6G Vehicular Networks: Vision, Standards, and Key Enabling Technologies for the Internet of Vehicles (IoV)

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Abstract

As 5G networks become fully developed, the pressure for fully autonomous driving combined with the delivery of captivating in-vehicle experiences has revealed serious shortcomings in terms of latency, reliability, and massive connectivity. In this paper, we propose a holistic vision for the use of 6G in Vehicular Networks, thus going beyond mere communication to an “Internet of Verticals” (6G-IoV) which virtualizes and orchestrates entire industry entities. We look into the standardization landscape changes with a specific highlight on the evolution from NR-V2X Side link to 6G protocols as per the 3GPP-Releases 20 and 21. The paper delineates five major enabling technologies: Terahertz (THz) communication for exchanging ultra-high throughput raw sensor data; Integrated Sensing and Communication (ISAC) for environmental awareness headlined by “native” without dedicated sensors; Reconfigurable Intelligent Surfaces (RIS) to solve blockage via server programmable propagation in urban canyons; On Terrestrial Networks (NTN) for 3D coverage experience with LEO satellites and UAVs; and Native AI for network autonomous orchestration and federated intelligence. In the end, the paper discusses research issues in security in decentralized vehicular ledgers and the physical-layer challenges of high-mobility 6G channels.

Keywords

6G-V2X, Integrated Sensing and Communication (ISAC), Terahertz (THz), Autonomous Vehicles, Internet of Verticals (6G-IoV), 3GPP Standards, Reconfigurable Intelligent Surfaces (RIS), Non-terrestrial Networks (NTN), Federated Learning

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Introduction

The entire global telecom industry is going through a transitional phase of first magnitude as 5th generation (5G) networks come to their deployment peaks and the academic research community starts to focus on the fundamental requirements of the 6th generation (6G). 5G has brought out new service concepts: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC). However, the real-life implementation of these services in the vehicular domain has revealed structural limitations which make impossible the attainment of fully autonomous transport systems. Operations of Level 4 and Level 5 autonomous driving real-time synchronization of super-accurate digital twins and completely engaging in vehicle extended reality (XR) experiences call for a performance break that 5G architectures cannot structurally support. According to the current foresights, 6G is going to be not only a new increment in data rates but the ultimate triumvirate of communication, sensing, and intelligence, which would turn the “Internet of Vehicles” (IoV) into a comprehensive “Internet of Verticals” (IoV).”[1].

The “Internet of Verticals” (IoV) concept stands for a major development in how our network is considered: from a network that just connects devices to a network that virtualizes (creates a virtual version of) and orchestrates whole industry entities. Automotive is one of the verticals IoV applies to. It means that cars, trucks, drones, and roadside infrastructure are no longer passive endpoints (devices at the end of a network) but rather active nodes in a distributed, intelligent fabric capable of real-time environmental perception and autonomous decision-making. This vision is based on the automotive sector, i.e., “vehicular sector”. The idea is inspired by one of the main reasons behind this visionary idea is to prepare for the huge volume of data that the world will have to deal with when the data traffic will have risen to 5 zettabytes by 2030[2]. As if that was not enough, there will also be more than 17 billion mobile users worldwide. If 6G is to be able to support this huge data traffic, it will have to provide a combination of ultra-high data rates (close to one terabit per second (Tbps)), ultra-low latency (the time delay reduced to 0.1 milliseconds (ms)), and ultra-high level of reliability (a hyper-reliability threshold of 99.99999%)[3].

The transition from 5G to 6G is characterized by the introduction of several groundbreaking technological pillars. One such example is Terahertz (THz) communications, which provide an enormous bandwidth allowing the exchange of raw sensor data between vehicles. This enables “cooperative perception”, a concept in which a vehicle can “see” the environment through the other vehicles’ sensors. Integrated Sensing and Communication (ISAC) enables the network to act as a high-resolution radar system, capable of detecting passive objects such as pedestrians and debris without requiring dedicated sensing hardware. Reconfigurable Intelligent Surfaces (RIS) solve the long-standing issue of signal blockage in heavily built up urban “canyons” by making the propagation environment itself programmable. Non-Terrestrial Networks (NTN) add connectivity to the third dimension by combining Low Earth Orbit (LEO) satellites and Unmanned Aerial Vehicles (UAVs) to provide continuous coverage even in rural and isolated areas. Finally, Native Artificial Intelligence (AI) performs as the “brain” of the network, coordinating intricate resource allocation and guaranteeing security in a decentralized, autonomous setting.

