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Sixth-Generation Nonterrestrial Networks: Where Standards and Technology Are Heading

While fifth-generation (5G) technology made satellites relevant to mainstream mobile networks, the sixth generation (6G) is setting the stage for satellites to become *native* to the cellular fabric.

Global Standards Outlook: 6G Nonterrestrial Networks

The International Telecommunication Union Radiocommunication Sector (ITU-R) sets a 6G/International Mobile Telecommunications (IMT)-2030 vision that treats nonterrestrial networks (NTNs) as native to the system, while the Third Generation Partnership Project (3GPP) moves from Release 20 (Rel-20) studies to Release 21 (Rel-21) specifications to operationalize terrestrial network (TN) and NTN (TN/NTN) convergence, positioning/synchronization, and handset viability. In parallel, regulatory and program tracks [the U.S. Federal Communications Commission (FCC); the United Kingdom's Office of Communications (Ofcom); and the European Union's Infrastructure for Resilience, Interconnectivity and Security by Satellite (IRIS^2)] are preparing spectrum, licensing, and funding frameworks that enable service scenarios such as direct-to-device messaging/voice, coverage extension and emergency connectivity, NTN-backhauled cells, and wide-area Internet of Things (IoT).

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In November 2023, the ITU-R finalized Recommendation M.2160, the framework for IMT-2030, i.e., 6G [1]. It lays out usage scenarios beyond IMT-2020 and an expanded capability set (coverage, reliability, positioning, sensing, sustainability, etc.) and, critically, positions interoperability with "other access systems," a door that many expect NTNs to step through as a first-class citizen. While it avoids dictating spectrum, it provides the reference architecture that standards bodies and regulators are now mapping against.

On the cellular side, Release 17 was the inflection point: 3GPP introduced normative requirements for 5G New Radio (NR)-NTN (for handsets in frequency range 1) and IoT-NTN [narrowband (NB) IoT, NB-IoT/enhanced machine type communication], turning satellites from a study topic into deployable features. That decision unlocked real device and network roadmaps for both continuity and coverage expansion [2]. Now, the center of gravity is Rel-20. In the week of 9 June, the cellular ecosystem gathered in Prague for 3GPP's 108th Plenary to chart the next phase of standards. After intense, productive deliberations, delegates reached several milestones, most notably a consensus on the initial scope of Rel-20, setting the stage for the next wave of wireless innovation. According to the 3GPP timeline, 3GPP Rel-20 will span a broad slate of wireless work, furthering 5G-Advanced and laying the groundwork for 6G. On the 5G side, as the sixth 5G-Advanced release, it is expected to refine system design, bolster existing deployments, and open new application areas. On the 6G side, it will launch formal study items in foundational technologies, seeding the work items planned for Rel-21. For NTNs, Rel-20 moves the work from "possible" to "workable with the network." It will study how to make satellites function like another cell layer: seamless handover between towers and low Earth orbit (LEO) beams, operation on ordinary handsets (power and link budget), handling LEO dynamics (Doppler and timing), and basic positioning/time sync without the Global Navigation Satellite System (GNSS). Rel-20 will advance both NR-NTN and IoT-NTN. To date, NTN operation has generally assumed access to GNSS information. Rel-20 will launch a one-year study of GNSS-independent procedures, covering initial access and connected-mode operation, and 3GPP will decide the next steps based on the findings. In parallel, the IoT-NTN work is expected to define radio enhancements that enable voice services over geostationary (GEO) satellite systems. In summary, R20 will set requirements and targets, leaving detailed NTN specifications to Rel-21. Subject to Rel-20 outcomes and 3GPP approval, Rel-21 is expected to translate those results into normative specifications. It would likely define signaling to support TN/NTN mobility and

> ***Rel-20 will launch a one-year study of GNSS-independent procedures, covering initial access and connected-mode operation, and 3GPP will decide the next steps based on the findings.***

service continuity, user equipment (UE) capability profiles for handheld NTNs, procedures for positioning and synchronization, and conformance requirements that account for Doppler effects and longer round-trip times. The final scope will depend on the Rel-20 study conclusions.

