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Review of Electrical and Electronic Architectures for Autonomous Vehicles: Topologies, Networking and Simulators

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Abstract

With the rapid development of autonomous vehicles, more and more functions and computing requirements have led to the continuous centralization in the topology of electrical and electronic (E/E) architectures. While certain Tier1 suppliers, such as BOSCH, have previously proposed a serial roadmap for E/E architecture development, implemented since 2015 with significant contributions to the automotive industry, lingering misconceptions and queries persist in actual engineering processes. Notably, there are concerns regarding the perspective of zone-oriented E/E architectures, characterized by zonal concentration, as successors to domain-oriented E/E architectures, known for functional concentration. Addressing these misconceptions and queries, this study introduces a novel parallel roadmap for E/E architecture development, concurrently evaluating domain-oriented and zone-oriented schemes. Furthermore, the study explores hybrid E/E architectures, amalgamating features from both paradigms. To align with the evolution of E/E architectures, networking technologies must adapt correspondingly. The networking mechanisms pivotal in E/E architecture design are comprehensively discussed. Additionally, the study delves into modeling and verification tools pertinent to E/E architecture topologies. In conclusion, the paper outlines existing challenges and unresolved queries in this domain.

Keywords Autonomous vehicles · Electrical and electronic architectures · Topology · Networking · Domain-oriented · Zone-oriented

Abbreviations

ACC	Adaptive cruise control
ADASs	Advanced driver assistance systems
AEB	Automatic emergency braking
AP	Adaptive platform
AUTOSAR	Automotive open system architecture
AVB	Audio and video bridge
CAN	Controller area network
CAN-FD	Controller area network with flexible datarate
CBS	Credit-based shaper
CC	Communication and computing
CP	Classic platform
CPAL	Cyber-physical action language
DCU	Domain control unit
DDoS	Distributed denial of service
DDS	Data distribution service
DoS	Denial of service
DYC	Direct yaw-moment control
E/E	Electrical and electronic
ECUs	Electronic control units
EMC	Electromagnetic compatibility
IP	Internet protocol
LAN	Local area network
LIN	Local interconnection network
MAC	Medium access control
MCU	Microcontroller unit
OEMs	Original equipment manufacturers
OPC	Open platform communications
QoS	Quality of service

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ROS	Robot operating system
SDN	Software-defined networking
SOA	Service-oriented architecture
SOC	System on chip
SOME/IP	Scalable service-oriented middleware over IP
ST	Scheduled traffic
STP	Shielded twisted pair
TSN	Time sensitive networking
UA	Unified architecture
UTP	Unshielded twisted pair
WCTT	Worst-case transmission time
ZCU	Zone control unit

1 Introduction

Automotive electrical/electronic (E/E) architectures serve as the foundational structure for in-vehicle components. These architectures describe the relationship among the components and with the environment, as well as the principles guiding the design and evolution. The pivotal role of these architectures is evident in their profound impact on the functions and performances of automotive E/E systems [1].

In recent years, the surge in electrification, intelligence, informatization and sharing has propelled advancements in modern vehicles, and the introduction of ADASs, intelligent cockpit and infotainment systems, wireless connection systems in modern vehicles continues to usher in novel experiences for users. Driven by these fast-updating technologies, the E/E components and the volume of software code in automobiles are increasing rapidly. Today, a modern vehicle may integrate dozens or even more than one hundred ECUs, driven by up to 100,000,000 lines of software code. This has led to persistent escalation of complexity and challenges in the design, development, validation, and maintenance of automotive E/E architectures [2–5].

Recently, the discussion on topologies of E/E architectures has become a hot topic. Over the past few decades, automotive E/E architectures have undergone several stages. In the early stage, when the number of Electronic Control Units (ECUs) in a vehicle was limited, a straightforward point-to-point connection was established through cables. However, with the escalating number of ECUs, this approach led to a proportional increase in E/E nodes and cable harnesses. To address this challenge, Bosch pioneered the introduction of Controller Area Network (CAN) bus technology in 1983 [6], widely implementing it in vehicles during the 1990s [7]. Thus, automotive E/E architectures evolved into a digital-bus paradigm, including CAN-based distributed control stages. With the gradual integration of chassis control, body, power, infotainment system functions, more and more digital buses appear, such as high-speed CAN bus applied in chassis, low-speed CAN bus chosen in body, and MOST bus equipped in infotainment, etc. The interaction between ECUs has become more complex, and unified message management and dis-patch center are required, so central gateway-based multiple-bus topology emerge. However, as functions and computational demands continued to surge, the number of ECUs increased substantially, resulting in complex wiring harness systems with heightened weight and cost [8]. Hence, the production and integration of ECUs and wiring harnesses became one of the most expensive components in a vehicle, trailing only the power and chassis systems in terms of cost. To address these challenges, concepts like domain-oriented architectures, characterized by functional concentration, were introduced to reduce ECUs and enhance computing power. Simultaneously, zone-oriented architectures, characterized by zonal concentration, were developed to improve wiring harness layouts. In 2015, BOSCH presented a serial roadmap for the development of E/E architectures [9], a framework widely acknowledged and discussed in both academic and industrial circles. However, misconceptions and queries persist, particularly concerning the serial roadmap's perception that zone-oriented E/E architectures follow in the footsteps of domain-oriented E/E architectures. Indeed, the serial roadmap appears challenging in satisfying the diverse requirements of Original Equipment Manufacturers (OEMs) or Tier1 suppliers due to their distinct development ecosystems and the varying demands of products and product series.

The discussion on networking technologies in the design of E/E architectures is another hot topic. In the traditional E/E architectures, E/E components are designed and developed in a distributed fashion, mainly using various bus technologies, such as CAN [10–14], CAN-FD [13–17], LIN [13, 14], FlexRay [13, 14, 18, 19] and MOST [13, 14], to connect in-vehicle ECUs for different E/E systems. These E/E/ architectures have been widely used in vehicles, such as BMW 7 series [20]. However, these bus technologies face limitations in bandwidth, characteristics, and applications, failing to meet the escalating demands of modern E/E architectures in autonomous vehicles. The inadequacies stem from two principal aspects. Firstly, none of the traditional bus technologies can adequately transmit high-definition video streams requisite for autonomous driving or advanced infotainment. For instance, a video stream with specifications of 1920×1080 resolution, 24 bits depth, 60fps, and a 10-times compression ratio demands approximately 300Mbps bandwidth [21]. Secondly, many traditional bus technologies lack security features [22], real-time capabilities, and MAC-based or IP-based scheduling capabilities, all of which are essential for modern vehicles [13, 14, 23]. In order to solve the above problems, new in-vehicle networking technologies have emerged. For example, automotive Ethernet provides high-bandwidth communication capabilities, TSN technology provides good real-time guarantees, and SOA technology provides service-oriented capabilities. While previous literature has analyzed specific vehicle networking technologies in, they are more focused on one networking technology [24–26]. There is a notable absence of comprehensive consideration for both vehicle system functions and network system design in existing literature.

In addition, modeling and simulation technologies are critical in the design phase of E/E architecture, because they can significantly reduce development costs and time. Most research, however, is focusing on the simulation of networking layer, mainly TSN technology [27], lacking discussion of the vehicle function.

This paper reviews the development of topologies for E/E architectures and networking technologies for E/E architectures. The main contributions are as follows:

(1) To solve the misconceptions and queries existing in the serial roadmap, this study conducts a comprehensive survey and analysis of E/E architecture topologies in both academic and industrial domains. Subsequently, a parallel roadmap for the development of E/E architecture topologies is proposed, concurrently evaluating domain-oriented and zone-oriented schemes.
(2) As an important role in the topology design of E/E architectures, networking technologies are studied from an up-to-date and comprehensive perspective.
(3) The simulators for E/E architectures are reviewed comprehensively, including both network layer and vehicle functions layer.

The rest of this paper is organized as follows. Section 2 reviews the development of E/E architecture topologies. Section 3 presents the application of networking technologies in E/E architectures comprehensively. Section 4 introduces the simulation verification method of the automotive E/E architectures. In Sect. 5, some challenges and open questions are discussed. Finally, Sect. 6 concludes the paper.