This paper dissects the entire 6G vehicular environment. First, it follows the standard evolution path from the original NR-V2X specs up to the upcoming 6G protocols. Next, it studies the main core enabling technologies, their physical phenomena, the most recent experiments, and the issues each one brings. The paper goes on to discuss the AI-native main framework that is to be 6G orchestration and ends with the identification of essential research gaps in decentralized security and high, mobility channel modeling. This work is a very detailed guideline for the future intelligent transportation systems of the next generation.

Evolution of V2X Standards

Vehicle communications standardization has been a continuous effort for more than ten years mainly managed by the Third Generation Partnership Project (3GPP) and directed by frameworks set out by the International Telecommunication Union (ITU). Moving from 4G LTE-V2X to 6G is more than just a change of technologies; it is also an evolution of the nature of the messages, from very simple ones for safety to a complex, intelligent orchestration[4].

A. The Legacy of C-V2X and NR-V2X

The initial standardized cellular vehicle-to-everything (C-V2X) technology was released in 3GPP Release 14 (which was finalized in 2017). It was mainly about the first basic road safety applications with the LTE air interface[5]. One big change was the Sidelink or PC5 interface, which means that the cars can talk to each other (V2V), to the infrastructure (V2I) without the need for a base station to mediate the communication. Release 15 made these perfect by adding new features for the advanced V2X applications.

5G New Radio (NR) Release 16 introduced the "NR-V2X" standard which brought about significantly lower latency and higher reliability[6]. NR-V2X moved away from the broadcast, only character of LTE-V2X by introducing unicast and groupcast transmissions that are important for cooperative driving scenarios such as vehicle platooning. The physical layer was also changed to include flexible numerologies, which offer both sub-6 GHz and millimeter-wave (mmWave) bands by letting sub, carrier spacings be scaled between 15 kHz and 480 kHz

B. 3GPP 6G Timeline and Milestones

3GPP had officially moved from 5G to 6G research early phases by the beginning of 2025. The evolution of 3 GPP Release 18-21 for vehicular communication.

Table 1. Evolution of 3GPP Releases 18–21 for Vehicular Communications[7,8]

3GPP Release	Status/Timeline	Primary Focus for Vehicular Networks
Release 18	Finalized (June 2024)	5G-Advanced baseline; AI/ML-based techniques at the air interface; smart energy; vehicle-mounted relays.
Release 19	Underway (Target Dec 2025)	5G-Advanced Evolution; initial study items on Integrated Sensing and Communication (ISAC); AI/ML for NG-RAN.
Release 20	Starts Aug 2025	The "6G Study Phase"; 6G RAN and Core architecture studies; multi-radio spectrum sharing; technical evaluation of candidate technologies.
Release 21	Starts 2027	The "6G Normative Phase"; first set of normative 6G specifications; submission of technology proposals to ITU-R IMT-2030.

The intention is to complete the first 6G specifications by the end of 2028, thus allowing 6G commercial systems to become available in 2030. In contrast to 5G, which at first was based on non-standalone (NSA) deployments with LTE as the anchor, 6G is already planned to be a "standalone" system from the very beginning, utilizing cloud native Kubernetes-based service architectures and native AI for control loop management.

