World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Check for updates

Automotive ethernet: High-speed in-vehicle networking for next-generation electronics

Aktarasayad Wallibai [1, *] and Gururaj. R. Deshpande [2]

[1] *Department of Mechanical Engineering, Government Polytechnic Vijaypur, Karnataka, India.*
[2] *Department of Automobile Engineering, Government Polytechnic, Belagavi, Karnataka, India.*

World Journal of Advanced Research and Reviews, 2020, 08(02), 353–368

Publication history: Received on 20 October 2020; revised on 24 November 2020; accepted on 27 November 2020

Article DOI: https://doi.org/10.30574/wjarr.2020.8.2.0359

Abstract

This research paper explores the adoption and implementation of Automotive Ethernet as a high-speed, low-latency in-vehicle networking solution that addresses the increasing demands of next-generation automotive electronics. The growing complexity of modern vehicles, driven by advancements in connectivity, autonomous driving technologies, and electric powertrains, has outpaced the capabilities of traditional automotive networks such as CAN, LIN, and MOST. Automotive Ethernet emerges as a scalable and flexible alternative, offering higher bandwidth, reduced wiring complexity, and improved interoperability with existing systems. The study begins by examining the evolution of in-vehicle networks, highlighting the limitations of legacy architectures and the need for more advanced networking solutions. It delves into the technical architecture of Automotive Ethernet, covering the physical layer, network topology, and key standards like 100BASE-T1 and 1000BASE-T1. Moreover, the paper discusses the integration of Time-Sensitive Networking (TSN) to ensure deterministic communication for critical automotive applications, such as Advanced Driver Assistance Systems (ADAS) and vehicle-to-everything (V2X) connectivity. Beyond technical details, the paper evaluates the diverse applications of Automotive Ethernet, ranging from infotainment systems to diagnostic and prognostic capabilities, and the role it plays in supporting domain controllers and zonal architectures in modern vehicle platforms. Performance factors, including signal integrity, electromagnetic compatibility (EMC), and quality of service (QoS), are analyzed to underscore the robustness of Automotive Ethernet in real-world environments. Finally, the paper addresses key integration challenges, such as coexistence with legacy networks, software and middleware development, and cybersecurity concerns. Looking ahead, it explores future trends and opportunities, including multi-gigabit Ethernet, energy-efficient designs for electric vehicles, and integration with 5G and V2X technologies. By synthesizing current research, industry standards, and future prospects, this paper provides a comprehensive outlook on the pivotal role of Automotive Ethernet in enabling the next generation of connected and autonomous vehicles.

Keywords: Automotive Ethernet; In-Vehicle Networking; High-Speed Networks; Time-Sensitive Networking; Advanced Driver Assistance Systems

1. Introduction

The automotive industry is undergoing one of the most significant transformations in its history, fueled by rapid advancements in electronics, connectivity, autonomous driving technologies, and the shift towards electric vehicles (EVs). These innovations are reshaping the architecture of modern vehicles, making them increasingly complex and data-intensive. From Advanced Driver Assistance Systems (ADAS) and infotainment to vehicle-to-everything (V2X) communication and predictive maintenance, modern automobiles are now sophisticated computing platforms that require high-speed, reliable data transmission for optimal performance [1].

*Corresponding author: Aktarasayad Wallibai

Traditional in-vehicle networking solutions, such as Controller Area Network (CAN), Local Interconnect Network (LIN), and Media-Oriented Systems Transport (MOST), were originally designed for simpler, lower-bandwidth applications. These technologies have served the industry well for decades but are now reaching their limitations as vehicle systems demand greater data bandwidth, lower latency, and more scalable architectures. In particular, the emergence of autonomous driving systems, advanced telematics, and real-time diagnostics requires a new kind of network infrastructure capable of supporting vast amounts of data in real-time, while maintaining robustness and security.

Automotive Ethernet has emerged as a promising solution to these challenges, offering a high-bandwidth, low-latency networking architecture that is both scalable and cost-effective. Unlike traditional Ethernet used in consumer and enterprise environments, Automotive Ethernet has been specifically tailored to meet the stringent requirements of automotive applications, such as electromagnetic compatibility (EMC), safety, and reliability. It supports data rates ranging from 100 Mbps (100BASE-T1) to 10 Gbps and beyond, enabling it to handle the high data throughput required for complex vehicle systems like sensor fusion, over-the-air (OTA) updates, and real-time communication between various vehicle domains.

The adoption of Automotive Ethernet not only enhances vehicle performance but also simplifies the overall electrical architecture. By reducing the complexity and weight of wiring harnesses, it leads to cost savings and improved fuel efficiency, particularly in electric vehicles. Furthermore, its ability to seamlessly integrate with legacy in-vehicle networks ensures that automakers can adopt this technology gradually without needing to completely overhaul existing systems.

This paper investigates the key characteristics, benefits, and challenges of implementing Automotive Ethernet in modern vehicles. The study begins by examining the evolution of in-vehicle networks, from early point-to-point wiring to bus-based systems like CAN and LIN, and the limitations of these legacy technologies. It then introduces the fundamental principles of Automotive Ethernet, including its architecture, physical and data link layers, and key standards such as 100BASE-T1 and 1000BASE-T1. The paper also explores the diverse applications of Automotive Ethernet in areas like ADAS, infotainment, and predictive maintenance systems. Additionally, it discusses performance factors, such as signal integrity, quality of service (QoS), and electromagnetic compatibility, which are critical for ensuring the reliability of automotive networks [2].

Finally, the paper addresses integration challenges, such as the coexistence of Automotive Ethernet with traditional networks, software development, network management, and cybersecurity concerns. It concludes by highlighting future trends, such as multi-gigabit Automotive Ethernet, its role in enabling autonomous driving technologies, and its potential integration with 5G and V2X communications. By providing a comprehensive analysis of Automotive Ethernet, this paper aims to shed light on its role in shaping the future of connected, autonomous, and electrified vehicles.

2. Evolution of In-Vehicle Networks

The evolution of in-vehicle networks reflects the growing complexity of automotive systems and the need for more efficient ways to manage and transmit data within a vehicle. Early vehicle networks were relatively simple, but as electronic systems became more advanced, the demands on in-vehicle communication grew significantly, leading to the development of more sophisticated networking technologies.

2.1. Early Point-to-Point Wiring Systems

In the early days of automotive manufacturing, vehicles relied on basic, point-to-point wiring systems to connect various electrical components. Each electrical device, such as headlights, ignition systems, and radios, required a dedicated wire running from a central power source. This wiring system was simple but highly inefficient, as every new feature added to a vehicle required additional wiring, leading to increased complexity, weight, and cost. As vehicles became more feature-rich with additional electronics, the sheer volume of wiring became impractical, adding unnecessary bulk and making the vehicle more difficult to manufacture and maintain [3].

2.2. Introduction of Bus Systems (CAN, LIN, MOST)

The introduction of bus systems revolutionized in-vehicle networking by providing a more efficient way to connect multiple components using fewer wires. The Controller Area Network (CAN), introduced in the 1980s, was one of the first widely adopted automotive bus systems. CAN allowed multiple electronic control units (ECUs) to communicate over a shared data bus, significantly reducing the amount of wiring needed. It became the standard for most automotive applications requiring real-time control, such as engine management, transmission control, and anti-lock braking systems.

Following CAN, other bus systems emerged to address specific needs. The Local Interconnect Network (LIN) was developed as a lower-cost alternative for non-critical applications, such as window regulators and climate control systems. LIN is a master-slave communication protocol that is slower than CAN but more cost-effective for simpler tasks. Another important system is Media-Oriented Systems Transport (MOST), designed for infotainment and multimedia applications. MOST provides high bandwidth for transmitting audio, video, and other data-intensive media throughout the vehicle, supporting advanced infotainment features.

