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Automotive Ethernet: Trends, Protocols, and Challenges with Reference to IEEE 1722

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Abstract: The rapid evolution of in-vehicle electronics and the growing demand for high-bandwidth, real-time data exchange have positioned Automotive Ethernet as a cornerstone of next-generation vehicle architectures. Although earlier advancements relied heavily on legacy protocols like CAN, LIN, and FlexRay, they increasingly fall short in supporting the scalability, flexibility, and performance required by modern ADAS, infotainment, and zonal systems. Automotive Ethernet, fortified by IEEE Time-Sensitive Networking (TSN) standards, now enables determin-istic, low-latency communication across multiple vehicular do-mains, fostering convergence of heterogeneous systems onto a unified backbone.

The development, important protocols, and current trends in automotive Ethernet deployment are all thoroughly examined in this review. The paper systematically examines critical technology gaps—including challenges in scalability, interoperability, real-time determinism, network complexity, and security—that impact the effectiveness and future readiness of in-vehicle networks. Drawing from current research and standardization efforts, the review proposes robust solutions and strategic directions—such as unified network architectures, advanced TSN scheduling, modular design, and integrated security frameworks—to address these systemic challenges. Specific protocols like IEEE 1722 are discussed as illustrative examples within the broader context. Ultimately, this work offers a holistic perspective on enabling scalable, interoperable, and secure Automotive Ethernet for next-generation vehicles.

Index Terms: Automotive Ethernet; IEEE 1722; Time-Sensitive Networking; AVTP (Audio Video Transport Protocol); Vehicle Communication; TSN Standards

I. INTRODUCTION

The automotive industry is undergoing a paradigm shift, driven by advancements in advanced driver assistance systems (ADAS), autonomous technologies, real-time diag-nostics, and next-generation infotainment. These applications demand high data rates, ultra-low latency, and predictable communication behavior. While traditional in-vehicle commu-nication protocols such as Controller Area Network (CAN), Local Interconnect Network (LIN), and FlexRay have served reliably for decades [6], they are increasingly unable to meet the data-centric and performance-driven requirements of mod-ern electronic control units (ECUs) and emerging software defined architectures as shown in Fig 1.

Fig. 1. Evolution of automotive communication networks: transitioning from LIN/CAN towards Automotive Ethernet with TSN and IEEE 1722.

To address these evolving demands, automotive manufac-turers are rapidly adopting Automotive Ethernet, a tech-nology that introduces the scalability, high-speed full-duplex communication, and standardized connectivity of Ethernet into in-vehicle networks [1]. Automotive Ethernet supports scalable bandwidths—from 10 Mbps to 10 Gbps—and, when combined with IEEE Time-Sensitive Networking (TSN) standards, can deliver deterministic, real-time communication suitable for safety-critical and mission-critical applications. TSN enhancements, including time synchronization (IEEE 802.1AS), traffic shaping (IEEE 802.1Qav/Qbv), and stream reservation (IEEE 802.1Qat), transform conventional Ethernet into a platform capable of supporting both control and high-bandwidth multimedia data across multiple vehicular domains [4].

A range of protocols and middleware operate over the Automotive Ethernet backbone to enable various functions, including diagnostics, over-the-air updates, sensor fusion, and synchronized audio-video streaming. Notably, protocols such as IEEE 1722 (Audio Video Transport Protocol, AVTP), SOME/IP, and Data Distribution Service (DDS) exemplify the breadth and diversity of communication standards in this domain. In order to meet the demanding requirements of contemporary vehicles, IEEE 1722—which was first created for professional audio-video applications—has been expanded to transport synchronized audio, video, and control streams in TSN-based automotive networks. It does this by collaborating with important TSN standards [9].

This paper provides a thorough analysis of Automotive Ethernet, looking at its development, underlying standards, and TSN integration. The review covers the current ecosystem of automotive communication protocols, explores emerging trends, and systematically identifies the most pressing tech-nology gaps—including those related to scalability, inter-operability, real-time performance, network complexity, and security. Drawing on recent research and industry initiatives, the paper also proposes strategic solutions and future directions for enabling robust, scalable, and interoperable in-vehicle networks. Protocols such as IEEE 1722 are discussed as illustrative examples within the broader framework. The structure of the paper is as follows: Section 2 discusses the foundations and standards of Automotive Ethernet and its integration with TSN; Section 3 presents an overview of communication protocols used in automotive networks; Section 4 provides an in-depth review of IEEE 1722 within the automotive context; Section 5 summarizes current industry trends; Section 6 identifies key technology gaps in Automotive Ethernet; Section 7 proposes solutions and future directions; and the paper concludes with a discussion of the outlook for in-vehicle networking [5].

