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Toward Globally Connected Vehicles: A Technical Analysis of NTN-V2X Integration, Security, and Standardization

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Abstract

The realization of globally connected and Automated Vehicles (CAVs) demands ubiquitous, reliable and secure Vehicle-to-Everything (V2X) communication. While 5G NR-V2X establishes a robust terrestrial foundation, critical coverage gaps persist in remote, rural, maritime, and disaster-affected areas. This paper presents a comprehensive technical and standardization-focused framework for integrating Non-Terrestrial Networks (NTNs), satellite constellations and High-Altitude Platform Stations (HAPS), into a Space-Air-Ground Integrated Network (SAGIN) for global V2X services. The paper does a comparative analysis of the evolution of V2X technology from IEEE 802.11p to 5G NR-V2X with explicit mapping of normative capabilities against unresolved NTN-V2X A technical analysis of the SAGIN architecture aligned with 3GPP TS 38.821 and O-RAN Alliance specifications, including standardised interface definitions and NTN handover signalling flows, while also highlighting a comprehensive security threat paradigm for Open RAN-based NTN-V2X systems, with countermeasures linked to 3GPP TS 33.501/33.536, ETSI TS 102 941, O-RAN WG11, and NIST FIPS 203–205 post-quantum standards. a concrete 3GPP Release 20 and 6G standardization roadmap with actionable work items addressing identified gaps is proposed.

Introduction

The global deployment of Intelligent Transportation Systems (ITS) and Connected and Automated Vehicles (CAVs) is fundamentally dependent on reliable, low-latency, and secure V2X communication for safety-critical functions, including cooperative collision avoidance, platooning, and remote driving, with 3GPP TS 22.186 [1] mandating latencies below 3 ms and reliability exceeding 99.999% for the most demanding eV2X scenarios [2]. Although the 3GPP C-V2X standard family of LTE-V2X (Release 14) through 5G NR-V2X (Releases 16–18) has established a robust terrestrial foundation, it remains constrained by the physical reach and economic viability of ground infrastructure. Persistent coverage gaps in remote highways, rural areas, maritime routes, and areas struck by calamity pose significant challenges for cooperative communication, data sharing, and remote driving applications that require constant connectivity, regardless of location.

Non-Terrestrial Networks (NTNs), comprising LEO, MEO, and GEO satellites and HAPS, offer a paradigm-shifting solution through their inherent broadcast capability, geographical ubiquity, and resilience against terrestrial infrastructure failures. LEO constellations at 500–1200 km altitude deliver 5-40 ms RTT, particularly relevant for latency-sensitive V2X services. The 3GPP recognised this transformative potential, initiating NTN feasibility studies in Release 15 and progressively incorporating direct access capabilities in Releases 18 and 19 (5G-Advanced). However, NTN integration creates a multi-domain SAGIN demanding solutions for propagation latency, Doppler shifts up to ±100 kHz at Ku-band, complex multi-domain mobility management, and dynamic spectrum coexistence. Critically, no 3GPP release through Release 19 defines a unified NTN-V2X service architecture. The transition to Open RAN further expands the cybersecurity attack surface, open interfaces (A1, E2, O1) introduce threats, including compromised xApp/rApp modules and AI model poisoning, while NTN assets introduce satellite signal jamming and long-lifecycle cryptographic vulnerabilities not addressed in current standards.

This paper presents a comprehensive technical and standardisation-focused analysis of NTN-V2X integration within a Space-Air-Ground Integrated Network (SAGIN), emphasising the complementary roles of satellite constellations, HAPS, and Open RAN in enabling globally connected and automated vehicles. We analyse the evolutionary trajectory of V2X standards from IEEE 802.11p through 5G NR-V2X, and map normative capabilities against unresolved standardisation gaps across 3GPP Releases 14–19. We then propose a technically grounded SAGIN architecture aligned with 3GPP TS 38.821 and O-RAN Alliance specifications, followed by a multi-layered

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Parameter	802.11p	LTE-V2X	5G NR-V2X	6G-V2X†
Data Rate	27 Mb/s	100 Mb/s	1 Gb/s	10 Gb/s+
Latency	20–100 ms	20–100 ms	3–10 ms	<1 ms
Reliability	90–95%	95–99%	99.9–99.999%	>99.9999%
Range	300–1000 m	500 m+	1000 m+	Adaptive
Mobility	250 km/h	250 km/h	500 km/h	1000 km/h+
Positioning	GNSS	GNSS	0.5 m*	0.1 m

TABLE 1. Performance Comparison of V2X Technologies (6G-V2X targets from [4]).

security framework anchored to 3GPP TS 33.501/33.536, ETSI TS 102 941, and NIST FIPS 203–205 post-quantum standards. Finally, we identify critical standardisation gaps and propose four concrete work items to guide 3GPP Release 20 and 6G toward a unified NTN-V2X service architecture.