2 Parallel Roadmap of E/E Architecture Topology Development

This section provides an in-depth review of the current landscape in the development of E/E architecture topologies within both academic and industrial realms. It begins by introducing a well-established serial roadmap for E/E architecture topologies, which has garnered widespread recognition [9, 23]. Some misconceptions and queries existing in the serial roadmap are discussed. Therefore, a parallel roadmap for the development of topologies of E/E architectures is proposed. Finally, hybrid E/E architectures integrated with domain-oriented and zone-oriented characteristics are expected.

2.1 State of the Art of E/E Architecture Topologies in Academia and Industry

This section provides a comprehensive examination of the current state of E/E architecture topologies in both academic and industrial domains.

In academia, Stolz et al. [28] from BOSCH pioneered the integration of functions from multiple ECUs into DCUs, addressing the burgeoning complexity in E/E architecture topologies. Navale et al. [9] from BOSCH firstly introduced a roadmap of the development of E/E architecture topologies with six main stages, including modular, integration, centralization, fusion, vehicle computer, and vehicle cloud computing stage. And they discussed how to attempt to make a paradigm shift in terms of networks, safety, and security, etc. Haas et al. [29], Baic et al. [30], Saidi et al. [31], Bandur et al. [23], and Tavella et al. [32] largely agreed with Navale et al., with the addition of the concept of zone orientation in the fifth stage. Yu et al. [33] fully agreed with the roadmap of the development of E/E architecture topologies proposed by Navale et al. in 2015. Zeng et al. [13] reviewed the achievements and challenges of in-vehicle networks including LIN, CAN, FlexRay, Ethernet, and MOST, and further proposed future E/E architecture topologies with four switches and several domain masters. Brunner et al. [24] and Wang et al. [34] surveyed networking and communications technologies for autonomous driving and claimed that topologies of E/E architectures will evolve from a top-down fashion to a heterogeneous fashion. Mody et al. [35] proposed a E/E architecture topology that is composed of a central gateway and functional domains for automatic driving. Jiang et al. [1] discussed the improvements that need to be made in the E/E architecture topologies in order to adapt to the new trends in the automotive industry, including dedicated central gateways, domain masters, and zone-oriented structs. From the viewpoint of autonomous driving demand, Zhu et al. [36] analyzed the features, strengths, and weaknesses of point-to-point, vehicle bus-based, domain-based, zone-based E/E architecture topologies. Dibaei et al. [37] proposed that the topologies of E/E architectures, as the underlying system technology of intelligent connected vehicles, will be developed towards a domain fashion into a centralized fashion. Walrand et al. [38] designed a topology of zone-oriented architecture with a three-layer network, which includes a core, fast, and slow network. Bandur et at. [23] considered how to use new communication technologies and modify ECU functions to promote the centralization of E/E architecture topologies, and also proposed two variants of the two centralized E/E architectures from the perspective of efficient and effective asset reuse [39]. Askaripoor et al. [40] reviewed the challenges and technologies that need to be solved in the process of configuring and integrating key applications into the vehicle central computer when the topologies of E/E architectures evolve from decentralized to centralized, such as challenges of software configuration and mapping for automotive systems, mapping techniques and optimization objectives for mapping tasks to multi-core processors. In a recent study, Deng et al. [41] studied the modeling and design methods from AVB to TSN, and proposed domain-based and zone-based TSN-based automotive E/E architectures.

In industry, the evolution of E/E architecture topologies have received extensive attention from OEMs and Tier 1 suppliers [42]. Taking the Tesla model series as an example, Tesla Model S/X uses the traditional E/E architecture topology with a central gateway, and Model S has a wiring harness system with a length of 3000 m. Model 3/Y adopts a zone-oriented three-domain E/E architecture, which greatly reduces its wiring harness to 1500 m and 100 m. Other OEMs such as Volkswagen [43], GM, BMW [44–48], and Toyota [43] have also adopted new E/E architecture topologies or released the concept of new E/E architecture topologies. In order to meet the needs of OEMs, Tier1 suppliers, such as BOSCH [9, 49], Continental [24, 49], Vector [50], Aptiv [51], and Huawei [52], are actively promoting research and development related to E/E architecture topologies. On the one hand, some Tier1 suppliers customize and develop platforms of E/E architecture for OEMs, such as Huawei's CC E/E architecture, and Aptiv's smart E/E architecture. On the other hand, some Tier1 suppliers are actively developing the core components required for the new architecture, such as DCUs.

In recent years, a typical and widely recognized serial roadmap for the development of E/E architecture topologies, initially proposed by entities like BOSCH, has been universally recognized, shown in Fig. 1. This serial roadmap includes six phases: modular, integration, centralization, domain fusion, vehicle computer with ZCUs, and vehicle cloud computing.

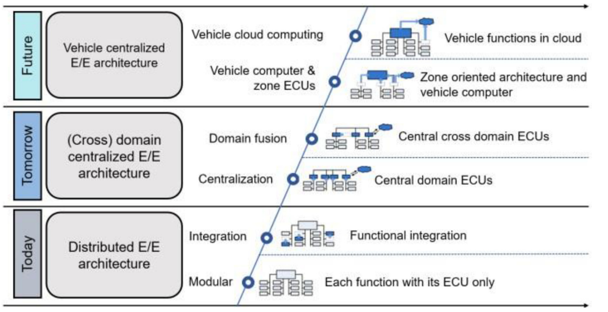


Fig. 1 A recognized serial roadmap for development of topologies of E/E architectures

2.2 Misconceptions and Queries on Serial Roadmap

The serial roadmap has provided great contributions to the research, development, and design of E/E architecture topologies for academia and industry. However, some misconceptions still exist in some publications and reports of OEMs and Tier1 suppliers R&D center, such as zone-oriented E/E architecture topologies are considered follow-up of domain-oriented E/E architecture topologies [23, 29–31]. Moreover, zone-oriented E/E architectures are considered equivalent to central-zonal E/E architectures, where a central vehicle computer is essential [24, 36, 53].

In fact, the current serial roadmap raises pertinent queries about its applicability to diverse product requirements and series specifications of OEMs and Tier1 suppliers. In practical engineering contexts, a spectrum of variants has emerged, deviating from the prescribed serial trajectory in response to distinctive technical statuses and market objectives. Illustrative instances encompass unconventional topologies like that of the Tesla Model 3, featuring left-body and right-body zone controllers along with a central control module, or Huawei's distinctive communication and computing architecture. This trend extends beyond passenger vehicles, as evidenced by non-compliant solutions tailored to the specific demands of construction-machinery vehicles, exemplified by SANY [54]. These variations highlight the substantial differences in products, product series, technical statuses, and market objectives, challenging the universality of the serial roadmap.

Moreover, for zone-oriented E/E architectures, a central vehicle computer is not essential. For example, in the E/E architecture of Tesla Model 3 or the new E/E architecture of BMW [48], functions are distributed across ECUs rather than centralized within a singular vehicle computer. The serial roadmap, inherently sequential, fails to capture the nuanced evolution of zone-oriented E/E architectures, consequently fostering misconceptions and queries among OEMs and Tier1 suppliers.

Since the above misconceptions and queries exist in the previous serial roadmap, it is necessary to clarify these issues by considering a parallel roadmap for the development of E/E architectures.

2.3 Proposed Parallel Roadmap for Development of E/E Architecture Topologies

To address the above misconceptions and queries and meet the requirements of different OEMs and Tier1 suppliers, a more fitting approach to the development of E/E architecture topologies is proposed—the parallel roadmap, as illustrated in Fig. 2.

The proposed parallel roadmap encompasses three distinct stages: the traditional E/E architectures stage, the current parallel development roadmap of E/E architecture topologies stage, and the future concentrated and vehicle cloud E/E architectures stage. In contrast to the preceding serial roadmap, the development of current E/E architecture topologies is bifurcated into a domain-oriented route and a zone-oriented route, dictated by the state of the art in E/E architectures and the diverse requirements of OEMs and Tier1 suppliers. The two routes are outlined as follows.