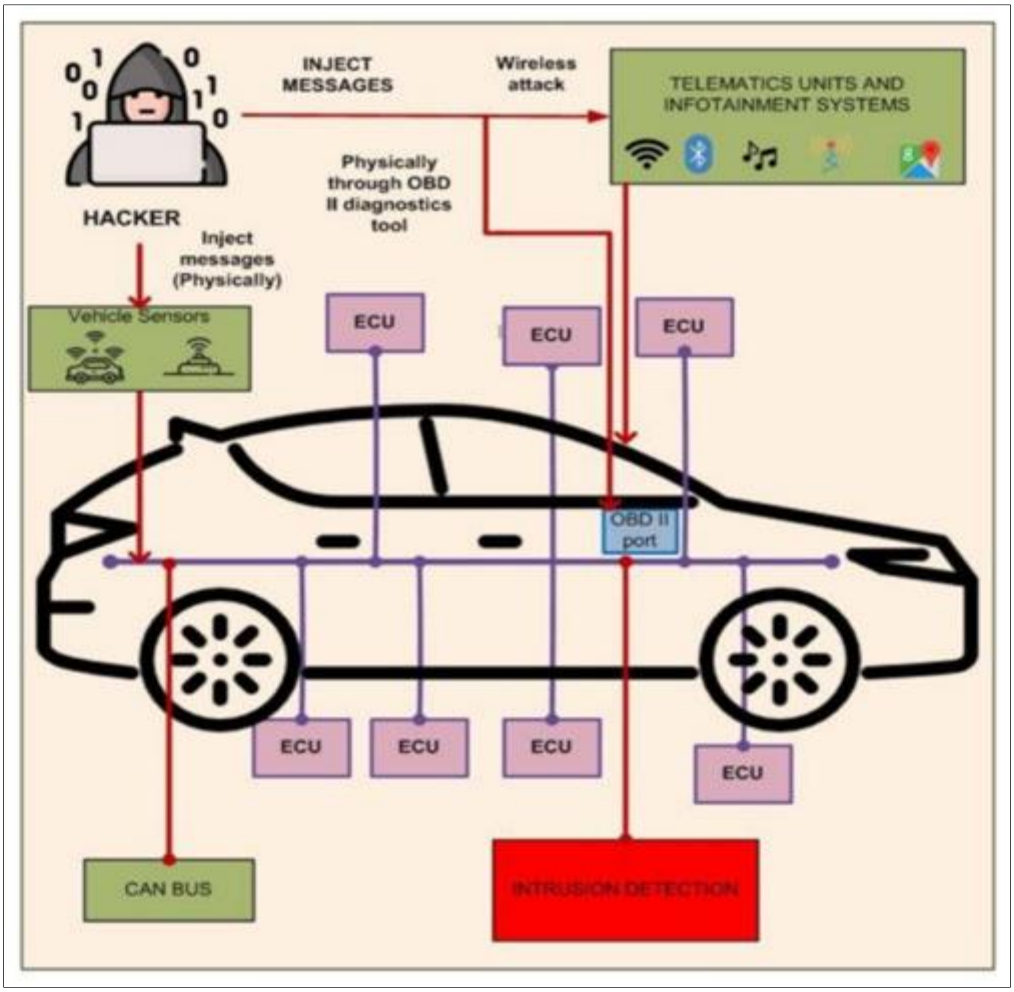

Figure 1 Timeline of In-Vehicle Network Evolution

2.3. Limitations of Traditional Automotive Networks

While CAN, LIN, and MOST have been successful in managing the growing complexity of vehicle electronics, they have their limitations. One of the main drawbacks is bandwidth. CAN, for example, operates at speeds of up to 1 Mbps, which is sufficient for many real-time control applications but inadequate for the data-intensive systems found in modern vehicles, such as high-definition infotainment, ADAS, and autonomous driving technologies. Furthermore, these systems were not designed to handle the massive amounts of data generated by the growing number of sensors, cameras, and other advanced components in next-generation vehicles.

Another limitation is scalability. Traditional bus systems, such as CAN, are not easily scalable to meet the increasing demands of interconnected vehicle domains. As more ECUs are added, managing communication between them becomes increasingly complex, and the limitations of shared bus systems in handling higher traffic loads become apparent. Additionally, maintaining multiple, separate networks for different vehicle functions (e.g., one for infotainment and another for critical control systems) adds to the complexity, weight, and cost of the vehicle's electrical architecture[4].

2.4. The Need for High-Speed, Scalable Networking Solutions

As the automotive industry moves towards more connected, autonomous, and electric vehicles, there is a pressing need for high-speed, low-latency networking solutions that can handle the vast amounts of data generated by modern vehicle systems. The proliferation of advanced driver assistance systems (ADAS), real-time diagnostics, vehicle-to-everything (V2X) communication, and over-the-air (OTA) updates requires networks that can support high bandwidth, low latency, and robust communication across multiple vehicle domains.

Automotive Ethernet addresses these requirements by offering higher data rates (ranging from 100 Mbps to 10 Gbps), reduced wiring complexity, and improved scalability. Its ability to support time-sensitive networking (TSN) for critical applications, such as ADAS and autonomous driving, makes it an ideal candidate for the future of in-vehicle networking. Furthermore, its compatibility with existing Ethernet standards allows for easier integration with broader vehicle architectures and faster innovation cycles.

3. Introduction to Automotive Ethernet

The complexity of modern vehicles, driven by the demands of advanced electronics, connectivity, and autonomous systems, has necessitated the development of a new kind of in-vehicle networking. Automotive Ethernet has emerged as a high-performance, scalable, and cost-effective networking solution specifically designed to meet the unique challenges of the automotive industry. In this section, we will define Automotive Ethernet, discuss its key features, compare it with standard Ethernet, and explore the advantages it offers over traditional automotive networks[5].

3.1. Definition and Key Features

Automotive Ethernet refers to a suite of Ethernet technologies optimized for the automotive industry. It builds on the foundational Ethernet protocols used in various industries but tailors them to meet the stringent requirements of automotive applications, such as robustness, electromagnetic compatibility (EMC), low latency, and high reliability. Unlike traditional automotive networks, which are domain-specific and often isolated from each other (e.g., CAN for control systems, MOST for infotainment), Automotive Ethernet provides a unified, flexible platform capable of handling the diverse data needs of modern vehicles. Key features of Automotive Ethernet include:

- High Bandwidth: Capable of supporting data rates from 100 Mbps (100BASE-T1) to 10 Gbps, enabling the transmission of large volumes of data required for applications like autonomous driving, ADAS, and multimedia streaming.
- Low Latency: Automotive Ethernet supports time-sensitive networking (TSN), ensuring deterministic communication and precise timing, which are critical for real-time applications like ADAS and safety systems.
- Scalability: The flexible and modular design of Ethernet networks allows automakers to scale bandwidth as needed, from simple sensor networks to fully autonomous driving systems.
- Standardization and Interoperability: Leveraging established Ethernet standards facilitates interoperability between different manufacturers and suppliers, promoting faster innovation cycles and reducing costs.

3.2. Differences Between Automotive Ethernet and Standard Ethernet

While Automotive Ethernet is based on the same fundamental principles as standard Ethernet used in consumer and enterprise networks, there are several key differences that make it suitable for automotive applications:

- Electromagnetic Compatibility (EMC): Automotive environments are subject to high levels of electromagnetic interference (EMI) from various components, including the powertrain and external sources. Automotive Ethernet is designed to operate reliably in these conditions, incorporating enhanced shielding, twisted-pair cables, and other techniques to minimize interference.
- Physical Layer (PHY) Optimization: Unlike standard Ethernet, which often uses bulky and expensive cabling, Automotive Ethernet employs lightweight, single-pair twisted cables (e.g., 100BASE-T1 and 1000BASE-T1), reducing the complexity and weight of wiring harnesses in vehicles. This is particularly important in electric vehicles, where weight savings contribute to improved range and efficiency.
- Latency and Determinism: Standard Ethernet protocols are optimized for general-purpose data transmission, often with varying latency. Automotive Ethernet, however, includes support for TSN, which ensures guaranteed delivery times for critical messages, such as those used in safety and real-time control systems.
- Cost and Space Efficiency: Automotive Ethernet systems are designed to minimize costs and space requirements by reducing the amount of wiring and connectors, which are significant factors in vehicle design. Traditional Ethernet installations in industrial or consumer settings do not prioritize these factors as critically.