V2X Communication Fundamentals and Evolution

Technology Analysis and Performance Benchmarks

V2X communications have evolved through two primary technological families with fundamentally different architectural philosophies. IEEE 802.11p/DSRC operates in the 5.9 GHz ITS band using a distributed CSMA/CA protocol for direct V2V and V2I communication. While technically mature and characterised by low signalling overhead, its performance degrades significantly in dense scenarios due to the hidden-node problem and the lack of coordinated resource allocation. Its long-term evolutionary path remains unclear, complicating integration with 3GPP-based NTN ecosystems. Security relies on the IEEE 1609.2 standard for certificate-based authentication, which faces scalability challenges in large-scale deployments.

3GPP C-V2X, introduced in Release 14, provides two complementary interfaces: the Uu interface for networkmanaged V2N communication, and the *PC5* sidelink for direct V2V/V2I/V2P communication. The PC5 interface supports Mode 3 (network-scheduled) and Mode 4 (autonomous, SB-SPS-based) resource allocation. Mode 4's Sensing-Based Semi-Persistent Scheduling (SB-SPS) mechanism allows vehicles to autonomously reserve radio resources without cellular network coordination, enabling safety communications outside terrestrial coverage and making it crucial for NTN-V2X scenarios with intermittent connectivity. LTE-V2X PC5 consistently achieves end-to-end latencies averaging 19 ms for typical Cooperative Awareness Message (CAM) sizes, meeting Day-1 safety requirements [3]. The transition to 5G NR-V2X (Release 16) introduced carrier aggregation up to 400 MHz, mmWave operation to 52.6 GHz, and URLLC achieving 3 ms latency with 99.999% reliability. NR sidelink Mode 2 incorporates partial sensing and configured grants, improving reliability in high-density scenarios and enabling sensor sharing; collective perception via Collective Perception Messages (CPM); and high-density platooning, which requires substantially higher data rates than basic safety messages. Finally, a comparative analysis of V2X technologies is presented in Table 1 based on different parameters.

Standardization Status by 3GPP Release

Release 14 (2017) normatively defined LTE-V2X in TS 22.185/36.300/36.321 including Mode 3 and Mode 4. Release 15 initiated NTN feasibility (TR 38.811) without normative NTN-V2X output. Release 16 (2020) specified NR-V2X use cases in TS 22.186 and NR sidelink Mode 1/2 in TS 38.300/38.321. Release 17 (2022) produced the first normative NTN specifications, TS 38.300 and TR 38.821, defining transparent and regenerative NTN deployment models and timing advance adaptations per TS 38.213. Release 18 (2024) produced normative UE-to-satellite direct access specifications with enhanced HARQ timing. *As of Release 19 (2025–2026), no dedicated NTN-V2X work item exists:* NTN and V2X enhancements proceed as separate tracks, leaving a unified NTN-V2X service architecture, cross-domain QoS, and integrated mobility management unresolved. This paper's proposals in the "Advanced NTN Architecture and AI-Native Integration," "Technical Challenges and Mitigation Strategies," "Security Framework for Open and Integrated NTN-V2X," and "Standardisation Roadmap and 6G Implementation Timeline" sections are designed to inform 3GPP SA2, SA3, RAN2, and O-RAN WG3 work items for Release 20.

Enhanced Spectrum and Regulatory Analysis

A critical, often constraining factor in global V2X deployment is the heterogeneous and fragmented regulatory landscape governing spectrum allocation. In the United States, the FCC has allocated 75 MHz in the 5.9 GHz band (5.850–5.925 GHz) for ITS services, while the European Union has designated similar spectrum through ETSI standards. A significant portion of future V2X services is expected to occur on New Radio Unlicensed (NR-U) spectrum via private networks, particularly for localised deployments. Licensed public spectrum is also available but is typically auctioned, creating risks of monopolisation and limiting bandwidth for smaller operators. This fragmented regulatory environment presents substantial challenges for designing globally consistent NTN-V2X services that require harmonised spectrum for seamless cross-border operation, a particular concern for satellite systems with inherently international footprints. Recent 3GPP and ITU-R developments are working toward greater harmonisation aligned with Resolution 241, but significant disparities remain that must be addressed through international cooperation and flexible software-defined radio implementations [5]. Hybrid positioning and location-based service continuity across terrestrial and satellite domains further compound these challenges [6].

