

Deterministic Transmission in Vehicular Networks: A Comprehensive Review of Architectures, Technologies, and Applications

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Abstract: This paper presents a comprehensive review of deterministic transmission technologies in vehicular networks, addressing the stringent communication requirements of modern Intelligent Connected Vehicles (ICVs). As automotive functions evolve towards advanced autonomous driving and complex Cooperative Intelligent Transport Systems (C-ITS), guaranteeing bounded latency, minimal jitter, and ultra-high reliability across both in-vehicle and vehicle-to-everything (V2X) networks becomes critical. We analyze the evolution of IoV technology architectures, highlighting the transition from DSRC to 5G-V2X, and review classical in-vehicle bus systems alongside the paradigm shift towards Automotive Ethernet. Key enabling technologies for deterministic communication, particularly Time-Sensitive Networking (TSN), Data Distribution Service (DDS), and intelligent resource scheduling optimization, are discussed in detail. Furthermore, the paper explores the architectures for wired-wireless convergence to achieve end-to-end determinism. Finally, the review concludes with application scenarios such as autonomous driving, emphasizing ongoing challenges and future research directions in constructing resilient and deterministic vehicular communication ecosystems.

Keywords: Deterministic Transmission; Vehicular Networks; Time-Sensitive Networking; V2X Communication; Data Distribution Service; Automotive Ethernet; Intelligent Connected Vehicles.

1. Introduction

The rapid advancement of Intelligent Connected Vehicles (ICVs) and autonomous driving technologies has fundamentally reshaped the landscape of automotive communication. Traditional vehicular networks, primarily designed for basic control and localized interactions, are increasingly inadequate to handle the massive, time-critical data streams generated by high-definition sensors, advanced driver-assistance systems (ADAS), and vehicle-to-everything (V2X) collaborative applications. To ensure operational safety and system efficiency, it is imperative to establish communication infrastructures capable of deterministic transmission—delivering data with guaranteed upper bounds on latency and jitter, alongside near-perfect reliability.

Deterministic transmission in vehicular contexts spans two interlinked domains: the in-vehicle network and the external IoV network [1]. Inside the vehicle, the shift from legacy domain-specific buses (like CAN and FlexRay) to centralized, Ethernet-based architectures has necessitated technologies like Time-Sensitive Networking (TSN) to prevent network congestion from compromising critical control signals. Externally, the evolution of V2X standards from DSRC to 5G-V2X provides the ultra-reliable, low-latency communication (URLLC) essential for complex vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) interactions. However, achieving true end-to-end determinism requires not only robust individual protocols but also their seamless integration and intelligent resource management across heterogeneous wired and wireless environments.

This review aims to provide a systematic overview of the current state of deterministic transmission technologies in

vehicular networks [2]. We first examine the technological architectures of both inter-vehicle and intra-vehicle communications. Subsequently, we delve into the core enabling technologies to achieve determinism, including TSN, Data Distribution Service (DDS) middleware, and advanced resource scheduling algorithms. We also explore the critical design aspects of wired-wireless convergence architectures. By synthesizing these elements and presenting relevant application scenarios, this paper outlines the technological trajectories, current bottlenecks, and future prospects of deterministic vehicular networking, serving as a comprehensive reference for researchers and practitioners in the field [3].

2. Architectures of Vehicular Communication Systems

2.1. Inter-Vehicle Network (V2X) Architecture

As an innovative integration of Intelligent Transportation Systems (ITS) and Internet of Things (IoT) technologies, the Internet of Vehicles (IoV) relies on the V2X (Vehicle-to-Everything) communication system as its core foundation. This system facilitates multi-dimensional interaction among vehicles and their surrounding environment, encompassing Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) communications, thereby building a comprehensive, intelligent mobility ecosystem. V2X communication primarily utilizes two key types of equipment: On-Board Units (OBUs) and Roadside Units (RSUs), enabling real-time data interaction through advanced wireless communication protocols.

The development of international IoV communication

standards has experienced a divergence and convergence of technological routes [4]. The early U.S.-led Dedicated Short-Range Communications (DSRC) technology, based on the IEEE 802.11p standard, adopted a Local Area Network (LAN) direct connection mode but exhibited significant reliability deficiencies in high-density scenarios. In contrast, Cellular V2X (C-V2X) technology innovatively combines the dual advantages of wide-area cellular networks and local direct connections, offering superior communication reliability and coverage range. As shown in Table I, a comparison of four mainstream IoV communication technologies—DSRC, LTE-V2X, 5G-V2X, and C-V2X—highlights their technical standards, architectures, performance indicators, and application scenarios. Table I specifically illustrates the differential performance of these technologies in key metrics such as latency and reliability, providing a comprehensive reference for understanding their respective advantages [5].

The application of 5G technology has catalyzed a qualitative leap in V2X communication. Based on the 5G-V2X technology defined in 3GPP Release 16 and beyond, which employs a dual-mode architecture comprising PC5 sidelink communication and the Uu cellular network, breakthrough progress has been achieved in latency, reliability, and connectivity. This technology supports V2I and V2P collaborative applications across complex scenarios. Specifically, 5G-V2X achieves an improvement of several orders of magnitude over its predecessor, LTE-V2X: latency is reduced to sub-5 ms, and reliability reaches 99.999%, fully satisfying the stringent requirements of advanced autonomous driving [6]. These performance breakthroughs primarily stem from technological innovations such as New Radio (NR) sidelink enhancement, centimeter-level high-precision positioning, and optimized resource allocation mechanisms (e.g., Mode 2/4). In 2020, the United States transitioned away from DSRC, allocating the relevant

frequency band to C-V2X, marking an international convergence toward cellular-based technical solutions.

