

Research Article

TSN-Based Backbone Network of Train Control Management System

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Time-sensitive network (TSN), as one of the latest real-time Ethernet techniques, has achieved great success in several scenarios that require strict communication latency and packet loss. This paper reviews the state-of-the-art in time-sensitive networks and investigates the drawbacks of current vehicle networks. By introducing TSN into the TCMS backbone network, next-generation smart vehicles can achieve high-quality data transmissions. This paper also analyzes the priority of the vehicle data and calculates the time-aware shaper slot to ensure that the control data is not affected by the multimedia data. Using the proposed structure, experimental results suggest that the network efficiency can be improved in the rail transit systems.

1. Introduction

With the increasing demand for intelligent, comfortable, and high-speed rail trains, the high bandwidth, high transmission rate, and high real-time performance of vehicle network communication remain key issues [1]. In traditional, the CAN bus and MVB bus have the problem of low bandwidth and low transmission rate, while the Ethernet bus faces the difficulty of uncertain transmission delay.

At present, there have been several studies on vehicle networks. For example, Jie and Zongyao studied the reliability and comprehensive load design of the LTE-M system and describe that with the continuous increase of rail transit mileage, the problem of lagging network speed has become increasingly prominent. When the train is running at high speed, the traditional WLAN network communication signal is unstable, and the problems of many interference sources are becoming more and more obvious. They purposed an LTE-M system that can effectively solve the problems of WLAN and provide guarantee for the safe and stable operation of the vehicles [2]. Besides, with the advent of technologies, fast-developing cloud network services, innovative applications in vertical industries, etc., have put forward

new requirements on the integrated network, in order to solve the problem of insufficient support for innovative services by the existing integrated network architecture and service opening mode, it is proposed that the next-generation integrated network should adapt to and lead the technological development trend and apply new technologies to simplify the network. In this direction, Meifang carefully researched the evolution of the vehicle integrated network, analyzed the problems of traditional integrated networks from the perspective of technology and management, proposed some key technologies for next-generation integrated networks, and gave the corresponding network architecture [3]. In [4–6], Zhu et al. studied the network security of vehicle communication systems to avoid attacks on vehicle networks. By introducing blockchain, model control algorithms, and edge intelligence, the methods they proposed can provide security for the vehicle network. However, the existing researches mainly focused on the fusion of train control data and do not integrate the vehicle subsystems. To solve these problems, it is urgent to realize a real-time control method based on intelligent vehicle network transmission.

This paper mainly focuses on proposing a TSN-based backbone network of train control management system

(TCMS). Firstly, this paper describes the introduced motivation and the background theories of TSN technology. Secondly, the network structure and the designed methodologies are detailed. The rail transit configuration of TSN is also carefully designed, including an algorithm for the time-aware shaper. After that, we perform comprehensive experiments to demonstrate the performance of the proposed structure. The experimental environments include indoor testing, the prototype development rail transit train line test, and the project demonstration.

2. Motivations

Due to the obvious difference of data types, the data transmitted in the on-board network of rail transit can be classified into three types of services TCMS, OMTS, and COS as follows [7].

2.1. TCMS Services. Train control and monitoring system (TCMS) includes all the control and monitoring functions of the train, taking into account both safety-related and nonsafety-related functions. All functions and equipment requiring certification shall be placed in the TCMS network. All security-related functions shall be located in the TCMS network; TCMS networks should be insensitive to changes in other networks. Communication between terminal devices of TCMS service is mission-critical communication. The prominent feature in TCMS networks is safe and secure communication between terminal devices to ensure the safety functions of trains or groups, such as safe train start and door control. For TCMS service, its communication requires higher priority, higher real-time performance, and lower transmission delay. Only when communication is deterministic (preset maximum delay) can secure communication be guaranteed. The representative business includes train traction, braking, auxiliary, door control, and other vehicle control services.

2.2. OMTS. On-board multimedia and telematic service (OMTS) business mainly includes all auxiliary system business for normal train operation, and all the contents considered are nonsafety-related functions. Over the life of the train, some innovations in functions and equipment will fall within this category. At the same time, the TCMS network should not be affected when new equipment is added to the network or new functions are provided to trains. Communication in the OMTS domain is not directly mission-critical; therefore, it is less sensitive to SIL security levels and more receptive to some of the typical limitations of network traffic. For OMTS service, because it does not affect train operation control, its communication requirements are moderate in priority and real-time transmission, and it can receive data delay to a certain extent. The representative business includes in-train, channel display, and PIS control business.

2.3. COS. Customer-oriented services (COS) mainly include services related to passenger services, such as passenger multimedia display screens or passenger WIFI services. During the life of the train, there will be a lot of innovation in func-

tions and equipment. Such services involve the risk of access to passenger terminal devices (such as smartphones); therefore, network isolation also needs to be considered. COS services are not mission-critical, and the public Internet access provided for passengers can be realized through similar mobile communication gateways. Therefore, information security between TCMS and OMTS needs to be considered, and security gateways need to be configured and some policy restrictions need to be implemented. As COS mainly serve passengers and have little impact on trains, they have the lowest requirements for communication, network data transmission priority, and real-time requirements and have a high tolerance for data transmission interruption. Therefore, they are more suitable for the background data service of the TSN network. The representative business includes passenger WIFI, train OLED screen, and other passenger services.

TSN is a new communication technology, which has become an industrial research hotspot in recent years. It has the characteristics of supporting the aperiodic and periodic data transmission to meet deterministic communication. At present, the underlying interoperability standards and specifications of TSN-based industrial application networks are being formulated by organizations such as IEEE and IEC. IEEE established the IEEE 802.1AVB working group in 2005, which is the predecessor of TSN technology. The establishment of IEEE represents the formulation of an audio/video transmission protocol that is set to solve the problems of real-time, low-latency, and flow control of data in the Ethernet, as well as compatible with ordinary Ethernet [8]. The TSN-based backbone network uses Gigabit Ethernet to comprehensively integrate the control, maintenance, and video surveillance networks. To solve the uncertainty of Ethernet data transmission, the TSN technology, which is currently used in the industrial field, is introduced into the rail transit system. Also, the TSN technology is appended on the Ethernet backbone network. Compared to the traditional TCMS network, the TSN-based backbone network has the following advantages.