The domain-oriented route closely resembles the earlier proposed serial route. Its primary stage is the domain concentration stage, characterized by the integration of functions from the central gateway and numerous ECUs within each functional domain into DCUs. This integration aims to reduce the number of ECUs within the functional domain, and these DCUs are linked with the central gateway through CAN or Ethernet [34]. The high-speed point-to-point Ethernet serves as the backbone network for interconnecting DCUs. Subsequently, there is a continual integration among DCUs, exemplified by merging powertrain DCU and chassis DCU into a motion-control DCU to enhance the management of vehicle dynamics and economy. Ultimately, all DCUs are amalgamated into a single vehicle computer, realizing the integration of computing power functions and the concentration of computing power.

The transition from domain-oriented to zone-oriented E/E architectures involves several stages, including zone-centralization, part-zone fusion (Master–slave), and full-zone fusion (multi-computing). In zone-centralization, ECUs are centralized in ZCUs, which share control functions. In part-zone fusion, master-ZCUs handle most functions, while slave-ZCUs focus on network communication. Full-zone fusion sees master-ZCUs forming a computing core for high-performance computing, communicating with surrounding functionally stripped ZCUs.

Table 1 summarizes key differences between these architecture routes, encompassing ecological compatibility, scalability, functional safety, backbone network requirements, and harness cost savings. The trend is toward more centralized and cloud-based E/E architectures, aiming for higher computational power, efficient sensor fusion, reduced ECU count, and lower wiring costs while harnessing the capabilities of vehicle cloud computing for enhanced features and services.

2.4 Case Analysis of Domain-Oriented and Zone-Oriented E/E Architecture

To facilitate a comparative analysis of domain-oriented and zone-oriented E/E architectures, this section establishes and models a representative example of each architecture type.

A typical domain-oriented E/E architecture specifically in the domain-centralization stage and a typical zone-oriented E/E architecture specifically in the zone-centralization stage described in Sect. 2.1 are modeled by using a commercial

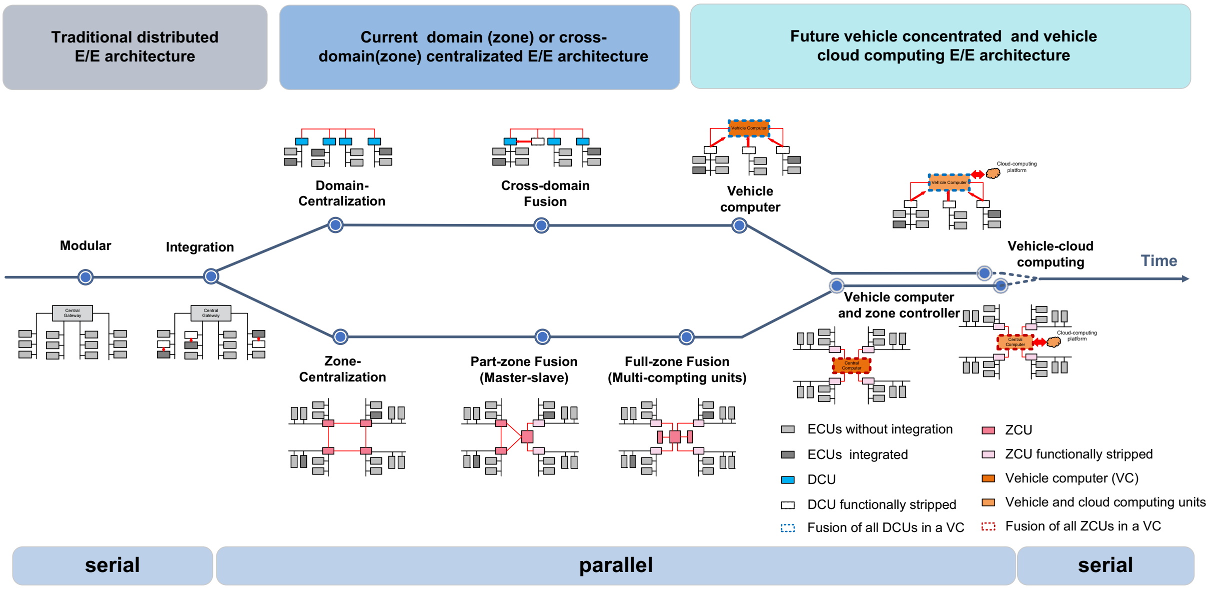


Fig. 2 Proposed parallel roadmap for development of topologies of E/E architectures

Table 1 Features and properties of domain-oriented and zone-oriented routes

	Domain-oriented route	Zone-oriented route
Features	Functions of ECUs are gradually integrated into DCUs, cross-domain DCUs and vehicle computer	Components of sensors, actuators and ECUs are connected to ZCUs nearby, with functions partly and fully centralized
Ecological compatibility	Roadmap is relatively smooth, which satisfies the ecology of most OEMs and Tier1 suppliers	More suitable for new car manufacturers in automotive industry (e.g., Tesla), and new Tier1 suppliers1 (e.g., Huawei)
Scalability and interchangeability	Subject to more limitations, such as wiring harness, intra-domain communication load, etc	Support more functional variants, plug and play with strong replaceability
Functional safety and real-time property	Integrate into domain controller according to function, it is easier to design the ASIL functional safety level of the domain controller [55]. This task is mostly accomplished by Tier1 suppliers	Difficult for functional safety design of ZCU to be provided by traditional OEMs to Tier1 suppliers for separate design. ZCU has high requirements for functional safety and multi-core controllers
Backbone network requirements	Most of data transmission is realized in each functional domain with relatively low requirements on transmission rate and transmission characteristics of Ethernet backbone	All kinds of signals will be transmitted to target electronic unit through backbone Ethernet, which imposes requirements and characteristics on transmission rate of backbone network
Harness cost saving	Less reduction in length and weight of wire harness	Reduce wiring harness and improve wiring efficiency and wiring automation

software, e.g., RTaW-Pesage [21], as shown in Fig. 3. The simulation parameters are set according to Refs. [56–58].

These two models of E/E architectures are assumed to have the same sub-system capabilities, including the same powertrain, chassis, body, infotainment, and ADAS functions [14], with the parameters of the corresponding message shown in Table 2. Other details are described as follows:

(1) In the CAN bus, chassis messages hold the highest priority, followed by powertrain messages, and then body messages.
(2) In the zone-oriented architecture, most of the chassis, powertrain and body messages involve the conversion between Ethernet and CAN networks, which is mixed transmission.
(3) ST Ethernet messages have a higher priority than AVB Ethernet messages.

In the domain-oriented E/E architecture model, the backbone comprises four DCUs: DCU1 (infotainment), DCU2 (body), DCU3 (powertrain and chassis), and DCU4 (ADAS), along with a switch. Each DCU establishes connections with the ECUs within its functional domain, facilitating message interactions for function calculation and control.

Conversely, in the zone-oriented E/E architecture model, the backbone features four ZCUs: ZCU1 (infotainment and body), ZCU2 (ADAS and body), ZCU3 (body), and ZCU4 (body, powertrain, and chassis), alongside four switches. Each ZCU connects to the nearest ECU. If the corresponding computing function is housed in the ZCU, the ECU's message is directly transmitted to the cell for computation. In cases where the computing function is not available, the ZCU utilizes only the routing function to transmit the message to another ZCU.