On the other hand, regulators are laying the groundwork for 6G NTNs by setting the legal and program frameworks needed for handset-grade satellite service and seamless integration between TNs and NTNs. In the United States, the FCC has adopted supplemental coverage from space rules that let satellite operators partner with mobile carriers to use a licensed mobile spectrum under defined coordination and public safety conditions. In the United Kingdom, Ofcom is moving to authorize direct-to-device services in bands already assigned to mobile operators, with interference protections and clear partnership requirements. Across the European Union, the IRIS^2 secure connectivity program is funding a multiorbit system targeting government and commercial services around 2030, anchoring demand and timelines that NTN standards can map to.

Industry Perspectives on 6G NTNs

On 8 September 2025, SpaceX stated that it had entered a purchase agreement with EchoStar for 50 megahertz (MHz) of the exclusive *S*-band spectrum in the United States and for global mobile satellite service licenses. The company presented this transaction as the foundation for a next-generation Starlink "Direct to Cell" constellation intended to deliver broadband connectivity to standard, unmodified smartphones worldwide. SpaceX also recounted the first phase of the program: the launch of Direct to Cell payloads beginning in January 2024, early demonstrations of texting and video calling on ordinary handsets, and the subsequent deployment of more than six hundred Direct to Cell satellites integrated with the broader laser-linked Starlink fleet. It further claimed active service across five continents, several million users, and roaming-style integration with mobile network operators (MNOs), positioning Direct to Cell as a complement to TNs.

Within the same update, SpaceX outlined its technical trajectory for the second generation. It described satellites built around SpaceX-designed silicon and large phased-array antennas capable of producing thousands of beams, and it asserted order-of-magnitude gains, approximately 20-fold per-satellite throughput and more than 100-fold system capacity, relative to the initial layer. According to the company, an exclusive mid-band spectrum and "optimized 5G protocols for satellite connectivity" would enable experiences comparable to terrestrial cellular service in many environments, delivered in partnership with MNOs. Independent reporting the same week corroborated the existence and scale of the EchoStar transaction and noted the commercial tie-ins envisaged for handset service.

Viewed from a standards and policy perspective, the announcement fit the broader evolution of NTNs toward mainstream cellular integration. By mid-2025, the 3GPP had begun Rel-20 studies on 6G radio and core topics, including tighter alignment of terrestrial and satellite access, while Rel-21 was identified as the point at which normative 6G specifications would commence. In parallel, the FCC's supplemental coverage from space framework established a U.S. licensing pathway for handset-grade satellite service using mobile operator spectra. Against that backdrop, SpaceX's move toward dedicated spectra, higher beam density, and satellite-tuned protocols represented a push to make the satellite layer behave as another cellular access, rather than a special-case add-on.

In summary, SpaceX framed Direct to Cell's first phase as proof that ordinary phones could connect via Starlink satellites, and it positioned the EchoStar spectrum deal as the lever for a higher-capacity second generation built on custom silicon, large phased arrays, and satellite-optimized cellular protocols. Set against the Rel-20 to Rel-21 standards transition and an emerging regulatory pathway in the United States, the company's plan aligned with the industry's direction for 6G NTNs: a satellite layer engineered to operate like conventional cellular access within a unified service fabric.

Eutelsat OneWeb is pushing LEO satellites from niche backhaul into the mainstream of cellular by demonstrating that 5G-Advanced NR-NTN can run over its constellation and by turning those capabilities into enterprise and operator offers. In February 2025, Eutelsat, MediaTek, and Airbus reported the world's first successful 5G (NR-NTN) connection over OneWeb LEO, a step meant to prove seamless interoperability between terrestrial and satellite domains; the trial used OneWeb satellites, a MediaTek NTN test chipset, Airbus satellite hardware, and additional partners such as Sharp and Rohde & Schwarz (R&S). That technical milestone matters because it maps neatly onto 3GPP's evolution from initial NTN enablement to tighter TN/NTN integration in early 6G work, signaling that LEO can behave more like another cellular layer rather than a bolt-on.