- (i) Simple Network Structure with Strong Expansion Capability Mixed transmission of time-sensitive data streams (control data and status/fault data) and nontime-sensitive data streams (stream data) in the same network can achieve the ability of non-critical loads without affecting the transmission delay of critical loads [9], improving the utilization rate of the network bandwidth. Therefore, the structure can reduce a certain number of vehicle circuits and also reduce the number of vehicle-through lines and the internal communication cables of the vehicle subsystem, resulting in a lower weight of the vehicle.
- (ii) Deterministic Communication. Based on the advantages of the TSN technology, the backbone network can ensure that the data transmission delay in the switching network meets the system requirements. Thus, the tolerance of network transmission delay and the accuracy of vehicle control are improved in the TCMS.

- (iii) *Standardized Interface.* Since the TSN backbone network carries the message data communicated between all subsystems on the vehicle, standardized communication interface protocols can be developed to operate multiple projects, meanwhile reduce manpower and time costs in the project planning stage.

The TSN-based backbone network mainly uses the two key technologies. The IEEE 802.1AS protocol in the TSN network is used for time synchronization for entire network, and the IEEE 802.1Qbv protocol is applied for the time-aware shaper for each network unit. The time slot is divided to ensure a large amount of streaming data that cannot affect the transmission of vehicle control data and status/fault data generated while the vehicle system is being operated.

(1) *Clock Synchronization.* The backbone network employs the IEEE 802.1AS [10] clock synchronization protocol in the TSN network to synchronize the time of the entire network, which can achieve nanosecond clock synchronization. After powering on the vehicle, each TSN switch and each end device in the backbone network automatically vote a TSN switch or an end device as the clock master through the protocol algorithm. The rest of the TSN switches and end devices in the network communicate with the clock master, respectively. Other clocks establish a synchronization relationship, which is called clock slaves. The master/slave clock inserts time information into the L2 layer data frame. The data frame is transmitted from the network to each node, and a clock synchronization relationship is finally built [8]. Different from the transmission of peer-to-peer (PTP) in the network at the L3 and L4 levels in the IEEE 1588v2 [11], the gPTP of IEEE 802.1AS only works at the L2 level. Based on the time synchronization of the entire network, deterministic communication is realized.

(2) *Time-Aware Shaper.* The backbone network uses IEEE 802.1Qbv [12] in the TSN protocol as its time-aware shaper, which is shown in Figure 1.

According to the preconfigured gating period, the data of each traditional network in the integrated backbone network is assigned with different priorities. The data is restricted to be transmitted only in the allocated time period. The time period defined by IEEE 802.1Qbv has the characteristics of dynamically providing an on/off control mechanism for the egress queue which is triggered by network time.

The TSN switches in the backbone network periodically scan the time slot and open different transmission queues according to the predefined slot size and sequence, thereby forming a time-aware shaping function [8]. After shaping the traffic, the bandwidth occupied by IEEE 802.1Qbv is located at the same time slot, avoiding the risk of low bandwidth utilization caused by the fallback of the overlap or conflict of different data streams. Applying this structure, the transmission and traffic of multiple traditional subsystems under the same backbone network can be comprehensively integrated, leading to the improvement of network efficiency.

3. Materials and Methods

Through the time-sensitive network (TSN) technology, the backbone network of the next-generation of intelligent vehicles is reconstructed into the structure in Figure 2. By building a redundant vehicle ring network, safety equipment can be connected to the switch through dual physical ports, and nonsafety equipment can be connected to the switch through a single physical port. The TSN network provides Gigabit transmission bandwidth and supports multiple types of data transmission such as control flow and data flow. Based on the TSN network, it can ensure the highly reliable and low-delay transmission of key data in the vehicle network. At the same time, the TSN network is compatible with the ordinary TRDP terminals of existing vehicle subsystems and can automatically convert the TRDP terminal protocol to support basic TSN transmission.

The basic steps of the time synchronization of the TSN-based TCMS-integrated backbone network are as follows:

- (i) The clock master initiates a time synchronization signal and transmits it to the secondary device through the connected port
- (ii) The secondary device receives the time synchronization signal of the clock master and calibrates its own clock to form time synchronization with the clock master
- (iii) The secondary devices use the remaining ports other than the main clock to send the time synchronization signal as the local clock master
- (iv) The third-level devices receive the time synchronization signal of the secondary devices and calibrate their own clock to form time synchronization with the secondary devices
- (v) The third-level devices use the remaining ports other than the secondary devices to send the time synchronization signal as the local clock master

In this network structure, the multifunctional vehicle control unit (MVCU) device is defined as the clock master in the entire network as shown in Figure 3, which can improve network performance.

- (i) MVCU is in the center of the upper and lower network topology in the network structure, and the clock synchronization effect is better
- (ii) MVCU supports the acquisition of time from the outside (ATP) and has a valid time source, and the time is synchronized to the upper and lower ring networks, respectively
- (iii) As the main controller, the MVCU supports the switchover between master and slave. The clock master can switch to the slave MVCU while a failure occurs, and the origin slave MVCU forms a new time synchronization

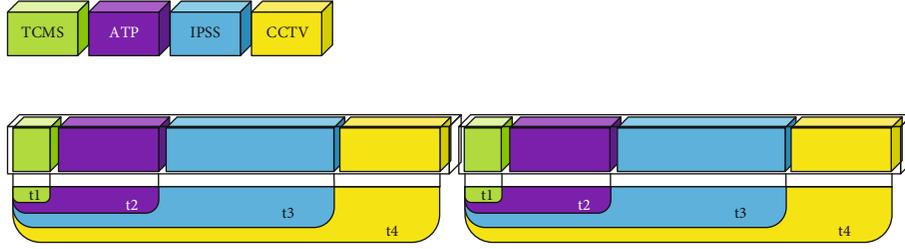


FIGURE 1: Time-aware shaper.