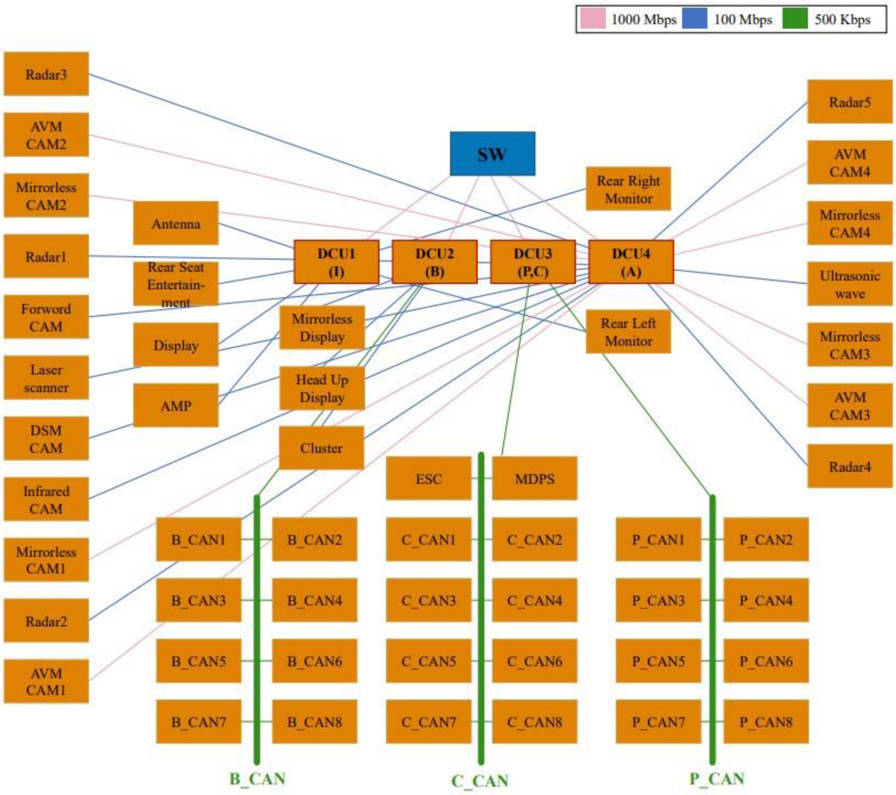
For the network performance analysis of automotive E/E architectures, the end-to-end WCTT serves as the upper limit for transmission delay and is considered the reference value for real-time message transmission [17, 21, 56–61]. The WCTT of various messages, including those related to body, chassis, powertrain, ST messages for ADAS, and AVB messages for ADAS and infotainment, are presented in Table 3. To compare the architecture performances, a radar chart is constructed using parameters such as ECU reduction, wiring harness neatness, and real-time capabilities for different functions, as depicted in Fig. 4.

2.5 Hybrid E/E Architectures

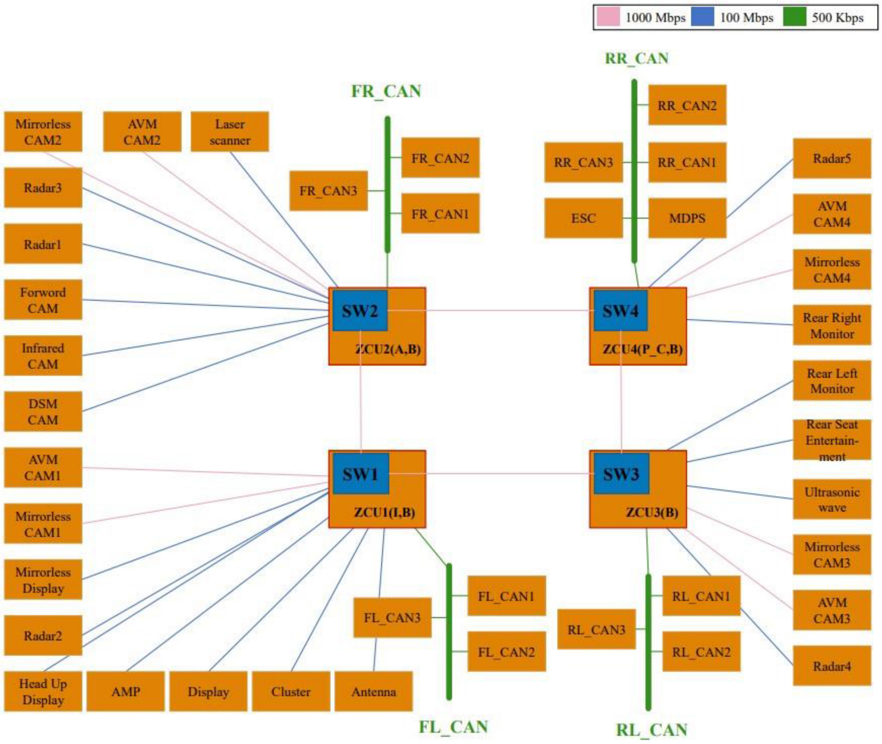
The development of hybrid E/E architectures intend to fully utilize advantages from both domain-based and zone-based architectures, aiming for superior overall performance. The envisioned roadmap, as depicted in Fig. 5, outlines the progressive stages in the evolution of hybrid E/E architectures.

In the initial phase, the hybrid architecture maintains the number of DCUs, but a shift occurs as functions residing in the DCUs transition to zonal controllers. This strategic move allows numerous ECUs to connect to nearby ZCUs, effectively minimizing wiring harness complexity. Subsequently, several DCUs collaboratively form a centralized control, interconnected either with each other or with ZCUs through high-speed Ethernet. The remaining ECUs exclusively connect to ZCUs, further streamlining the wiring harness.

Fig. 3 Models for two different E/E architectures



(a) Domain-oriented E/E architecture



(b) Zone-oriented E/E architecture

Table 2 Modeling parameter setting

Functions	Message parameters settings
Powertrain	16 messages with 20 ms period
Chassis	20 messages with 20 ms period
Body	16 messages with 50 ms period, 2 streams with 100 Mbps
Infotainment	5 messages with 100 Mbps (AVB)
ADAS	10 messages with 100 Mbps (AVB, ST), 8 messages with 1000 Mbps (AVB)

Table 3 Average WCTT of E/E architectures for various messages

Message types	Average WCTT with domain-oriented E/E architecture	Average WCTT with zone-oriented E/E architecture
Body	16.833 ms/16	21.842 ms/16
Chassis	25.52 ms/20	12.510 ms/20
Powertrain	16.8 ms/18	17.4 ms/18
ST Ethernet	0.402 ms/9	1.184 ms/9
AVB Ethernet	0.692 ms/14	1.674 ms/14

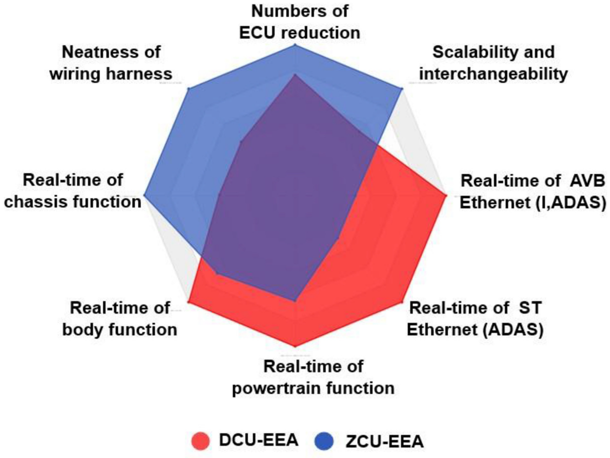


Fig. 4 Performance comparison between two architectures

As the evolution continues, a high-performance, heterogeneous vehicle computing platform takes the place of multiple DCUs for centralized computing. At the same time, all ZCUs are interconnected with the vehicle computing platform to collect and transmit information about ECUs around the vehicle. Ultimately, this high-performance platform establishes a connection with the cloud, culminating in an integrated control architecture spanning both the vehicle and the cloud.

Hybrid E/E architectures, illustrated in Fig. 6, are deemed to exhibit more comprehensive performance compared to both domain-oriented and zone-oriented counterparts. This hybrid approach combines the merits of zone-oriented architectures by leveraging ZCUs to effectively minimize the number of ECUs. This leads to enhancements in wiring harness organization, scalability, and interchangeability. Simultaneously, hybrid architectures integrate characteristics from domain-oriented E/E architectures, which adhere to the principle of centralizing the calculation of coupled functions. In the initial phases of hybrid E/E architectures, DCUs are strategically retained to facilitate functional computations within each domain. Subsequently, there is a convergence of DCU functions into the central vehicle computer, with partial integration into ZCUs. This approach fosters functional integration, efficient message transmission, and calculation of diverse message types. The outcome is a well-optimized real-time performance for various message transmissions, and conducive to meeting the needs of different products or product series.