Advanced NTN Architecture and AI-Native Integration

SAGIN Framework With Multi-Orbit Coordination

The ultimate vision for ubiquitous V2X connectivity is a multi-tier SAGIN that leverages the complementary strengths of heterogeneous network segments through intelligent coordination:

- **Space Segment (GEO/MEO/LEO Satellites):** GEO satellites (≈36 000 km) provide stable coverage for broadcast services with 240–280 ms RTT. MEO satellites at 8,000–20 000 km balance coverage and latency (70–120 ms RTT). LEO constellations at 500–1200 km with 90–120 minute orbital periods deliver 5–40 ms RTT essential for interactive V2X services, though requiring complex handover management due to rapid movement relative to Earth's surface.
- **Air/Aerial Segment (HAPS/UAVs):** HAPS at ≈20 km altitude offer quasi-stationary coverage over 100–200 km diameters and host substantial edge computing resources, serving as intermediate nodes to reduce latency. UAVs offer more flexible but lower-endurance deployment for temporary events or emergency response.
- **Ground Segment (Terrestrial 5G/6G, RSUs):** Delivers ultra-high capacity, reliability, and lowest latency in urban cores and along highways, remaining the primary bearer for sub-10 ms cooperative manoeuvres. Roadside Units (RSUs) with dual PC5/Uu interfaces serve as critical anchors between terrestrial and non-terrestrial networks.

Standardized Interface Architecture

The SAGIN control plane is anchored to 3GPP TS 23.501 and NTN-specific adaptations in TS 38.300/TR 38.821, which define two normative deployment models. In the **Transparent (Bent-Pipe)** model, the satellite relays NR Uu signals to a ground-based gNB; the TA mechanism per TS 38.213 §4.2 is extended for delays up to 272 ms (GEO) and 40 ms (LEO), and HARQ windows are adapted per TR 38.821 §5.3. In the **Regenerative** model, the satellite hosts a full gNB-DU (TS 38.473), with the F1 interface running to a terrestrial gNB-CU, enabling on-board scheduling and reduced over-the-air latency. For the O-RAN layer, the Near-RT RIC communicates with O-DUs via the E2 interface (O-RAN.WG3.E2AP-v03.00), the Non-RT RIC exchanges AI/ML policy guidance via A1 (O-RAN.WG2.A1-v05.00), and O1 (O-RAN.WG10.O1) provides configuration and fault management. No NTN-specific E2 Service Model (E2SM) currently exist;, E2SM-KPM, E2SM-RC, and E2SM-NI expose no NTN parameters (satellite ephemeris, beam footprint, NTN TA state). A new O-RAN WG3 NTN-V2X E2SM work item is a mandatory prerequisite for the xApp-based management architecture described below.

NTN Handover Signaling

NTN handover follows the Conditional Handover (CHO) framework of TS 38.331 §5.3.5.7, adapted to use satellite ephemeris data instead of UE-measured RSRP. The Near-RT RIC Mobility Management xApp computes the predicted time-to-handover T_{HO} from satellite beam boundary crossing time; at $T_{HO} - \Delta$, an E2 CONTROL message initiates CHE criteria preparation; the UE autonomously executes handover upon meeting the trigger condition, eliminating a full NTN round-trip (≤40 ms LEO) from the critical path, essential for sub-10 ms V2X service continuity per TS 22.186.

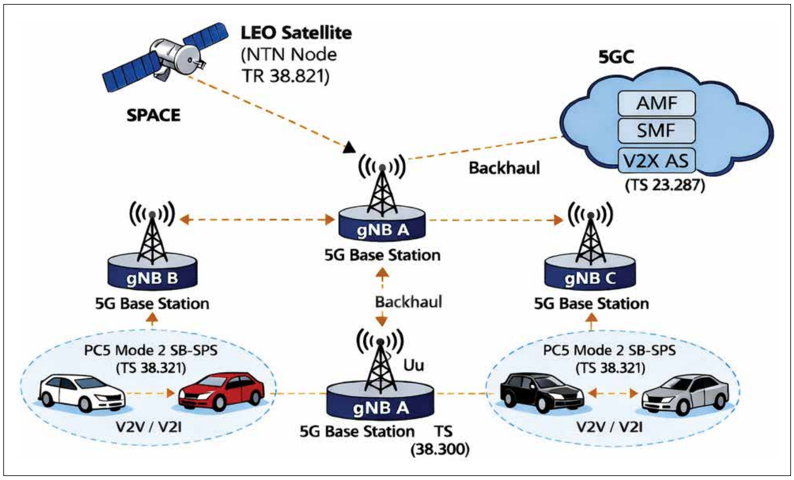

FIGURE 1. Vehicular Communication Scenarios in a Hybrid Terrestrial NTN SAGIN. Base Stations A–C are 5G gNBs (Uu interface, TS 38.300). Dashed circles: PC5 Mode 2 SB-SPS sidelink zones (TS 38.321). Satellite: LEO NTN node (TR 38.821). Cloud: 5GC (AMF, SMF, V2X AS per TS 23.287).

