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6G-Enabled Communication Frameworks for Autonomous Vehicles in Smart Cities

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Abstract

Sixth-Generation (6G) wireless systems are expected to fundamentally transform Autonomous Vehicle (AV) communications by delivering ultra-low latency, exceptional reliability, and intelligent network management required for next-generation smart city environments. In contrast to fifth-generation (5G) networks, which face constraints in latency performance and large-scale scalability, 6G aims to achieve sub-millisecond end-to-end communication, terabit-level data rates, and reliability beyond 99.99999%, enabling extremely dense vehicular deployments. This chapter provides a detailed examination of 6G-enabled vehicle-to-everything (V2X) communication frameworks, focusing on architectural advancements, core enabling technologies, and security considerations. A hierarchical three-layer architecture is introduced that combines terahertz communications, integrated sensing and communication, AI-native network slicing, and quantum-resilient cryptographic mechanisms to support collision-free platooning, cooperative perception, and intelligent traffic coordination. The chapter further explores emerging concepts such as semantic communication, federated learning-based mobility intelligence, and edge-assisted blockchain for secure data exchange. Performance evaluations indicate substantial reductions in collision risk and significant latency improvements in dense urban scenarios. The chapter concludes by outlining open research challenges and a forward-looking roadmap toward 2030, emphasizing quantum-safe security and satellite–air–ground network convergence for resilient autonomous mobility.

Keywords: 6G wireless networks, Autonomous vehicles, V2X communication, Terahertz communication, AI-native networking, Quantum-safe security, Integrated sensing and communication

1. Introduction

The rapid increase in connected devices and the emergence of data-intensive applications—such as immersive media, advanced interactive services, and autonomous driving—are placing unprecedented demands on wireless networks. These applications require extremely high data rates, ultra-low latency, and consistent reliability, which existing 5G systems struggle to deliver, particularly under dense and dynamic operating conditions. As a result, the limitations of current wireless technologies have become increasingly evident, motivating the transition toward sixth-generation (6G) networks capable of supporting future communication requirements [1].

Within this context, autonomous vehicles have emerged as a cornerstone of next-generation intelligent transportation systems. By enabling automation and cooperative driving functions such as platooning and coordinated maneuvers, autonomous mobility promises improved road safety, smoother traffic flow, reduced energy consumption, and more sustainable transportation. However, realizing these benefits depends on the availability of communication infrastructures that can support real-time, ultra-reliable interactions among vehicles, roadside infrastructure, pedestrians, and cloud platforms. In dense urban environments, high mobility, rapidly changing network topologies, and diverse service demands further challenge network performance, underscoring the need for advanced 6G-enabled communication solutions [3], [6].

Sixth-generation (6G) wireless networks are widely regarded as a fundamental technological enabler for achieving fully autonomous mobility at scale. Building upon the foundations of 5G, 6G introduces transformative innovations in spectrum utilization, network intelligence, and security design. The use of terahertz (THz) frequency bands enables unprecedented data rates and ultra-low latency, supporting high-resolution sensor data exchange and real-time cooperative perception among vehicles. At the same time, AI-native network control allows dynamic resource allocation, predictive mobility management, and self-optimizing network behavior tailored to highly dynamic vehicular environments. Furthermore, sensing-aware networking capabilities enable tighter integration between communication and environmental awareness, improving reliability and situational understanding. Through these advancements, 6G is expected to address the limitations of existing systems and enable seamless, large-scale deployment of autonomous vehicles within future smart city ecosystems [2], [11].