On the commercial side, in June 2025, Orange signed a multiyear agreement to package Eutelsat OneWeb's LEO service for enterprise, government, and mobile backhaul customers, combining LEO coverage with Orange's terrestrial footprint to improve resilience and reach in remote or underserved locations. The deal emphasizes low latency, continuity of service, and "sovereign" options, positioning LEO as a practical tool for high-availability connectivity and 5G/5G-Advanced offload where fiber or microwave is impractical. Taken together, the NR-NTN space trial and the Orange backhaul/enterprise rollout sketch a coherent path for OneWeb: prove 5G-Advanced NTN in orbit, then monetize it as resilient backhaul and managed enterprise connectivity now, while the standards track moves toward deeper TN/NTN convergence for 6G. Orange's Jean Louis Le Roux, executive vice president for international networks, emphasized the strategic rationale: "It is of strategic importance for Orange to invest in the unique LEO European solution." He added that the partnership is vital to support customers' digital transformation. Eutelsat's Cyril Dujardin, president of the connectivity business unit, underlined operator demand: "LEO-enabled services are becoming an integral technology for global telco operators." In summary, the Orange–Eutelsat arrangement presents LEO NTN as a pragmatic, near-term tool for resilient enterprise connectivity and mobile backhaul, while reinforcing a long-term model where satellite access complements TNs.

Amazon reports that Project Kuiper has progressed from prototype demonstrations to full-scale deployment of its LEO broadband constellation. The company began production launches on 28 April 2025 with twenty-seven satellites aboard a United Launch Alliance Atlas V and has since conducted additional Atlas V and SpaceX Falcon 9 missions. According to Amazon's running update, the constellation has surpassed one hundred satellites in orbit, with the Kuiper Atlas-03 Atlas V mission, carrying a further twenty-seven spacecraft, projected to bring the total to approximately one hundred twenty-nine. The company reiterates a launch campaign of more than eighty missions to establish an initial network of more than three thousand two hundred satellites and highlights a 140-million-dollar processing facility at the National Aeronautics and Space Administration's Kennedy Space Center to sustain manufacturing and launch cadence. Recent public reporting broadly aligns with Amazon's account, noting the "more than one hundred satellites" milestone, plans for near-term service pilots, and early commercial pathways such as in-flight connectivity and initial national deployments as coverage expands through 2025–2026. From the perspective of 6G NTNs, Project Kuiper can be framed as a scaling LEO access layer designed to complement TNs. The combination of high launch cadence, ground segment readiness, and progressive service pilots positions Kuiper for wide-area broadband coverage while preserving optionality for future integration scenarios between TNs and NTNs.

AST SpaceMobile has moved beyond proofs of concept to the early stages of an LEO network built specifically for direct connections to ordinary smartphones. AST SpaceMobile has advanced its direct-to-device program from one-off demonstrations to an initial commercial build-out. The company launched its first five BlueBird commercial satellites on a SpaceX Falcon 9 from Cape Canaveral on 12 September 2024, marking the start of a production constellation designed to connect ordinary smartphones over LEO links. Those launches followed a sequence of technical firsts achieved with the BlueWalker-3 testbed: a space-to-ground voice call using an unmodified handset (April 2023) and the first 5G cellular connectivity from space to a standard smartphone (September 2023). The trials were conducted with operator and vendor partners and were intended to prove that everyday devices could register on a satellite cell without hardware changes.

In 2025, Lynk Global moved from demonstrations to defined service paths and scale-up infrastructure, securing investment and channel support, executing a landmark smartphone voice call under national authorization, obtaining a U.S. regulatory modification for commercial service in specific territories, exiting a public markets transaction, and preparing further national trials. On 10 March 2025, Lynk Global and Société Européenne des Satellites (SES) announced a strategic technical partnership to accelerate direct-to-device service, under which SES would supply multiorbit ground infrastructure, medium-Earth-orbit (MEO) relay and teleport resources to help Lynk scale handset connectivity and integrate satellite access with MNO cores. On 27 March 2025, Mobile Telephone Networks South Africa and Lynk Global completed what they described as Africa's first satellite voice call on a standard, unmodified smartphone, in a technical trial authorized by the Independent Communications Authority of South Africa; the session also validated Short Message Service over an LEO link. On 30 April 2025, the U.S. FCC granted Lynk Global a license modification authorizing commercial direct-to-device service with DOCOMO Pacific in Guam and the Northern Mariana Islands, establishing a concrete service path that interworks with a terrestrial mobile core.

