# Topology design of electronic and electrical architecture for Time-Sensitive Network

Jiaxing Li[1], Yanzhao Su[1], Mengmeng Yang[1] and Zonghui Li[2], Jin Huang[1,*], Zhihua Zhong[1]
[1]School of Vehicle and Mobility, Tsinghua University, Beijing, China
[2]School of Computer and Information Technology, Beijing Jiaotong University, Beijing, China
jiaxing-20@mails.tsinghua.edu.cn, yanzhaosu66@163.com, yangmm_qh@tsinghua.edu.cn
lizonghui@bjtu.edu.cn, huangjin@tsinghua.edu.cn, zzh@cae.cnr
*corresponding author

Abstract—The vehicle's Electrical/Electronic Architecture (EEA) serves as the foundation for implementing various functions of intelligent vehicles. This paper analyzes and summarizes the layout of the distributed vehicle EEA and discusses the advantages of Time-Sensitive Network (TSN) in the field of in-vehicle communications. Building upon the analysis, this paper combines the advantages of function-oriented and zone-oriented EEA and proposes a function-zone EEA for TSN. Four EEA network topology forms are evaluated based on communication delay, network load, cost and flexibility. Based on the OMNET++ framework, this paper conducts simulation verification of autonomous driving and body control data flows. The results show that the ring and mesh network topology can significantly reduce communication delays, enabling high-speed and scalable transmission for in-vehicle communication.

Keywords–electrical/electronic architecture; intelligent vehicle; software-defined vehicle; Time-Sensitive Network(TSN); OMNET

## 1. Introduction

In recent years, with the rapid development of science and technology, the advancement of automobile intelligence, connectivity, electrification and sharing processes is ongoing. The continuous development of automotive electronics and software applications has further promoted the revolution of in-vehicle communication networks[1].

The advancement of automobile intelligent technology and the enhancement of infotainment systems have led to a significant increase in the functional complexity of vehicle electronic systems. At the same time, due to the implementation of new technologies such as autonomous driving and over-the-air upgrades (OTA), the quantity of electronic control units (ECUs) in the new generation of software-defined vehicles (SDV) is also on the rise. As the number of ECUs increases, the in-vehicle communication network becomes increasingly complex. However, traditional vehicle communication networks based on CAN and LIN have become increasingly challenging to support and manage due to high real-time and high-bandwidth communication requirements[2]. The data communication traffic generated by a large number of new ECUs is more likely to lead to congestion in in-vehicle communication systems, resulting in increased delays in data transmission within the vehicle[3]. High-priority vehicle data is closely related to the normal operation of the vehicle. If this data is delayed or abnormal, it could significantly impact the operation of vehicles.

The complex intelligent functions of automobiles not only pose significant challenges to vehicle communication technology, but the growing number of ECUs has also resulted in a substantial increase in vehicle wiring harnesses. After years of development, the vehicle wiring harness has evolved from a few wires to thousands of independent wires in SDVs. High data traffic and high-priority environment sensing sensors related to autonomous driving functions, such as LiDAR and high-definition cameras, require higher-cost special cables for communication. At the same time, to ensure the high-reliability operation of SDVs, the communication redundancy requirements of the entire vehicle have increased the complexity of the wiring harness. The use of traditional automotive wiring harness layout methods may pose obstacles to the lightweight development of the entire vehicle.

Time-Sensitive Network (TSN) is a series of standards specified by the IEEE 802.1 task group to address key issues in Ethernet technology, such as precise time synchronization, traffic shaping, queuing and forwarding protocols, frame preemption and other scheduling mechanisms[4]. Compared with CAN, which is commonly used in in-vehicle communication networks, TSN offers high bandwidth, low latency, and high reliability. Therefore, in the field of automotive communications, TSN technology will address the limitations of traditional automotive in-vehicle communication networks, which are based on multi-channel CAN buses and supplemented with in-vehicle Ethernet. This technology will improve communication latency, reliability, and real-time performance[5], making it a crucial component in shaping the future design of SDV communication architecture.

Moreover, applying the TSN protocol directly to the in-vehicle network also faces certain challenges. A modern smart car with hundreds of ECUs and over 2,000 signals [6] forms an interconnected distributed system. From the perspectives of cost and risk, it is highly unlikely that the vehicle communication network will be directly transformed from the existing architecture system to a structure based on TSN Ethernet. The formation of a new

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vehicle communication network with the TSN network as the core will facilitate the transition of this process. Therefore, realizing the integration of TSN with the existing network, especially the bridging with CAN, is also crucial for enabling the TSN-based network to connect to the in-vehicle network. The EEA, in which the traditional CAN network and real-time Ethernet coexist, will become the implementation form of the next generation of TSN-based EEA.