3 Networking Technologies for E/E Architectures

Networking technologies assume a pivotal role in shaping the development of E/E architectures, offering crucial features such as high bandwidth, low latency, and low-jitter network transmission.

This section initiates with an exploration of automotive Ethernet communication technology, identified as one of the most promising in-vehicle network technologies for the future of E/E architectures [13]. Its influence is instrumental in steering the paradigmatic evolution of automotive E/E architectures. Following this, an analysis of advanced networking technologies is presented, encompassing fundamental capabilities such as reliable communication, service-oriented frameworks, and centralized control for E/E architectures. While existing literature has predominantly concentrated on the communication layer of networking technologies in the automotive domain, this section takes a more holistic approach by considering their integration into the automotive composite system, which comprises the vehicle control model, the model of automotive E/E architectures, and more. From this contemporary standpoint, the discussion unfolds to elucidate the driving roles of TSN, SDN, SOA, and converged networking technologies in shaping automotive E/E architectures.

3.1 Automotive Ethernet

Bus technologies such as CAN, LIN, and FlexRay have been widely used in the past automotive E/E architectures. However, the surge in data volume and stringent real-time requirements driven by technologies like autonomous

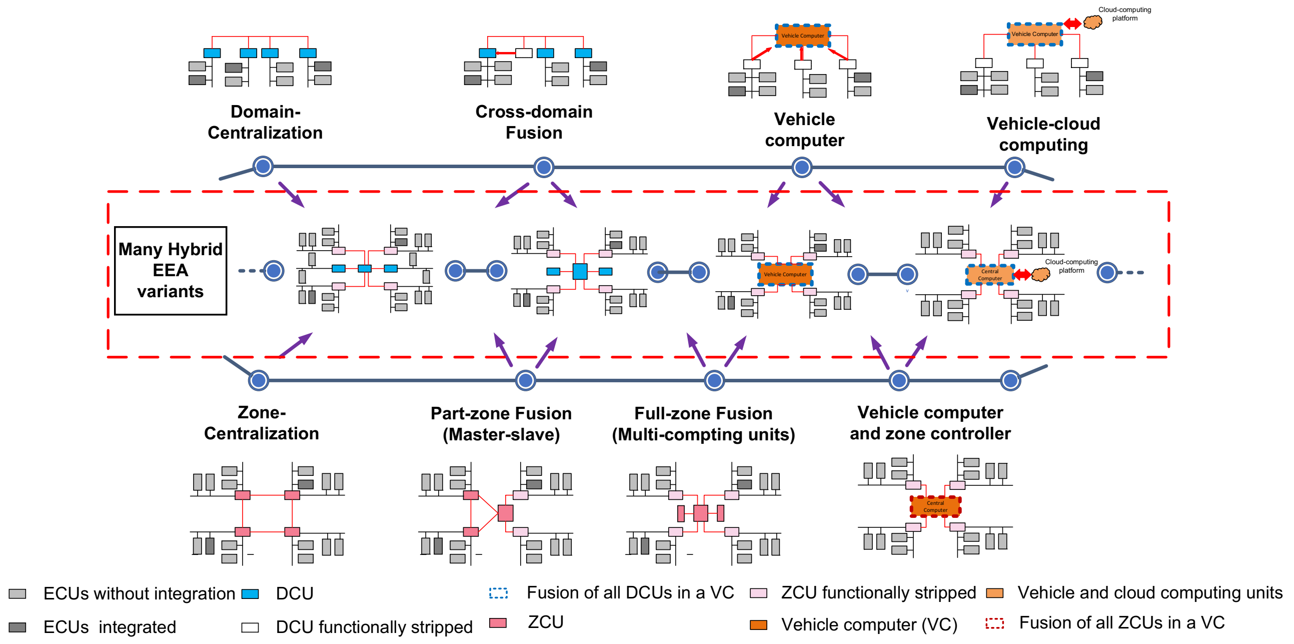


Fig. 5 A development roadmap of topologies of hybrid E/E architectures

driving and intelligent cockpit functionalities has exposed limitations in terms of network bandwidth and scheduling capabilities for these traditional bus technologies. Consequently, automotive Ethernet, renowned for its high bandwidth and QoS, has gradually found application in automobiles [13]. This ascent of automotive Ethernet has carved out a new realm for the evolution of E/E architectures [62]. Unlike traditional industrial Ethernet technology, which typically employs LAN technology, automotive Ethernet stands out by utilizing Unshielded Twisted Pair (UTP) instead of two pairs of Shielded Twisted Pair (STP) to meet the complex Electromagnetic Compatibility (EMC) requirements within a vehicle [63].

Presently, automotive Ethernet supports full-duplex transmission rates ranging from 100 Mbps, 1 Gbps, multiple Gbps, to arbitrated transmission of 10 Mbps. This is standardized by IEEE 802.3bw-2015 [64], IEEE 802.3 bp-2016 [64], IEEE 802.3ch-2020 [27], and IEEE 802.3cg-2019 [27, 65]. These standards cater to the high bandwidth requirements of next-generation high-performance autonomous vehicles. Automotive Ethernet, with extended Time-Sensitive Networking (TSN) protocol support, facilitates flow synchronization, flow management, flow control, and flow integrity. This capability ensures low-latency, low-jitter, and safe communication essential for autonomous driving [27, 41, 66, 67].

Operating at the upper layer with protocols like TCP or UDP, automotive Ethernet can employ the SOME/IP protocol. This protocol, standardized in 2016 by AUTOSAR [44], is built on a scalable service-oriented network middleware. Its usage enhances the flexibility of in-vehicle systems to adapt to operational changes [25, 33, 68–70].

The high bandwidth, low delay, and low jitter characteristics of automotive Ethernet make significant contributions to the paradigm shift in automotive E/E architectures [36]. Firstly, the high bandwidth enables the in-vehicle network to transmit a greater number of audio and video streams. Secondly, the low delay and low jitter characteristics ensure Quality of Service (QoS) for various types of messages. Recognized as the backbone of next-generation and future automotive E/E architectures, automotive Ethernet is poised to play a pivotal role in shaping the future of vehicular communication [5, 13, 14, 62, 71–75].

3.2 Automotive TSN Technology

The Time-Sensitive Networking (TSN) protocol family, evolving from the AVB protocol family in 2012, is set to empower automobiles with high-bandwidth and high-real-time communication capabilities, in tandem with automotive Ethernet [41]. Currently, the industry is inclined to adopt the Credit-Based Shaper (CBS) protocol within TSN for automotive systems, primarily due to its lower costs in design and embedded development compared to other TSN protocols [38, 76]. Noteworthy features expected to augment automotive systems encompass guaranteed Quality of Service (QoS) [77, 78], clock synchronization [79, 80], communication redundancy [81], functional safety [82], and information security [83], among others.