3.3. Automotive Ethernet Standards

A key aspect of Automotive Ethernet is its adherence to specific standards, ensuring compatibility and performance across different manufacturers and suppliers. Some of the prominent standards include:

- 100BASE-T1: This standard supports 100 Mbps full-duplex communication over a single twisted pair of wires. It is widely used for infotainment and other medium-bandwidth applications.
- 1000BASE-T1: Supporting 1 Gbps over a single twisted pair, 1000BASE-T1 is used for high-bandwidth applications, such as ADAS, camera systems, and sensor fusion.
- 10GBASE-T1: A newer standard in development, supporting 10 Gbps communication, is expected to be a key enabler for future autonomous driving applications, which require massive amounts of data from sensors, cameras, and LIDAR systems to be processed in real-time.
- Time-Sensitive Networking (TSN): A suite of IEEE standards that ensure low-latency, deterministic data transmission across Ethernet networks. TSN is crucial for real-time automotive applications like ADAS, where precise timing and synchronization are essential for safety and performance.
- OPEN Alliance Standards: The OPEN Alliance (One-Pair Ethernet) Special Interest Group (SIG) develops additional specifications and conformance tests for Automotive Ethernet to ensure industry-wide compatibility and performance.

3.4. Advantages Over Traditional Automotive Networks

Automotive Ethernet offers several advantages over legacy automotive networks like CAN, LIN, and MOST. These benefits include:

- Higher Bandwidth: Traditional automotive networks such as CAN (1 Mbps) and LIN (20 kbps) are unable to support the high data rates required for advanced applications like autonomous driving, real-time diagnostics, and high-definition infotainment. Automotive Ethernet can provide up to 10 Gbps, making it suitable for future vehicle systems.
- Scalability and Flexibility: Ethernet's modular architecture allows automakers to scale their network infrastructure as needed, supporting everything from simple sensor networks to fully autonomous driving systems. The flexibility to add bandwidth or new applications without a complete redesign is a significant advantage in a rapidly evolving automotive landscape.
- Cost-Effectiveness: Automotive Ethernet reduces the complexity and cost of wiring harnesses by using lightweight, single-pair twisted cables. This not only lowers manufacturing costs but also reduces vehicle weight, which is particularly important for electric vehicles.
- Standardization and Interoperability: By adhering to widely adopted Ethernet standards, Automotive Ethernet ensures compatibility between different manufacturers and suppliers, simplifying integration and accelerating the adoption of new technologies. This standardization also helps reduce costs by leveraging existing technology and expertise from other industries, such as IT and telecommunications.

4. Automotive Ethernet Architecture

The architecture of Automotive Ethernet is designed to meet the rigorous demands of modern automotive systems, including high-speed data transmission, low-latency communication, and robustness against the harsh automotive environment. This section delves into the key layers and components that define the architecture, from the physical layer to switch-based network designs, ensuring that the network can accommodate a wide range of applications in connected and autonomous vehicles[6].

4.1. Physical Layer Considerations

The physical layer (PHY) is a critical component in Automotive Ethernet as it determines the medium over which data is transmitted and the electrical or optical signaling methods used. Key considerations for the physical layer include:

- Cabling: Automotive Ethernet typically employs single-pair twisted cables (SPC), such as those used in standards like 100BASE-T1 and 1000BASE-T1. These cables are lightweight, cost-effective, and offer good electromagnetic interference (EMI) resistance, making them ideal for use in automotive environments. The use of single-pair cables also reduces the overall weight of the vehicle, contributing to fuel efficiency or improved electric vehicle range.
- EMC and EMI Resistance: Since the automotive environment is fraught with electromagnetic interference from various systems like the powertrain and external sources, the physical layer must be resilient to these

disturbances. Special shielding and twisted-pair designs are employed to maintain data integrity.
- Connectors and Durability: The physical components of the Ethernet network, such as connectors, must be highly durable and able to withstand extreme temperatures, vibration, and other harsh conditions typically encountered in automotive applications.

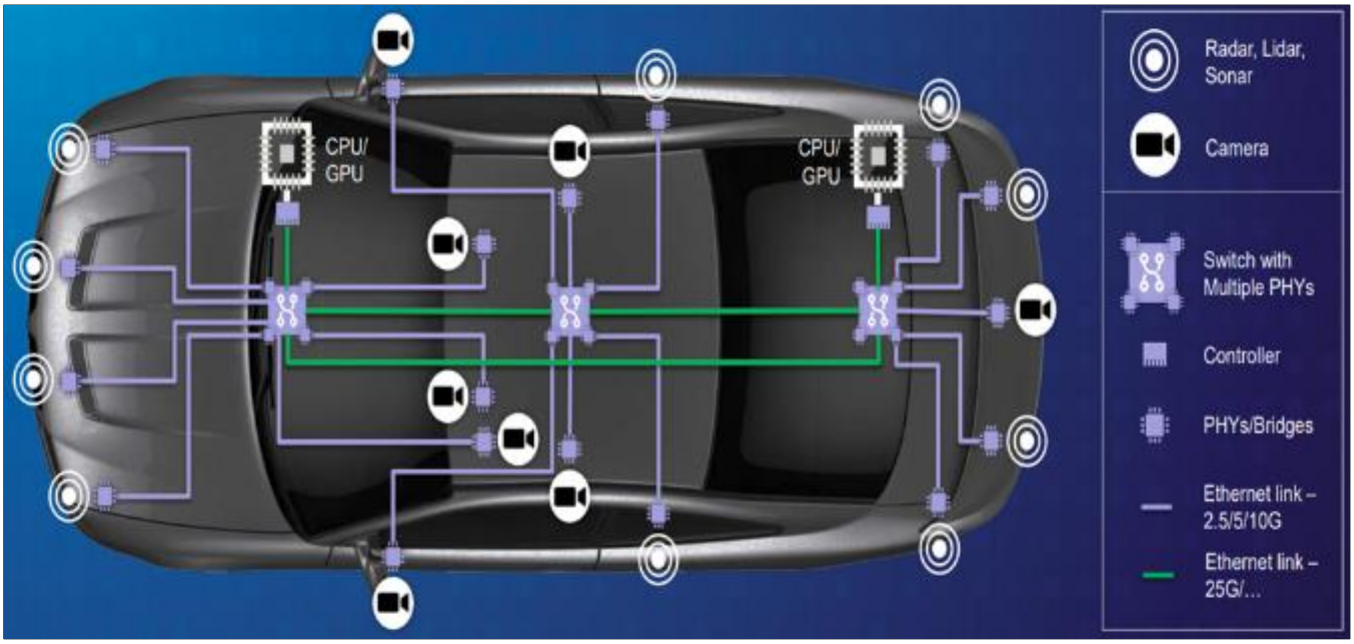

Figure 2 Automotive Ethernet Network Topology

4.2. Data Link Layer and Ethernet Frames

The data link layer in Automotive Ethernet is responsible for data framing, error detection, and medium access control (MAC). This layer ensures that data transmitted across the network is properly packaged and delivered, and manages communication between network devices.

- Ethernet Frames: At the data link layer, information is transmitted in standardized Ethernet frames. These frames consist of several fields, including the destination and source MAC addresses, frame type, payload (data), and error-checking mechanisms. The format and size of these frames allow for efficient data transmission with minimal overhead.
- Medium Access Control (MAC): The MAC sublayer controls how data is placed onto the physical medium and how access to the medium is shared among devices. In the context of Automotive Ethernet, this is crucial to ensure that multiple in-vehicle systems such as ADAS, infotainment, and control systems can communicate without collisions or delays.
- Time-Sensitive Networking (TSN): TSN protocols are integrated into the data link layer to ensure deterministic, real-time communication. This feature is essential for applications like ADAS and autonomous driving, where data transmission must happen within predictable time frames to ensure safe vehicle operation.