In view of the complex functional requirements of the new generation of SDVs, the paper has the following structure. Section 2 presents the electronic and electrical communication architecture of the vehicle functional zone based on TSN. Section 3 introduces the priority of vehicle data. Section 4 describes the TSN connection method based on common network topology forms. Section 5 utilizes the OMNET++ framework to create a simulation environment for vehicle communication, focusing on specific communication scenarios of SDVs. Finally, the paper comparatively evaluates the advantages and disadvantages of different TSN communication topology architectures and verifies the feasibility and superiority of the proposed electronic and electrical communication architecture compared to traditional EEA.

## 2. Function-zonal EEA

The EEA serves as the foundation of the vehicle's underlying framework. It integrates various sensors, ECUs, wiring harness topology and electronic and electrical distribution systems in the vehicle to perform computing, power and energy distribution. This integration enables the vehicle to realize various functions. Faced with the diverse demands of modern automobiles, such as big data calculations, continuous vehicle software upgrades and autonomous driving function requirements, EEA also needs to embark on the path of intelligent evolution.

### 2.1 Current automotive EEA form

Traditional cars mostly use distributed EEA. Under this architecture, each ECU is typically responsible for a single functional unit and operates independently of the others. As the number of ECUs increases, not only will the length and weight of the vehicle wiring harness increase significantly, but the deeply intertwined software and hardware functions will also restrict the compatibility and scalability development of the vehicle system. At the same time, the realization of complex functions of SDVs requires in-vehicle communication networks to efficiently transmit large amounts of data. Traditional EEA also has limitations in terms of high bandwidth and high real-time communication capabilities. Therefore, utilizing high-performance computing units and real-time communication technology forms the foundation of the current automotive EEA design strategy.

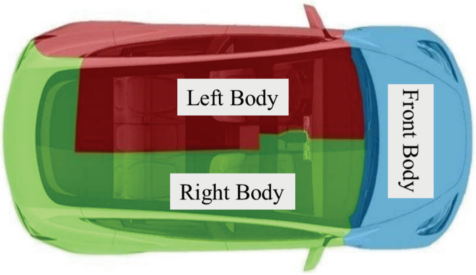

Figure 1. Zonal electric/electrical architecture

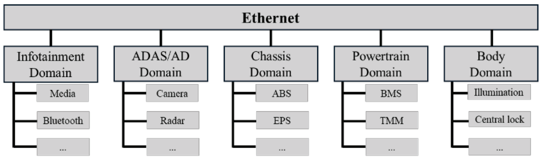

Figure 2. Functional domain electric/electrical architecture

According to the various functions and equipment locations of the vehicle model, Tesla has proposed an electronic/electrical architecture based on zonal division. The entire vehicle is divided into three body zones (Figure 1), with zonal controllers responsible for controlling specific electronic equipment. In addition to Tesla, other automobile companies are willing to separate the electronic and electrical architecture based on functions, which is more in line with people's intuitive understanding. Companies such as Xpeng, SAIC, GAC, BYD and others have segmented the automotive electronic and electrical architecture into the infotainment domain, ADAS/AD domain, chassis domain, powertrain domain and body domain[7], and configured them accordingly with in-vehicle Ethernet (see Figure 2).

In the zonal EEA solution, a large number of sensors, actuators, controllers and other components throughout the car are directly connected to the nearest zone controller. This approach effectively addresses the issue of excessively long wiring harnesses throughout the entire vehicle. However, since the electronic and electrical components of the vehicle are not evenly distributed inside the car, in the zonal EEA, the electronic and electrical components used to achieve the same function may belong to different zone controllers based on their location. For example, an air conditioning outlet controller, left and right wiper controller and lighting controller serve as components of the Front Body Domain. It results in the delay in the realization of certain functions. Therefore, the zonal EEA affects the integrity of the controller with similar functionality to some extent and also places greater demands on the real-time communication of the vehicle network. In contrast, the EEA functional domain integrates the same types of hardware components. However, since the same functions (such as environmental perception sensors, etc.) are distributed throughout the vehicle, the length and weight of the vehicle's wiring harness significantly increase to accommodate the implementation of new autonomous driving functions reliant on large-scale data transmission. This increase is not conducive to the lightweight development of SDVs.

## 2.2 Function-zonal EEA based on TSN

EEA based on functional module division has strong integration capabilities. The functional domain controller can efficiently adapt to the complex functions of SDVs. However, since hundreds of functional controllers are spread throughout the vehicle, the complexity of the vehicle wiring harness and the space under the functional domain EEA has also increased significantly. Therefore, the paper proposes a functional zonal electronic and electrical communication architecture that combines the advantages of the functional EEA and the zonal EEA to harness space advantages.