C. ITU-R IMT-2030 Framework

The ITU-R Recommendation M.2160 sets out a “Framework and overall objectives of the future development of IMT for 2030 and beyond”. It outlines a framework where the original three 5G usage scenarios are expanded to six categories which essentially describe the 6G vision[9,10]:

- Immersive Communication: Originally eMBB, the scenario now supports holographic communication and the most advanced XR.
- The Massive Communication use case: Originally mMTC, the scenario is now facilitating massive IoT with connection densities up to 10^8 devices/km^2.
- Hyper-Reliable and Low-Latency Communication (HRLLC): Originally URLLC and now ultra-precise industrial and vehicular control.
- Ubiquitous Communication: This is a brand, new scenario that puts emphasis on seamless connectivity across terrestrial and non-terrestrial layers (satellites, drones).
- Integrated Sensing and Communication (ISAC): This new scenario uses radio waves not only for communication but also to sense the physical world.
- AI and Communication: A brand-new paradigm where AI not only optimizes the communication link but also enables new intelligence, based services.

These scenarios are governed by four overarching design principles: sustainability (net-zero goals), security and resilience (zero-trust architecture), ubiquitous intelligence, and connecting the unconnected.

Key Enabling Technologies

The transition to 6G vehicular networks requires the integration of several breakthrough technologies that redefine the physical and network layers.

I. Terahertz (THz) Communications

Going beyond the Terahertz spectrum (generally from 100 GHz to 10 THz) is the main approach to bringing about the extremely high data rates that would be necessary for 6G[11]. In the case of vehicles, THz communications give enough bandwidth to “raw sensor data exchange, ” which means that vehicles can share high-definition LiDAR point clouds and 4K video feeds instantly. THz waves have incredibly short wavelengths (millimeter to sub-millimeter), which makes it possible to pack ultra-massive MIMO (UM-MIMO) arrays with thousands of antenna elements into a tiny form factor. Nonetheless, THz signals experience several harsh propagation limitations, such as[12,13]:

- High Path Loss: Free space path loss increases quadratically with frequency according to the formula $L_{\text{FSPL}} = 20\log_{10}(4\pi fd/c)$.
- Atmospheric Absorption: Water vapor, even in relatively dry conditions can cause significant absorption losses due to resonant peaks, up to 1020 dB/km.
- Molecular Absorption: Terahertz (THz) signals are absorbed when interacting with the air molecules’ rotational and vibrational states, which results in frequency, dependent attenuation.

Research by Huawei has shown that THz is suitable not only for short-range imaging but also for communication over medium distances. During the prototype demonstration in 2025, a THz terminal working at 140 GHz as the carrier frequency was able to obtain millimeter, level imaging resolution of objects concealed inside sealed boxes by using a virtual aperture MIMO array[14,15]. Also, the group made an unprecedented world record 240 Gbps outdoor data transmission over a 500 meter line of sight (LOS) link at 220 GHz, thus demonstrating that THz can be used as a high-capacity backhaul or vehicle to infrastructure (V2I) link[14,15].

II. Integrated Sensing and Communication (ISAC)

ISAC represents a major change in wireless network philosophy, where a network not only transports data but also can sense its surroundings[16]. 6G base stations and vehicles are thus able to serve as a network of radar sensors simply by sharing the same radio frequency (RF) front, end and a single waveform for communication and sensing. ISAC paves the way for numerous essential safety features[17]:

- Pedestrian and obstacle detection: Base stations can spot pedestrians hiding in the blind spots at the intersections and then warn the vehicles that are coming.
- Environmental mapping: Cars can rely on communication signals to chart the immediate vicinity of the road thus developing real, time 3D models that can be used for autonomous navigation.
- Precise localization: ISAC enables high accuracy positioning that can reach a level of a few centimeters which is more than six times the precision provided by the current GNSS in urban canyons.

NTT Corporation and Sophia University successfully demonstrated a world-first human detection using radio propagation information from existing commercial base station signals[18]. Variation in the Received Signal Strength Indicator (RSSI) through AI analysis was used to accurately estimate pedestrian counts and detect human presence without the use of cameras or dedicated sensors. This demonstrates the privacy-friendly approach of ISAC, which detects the presence of objects through radio waves instead of optical imaging.