4.3. Network Topologies for Automotive Ethernet

Automotive Ethernet networks can be designed using various topologies, each suited to different applications and vehicle architectures:

- Star Topology: In a star topology, all devices in the network are connected to a central switch or controller. This design is commonly used in centralized architectures, where a main computing unit or domain controller processes data from multiple sensors and systems.
- Bus Topology: Although less common in Ethernet-based systems, some legacy automotive networks use a bus topology, where all devices are connected along a single communication line. This can reduce wiring complexity but is not ideal for high-bandwidth applications, making it less suitable for Automotive Ethernet.
- Ring Topology: A ring topology connects devices in a circular fashion, providing redundancy in case one

connection fails. This topology is more frequently used in safety-critical applications, such as ADAS, where reliability is paramount.
- Zonal Topology: Zonal architectures are emerging as a leading design in modern vehicles, where different zones (e.g., front, rear, driver, passenger) have their own controllers that communicate with each other via Ethernet. This approach reduces the overall amount of wiring and supports high-speed, low-latency communication between different vehicle subsystems.

4.4. Switch-Based Network Architecture

A switch-based network architecture is a defining characteristic of Automotive Ethernet, allowing for flexible, high-speed communication between multiple devices. Unlike traditional point-to-point or bus-based automotive networks, Ethernet switches can intelligently route data to its destination, avoiding unnecessary data flooding and ensuring efficient bandwidth utilization[7].

- Ethernet Switches: In Automotive Ethernet networks, switches are used to manage the flow of data between nodes (e.g., sensors, control units, infotainment systems). They operate at the data link layer and are responsible for forwarding Ethernet frames to the appropriate device based on MAC addresses. Switches help to reduce network congestion by ensuring that only the intended recipient device receives the transmitted data.
- VLANs and Segmentation: To improve performance and security, virtual LANs (VLANs) can be used to segment traffic in an Ethernet network. For example, critical data from safety systems can be isolated from less important data streams, such as infotainment traffic, ensuring that high-priority traffic gets through with minimal delay.
- Quality of Service (QoS): QoS features are built into switch-based Ethernet architectures to prioritize critical data flows. This ensures that time-sensitive applications like ADAS or braking systems receive higher priority over less time-sensitive services like media streaming.
- Redundancy and Fault Tolerance: Switch-based networks can implement redundancy mechanisms to ensure continued operation even in the event of a failure. For example, multiple paths can be set up between key systems, so if one switch or link fails, data can still be routed through alternate paths.

5. Automotive Ethernet Protocols and Standards

Automotive Ethernet operates within a framework of well-established and evolving protocols and standards that ensure compatibility, performance, and reliability. These standards are essential to ensure that vehicles equipped with Ethernet-based systems can meet stringent automotive requirements for safety, performance, and communication integrity. This section explores the key protocols and standards that govern Automotive Ethernet and their role in creating robust in-vehicle networks[8].

5.1. IEEE 802.3 Standards for Automotive Ethernet

The IEEE 802.3 standard forms the foundation of Ethernet technologies, governing the physical and data link layers of network communication. For Automotive Ethernet, several specific IEEE 802.3 standards have been developed to meet the unique requirements of in-vehicle networking:

- 100BASE-T1: This is one of the most widely adopted standards for Automotive Ethernet, offering 100 Mbps speed over a single twisted pair of copper wires. Its design focuses on reducing weight, cost, and complexity, all of which are critical for automotive applications. 100BASE-T1 also supports full-duplex communication, meaning data can be sent and received simultaneously.
- 1000BASE-T1: As vehicles require higher bandwidth for advanced functions such as ADAS and infotainment, the 1000BASE-T1 standard was introduced. It supports 1 Gbps speed over a single twisted-pair cable, while maintaining the automotive focus on low weight and reduced wiring complexity. This standard is suitable for high-resolution cameras, sensor fusion, and other data-intensive applications.
- 10BASE-T1S: This more recent standard supports 10 Mbps Ethernet over a single twisted pair and is designed for low-speed, high-robustness applications like low-end sensors and control units. It is optimized for low-cost applications and provides a scalable solution to connect various low-speed devices to the same Ethernet backbone.

These IEEE 802.3 standards have been adapted to meet automotive requirements, particularly in areas like electromagnetic interference (EMI) resistance, reduced wiring weight, and durability in harsh environments.

5.2. OPEN Alliance SIG and TC8 Specifications

The **OPEN Alliance Special Interest Group (SIG)** is an industry consortium formed to promote the wide-scale adoption of Ethernet-based communication in vehicles. This group has developed key specifications and guidelines for Automotive Ethernet, ensuring standardization and interoperability across different manufacturers and vendors.

- TC8 Specifications: The TC8 (Technical Committee 8) is responsible for developing test specifications for Automotive Ethernet components. These test suites cover various aspects of Ethernet communication, including compliance, robustness, interoperability, and electromagnetic compatibility (EMC). Compliance with TC8 specifications ensures that Automotive Ethernet components from different suppliers can seamlessly interoperate in a vehicle environment.
- Interoperability and Certification: The OPEN Alliance offers certification programs to ensure that automotive-grade Ethernet devices comply with the required standards. These certification processes help foster a competitive ecosystem where different manufacturers can produce standardized, reliable Ethernet components that work together effectively.

5.3. Time-Sensitive Networking (TSN) for Automotive Applications

Time-Sensitive Networking (TSN) is a crucial set of IEEE 802.1 standards designed to provide deterministic, low-latency, and reliable communication over Ethernet. TSN is especially vital for applications that require real-time data transmission, such as ADAS, autonomous driving systems, and drive-by-wire technologies.

Key TSN features for automotive applications include:

- Time Synchronization (IEEE 802.1AS): This standard allows devices within the Ethernet network to synchronize their clocks with high precision. In automotive applications, this ensures that data from different sensors (e.g., cameras, LIDAR, and radar) can be accurately correlated based on time, which is crucial for real-time decision-making in ADAS and autonomous systems.
- Traffic Shaping (IEEE 802.1Qav and IEEE 802.1Qbv): These standards define mechanisms for prioritizing network traffic. In an automotive network, critical data like braking commands or collision warnings are given higher priority over less time-sensitive data, such as infotainment streaming, ensuring that the most important information is delivered without delay.
- Frame Preemption (IEEE 802.1Qbu): Frame preemption allows high-priority data frames to interrupt and preempt less critical transmissions, reducing overall latency for time-sensitive data. This is especially important in safety-critical applications where delays in communication could result in accidents or system failures.
- Fault Tolerance and Redundancy: TSN incorporates mechanisms for network redundancy, ensuring that even if part of the network fails, communication can continue via an alternate path. This feature is essential for ensuring the reliability of safety-critical systems such as ADAS and autonomous driving.

5.4. Security Protocols for Automotive Ethernet

With the increasing use of Ethernet networks in vehicles, cybersecurity has become a significant concern. Automotive Ethernet networks must be secure to prevent unauthorized access, data tampering, and system attacks that could compromise vehicle safety. Several security protocols and mechanisms are employed to protect Automotive Ethernet communication:

- MACsec (IEEE 802.1AE): This protocol provides security at the MAC (Media Access Control) layer, ensuring that data frames are encrypted and authenticated. MACsec prevents unauthorized devices from participating in the network and protects data from being intercepted or modified during transmission. It also includes features for replay protection, ensuring that previously transmitted data frames cannot be maliciously resent to disrupt system operation.
- IPsec (Internet Protocol Security): Although IPsec is traditionally used in IP-based networks, it can also be applied to Automotive Ethernet when TCP/IP protocols are used. IPsec ensures end-to-end encryption and authentication of IP packets, providing a secure communication channel for data transmission between different systems in the vehicle.
- Secure Boot and Firmware Updates: Secure boot mechanisms ensure that only trusted firmware and software can run on automotive control units. This prevents malicious code from being executed during vehicle startup. In addition, secure firmware update protocols are essential to ensure that any updates to the vehicle's Ethernet-based systems are authenticated and encrypted, preventing unauthorized modifications.