Under the new functional electronic and electrical communication architecture, each functional gateway will integrate and schedule controller communication data of multiple different functional types. After the introduction of the TSN protocol, communication efficiency and scheduling accuracy will be greatly improved[7]. Therefore, utilizing the TSN gateway as the foundation of the electronic and electrical communication architecture based on SDV function is crucial for implementing this architecture. The TSN gateway communication objects are illustrated in Figure 3. Each TSN gateway communicates with essential components like the traditional CAN or LIN bus network and large data traffic devices to facilitate real-time interaction and data transmission.

Network load balancing is a significant strategy to enhance the efficiency of vehicle network communication and data throughput[8]. According to a comprehensive evaluation of the current electronic and electrical architecture hardware functions and their communication relationships, it can be observed that the hardware for large data volume communication is primarily concentrated in the vehicle environment perception sensors and ADAS/AD domain controller module. By appropriately categorizing these hardware components into groups and integrating them with other peripheral functional hardware associated with the zonal division, the controller modules can be established under each TSN gateway.

Referring to the layout of environment-sensing sensors in mainstream autonomous driving solutions on the market, they can be divided into several modules based on their installation positions. The number of sensors and the communication data traffic between each module are roughly similar. At the same time, due to the significant computing power requirements of the autonomous driving control and power modules of future SDVs, a control-powertrain module is proposed. As shown in Figure 4, this paper proposes an EEA system consisting of six TSN gateways. The corresponding vehicle functional equipment lists are as follows:

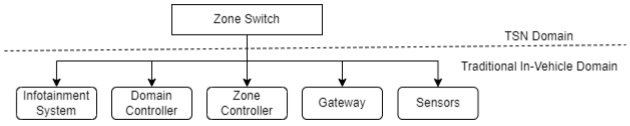

Figure 3. TSN domain-traditional domain communication

The left front trunk gateway module mainly includes the left front sensing group, such as the left front radar; front devices group installed in the front part of the vehicle, such as lidar and millimeter-wave radar; left-front wheel detection group, including the left front wheel speed sensor and tire pressure sensor; left-front lighting control group; front windshield control group, including the front wiper controller and defogger controller; left side speaker control group; cabin battery control group; air conditioning control group; left air outlet control group.

The right front trunk gateway module mainly includes the following components: the right front sensing group, such as the right front radar; the right-front wheel detection group with the right front wheel speed sensor and tire pressure sensor; the right-front light group; the vehicle washer group; the right side speaker control group; the passenger cabin power distribution group; and the right air outlet control device group.

The control-powertrain gateway module mainly includes the following components: airbag control groups; the instrument control group; the body domain controller; ADAS/AD domain controller; the vehicle internal sensors such as the occupant detector; vehicle front audio amplifier group; central display group; in-car charging group; turn signal and rearview mirror sensing group; battery pack system; cooling water sensing group; DC/DC conversion control group.

The left body gateway module mainly includes the left side sensing and detection group, such as the side impact sensor; left door control group; central lock control group; vehicle antenna control group; vehicle interior lighting group; and left audio control group.

The right body gateway module mainly includes the right side sensing and detection group, such as the side impact sensor; right door control group; right vehicle interior lighting group; and right audio control group.

The roof-trunk gateway module mainly includes the power battery charger control group; the sunroof control group;

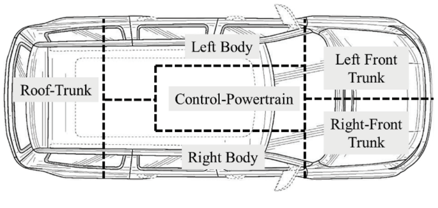

Figure 4. Function-zonal based electric/electrical architecture

body environment sensing control group; the rear side sensor control group, which includes the rear millimeter-wave radar and ultrasonic radar; trunk control group.

Under the TSN gateway communication architecture described above, each functional area module is equipped with a TSN switch to forward data from the subcomponents within the module without performing any computational tasks. It integrates and transmits the original bus communication data of various types within the vehicle, ensuring that the internal data of the entire vehicle can be communicated at high speed and reliably, while balancing the communication load of each functional area module.

## 3. Function-zonal EEA data integration

Currently, there are various gateway forwarding technologies that enable communication between vehicle communication buses such as LIN, CAN and Ethernet. These technologies encapsulate multiple CAN frames within an Ethernet frame to more effectively utilize the high-bandwidth properties of Ethernet. However, implementing this encapsulation mechanism on a TSN gateway may introduce significant delays while waiting for encapsulation, thereby compromising the real-time nature of communication. This section introduces a model for addressing the encapsulation issue of TSN data. It utilizes frame aggregation technology to consolidate vehicle data based on communication priority.