III. Reconfigurable Intelligent Surfaces (RIS)

RIS technology is the application of programmable meta surfaces that are able to adaptively control the reflection, refraction and absorption of electromagnetic waves[19]. This way, the network can “engineer” the wireless environment, a notion that is referred to as Smart Radio Environment (SRE). Vehicular networks that use mm Wave and THz bands are extremely prone to the signal blocking by buildings, trees, and even other vehicles[20]. By using RISs on the outside walls of buildings or integrating them into the roadside infrastructure, they can serve as “smart mirrors” that can reflect the signals around the obstacles thus keeping the line-of-sight (LoS) or a good non-line-of-sight (NLoS) path. The performance of RIS depends on the joint optimization of the base station’s beamforming and the RIS phase shifts. Mathematically, the goal is often to maximize the Signal-to-Interference-plus-Noise Ratio (SINR):

$$\max_{\Phi} \text{ SINR } \text{ subject to } |\phi_m| = 1, \ \forall m \in \{1, \ldots, M\} \tag{1}$$

where Phi is the phase shift matrix of the RIS elements. Recent studies have shown that active RIS prototypes based on Liquid Crystals (LC-RIS) can achieve power gains of up to 26 dB indoors and 14 dB over 500 meters, effectively mitigating the high path loss of mmWave signals[21,22].

IV. Non-Terrestrial Networks (NTN)

6G anticipates a three dimensional (3D) multi-layered architecture that combines terrestrial base stations with non-terrestrial components such as LEO satellites, UAVs, and HAPS[23]. NTNs play a crucial role in vehicular networks to ensure continuous connectivity on long highway stretches, in maritime environments, and remote rural areas where the deployment of terrestrial infrastructure is not economically viable. LEO satellites, which revolve at an altitude of 5002, 000 km, provide low latency communication links that can be used for vehicular telemetry[24].

The very fast movement of low earth orbit (LEO) satellites at several kilometers per second as well as high-speed vehicles lead to the generation of large Doppler shifts that may adversely affect communication. Several studies have suggested conceptual frameworks for Doppler measurement and correction using linear and point estimation methods based on signal chirps[25,26]. Such research aims at increasing the duration over which communication can be maintained and enhancing overall S2V network performance.

V. Native AI for Autonomous Orchestration

The complexity of 6G vehicular networks, with their diverse layers and super-fast changes, requires an AI-native design in which intelligence is embedded at every layer of the protocol stack.

In 5G, AI is mostly a tool for optimizing the use of a few specific tasks. In 6G, AI will be the control loop of the RAN and the core lifecycle management. This shall encompass the following[27,28]:

- AI-Enhanced Physical Layer: Exploiting deep learning (DL) methodologies for channel estimation, beam management, and adaptive modulation.
- Smart Resource Allocation: Leveraging Deep Reinforcement Learning (DRL) to efficiently manage spectrum and power in a dense vehicular setting, on the fly.
- Network Slicing and Orchestration: Employing AI to develop and administer virtual network slices that are customized for different vehicular services (e.g., safety, critical vs. infotainment).

One of the privacy measures for vehicular data in 6G will be Federated Learning. This approach enables vehicles to develop machine learning models using their sensor data locally and only communicate the resulting model updates (weights) to a central server, thus raw telemetry data is not exposed outside of the vehicles.

AI-Native Architecture: Comparative KPI Analysis

The jump from 5G-V2X to 6G-V2X can be most simply understood by looking at the improvement of the Key Performance Indicators (KPIs) set by ITU-R and 3GPP (Table 2).

These figures aside the architectural progression is really about the idea of the “Internet of Verticals” where the network not only virtualizes but also federates whole vertical entities. For this, the core network has to be drastically changed to be completely (SA), cloud, native, and AI, driven right from “Day One”

Table 2. Comparative KPI Analysis: Transitioning from 5G-V2X to 6G-V2X Performance Targets[10,29]

KPI Metric	5G-V2X (IMT-2020)	6G-V2X (IMT-2030)	Improvement/ Significance
Peak Data Rate	20 Gbps	100 Gbps – 1 Tbps	Enables raw sensor sharing and holographic XR.
User Experienced Rate	100 Mbps	1 Gbps – 10 Gbps	Guaranteed performance for ultra-fast mobility.
Air Interface Latency	1 ms	0.1 – 1 ms	Crucial for remote driving and tactile internet.
Reliability	99.999%	99.99999%	Essential for Level 5 autonomous safety.
Connection Density	10^6 devices/km^2	10^7 – 10^8 devices/km^2	Supports massive IoT and smart city sensors.
Mobility	500 km/h	500 – 1,000 km/h	Support for high-speed trains and aerial vehicles.
Positioning Accuracy	1 meter	1 – 10 centimeters	Centimeter-level precision for lane-level control.
Energy Efficiency	Baseline	10x – 100x improvement	Focus on sustainable, net-zero networks.