1.1 Evolution from 5G to 6G V2X

Fifth-generation (5G) V2X communication marked a significant milestone in vehicular networking by introducing ultra-reliable low-latency communication (URLLC) and sidelink-based direct links between vehicles and nearby infrastructure. These capabilities enabled the deployment of early autonomous driving functions, including forward collision alerts, emergency braking assistance, and cooperative adaptive cruise control. Despite these advances, 5G systems still exhibit end-to-end latency typically in the range of 1–5 ms, with reliability levels close to 99.999%, which are not sufficient for fully autonomous Level 5 driving scenarios. In such scenarios, vehicles are required to make instantaneous, safety-critical decisions without any human involvement, leaving minimal tolerance for communication delays or packet loss [4], [5]. Additionally, the limited bandwidth available in 5G networks restricts the continuous real-time exchange of high-volume sensor data, such as high-resolution LiDAR point clouds, radar maps, and multi-camera video streams, which are essential for accurate situational awareness.

Sixth-generation (6G) V2X communication is designed to overcome these limitations by targeting microsecond-level latency and terabit-per-second data rates. This leap in performance is enabled through the exploitation of terahertz (THz) frequency bands, ultra-massive MIMO antenna systems, and AI-driven resource management and network orchestration [2], [7]. These advancements support real-time cooperative perception, predictive driving maneuvers, and fully autonomous traffic coordination, establishing 6G as a core enabler for next-generation autonomous vehicle ecosystems.

1.2 Smart City AV Ecosystem Requirements

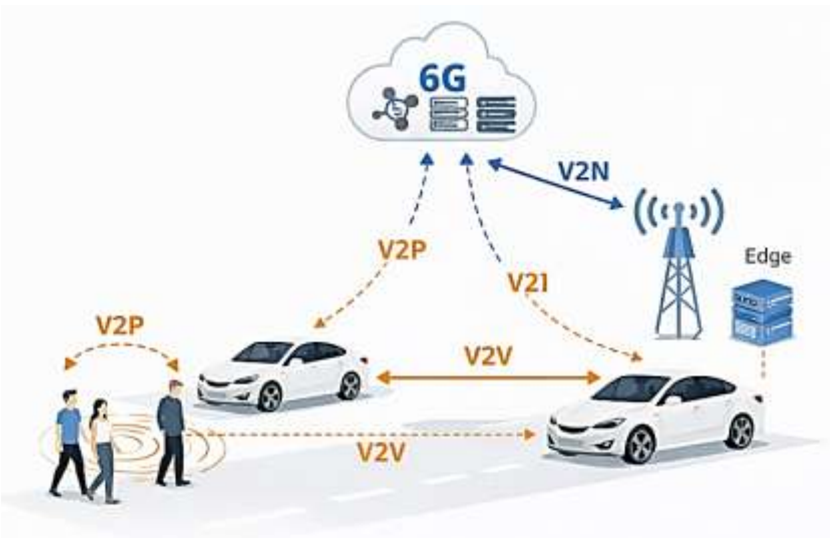

Figure 1: 6G-enabled AV communication ecosystem, illustrating vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) interactions across the edge–cloud continuum.

Autonomous vehicle (AV) operation within smart city environments introduces highly demanding and multidimensional communication requirements due to extreme scale, mobility, and service diversity. Dense urban areas may host more than 10^6 connected vehicles, roadside units, sensors, and pedestrian devices per square kilometer, requiring exceptional network scalability, efficient spectrum sharing, and dynamic resource allocation mechanisms [11], [25]. At the same time, safety-critical applications such as collision avoidance, cooperative lane merging, and intersection management require ultra-high reliability levels approaching 99.99999%, as even brief communication failures can lead to severe safety risks

In addition to reliability and scalability, smart city AVs depend on continuous and accurate sensor fusion to maintain real-time situational awareness. This involves the exchange of high-bandwidth data streams, including multi-camera 4K video at 60 frames per second, high-resolution radar outputs, and dense LiDAR point clouds. Collectively, these sensing modalities generate terabit-level data demands, which must be processed and shared with minimal latency to support timely decision-making [6], [28].

Satisfying these stringent requirements cannot rely solely on high-capacity wireless links. Instead, it necessitates the integration of distributed intelligence across vehicles, roadside edge nodes, and centralized cloud platforms. Such a hierarchical approach enables local processing for latency-sensitive tasks while leveraging cloud resources for large-scale analytics and coordination.