### 3.1 TSN data encapsulation technology

Upgrading the vehicle communication system does not happen overnight. Due to the complex and changeable functions of vehicle hardware equipment, traditional CAN and LIN buses still play a pivotal role in the electronic and electrical architecture of SDVs. Therefore, realizing CAN-TSN interconnection is a key requirement for TSN-based electronic and electrical communication architecture.

Encapsulation and forwarding technology effectively transmit CAN frames from the CAN bus network to the corresponding nodes of the TSN network. CAN frames that traverse different functional zonal modules are considered inter-domain frames. In a TSN-based communication EEA, the maximum number of inter-domain frames that can be encapsulated in a single TSN frame is limited by its maximum payload. A TSN frame can carry a maximum payload of 1500 bytes[9], while the maximum size of any CAN frame, including all its overhead, is only about 17 bytes. Therefore, under the influence of encapsulation technology, up to 88 CAN frames can be encapsulated in a TSN frame[10]. This will establish a solid foundation for the entire TSN-based communication EEA on the traditional vehicle communication bus.

Based on encapsulation and forwarding technology, many researchers have proposed various technologies to map CAN frames to Ethernet frames. This has led to the gradual development and implementation of the design and research of CAN-TSN gateways.

The earliest technology to establish a communication connection between multiple CAN frames and traditional Ethernet is to encapsulate a specific number of CAN frames accumulated in the waiting queue into an Ethernet frame, and then send it to the gateway through Ethernet[11] , as shown in Figure 5[10]. This method causes a significant delay in the CAN frame while waiting for the queue to be filled, greatly affecting the real-time performance of the communication. To solve this problem, Kern et al. proposed the concept of ”emergency” frames, which allows certain CAN frames to be transmitted immediately[12]. This idea also draws inspiration from the TSN traffic priority mechanism. Since then, the design and development of a CAN frame aggregation scheduler has significantly reduced the frame loss rate. This was achieved by implementing a priority scheduling mechanism based on the expiration time for forwarding to Ethernet[13]. At the same time, a CAN-AVB gateway utilizing frame aggregation mechanism can achieve specific real-time forwarding capabilities[14]. It aims to increase the payload of Ethernet frames and reduce delays through frame aggregation, which will have a long-term impact on the design and development of CAN-TSN gateways.

In order to enable the alternate transmission of data in the two major communication bus domains of CAN and TSN, the CAN frame must first be transmitted to the gateway through the CAN network, stored in the receiving buffer and generate an interrupt[15]. The gateway then reads the frame based on the TSN protocol. The order in which frames are read in the TSN queue depends on the queuing technology, which can be one-to-one, first-in-first-out (FIFO), or fixed priority (FP).

The one-to-one technique is a straightforward method. It encapsulates each CAN frame within a single TSN frame to minimize the delay in the forwarding stage of data communication. However, this technology cannot leverage the payload of TSN frames, which is dozens of times higher than that of CAN frames. This significantly consumes TSN network bandwidth and increases communication costs. FIFO forwarding technology will add each CAN frame to one of the queues, and the order of arrival is the order of dequeuing, which can ensure the fairness of frame forwarding. However, it is very likely to cause greater delays for later-arriving key frames[16]. FP technology assigns a priority to each CAN. In the storage queue,

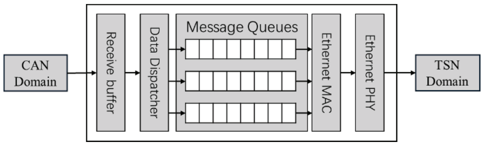

Figure 5. CAN-TSN encapsulation method

high priority is queued first, which ensures instant communication of key frames[17]. However, this can also easily lead to the accumulation of a large number of low-priority CAN frame data, affecting vehicle safety communication. Therefore, in the design of a CAN-TSN gateway, the precise configuration of data traffic priority is crucial to ensuring the safe and reliable communication of the entire vehicle. A reliable and efficient data prioritization mechanism will guarantee that conventional vehicle network communication data is promptly transmitted via the TSN-based communication EEA.

### 3.2 Vehicle data priority

After the data frame in the traditional vehicle communication domain enters the TSN-based communication EEA, the time-aware shaping technique related to IEEE 802.1Qbv is used to define the transmission selection mechanism[18]. Among them, Strict Priority (SP) is the default mechanism. This mechanism will strictly ensure that all high-priority data frames are scheduled before scheduling the next-priority data. Enhanced Transmission Selection (ETS) allows users to choose from multiple waiting queues. The queues are scheduled according to the absolute priority method. The selection queue can be chosen using weighted polling or deficit polling[19]. Credit-Based Shaping (CBS) is a classic scheduling method in the AVB era. It records the "backlogged" data frames after high-priority data is scheduled, so that this part of low-priority data can receive a certain amount of transmission opportunities when high-priority data is queued[20]. Asynchronous Traffic Scheduling (ATS) determines the permissible scheduling time for data frames during queuing, enhancing the flexibility of data scheduling and improving communication network performance to a certain extent[21]. Time-Aware Shaping (TAS) is a scheduling technique based on time gating configuration. It establishes a "green channel" for crucial data frames by coordinating the gating switch's schedule to guarantee the immediate transmission of essential data[22].