- Intrusion Detection and Prevention Systems (IDPS): Automotive Ethernet networks can also implement IDPS to detect and mitigate security threats in real time. These systems monitor network traffic for signs of abnormal activity or known attack patterns and take corrective actions, such as isolating compromised devices or blocking malicious traffic.

6. Applications of Automotive Ethernet

As vehicles become increasingly connected, autonomous, and data-driven, Automotive Ethernet plays a pivotal role in enabling various high-performance applications. These applications require fast, reliable, and scalable communication networks to function optimally. This section explores the key areas where Automotive Ethernet is being deployed, revolutionizing the architecture and capabilities of modern vehicles[9].

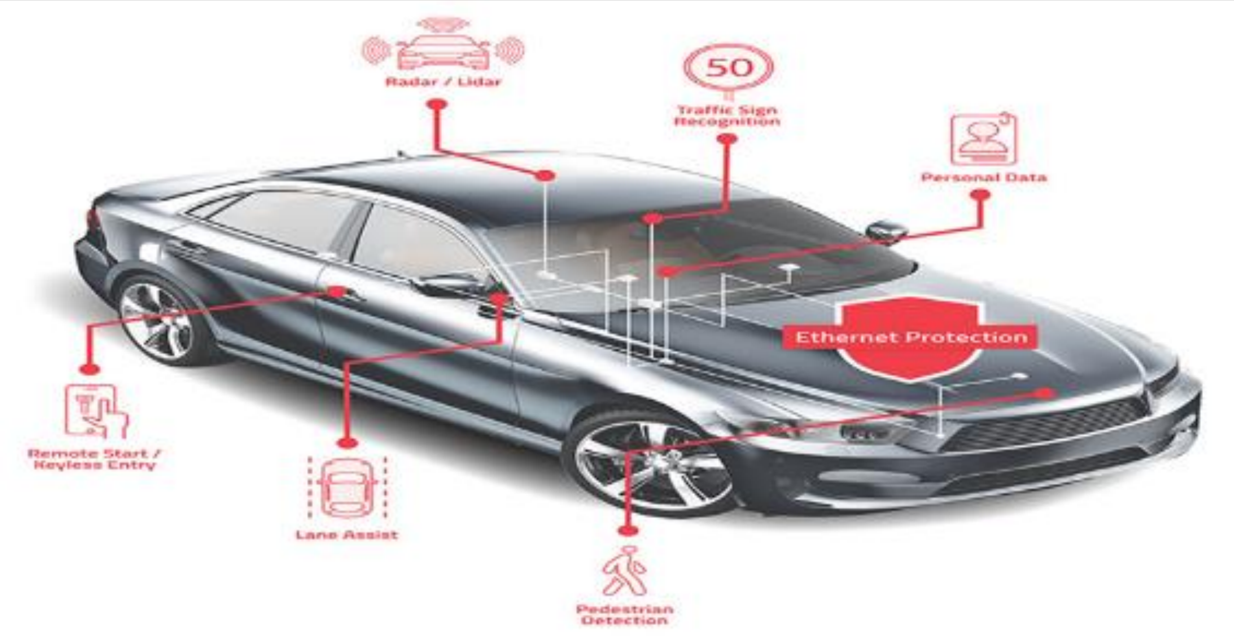

Figure 3 Automotive Ethernet Applications in Modern Vehicles

6.1. Advanced Driver Assistance Systems (ADAS)

Advanced Driver Assistance Systems (ADAS) are among the most data-intensive applications in modern vehicles. ADAS technologies, such as lane-keeping assistance, adaptive cruise control, emergency braking, and parking assistance, rely on multiple high-resolution sensors like cameras, radar, and LIDAR. These systems require real-time data processing to enhance vehicle safety and automation.

Automotive Ethernet enables ADAS by providing high-bandwidth, low-latency communication between various sensors, actuators, and control units. Some of the key advantages of using Ethernet in ADAS include:

- High Bandwidth: With data from cameras and sensors streaming at high resolutions, Automotive Ethernet provides the necessary bandwidth for fast and efficient communication.
- Real-Time Data Processing: Ethernet's low latency and support for Time-Sensitive Networking (TSN) ensure that critical sensor data is transmitted and processed without delay, enabling quick decision-making for collision avoidance, pedestrian detection, and lane correction.
- Scalability: Automotive Ethernet can support multiple ADAS features simultaneously, ensuring that as new technologies are developed, they can be integrated into the same network without compromising performance.

6.2. Infotainment and Connected Car Services

The modern vehicle is no longer just a mode of transport—it has become a connected entertainment hub. Infotainment systems, including high-definition video streaming, navigation, hands-free calling, and internet access, demand reliable high-speed data transmission to ensure a seamless user experience. Automotive Ethernet is critical in enabling these systems:

- High-Definition Video Streaming: Ethernet can handle the large data streams required for high-definition video, allowing for crystal-clear display and real-time entertainment.
- Fast Data Sharing: With multiple passengers often connecting their devices to the car's network, Ethernet's high throughput ensures fast data sharing and internet access without latency.
- Connected Car Services: Automotive Ethernet supports vehicle-to-everything (V2X) communication, allowing cars to communicate with infrastructure, other vehicles, and cloud services. This enables features like real-time traffic updates, remote diagnostics, and over-the-air (OTA) updates, keeping the vehicle's software up-to-date and improving user experience.

6.3. Diagnostic and Prognostic Systems

Automotive Ethernet plays a key role in enabling advanced diagnostic and prognostic systems within vehicles. These systems continuously monitor the health and performance of critical components, identifying issues before they become severe and allowing for predictive maintenance.

- Real-Time Diagnostics: Ethernet enables the continuous flow of data from various electronic control units (ECUs) and sensors to central processing units, where it is analyzed for any signs of wear or malfunction. This real-time diagnostic capability ensures that vehicle health is constantly monitored, minimizing the risk of unexpected failures.
- Predictive Maintenance: Using Ethernet-based communication, data from the vehicle is transmitted to cloud-based servers, where advanced analytics can predict when certain parts or systems are likely to fail. This allows vehicle owners and fleet managers to schedule maintenance proactively, reducing downtime and improving vehicle reliability.
- Remote Updates and Monitoring: Through connected services enabled by Ethernet, vehicle diagnostic data can be sent to the manufacturer or service provider remotely. This allows for over-the-air software updates and remote issue resolution without the need for a physical visit to a service center.

6.4. Domain Controllers and Zonal Architectures

As vehicles evolve towards more centralized and modular architectures, domain controllers and zonal architectures are becoming increasingly common. In these setups, vehicle functions such as body control, powertrain, infotainment, and ADAS are managed by centralized domain controllers, reducing the complexity of wiring and control units.

Automotive Ethernet is essential to enabling these architectures:

- Domain Controllers: Domain controllers manage specific vehicle domains (e.g., powertrain or ADAS), requiring high-speed communication between the sensors, actuators, and controllers. Ethernet's scalability and high bandwidth make it an ideal solution for transmitting large amounts of data between these systems.
- Zonal Architectures: In a zonal architecture, the vehicle is divided into several zones, each with its own controllers that communicate with the central control unit over Ethernet. This reduces the complexity and weight of the wiring harness, as multiple systems in a zone can share the same communication backbone. Ethernet also simplifies the integration of new systems as vehicle architectures evolve. Zonal architectures supported by Automotive Ethernet offer several advantages, including:
- Reduced Wiring Complexity: Fewer, more efficient wiring connections reduce both the cost and weight of the vehicle.
- Scalability: New features can be added to zones without needing major changes to the vehicle's overall network architecture.
- High Data Transfer Rates: Ethernet supports the rapid data exchange required to operate multiple subsystems within each zone, such as sensors, cameras, and actuators.

