6G Evolution: Architectural Framework for AI-Native Non-Terrestrial Networks (NTN) and 3D Integrated Connectivity

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Abstract:
The standard 5G architecture was primarily optimized for terrestrial coverage, with NonTerrestrial Network (NTN) support added as a secondary extension. As the telecommunications industry pivots toward 6G (IMT-2030), the integration of Space-Air-Ground components must be "native" rather than "additive." This white paper presents a technical deep-dive into the core enablers for 6G NTN, specifically focusing on regenerative satellite payloads, delay-doppler domain processing via OTFS waveforms, and AI-driven proactive mobility management. We analyze the transition toward Very Low Earth Orbit (VLEO) constellations and provide empirical performance targets for latency, spectral efficiency, and link reliability in the 6G era.

Keywords: 6G, NTN, VLEO, OTFS Waveform, AI-Native RAN, SAGIN Architecture, Integrated Sensing and Communication (ISAC).

I. INTRODUCTION

The dawn of the 6G era represents a fundamental shift in the global telecommunications landscape, moving from a terrestrial-centric paradigm to a truly ubiquitous, three-dimensional (3D) connectivity framework. As defined by the International Telecommunication Union (ITU-R) in its IMT-2030 framework, 6G aims to provide hyper-connectivity with peak data rates exceeding 100 Gbps, submillisecond latency, and unprecedented reliability. Central to this vision is the integration of NonTerrestrial Networks (NTN), which include Very Low Earth Orbit (VLEO) and Low Earth Orbit (LEO) satellite constellations, High-Altitude Platform Stations (HAPS), and Unmanned Aerial Vehicles (UAVs).

While 5G-Advanced (3GPP Release 17/18) introduced the initial support for NTN, it was primarily designed as an "add-on" to bridge coverage gaps in remote areas. These early deployments often relied on "transparent" payloads, where satellites acted as simple radio frequency (RF) repeaters, leading to significant latency and spectral efficiency bottlenecks. In contrast, 6G mandates a "native" NTN integration, where non-terrestrial components are deeply embedded in the Radio Access Network (RAN) architecture. This evolution requires overcoming formidable technical challenges, such as extreme Doppler shifts caused by high orbital velocities, long propagation delays, and the need for seamless, proactive mobility management across heterogeneous layers. This white paper explores the critical technical pillars—regenerative payloads, OTFS waveforms, and AI-native orchestration—that will enable 6G NTN to deliver on its promise of 100% geographical coverage and fiber-like performance from space.

II. Architectural Pillar: SAGIN and Regenerative Payloads

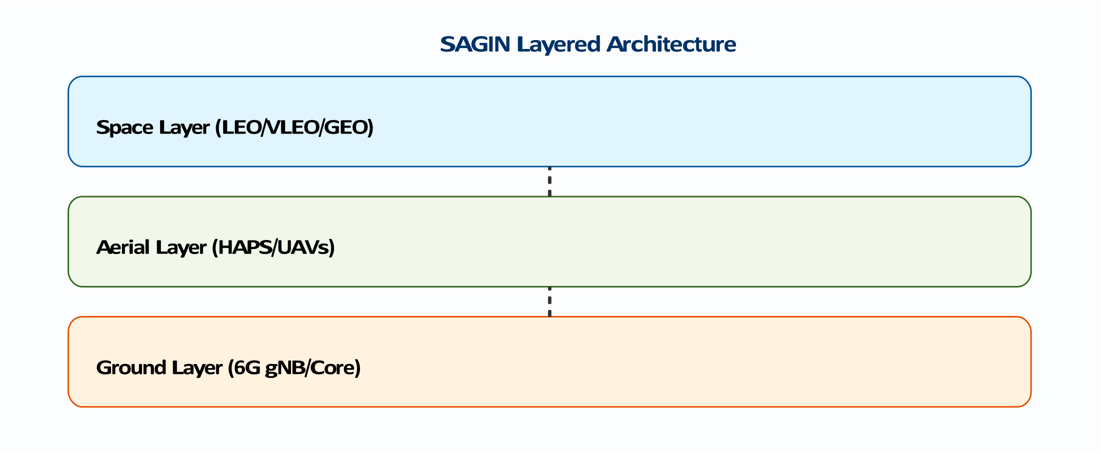

Figure 1: Layered Space-Air-Ground Integrated Network (SAGIN) for 6G.