The principle of using time-aware shaper in TSN-based TCMS-integrated backbone network is shown in Figures 4 and 5, as the following examples:

- (i) At time T0, the drive control unit (DCU) sends data packets. At this time, all switches in the network open the time slot belonging to DCU due to the effective clock synchronization, and DCU data packets reach the MVCU unimpeded
- (ii) At the same time, since the current time slot does not belong to brake control unit (BCU), the BCU data packet cannot pass through the switch
- (iii) At time T1, since the current time does not belong to DCU, all switches in the network close the time slot of DCU, and the DCU data packet cannot pass through the switch
- (iv) At the same time, since the current time is the time when the BCU time slot is opened, BCU data packets can pass through the switch unimpeded

The TSN-based TCMS-integrated backbone network is configured with different priorities for control data and streaming data. The priority configuration follows the following principles:

- (i) The data relating to driving safety and vehicle control has a higher priority
- (ii) Nondriving-related control data or service-related control data, with the second priority
- (iii) For multimedia information such as video, in the case of sudden degradation, the data with less impact on the safe operation of the vehicle has the lowest priority

For example, for trains on a line in Beijing, the vehicle subsystem includes remote input/output module (RIOM), BCU, human machine interface (HMI), DCU, auxiliary control unit (ACU), multifunctional door control unit (MDCU), speed-distance unit (SDU), train eye system (TES), battery management system (BMS), heating ventilation and air conditioning (HVAC), passenger information system (PIS), and intelligent passenger service system (IPSS). These vehicle subsystems can be divided into several priorities in Table 1.

For the calculation of the time slot, an algorithm is proposed.

The size of the time slot must be at least greater than the transmission time of a complete data packet:

$$t_n > t_{sub}, \quad (1)$$

where t_n is the size of the time slot and t_{sub} is the transmission time of a complete data packet generated by subsystems. For control data, the length of the data packet is different in application scenarios, and the calculation is as follows:

$$t_{sub} = \frac{L_{sub}}{B}, \quad (2)$$

where L_{sub} is the data length generated by subsystems and B is the network bandwidth. For streaming data, corresponding calculations need to be performed according to the statistical data rate. The time slot required for a single data packet transmission is as follows:

$$t_{sub} = \frac{L_{max}}{B}, \quad (3)$$

where L_{max} is the maximum data length for single packet. For the above two types of data, the number of data packets transmitted in each time period must be considered. For the response time of different systems, refer to the following formula:

$$T = \frac{t_{resp}}{np} (np), \quad (4)$$

where T is the time period, t_{resp} is the response time for subsystems, n is the number of subsystems in each priority, and p is a corrected parameter used to adjust the acceptable range. The premise of satisfying streaming data transmission is that the number of data packets that can be passed per second exceeds the data packets per second required by the statistical rate:

$$n_{sub} t_{sub} > \frac{B_{sub}}{L_{max} T}, \quad (5)$$

where n_{sub} is the number of packets for each subsystem that should be transmitted in a time period. On this basis, the time slot size of various types of data in a time period is obtained:

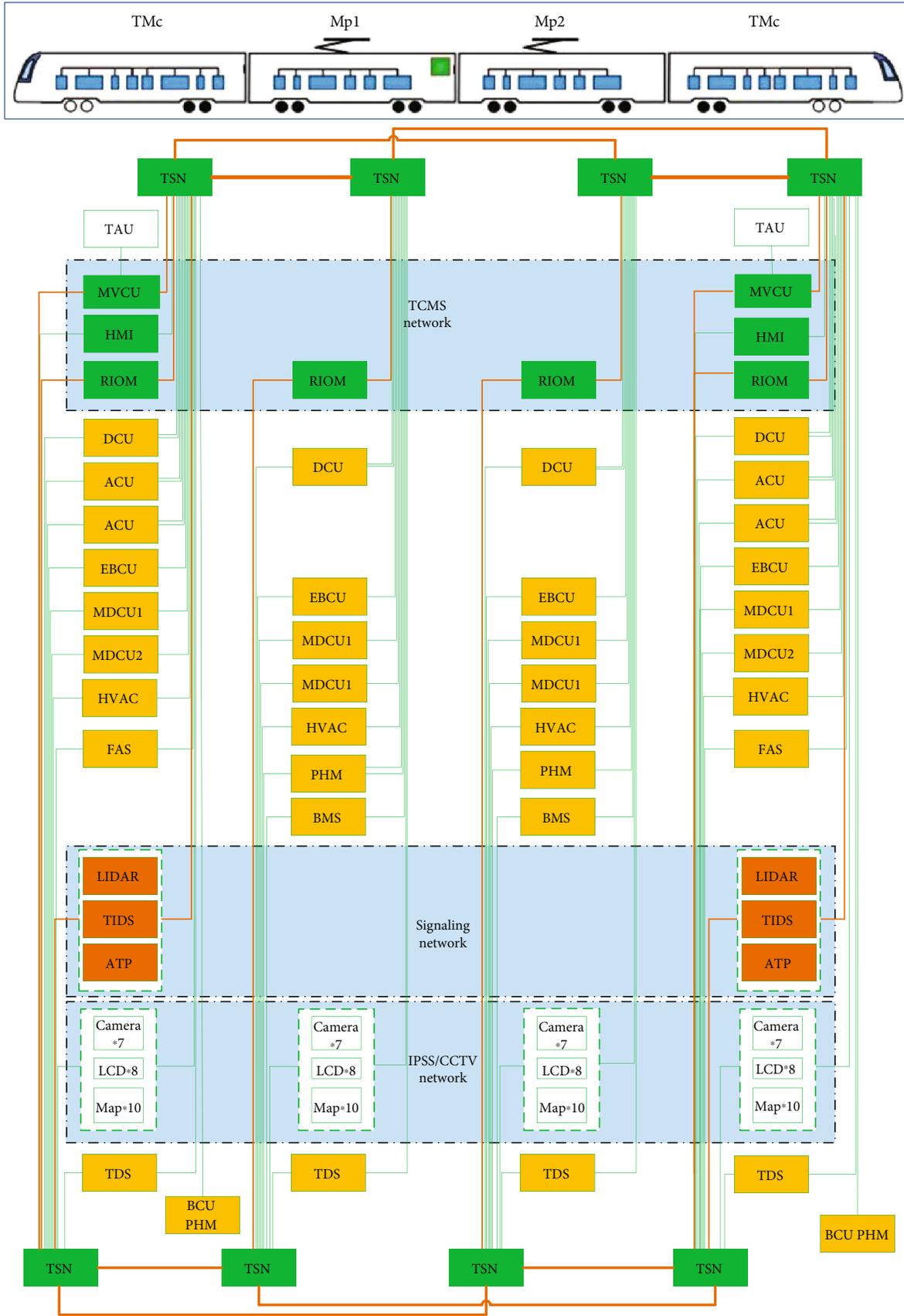


FIGURE 2: TSN-based backbone network topology for TMCS.

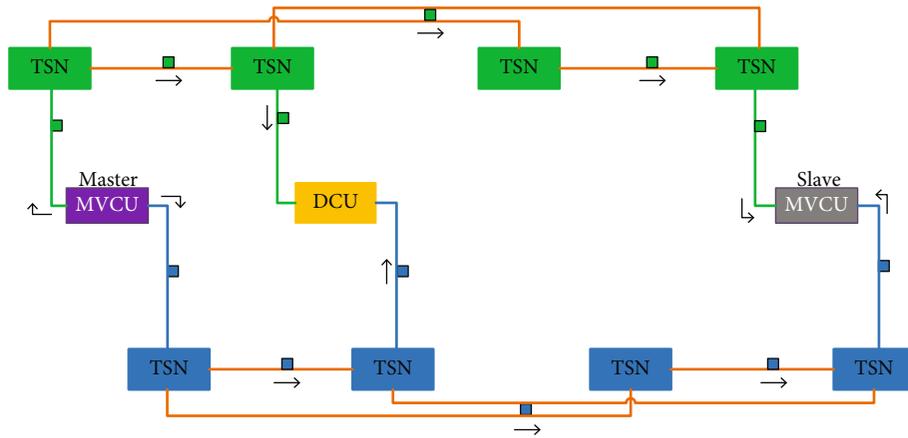


FIGURE 3: Time synchronization.

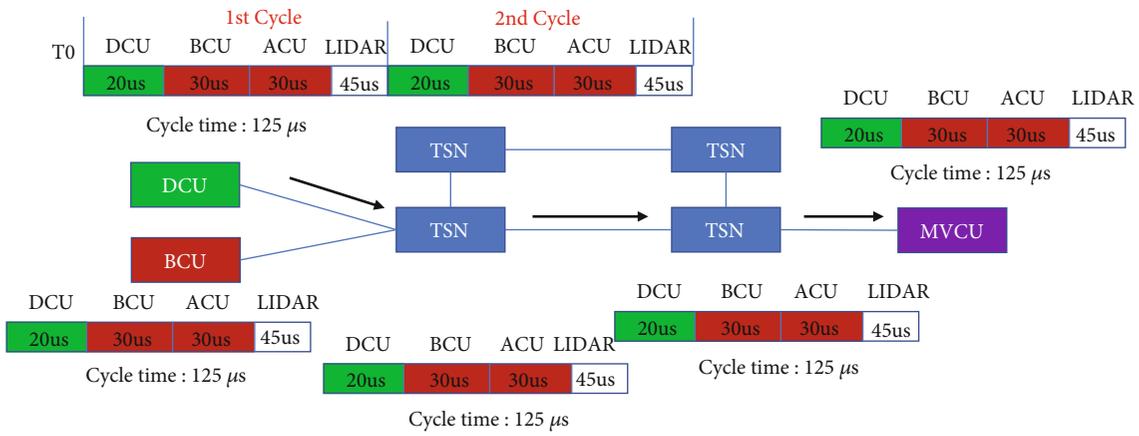


FIGURE 4: Time slot theory for time T0.

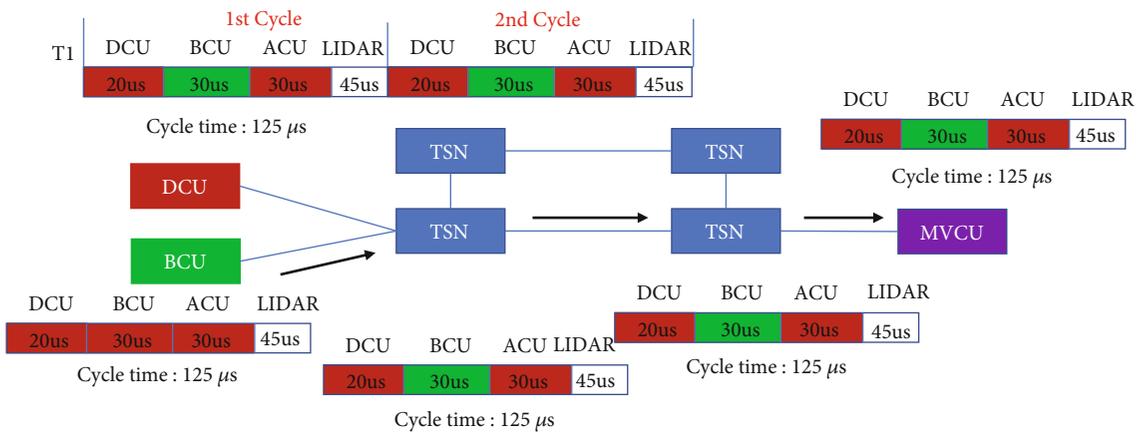


FIGURE 5: Time slot theory for time T1.