On 23 December 2024, the European Space Agency (ESA), Telesat, and Amarisoft reported a world-first 3GPP 5G NR-NTN link over LEO, using Telesat's LEO-3 demo satellite and a *Ka*-band waveform. The team maintained a bidirectional link through the pass, reached 3 bits/s/Hz spectral efficiency with adaptive modulation up to 64 quadrature amplitude modulation, and used System Information Block Type 19 ephemeris messaging to

ON 5 SEPTEMBER 2025, NOKIA PUBLICLY ARGUED THAT 6G-ERA DEVICES WILL NATIVELY INCLUDE SATELLITE CONNECTIVITY, POSITIONING NTNS AS A FUNDAMENTAL CAPABILITY ALONGSIDE WI-FI OR GNSS AND SPANNING TEXT, VOICE, AND BROADBAND.

keep Doppler and timing aligned, evidence that standardized NTN procedures are working on real spacecraft.

On 5 June 2025, Telesat highlighted a *Q*-band NTN link demonstration with ESA and Rutherford Appleton Laboratory Space, extending its NTN research beyond *Ka*-band toward higher-frequency building blocks relevant to 6G. On 19 August 2025, Telesat Government Solutions and ALL.SPACE announced a terminal collaboration to integrate multiorbit, multilink UE with Lightspeed, ground hardware preparedness that complements the space segment for operator-grade services. Executive commentary underscored the defense and resilience rationale. Telesat Government Solutions president Chuck Cynamon said, “Secure, ruggedized multiband and multiorbit terminals provide increased flexibility and resiliency,” adding, “The combination of our secure, advanced Telesat Lightspeed services and innovative ALL.SPACE terminals will increase operational advantage for the DoD in the digital battlespace.” ALL.SPACE chief executive Paul McCarter framed the architecture shift: “The future of resilient, global connectivity hinges on multiorbit, multinetwork architectures,” and “Integrating our field-proven Hydra terminals with the advanced Telesat Lightspeed LEO capabilities will give government and defense users a critical operational edge.”

Globalstar operated an LEO mobile-satellite service (MSS) system using *L*-band uplink and *S*-band downlink and held authority to use a portion of its licensed *S*-band terrestrially. On 12 December 2024, Globalstar reported a first 5G data call, a technical milestone for its terrestrial spectrum that complemented MSS services and pointed to tighter device/radio access network (RAN) ecosystem support for future integration. Throughout 2023–2024, Apple extended the iPhone satellite feature set (Emergency SOS, Roadside Assistance via satellite, and Messages via satellite in iOS 18), operationalizing direct-to-handset workflows over the Globalstar network. On 15 September 2025, Globalstar said it had begun the formal process to activate a new international filing, submitted via the French administration, for its next-generation satellite network. The plan called for more satellites, additional orbital layers at different altitudes, and a wider range of radio frequencies than the company uses today. In particular, it sought extra airwaves for the direct connection between mobile phones and satellites and more airwaves for the high-capacity links that carry traffic between satellites and ground stations. In short, the filing set out how Globalstar aimed to build a larger, more flexible LEO network with higher capacity.

On 5 September 2025, Nokia publicly argued that 6G-era devices will natively include satellite connectivity, positioning NTNs as a fundamental capability alongside Wi-Fi or GNSS and spanning text, voice, and broadband. Nokia cited first-wave handsets supporting standardized satellite messaging via narrowband-IoT over NTNs and then mapped the 3GPP evolution: Release 18 broadening device types and mobility; Release 19 introducing regenerative payloads in orbit; and 6G targeting three pillars, “NTN in every single device,” “No GNSS needed,” and seamless TN–NTN interworking for service continuity. Nokia tied this view to its device architecture work inside 3GPP. In a 26 May 2025 post, company standards leads described the industry consensus around “a single technology stack that applies to all 6G device types,” replacing today’s add-ons for IoTs and satellite with a common foundation from low-power sensors to extended-broadband devices. That stack is the backdrop for treating satellite as a first-class access layer in 6G.