No matter which scheduling technology is utilized, the definition of vehicle data traffic priority serves as the foundation for implementing the aforementioned technology. A precise definition of priorities is essential to guarantee efficient, stable, and scalable communication of vehicle data traffic.

The types and functions of internal communication in automobiles are complex and changeable. There are significant differences in system complexity, communication rate, data response speed, and communication reliability. The Society of Automotive Engineers (SAE) categorizes automotive data transmission buses into 5 classes: A, B, C, D and E. Class A primarily consists of low-speed networks for basic sensors/actuators, utilized for controlling parts of the body like rear-view mirror adjustment, electric windows, wipers, air conditioning, lighting, etc.; Class B mainly comprises medium-low-speed networks for data exchange between independent modules, used for body electronic comfort modules, instrument display and other systems; Class C mainly involves real-time control of medium and high-speed multiplex transmission networks, used for power control, ABS control and other systems; Class D mainly encompasses high-speed transmission networks for media information, used for infotainment systems such as car audio, car video, and navigation; Class E mainly includes high-speed real-time networks for passenger safety systems, applied in the realm of vehicle passive safety[23]. However, the above data transmission classification is mainly divided based on communication speed, and the classification of big data traffic and security data is still not detailed enough. Therefore, based on this standard and combined with the development trend of contemporary smart car control and intelligence, the paper proposes the classification of vehicle data priority as shown in Table 1.

The data traffic prioritization method proposed in this article can effectively schedule the transmission of large data to prevent congestion in the TSN-based communication EEA and ensure the smooth and safe operation of SDVs.

## 4. EEA topology design

Based on the discussion above regarding the vehicle's functional zonal modules and communication traffic priority, this section will outline the design of the topology for the TSN-based electronic and electrical communication architecture. With reference to mainstream network topology such as bus, star, ring and mesh, the TSN-based communication EEA is gradually being designed, and its advantages and disadvantages are preliminary analyzed[24].

### 4.1 Bus network topology

The TSN-based EEA with a bus network topology is illustrated in Figure 6. Its essence lies in the presence of a bidirectional bus network path, with each TSN gateway distributed on both sides of the bus. The overall network structure is simple, and the number of gateways can be increased or reduced according to the needs of different SDVs, providing high flexibility. However, this topology may lead to a high volume of TSN frames being consistently scheduled and forwarded on the bus. This

Table 1. Vehicle data priority classification

| Priority | Vehicle Layer | Device Examples |
|---|---|---|
| 0 | Basic actuator | rear-view mirror |
| 1 | Info. display | instrument display |
| 2 | Powertrain system | battery storage system |
| 3 | Dynamic system | electric power steering |
| 4 | Cloud info. system | navigation information |
| 5 | Media system | in-vehicle audio |
| 6 | ADAS/AD system | lidar, camera |
| 7 | Safety system | passive safety system |

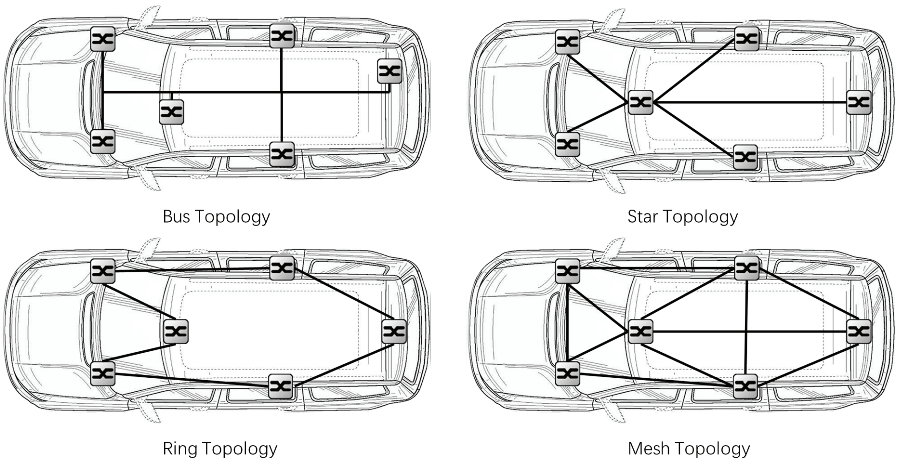

Figure 6. TSN-based communication EEA topology architecture

situation can potentially result in congestion within the communication network, thereby impacting the real-time performance of the communication to some extent.

