one of the key practices for increasing availability and QoS -critical services.

Advantages: high fault tolerance, flexible traffic management (latency – sensitive vs bulk).

Limitations: complexity of multipath management TCP / QUIC, the need for coordinated resource management and possible doubling of signalling [10].

5. Regenerative satellites, intersatellite links (ISL) and on - orbit Satellites with regenerative load (on - board processing) and inter-satellite Laser /radio links (ISL) enable routing and computing in space, reducing latency to some destinations and easing the load on terrestrial gateways. This model enables distributed services (edge in space).

Advantages: reduction of the packet "journey" to a single terrestrial gateway, network flexibility, cloud service capabilities in orbit.

Limitations: complexity of orbital network management, power consumption, high CAPEX / OPEX on laser ISL and regenerative payload [11].

6. SDN / NFV / O - RAN approaches (software-defined networks). Application of SDN / NFV and O - RAN principles to unify TN and NTN management: centralized orchestration , virtualization of RAN / Core functions , dynamic resource reallocation, and open interfaces. O - RAN approaches offer

flexible CU / DU / MONO components suitable for orchestrating heterogeneous topologies (including HAPS / LEO).

Advantages: flexibility, rapid service development, ability to use AI / ML in controllers to adapt to rapidly changing satellite geometry.

Limitations: the need to standardize new open interfaces for NTN , security requirements for virtualized functions [12].

Table 1 - Comparison of architectural models

Model	**Key idea**	**Technical requirements**	**Pros**	**Cons**
Overlay (additional access / reserve)	Satellite as an independent access channel/ backup	IP routing, VPN, separate APNs	Easy implementation, fast coverage	Low coordination with RAN/ Core , limited QoS
RAN/ Core integration (tight)	Satellite = element of a single 5G architecture (DU/CU/ edge)	F1/ eCPRI / midhaul / fronthaul adaptation, synchronization, 3GPP TR23.737/38.821 standards	Full-fledged QoS , unified management policy	Complexity, strict latency/synchronization requirements
Satellite as Backhaul / IAB	Satellite = backhaul for ground BS/IAB nodes	Feeder capacity, fronthaul / midhaul support	Minimal changes to ground RAN	Limitations for time-sensitive functions
Multi-connectivity	Simultaneous connection of UE to TN and NTN	Multipath matching , flow-split , signalling	High reliability, flexible traffic distribution	Complex TCP/QUIC coordination , signaling overhead
Regenerative satellites + ISL	In-Space Processing and Routing (ISL)	On-board compute , laser/radio ISL, orbital control	Reduced end-to-end delays, flexible routes	High CAPEX/OPEX, network management in space
SDN/NFV/O-RAN	Function virtualization, centralized orchestration	Open interfaces, orchestrator, AI/ML controllers	Flexibility, automation, fast rollout of services	Requires standardization of new interfaces and security

The choice of architecture for integrating satellite (NTN) and terrestrial (TN) networks directly depends on the desired objectives, service level (QoS), and investment readiness. For pilot projects and rapid coverage expansion with minimal impact on existing network infrastructure, the following models are preferred:

1. Overlay . The satellite acts as an independent channel.
2. Satellite as Backhaul . The satellite is used only as a backhaul channel for ground nodes.

These approaches allow for rapid assessment of the economic feasibility and functionality of NTN without deep architectural changes to the network core .

For services requiring predictable quality of service (QoS) and seamless handover , deep integration is required:

1. Tight Integration (RAN/ Core) provides unified management and better synchronization.
2. Multi-connectivity ensures fault tolerance and the ability to dynamically distribute traffic, which is critical for aviation, V2X, and emergency services.

These models require intelligent orchestration and more complex changes to the network architecture. The most promising, but also the most capital-intensive direction is the development of regenerative satellites and ISL (Inter-Satellite Links): Creating full-fledged "networks in space." This model provides maximum latency reduction and flexibility, but requires significant investment and the development of new operating models for managing orbital networks.

Successful integration of satellite systems into mobile communications architecture faces a number of complex technological and regulatory challenges:

1. High and variable latency. Satellite links, especially GEO, have significantly higher RTT than terrestrial networks → protocol adaptation, buffering, and routing optimization are required.
2. Doppler shift and rapidly changing channel kinematics. LEO constellations are characterized by high satellite speeds → complex synchronization and adaptive frequency/phase correction.
3. Difficulties with radio planning and spectrum management. Frequency sharing, interference prevention between the TN and NTN, and international coordination between operators are necessary.
4. Mobility and roaming management. Seamless handover mechanisms between the satellite and the terrestrial network are needed, as well as a unique session identification and control system.
5. Time and frequency synchronization. Precise synchronization is required across multiple reception points and large geographic service areas.
6. QoS and resource management in a heterogeneous infrastructure. Adaptive distribution of radio resources between TN/NTN, especially under dynamic traffic conditions and variable satellite visibility.
7. TCP/QUIC and transport layer optimization. Traditional congestion control mechanisms are ineffective with highly variable delays → stack modifications are required.
8. Security and encryption. The satellite channel is vulnerable to interception/jamming → enhanced cybersecurity measures and signal protection are needed.
9. Economics and operating models. High CAPEX/OPEX for satellite infrastructure → need for new partnership and distributed business models.

The integration of satellite and terrestrial networks provides continuous and resilient communications, which is critical in environments where traditional infrastructure is absent or unreliable.

Table 2 – Examples of application scenarios

Scope of Application	**The Role of NTN**	**Key Benefit**
1. Eliminating the digital divide	Providing basic internet access to remote, rural and hard-to-reach areas around the world.	Reducing the digital divide and stimulating economic development.
2. Maritime and aviation communications	Providing the only reliable communication channel over oceans and at high altitudes for aircraft and ships.	Support of navigation, operational services and provision of on-board Wi-Fi .
3. Industrial IoT and telemetry	NB- IoT /LTE-M services via satellites (3GPP Rel.17).	Massive global sensor connectivity for energy, transportation and agriculture.
Disaster recovery recovery)	Instant satellite deployment backhaul for emergency communications in the event of destruction or shutdown of terrestrial networks.	Ensuring the resilience of critical infrastructure and communications for rescue services.
5. Transport and logistics (smart mobility)	Maintaining continuous connectivity of transport on remote highways and routes outside the coverage area of terrestrial networks.	Implementation of continuous telematics and logistics services .

Thus, the successful implementation of hybrid satellite -terrestrial networks requires a coordinated approach that includes technological, regulatory and operational steps:

1. Active cooperation between all key stakeholders is essential : satellite network operators, mobile operators, and regulators (e.g., the ITU). This is necessary for the successful implementation of pilot deployments and the harmonization of radio spectrum use.
2. Hybrid multi- connectivity is recommended as an intermediate and most reliable step toward full integration. This model allows end devices to simultaneously use terrestrial and satellite channels, increasing fault tolerance and availability until full architectural integration is achieved.
3. It is necessary to implement practical testing programs to objectively assess the QoS (quality of service) and economic sustainability of NTN services in real, complex scenarios (e.g., maritime zones, hard-to-reach rural regions, emergency situations).

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