AI Open RAN Integration for Dynamic SAGIN Management

O-RAN's hardware/software disaggregation, open standardised interfaces, and RAN programmability are key enablers for managing SAGIN complexity and scalability [7]. The Non-RT RIC (timescale >1 s) hosts rApps for long-term mobility prediction, traffic forecasting, and AI/ML model training for capacity planning. The evolution towards 6G NTN-V2X systems will be heavily influenced by AI-driven technologies and standardization roadmaps, as highlighted in recent studies on AI-empowered satellite-based NTNs in 6G [15]. The Near-RT RIC (10 ms to 1 s) hosts three critical xApps for NTN-V2X:

- **Mobility Management xApp:** Orchestrates seamless handovers between terrestrial and non-terrestrial nodes using vehicle trajectory predictions, satellite ephemeris data, and network load conditions.
- **Cross-Domain Scheduler xApp:** Dynamically allocates radio resources across terrestrial and NTN segments based on real-time demand, V2X service priority, and link conditions.
- **Beam Management xApp:** Optimises satellite beamforming and steering parameters for high-mobility vehicular users, compensating for Doppler effects and signal blockage.

This AI-native, software-defined approach allows the network to dynamically adapt to the rapid movement of LEO satellite cells (velocities up to 7.5 km s^{-1}), fluctuating vehicular density, and diverse V2X QoS requirements. Fig. 1 illustrates the multi-segment vehicular communication topology. Terrestrial gNBs (Base Stations A–C) provide V2I via the Uu interface (TS 38.300); PC5 sidelink zones use Mode 2 SB-SPS (TS 38.321); the LEO satellite provides supplemental V2N backhaul for inter-cell gaps (TR 38.821 Earth-Fixed Cell scenario, §5.4); and the 5GC (AMF, SMF, V2X AS per TS 23.287) anchors all segments.

Technical Challenges and Mitigation Strategies

Advanced Latency Management and Protocol Adaptation

NTN propagation delays (5-40 ms RTT (LEO), 240-280 ms RTT (GEO)) directly challenge the 10 ms URLLC target of TS 22.186. Traditional terrestrial protocols require significant adaptation across four strategies:

- **Latency-Aware HARQ:** Standard HARQ feedback timelines become impractical over GEO links. Solutions include extending HARQ feedback windows (TS 38.321, Release 18), employing asynchronous HARQ processes, or transitioning to ARQ with forward error correction for GEO while maintaining standard HARQ for LEO and terrestrial links.
- **Edge Computing Deployment:** Lightweight containerised applications on regenerative satellite payloads perform basic safety message filtering and aggregation. Substantial HAPS-based edge computing handles localised cooperative perception processing, while ground-based MEC servers manage complex intersection coordination and HD map updates.
- **Predictive Forwarding and Caching:** Non-RT RIC AI algorithms analyse vehicle trajectories, traffic patterns, and historical data to proactively disseminate safety alerts, map updates, and traffic conditions via satellite broadcast before vehicles enter potentially disconnected zones.
- **Hybrid Multi-Connectivity:** Vehicles maintain simultaneous connections to multiple network segments, terrestrial links for sub-10 ms critical events (emergency braking per TS 22.186) and NTN links for non-time-critical data and safety-message backup, supported by Multi-RAT Dual Connectivity (MRDC, TS 37.340).

Doppler Compensation and Advanced Beam Management

LEO satellite velocities (≈7.5 km s^{-1}) induce severe, continuously varying Doppler shift during a satellite pass. The maximum shift is:

$$f_d = \frac{v \cdot f_c}{c} \cdot \cos\theta , \tag{1}$$

where v is the relative velocity, f_c the carrier frequency, c the speed of light, and θ the elevation angle between the satellite velocity vector and the satellite-to-vehicle line of sight. At Ku-band (f_c = 12 GHz, $\theta = 0$), f_d exceeds ±100 kHz, far beyond the sub-kHz Doppler tolerance of terrestrial NR systems. Mitigation strategies include:

- **Predictive Beam Steering and Handover:** Near-RT RIC xApps utilise precise satellite ephemeris data, vehicle GNSS information, and digital terrain models to predict beam handover timing, enabling network-initiated make-before-break handovers transparent to vehicular applications.
- **Multi-Layer Beamforming:** Advanced phased-array antennas support wide beams for initial access and signalling, and narrow high-gain beams for data transmission to specific vehicles or highway segments, with dynamic beam shaping adapting to vehicle density patterns.
- **UE and Network-Side Pre-Compensation:** Using known satellite trajectory and vehicle GNSS data, the majority of the Doppler shift is pre-compensated at the transmitter (satellite/gNB). Residual Doppler is corrected via enhanced reference signals and tracking loops in the vehicular modem.