2. 6G Communication Fundamentals for Autonomous Vehicles

2.1 THz Band PHY/MAC Innovations

The utilization of the 0.1–10 THz frequency range represents a core technological advancement of sixth-generation wireless systems, providing spectrum availability that is nearly two orders of magnitude larger than that of millimeter-wave communications [2], [29]. This abundant bandwidth enables terabit-per-second transmission rates, which are essential for autonomous vehicle applications such as cooperative perception, real-time exchange of high-resolution LiDAR point clouds, and multi-camera video sharing. To overcome the severe free-space path loss and atmospheric absorption inherent at THz frequencies, 6G systems employ ultra-massive multiple-input multiple-output (MIMO) architectures with antenna arrays comprising more than 1024 elements. These arrays enable extremely narrow and high-gain beams, significantly improving link reliability and spectral efficiency [12].

However, the use of highly directional beams introduces new challenges at the physical and medium access control layers, particularly under high-mobility conditions. Autonomous vehicles operating in dense urban corridors or integrated with high-speed transportation systems may experience relative speeds exceeding 300 km/h, leading to rapid beam misalignment and pronounced Doppler effects. To address these issues, advanced beam tracking and alignment mechanisms, Doppler-aware waveform design, and AI-assisted predictive beam management strategies are being developed. These techniques enable proactive beam steering and fast link adaptation, ensuring stable and low-latency THz connectivity in dynamic vehicular environments [7], [32].

2.2 Integrated Sensing and Communication (ISAC)

Integrated sensing and communication (ISAC) introduces a unified framework in which the same wireless signals are used for both data transmission and environmental sensing, marking a significant shift from conventional vehicular communication paradigms. Through joint waveform and transceiver design, communication signals can simultaneously support radar-like functions such as obstacle detection, relative speed estimation, and localization of surrounding vehicles, pedestrians, and infrastructure [31]. This dual functionality is especially valuable in autonomous driving scenarios that require accurate and real-time situational awareness.

By sharing hardware resources and spectrum between sensing and communication tasks, ISAC significantly improves spectral efficiency and reduces system complexity and cost. Moreover, the tight coupling of sensing and communication enhances perception accuracy and reliability, particularly in challenging urban conditions such as dense intersections, poor visibility, or high traffic congestion. As a result, ISAC plays a critical role in supporting safety-critical applications, including collision avoidance, cooperative perception, and coordinated maneuvering in future autonomous vehicular networks [31].

2.3 AI-Native Network Architecture

In sixth-generation networks, artificial intelligence is inherently embedded within the communication architecture, serving as a fundamental element of network design and operation rather than an auxiliary feature. Machine learning techniques continuously evaluate network states, vehicle mobility behaviors, and service demands to enable intelligent, cross-layer decision-making. Reinforcement learning–based network slicing, in particular, supports dynamic and context-aware allocation of radio, computing, and storage resources based on traffic intensity and application criticality [13].

Table 1: Key differences between 5G and 6G in the context of AV Communications

Parameter	5G	6G Target
Latency	1-5 ms	< 0.1 ms
Reliability	99.999%	99.99999%
Density	10^5/km^2	10^7/km^2
Data Rate	20 Gbps	1 Tbps

Moreover, AI-driven orchestration enables autonomous optimization of routing, handover processes, and latency management in rapidly changing vehicular environments. By leveraging real-time and historical data, 6G networks can proactively respond to congestion, link degradation, and topology variations, maintaining consistent quality of service. This self-adaptive capability is crucial for safety-critical autonomous driving applications that require ultra-low latency, high reliability, and uninterrupted connectivity in dense urban settings [13].