From a system architecture perspective, IoV communication can be categorized into intra-vehicle and inter-vehicle networks. Inter-vehicle communication includes V2V, V2I, and V2P, which collectively constitute the V2X technology framework [7]. DSRC technology, grounded in the IEEE 802.11p and IEEE 1609 standard series, is characterized by maturity and stability. Conversely, C-V2X evolved from 3G/4G/5G cellular network technologies, comprising LTE-V2X and 5G-V2X. These two technological routes form a complementary relationship: DSRC is suitable for short-range, low-complexity safety applications, while C-V2X handles more complex scenarios, meeting strict demands for low latency, high reliability, and large bandwidth.

Currently, the global industry is actively promoting the deep integration of 5G and C-V2X [8]. Roadmap 3.0, released by the 5G Automotive Association (5GAA), focuses on key directions such as the convergence of V2X and Advanced Driver Assistance Systems (ADAS), space-air-ground integrated networks, and Multi-access Edge Computing (MEC) deployment. The 3GPP organization continues to optimize cellular mobile communication technologies, consistently improving key technical characteristics—such as direct communication, precise positioning, and energy efficiency management—by enhancing transmission capacity, latency reliability, and handover performance. Notably, 3GPP is driving the integrated convergence of terrestrial cellular networks, short-range direct communication, and satellite communication to provide comprehensive guarantees for the IoV. At the application level, 5G-V2X employs high-order modulation and bidirectional group communication to support collaborative autonomous driving functions, such as lane merging and advanced sensor data sharing [9].

Table 1. Comparison of Main V2X Communication Technology Standards

Technical Standard	Communication Architecture	Latency Performance	Reliability	Bandwidth Capability	Main Application Scenarios	Technical Features	International Development Status
DSRC	LAN direct connection based on IEEE 802.11p	-	Insufficient reliability in high-density scenarios	-	Short-range, low-complexity safety applications	Mature and stable	Early standard led by the US; band reallocated in 2020
LTE-V2X	Dual-mode cellular network and local direct connection	-	-	-	Basic V2I/V2V scenarios	Developed within 3GPP	-
5G-V2X	Dual-mode PC5 sidelink and Uu cellular network	< 5 ms	99.999%	Large bandwidth	Advanced autonomous driving, cooperative driving	NR sidelink enhancement, centimeter-level positioning	Maintained within 3GPP standards
C-V2X	Integration of wide-area cellular network and local direct connection	-	Superior to DSRC	-	Complex application scenarios	Supports high-order modulation and bidirectional group communication	Continuously optimized by 3GPP

2.2. Intra-Vehicle Network Architecture

Modern in-vehicle networks exhibit significant technological diversity, with various communication protocols working synergistically according to application scenario requirements to build a hierarchical communication system. As the core technology of traditional in-vehicle networks, the Controller Area Network (CAN) bus occupies a dominant position in the distributed Electronic Control Unit (ECU) architecture. Its high-speed version (CAN-HS) supports a transmission rate of 1 Mbps, while the low-speed version (CAN-LS) operates between 40 Kbps and 250 Kbps, achieving efficient communication via a multi-master architecture design. In domains with strict reliability requirements, such as powertrain and chassis control, the CAN bus demonstrates excellent performance [10]. The CAN Flexible Data-Rate (CAN FD) standard, introduced in 2012, increased the transmission rate to 12 Mbps, providing sufficient bandwidth for early autonomous driving systems.

As a supplement to the CAN bus, the Local Interconnect Network (LIN) bus enables the effective control of simple devices at exceptionally low costs. A transmission rate of 19.2 Kbps is adequate for basic functions such as window and seat controls, and its 12-node limit significantly simplifies the complexity of electronic systems. The FlexRay bus represents the peak performance of traditional bus technologies; its 10 Mbps bandwidth, combined with a time-triggered mechanism, makes it ideal for high-safety applications such as drive-by-wire systems, ensuring precise timing control for critical tasks [11].

Historically, in-vehicle multimedia systems widely adopted the Media Oriented Systems Transport (MOST) bus, with 25 Mbps and 50 Mbps versions providing professional solutions for audio and video transmission. However, with

technological advancements, the Low-Voltage Differential Signaling (LVDS) protocol achieves 850 Mbps high-speed transmission over twisted-pair copper cables, demonstrating significant advantages in short-distance communication for cameras and displays. These differentiated technologies collectively constitute an automotive communication infrastructure adapted to myriad operational needs. Table II compares the transmission rates, application fields, and technical characteristics of current mainstream in-vehicle bus technologies, illustrating the functional positioning and evolution of vehicular network architectures [12].

The emergence of automotive Ethernet marks a new stage in vehicle network technology. The single-twisted-pair design, based on PAM3/PAM4 modulation, reduces system weight and cost while fulfilling the unique requirements of the automotive environment. The IEEE 802.3 standard series has gradually expanded the technical spectrum from 100 Mbps to 1 Gbps, enhancing interoperability. Broadcom's BroadR-Reach technology, utilizing innovative coding strategies, provides 2500 V grounding protection capability while ensuring 66 Mbaud/s transmission efficiency under harsh conditions [13].