II. AUTOMOTIVE ETHERNET: BACKGROUND AND STANDARDS

The amount of data created, processed, and exchanged within automotive systems has increased exponentially as a result of the complexity of contemporary automobiles. Tradi-tional in-vehicle networking technologies, such as Controller Area Network (CAN), Local Interconnect Network (LIN), Media Oriented Systems Transport (MOST), and FlexRay, face significant limitations in meeting the requirements of bandwidth-intensive and latency-critical automotive applica-tions. Although CAN and LIN offer robust, low-cost solutions suitable for simple control tasks, they lack the necessary bandwidth for advanced multimedia, real-time sensor fusion, and autonomous driving functions. FlexRay and MOST, while providing higher bandwidth and deterministic timing, often impose high complexity, cost, and lack flexibility for rapidly evolving automotive architectures [2].

To overcome these limitations, the automotive industry has adopted Ethernet technology, known as Automotive Ethernet, as the communication backbone for next-generation vehicles. Essentially based on IEEE 802.3 Ethernet, automotive Ethernet is modified to meet automotive-specific needs like determinis-tic communication, robustness against extreme weather, and electromagnetic compatibility using IEEE’s Time-Sensitive Networking (TSN) standards.

Automotive Ethernet provides substantial advantages over legacy protocols, notably higher data rates, full-duplex com-munication capability, and significantly simplified cable har-nesses, which in turn reduce vehicle weight and manufacturing costs. Initially, Ethernet found its automotive use primarily in diagnostics and infotainment domains. However, due to continuous enhancements, Ethernet now extends into safety-critical applications such as Advanced Driver Assistance Sys-tems (ADAS), real-time sensor integration, and even vehicle control systems [14].

Central to Automotive Ethernet’s deterministic capabilities are several IEEE TSN standards, which enable precise timing, low latency, and reliable data transmission. Specifically, the following TSN standards play crucial roles in automotive networks:

- IEEE 802.1AS (Generalized Precision Time Protocol - gPTP) which provides acurate synchronization all over the network devices.
- IEEE 802.1Qav introduces Credit-Based Shaper (CBS), enabling low-latency transmission for audio-video streams.
- IEEE 802.1Qbv (Time-Aware Shaping) ensures pre-dictable latency by scheduling transmission windows for critical traffic.
- IEEE 802.1Qcc defines centralized and distributed stream reservation and scheduling mechanisms.
- IEEE 802.1Qci (Ingress Policing) prevents network over-load by filtering non-conforming traffic at network ingress points.
- IEEE 802.1CB (Frame Replication and Elimination) in-creases reliability through redundant transmission paths.
- IEEE 802.1DG – TSN Profile for Automotive In-Vehicle Ethernet:

Defines a tailored TSN profile for automotive use, com-bining key TSN standards (e.g., 802.1AS, Qav, Qbv, CB, Qcc) to ensure interoperability, reliability, and determin-istic communication in in-vehicle Ethernet networks.

These TSN standards collectively guarantee bounded la-tency, accurate synchronization, and deterministic network behavior—critical prerequisites for automotive applications involving real-time constraints [5].

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At the physical layer, Automotive Ethernet has adopted spe-cialized PHY standards optimized for vehicle environments:

- IEEE 100BASE-T1 offers 100 Mbps transmission over single twisted-pair cables, significantly reducing cabling complexity [23].
- IEEE 1000BASE-T1 supports gigabit Ethernet for high-bandwidth applications, particularly useful in sensor fu-sion scenarios and ADAS [15].
- IEEE 10BASE-T1S provides a cost-effective, low-speed Ethernet connection (10 Mbps) suitable for sensor and actuator networks, replacing legacy bus protocols in low-bandwidth scenarios [17].
- Multi-gigabit Ethernet (2.5/5/10 Gbps) is an emerging technology aimed at supporting future applications in autonomous and connected vehicles.

In parallel, Automotive Ethernet has driven architectural changes toward zonal and centralized vehicle architectures, moving away from traditional point-to-point wiring. A zonal architecture as shown in Fig 2. aggregates data from multi-ple sensors, actuators, and Electronic Control Units (ECUs) within a specific vehicle region or ”zone,” simplifying wiring harnesses and reducing costs. Zonal gateways or switches consolidate data flows, facilitating centralized processing, and enabling more efficient software-defined vehicle strategies, such as over-the-air (OTA) updates and dynamic functionality [20].