On 5 March 2025, Ericsson, Qualcomm Technologies, and Thales Alenia Space reported a 5G NR-NTN milestone tied to the Mobile World Congress. In a French test laboratory, the partners placed a standards-based 5G NTN call over a simulated LEO channel, exercising procedures for space links while using ordinary mobile network components on the ground. Ericsson’s release said the demo validated “key technical functionalities” and explored delay tolerance, Doppler handling, and satellite handover, the building blocks required for seamless operation as a device moves between terrestrial cells and satellite beams. The companies also emphasized that an NTN-capable device could connect “without the need for additional satellite signal receiving equipment, such as a dish.” Ericsson Executive Vice President Fredrik Jejdling called it “not just a technological breakthrough” but proof of the “practical viability of integrating satellite technology within existing terrestrial frameworks” to make future systems “more inclusive, resilient, and globally accessible.” Qualcomm Senior Vice President John Smee said the collaboration was “crucial in leveraging 3GPP standards for satellite communications,” adding that the goal is “seamless integration of 5G nonterrestrial networks and terrestrial networks.” Thales Alenia Space Chief Executive Hervé Derrey noted that 5G-standardized NTN solutions are now reflected in the firm’s satellite payload designs, “supporting either Broadband or Direct-To-Device (D2D) services,” and argued that combining space payload expertise with 5G networks and chipsets is “making significant headway” toward TN/NTN integration.

THE DEMONSTRATION USED AST SPACEMOBILE'S BLUEBIRD SATELLITES IN LEO, AND VODAFONE INDICATED PLANS TO BEGIN ROLLING OUT CUSTOMER SERVICE ACROSS EUROPE LATER IN 2025 AND INTO 2026.

On 23 February 2023, Samsung announced a 5G NTN modem technology program built on its Exynos Modem 5300 reference platform, describing LEO-link techniques such as Doppler compensation and satellite position prediction and stating that future Exynos modems were intended to support two-way text, as well as high-definition image and video sharing over satellite. On 12 June 2024, Samsung's System LSI division published a technical blog on the Exynos Modem 5400, highlighting simultaneous support for NB-IoT NTNs and 5G NTNs in a single-chip solution, framing handset-grade satellite messaging and IoT as part of its modem roadmap.

On 4 January 2023, Keysight and Qualcomm demonstrated call signaling and data transfer for 5G NTNs using orbit-trajectory emulation, positioning the setup as groundwork for remote coverage services. On 23 February 2023, Keysight and Samsung showed two-way SMS over a live 5G NTN link using a Samsung System LSI modem, an early device path validation for handset connectivity. On 27 February 2024, Keysight and Skylo announced 145 approved test cases for Skylo's NTN certification program, spanning GEO and other orbital profiles and real-world signal-to-interference-plus-noise ratio conditions.

On 22 February 2024, R&S and MediaTek showcased a Release 17 NR-NTN connection at the Mobile World Congress using the CMX500 one-box signaling tester and a MediaTek NTN device. On 20 August 2025, R&S said it had verified initial NR-NTN test cases with Tier 1 chipset partners, framing it as a step toward commercial rollouts and formal conformance. R&S also documents a joint digital twin NTN testbed with VIAVI, combining CMX500, TM500 AS2, and TeraVM, covering LEO/MEO/GEO end-to-end behaviors; the CMX500 product pages emphasize multiband/multiorbit support and a dedicated NTN workspace.

In January 2024, Anritsu and Skylo said they would add Skylo NTN test cases to support device compatibility; on 4 April 2024, Anritsu introduced protocol test enhancements for NB-IoT over GEO, expanding NTN device coverage. On 29 July 2025, Anritsu announced MT8000A updates to simulate propagation delay and Doppler for 5G NR-NTN device development, bridging from NB-IoT to NR-NTN.