Spectrum Coexistence and Dynamic Sharing Mechanisms

Coexistence of IEEE 802.11p and C-V2X on shared or adjacent channels is a critical challenge for interference management, as mutual interference can degrade safety-critical communications. Investigated mechanisms include [8]:

- **Preamble-Based Detection:** Inserting an IEEE 802.11 p-compliant preamble at the start of LTE-V2X or NR-V2X transmissions allows 802.11pdevices to detect the channel as busy via their CCA mechanism and defer access, reducing collisions without modifying the 802.11p protocol stack.
- **Cross-Technology Sensing:** V2X devices sense both C-V2X and 802.11p transmissions and make intelligent channel access decisions based on the combined system activity.
- **Network-Coordinated Sharing:** A centralised spectrum controller xApp in the Near-RT RIC dynamically allocates

Challenge	NTN-Specific Causes	Mitigation Strategies
Propagation Latency	LEO: 600–2000 km; GEO: 36 000 km. Violates 10 ms URLLC target, degrades TCP and control loops.	Adaptive HARQ, regenerative payload edge computing, predictive caching, protocol splitting.
Doppler Effects	LEO velocity: 7.5 km/s; CFO ±100 kHz at Ku-band; synchronisation loss; BER increase.	Ephemeris-based pre-compensation, enhanced reference signals, adaptive phase tracking, SCS adaptation.
Mobility Mgmt.	LEO orbital period: 90–120 min, beam speed: 7 km/s; frequent handovers and signaling overhead.	AI/ML predictive CHO via RIC xApps, multi-satellite connectivity, trajectory-based resource reservation.
Link Blockage	Elevation variation, urban canyons, rain fade; intermittent connectivity and packet loss.	Multi-satellite macro-diversity, HAPS integration, V2V relaying, adaptive MCS.
Time Sync.	TN-NTN timing mismatch; satellite motion affects TA; OFDM symbol misalignment and interference.	GNSS-assisted sync, ephemeris-based TA correction, enhanced NTN timing advance.

TABLE 2. NTN-V2X Technical Challenges and Mitigation Strategies.

time-frequency resources between V2X technologies based on traffic loads and QoS requirements.
- **Dynamic Spectrum Sharing (DSS) Extension:** DSS techniques developed for 4G/5G coexistence are extended to manage spectrum between V2X technologies, with network guidance provided via the Uu interface. Finally, Table 2 focuses on NTN-specific causes and mitigation strategies for different challenging parameters.

Security Framework for Open and Integrated NTN-V2X

Standards Landscape

The security architecture for terrestrial 5G V2X relies on complementary specifications across multiple bodies. 3GPP TS 33.501 defines the 5G security architecture including 5G-AKA authentication and the N3IWF framework for non-3GPP (including satellite) access security. 3GPP TS 33.536 specifies V2X authorisation, VCF roles, and pseudonymous credential management for vehicle privacy. ETSI TS 102 940/103 097 defines the ITS Security Architecture and secure message format, while ETSI TS 102 941 specifies the C-ITS Trust Model certificate management protocols. O-RAN WG11 has published O-RAN. WG11.Security-Req-v05.00 and O-RAN.SFG. Threat-Model-v04.00 provides xApp sandboxing requirements and a structured threat taxonomy. A critical gap exists as No joint 3GPP SA3 or ETSI TC ITS work item defines a unified security architecture for NTN-assisted V2X, leaving the satellite relay trust model, cross-domain authentication, and NTN-specific cryptographic adaptations unresolved.

Threat Analysis in O-RAN-Based NTN-V2X Systems

The O-RAN RIC framework, particularly its xApp/rApp ecosystem, introduces critical attack vectors beyond traditional monolithic RAN deployments:
- **Compromised xApp/rApp:** Malicious modules can issue shutdown commands to E2 nodes, causing DoS, manipulate handover decisions to steer vehicles toward malicious cells, degrade QoS via scheduling manipulation, and exfiltrate sensitive network or user data through standardised interfaces.
- **Interface-Based Attacks:** Open interfaces (A1, E2, O1, Open Fronthaul) expand the attack surface. The E2 interface is vulnerable to man-in-the-middle attacks that modify control messages; the A1 interface can be exploited to inject malicious policies, causing gradual performance degradation.
- **AI/ML Model Poisoning:** Adversaries can poison RIC training data or manipulate model updates, causing suboptimal or harmful network behaviour, e.g., a poisoned mobility prediction model triggering premature handovers or connection drops.