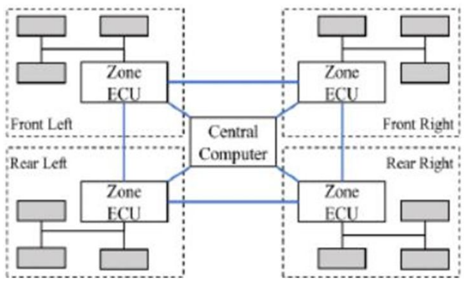

Fig. 2. Zonal Architecture [24]

In summary, Automotive Ethernet, empowered by TSN and automotive-specific physical layer standards, is rapidly becom-ing the standard backbone for future vehicles, addressing the limitations of legacy protocols, reducing complexity and costs, and meeting stringent latency and reliability requirements.

III. COMMUNICATION PROTOCOLS OVER AUTOMOTIVE ETHERNET

As Automotive Ethernet establishes itself as the foun-dational communication backbone within modern vehicles, several higher-layer communication protocols have emerged to operate effectively over this high-bandwidth, low-latency medium. These protocols enable specific applications across various automotive domains, including infotainment, diagnos-tics, control, and sensor data transmission. Key protocols as shown in Fig 3 that leverage Ethernet-based automotive networks include Scalable service-Oriented Middleware over IP (SOME/IP), Data Distribution Service (DDS), Message Queuing Telemetry Transport (MQTT), and particularly IEEE 1722, also known as Audio Video Transport Protocol (AVTP) citeref7.

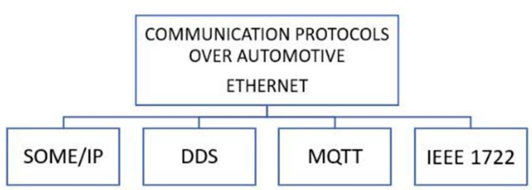

Fig. 3. Communication Protocols over Automotive Ethernet.

A. SOME/IP

An automotive middleware solution called Scalable Service-Oriented Middleware over IP (SOME/IP) makes it possible for electronic control units (ECUs) to communicate with one another in a service-oriented manner. Service discovery, event notifications, publish-subscribe communication patterns, and remote procedure calls (RPCs) are all supported by SOME/IP. SOME/IP, which is especially well-suited for automotive Eth-ernet, is a lightweight and scalable protocol that makes it easier for heterogeneous ECUs made by various vendors to communicate with one another [18].

B. Data Distribution Service (DDS)
DDS, an Object Management Group (OMG) standard, is a real-time publish-subscribe middleware designed to provide high-performance data exchange with low latency and guar-anteed Quality of Service (QoS). DDS is widely adopted in automotive applications where high reliability, determinism, and real-time communication among multiple nodes are criti-cal, such as autonomous driving systems, ADAS sensor fusion [20].

C. MQTT
MQTT is a lightweight publish-subscribe messaging proto-col suitable for automotive applications involving telemetry, diagnostics, and cloud communication. Its minimal overhead and efficient bandwidth usage make MQTT ideal for applica-tions like remote diagnostics, data logging, and fleet manage-ment systems. MQTT operates effectively over Ethernet-based vehicle networks and plays a role in interfacing in-vehicle data with cloud platforms [21].

D. IEEE 1722 – Audio Video Transport Protocol (AVTP)

Destination Address	Source Address	Ethertype	Payload
6 bytes	6 bytes	2 bytes	0-1500 bytes
AVTPDU			

Fig. 4. IEEE 1722 Audio Video Transport Protocol (AVTP) typical frame format. [7]

The frame format of IEEE 1722 is shown in Fig 4. IEEE 1722 (AVTP) is a key standard for transporting audio, video, and control data streams over Ethernet networks with deter-ministic timing. Originally developed to support high-quality audio-video streaming in professional applications, IEEE 1722 has been increasingly adapted within automotive contexts due to its synchronization capabilities, low-latency performance, and interoperability with TSN standards [14].

IEEE 1722 operates directly at Layer 2 (Data Link layer) of the OSI model, utilizing IEEE 802.1 standards (802.1AS for timing and 802.1Qav for traffic shaping) to achieve deter-ministic transmission. Key capabilities include:
- Precise Timing: Timestamps and synchronized presenta-tion time via IEEE 802.1AS (gPTP).
- Payload Diversity: Supports a variety of payload types including raw and compressed audio/video streams, time synchronization data, control data (via IEEE 1722.1 AVDECC), and CAN messages encapsulated over Eth-ernet.
- Multicast Stream Support: Uses multicast addressing to efficiently deliver streams to multiple listeners.