### 4.2 Star network topology

The TSN-based communication EEA with a star network topology is shown in Figure 6. This structure utilizes the central TSN switch (control-powertrain switch) as the core to connect with other switches in a radial manner. Similar to the bus type, this system can flexibly increase or decrease the number of switches according to the needs of SDVs, and the topology exhibits good scalability. However, this topology places high demands on the data forwarding and processing capabilities of the central switch, and current TSN switches have limited configurable communication interfaces. The cost of installing and redesigning the central core switch is high, making it relatively unsuitable for TSN-based communication EEA.

### 4.3 Ring network topology

The TSN-based communication EEA with a ring network topology is shown in Figure 6. The information transmission route of TSN switches in each functional-zonal module forms a closed ring. The switches are connected end-to-end, and the communication data traffic flows continuously, forwarded and transmitted in the ring. This mechanism ensures that in case of a fault or congestion in data transmission between two switches, an alternative direction is automatically chosen for data transmission. This guarantees that critical data can be successfully transmitted to the target hardware. However, since communication data may need to be forwarded and transmitted through multiple switches, it may have a certain impact on transmission delay.

### 4.4 Mesh network topology

The TSN-based communication EEA with a mesh network topology is illustrated in Figure 6. Its essence lies in the possibility of having a communication line between switches in each functional zone. This form will greatly enhance the operational stability of the entire TSN-based architecture in the event of a failure at any location. At the same time, choosing a closer TSN switch communication line can expedite the forwarding of data communication traffic to the target hardware object. However, the displacement scheme of this network structure is complex, the overall communication harness length is long, and the challenge of managing communication data traffic also increases with mesh topology.

## 5. Network topology simulation

In order to evaluate the TSN traffic prioritization and transmission mechanism mentioned above, as well as the TSN-based electronic and electrical communication architecture topology, this section will utilize the OMNET++ framework to compare the TSN backbone network with the traditional mainstream CAN communication network. It will also conduct simulation tests and evaluations on four TSN backbone network topology architectures.

### 5.1 OMNET++ framework

OMNET++ is an open-source network testing platform framework based on C++. It adopts a modular design to separate the discrete event simulation engine from the network model it is built on. In addition to modeling sequences of events in a discrete-time example, OMNET++ also provides a mechanism for simulated entities (such as hosts, servers, switches, etc.) to send or receive data through wired or wireless connections. The framework includes multiple network models, such as traditional TCP/IP, cellular networks, and vehicle networks. This framework can effectively meet the simulation requirements of vehicle communication network[25].

On the basis of OMNET++, many researchers have also conducted in-depth research and expansion. INET is an

OMNET++ open-source model library that supports multiple Internet protocols (TCP, UDP, IPv4, IPv6, etc.) and link layer protocols (Ethernet, IEEE 802.1, sensor MAC protocol, etc.) [8]. The CoRE4INET package developed on this basis can effectively adapt to the TSN protocol. The subordinate FiCo4OMNeT package supports CAN and FlexRay communications. The SignalsAndGateways package offers a wide range of CAN-TSN gateway models for the overall framework[26]; SOA4CoRE package presents a service-oriented simulation model (as illustrated in Figure 7) [27]. Therefore, applying INET and CoRE4INET in the OMNET++ framework can be well adapted[28]. The EEA topology evaluation, based on the TSN-based communication EEA proposed in this article, provides a robust simulation environment for the development and testing of future SOA functions.

### 5.2 Superiority of TSN network

CAN network is the most widely used bus protocol in vehicle communication networks. It is utilized for various functions such as fault diagnosis, instrument display, power supply, body control, and chassis control. This paper investigates 256 vehicle CAN messages and utilizes the OMNET and FiCo4OMNET framework to simulate the transmission of some of the CAN message information. Data flows 1-7 in Table 3 present parts of these CAN message. At the same time, communication is established between the sending and receiving objects of this message segment and the TSN switch of the corresponding functional area module to implement the TSN-based network test scenario.

Benefiting from the TSN data encapsulation technology mentioned in Section 2.2, the TSN backbone communication network can effectively integrate CAN message data and achieve higher data transmission loads in the TSN Ethernet transmission environment. Under the OMNET simulation framework, the same data flows can pass through a traditional CAN bus network or a typical TSN switch. The data flow definition is shown in Table 3 (data flows No. 1-7), and the comparison results are presented in Table 2. This simulation only considers end-to-end communication.