7. Performance and Testing

The performance and reliability of Automotive Ethernet are critical to its success in modern vehicles. As with any high-speed networking technology, Automotive Ethernet must meet stringent requirements in areas like electromagnetic compatibility (EMC), signal integrity, latency, and overall quality of service (QoS). Testing for conformance and interoperability is equally crucial to ensure that various components and systems work seamlessly together. This section outlines the key performance factors and testing methodologies used to validate the robustness of Automotive Ethernet in automotive environments [10].

7.1. Electromagnetic Compatibility (EMC) Considerations

Electromagnetic compatibility (EMC) is a major concern for any communication system in an automotive environment due to the presence of various electrical systems that can generate electromagnetic interference (EMI). These systems include powertrains, infotainment systems, ADAS sensors, and more, all of which can cause interference in the high-speed Ethernet network if not properly managed.

- **Shielding and Grounding**: Ethernet cables and connectors used in vehicles must be shielded to protect against electromagnetic interference. Effective grounding is also necessary to minimize EMI.
- **EMC Standards**: Automotive Ethernet must comply with stringent EMC standards, such as ISO 7637 (for transient disturbances) and CISPR 25 (for radiated and conducted emissions). These standards ensure that the Ethernet system does not cause interference with other vehicle electronics and is immune to external noise.
- **Testing for EMC**: EMC testing involves subjecting the Automotive Ethernet system to various forms of electrical noise and measuring its performance. This is typically done in specialized EMC testing chambers that simulate the harsh electromagnetic environment of a vehicle.

7.2. Signal Integrity and Noise Reduction Techniques

Signal integrity is essential for reliable communication over Ethernet in automotive environments. Factors such as long cable runs, electromagnetic noise, and varying environmental conditions (e.g., temperature and humidity) can degrade signal quality, leading to data loss or transmission errors.

- **Twisted-Pair Cabling**: Automotive Ethernet typically uses twisted-pair cables (e.g., 100BASE-T1 and 1000BASE-T1) that are designed to reduce electromagnetic interference between the two wires. This minimizes crosstalk and improves signal integrity.
- **Noise Reduction**: To further improve signal integrity, Automotive Ethernet employs various noise reduction techniques, such as echo cancellation, which helps filter out unwanted noise that may interfere with data transmission.
- **Advanced Signal Processing**: Modern Automotive Ethernet implementations use advanced signal processing techniques to correct for any transmission errors. For instance, error detection and correction algorithms ensure that corrupted data is identified and retransmitted, improving overall reliability.

7.3. Latency and Quality of Service (QoS) Management

Latency and QoS are critical performance metrics for Automotive Ethernet, particularly in applications that require real-time communication, such as ADAS, autonomous driving, and safety-critical systems. Low-latency communication ensures that data from sensors and controllers is transmitted and processed quickly, allowing the vehicle to respond to changes in the environment in real time.

- **Time-Sensitive Networking (TSN):** TSN is a set of IEEE 802.1 standards that provide mechanisms for deterministic (predictable and time-bound) communication over Ethernet. TSN ensures that critical data, such as sensor data for ADAS, is prioritized over less critical data, like infotainment, to guarantee timely transmission.
- **Latency Testing**: Testing for latency involves measuring the time it takes for data to travel across the network and identifying any bottlenecks. Specialized tools are used to inject test packets into the network and measure the round-trip time.
- **QoS Management**: Quality of Service (QoS) techniques are employed to manage data traffic on the network, ensuring that critical data is given priority over less important data. This is essential for maintaining the performance of safety-critical systems in the vehicle. QoS testing ensures that the network prioritizes time-sensitive data as intended.

7.4. Conformance and Interoperability Testing

Conformance and interoperability are essential for ensuring that all components in an Automotive Ethernet network work seamlessly together, regardless of the manufacturer. Given the complexity of modern vehicles and the variety of components that need to communicate over Ethernet, rigorous testing is required to ensure interoperability.

- **Conformance to IEEE Standards**: Automotive Ethernet implementations must conform to industry standards such as IEEE 802.3 for Ethernet physical layer specifications and IEEE 802.1 for Ethernet-based networking. Conformance testing verifies that the implementation adheres to these standards, ensuring compatibility across different systems.
- **Interoperability Testing**: Interoperability testing involves verifying that different devices (e.g., ECUs, sensors, switches) can communicate effectively over the Ethernet network, even if they are from different manufacturers. This is typically done through collaboration between industry groups like the OPEN Alliance SIG, which provides test specifications for ensuring interoperability.
- **Test Automation**: Many aspects of conformance and interoperability testing are automated to accelerate the process and ensure thorough testing. Automated test systems can simulate various network conditions, including high traffic loads, noise, and failures, to ensure that the Ethernet system performs as expected under all conditions[1].

8. Integration Challenges

The adoption of Automotive Ethernet in modern vehicles offers significant advantages in terms of bandwidth, scalability, and flexibility. However, integrating it into an existing automotive ecosystem presents several challenges. These challenges stem from the need to coexist with legacy in-vehicle networks, develop appropriate software and middleware, manage complex network diagnostics, and ensure robust cybersecurity. This section delves into the key obstacles that manufacturers and engineers face when introducing Automotive Ethernet into vehicles and discusses potential solutions to these challenges.

8.1. Coexistence with Legacy In-Vehicle Networks

One of the most significant challenges in adopting Automotive Ethernet is ensuring its seamless coexistence with legacy in-vehicle networks, such as Controller Area Network (CAN), Local Interconnect Network (LIN), and Media-Oriented Systems Transport (MOST). These networks are still widely used for various vehicle functions, especially in lower-bandwidth applications like body control modules, power windows, and lighting systems.

- **Multi-Protocol Communication**: Many modern vehicles are hybrid environments where Ethernet coexists with legacy networks. This requires the development of gateways that can translate data between different communication protocols, ensuring that information flows smoothly between systems using different technologies. For instance, data from sensors on a CAN bus may need to be communicated to an Ethernet-based ADAS system, necessitating efficient protocol conversion.
- **Incremental Integration**: Due to cost constraints and the long lifecycle of automotive platforms, Ethernet integration is often implemented incrementally. This means that in the early stages of deployment, Ethernet will coexist with legacy systems, gradually replacing them as vehicles evolve. This requires careful planning of network architecture to ensure backward compatibility while leveraging the benefits of Ethernet.
- **Weight and Complexity Reduction**: While Ethernet can reduce wiring complexity in zonal architectures, the need to retain legacy networks during the transition period can initially increase the overall complexity and weight of the wiring harness. Managing this transitional phase is crucial for automotive manufacturers as they work towards fully Ethernet-based architectures [8].

8.2. Software and Middleware Development

Another significant challenge is the need for new software and middleware solutions that can support the high-speed, real-time communication required by Automotive Ethernet. Traditional vehicle networks like CAN and LIN have well-established software stacks, but Automotive Ethernet introduces new complexities due to its higher data rates and broader range of applications.

- **Middleware Development**: Middleware serves as a bridge between hardware and application software, managing communication between different electronic control units (ECUs). In an Ethernet-based system, middleware must be capable of handling higher data throughput and more complex network topologies. Middleware also plays a role in managing priorities for data transmission, especially in systems that use Time-Sensitive Networking (TSN).
- **Real-Time Operating Systems (RTOS):** Many automotive systems, especially safety-critical applications like ADAS, require real-time processing. The software must be optimized to handle real-time data processing, ensuring low-latency communication and adherence to strict timing requirements. This can be challenging when moving from legacy networks, which have deterministic timing characteristics, to Ethernet, which is

inherently non-deterministic without enhancements like TSN.

- **Software Complexity**: The integration of Ethernet in automotive systems increases the complexity of the software stack. Engineers must deal with a variety of challenges, such as synchronizing data streams, managing congestion, and ensuring that real-time and non-real-time data can coexist on the same network.

8.3. Network Management and Diagnostics

Managing and diagnosing issues in an Automotive Ethernet network is far more complex than in traditional vehicle networks. Ethernet introduces a range of new features, such as switches, routers, and multiple communication paths, which need to be monitored and managed effectively.