In addition to multimedia, IEEE 1722's flexibility allows encapsulation and transport of legacy automotive protocols, such as CAN bus data, bridging traditional automotive commu-nication into Ethernet-based networks. This interoperability is essential for phased transition strategies where existing vehicle infrastructure gradually migrates to Ethernet-based solutions [22].

IV. IEEE 1722 – DETAILED OVERVIEW

A. Introduction to IEEE 1722 and Its Role in Automotive Networks
The evolution of vehicle architectures from domain-based to Ethernet-based zonal designs has increased the demand for time-sensitive communication protocols that are both scalable and highly interoperable. IEEE 1722, known as the Audio Video Transport Protocol (AVTP), addresses this need by providing a standardized method for transporting synchronized audio, video, and diverse control data over Ethernet with de-terministic performance. Originally developed for professional audio-video (AV) installations, IEEE 1722 has become inte-gral to automotive Ethernet networks, enabling seamless data sharing between ECUs, sensors, and actuators, and ensuring interoperability across multiple communication domains [7].
IEEE 1722's importance is underscored by its ability to unify media streaming and legacy control traffic within a common transport framework. As vehicles integrate more advanced driver assistance systems (ADAS), infotainment, and real-time control functions, AVTP's extensibility and compat-ibility with TSN standards make it a cornerstone of modern in-vehicle networks.

B. AVTP Protocol Format and TSN Integration

IEEE 1722 operates at the Data Link (Layer 2) of the OSI model, encapsulating payloads within Ethernet frames and ensuring real-time delivery by leveraging TSN mechanisms. Its reliance on IEEE 802.1AS (gPTP) provides sub-microsecond network-wide time synchronization, while IEEE 802.1Qav and Qbv provide deterministic queuing and scheduling [13].

AVTP's design enables multiple stream types to coexist, including audio, video, and control data, by utilizing a set of well-defined message formats and flexible addressing schemes. Each AVTP stream is uniquely identified, timestamped, and synchronized with network clocks, which is critical for ap-plications such as surround audio, synchronized multi-camera systems, and vehicle-wide clock distribution.

TSN integration enables:

- Deterministic delivery: Guaranteed end-to-end latency, critical for safety and control applications.
- Precise synchronization: Accurate stream alignment, vital for audio-video and sensor data fusion.
- Stream redundancy and reliability: Through IEEE 802.1CB, supporting fault tolerance in safety-critical do-mains.

C. AVTP Message Types and Automotive Applications

IEEE 1722 defines multiple AVTP message types, each designed to support a unique aspect of automotive commu-nication:

1) AVTP Stream Data Messages: These are used for real-time transport of multimedia data such as:

- Uncompressed Audio (e.g., PCM): Delivers high-fidelity, low-latency audio streams, supporting advanced audio experiences such as surround sound, active noise can-cellation, and intercom systems.
- Video Streams: Transports both raw and compressed video, enabling low-latency camera feeds for driver as-sistance, parking systems, and entertainment.

Use Case Example: Multi-zone audio streaming in luxury vehicles, where AVTP ensures simultaneous, jitter-free playback across the vehicle.

2) AVTP Control Format (ACF) Messages: ACF messages enable the encapsulation of control-oriented data, supporting legacy and emerging automotive standards:

- CAN Bus Data Encapsulation: ACF allows encapsulation of classic CAN frames, providing backward compatibility and enabling phased migration from CAN to Ethernet. This is essential for existing vehicle subsystems, such as body control or powertrain ECUs.
- FlexRay and LIN Integration: Similar encapsulation sup-port for other protocols (e.g., FlexRay, LIN), facilitating data exchange between Ethernet and non-Ethernet nodes.

Use Case Example: Real-time gatewaying of CAN bus messages for diagnostic or control applications, using a single Ethernet backbone.

3) AVTP Clock Reference Format (CRF) Messages: CRF messages distribute network clock reference information, es-sential for:

- Maintaining tight synchronization between distributed AV endpoints.
- Enabling phase-locked audio and video playback, which is crucial for immersive infotainment and accurate sensor data fusion in ADAS.

Use Case Example: Synchronizing audio output across multiple amplifiers or speakers in a zonal architecture, eliminating perceptible de-lays.

4) AVTP Audio and Video Formats: AVTP defines separate formats optimized for audio and video streams, each with dedicated timestamp and payload handling.