TABLE 1: Example: priority allocation.

Priority	Subsystem
7	RIOM/BCU/HMI
6	DCU/ACU/MDCU/SDU
5	TES
4	BMS/HVAC
3	FAS
2	PIS control
1	N/A
0	PIS/IPSS camera

$$T = \sum_{i=1}^n t(\text{sub}, i). \quad (6)$$

For example, some of the time slot sizes involved in the test are shown in Table 2.

4. Test Scheme

4.1. Test Environment

4.1.1. Indoor Test. The indoor test stage is divided into two parts. The first part mainly conducts related verifications of TSN switches, including the multiswitch transmission delay test (0% load/50% load/100% load) and the non-TSN end device access test. The second part mainly consists of testing the network functions. By adding subsystem simulation programs, we test the packet delay, packet loss, and jitter in the case of adding/canceling multimedia streaming data such as PIS/CCTV.

4.1.2. Rail Transit Train Line Test. The TSN-based TCMS backbone network is prototyped. Based on the experimental results of the real critical subsystems and the noncritical simulation subsystems, the network performance is further verified.

4.1.3. Project Demonstration. The TSN-based backbone network will also be used for demonstration projects on Beijing Metro Line 11. This stage tests the network through fully vehicle subsystems and also focuses on testing the redundancy scheme and the network performance. Experiments in this part include the dual redundancy scheme in compliance with the IEC61375 standard, the optimization scheme of the IEEE 802.1Qbv time window, and the optimization scheme of priority allocation.

4.2. Test Methodologies. The TSN-based backbone network architecture adopted in the test phase adopts the physical redundant double ring network topology, which is connected to the vehicle subsystems. The network topology is shown in Figure 6. Based on the 4-consist vehicle, the network adopts 8 TSN switch nodes as the train backbone network switches, forming two physical ring network structures. Two TSN switches are deployed in each carriage and connected to different ring networks, respectively. According to different test scenarios, vehicle subsystems are con-

TABLE 2: Example: time slot for subsystems.

Sequence	Time slot	Priority	Note
0	>6 μ s	7	High priority (e.g., BCU)
1	>26 μ s	5	Medium priority (e.g., LIDAR)
2	>39 μ s	0	Low priority (e.g., camera)
3	<54 μ s	Others	Other subsystems
Total	125 μ s		

nected to the TSN backbone network in different ways (i.e., software simulation or real equipment) to form integrated load. Control data related to TCMS and audio and video data related to multimedia are jointly transmitted in the same backbone network.

The vehicle subsystem includes all subsystems required by rail transit train operation. In the indoor test scenario, some vehicle subsystems are simulated and tested. In the scene of the rail transit test line, the vehicle subsystem supporting driving safety is not connected to the test temporarily to ensure driving safety. In the demonstration engineering scenario, all vehicle subsystems are tested.

According to different business requirements and equipment maturity, the vehicle subsystems in the demonstration project employ different methods to connect to the TSN backbone network. Table 3 shows the access method defined in this test.

4.3. Test Content. For indoor test and rail transit train line test scenarios, we test the basic function of TSN protocols (IEEE 802.1AS and IEEE 802.1Qbv), to evaluate network packet loss rate parameters by controlling whether to enable the TSN function, using the traffic generator import different levels of network load, respectively, test vehicle subsystem packet priorities. Besides, the camera receiver video image quality has been observed to evaluate test results.

In the project demonstration scenario, we enabled the TSN functions and tested the network quality by controlling the streaming data introduced or not under real vehicle subsystems. The packet latency has been recorded and calculated. Differences have been compared as well.

5. Results and Discussions

In the indoor test scenario, data between traction control unit (TCU) and the vehicle control unit (VCU) has been tested, and the camera with its receiver is introduced at the same time to test the latency and packet loss rate. The average value obtained through multiple tests is shown in Figure 7. When the TSN function is turned on, the average delay of TCU data packet transmission is stable around 17 ms under different load conditions. However, at 0% load, the camera image is displayed smoothly; at 50% load, the camera image appears blurry; and at 100% load, the camera image freezes.

Indoor test results are as follows:

- (i) The switch has the TSN functions with stable delay, while the IEEE 802.1AS and IEEE 802.1Qbv protocols are effective

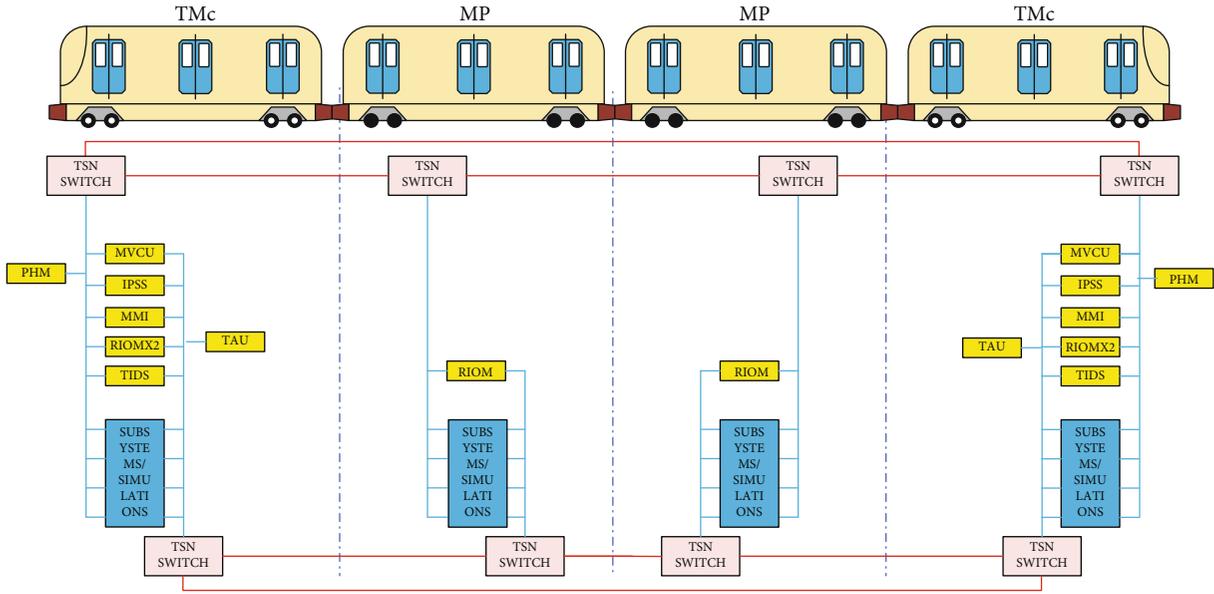


FIGURE 6: Test topology.