MNO Readiness for 6G NTNs

On 30 January 2025, Vodafone reported that it had conducted what it described as the world's first video call via satellite using a standard, unmodified smartphone, placing the call from a remote location in the Welsh mountains to Chief Executive Margherita Della Valle. The demonstration used AST SpaceMobile's BlueBird satellites in LEO, and Vodafone indicated plans to begin rolling out customer service across Europe later in 2025 and into 2026. According to the company's account, the call formed part of a broader program to extend coverage to areas without terrestrial signal. Vodafone said the satellite link could deliver up to 120 Mb/s to ordinary handsets and noted that it is an investor in AST SpaceMobile alongside other industry participants. The event coincided with the launch of a space-to-land gateway at Vodafone's U.K. headquarters in Newbury, which receives signals from user devices via satellite and connects them into Vodafone's core network.

T-Mobile has published a sequence of official announcements and product pages that document its Starlink-based Direct to Cell program from launch through commercial availability. On 25 August 2022, T-Mobile announced "Coverage Above and Beyond," a partnership with SpaceX to extend service into cellular dead zones by connecting ordinary smartphones to Starlink satellites using terrestrial mobile spectra. On 3 January 2024, T-Mobile stated that SpaceX had launched the first batch of Starlink satellites with Direct to Cell payloads, enabling field testing for handset connectivity. On 16 December 2024, T-Mobile opened public beta registration for the satellite service, citing recent FCC approvals and targeting the roughly 500,000 square miles in the United States without ground-based coverage. On 9 February 2025, T-Mobile expanded the beta, announcing that registration was open to all consumers in the United States, including customers of other carriers, for free access through midyear. On 23 July 2025, T-Mobile moved from beta to commercial availability under the T-Satellite brand, reporting nearly two million beta participants, daily usage metrics, and performance during U.S. disasters (including delivery of wireless emergency alerts when TNs were impaired).

On 24 February 2025, AT&T and Verizon each announced satellite-to-smartphone video call milestones conducted with AST SpaceMobile's BlueBird satellites, which had been launched in September 2024. AT&T stated that it had completed a video call by satellite using an AT&T-licensed spectrum, adding that the same satellites were intended to underpin forthcoming commercial service; the company located the demonstration between Midland, TX, USA, and Dallas and framed it as a step toward extending service to rural and remote areas, as well as public safety users on FirstNet. Verizon reported that it had completed its first "satellite to cellular–enabled" video call, describing a live call between two smartphones in which one device connected via satellite and the other used Verizon's TN. Verizon tied the event to recent FCC authorization for AST SpaceMobile to test with Verizon spectrum in the United States and presented the call as a step toward a satellite-to-device layer capable of text, voice, and live video. Executive commentary emphasized the goal of adding coverage and reliability in places where terrestrial service was unavailable. Taken together, the operators' own disclosures indicated progression from proofs of concept to operator-branded demonstrations performed on licensed mobile spectra and interworked with each carrier's core network, an incremental but meaningful move toward packaging direct-to-device satellite access as a complement to terrestrial coverage in future service offers.

On 28 April 2025, Rakuten Group reported that Rakuten Mobile and AST SpaceMobile successfully conducted what it described as the first broadband video call in Japan between standard, unmodified smartphones using an LEO satellite. The demonstration was presented at a press conference, where a live video call linked Fukushima Prefecture and Tokyo. Rakuten framed the event as evidence that satellite links to ordinary handsets can support data-intensive applications (such as video streaming and social media) and noted that the satellite antenna employed is described as up to approximately thirty-six times larger than competitors' implementations. The company also referenced plans for a forthcoming "Rakuten SAIKYO Satellite Service." From an NTN perspective, the trial positioned handset-grade LEO connectivity as a complement to terrestrial coverage in Japan, moving beyond basic messaging trials toward real-time video capability on everyday devices.