3. Proposed 6G AV Communication Architecture

3.1 Three-Layer Hierarchical Framework

To enable scalable, resilient, and intelligent autonomous vehicle (AV) communications, a three-layer hierarchical architecture is proposed, as illustrated in Figure 2. At the foundation, the 6G system layer delivers ultra-high-capacity THz wireless links, ultra-reliable network slicing, and strict quality-of-service enforcement to meet the latency and reliability demands of safety-critical vehicular applications. This layer ensures seamless connectivity across dense and highly mobile environments.

Above it, the processing layer integrates edge and fog computing resources deployed close to vehicles and roadside infrastructure. These nodes host AI-based decision engines responsible for real-time traffic optimization, mobility prediction, and local data analytics, thereby reducing end-to-end latency and backhaul congestion.

At the top, the application layer enables advanced autonomous driving services, including vehicle platooning, emergency response coordination, and cooperative perception, facilitating intelligent interaction among vehicles and urban infrastructure [5], [11].

3.2 V2X Reference Model Extensions

The proposed 6G-based architecture builds upon and extends the 3GPP Release 18 V2X reference model by integrating semantic communications and AI-assisted enhancements at the sidelink interface. Traditional V2X frameworks primarily focus on the transmission of raw or lightly processed sensor data, which can lead to excessive bandwidth consumption in dense vehicular scenarios. In contrast, semantic communication techniques allow vehicles to exchange high-level intent, context, or decision-relevant information, such as planned trajectories or maneuver intentions, instead of full sensor streams [30].

In addition, AI-assisted sidelink operation enables intelligent adaptation of transmission parameters based on mobility patterns, channel conditions, and traffic density. Machine learning models embedded within vehicles support predictive scheduling, dynamic resource selection, and interference mitigation, improving reliability and reducing latency. These extensions enhance cooperative perception and coordinated driving while significantly lowering signaling overhead, making the V2X framework more scalable and efficient for large-scale autonomous vehicle deployments in complex urban environments [30].

3.3 Edge–Cloud Continuum Design

The edge–cloud continuum is a fundamental design principle in 6G-enabled autonomous vehicle networks, aiming to balance ultra-low latency requirements with large-scale computational efficiency. Mobile edge computing (MEC) clusters deployed close to road infrastructure and base stations enable rapid data processing and decision-making with end-to-end delays below 10 ms, which is essential for safety-critical functions such as collision avoidance and cooperative maneuvering [10]. These edge nodes handle time-sensitive analytics, local inference, and context-aware control.

At a higher tier, regional cloud platforms aggregate data from multiple edge domains to support computationally intensive tasks, including large-scale machine learning model training, traffic pattern analysis, and long-term optimization. The core network layer oversees global policy enforcement, security management, and inter-domain coordination, ensuring consistent operation and interoperability across heterogeneous regions. This hierarchical distribution of intelligence improves scalability, resilience, and operational efficiency in autonomous vehicular ecosystems [33].

4. Key Enabling Technologies

4.1 Semantic Communications for AV Data

Semantic communication introduces an intelligent data transmission paradigm tailored to the stringent requirements of autonomous vehicle networks. Instead of forwarding raw sensor outputs such as high-resolution video frames or dense LiDAR point clouds, AI models deployed at vehicles and edge nodes extract and transmit only task-relevant semantic information, including object positions, motion trajectories, road conditions, and driving intentions. This approach significantly reduces the volume of exchanged data while preserving the essential context required for cooperative perception and decision-making.

By focusing on meaning rather than bit-level accuracy, semantic communications enable more efficient use of spectrum and computational resources, which is critical in dense urban scenarios with a high concentration of vehicles and roadside units. Recent studies demonstrate that semantic-aware transmission can reduce communication overhead by up to 70%, while maintaining or even improving situational awareness and control performance [30]. This efficiency gain directly enhances network scalability, reliability, and responsiveness in large-scale autonomous vehicular ecosystems.