Through precise clock synchronization and traffic scheduling mechanisms, Ethernet has gained deterministic transmission capabilities. This innovation provides low-latency, low-jitter guarantees for critical applications such as intelligent driving. The current shift toward a domain-controller architecture divides the vehicle into multiple functional domains, where automotive Ethernet serves as the inter-domain backbone, effectively alleviating the bandwidth limitations of traditional networks. This architectural transformation improves system performance and lays the foundation for future software-defined vehicles and centralized computing topologies [14].

Table 2. Performance and Applications of In-Vehicle Network Bus Technologies

Bus Type	Transmission Rate	Main Application Fields	Technical Features	Development Evolution
CAN Bus	HS: 1 Mbps; LS: 40-250 Kbps	Reliability-critical areas (powertrain, chassis)	Multi-master architecture for efficient communication	CAN FD standard (2012) increased rate to 12 Mbps
LIN Bus	19.2 Kbps	Basic functions (windows, seats)	12-node limit simplifies complexity	Cost-effective supplement to CAN
FlexRay	10 Mbps	High-safety applications (X-by-wire)	Time-triggered mechanism provides deterministic communication	High performance for legacy bus technologies
MOST Bus	25 Mbps and 50 Mbps	In-vehicle multimedia systems	Designed for audio/video transmission	Gradually replaced by Ethernet/LVDS
LVDS	850 Mbps	Short-range communication (cameras, displays)	High-speed transmission via twisted-pair copper	Highly advantageous in localized scenarios
Automotive Ethernet	100 Mbps to 1 Gbps	Inter-domain backbone network	PAM3/PAM4 modulation, single twisted pair, standardized protocols	Supports TSN for deterministic transmission

3. Enabling Technologies for Deterministic Transmission

The rapid development of Intelligent Connected Vehicles (ICVs) exposes in-vehicle networks to novel deterministic transmission challenges. Modern networks must

simultaneously process diverse data streams generated by complex applications like ADAS, autonomous driving, and in-vehicle infotainment systems, which differ significantly in real-time performance, reliability, and bandwidth requirements. Critical control commands (e.g., braking and steering) impose the strictest requirements, necessitating microsecond-level latency, extremely low jitter, and high

reliability. Conversely, audio and video data from sensors like high-definition cameras and Light Detection and Ranging (LiDAR) tolerate slight latency but still require substantial bandwidth and controlled jitter [15]. Diagnostic data, typically non-real-time, is assigned a lower priority.

The technical indicators of deterministic networks are evaluated across four dimensions: bandwidth, latency, jitter, and packet loss rate. In IoV contexts, deterministic Quality of Service (QoS) requires a guaranteed upper limit for latency and jitter, an upper limit for packet loss, and lower limits for reliability and bandwidth. For instance, 5G-V2X achieves latency below 5 ms and reliability of 99.999%, fully supporting Level 4 autonomous driving requirements [16]. Such stringent demands have accelerated the adoption of technologies like Time-Sensitive Networking (TSN), which provides critical support for unmanned driving.

In scenarios like vehicle platooning, the Ultra-Reliable Low-Latency Communication (URLLC) and enhanced Mobile Broadband (eMBB) functions of 5G networks demonstrate substantial advantages. Grant-free transmission mechanisms reduce access latency from 8 ms to within 1 ms, satisfying emergency braking needs. Semi-Persistent Scheduling (SPS) stabilizes control-plane latency within 2 ms by pre-allocating periodic resources—a 60% reduction compared to dynamic scheduling—with jitter controlled to ± 0.1 ms [17].

Deterministic networks maintain parameters within defined bounds by precisely controlling data forwarding behavior. Utilizing mechanisms like time synchronization and traffic shaping, TSN effectively resolves traditional Ethernet's inability to provide deterministic services, thereby preventing network congestion from inducing latency risks for critical tasks. The synergistic application of TSN and Data Distribution Service (DDS) technologies offers a communication infrastructure with strict QoS guarantees. TSN, based on the IEEE 802.1 standard family, ensures deterministic transmission at the link layer, while DDS middleware (utilizing a publish-subscribe model) facilitates dynamic real-time data distribution across distributed environments via configurable QoS policies [18]. This converged architecture accommodates new applications like autonomous driving and remote diagnostics.

3.1. Time-Sensitive Networking

TSN, encompassing a suite of enhanced Ethernet technologies defined by the IEEE 802.1 standard family, resolves traditional Ethernet's deficiencies in deterministic transmission through precise time synchronization and intelligent traffic scheduling. Originating from the Audio Video Bridging (AVB) working group, TSN was expanded in 2012 to accommodate strict real-time requirements such as those found in industrial control and autonomous driving. The TSN framework includes core components like IEEE 802.1AS (Time Synchronization), IEEE 802.1Qbv (Time-Aware Shaper, TAS), and IEEE 802.1CB (Frame Replication and Elimination for Reliability, FRER), which collectively provide microsecond-level deterministic service guarantees [19].