- **Network Topology Management**: Ethernet's flexibility allows for various network topologies, such as star, ring, or daisy-chain configurations. However, managing the complexity of these topologies—especially in a zonal architecture—requires advanced network management tools. Automotive engineers need to ensure that communication between all ECUs, sensors, and actuators remains stable and efficient.
- **Diagnostics and Fault Tolerance**: In an Ethernet-based system, diagnosing faults can be more difficult compared to simpler bus systems like CAN. Ethernet introduces new failure points, such as switches, connectors, and cables, which need to be continuously monitored. Diagnostic tools that can detect issues like packet loss, latency spikes, or bandwidth bottlenecks are essential for maintaining the network's health.
- **Remote Diagnostics and Over-the-Air (OTA) Updates**: One of the advantages of Ethernet is the ability to enable remote diagnostics and OTA updates. However, implementing these features introduces additional complexity in terms of network security, reliability, and bandwidth management. The system must be able to update software components or diagnose issues without disrupting real-time critical functions.

8.4. Cybersecurity Considerations

As vehicles become increasingly connected, cybersecurity is a top priority for manufacturers and regulators. Automotive Ethernet, with its higher data transfer rates and external connectivity (e.g., V2X communication), introduces new vulnerabilities that must be addressed.

- **Attack Vectors**: Ethernet's connection to external networks (such as the internet for connected services) opens up multiple attack vectors. Hackers could potentially gain access to critical vehicle systems, including those responsible for safety functions like braking or steering. This makes it essential to implement robust security measures at every layer of the Ethernet stack.
- **Encryption and Authentication**: Secure communication over Ethernet requires encryption and authentication mechanisms to protect against unauthorized access. Industry standards like Secure Onboard Communication (SecOC) are being developed to secure the transmission of data over Ethernet in automotive systems. However, implementing these security measures without impacting the real-time performance of the network can be a challenge.
- **Security Protocols:** Time-Sensitive Networking (TSN) introduces challenges in securing real-time communications. Security protocols must be lightweight enough not to introduce latency, while still offering robust protection. This includes ensuring secure boot processes, firewalls at the network layer, and intrusion detection systems.
- **Compliance with Security Standards**: The automotive industry is working towards compliance with emerging cybersecurity standards, such as ISO/SAE 21434, which outlines requirements for cybersecurity risk management in road vehicles. Ensuring that Ethernet-based systems meet these standards requires both hardware and software-level security considerations, from ECU-level protection to network-wide defense mechanisms[7].

9. Future Trends and Opportunities

As the automotive industry rapidly evolves, the role of Automotive Ethernet is expected to expand significantly, driven by the increasing demand for high-speed data transfer, advanced connectivity, and autonomous driving capabilities. The following trends and opportunities highlight the future direction of Automotive Ethernet, particularly as vehicles transition to more complex architectures with enhanced data-driven systems.

9.1. Multi-Gigabit Automotive Ethernet

The current deployment of Ethernet in vehicles primarily utilizes standards such as 100BASE-T1 and 1000BASE-T1, which offer bandwidths of 100 Mbps and 1 Gbps, respectively. However, future automotive applications will require even higher bandwidths to support advanced features like autonomous driving, high-resolution sensor data, and real-time data processing.

- **Multi-Gigabit Speeds**: Multi-gigabit Automotive Ethernet (e.g., 2.5 Gbps, 5 Gbps, and even 10 Gbps) is emerging as a critical requirement for handling the increased data volumes generated by modern sensors, cameras, and infotainment systems. These higher speeds will be necessary for the integration of high-definition video streams, radar, and LiDAR data used in autonomous driving applications.
- **Advanced Applications**: Multi-gigabit Ethernet will play a vital role in advanced driver assistance systems (ADAS), artificial intelligence-based decision-making algorithms, and high-speed communication between domain controllers. With multi-gigabit speeds, vehicles will be able to process massive amounts of data in real time, enhancing both safety and driving experience.
- **Future-Proofing:** As vehicles become more reliant on data-driven technologies, multi-gigabit Ethernet will provide a future-proof networking solution, ensuring that in-vehicle communication systems can support upcoming innovations without requiring significant overhauls of network infrastructure.

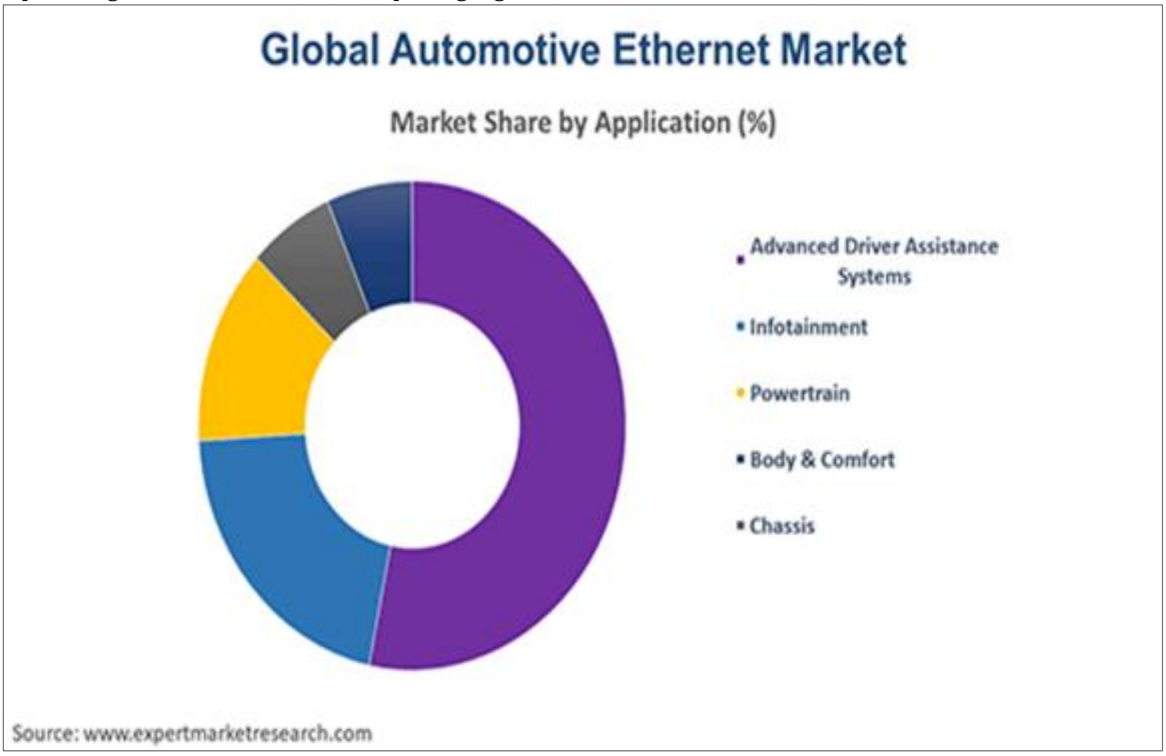

Figure 4 Projected Growth of the Automotive Ethernet Market

9.2. Integration with 5G and V2X Communications

The integration of Automotive Ethernet with emerging technologies like 5G and Vehicle-to-Everything (V2X) communications will be key to enabling connected and autonomous vehicles. These technologies, combined with Ethernet, will allow for seamless data exchange between vehicles and external infrastructure, improving overall vehicle performance and safety.

- **5G Connectivity**: The advent of 5G technology offers ultra-low latency and high data transfer rates, making it ideal for connected cars. Automotive Ethernet can work in tandem with 5G to support applications such as cloud-based services, over-the-air (OTA) updates, and real-time communication between vehicles and cloud systems for enhanced navigation, diagnostics, and autonomous decision-making.
- **V2X Communications**: V2X allows vehicles to communicate with other vehicles (V2V), infrastructure (V2I), pedestrians (V2P), and networks (V2N), improving traffic flow and safety. Ethernet-based networks inside the vehicle will handle the high-speed, low-latency data transfers required for V2X applications, ensuring that critical information is processed in real time for advanced driving assistance or collision avoidance systems.
- **Enhanced Traffic Managemen**t: The combination of 5G and V2X communications with Automotive Ethernet will enable intelligent transportation systems (ITS) where vehicles communicate with each other and the road infrastructure to optimize traffic management, reduce congestion, and increase fuel efficiency[6].