Threat Vector	Impact on V2X	Countermeasures	Relevant Standards	Standardization Gap
Satellite Signal Jamming	Wide-area DoS; safety message disruption over large geographic areas	FHSS/DSSS; phased-array spatial nulling; multi-constellation fallback	ITU-R RR No. 15; 3GPP TS 33.501 §6.11; ETSI EN 303 413	No NTN-specific anti-jamming for V2X sidelink; jammer-detection xApp not standardized
GNSS Spoofing	Position manipulation; false alerts; erroneous TA causing OFDM interference	Multi-GNSS; Galileo OSNMA ICD v1.1; 5G positioning (TS 38.305); cryptographic GNSS	3GPP TS 33.501 §9.10; ETSI TS 103 097; ESA OSNMA ICD v1.1; TS 38.305	No GNSS-spoofing protection in ETSI TS 102941 for NTN; NTN-V2X positioning unspecified
False Data Injection (Sybil)	Fake safety messages; induced emergency braking; collision induction	Pseudonymous signatures (TS 102 941); behavior plausibility checks; MBDR (TR 103 460)	ETSI TS 102 941; TR 103 460; 3GPP TS 33.536; IEEE 1609.2a	MBDR reporting undefined for NTN-relayed V2X; revocation via satellite broadcast not standardized
O-RAN xApp/rApp Compromise	Handover manipulation; DoS; data exfiltration via E2/A1 interfaces	xApp security certification; TEE-based runtime attestation; microsegmentation; zero-trust	O-RAN WG11 Security-Req-v05.00; O-RAN.SFG. Threat-Model-v04.00; NIST SP 800-190; TS 33.501	No mandatory TEE attestation for xApps; NTN gateway security in xApp control loops not addressed
Post-Quantum Obsolescence	Retrospective decryption; long-term compromise of 15+ yr satellite key material	NIST PQC (FIPS 203/204/205); hybrid ECC+ML-KEM; crypto agility in V2X cert profiles	NIST FIPS 203/204/205 (2024); ETSI GS QKD 014; 3GPP TR 33.848 (study)	No normative PQC specification in 3GPP SA3; V2X certificate profiles lack PQC migration plan
Supply Chain Attacks	Persistent backdoors in satellite payloads, gNB-DUs, and vehicle OBUs	Hardware Root of Trust; secure boot; SBOM; independent third-party audits	ETSI EN 303 645; NIST SP 800-161r1; 3GPP TR 33.849; O-RAN WG11 §7	No NTN-V2X-specific supply chain standard; SBOM requirements not mandated in 3GPP/O-RAN

TABLE 3. Security Threat Matrix for NTN-V2X Systems.

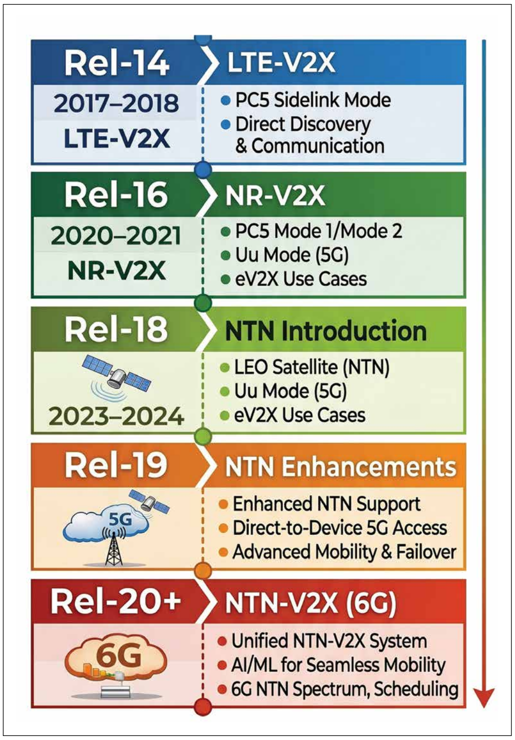

FIGURE 2. Progression of NTN-V2X from LTE to 6G across 3GPP Releases, enabling advanced mobility and seamless communication.

- **Supply Chain Vulnerabilities:** Multi-vendor disaggregation heightens the risk of compromised hardware or software components, enabling persistent backdoor access across the SAGIN [9].

Multi-Layered Defense Framework

1) Secure O-RAN Implementation: Mandatory xApp/rApp security certification covering code analysis, vulnerability assessment, and runtime behaviour monitoring; strict microsegmentation with least-privilege network access per xApp; continuous anomaly detection agents monitoring abnormal API call patterns and unauthorised data access; and secure development lifecycle enforcement for all O-RAN component vendors.