- Audio Format: Ensures low-latency, high-fidelity audio transmission.
- Video Format: Supports both high-resolution video and low-bitrate camera feeds, allowing scalable integration from infotainment to safety-critical ADAS cameras.

C. Common AVTP Frame Features

All AVTP message types share several key features:

- Stream ID: Uniquely identifies each stream on the net-work, supporting multicast and unicast delivery.
- Timestamps: Facilitate precise playback scheduling and loss recovery.

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- Sequence Numbers: Enable detection of lost or out-of-order packets.
- Payload Types: Indicate the content carried (audio, video, control, clock).

This unified framing ensures that any AVTP-compliant device can parse and process streams according to application needs, enabling seamless integration and interoperability.

V. CURRENT TRENDS IN AUTOMOTIVE NETWORKING

The automotive industry is witnessing a period of rapid transformation, propelled by the integration of high-speed networking technologies and the shift toward software-defined, data-centric vehicle architectures. As vehicles become in-creasingly complex, several significant trends are shaping the deployment and evolution of automotive Ethernet networks and their protocol ecosystems, including IEEE 1722 [8].

1) *Migration Towards Zonal and Centralized Architectures:* Vehicle networking has historically been based on domain-based architectures, with specific communication buses for chassis, infotainment, powertrain, and body control. But the proliferation of sensors, actuators, and electronic control units (ECUs) has led to complicated and heavy wiring harnesses, which have increased in weight and cost. Automobile man-ufacturers are implementing zonal architectures in order to overcome these difficulties. These architectures divide the vehicle into physical zones, each of which is controlled by a zonal gateway ECU that is connected to a central processing node via high-speed Ethernet. This method facilitates the flexible integration of new features, increases scalability, and simplifies wiring [23].

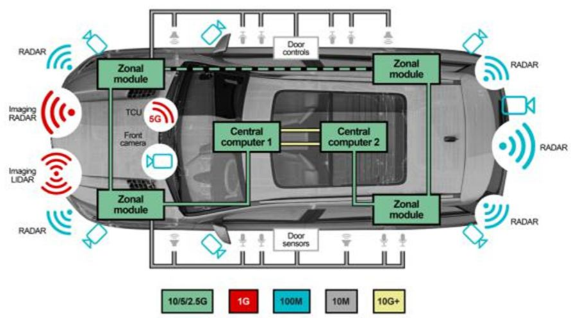

Fig. 5. Zonal architecture in a modern vehicle enabled by an Ethernet backbone [24].

Key advantages:

- Significant reduction in cabling, which lowers weight and manufacturing costs.
- Enhanced modularity, making it easier to upgrade or add features to specific zones.
- Simplified diagnostic and maintenance processes.

2) Adoption of Time-Sensitive Networking (TSN): As more safety-critical and latency-sensitive applications emerge—such as Advanced Driver Assistance Systems (ADAS), real-time video streaming, and coordinated actuation—deterministic communication becomes essential. The adoption of IEEE TSN standards (e.g., IEEE 802.1AS, 802.1Qav, 802.1Qbv) is ac-celerating within automotive Ethernet networks. TSN enables bounded low latency, guaranteed Quality of Service (QoS), and robust synchronization across the vehicle's communication backbone [9].

Industry initiatives:

- Development of IEEE 802.1DG: A profile for TSN tailored for in-vehicle networks.
- Increased deployment of TSN-compliant switches and ECUs from leading Tier 1 automotive suppliers.

3) Integration of Multiple Communication Domains: Au-tomotive Ethernet is enabling the convergence of previously isolated domains—such as infotainment, powertrain, chassis, ADAS, and telematics—onto a common high-bandwidth back-bone. This convergence supports advanced features such as sensor fusion, centralized vehicle control, over-the-air (OTA) software updates, and unified diagnostics.

4) Increasing Bandwidth and Physical Layer Innovations: The bandwidth requirements of modern vehicles continue to rise with the proliferation of high-resolution cameras, radar, lidar, and cloud connectivity. The introduction of new Ethernet physical layer standards is supporting this growth:

- 100BASE-T1 and 1000BASE-T1: Provide 100 Mbps and 1 Gbps over single twisted-pair cables, respectively.
- 10BASE-T1S: Designed for low-cost, multi-drop sensor networks.
- Multi-gigabit Ethernet (2.5/5/10 Gbps): Emerging for future applications in autonomous driving and connected vehicles.