TABLE 3: Example: access method for subsystems.

Subsystems	Method
Critical subsystems (MVCU, RIOM, etc.) (high priority)	The subsystem itself supports the TSN network and is directly connected to the backbone network through the TSN switch.
Critical subsystems (MDCU, ACU, etc.) (medium priority)	The subsystem itself does not support the TSN network and needs to be converted to a TSN network through a TSN switch and then connected to the backbone network.
Noncritical subsystems (PIS, CCTV, etc.) (low priority)	The subsystem itself does not support the TSN network and does not need to be converted to a TSN network through a TSN switch, connected to the backbone network directly.

Network topology			TSN-based backbone network		
TSN function			On		
Traffic generator percent			0%	50%	100%
Data type	Traffic	Parameters	Max, Min, Avg	Max, Min, Avg	Max, Min, Avg
Critical data	TCU	Packet loss	1/22940	1/18425	0/17490
		Latency	Max:33.382 ms	Max:42.163 ms	Max:33.154 ms
			Min:2.210 ms	Min:2.222 ms	Min:2.297 ms
		Avg:17.338 ms	Avg:17.553 ms	Avg:17.668 ms	
Non-critical data	Camera	Image quality	Fluency	Fuzzy	Stop
TSN protocol	802.1AS		Effective		
	802.1Qbv		Effective		

FIGURE 7: Test results for indoor test.

- (ii) Non-TSN end device is capable of providing basic TSN functions. It can also support the configuration of the default priority through the switch
- (iii) We verify that the TSN-based backbone network is feasible. The transmission of a large amount of streaming data has no impact on the control data transmission. The packet loss is observed to be 0%, which means the delay is also stable at the system level
- (iv) Network equipment in the proposed structure realizes redundancy functions through the dual physical network port access
- (v) Using the mentioned optimization schemes, the proposed structure can support the multimedia streaming data transmission with a minimum bandwidth of 650Mbps, under the premise of ensuring that all control data remains unaffected

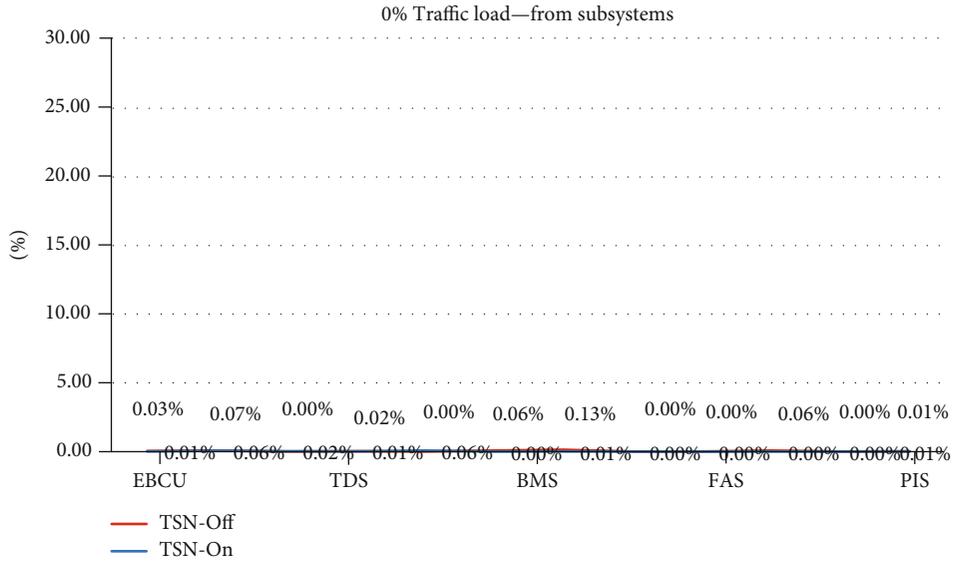


FIGURE 8: Test result: 0% traffic load from subsystems.

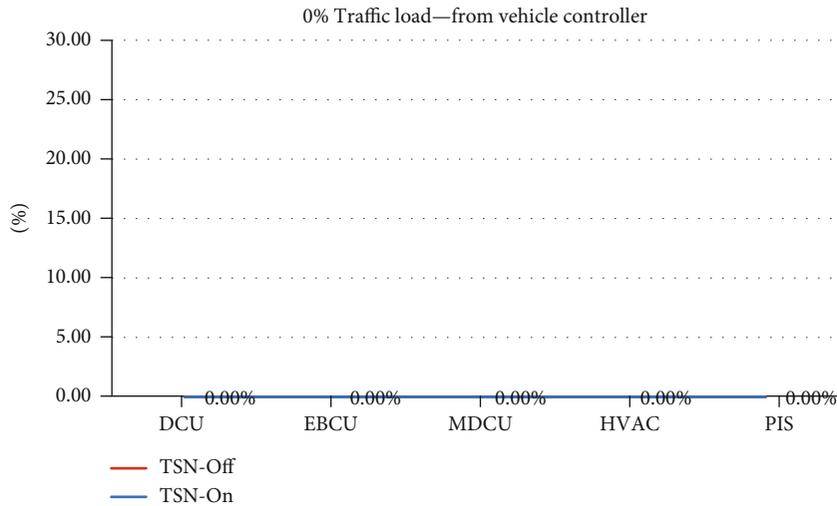


FIGURE 9: Test result: 0% traffic load from vehicle control unit.