A critical technical shift in 6G is the implementation of **functional splits on-board the satellite**. By hosting the Distributed Unit (DU) and a localized User Plane Function (UPF) on VLEO satellites, 6G minimizes the backhaul latency bottleneck. This allows for edge computing in orbit, enabling real-time processing of sensor data from the Integrated Sensing and Communication (ISAC) modules.

A. On-Board Edge AI Orchestration

In the dynamic and complex environment of a 6G Space-Air-Ground Integrated Network (SAGIN), traditional centralized network management becomes a bottleneck. The sheer number of moving nodes —thousands of LEO satellites and millions of highly mobile User Equipments (UEs)—coupled with the round-trip time (RTT) to ground-based controllers, necessitates a shift toward autonomous, decentralized orchestration. 6G NTN addresses this through **On-Board Edge AI Orchestration**, where localized intelligence is deployed directly on the satellite payload.

On-board AI agents serve multiple critical functions. First, they enable **Autonomous Radio Resource Management (RRM)**. By processing local channel state information (CSI) and interference patterns in real-time, these agents can dynamically allocate power, frequency, and time resources across thousands of narrow beams without waiting for instructions from a ground gateway. This is particularly vital for mitigating the fast-fading effects and atmospheric scintillation common in Ka and sub-THz bands. Second, AI-native orchestration facilitates **Predictive Trajectory-Based Handover**. Utilizing orbital ephemeris data and machine learning-based UE movement prediction, the network can perform "makebefore-break" connections, ensuring zero-packet loss during high-speed transitions between satellite footprints. Furthermore, on-board AI allows for **Orbital Traffic Steering**, where data packets are intelligently routed through the inter-satellite laser link (ISL) mesh to the most efficient ground entry point, bypassing congested gateways and optimizing the overall network throughput.

III. Physical Layer Innovation: OTFS Waveform

Traditional OFDM suffers significantly in the LEO/VLEO environment due to massive Doppler shifts. 6G proposes **Orthogonal Time Frequency Space (OTFS)**, which modulates symbols in the Delay-Doppler domain.

$$y(\tau, \nu) = \int \int h(\tau, \nu)\, x(\tau - \tau', \nu - \nu')\, e^{j 2 \pi \nu (\tau - \tau')}\, d\tau'\, d\&nu'$$

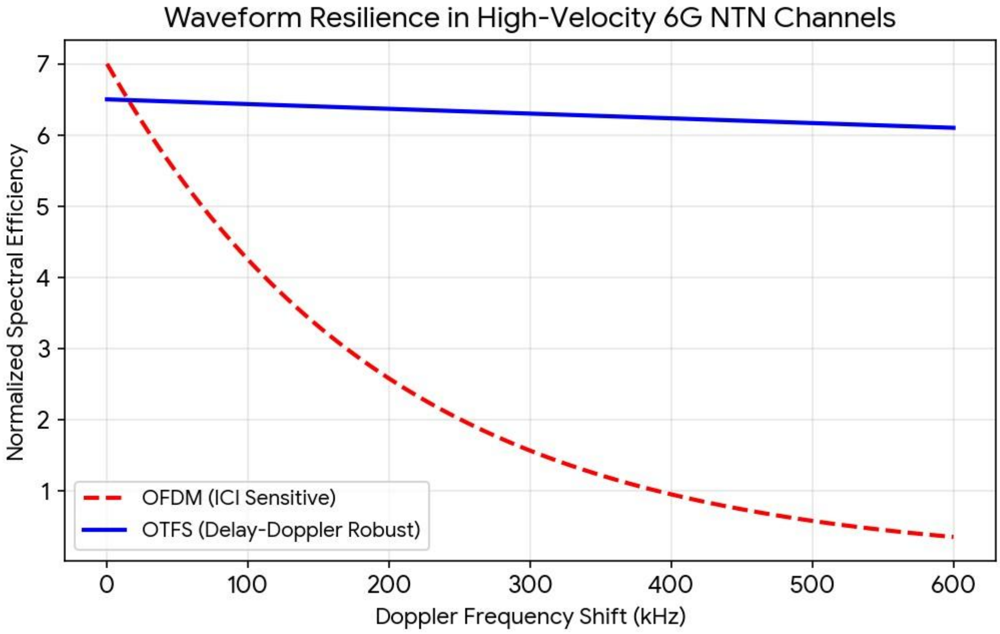

Figure 2: Performance analysis of OTFS vs. OFDM under extreme Doppler shifts.