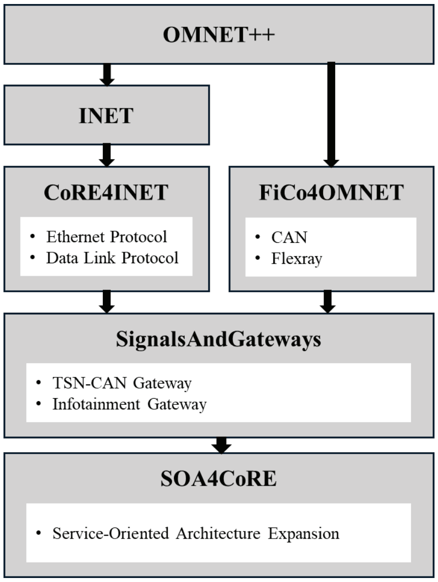

Figure 7. Functions supported by OMNET++ framework

It can be seen from Table 2 that compared with the traditional CAN bus network, the TSN backbone communication network can significantly reduce communication delays and greatly improve communication efficiency.

### 5.3 Latency evaluation

In order to evaluate the TSN-based architecture topology proposed in this article, a simulation environment is designed based on SDV communication scenarios. Based on the traditional vehicle-mounted CAN communication network, this paper incorporates additional large data flow communication data from intelligent driving environment perception sensors for simulation testing. Figure 8 depicts the simulation scenario for intelligent vehicle communication developed in this paper using the OMNET framework. The simulation scenario includes a TSN backbone network[29]. Each switch is connected to three traditional communication network objects, and each node represents an application. Nodes exchange communication data with other nodes in pairs, and each data traffic has its corresponding priority level.

The left-front trunk module contains two radars (Radar1-2) and a front-facing high-definition camera (CAM1); the

Table 2. Data flows definition

| No. | CAN($\mu$s) | TSN($\mu$s) |
|---|---|---|
| 1 | 392.6 | 0.796 |
| 2 | 274.8 | 1.642 |
| 3 | 231.2 | 1.335 |
| 4 | 135.4 | 0.472 |
| 5 | 278.6 | 0.971 |
| 6 | 253.9 | 1.027 |
| 7 | 195.4 | 0.668 |

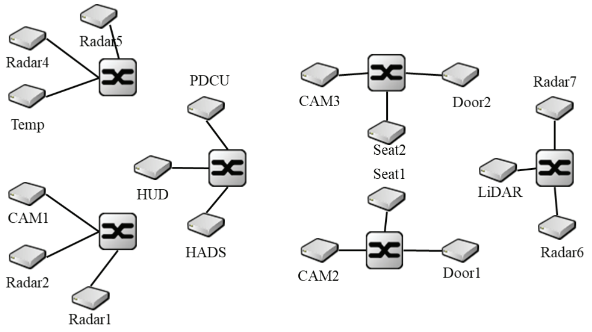

Figure 8. OMNET based simulation scenario

right-front trunk module contains two radars (Radar4-5), an external temperature sensor (Temp) and an air conditioner controller(AC); the control-powertrain module includes a central display screen (HUD), the ADAS/AD domain controller (ADC) and the body control module (BCM); the left body module includes a fisheye camera (CAM2), a left crash sensor (Door1) and a seat control sensor (Seat1); the right body module contains a fisheye camera (CAM3), the right crash sensor (Door2) and a seat controller (Seat2); the roof-trunk module contains a lidar (LiDAR) and two rear radars (Radar6-7).

The data flow simulation definitions of each function are shown in Table 3. Data flow 1 transfers the temperature information outside the vehicle; data flows 2-3 transfer the state information; data flows 4-5 transfer the commands for adjusting the in-vehicle temperature; data flow 6 transfers door state information; data flow 7 transfers the commands for adjusting the posture and temperature of the seat; data flow 8 transfers information about autonomous driving; data flows 9-17 transfer diagnostic signals and image data from the perception sensors.

After completing the design of the communication model between the TSN domain and the traditional CAN domain, the TSN zonal switches are connected according to the various network topology described in Section 3 and the simulation test is initiated.

From Figure 9, it can be observed that for most data flows, the communication delay of the ring and mesh TSN-based network topology architecture is significantly shorter than that of the bus and star topology architecture. This characteristic enables more efficient communication throughout the entire vehicle.

## 5.4 Scalability of TSN network

With the continuous development of CAN-TSN gateway technology, more and more intelligent vehicle functional hardware will be connected to vehicles, leading to a significant increase in the number of in-vehicle data streams. In order to ensure that the proposed TSN-based network architecture can effectively accommodate the growing data traffic, it is essential to maintain good and efficient transmission characteristics of the TSN-based network as the data traffic increases. In this paper, we aim to enhance the number of data streams for each data stream transceiver component and conduct simulation tests on the scheduling time of data streams in a TSN backbone network switch within the provided simulation environment. The simulation results are shown in Figure 10. As the number of data streams increases, the waiting scheduling time of data streams in TSN-based network switches also increases linearly and gradually, with no significant congestion. Among the four network topologies, the scheduling time of the ring architecture increases at a relatively slow pace with the number of data flows. This characteristic indicates good scalability, enabling it to meet the future demand for efficient communication of data flows with more intelligent functions in vehicles.