In the rail transit train line test scenario, a part of vehicle critical subsystems and noncritical simulation subsystems is tested, and multiple test scenarios are compiled. We tested whether turning on the TSN function under three different load conditions and the subsystems recorded and calculated the packet loss rate. The packets has been captured from both vehicle subsystem side and vehicle controller side. Figures 8 and 9 show the test results.

In Figures 8 and 9, the data packets sent by the vehicle subsystem side and the data packets sent by the vehicle controller side are captured and analyzed this time. Both TSN-on and TSN-off scenarios have been involved, and it can be seen that at 0% load, the packet loss rates are around 0% whether enabling the TSN function or not. This means enabled TSN function does not affect the normal packet transmission and does not increase the loss rate of the subsystem.

Similarly in Figures 10 and 11, the data packets sent by the vehicle subsystem side and the data packets sent by the vehicle controller side are captured and analyzed this time. Both TSN-on and TSN-off scenarios have been involved, and it can be seen that at 50% load, the packet loss rates are around 0% whether enabling the TSN function or not. This means that network load is not serious enough to influence the normal packet transmission and TSN function does not increase the loss rate of the subsystem.

However in Figures 12 and 13, when the load is 100% as well as the TSN function is not enabled, the subsystem will experience a lot of packet loss, and the communication will be severely affected by the network load. After the TSN function is enabled, the communication of the subsystem returns to normal and there is nearly no packet loss phenomenon. Note that the packet loss rate is not completely

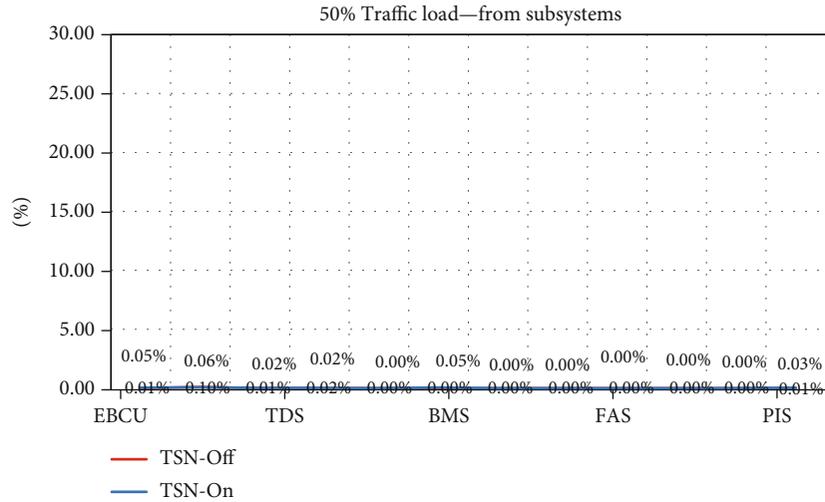


FIGURE 10: Test result: 50% traffic load from subsystems.

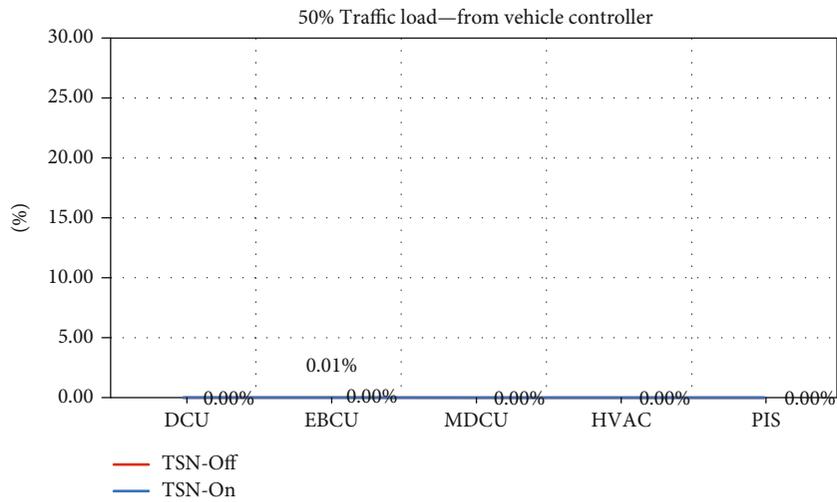


FIGURE 11: Test result: 50% traffic load from vehicle control unit.

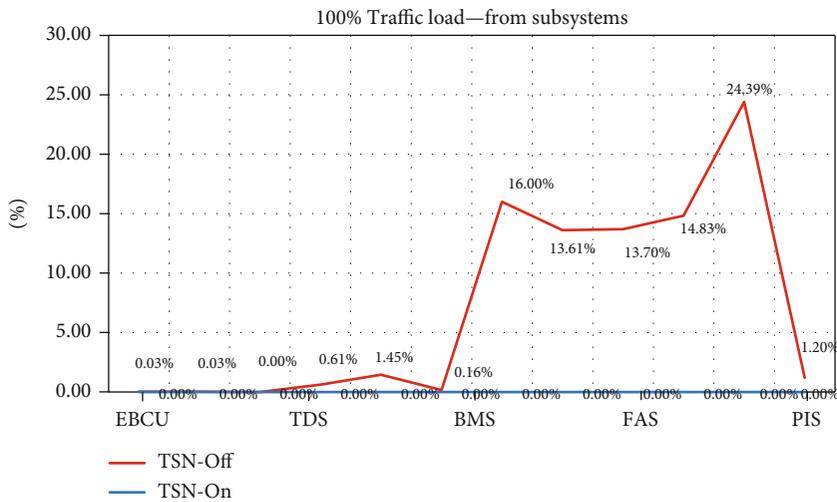


FIGURE 12: Test result: 100% traffic load from subsystems.