Precise clock synchronization is foundational for TSN. The IEEE 802.1AS standard, based on the generalized Precision Time Protocol (gPTP), establishes a master-slave clock hierarchy, achieving nanosecond-level synchronization across the network via interaction mechanisms involving *Sync*, *Follow_Up*, *Delay_Req*, and *Delay_Resp* messages. In

this mechanism, the domain controller or central gateway acts as the Grandmaster Clock (GM), and nodes continually compensate for local clock offsets to mitigate temperature drift and oscillator errors. Experimental data indicates synchronization accuracy of ± 50 ns [20]. In converged 5G-V2X and TSN applications, synchronization error can be bounded within ± 1 μ s, offering reliable timing for cooperative driving.

Traffic scheduling and shaping mechanisms ensure real-time transmission of critical data. TAS (IEEE 802.1Qbv) adopts a Gate Control List (GCL) strategy, dividing time into fixed cycles (e.g., 1 ms) and assigning specific transmission windows to different priority queues. For example, control traffic might be allocated the first 200 μ s, audio/video data the subsequent 400 μ s, and diagnostic data the final 400 μ s [21]. This temporal isolation ensures high-priority traffic occupies channel resources exclusively, averting queuing delays. TSN networks utilizing TAS can control data transmission jitter to below 5 μ s.

Frame preemption and redundancy mechanisms further enhance TSN reliability. IEEE 802.1Qbu (Frame Preemption) allows high-priority frames to interrupt the transmission of low-priority frames, reducing critical data queuing delays to the microsecond level [22]. Concurrently, IEEE 802.1CB achieves multi-path parallel transmission via FRER, ensuring reliable data delivery even if a single path fails. For safety-critical systems like braking, this guarantees worst-case transmission delays do not exceed safety margins (e.g., 2 ms). Hardware-accelerated TSN switches can achieve end-to-end latencies under 100 μ s.

3.2. Data Distribution Service (DDS) Middleware

Data Distribution Service (DDS), a distributed middleware technology, demonstrates profound advantages in IoV applications [23]. Employing a publish-subscribe paradigm, DDS constructs a decentralized, data-centric global shared space, enabling efficient multi-source heterogeneous data interaction within ICVs. The core competency of DDS stems from its comprehensive QoS control system, featuring over 20 customizable policies that precisely adjust data transmission timeliness, reliability, and resource utilization. Optimized DDS implementations can achieve millisecond-level transmission latency for critical commands. The DDS Real-Time Publish Subscribe (RTPS) protocol underpins DDS operations, ensuring real-time performance through optimized message interactions [24]. Built over User Datagram Protocol/Internet Protocol (UDP/IP), RTPS uses multicast for efficient one-to-many data distribution, supplemented by heartbeat and acknowledgment mechanisms to maintain link stability. During service discovery, nodes dynamically exchange metadata (endpoint information, QoS configurations, topics) to establish optimal communication paths. Lightweight DDS implementations (e.g., Fast DDS) can reduce memory footprint by 40% while preserving functional integrity, making them highly suitable for embedded vehicular systems.

Collaboratively, DDS and TSN provide end-to-end deterministic capabilities [25]. The Object Management Group (OMG) continues to standardize the mapping of DDS application-layer QoS policies to TSN link-layer configurations. In this architecture, DDS handles abstract data delivery and service discovery, while TSN enforces determinism. For instance, utilizing the DDS Flow

Identification Algorithm (DFIA) within a Centralized Discovery Architecture (CDA) allows critical streams to be mapped to TSN reserved channels autonomously, reducing transmission latency to 10% of traditional Ethernet norms while maintaining microsecond-level jitter. DDS's dynamic service discovery utilizes a topic-type-instance data model, enabling flexible endpoint management [26]. Centralized discovery within the vehicle simplifies configuration. Furthermore, DDS supports content-based filtering, significantly reducing network load by selectively delivering data. In multi-sensor fusion tests, optimized DDS service matching completes in milliseconds, constituting a core architecture for next-generation, software-defined vehicles.

3.3. Resource Scheduling and Optimization Algorithms

Table 3. Key Technologies and Performance Indicators in IoV Resource Management

Technology Category	Key Technology	Performance Indicators	Application Scenarios
Time-Sensitive Networking	IEEE 802.1Qbv TAS with ILP modeling	Realizes precise time window control, improving deterministic performance	In-vehicle deterministic transmission
Intelligent Scheduling	Improved Genetic Algorithms	Highly accurate and efficient routing and load balancing	IoV resource allocation
Predictive Allocation	Trajectory prediction algorithms	Reduces resource conflict by 30%, caps latency near 3 ms	Cellular V2X at intersections
Dynamic QoS	Edge-based real-time optimization	Reduces high-priority packet loss by an order of magnitude	Dynamic connected environments
Hierarchical Scheduling	Multi-domain scheduling via centralized PCE	Enhances system scalability	Complex topologies under high load
Intelligent Optimization	Multi-agent deep reinforcement learning	Collaborative optimization of routing and scheduling	In-vehicle network routing

Efficient in-vehicle network operation relies heavily on resource scheduling and deterministic optimization [27]. The TAS mechanism (IEEE 802.1Qbv) provides the basis for precise time window control. Applying Integer Linear Programming (ILP) models to time-sensitive data scheduling enhances TAS robustness and enables automated schedule computation via Software-Defined Time-Sensitive Networking (SD-TSN). The SD-TSN architecture gathers requirements through a Centralized User Configuration (CUC) entity, computes schedules via a Centralized Network Configuration (CNC) entity, and distributes configurations using YANG models.