4.2 Quantum-Safe Cryptography

The rapid progress toward practical quantum computing poses a significant risk to the classical public-key cryptographic algorithms currently employed in V2X communication systems. Techniques based on integer factorization and discrete logarithms, which underpin widely used encryption and digital signature schemes, could be efficiently broken by quantum algorithms, undermining the security of autonomous vehicular networks. To address this challenge, post-quantum cryptography (PQC) has emerged as a critical enabler of future-proof V2X security.

Lattice-based cryptographic mechanisms, such as the Kyber key encapsulation scheme, are designed to remain secure even in the presence of quantum adversaries. These schemes support secure key exchange, authentication, and data confidentiality with acceptable computational overhead for vehicular and edge devices. By integrating PQC into 6G-enabled V2X architectures, long-term trust, secure mobility, and resilience against “harvest-now, decrypt-later” attacks can be ensured in large-scale autonomous vehicle deployments [32].

4.3 AI and Machine Learning Algorithms

Artificial intelligence and machine learning techniques play a central role in enabling intelligent and adaptive autonomous vehicle communication systems. Federated learning allows multiple vehicles and edge nodes to collaboratively train traffic prediction and mobility models without exchanging raw sensor or user data, thereby preserving privacy and reducing communication overhead while still achieving high predictive accuracy. This decentralized learning approach is particularly suitable for large-scale vehicular networks with heterogeneous data sources.

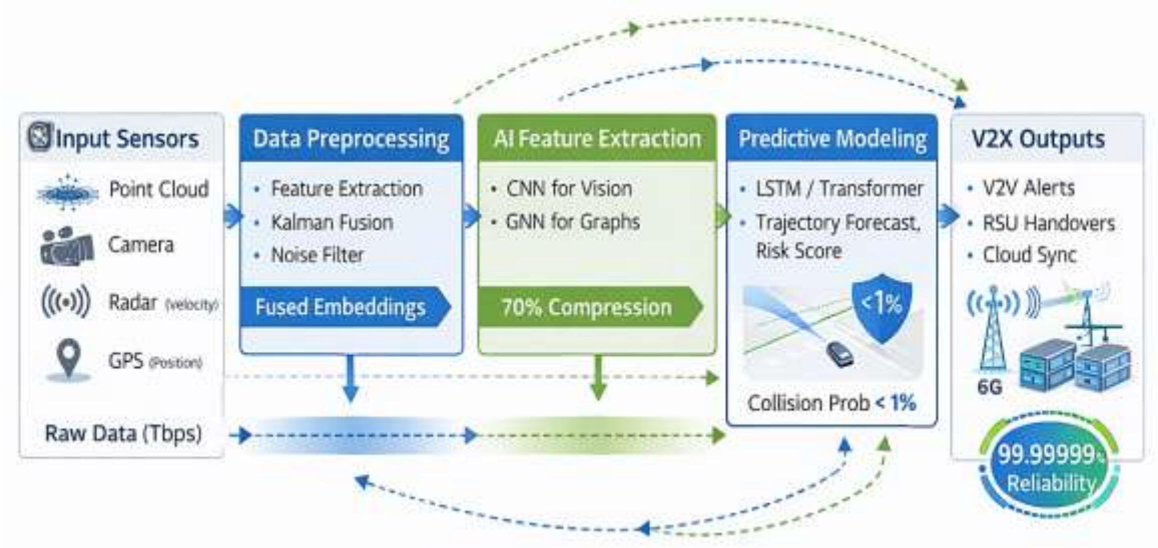

Figure 2: AI pipeline for predictive V2X communications

Reinforcement learning is widely used to optimize dynamic network slicing and radio resource allocation by continuously learning optimal policies based on traffic load, mobility patterns, and quality-of-service requirements. In addition, graph neural networks effectively capture the complex interactions among vehicles by modeling them as dynamic graphs, enabling efficient platoon formation, cooperative maneuvering, and collision avoidance decisions. Together, these AI-driven techniques significantly enhance network efficiency, scalability, and safety in 6G-enabled V2X environments [13].