5) Evolving Role of IEEE 1722: IEEE 1722 continues to evolve to address these new trends. Recent standardization efforts focus on:

- Enhanced support for mixed-criticality flows.
- Improved interoperability with legacy and IP-based do-mains.
- Expansion of AVTP message types to support emerging automotive use cases (e.g., sensor data, control plane traffic).

VI. TECHNOLOGY GAPS IN AUTOMOTIVE ETHERNET

A. *Justification and Problem Analysis*

To fully realize the potential of Automotive Ethernet in vehicles, a number of technological gaps and challenges need to be addressed, according to recent studies. These gaps span interoperability and integration of diverse networks, meeting real-time performance requirements, managing congestion and latency, integrating domain-specific systems, cost and scal-ability concerns, and ensuring robust security. Below, we summarize the key gaps identified in the literature, with citations to the findings of the three referenced works.

1) Real-Time Communication and Latency [5]: Providing deterministic, real-time communication over Ethernet is a central technical gap for automotive applications. Standard Ethernet was designed as a best-effort network without guaran-tees on latency or delivery order, whereas automotive control systems (e.g. for powertrain or advanced driver assistance) require predictable and low-latency data delivery. To address this gap, the industry has developed Time-Sensitive Network-ing (TSN) extensions for Ethernet.Indeed, in order to expand Ethernet with real-time services in upcoming vehicle archi-tectures, a specific TSN profile for automotive Ethernet has been developed. TSN introduces features like time-triggered scheduling and traffic shaping to bound latencies. However, achieving strict determinism remains challeng-ing – different TSN scheduling strategies involve trade-offs. For instance, Time-Aware Shaping (TAS) can guarantee the shortest worst-case latency for high-priority message streams, but it may increase the transmission delay for lower-priority traffic. On the other hand, Asynchronous Traffic Shaping (ATS) reduces determinism for critical traffic in exchange for improved average latency for all streams. These findings high-light the continuous difficulty in satisfying real-time demands: the network must give priority to urgent control messages without depriving other data of information. Ensuring bounded end-to-end latencies throughout a whole vehicle is still an open problem, and scheduling configuration is complicated and scenario-dependent even with TSN. Notably, legacy automotive networks like FlexRay were designed for determinism and fault tolerance; they excel at predictable timing but at higher cost and lower bandwidth Automotive Ethernet must close this gap by delivering comparable determinism and reliability. Recent advancements (AVB/TSN and even time-triggered Ethernet) have started to provide minimal delays and deterministic behavior over Ethernet [11], but guaranteeing real-time performance under all load conditions (and in safety-critical scenarios) is still a primary concern.

2) Interoperability and Network Integration [1]: Mod-ern vehicles contain a labyrinth of heterogeneous in-vehicle networks – including legacy buses like CAN and LIN, mid-speed networks like FlexRay, and newer high-speed links like Ethernet – which must all work in unison. Today's cars can have over a hundred electronic control units (ECUs) on board, connected by multiple bus systems and interfaces, each oper-ating at different speeds and data types. This diversity leads to complex gateways and interface requirements to enable interoperability between subsystems. For example, specialized multimedia networks (such as MOST) were introduced as a solution to link different devices and domains, illustrating the challenge of communication between heterogeneous compo-nents. A key gap is the lack of a unified networking framework Automotive Ethernet needs to seamlessly integrate with or even replace these disparate networks to simplify communi-cation architecture. Additionally, as vehicles become part of the IoT ecosystem, wireless and external connectivity must interoperate with in-vehicle Ethernet. IoT connectivity and ve-hicular networks have created new opportunities, but they have also presented difficulties, such as erratic Quality of Service (QoS) and integration difficulties. Therefore, one of the most important challenges is to ensure seamless interoperability across all of these domains.

3) Security and Safety [6]: With greater connectivity and higher data throughput, security in the in-vehicle network has become a critical gap. Traditional automotive communication buses (e.g. CAN) were not designed with cybersecurity in mind; they are inherently open and trust all nodes on the network, making it trivial for a malicious node to eavesdrop or inject messages. As a result, modern vehicle networks face risks of intrusion, data tampering, and denial-of-service attacks if not properly secured. Studies have observed that intrusions and cyber-attacks are an evident problem in vehicular systems and can degrade network performance and safety. When mov-ing to Ethernet, this challenge does not disappear – Ethernet itself has no built-in encryption or authentication at the data link layer by default. Thus, a gap exists in how to incorporate robust security measures (such as authentication, message integrity checks, and encryption) into automotive Ethernet frameworks without compromising real-time performance.