White Papers on 6G NTNs

In April 2024, the 6G-NTN project announced a white paper titled "Vision on Non-Terrestrial Networks in 6G systems (IMT-2030)" that explores the future of connectivity in the 6G ecosystem, the next generation of wireless communication technology [3]. It provides a consolidated view on the importance of NTNs in 6G, identifying market segments, connectivity scenarios, and general design principles for NTN integration. It also proposes a standardization approach to ensure seamless integration and enhanced connectivity for users. The white paper distinguishes three demand profiles and the service cases that follow from them. On the demand side, it notes that consumers using smartphones and wearables look for extended coverage and seamless movement between satellite and TNs; enterprises operating in rural or underdeveloped areas need connectivity where terrestrial options are absent; and certain verticals, such as aviation, railways, and government, prioritize autonomy, security, and sovereignty. On the service side, it outlines NTN options that include direct access for smartphones and wearables (including light indoor and in-vehicle use); broadband for land vehicles; broadband links for uncrewed aerial vehicles used in observation and communications; low-latency access for homes and small offices; high-speed connectivity on transport platforms to support operational assistance and passenger entertainment; and rapid, temporary deployments for utilities and public safety operations.

In February 2025, Open Radio Access Network Alliance (O-RAN) published a white paper that provides an overview of the integration of network architecture and a 3GPP NTN, detailing their significance, current status, future challenges, and security considerations [4]. The paper frames satellites as an extension of the open RAN fabric rather than a bolt-on and explicitly targets both transparent (bent-pipe) and regenerative (onboard gNodeB, gNB) payloads. The white paper notes that O-RAN must "accommodate such NTN-specific interfaces" and expose satellite parameters (ephemeris, beam footprints, power, and delay control) to the service management and orchestration and RAN intelligent control (RIC) so automation apps can make decisions. The authors stress that the position of O-RAN nodes and controllers has to be chosen with the satellite path delay in mind, especially the timing of near-real-time RIC control loops versus LEO/GEO round-trip delays. That guidance is paired with reference topologies that map 3GPP's Next Generation RAN NTN diagrams onto O-RAN entities owned by MNOs and satellite network operators.

In February 2025, 5G Americas released a white paper titled "New Developments and Advances in 5G and Non-Terrestrial Networks" that sets out how space systems can supplement terrestrial 4G/5G coverage and evolve toward deeper integration as the industry approaches the 6G era [5]. It explains that the satellite industry, working with the 3GPP ecosystem, can extend coverage and public safety reach while commercial architectures and partnerships mature. It also frames the near-term business context, citing a total addressable market for wholesale satellite partnerships that could exceed US$28 billion by 2030. 5G Americas characterizes today's activity as supplementary coverage from space (including the U.S. supplemental coverage from space framework) rather than full 3GPP NR-NTN. Initial offers are expected to prioritize coverage enhancement and emergency services (e.g., E911 and wireless emergency alerts) while constellations scale. Early phases will include intermittent coverage because satellites move and hand over beams, and capacity will be constrained by constellation size and Earth station placement. The paper underscores that as of early 2025, "there are no 3GPP NR NTN systems in existence today and probably will not be for at least a few years," so supplementary services proceed on parallel regulatory and technical tracks.

In February 2025, ESA published a white paper [6] titled "Topology Semantic Routing for Mega-Constellations" that asks a pragmatic question: How should routing work when thousands of satellites form a moving, multiorbit fabric that changes faster than conventional protocols can converge? Its answer is a new control concept, topology semantic routing, that blends precomputed knowledge of "what links could exist" with lightweight, local decisions about "what links exist now," so the network stays stable without constant global resignaling. This white paper introduces "topology semantic routing," which blends precomputed knowledge of potential links and time-repeating orbital patterns with lightweight, local decisions so the network avoids constant, system-wide resignaling. It argues that centralized preplanning is useful but must be complemented by on-board local adaptation, given minute-scale dynamics, weather-dependent feeder links, and limited satellite compute. This white paper details practical uses (fast reroute on failures, weather-aware feeder handovers, and interlayer forwarding) and sets a staged path to validation via large-scale emulation and cross-layer integration with 5G service intents. It concludes that a semantic control layer can make satellite meshes behave like another access within TNs for 6G NTNs, trading occasional suboptimal paths for stability, lower overhead, and manageable interworking.

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FROM THE EDITOR *(continued from page 3)*

As usual, I hope that you enjoy reading the articles, columns, and various IEEE Vehicular Technology Society news in this issue. Please do not hesitate to send us your feedback, and consider contributing your work to the magazine.

Appendix: Related Articles

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