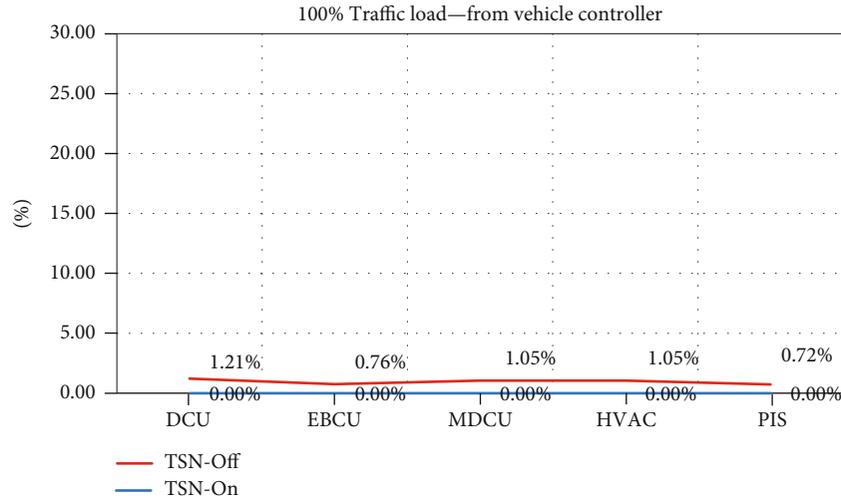


FIGURE 13: Test result: 100% traffic load from vehicle control unit.

Network				TSN-base backbone network									
Streaming data				Off			On			Difference			
Traffic	ConnID	Data length (Bytes)	Period (ms)	Avg latency (ms)	Max latency (ms)	Min Latency (ms)	Avg latency (ms)	Max latency (ms)	Min latency (ms)	Avg latency (ms)	Max latency (ms)	Min latency (ms)	
Critical Data	BCU1	2101	168	50	2.873	8.461	1.537	2.595	7.567	1.536	-0.278	-0.894	-0.001
	BCU2	2201	168	50	2.756	7.041	1.537	2.892	7.155	1.535	0.136	-0.114	-0.002
	TCU	2102	592	30	2.209	8.331	0.056	2.201	6.883	1.518	-0.008	-1.448	1.462
	ACU	2103	240	50	2.491	7.006	0.500	2.538	7.077	1.540	0.047	0.071	1.040
	PHM	2104	400	1000	2.551	7.453	1.549	2.570	6.330	1.547	0.019	-1.123	-0.002
	BMS	2106	200	1000	2.064	4.663	1.518	2.090	4.387	1.521	0.026	-0.276	0.003
	PMS	2107	200	1000	2.060	6.622	1.524	2.256	7.212	1.523	0.196	0.590	-0.001
	ERM&SGW	2108	400	1000	2.168	7.184	1.536	2.276	6.135	1.534	0.108	-1.049	-0.002
	EDCU1	2109	264	200	2.752	7.837	1.544	2.231	4.781	1.544	-0.521	-3.056	0.000
	EDCU2	2209	264	200	2.799	8.881	1.547	2.235	4.969	1.544	-0.564	-3.912	-0.003
	ACC	2110	400	1000	2.989	7.525	1.786	2.450	4.710	1.792	-0.539	-2.815	0.006
	FAS	2111	200	1000	2.136	6.134	1.456	2.075	4.867	1.453	-0.061	-1.267	-0.003
	PIS	2112	300	1000	2.419	5.507	1.695	2.490	5.581	1.698	0.071	0.074	0.003
	ITP	2113	1000	80	2.373	6.725	1.718	2.403	7.508	1.791	0.030	0.783	0.073
RIOM1&2&3&4	2115	160	30	2.134	7.113	0.227	2.150	6.759	1.408	0.016	-0.354	1.181	
Non-critical data	CCTV		Effective or not							Effective			
	TES		Effective or not							Effective			
TSN Protocol	802.1AS		Effective or not							Effective			
	802.1Qbv		Effective or not							Effective			

FIGURE 14: Test results for project demonstration.

0%. This is because the first/last data packet may be lost in the process of multiple interceptions, which does not affect the test results.

Rail transit train line test results are as follows:

- (i) 43 network test cases are carried out and passed in this part, demonstrating that the TSN-based TCMS-integrated backbone network can be used as the backbone network of rail transit vehicles to support train operation

In the project demonstration scenario, all vehicle subsystems are verified with real equipment. Based on the enabled TSN function, test whether the streaming data in the TSN-base backbone network has an impact on the control data under real train operation. This test involves multiple subsystems, and the test results are shown in Figure 14 below. By comparing the differences between the two test types, it can be seen that whether to introduce streaming data has little impact on the vehicle subsystem (the differences are positive/negative, and it is considered that it is caused by the recording tool accuracy).

Project demonstration results are as follows:

- (i) TSN-based backbone network can be used in real vehicles. The designed priorities and time slots are available to use and can be improved as well in the future studies

6. Conclusion

In conclusion, to solve the problems of low bandwidth, low transmission rate, and uncertain transmission delay in traditional vehicle networks, it is necessary to design a real-time vehicle backbone network in rail transit. After thorough research, testing, and evaluation of the TSN technology, it has been possible to ensure that the technology can be used to provide effective support to the backbone network. At the same time, the TSN-based TCMS backbone network proposed in the article has the characteristic that controls data not affected by streaming data, which can meet the communication requirements of rail transit for low latency, high reliability, and high bandwidth and avoid negative effects caused by unstable streaming data. In more detail, this

article designs the rail transit configuration of TSN and proposes an algorithm for time-aware shaper calculation. Using this advanced algorithm can avoid the risk of low bandwidth utilization caused by the fallback of the overlap or conflict of different data streams while effectively improving the network efficiency of the rail transit system. On this basis, the indoor test, prototype development rail transit train line test, and project demonstration have been carried out to demonstrate the efficiency of the structure.

Data Availability

Data can be found in Traffic Control Technology Co., Ltd. test results.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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