2) Cross-Domain Trust and Authentication: Federated identity management spanning terrestrial operators, satellite service providers, and vehicular credentials with blockchain-based decentralised identity solutions providing tamper-proof credentials without a single point of failure; multi-factor authentication requiring verification from both terrestrial and NTN providers for critical operations; and zero-trust principles ("never trust, always verify") with continuous authentication across all domain interactions.

3) Post-Quantum Cryptography (PQC) Readiness: The 15+ year operational lifecycle of satellite hardware makes PQC transition critically urgent for NTN-V2X. The primary applicable standards are NIST FIPS 203 (ML-KEM, key encapsulation), FIPS 204 (ML-DSA, certificate signing replacing ECDSA), and FIPS 205 (SLH-DSA, hash-based fallback), finalised August 2024. Although 3GPP TR 33.848 has analysed these candidates, no normative PQC specifications exist through Release 19. For Release 20, we recommend: (i) normative adoption of ML-KEM-768 and ML-DSA-65 in TS 33.536 and ETSI TS 102 941; (ii) a hybrid X25519+ML-KEM-768 profile for backward compatibility during fleet-wide transition; and (iii) a Cryptographic Agility Framework enabling algorithm negotiation between vehicles and the V2X Application Server without simultaneous fleet-wide firmware updates. For satellite feeder links, QKD per ETSI GS QKD 014 and GS QKD 004 should be evaluated for ground-to-satellite key bootstrapping, pending space-based QKD demonstrations.

4) AI-Driven Threat Detection and Response: Federated learning across vehicles and network nodes for privacy-preserving collaborative intrusion detection model training without sharing raw data [10]; behavioral anomaly detection learning normal network behavior patterns to identify deviations indicative of attacks (unusual handover patterns, abnormal message rates, suspicious signal characteristics); and automated RIC-integrated incident response playbooks for rapid isolation of compromised components, traffic rerouting, and authentication escalation. Moreover, a security threat matrix for NTN-V2X systems based on different parameters has been defined in Table 3.

Standardisation Roadmap and 6G Implementation Timeline

3GPP Evolution for NTN and V2X Integration

The 3GPP standardisation roadmap reflects progressive but parallel NTN and V2X enhancement tracks, though a dedicated NTN-V2X work item remains a critical future need. Fig. 2 depicts the timeline of the standardisation roadmap. Recent comprehensive roadmaps for 6G NTN-V2X [15] and industry 6G technology outlooks [11] further inform the evolution outlined below.

- **Releases 14-15 (2017-2018):** Established LTE-V2X with basic PC5 sidelink capabilities (TS 22.185) and initiated NTN feasibility studies through TR 38.811, identifying key technical challenges and defining baseline deployment scenarios.
- **Releases 16-17 (2020–2022):** Defined advanced NR-V2X use cases and service requirements in TS 22.186, introducing eV2X services. Release 17 completed the first normative NTN specifications for 5G systems (TR 38.821), including transparent and regenerative deployment models.
- **Release 18 (5G-Advanced, 2024):** First comprehensive normative specifications for direct NTN access, adapting initial access, random access, HARQ timing, and timing advance procedures for satellite propagation delays. Enhanced support for high-speed mobility relevant to vehicular users.
- **Release 19 (2025-2026):** Focuses on regenerative payload operation with on-board processing, improved intra-NTN mobility, enhanced network slicing for integrated terrestrial-NTN services, satellite-based positioning enhancements, and further NTN latency reductions.
- **Release 20+ (6G Start, 2028+):** Expected to formally integrate NTN-V2X as a dedicated

NTN-V2X Challenge	Status	Relevant Specification(s)	Responsible Body	Recommended Action (Rel-20+)
NTN Timing Advance for V2X Safety Messaging	Partial	TS 38.213; TR 38.821 (generic NTN TA)	3GPP RAN2	V2X-specific TA optimization for Mode 2 sidelink (new WID)
Cross-Domain V2X Identity & Trust	Not Addressed	TS 33.536; ETSI TS 102941 (terrestrial only)	3GPP SA3 + ETSI TC ITS	Joint SA3/TC ITS study on NTN relay trust chain
NTN-V2X E2 Service Model (O-RAN)	Not Addressed	O-RAN.WG3.E2AP (no NTN-V2X E2SM defined)	O-RAN WG3 + 3GPP RAN2	New O-RAN WG3 NTN-V2X E2SM work item
PQC for V2X Certificate Profiles	Not Addressed	3GPP TR 33.848 (study); NIST FIPS 203/204/205	3GPP SA3 + ETSI TC ITS	Normative PQC profile for TS 33.536 and TS 102941
Spectrum Harmonization—NTN+ITS Bands	Not Addressed	ITU-R Resolution 241 (IMT-2030)	ITU-R WP 5D + WP 5A	Joint ITU-R study on NTN-ITS spectrum coexistence
Cross-Domain QoS for V2X over NTN	Not Addressed	3GPP TS 23.501; TS 22.186	3GPP SA2 + SA5	New SA2 WID: NTN-V2X QoS flow mapping architecture
Misbehavior Detection Reporting via NTN	Not Addressed	ETSI TR 103 460 (terrestrial MBDR only)	ETSI TC ITS WG5	NTN-relay MBDR reporting protocol extension
NTN Handover Optimized for V2X Latency	Partial	TS 38.331 CHO (generic NTN, Rel-17)	3GPP RAN2 + RAN3	V2X latency-aware CHO trigger conditions and E2SM KPI definitions