To address burst traffic and path conflicts under heavy

loads, hierarchical scheduling partitions the network into multiple domains, each with independently configured GCLs coordinated by a centralized Path Computation Element (PCE) [28]. Ingress filtering and policing (IEEE 802.1Qci) prevent bandwidth abuse, while frame preemption (IEEE 802.1Qbu and IEEE 802.3br) prevents long low-priority frames from blocking critical traffic. The Stream Reservation Protocol (SRP) further guarantees bandwidth and latency requirements end-to-end. Table III summarizes key technologies for IoV resource optimization. Artificial intelligence presents promising avenues for resource optimization [29]. Deep reinforcement learning paradigms, such as multi-agent Distributed Deep Q-Networks (DDQN), demonstrate exceptional capability in routing and scheduling optimization. Task-Oriented Joint Resource Allocation Schemes (TOJRAS) integrate sensing, communication, and computing resources, experimentally improving mean average precision (mAP) performance while satisfying resource constraints. Furthermore, in URLLC scenarios, integrating redundancy coding and decoding with optimized network topologies can dramatically enhance system reliability and real-time responsiveness.

4. Wired-Wireless Converged Network Architectures

A converged wired-wireless architecture is foundational for end-to-end deterministic transmission in the IoV [30]. This architecture seamlessly integrates wired networks (automotive Ethernet, CAN) with wireless technologies (5G-V2X, millimeter-wave communication). Primary design challenges include heterogeneous protocol conversion, dynamic resource allocation, and differentiated QoS assurance, alongside strict adherence to safety and real-time standards. Utilizing modular designs and network virtualization efficiently supports diverse application demands, from autonomous driving to in-vehicle infotainment.

4.1. Heterogeneous Network Integration Frameworks

Integrating heterogeneous protocols seamlessly is highly critical [31]. Innovative gateway designs merge in-vehicle wired domains with wide-area wireless nodes. Advanced gateways employ multi-level buffering and traffic shaping during protocol conversion. For instance, when routing traffic from Ethernet to CAN, high-priority data receives immediate forwarding rights, while low-priority data is probabilistically delayed or dropped, effectively bridging the QoS gap between fundamentally different networking paradigms.

Current design architectures generally fall into two categories: modular hardware solutions and domain-centralized computing [32]. Modular solutions integrate multi-functional antennas (incorporating Tuner, GPS, and Wi-Fi), reducing wiring harness complexity. Conversely, domain centralization concentrates logic within a central gateway, efficiently supporting over-the-air (OTA) updates and complex V2V interactions. The selection depends heavily on deployment complexity and required scalability.

Network virtualization offers scalable resource management [33]. By virtualizing network functions, resources can be elastically deployed and dynamically partitioned to guarantee QoS across diverse service levels. TSN underpins the determinism of this converged

architecture; frame preemption and ingress policing secure critical flows, preventing localized congestion or Denial-of-Service (DoS) attacks from degrading overall system performance.

4.2. Performance Optimization for Converged Networks

Optimizing the converged architecture spans bandwidth allocation, latency control, and reliability enhancement. In certain deployments, integrating automotive Ethernet with 5G cellular connectivity ensures stable transmission rates in the 1–10 Gbps range through multi-base-station redundancy and network slicing, effectively combating urban signal attenuation [34].

To optimize latency, 5G-V2X implements a hierarchical architecture. The PC5 interface handles direct V2V/V2I interaction, frequently reducing latencies below 10 ms. Concurrently, deploying MEC nodes localizes data processing, effectively reducing overall system latency by an additional 30% to 50%. Research into joint Wi-Fi and TSN scheduling has shown that distributed estimation algorithms can reduce conflict probabilities by 30% at congested intersections [35].

Reliability optimization heavily relies on TSN integration at the gateway level. The microsecond-level synchronization achieved via IEEE 802.1AS vastly improves data alignment. Systems equipped with full TSN stacks can maintain end-to-end latencies under 2 μ s on the wired link, effortlessly fulfilling the rigid real-time constraints of ADAS. One primary ongoing challenge is maintaining multi-clock domain synchronization across wide-area cellular networks; collaborative 5G-V2X and TSN synchronization strategies aim to keep end-to-end timing errors within ± 1 μ s [36].

4.3. Standardization and Interoperability Design

Achieving interoperability among heterogeneous, multi-vendor equipment is a major challenge for the converged IoV. Modern vehicles may run dozens of protocols concurrently (CAN, LIN, FlexRay, Ethernet). Addressing compatibility—particularly in vehicle diagnostics like Diagnostics over IP (DoIP)—requires rigid adherence to standards (e.g., ISO guidelines) to bridge ECUs and external diagnostic tools without introducing fault vectors.

The LTE-V2X and 5G-V2X standard families define rigorous technical specifications, but deploying interoperable roadside equipment still requires robust cross-industry collaboration [37]. Within the vehicle, while the IEEE 802.3 physical layer standards for Ethernet are mature (e.g., 100BASE-T1, 1000BASE-T1), upper-layer interoperability remains reliant on industry consortia like the OPEN Alliance.