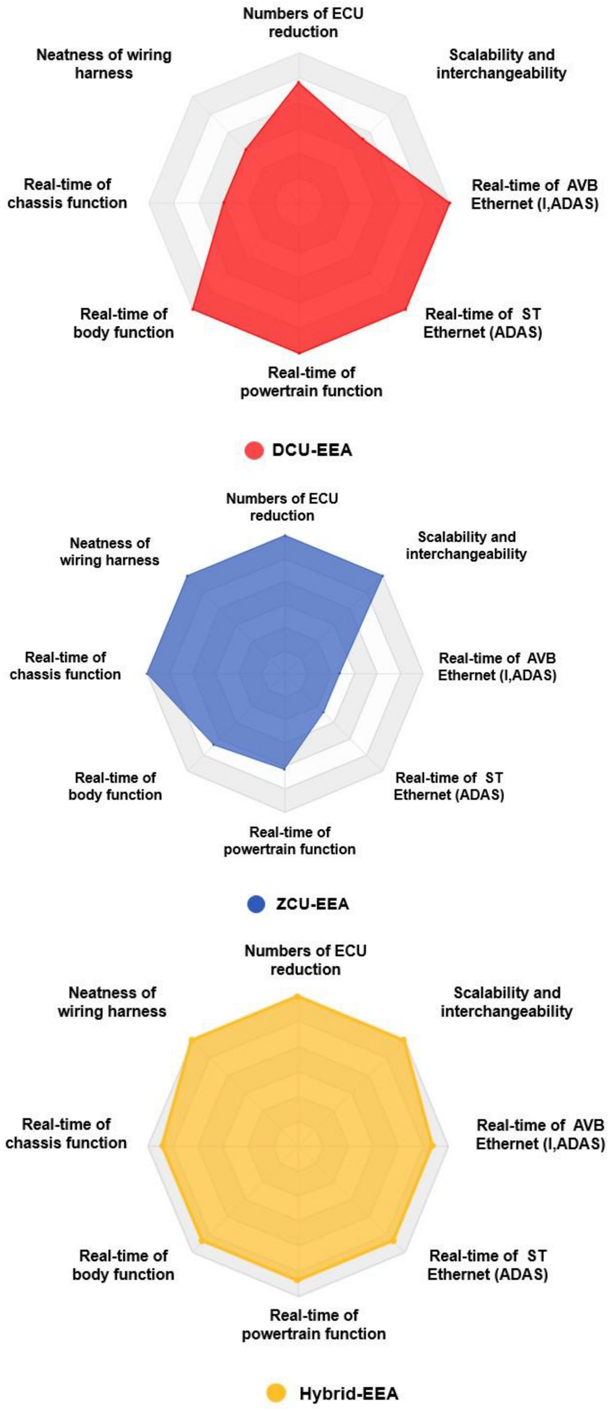


Fig. 6 Performance comparison of three types of topologies of E/E architectures

An inherent advantage of TSN lies in its ability to classify messages effectively, offering distinct transmission characteristics for control messages, audio and video messages, or best-effort messages. These advantages play a pivotal role in ensuring the reliability and stability of vehicle control functions, thereby upholding vehicle functional safety. Moreover, TSN provides optimal streaming characteristics for audio and video communication requirements, such as those for cameras and displays, while contributing intelligent features to vehicles.

Considered for deployment in both domain-oriented and zone-oriented automotive E/E architectures, TSN technology facilitates real-time and reliable message transmission over Ethernet as the backbone. Messages are directed to Domain Control Units (DCUs) or Zone Control Units (ZCUs) for computation, possibly facilitated through gateway routing units [41].

3.3 Automotive SDN Technology

Software-Defined Networking (SDN) has emerged as a networking technology in recent years, introducing a paradigm that decouples the control plane from the data plane. This separation enables the dynamic configuration of the network plane through network ports, catering to flexible service requirements [84]. In the context of the new generation of automotive E/E architectures, where automotive Ethernet serves as the backbone network and various network equipment, including DCUs, ZCUs, and switches, act as communication units, the deployment of SDN technology becomes crucial. It facilitates the control and dynamic scheduling of network traffic on demand.

SDN technology offers flexible control over functions in DCUs, ZCUs, or switches, allowing for comprehensive management of network conditions. For instance, during high-speed vehicle operation, consideration can be given to increasing the transmission frequency of relevant messages to achieve higher performance, reverting to a normal state during low-speed operation. Looking ahead, SDN technology is poised to meet the real-time, safety, security, functional, and additional non-functional requirements essential for autonomous vehicles [85].

3.4 Automotive SOA Technology

In contrast to the conventional communication matrix reliant on fixed message transmission intervals, Service-Oriented Architecture (SOA) technology, based on the SOME/IP protocol, dynamically defines transmission services according to real-time requirements. This approach proves effective in curtailing communication loads and ECU power consumption [86]. Acting as a conduit between the underlying hardware and upper-layer service applications, SOA facilitates flexible invocation of upper-layer services.

For instance, with SOA, communication with light ECUs can be activated only when the lights are in demand. In the context of autonomous driving functions, whether it's the DCU of ADAS in domain-oriented E/E architectures or the ZCU integrated with ADAS functions in zone-oriented E/E architectures, decisions about activating functions like ACC [87] or AEB [88] are made. This includes determining whether communication services are needed to invoke other control units. Undoubtedly, SOA technology plays a pivotal role in streamlining communication messages within E/E architectures, thereby contributing to reduced power consumption in embedded platforms.

3.5 Future Converged Networking Technology

TSN technology primarily ensures the real-time performance of communication message transmission, characterized by low delay and low jitter. SDN technology introduces a controllable management layer into in-vehicle network architectures. SOA technology enhances the flexibility of services in E/E architectures by incorporating service-based features. Table 4 provides an overview of the development status of converged networking technologies. Looking ahead, the integration of these three technologies could be a prospect for future automotive E/E architectures, imparting higher levels of safety, reliability, and intelligence to future vehicles. Figure 7 outlines a developmental trajectory for networking technologies in automotive E/E architectures.

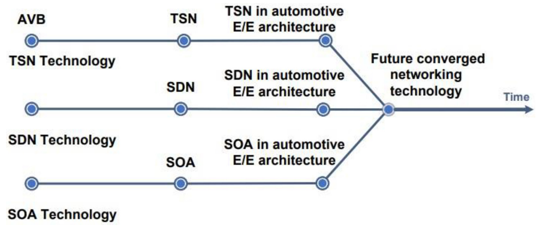


Fig. 7 A route of development of networking technologies of automotive E/E architectures

4 Modeling and Simulation Technology for E/E Architectures

Designing topologies and networking of E/E architectures may involve many different fields with high complexity. It is necessary to examine them by modeling and simulating before deployment. In this section, some commonly used simulators are discussed for design and verification, mainly including some topology and networking simulators commonly used in the communication field, such as OMNET + +, RTaw-Pesage and PREEvision, and topology and networking's application simulators in the

Table 4 Development status of converged networking technologies

Study	Time	Networking technologies	Contributions
Said et al. [89]	2018	SDN and TSN	A fully centralized architecture proposed with centralized user configuration, centralized network configuration and TSN data plane
Meyer et al. [90]	2019	SDN and TSN	Claim that the control overhead of SDN can be added without a delay penalty for TSN traffic when protocols are mapped properly
Haugg et al. [91]	2021	SDN and TSN	A time-synchronous transactional model with TSSDN introduced, which can reconfigure TSN devices during runtime without affecting the latency of existing and added real-time traffic
Chahed et al. [92]	2021	SDN and TSN	A micro-service-based architecture proposed including main-service, TSN-service, mediator, topology-service, monitor-service and config-service to enable easy integration of TSN technology with SDN controller in real scenarios
Kostrzewa et al.[82]	2021	SDN and TSN	An SDN-based centralized network management unit introduced for TSN Ethernet in automotive system that enables fail-operational behavior of network and guarantees reconfiguration of switching between modes
Hackel et al. [93]	2022	SDN and TSN	A secure switching architecture proposed, which integrating TSN with SDN that enables real-time and security, and first tested on a production vehicle
Arestova et al. [94]	2021	SOA and TSN	An integration approach of AUTOSAR AP, SOA proposed using OPC UA, and TSN, and a deterministic communication schema verified in an end-to-end scenario
Villanueva et al. [95]	2021	SOA and TSN	A service-oriented architecture proposed over TSN Ethernet backbone for optimizing TSN configuration which can reduce latency and improve memory utilization

automotive areas, such as Matlab. Besides, some future comprehensive simulators are envisaged.

4.1 Topology and Networking Simulator

Simulation technologies for the topology and networking of E/E architecture have been increasingly used in recent years.

OMNET + +, an open-source discrete-event network simulator since 1997, is adept at simulating various industrial networks, including automotive in-vehicle TSN networks [56–58, 79]. It enables the construction of an Ethernet model for the new functional domain-oriented and zone-oriented E/E architectures. Algorithms for various TSN, SOA, and SDN [90] protocols can be designed within OMNET + + to ensure the QoS characteristics of diverse Ethernet traffic. While OMNET + + was not originally developed for automotive networks, particularly in-vehicle networks, it lacks simulation models for CAN, LIN, FlexRay, and other in-vehicle networks, along with corresponding gateway models.