9.3. Automotive Ethernet for Autonomous Vehicles

Autonomous vehicles (AVs) represent one of the most significant opportunities for Automotive Ethernet, as these systems require ultra-reliable, high-bandwidth, and low-latency communication between various sensors, actuators, and control units.

- **Data-Intensive Systems**: Autonomous vehicles rely on data from multiple sources, including cameras, LiDAR, radar, and ultrasonic sensors. These sensors generate vast amounts of data that must be processed in real-time to make safe and accurate driving decisions. Automotive Ethernet, with its high bandwidth and low-latency capabilities, is well-suited to handle this data load, ensuring that the vehicle can respond instantly to its environment.
- **Centralized Architectures**: AVs are shifting towards centralized computing architectures, where multiple electronic control units (ECUs) are replaced with powerful domain controllers. Ethernet facilitates communication within these centralized architectures, ensuring that data is transferred quickly and efficiently between different parts of the vehicle, such as the sensor arrays, decision-making algorithms, and control systems.
- **Reliability and Fault Tolerance**: Autonomous vehicles must operate with high levels of reliability and redundancy. Automotive Ethernet supports fault-tolerant communication and redundancy protocols, ensuring that even in the event of a network failure, the vehicle can continue to function safely. Time-Sensitive Networking (TSN) protocols are particularly relevant for AVs, as they guarantee deterministic communication for safety-critical systems.

9.4. Energy-Efficient Ethernet for Electric Vehicles

As the automotive industry transitions toward electric vehicles (EVs), energy efficiency is becoming a critical focus in all aspects of vehicle design, including networking systems. Automotive Ethernet is poised to play a key role in reducing the energy consumption of EVs, supporting both performance and sustainability goals.

- **Power Efficiency**: Ethernet's inherent ability to support energy-efficient standards, such as Energy-Efficient Ethernet (EEE), helps reduce power consumption by minimizing energy use during periods of low network activity. This is particularly beneficial for electric vehicles, where preserving battery life is essential to maximizing driving range.
- **Vehicle Power Optimization**: EVs rely on sophisticated power management systems to monitor and optimize battery performance. Ethernet's high bandwidth and low latency allow for real-time monitoring and control of these systems, improving the vehicle’s energy efficiency and range. It can also support communication between the vehicle’s electric motor, battery management system (BMS), and charging infrastructure.
- **Supporting EV Charging Networks**: With the increasing deployment of fast-charging infrastructure, Ethernet can play a role in optimizing the communication between EVs and charging stations. Real-time data exchange facilitated by Ethernet will allow for more efficient charging sessions and advanced billing systems, further enhancing the EV ecosystem.

10. Conclusion

Automotive Ethernet is rapidly emerging as the backbone of next-generation in-vehicle networking, offering a high-speed, scalable, and reliable solution to meet the increasing data demands of modern automotive systems. As vehicles become more connected, data-intensive, and autonomous, traditional networking technologies such as CAN, LIN, and MOST are proving insufficient to handle the high-bandwidth and low-latency requirements of advanced driver assistance systems (ADAS), infotainment systems, and vehicle-to-everything (V2X) communications. This research has demonstrated that Automotive Ethernet's advantages in terms of bandwidth, scalability, and cost-effectiveness make it an essential technology for the future of automotive networking. With standards like 100BASE-T1 and 1000BASE-T1, and the introduction of multi-gigabit Ethernet, vehicles can now process and transmit vast amounts of data in real time, ensuring optimal performance, safety, and driving experience. The adoption of Automotive Ethernet is also critical for the development of autonomous vehicles, which require fast and reliable communication between sensors, domain controllers, and actuators. Moreover, its integration with emerging technologies like 5G, V2X, and energy-efficient systems for electric vehicles positions Automotive Ethernet as a key enabler of innovation in the industry. However, challenges remain in terms of coexistence with legacy networks, software development, cybersecurity, and the integration of complex, high-speed Ethernet systems into existing vehicle architectures. These challenges must be addressed to fully realize the potential of Automotive Ethernet, but ongoing research and industry collaboration such as the efforts of IEEE, OPEN Alliance, and other standardization bodies,are helping to pave the way for widespread adoption. Looking forward, the future of Automotive Ethernet is promising, with multi-gigabit capabilities, enhanced security protocols, and integration with 5G networks and autonomous systems all pointing toward a fully connected, data-driven, and efficient automotive ecosystem. As the automotive landscape continues to evolve, Automotive Ethernet will play a pivotal role in driving innovation, improving vehicle performance, and shaping the future of transportation. In conclusion, Automotive Ethernet represents not only an upgrade in vehicle networking technology but also a fundamental shift toward smarter, safer, and more efficient vehicles. As the demand for connectivity, autonomy, and electrification grows, Automotive Ethernet will serve as the foundation for the automotive industry's digital transformation. By enabling seamless communication between various in-vehicle systems and external networks, it will unlock new possibilities for advanced vehicle functionalities, ultimately redefining how vehicles interact with their environment and each other.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Hank, Peter, Steffen Müller, OvidiuVermesan, and Jeroen Van Den Keybus. "Automotive ethernet: in-vehicle networking and smart mobility." In 2013 Design, Automation & Test in Europe Conference & Exhibition (DATE), pp. 1735-1739. IEEE, 2013.

[2] Mahmud, Syed Masud. "In-vehicle network architecture for the next-generation vehicles." In Automotive Informatics and Communicative Systems: Principles in Vehicular Networks and Data Exchange, pp. 283-302. IGI Global, 2009.

[3] Tuohy, Shane, Martin Glavin, Edward Jones, Mohan Trivedi, and Liam Kilmartin. "Next generation wired intra-vehicle networks, a review." In 2013 IEEE intelligent vehicles symposium (IV), pp. 777-782. IEEE, 2013.

[4] Schmidt, Karsten, UdoDannebaum, and HaraldZweck. "GBit Ethernet-The Solution for Future In-Vehicle Network Requirements?." SAE International Journal of Passenger Cars-Electronic and Electrical Systems 8, no. 2015-01-0200 (2015): 289-295.

[5] Zeng, Weiying, Mohammed AS Khalid, and Sazzadur Chowdhury. "In-vehicle networks outlook: Achievements and challenges." IEEE Communications Surveys & Tutorials 18, no. 3 (2016): 1552-1571.

[6] Lim, Hyung-Taek, Lars Völker, and Daniel Herrscher. "Challenges in a future IP/Ethernet-based in-car network for real-time applications." In Proceedings of the 48th Design Automation Conference, pp. 7-12. 2011.

[7] Saraf, Pranay, PrashantBorkar, Amit Welekar, and R. C. Dharmik. "The traditional and new generation in-vehicle networks in automotive field." In Proc. of Intl. Conf. on Advances in Computer, Electronics and Electrical Engineering, pp. 535-540. 2012.

[8] Varun, C., and M. Kathiresh. "Automotive Ethernet in on-board diagnosis (Over IP) & in-vehicle networking." In 2014 International Conference on Embedded Systems (ICES), pp. 255-260. IEEE, 2014.

[9] Shreejith, Shanker, Suhaib A. Fahmy, and Martin Lukasiewycz. "Reconfigurable computing in next-generation automotive networks." IEEE embedded systems letters 5, no. 1 (2013): 12-15.

[10] Jadhav, Shriram, and Deepak Kshirsagar. "A survey on security in automotive networks." In 2018 Fourth international conference on computing communication control and automation (ICCUBEA), pp. 1-6. IEEE, 2018.Marouf, Alaa, Mohamed Djemai, ChoukiSentouh, and Philippe Pudlo. A new control strategy of an electric-power-assisted steering system. IEEE Transactions on Vehicular Technology 61, no. 8 (2012): 3574-3589.