Standardizing TSN configurations remains a priority. Adopting protocols like NETCONF/YANG streamlines the distribution of TSN configuration parameters to switches compliant with IEEE 802.1Qcc, fostering multi-vendor compatibility. Globally, harmonizing C-V2X and DSRC standards—and defining rigorous cybersecurity frameworks like ISO/SAE 21434—will reduce integration overhead and accelerate the large-scale deployment of ICVs [38].

5. Typical Application Scenarios

The efficacy of deterministic transmission has been validated across multiple IoV domains. These

implementations demonstrate both engineering feasibility and avenues for iterative technological improvement.

5.1. Advanced Autonomous Driving

Deterministic transmission is non-negotiable for autonomous operation. Converged testbeds integrating dozens of sensors (high-definition cameras, LiDAR, radar) over TSN and robust wireless links explicitly demonstrate improved safety margins [39]. For example, edge-coordinated V2I communication allows a vehicle traveling at 80 km/h to process LiDAR data from an out-of-sight RSU and trigger an emergency braking maneuver 300 meters ahead of an obstacle. Sensory data fusion poses immense bandwidth challenges. Using IEEE 802.1Qbv, dedicated transmission windows can be reserved. For instance, braking commands mapped to priority level 7 can be granted exclusive access to a 100 μ s transmission window every 1 ms cycle, completely avoiding interference from bandwidth-heavy video streams [40]. This hierarchical transmission strategy effectively ensures critical safety instructions are executed in real time. TSN's low latency and jitter also facilitate complex L4/L5 autonomous operations. In localized industrial parks, direct optical fiber connections to computing centers create a “closed-loop” data architecture, minimizing processing latency and vastly improving data security, proving highly effective for advanced machine learning workflows in intelligent networks.

5.2. Vehicle Body Control Systems

Body control subsystems increasingly leverage deterministic technologies for distributed actuator coordination [41]. Traditional CAN/LIN wiring harnesses are often supplemented by single-wire deterministic UART-based designs or automotive Ethernet. Implementing TSN in body control eliminates timing uncertainty. High-priority streams for actuators (e.g., precise motor control, battery management synchronization) utilize IEEE 802.1Qbv scheduling and IEEE 802.1AS synchronization to achieve nanosecond-level clock precision. This robust scheduling allows heterogeneous hardware to operate collaboratively without timing drift [42]. Furthermore, moving specific non-critical nodes to wireless architectures minimizes the physical wiring harness burden, improving manufacturing scalability while maintaining the required deterministic performance for safety-critical functions via the wired TSN backbone. This structural flexibility also simplifies OTA update deployments and remote diagnostic routines.

5.3. Vehicular Edge Computing

Edge computing fundamentally addresses the latency constraints of traditional centralized cloud architectures. By migrating computational tasks to MEC nodes (e.g., at RSUs or base stations), an optimal “Terminal-Edge-Cloud” topology is achieved [43]. MEC integration localizes over 70% of data processing, dramatically reducing physical transmission distances. Field data demonstrates single-hop transmission latencies dropping from ~20 ms to below 2 ms. MEC platforms exploit Network Function Virtualization (NFV) and containerization to elastically parse and allocate computational resources. Edge clusters can stabilize processing latencies to ± 0.5 ms using optimized scheduling algorithms (e.g., Q-Learning), well within the tolerance needed for high-velocity scenarios [44]. Moreover, User Plane Function (UPF) sinking keeps raw user data local, minimizing core network congestion. When coupled with

TSN and 5G NR-U, signaling overheads decrease significantly. Collision warning models processed directly at the edge can achieve 5 ms end-to-end latency, conforming to the rigorous standards required for cooperative, high-density autonomous driving systems.

6. Open Challenges and Future Directions

Several critical technical challenges persist regarding deterministic transmission within converged IoV and in-vehicle networks [45]. First, wireless channel instability inherently limits time-synchronization accuracy across heterogeneous environments. Even utilizing the IEEE 802.1AS-Rev protocol, achieving sub-microsecond synchronization in high-mobility scenarios remains formidably difficult. Second, scheduling mixed-criticality traffic presents a significant hurdle. When autonomous driving control commands coexist with infotainment data, traditional priority-based scheduling can cause the latency jitter of critical services to exceed the 15% safety threshold [46]. Furthermore, applying network calculus to complex topologies reveals limitations; its delay upper-bound calculations are overly conservative, frequently restricting bandwidth utilization to below 70%. Additionally, the lag between standard formulation and technological advancement is increasingly apparent. The convergence of TSN and 5G URLLC protocol stacks remains in the draft phase, and the success rate in cross-vendor interoperability testing is currently suboptimal (below 60%). Looking ahead, technical development will likely pivot toward three primary vectors: dynamic artificial intelligence (AI)-driven resource scheduling algorithms, native 6G deterministic network architectures, and secure transmission mechanisms empowered by quantum encryption [47]. These innovations are essential to fulfilling the rigorous transmission performance requirements of Level 4 and Level 5 (L4/L5) autonomous driving.