TCN Time Analysis [96], developed by Time Critical Networks in 2017, serves as a software tool facilitating the construction of architecture and network digital twins. This tool allows designers of networks and automotive electrical architectures to conduct architecture exploration and what-if analyses through simulation. The latest version provides basic support for CAN, LIN, FlexRay, Ethernet, and some TSN protocols. Notably, while recent literature [92] suggests the use of TCN Time Analysis for validating TSN and SDN techniques, it is not an open-source network simulation framework, limiting the implementation of new extensions with protocols or features.

RTaW-Pesage [20, 97], introduced by INRIA in 2007, stands as a commercial vehicle network simulator with widespread industry usage. It has garnered adoption by prominent entities such as Mercedes-Benz, NIO, Bosch, Aptiv, and Huawei. This simulator excels in constructing automotive networks, including CAN, LIN, FlexRay, Ethernet, and others. Notably, it supports the simulation of cutting-edge Ethernet protocol stacks, encompassing TSN and SOME/IP. Distinguishing itself from OMNET + + and TCN Time Analysis, RTaW-Pesage actively incorporates new in-vehicle network technical features.

PREEvision [50], developed by Aquintos in 2008, emerges as a commercial model-based development tool tailored for the design and assessment of E/E systems. Its applications span conceptual development, design, evaluation, and optimization of requirements and functional characteristics within E/E architectures. PREEvision accommodates in-vehicle protocols, including Ethernet, CAN, FlexRay, LIN, and supports SOA design. Setting it apart from OMNET + + simulation software, PREEvision has the capability to design the entire vehicle wiring harness, adheres to AUTOSAR and ISO26262 standards for system design, and enables evaluations based on criteria such as technology, cost, weight, and scalability.

4.2 Topology and Networking's Application Simulator

The performance of topology and networking needs to be analyzed and continuously improved according to the applications of in-vehicle environment.

Matlab, a numerical simulation software developed by MathWorks in 1984, serves as a convenient tool for establishing and verifying vehicle control models within the E/E architectures. However, its precision in vehicle modeling may be limited. In contrast, Carsim, a specialized vehicle dynamic modeling tool developed by MSC in 1996, enhances simulation accuracy. The commonly employed co-simulation of Matlab and Carsim [98] is integral in simulating vehicle systems, particularly for investigating control systems in the automotive domain, encompassing ACC [99, 100], AEB [101], and more.

Truetime, introduced in 1999 by the Lund Institute of Technology in Sweden, stands out as a networked control tool equipped with CAN and Ethernet simulation models. This tool can be seamlessly integrated into the co-simulation of Matlab and Carsim. The tripartite co-simulation involving Matlab, Carsim, and Truetime [102–104] facilitates the construction of vehicle control models under diverse E/E architecture topologies. This approach allows for the examination of various control algorithms across different topologies and networking characteristics. For instance, a recent study [104] delves into the analysis of the impact of different control algorithms on ACC function through the aggregation loop under a domain-based E/E architecture. It's worth noting that this co-simulation, while robust, lacks support for accurate network models and the simulation of emerging networking technologies such as TSN, SDN, or SOA.

4.3 Future Comprehensive Simulator

Various simulators exhibit diverse characteristics, catering to specific analyses such as network performance, application performance, and cost constraints. Table 5 summarizes some mainstream simulator software for E/E architectures. To comprehensively analyze E/E architecture topologies, a synergy with the aforementioned simulator software is imperative. Certain software provides direct interfaces for

Table 5 Summary of mainstream simulation software for E/E architectures

Simulator	Release time	Type	Characteristics and Support functions	Application scenarios
OMNET++	1997	Topology and Networking Simulator	1. Rich Ethernet network protocols, supporting TSN, SDN and SOA 2. Open source, good scalability, widely used 3. Lack of simulation models for CAN, LIN, FlexRay and other in-vehicle networks	Mainly for verification and optimization of network characteristics of Ethernet backbone network
TCN Time Analysis	2017		1. Rich in-vehicle protocols including Ethernet, CAN, LIN, FlexRay 2. Supports the latest Ethernet protocols including TSN 3. Not allow implementing new extensions with protocols or features	Mainly for verification and optimization of network characteristics of in-vehicle Ethernet backbone and subnet network with CAN, LIN, and FlexRay
RTaW-Pesage	2007		1. Rich in-vehicle protocols including Ethernet, CAN, LIN, FlexRay 2. Support the latest Ethernet protocols including TSN and SOA 3. Commercial software adopted by OEMs and Tier1 suppliers with high credibility, but expensive	Mainly for verification of network characteristics of in-vehicle Ethernet backbone and subnet network with CAN, LIN, and FlexRay
PREEvision	2008		1. Rich in-vehicle protocols including Ethernet, CAN, FlexRay, LIN 2. Support SOA design 3. Support wire harness simulation and system design which meets ISO26262 and AUTOSAR standards 4. Commercial software adopted by OEMs and Tier1 suppliers with high credibility, but expensive	1. Mainly for verification and optimization of requirements and function characteristics 2. Simple verification and optimization of in-vehicle network 3. Optimization of wiring harness system
Matlab and Carsim and Truetime	1984 1996 1999	Topology and Networking's application simulator	1. Numerical computing and control theory for in-vehicle application 2. Accurate vehicle dynamics model 3. Simple network model, not support TSN, SDN or SOA	Mainly for verification and optimization of vehicle function under influence of different topologies and networking technologies

co-simulation, establishing a new simulation framework for exhaustive performance and bottleneck analysis. This approach ensures the safer and more reliable development of automotive E/E architectures while concurrently minimizing verification and development costs for embedded platforms.

Among the commonly used combinations, PREEvision and Matlab stand out for creating more comprehensive E/E architecture simulation models. Sander et al. [105] demonstrated the development of an automatic gateway prototype generation for optimizing E/E architectures. This involved setting topology, hardware architecture, functional network, and requirement layers in PREEvision, with the design function features implemented in Matlab. Stoll et al. [106] integrated ROS into PREEvision for describing AUTOSAR-compliant E/E architectures. ROS, developed by MATLAB with the extension Robotics System Toolbox, facilitated communication interfaces. Neubauer et al. [107] proposed a framework leveraging both PREEvision and Matlab to autonomously synthesize hardware-centric Matlab models from multiple PREEvision E/E architecture layers.

RTaW-Pesage and Matlab can be effectively employed in co-simulation, with CPAL serving as a domain-specific language developed by RealTime-at-Work and the University of Luxembourg. CPAL, detailed in Ref. [108], plays a pivotal role in interfacing with RTaW-Pegase for modeling high-level protocol layers within the E/E architecture. Simultaneously, it interfaces with Matlab for the development of vehicle control systems within the E/E architecture.

Given the intricate characteristics of topology, network, and application, the future demands more comprehensive simulators for realistic simulation analysis. Figure 8 outlines the anticipated development of simulators for automotive E/E architectures.

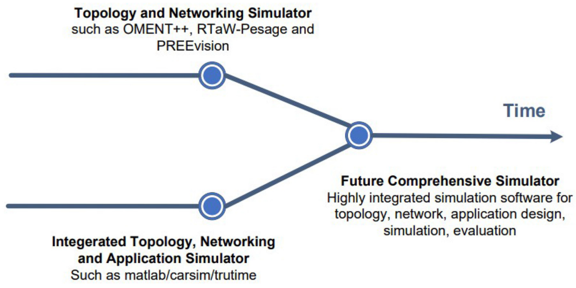


Fig. 8 A development of simulators of automotive E/E architectures

5 Challenges and Open Problems

In this section, some challenges and open problems of E/E architectures are discussed.

5.1 Co-design of Multi-networking Mechanisms

The continual evolution of E/E architecture topologies and networking technologies poses a challenge in co-designing them in conjunction with multiple networking technologies and novel E/E architectures.