TABLE 4. NTN-V2X Standardization Challenges and Recommended Actions (Release 20+).

work item, defining end-to-end service architectures, cross-domain QoS, seamless mobility procedures, and standardised cross-domain management APIs, with native NTN integration as a fundamental 6G design principle [11], [15].

Release 20 and 6G Standardisation Work Item Recommendations

Based on the gap analysis in Table 4 and technical challenges in the "Advanced NTN Architecture and AI-Native Integration," "Technical Challenges and Mitigation Strategies," and "Security Framework for Open and Integrated NTN-V2X" sections, we propose four concrete work items for 3GPP Release 20:

NTN-V2X Service Architecture (3GPP SA2): Define end-to-end V2X service architecture delivered via NTN, including QoS flow establishment and mapping across N2/N3 interfaces for NTN access nodes, NTN-specific PDU session handling, and cross-domain mobility management. *Scope:* Extension of TS 23.287 and a new TR for NTN-V2X service requirements.

NTN-V2X Security Profile (3GPP SA3 + ETSI TC ITS): Define authentication/authorisation for vehicles via NTN relay nodes, satellite relay trust chain model, NTN-adapted pseudonymous certificate lifecycle, and PQC algorithm selection (ML-KEM-768 for key agreement, ML-DSA-65 for signing, per NIST FIPS 203/204). *Scope:* New TR leading to amendments of TS 33.536 and ETSI TS 102941.

NTN-V2X Radio Protocol Enhancements (3GPP RAN2): Specify optimised Mode 2 sidelink resource management and TA procedures, V2X-aware CHO trigger conditions, and HARQ configurations for NTN satellite links used for V2X safety message delivery. *Scope:* Amendments to TS 38.321 and TS 38.331.

NTN E2SM for V2X (O-RAN WG3 + 3GPP RAN2): Define E2SM-NTN-V2X exposing satellite ephemeris data, beam footprint position, NTN TA state, per-vehicle link quality metrics, and control actions (beam steering, NTN handover preparation trigger) to the Near-RT RIC, a mandatory prerequisite for the xApp architecture in the "Advanced NTN Architecture and AI-Native Integration" section.

For 6G (IMT-2030, anticipated Release 21+): (i) native unified terrestrial-NTN sidelink eliminating the PC5/Uu separation; (ii) ISAC standardized for joint NTN-based V2X positioning and communication [12]; and (iii) network digital twins as a first-class SAGIN management abstraction within the O-RAN framework.

Conclusion and Future Directions

The integration of NTNs into the V2X ecosystem represents a critical evolution toward ubiquitous, resilient, and intelligent global transportation systems. This paper has provided a technically grounded, standards-anchored analysis of SAGIN architectural frameworks aligned with 3GPP TS 38.821 and O-RAN Alliance specifications, quantitative Doppler compensation modeling, and a comprehensive multi-layered security framework for NTN-V2X convergence. While 3GPP Release 19 establishes a foundational platform, significant gaps remain in cohesive service architectures, cross-domain security profiles, and unified SAGIN management. The four proposed Release-20 work items target the most critical of these: the NTN-V2X service architecture, the security profile, radio protocol enhancements, and the O-RAN E2 Service Model.

To fully realise the potential of NTN-V2X technologies, several key research areas need to be prioritized. The following research directions are essential for the successful integration of NTN-V2X systems:

- AI-driven SAGIN orchestration for autonomous cross-domain resource management [5], [15].
- Large-scale field trials validating NTN-V2X latency and reliability under realistic vehicular mobility [13], [14].
- Privacy-preserving security architectures for disaggregated systems, including

post-quantum migration aligned with NIST FIPS 203–205.
- Dynamic spectrum sharing among NTN, C-V2X, and IEEE 802.11p in the 5.9 GHz ITS band and adjacent NR-U spectrum.
- Active contributions to 3GPP Release 20 and 6G standardization.

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