Challenges and Future Directions

Although the 6G vision seems to be very promising, there are still many open research challenges, among which security in decentralized systems and the physical complexities of high, frequency channels are two of the most important issues.

A. Security in Decentralized Vehicular Ledgers

In 6G vehicular networks, the operations will be very decentralized where vehicles will rely more on vehicle to vehicle interactions and fog/edge nodes for their decision-making. The distributed nature of such networks brings about a complex threat landscape, which existing security frameworks cannot cope with. Vehicular networks are exposed to Sybil attacks in which one malicious car creates many fake identities to pose a threat to traffic information or voting processes. Centralized authentication systems that rely on a single authority also have problems with latency and scalability in 6G. Recent research studies unveil a blockchain, powered security architecture that unifies[30,31]:

- Adaptive Trust Evaluation: Continuously monitoring car behavior to detect the presence of any abnormal actions.
- Lightweight Proof of Trust (PoT) Consensus: A consensus layer highly optimized for high, mobility scenarios, which facilitates decision, making verification with total roundtrip times less than 20 ms.
- Smart Contracts: For the automatic implementation of the security policies and fighting of the attacks without any central control.

Due to the extremely directional nature of beams, communication employing THz and mmWave bands are naturally protected against eavesdropping. Nevertheless, the employment of RIS and the intricacy of high-frequency hardware opens the gate to novel vulnerabilities such as “pilot contamination” and beam, splitting attacks. One of the ways that research into PLS for THz-MIMO systems is carried out is by trying to get secret keys out of the unpredictable properties of the wireless channel, which is a form of security mathematically unbreakable even by quantum computers.

B. Physical-Layer Complexities of High-Mobility 6G Channels

Operating in the THz band at very high speeds (e.g., 5001, 000 km/h) results in physical-layer challenges never faced before[32]. 6G wireless networks channels are characterized by non-stationarity and unknown propagation. At THz frequencies, as a vehicle moves, the scattering and reflection features of the objects change so fast that it is necessary to do the channel estimation in real-time, which traditional static models are not able to provide.

Meetings in Tokyo shed light on the urgent need to have proactive blockage detection capabilities with the help of a spectral, domain analysis (Short, Time Fourier Transform, STFT) as the most recent research shows[33]. These blockage detection algorithms can predict a human or vehicular blockage event at least 150 ms in advance and thus giving a sufficient time for multi, connectivity to be implemented or rerouting strategies to be performed via RIS.

Conclusion

The move to 6G-based vehicular networks is a landmark event in the evolution of mobile communications that not only allows us to connect but also to form an “Intelligent Network of Everything.” This report has elaborated on the elaborate 6G-V2X vision where communication, sensing, and intelligence are integrated into a network running like a brain.

The roadmap for standardization is clear and focused, with work beginning in 2025 for Release 20 (technical study) and Release 21 (specifications) aiming for a commercial launch in 2030. The five key enablers THz, ISAC, RIS, NTN, and Native AI are major upgrades over 5G that allow, among other things, pure sensor data sharing, very precise positioning, and even coverage in the hardest of spots.

Nonetheless, there are still many impediments that need to be addressed to make the dream a reality. Security, for one, should be considered as decentralized, AI, assisted, able to defeat Sybil attacks and maintain privacy in the ultra, connected world. Physical, layer research has to come up with solutions to extreme Doppler shifts of THz transmission as well as the fluctuating characteristics of high, speed channels. While R&D teams are tackling such problems, the systems presented in this document will constitute the blueprint of a dazzling futuristic era marked by safe, green, and highly autonomous ITS.”

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