Table 3. Data flows definition

| No. | Publisher | Subscriber | Period(ms) | Size(B) |
|---|---|---|---|---|
| 1 | Temp | BCM | 100 | 400 |
| 2 | Door | BCM | 100 | 46 |
| 3 | Seat | BCM | 100 | 46 |
| 4 | HUD | AC | 1000 | 200 |
| 5 | BCM | AC | 1000 | 200 |
| 6 | HUD | Door | 500 | 46 |
| 7 | BCM | Seat | 1000 | 200 |
| 8 | ADC | HUD | 5 | 2500 |
| 9 | LiDAR | ADC | 1000 | 46 |
| 10 | LiDAR | ADC | 200 | 46 |
| 11 | LiDAR | ADC | 16.66 | 250000 |
| 12 | Radar | ADC | 1000 | 46 |
| 13 | Radar | ADC | 200 | 46 |
| 14 | Radar | ADC | 16.66 | 5000 |
| 15 | CAM | ADC | 1000 | 46 |
| 16 | CAM | ADC | 200 | 46 |
| 17 | CAM | ADC | 16.66 | 43380 |

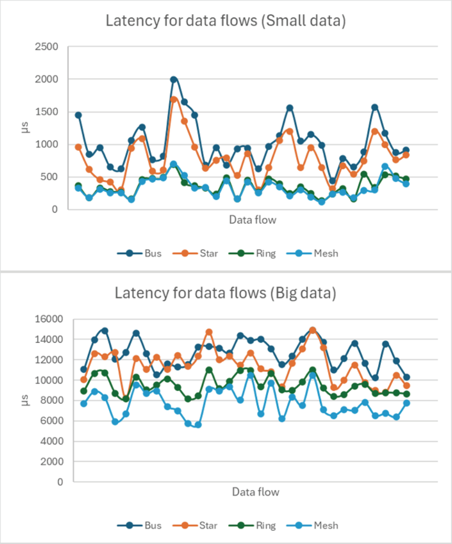

Figure 9. Latency of data flows under 4 topology

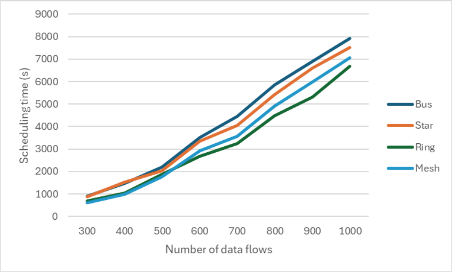

Figure 10. Scheduling time of data flows

## 6. Conclusion

Based on the traditional EEA, this article categorizes and analyzes the features of a new distributed EEA, segmented into functional and zonal domains. Combined with the advantages of time-sensitive networks, a new EEA for functional zones based on TSN is proposed. This approach can reduce the complexity of vehicle wiring harness layout, improve vehicle efficiency, achieve a certain level of functionally centralized communication transmission and data processing efficiency, and ensure communication security and reliability. Taking into consideration the data traffic communication requirements of the vehicle's functional hardware and its location, this article divides the vehicle into 6 functional zone modules and categorizes the vehicle data traffic into 8 priorities based on the vehicle data classification method suggested by the SAE Association. Enhance the adaptability of the vehicle communication architecture and TSN traffic scheduling function to achieve more efficient and reliable transmission of vehicle data traffic.

According to traditional network topology principles, this paper designs four TSN-based network topologies with specific feasibility. The TSN-based network with various communication topologies is simulated using the communication simulation model within the OMNET++ framework. Comprehensive evaluation shows that compared with the traditional vehicle-mounted CAN bus network, the TSN-based network has obvious advantages in communication latency. At the same time, based on the four TSN-based network topology architectures, the ring TSN backbone network can better adapt to the addition of a large number of vehicle-mounted data streams in the future. This adaptation helps in reducing network delay, thereby enabling efficient and reliable interactive transmission of vehicle data traffic.

In order to align the simulation scenario more closely with the actual situation, it will be necessary to conduct data simulation collection and test verification on real vehicles in the future. Additionally, communication network reliability testing should be added to comprehensively evaluate the strengths and weaknesses of various TSN-based network topologies. At the same time, more advanced TSN gateways, data encapsulation and forwarding technologies can also be utilized to facilitate the transition of the vehicle communication backbone network to TSN, fully leveraging the benefits of TSN.

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