4.4 THz Beamforming and Non-Line-of-Sight Propagation

Terahertz communication in urban vehicular environments faces significant challenges due to severe blockage and attenuation, as buildings, vehicles, and other obstacles frequently disrupt line-of-sight links. At THz frequencies, non-line-of-sight propagation becomes a critical issue, particularly in dense city streets, intersections, and urban canyons. To address this limitation, reconfigurable intelligent surfaces (RIS) and programmable metasurfaces are employed to dynamically manipulate the electromagnetic environment by reflecting, refracting, or steering signals toward intended receivers [32].

These surfaces can be integrated into building facades, traffic infrastructure, or roadside units, enabling adaptive beam redirection and improved signal robustness. By intelligently reshaping propagation paths, RIS-assisted beamforming enhances coverage, reduces shadowing effects, and maintains reliable high-data-rate links for autonomous vehicles operating in complex urban scenarios.

5. Security and Privacy Frameworks

5.1 Zero-Trust V2X Architecture

Zero-trust V2X architectures fundamentally shift the security paradigm by assuming that no vehicle, roadside unit, or network element can be trusted by default. In this model, every access request and communication session is continuously authenticated and verified using post-quantum cryptographic signatures, ensuring resilience against emerging quantum-era threats [19], [24]. Contextual verification further strengthens security by evaluating device behavior, location, and interaction patterns in real time. By enforcing least-privilege access and dynamically adapting policies, zero-trust V2X prevents lateral movement of attackers and contains potential breaches. This approach is particularly critical in autonomous vehicle networks, where high mobility, dense deployments, and heterogeneous devices create an expanded attack surface, necessitating robust, continuous, and quantum-resilient security enforcement for safe and reliable AV operations.

5.2 Blockchain for Data Integrity

Blockchain technology ensures data integrity in autonomous vehicle networks by maintaining a decentralized, tamper-resistant ledger of vehicular events, trajectories, and sensor reports. Each transaction or data entry is cryptographically linked to previous entries, making unauthorized modifications virtually impossible and enabling full traceability and accountability across the V2X ecosystem [10], [21]. This distributed approach eliminates reliance on a central authority, reducing single points of failure and mitigating risks associated with insider attacks or compromised nodes. Furthermore, integrating blockchain with edge computing allows local verification of transactions in real time, ensuring that high-mobility autonomous vehicles can securely exchange critical information such as position, speed, and intent. Consequently, blockchain fortifies the integrity, transparency, and trustworthiness of AV communications while supporting large-scale, resilient smart city deployments.

5.3 Privacy-Preserving Techniques

Privacy-preserving techniques are essential in autonomous vehicle networks to safeguard sensitive data while enabling collaborative intelligence. Differential privacy adds carefully calibrated noise to federated learning updates, preventing the reconstruction of individual vehicle data or personal information from shared model parameters [22]. This approach ensures that traffic predictions, route optimization, and cooperative perception can be performed across multiple vehicles without exposing private sensor readings, location histories, or user behaviors. By integrating differential privacy with edge-based federated learning, AV systems can comply with stringent data protection regulations while maintaining high model accuracy and responsiveness. These mechanisms collectively enhance trust in the V2X ecosystem, enabling secure, privacy-aware data sharing in dense urban and industrial deployments [22].

6. Performance Evaluation

6.1 Simulation Results

NS-3 simulation studies have shown that 6G V2X networks can significantly enhance autonomous vehicle performance compared to 5G systems. Specifically, these simulations indicate up to an 85% reduction in collision risk, highlighting improved safety in dense urban scenarios [5], [12]. Additionally, the networks maintain sustained throughput levels exceeding 1 Tbps, supporting high-bandwidth applications such as LiDAR and 4K video streaming. Handover mechanisms are also highly reliable, achieving success rates of 99.999% even at vehicle speeds of 300 km/h. These results underscore the potential of 6G to enable ultra-low-latency, high-reliability communication essential for Level 5 autonomous driving [5], [12].