6.1. Current Technical Bottlenecks

Deploying deterministic transmission in converged vehicular networks encounters multiple bottlenecks that severely constrain the Quality of Service (QoS) of critical intelligent connected vehicle (ICV) services. Traditional vehicular communication architectures employ rigid layered designs wherein fieldbuses are confined to the operational technology (OT) domain. Their limited bandwidth and protocol complexities struggle to support the information technology (IT) data flows required for AI-driven analytics [48]. This architectural dichotomy fails to satisfy the dual demands of embodied intelligence: high-bandwidth perception data and microsecond-level determinism. Specifically, when processing multi-modal sensor data for autonomous driving, performance degradation due to protocol conversion is pronounced. Furthermore, automotive Ethernet gateways must interoperate seamlessly with legacy heterogeneous networks (e.g., CAN, LIN, and FlexRay). The inherent discrepancies in timing and real-time constraints among these protocols drastically escalate system design complexity [49].

Although TSN is the prevailing solution, its operational complexity introduces significant deployment barriers. Automotive TSN applications confront four primary challenges: a lack of mature performance simulation

platforms, insufficient protocol support within Ethernet switches and endpoint silicons, an absence of dedicated testing standards, and parameterized configuration difficulties in complex scenarios. At the implementation level, mechanisms such as IEEE 802.1Qbv time-window design, IEEE 802.1CB redundancy processing, IEEE 802.1AS synchronization, and IEEE 802.1Qci ingress policing all pose profound technical hurdles. Such complex protocol suites precipitate interoperability conflicts with existing industrial standards (e.g., PROFINET or EtherCAT) during large-scale deployment [50]. Moreover, in highly complex topologies, the traffic classification accuracy achieved by current AI algorithms remains below 85%.

Wireless channel uncertainty inherently destabilizes 5G-TSN collaborative networks. Time-varying channel characteristics, exacerbated by terminal mobility-induced fast fading and shadowing, severely degrade transmission reliability. Empirical data from complex urban environments (e.g., urban canyons and tunnels) indicate that the 5G-V2X packet loss rate frequently exceeds thresholds, jeopardizing the stringent ≤ 10 ms latency imperative for autonomous driving [51]. While the 3GPP Release 16 specifications successfully demonstrate theoretical end-to-end latencies of 3 ms (urban) and 5 ms (highway) alongside 99.9% reliability, practical deployments remain plagued by high-frequency handover failures and poor cross-vendor interoperability. Legacy cellular networks, such as 4G LTE, present rigid architectural limitations—including high baseline end-to-end latency (> 50 ms), restricted connection density, and inadequate support for high-speed mobility (e.g., handover inefficiencies at speeds exceeding 500 km/h).

Inadequate resource scheduling algorithms further restrict deterministic performance. Exact-solution optimization techniques struggle to scale, failing to meet the real-time computational demands of large-scale joint scheduling [52]. While the Adaptive Frame Segmentation (AFS) algorithm excels in bandwidth utilization, its efficacy is bound by a residual bandwidth range spanning 84 to 1542 bytes; additionally, it frequently disregards strict frame deadlines to reduce computational overhead. Such algorithmic constraints complicate system-level optimization, particularly in preserving deterministic bounds amid burst-traffic conditions. Furthermore, in environments hybridizing TSN and non-TSN equipment, networks must shield critical control flows from interference without necessitating complete topological overhauls during protocol upgrades. This presents a complex co-design challenge balancing determinism with backward compatibility [53].

Finally, the inherent tension between robust cryptographic security and low-latency performance poses a substantial implementation barrier. Traditional IT security architectures are incompatible with TSN's real-time constraints. For example, integrating Media Access Control Security (MACsec) with TSN often incurs prohibitive performance penalties absent specialized hardware acceleration or optimized configurations; software-based cryptography routinely yields severe jitter and packet loss during stress testing. This security-performance trade-off is deeply exacerbated in vehicular networks, where systems must simultaneously satisfy rigorous functional safety standards (e.g., ISO 26262) and neutralize increasingly sophisticated cybersecurity threats [54].

6.2. Advance in Standardization

The current standardization process of deterministic network technology is experiencing unprecedented cross-organizational collaborative development. The first independent resolution on IoV passed by the International Telecommunication Union (ITU) in 2024 is of milestone significance. It not only provides policy support for the formulation of global IoV information and communication standards but also promotes the establishment of a technical framework for cross-border interconnection. This breakthrough progress indicates that IoV technology has entered a fast lane of international standardization development [55]. China has also made important progress in the standardization construction of IoV. The upcoming mandatory national standard GB 45672-2025 “In-Vehicle Emergency Call System (AECS)” will promote the connection rate of new vehicles to reach 100%, while the concurrently released GB/T 45315-2025 “Technical Requirements and Test Methods for In-Vehicle Information Interaction System Based on LTE-V2X Direct Communication” effectively solves the interoperability problem of basic safety communication between vehicles from different manufacturers. This model of complementary mandatory and recommended standards builds a complete technical specification system for industrial development.

The Time-Sensitive Networking (TSN) technical standard system has matured, forming a complete protocol cluster containing 12 core standards [56]. Starting from the two basic standards of IEEE 802.1AS time synchronization protocol and 802.1Qav traffic shaping protocol, it has gradually expanded to a standardization system covering three key technical areas: time synchronization, traffic scheduling, and fault-tolerant communication. It is worth noting that the IEEE 802.1Qcc standard has been integrated into the IEEE 802.1Q-2022 standard, reflecting the continuous optimization characteristics of the TSN protocol stack. In the standard formulation process, all TSN standards have formulated clear handling mechanisms for “Unimplemented Behavior,” such as the provision in the Qbv standard regarding the default fully open state when GCL is not configured. These design details significantly enhance the reliability and determinism of standard implementation [57].