B. Proposed Solutions

To address the identified scalability and interoperability challenges, the following solutions are proposed, each sup-ported by emerging standards and industry consensus:

1) Advanced TSN-Oriented Network Design for Real-Time Communication and Latency: To address the challenge of deterministic, real-time communication over Ethernet, next-generation automotive networks should fully leverage the capabilities of the latest Time-Sensitive Networking (TSN) standards. This includes deploying a hierarchical TSN man-agement system with a centralized network controller (CNC) that dynamically configures and monitors traffic schedules across all network nodes. Such a system enables adaptive re-configuration of time-aware shapers (TAS) and queue policies based on real-time traffic patterns, system state, or fault events. By combining Time-Aware Shaping (TAS) for the most critical safety and control flows and Asynchronous Traffic Shaping (ATS) for less time-sensitive or best-effort traffic, the network can guarantee strict worst-case latency for high-priority streams while maintaining efficient utilization for all other data. Integrated network analytics should provide con-tinuous feedback on delay, jitter, and loss, enabling dynamic tuning to ensure end-to-end latency guarantees are met under all load conditions. Furthermore, network simulation and digital twin models should be employed during design to validate scheduling policies under diverse scenarios, ensuring the configuration is robust to future changes in traffic load or application re-quirements. Such simulation-driven design reduces the risk of latency violations in real deployments, especially as vehicles become more software-defined and modular.

2) Middleware-Driven, Unified Communication Frame-work for Interoperability: Overcoming the fragmentation between legacy buses and modern Ethernet networks requires an intelligent, middleware-driven integration architecture. A standardized automotive middleware platform—built on top of the service-oriented architecture (SOA) paradigm—should be introduced to abstract the differences between communi-cation protocols, providing a common API for all application domains. Unified gateway ECUs would translate between legacy buses (CAN, LIN, FlexRay) and Ethernet, encapsulating mes-sages in a common format while preserving timing and QoS information. Such gateways should support dynamic protocol adaptation and automatic QoS mapping, ensuring that mission-critical data receives the appropriate network priority regard-less of its source. To further enhance interoperability, the middleware should support seamless integration with IoT/cloud services, em-ploying modern publish/subscribe mechanisms (e.g., DDS, SOME/IP) and supporting remote diagnostics, updates, and data analytics. This approach enables plug-and-play expan-sion of vehicle capabilities, simplifies cross-domain commu-nication, and supports a scalable path from current mixed-architecture vehicles to future all-Ethernet designs.

3) Integrated Security and Safety Frameworks Tailored for Automotive Ethernet: To close the security and functional safety gap, automotive networks must implement a multi-layered, integrated security framework that provides robust protection without compromising real-time operation. At the link layer, standards like IEEE 802.1AE (MACsec) should be adopted to deliver data encryption and integrity checking natively on Ethernet. For higher-layer security, authenticated key management protocols and secure boot processes should be used to establish trust anchors and prevent unauthorized device access. For functional safety, network redundancy should be achieved through techniques like frame replication and path diversity, ensuring graceful degradation and fail-operational capabilities in the event of faults or attacks. Centralized monitoring and real-time diagnostics should be employed to detect failures early, trigger redundancy protocols, and in-form vehicle-level safety management. This holistic approach ensures that the network remains both secure and reliable, supporting the stringent requirements of next-generation, con-nected vehicles.

VII. CONCLUSION

The ongoing evolution from traditional fieldbus architec-tures to high-speed, deterministic Automotive Ethernet marks a fundamental shift in the design of in-vehicle networks. Automotive Ethernet now stands at the core of next-generation mobility, providing the scalability, bandwidth, and flexibility required for increasingly complex applications—ranging from real-time control and safety systems to rich infotainment and connected vehicle services. To fully realize the potential of Ethernet-based car architectures, new issues brought about by this transition must be methodically resolved.

This review has identified three major technology gaps that currently limit the widespread adoption of Automotive Ethernet: ensuring strict real-time communication and la-tency guarantees, achieving seamless interoperability across heterogeneous networks and legacy systems, and providing robust security and functional safety in the face of rising connectivity and cyber threats. While recent advances such as Time-Sensitive Networking (TSN) have laid the groundwork for improved real-time performance, and middleware-driven approaches promise to bridge legacy and next-generation do-mains, significant work remains.