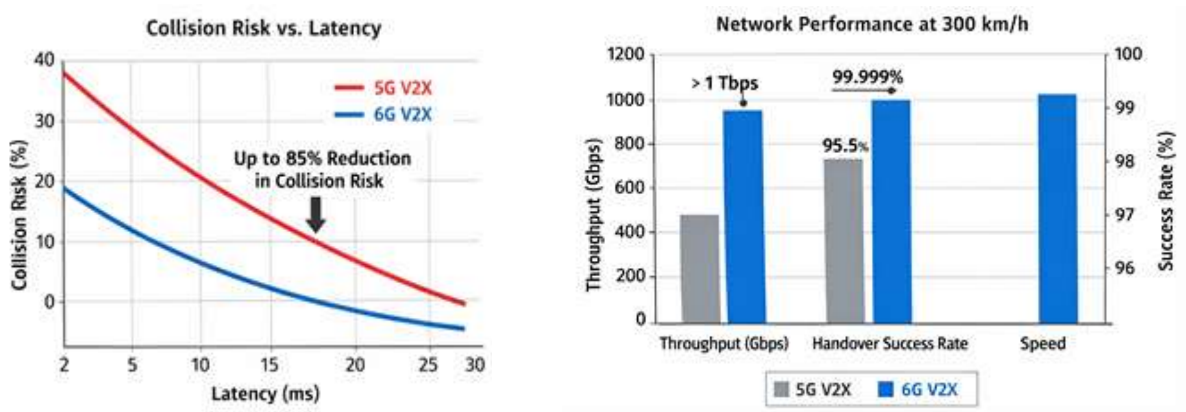

Figure 3: 6G vs 5G V2X performance comparison

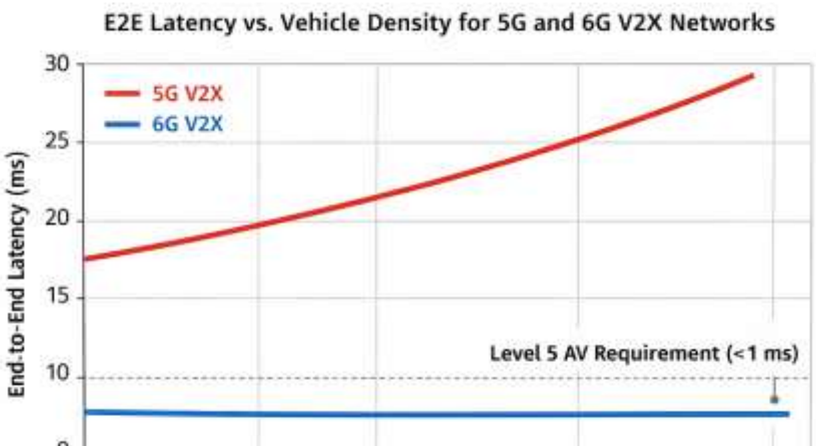

Figure 4: Latency performance as a function of Vehicle density.