IV. AI-Native Resource and Mobility Management

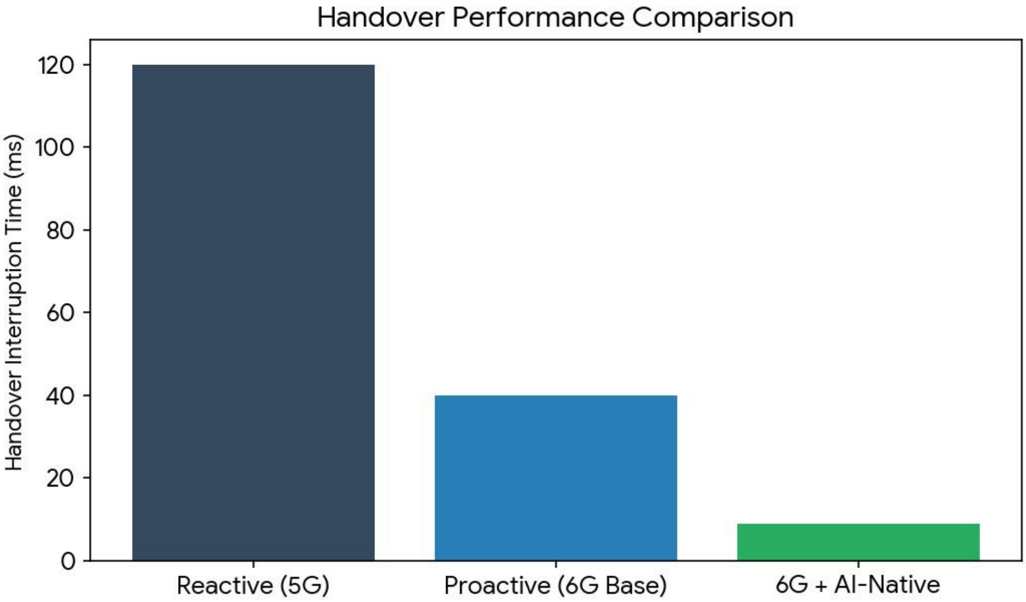

Figure 3: Reduction in interruption time via AI-driven proactive handover.

V. Technical Comparison: 5G vs. 6G NTN

Metric	5G NTN (Rel-17)	6G NTN (Target)
Waveform	CP-OFDM	OTFS / DD-Domain
Payload	Transparent	Regenerative (On-board gNB)
Latency	30 - 50 ms	< 10 ms
Mobility	Up to 1,200 km/h	Up to 28,000 km/h

VI. Conclusion and Strategic Outlook

The transition from 5G to 6G Non-Terrestrial Networks represents the most significant architectural evolution in the history of mobile communications. This technical deep-dive has demonstrated that the integration of space-based assets is no longer an optional "coverage extension" but a fundamental requirement for the 6G ecosystem to achieve its goals of global inclusion and extreme performance. By transitioning from transparent payloads to **regenerative on-board architectures** and adopting **OTFS waveforms** in the Delay-Doppler domain, 6G effectively overcomes the physical constraints of high Doppler shifts and long propagation delays that limited the commercial viability of 5G NTN.

The findings of this paper highlight that **AI-Native RAN orchestration** is the primary enabler for managing the complexity of next-generation mega-constellations. As the network moves toward VLEO orbits to reduce latency, the frequency of handovers and the volatility of the radio environment increase exponentially. The implementation of Deep Reinforcement Learning (DRL) for proactive mobility management and on-board edge intelligence ensures that 6G can maintain the 99.999% reliability and sub-10ms latencies required for mission-critical applications like autonomous maritime logistics, remote environmental sensing, and global disaster response.

Looking forward, the success of 6G NTN depends on three strategic pillars: **Standardization, Spectrum, and Sustainability**. Regulatory bodies must prioritize the harmonization of mid-band and sub-THz spectrum to facilitate seamless terrestrial-satellite coexistence. Simultaneously, the industry must align on "Direct-to-Cell" protocols within 3GPP Release 20 and 21 to ensure that 6G smartphones can access satellite services without specialized hardware. Finally, orbital sustainability—addressing space debris and de-orbiting protocols—must be a core design principle for all 6G constellations. Ultimately, 6G NTN is not just a technological feat; it is the bridge to a truly unified global digital fabric, unlocking trillions of dollars in economic value and ensuring that no region on Earth is left behind in the digital future.

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