To address these challenges, we have proposed a set of future directions: leveraging advanced TSN scheduling and centralized control for deterministic communication; deploy-ing middleware-driven frameworks and unified gateways for transparent network integration; and adopting multi-layered security and redundancy strategies tailored for automotive re-quirements. These approaches, when combined with rigorous industry standardization and collaborative ecosystem develop-ment, will be crucial for delivering scalable, interoperable, and resilient in-vehicle networks.

Ultimately, the continued collaboration between standard-ization bodies, OEMs, suppliers, and the research community will drive the successful realization of truly future-proof automotive Ethernet networks. By proactively addressing these technology gaps, the automotive industry can pave the way for safer, smarter, and more connected mobility—meeting the demands of tomorrow's vehicles and their occupants.

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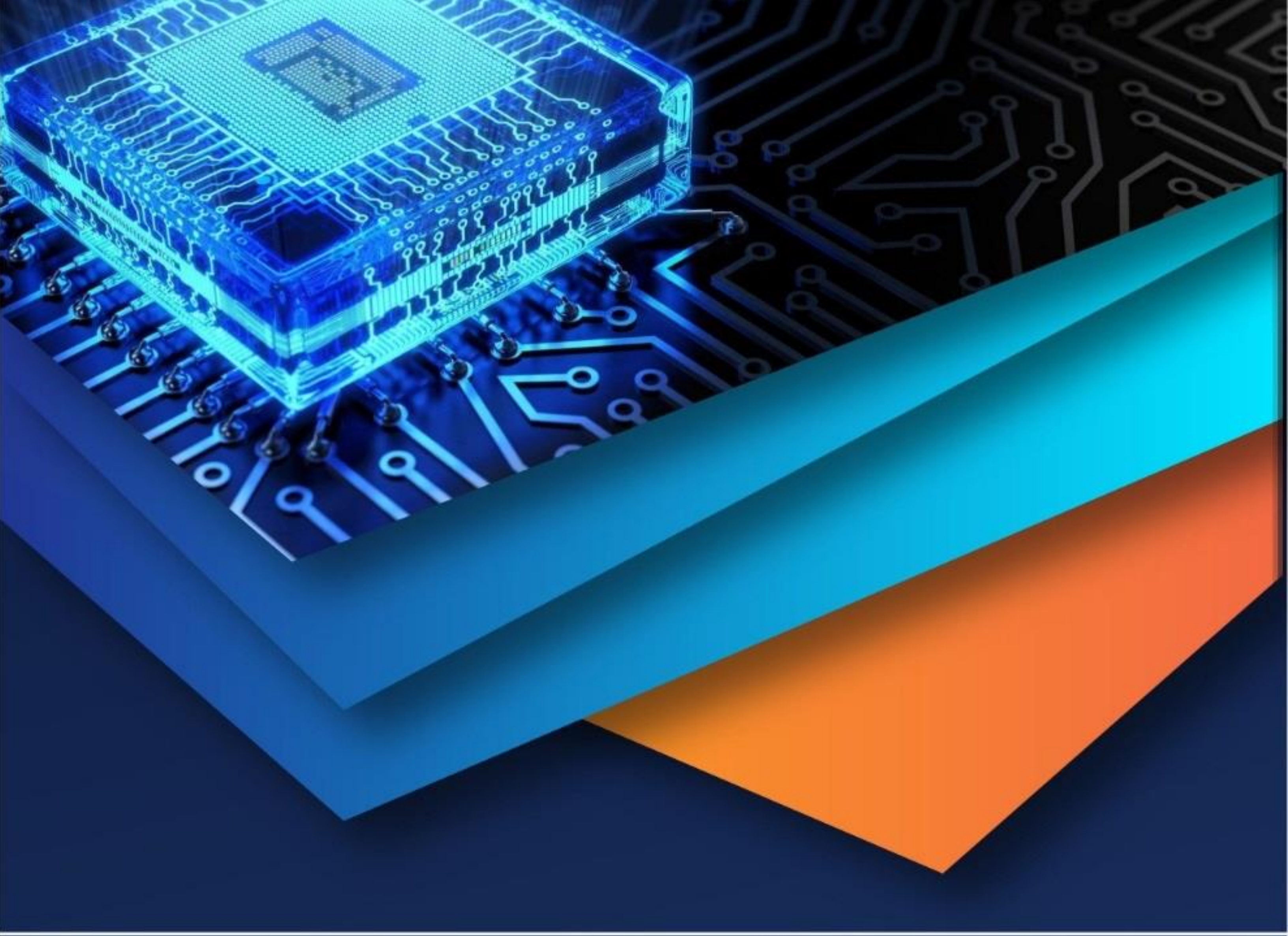

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