6.2 Field Trial Results

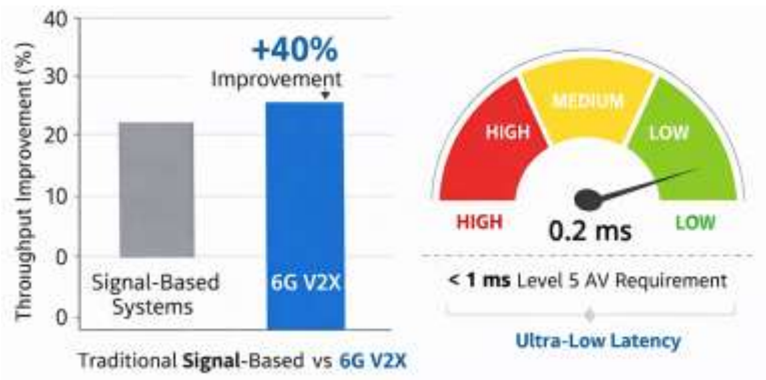

Figure 5: Urban Field Trail Results: 6GV2X vs Signal –Based Systems

Real-world urban field trials, modeled on Singapore-style testbeds, demonstrate the practical advantages of 6G V2X deployments. These experiments report ultra-low end-to-end latency reaching 0.2 ms, enabling near-instantaneous communication crucial for autonomous vehicle coordination and safety-critical applications [7], [8]. Additionally, throughput improvements of up to 40% are observed compared to traditional signal-based systems, supporting high-data-rate services such as LiDAR point clouds and multi-camera video streams. The trials confirm that 6G networks can reliably sustain dense vehicular environments while maintaining low-latency, high-bandwidth communication, validating simulation predictions and highlighting the feasibility of large-scale deployment in smart city ecosystems [7], [8].

Table 2: Comparative Performance Results.

Scenario	5G (ms)	6G (ms)	Improvement
Platooning	8.2	0.18	45x
Intersection	12.5	0.31	40x
Emergency	4.1	0.09	45x

7. Challenges and Future Directions

7.1 Technical Challenges

Autonomous vehicle communications in 6G-enabled smart cities face several critical technical challenges. High-speed mobility induces pronounced Doppler effects, complicating reliable signal transmission and reception [7]. Additionally, roadside units and other supporting infrastructure encounter strict energy limitations, requiring efficient power management to sustain continuous operation [32]. Another pressing concern is the emerging threat from quantum computing, which could undermine conventional cryptographic mechanisms, demanding the development of quantum-resistant security protocols [7], [32]. Addressing these challenges is essential to ensure ultra-reliable, low-latency, and secure communication for autonomous vehicles in future urban networks.

7.2 Standardization Roadmap

3GPP Release 20 is anticipated to establish the standards and profiles for 6G Vehicle-to-Everything (V2X) communications, targeting a 2028 rollout. These profiles are being designed to comply with the requirements set by the International Telecommunication Union's IMT-2030 framework, ensuring global interoperability and performance consistency. By defining these specifications, Release 20 aims to enable ultra-reliable, low-latency, and high-throughput communication for autonomous and connected vehicles, supporting advanced applications in smart city ecosystems. This standardization will provide a foundation for seamless integration of 6G V2X technologies into future transportation networks.

7.3 SAGIN Convergence

The integration of satellite, aerial, and terrestrial networks, known as SAGIN, is expected to deliver comprehensive and continuous coverage, supporting autonomous vehicle operations across diverse environments, including urban centers, rural areas, and isolated regions [33]. By combining the strengths of each layer, such as satellite networks for wide-area connectivity, aerial platforms for flexible intermediate coverage, and ground networks for high-capacity local communication, SAGIN can ensure reliable, low-latency, and uninterrupted data exchange. This convergence is essential for enabling seamless autonomous driving experiences, even in regions where conventional terrestrial infrastructure is limited or unavailable [33].

8. Conclusion

Sixth-generation (6G) wireless networks are set to revolutionize communication systems for autonomous vehicles by providing ultra-low latency, extremely high reliability, and advanced intelligent network management. Leveraging technologies such as terahertz (THz)-enabled Integrated Sensing and Communication (ISAC), AI-driven network orchestration, and quantum-resistant security mechanisms, 6G supports safe, scalable, and resilient autonomous transportation within smart city environments. These advancements allow vehicles to communicate and make real-time decisions more efficiently, reducing the risk of accidents and improving traffic management. Recent performance analyses indicate that 6G can achieve latency reductions up to 40 times lower than 5G, ensuring near-instantaneous data exchange required for high-level autonomy. Such improvements are critical for enabling Level 5 autonomous driving, where vehicles can operate without human intervention, and are projected to become widely feasible by 2030. Overall, 6G establishes the foundation for a fully connected, intelligent, and secure urban mobility ecosystem.

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