Key technologies such as TSN, SDN, and SOA play instrumental roles in propelling the development of modern intelligent network technology. Their application in the automotive domain can significantly advance the progress of automotive E/E architectures. However, their incorporation into the automotive field necessitates careful consideration of the unique attributes of vehicles. This consideration goes beyond the typical concerns of low latency and low jitter in many cases within automotive E/E architectures, especially those involving sensor-controller-actuator structures like DYC and ACC, the paramount consideration becomes the end-to-end aggregation loop delay. Automotive network control involves various task trigger modes, including time-trigger and event-trigger modes, and network control loops, encompassing sensor-controller, controller-actuator, and actuator-controller (feedback) loops. These different factors also need to be considered in the process of networking design.

5.2 Ultra-High-Speed Automotive Networks

The new topologies of E/E architectures and networking technologies need the support of ultra-high-speed in-vehicle network technologies.

In the context of future centralized E/E architectures, ensuring the precision of communication delay boundary calculations mandates a primary network utilizing automotive Ethernet with a transmission rate of up to 10Gbps [38]. Additionally, in-vehicle optical fiber communication technologies, characterized by ultra-high transmission rates, low EMI, and lightweight properties, are recognized as pivotal components in the blueprint of future centralized E/E architectures [109].

Whether it be in-vehicle Ethernet technology, in-vehicle optical fiber communication technology, or other ultra-high-speed in-vehicle network technologies, it is unequivocal that they have not yet reached a mature application stage. Notably, the PHY chip of 10 Gbps in-vehicle Ethernet, for instance, has seen development only in recent years [38].

5.3 Safety Enhancement and Security Enhancement

The enhancement of safety and security in the evolving E/E architecture topologies is paramount [110].

As the topologies of E/E architectures undergo changes, the sensor-controller-actuator loop within the automotive E/E system is also altered. This modification in the message loop necessitates a reassessment and reinforcement of functional safety.

The continuous integration of new networking technologies within the new architecture provides the in-vehicle network with a more flexible and sophisticated scheduling mechanism. However, this advancement also introduces heightened security risks. For instance, the utilization of IP-based SOA technology, while offering advantages, exposes the system to potential IP-based security threats such as DoS or DDoS attacks. Consequently, there is an ongoing imperative to fortify security measures in the emerging topologies of E/E architectures.

5.4 Standardization of In-Vehicle Networks

The automotive industry, given its emphasis on safety, security, and energy conservation, necessitates rigorous scrutiny and the establishment of standards for the development of each technology. Automotive E/E architectures span diverse domains, including communication, software, and control. It is imperative to continually establish and enhance standards across these domains to foster the advancement of automotive E/E architectures. Notable examples include the collaborative efforts of the 802.1 working group and the AVNU alliance in advancing the Time-Sensitive Networking (TSN) standard, the ongoing progress of the AUTOSAR standard, and the continuous evolution of standards such as ISO26262 and ISO13400. These endeavors contribute significantly to the robust and standardized development of technologies within the automotive sector.

5.5 Application to Embedded Platforms

In the continuous evolution of automotive E/E architectures, embedded platforms, including DCUs, ZCUs, and in-vehicle

Ethernet switches, have undergone gradual advancements. Currently, various OEMs and Tier1 suppliers endorse multi-core heterogeneous DCUs and ZCUs, along with in-vehicle Ethernet switches that support the in-vehicle Ethernet interface.

The design of DCUs and ZCUs necessitates a thorough analysis and allocation of functional requirements tailored to different vehicle models. The implementation of multi-core and heterogeneous designs in DCUs and ZCUs is contingent on the prior assignment of functions. Particularly, in the realm of Service-Oriented Architecture (SOA) technology, on-board services must be comprehensively designed in alignment with functional requirements to ensure real-time, safety, and security. Concerning in-vehicle switches, positioned as general network devices, there is an expectation for enhanced versatility. These switches are anticipated to support protocols like TSN IEEE 802.1Qav, IEEE 802.1Qbv, and others, while also accommodating top-level Software-Defined Networking (SDN) or SOA scheduling designs.

The deployment of technologies like TSN and SOA on embedded platforms underscores the critical role of automotive software architecture and design. Different embedded platforms, such as Microcontrollers (MCUs) or System-on-Chips (SoCs), exhibit distinct bottom-layer operating systems like Linux or QNX, AUTOSAR architecture for Central Processing (CP) or Application Processing (AP), and middleware for SOME/IP or DDS. These diverse platforms necessitate unique software frameworks for effective design and performance optimization.

5.6 Cost and Performance Optimization

Cost and performance are critical to E/E architecture. The optimization of these facets can significantly enhance a vehicle's competitiveness. As mentioned in Ref. [50], optimization objectives are multi-dimensional, varying across distinct feature selections and vehicle configurations, leading to the absence of a universally accepted optimization goal. Each automobile manufacturer harbors specific optimization goals and procedures for E/E architecture, often deemed as intellectual property.

The cost of E/E architecture includes hardware and wiring harness, and software development. Notably, the emphasis on hardware and wiring harness costs in E/E architecture design is due to their pronounced influence, with the cost of software development being more closely tied to functional requirements. In terms of cost optimization, this paper aligns with the four methods proposed in Ref. [8]: 1) physical architecture and topological optimization, 2) optimization of conducting medium, 3) variant optimization, and 4) redesign-to-cost approach. At the same time, the costs of CAN, LIN, FlexRay, Ethernet, and MOST in-vehicle communications, including transceivers and wiring harnesses, are analyzed in detail in Ref. [13].

The performance of E/E architecture encompasses real-time capabilities, diagnostic and service requirements, functional safety, and physical attributes such as weight, package dimensions, geometry, and power consumption. In Ref. [50], an optimization method based on PREEVision is introduced, exploring networking/deployment, hardware/geometry, hardware/geometry, communication/software, and functions/features/requirements aspects. Ref. [111] proposes a new formulation for architecture optimization, simultaneously exploring the design space of processor/bus selection, physical architecture integration (including bus connections), and task/message assignment under uncertainty about the software processing load. Additionally, recent research has delved into the application of networking technologies, such as TSN [76–83, 89–95], SDN [84, 85, 89–93], SOA [86, 94, 95], aiming to enhance real-time capabilities, diagnostic and service functionalities, as well as safety and security within E/E architecture.

However, there are few examples of publicly available research on the cost and performance optimization of the overall E/E architecture, because it often involves some sensitive business information.

6 Conclusions

This paper provides an exploration of the evolution of automotive E/E architectures, shedding light on the intricacies of networking technologies within these architectures.

Firstly, different from the conventional linear roadmap, this paper introduces a novel parallel roadmap for the evolution of automotive E/E architectures. This divergence aims to dispel misunderstandings embedded in the serial roadmap. Two distinct trajectories, namely the domain-oriented route and the zone-oriented route, are proposed to cater to the diverse requirements of OEMs and Tier1 suppliers. Each route offers unique advantages; domain-oriented architectures enhance real-time transmission within domains, while zone-oriented architectures present advantages in wiring simplicity, reduced ECUs, scalability, and interchangeability. The prospect of hybrid E/E architectures, combining the strengths of both, emerges as a promising avenue for future applications.

Secondly, the paper delves into the applications of Time-Sensitive Networking (TSN), Software-Defined Networking (SDN), and Service-Oriented Architecture (SOA) within E/E architectures. Anticipations for future integrated networking technologies, combining multiple paradigms, are articulated. This forward-looking perspective reflects the evolving landscape of networking requirements in the automotive sector.

Thirdly, a detailed exposition on topology and network simulators for E/E architectures is provided. The paper introduces simulators for both architecture topology and networking applications. While current simulators offer valuable insights, the envisaged future calls for comprehensive simulators capable of delivering more realistic simulation analyses. This shift toward more sophisticated simulation tools aligns with the growing complexities of modern E/E architectures.

Finally, the paper concludes by addressing the challenges and open problems looming over the development of E/E architectures. These challenges span the realms of technology, integration, and simulation.

A collaborative effort between academia and industry is posited as imperative for overcoming these hurdles and steering the trajectory of future E/E architectures, particularly in the context of autonomous vehicles.

The development of future E/E architectures in autonomous vehicles requires the continuous joint efforts of both academia and industry areas.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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