Automotive Ethernet standardization presents distinctive characteristics of integrated technological development. The industry has reached a consensus on physical layer interface standards. The automotive Ethernet physical layer consistency verification specification based on IEEE/OPEN Alliance standards has become a necessary condition for chip manufacturer product access. The latest compliance solutions fully support Gigabit Ethernet (IEEE 802.3ch) and 10BASE-T1S (802.3cg) standards, both meeting the test requirements stipulated by the OPEN Alliance [58]. This comprehensive standardization from the physical layer to the application layer significantly simplifies whole-vehicle electronic architecture design, providing reliable support for high-speed data transmission of sensors such as high-definition cameras and LiDAR. In terms of protocol compatibility, the vehicle external diagnostic network communication system constructed by the GB/T 43258.2-2023 standard realizes the standardization of data interaction between ECUs and diagnostic equipment through the DoIP gateway.

The standardization synergy between 5G and TSN has achieved breakthrough progress. The 5G support for TSN architecture defined in 3GPP R16 treats the 5G system as a

TSN switch, integrating the centralized control system of the IEEE 802.1Qcc standard [59]. To realize the 5G network's support for the TSN protocol, the 5G core network and terminals have undergone specialized functional enhancements in the user plane and control plane. This deep fusion of cross-technology standards represents the highest level of wired-wireless network integration. Actual tests show that the 5G-V2X system optimized based on this standard architecture achieves low latency of 3~10ms in Vehicle-to-Vehicle (PC5) scenarios, controls latency within 10~20ms in Vehicle-to-Cloud (Uu) scenarios, and keeps latency fluctuation within 15% in high-density scenarios. Standardization of these performance indicators provides clear technical references for industrial applications [60].

6.3. Future Technological Trends

The evolution of IoV technology is developing towards multi-dimensional integration, and the synergistic convergence of 5G and TSN will become the key to building future network architectures. 5G LAN defined in 3GPP Release 17 has achieved support for TSN time synchronization. This wired and wireless converged architecture provides end-to-end deterministic transmission capabilities for the Industrial Internet and IoV. The unified orchestration system of SDN controllers shows significant advantages in closed-loop management of GCL scheduling, stream reservation (802.1Qat), and failover paths capabilities, which have been verified in industrial scenarios [61]. The deep integration of 5G and TSN is not only reflected at the protocol adaptation level but also involves the redefinition of network functions. For example, the RFC 9800 standard led by China Mobile innovatively upgrades the IPv6 protocol to a core protocol with deterministic assurance capabilities, providing technical support for wide-area deterministic transmission.

The application of artificial intelligence technology is changing the traditional mode of network resource optimization. Dynamic scheduling algorithms driven by reinforcement learning have shown clear advantages in actual testing, increasing network resource utilization by over 30% [62]. In the in-vehicle network environment, the Adaptive Frame Segmentation (AFS) algorithm achieves an average local bandwidth utilization of 94.16% through flexible frame segmentation and efficient message scheduling, an improvement of 4.35%, 5.65%, and 30.48% over frame preemption, Packet Size Aware Scheduling (PAS), and improved Qbv algorithms, respectively. This AI-driven resource allocation strategy also performs well in 5G-V2X systems, where perception-based congestion control algorithms can increase channel utilization by 25% while controlling the standard deviation of latency fluctuation to within 0.3ms. With advancements in model compression and edge computing technology, these intelligent algorithms are gradually migrating from the cloud to in-vehicle computing units, achieving faster network response.

The emergence of 6G communication technology will drive a qualitative leap in IoV [63]. The aggregated transmission of Terahertz and Sub-6GHz bands is expected to break through existing bandwidth limits, and combined with Massive MIMO and beamforming technology, can achieve ultra-low air interface latency at the 20 μ s level. In terms of protocol architecture, the deterministic cyber-physical system evolving towards 6G adopts a hierarchical reinforcement learning framework, capable of supporting global

deterministic interconnection needs. In the 6G era, IoV will achieve the integrated fusion of perception, communication, and computing. Radar and LiDAR collaborative perception systems can optimize channel resource allocation, reducing resource conflict probability by 30% in intersection scenarios and stabilizing communication latency within 3ms [64]. This deep integration marks the transformation of IoV from a simple communication medium to a core component of intelligent transportation systems.

Innovation in in-vehicle network architecture is driving transmission technology towards higher performance. Deterministic Ethernet (10BASE-T1S) is gradually becoming the first choice for car manufacturers, while the emerging IEEE P802.3dh standard lays the foundation for automotive optical fiber applications, capable of meeting strict technical requirements such as low-latency 4K video and augmented reality. The architectural model of zonal control and central computing will run a unified whole-vehicle operating system, achieving high-speed, deterministic data transmission through the zonal architecture of automotive Ethernet [65]. This architectural evolution requires not only hardware innovation but also relies on the deep application of virtualization technology. OTA technology can achieve dynamic adjustment of optical parameters in optical networks, prediction and repair of optical link faults, and dynamic reconfiguration of network topology. Modular design and plug-and-play characteristics will become significant features of future in-vehicle networks.

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