Networking and Communications in Autonomous Driving: A Survey

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***Abstract*—The development of light detection and ranging, Radar, camera, and other advanced sensor technologies inaugurated a new era in autonomous driving. However, due to the intrinsic limitations of these sensors, autonomous vehicles are prone to making erroneous decisions and causing serious disasters. At this point, networking and communication technologies can greatly make up for sensor deficiencies, and are more reliable, feasible and efficient to promote the information interaction, thereby improving autonomous vehicle's perception and planning capabilities as well as realizing better vehicle control. This paper surveys the networking and communication technologies in autonomous driving from two aspects: intra- and inter-vehicle. The intra-vehicle network as the basis of realizing autonomous driving connects the on-board electronic parts. The inter-vehicle network is the medium for interaction between vehicles and outside information. In addition, we present the new trends of communication technologies in autonomous driving, as well as investigate the current mainstream verification methods and emphasize the challenges and open issues of networking and communications in autonomous driving.**

***Index Terms*—Autonomous driving, intra-vehicle network, inter-vehicle network, verification method, survey.**

I. Introduction

IN RECENT years, both the academia and industry have shown great interest in the development of autonomous driving, which will liberate drivers physically and mentally, greatly improve traffic safety and energy efficiency, as well as make better use of public resources. Universities and research groups are actively involved in autonomous driving competitions and technical challenges. Stanford University and Carnegie Mellon University have done well in "DARPA Urban Challenge" [1], a top class competition for autonomous driving techniques organized by DARPA (Defense Advanced Research Projects Agency). Traditional car companies such as General Motors, Toyota, Volvo, Volkswagen and BMW as well as Internet auto companies such as Google, Uber and Tesla, have joined the ranks of autonomous vehicle manufacturing and research. SAE International divides autonomous driving into 5 different levels [2]. Tesla Model S claims to have reached level 2.5 of autonomous driving; the new Audi A-8 has reached level 3, making Audi the first automaker to offer a level 3 autopilot. Although the final winner in this area is still difficult to judge, the emergence of autonomous vehicles will make a historic change in the way people and goods are transported.

The core functions of existing autonomous vehicles are mainly actualized by three parts: perception, planning and control [3]. Sensors such as image sensor (camera), LIDAR (LIght Detection And Ranging), ultrasonic Radar (RAdio Detection And Ranging) and millimeter-wave Radar generate information as input to the perception layer (including vehicle location and target recognition), which can be regarded as the prerequisite for realizing autonomous driving. The accurate position of the vehicle is obtained mainly through the integration of information from LIDAR, GPS (Global Positioning System), IMU (Inertial Measurement Unit), etc., while the object recognition is mainly realized by LIDAR and camera. The input of the planning layer includes the information from the perception layer, as well as the feedback information from the control layer. Its planning instructions include following, overtaking, accelerating. According to the instructions issued by the planning layer, the control layer implements the specific control over the vehicle, including throttle, brake and gear control.

Various advanced sensors (e.g., LIDAR, Radar, camera, etc.) equipped on a representative autonomous vehicle are shown in Fig. 1. However, these sensors have the following limitations. (i) *Unreliability*. Decision making by sensors alone has led to a lot of serious accidents. On May 7th, 2016, a Tesla Model S crashed into the side of a truck on a Florida highway, killing the owner on the spot [4]. According to Tesla's official explanation, the camera was blocked from sight because of the white towed car corner. Nevertheless, even if the sensors correctly detect the objects around the autonomous vehicle, it is difficult for the planning layer to determine how the vehicle should react to these objects. For example, the most recent incident occurred on March 19, 2018, although the sensors equipped on one of Uber's autonomous car detected the pedestrian, the software system decided that no immediate evasive action was required, leading to the tragedy of a 49-year-old woman's death while crossing a Tempe, Ariz. Street [5]. (ii) *Infeasibility*. The sensors have restricted perception capacities and operating conditions due to their intrinsic features. Fading lane line, broken or irregular traffic lights and signs can make the autonomous vehicle unable to identify

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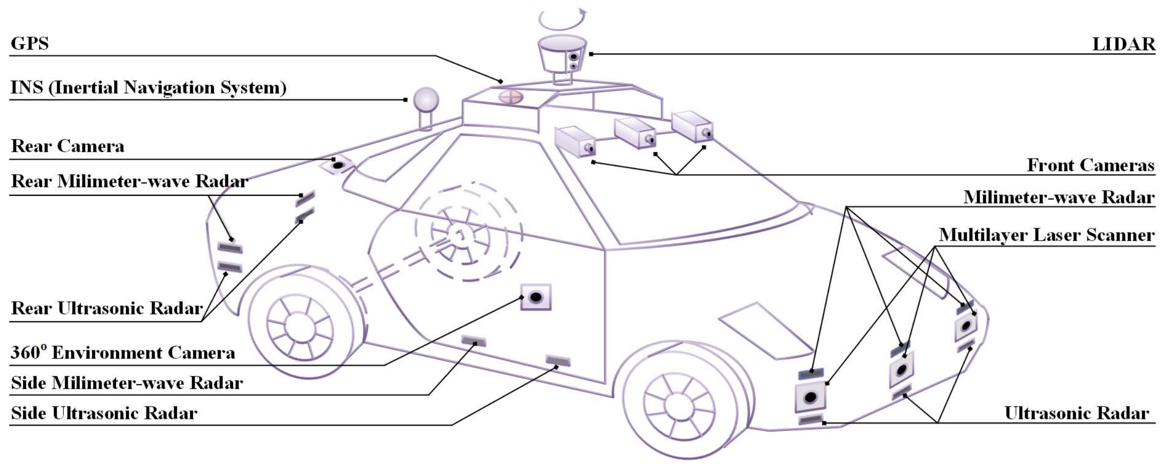


Fig. 1. Illustration of various sensors equipped on a representative autonomous vehicle.

their characteristics or become chaotic. At rather complex intersections, dense pedestrian flow and huge traffic flow all bring great difficulties to the object recognition. Under severe weather conditions, the reflective properties of the road will change due to ice, snow or rain. Consequently, the LIDAR is vulnerable to this confusing reflection as it detects the target by emitting laser light and capturing reflected signals. Debris such as leaves and plastic bags fluttering in the wind can also cover sensors directly and block their sight. Besides, the absence of high precision maps or GPS signals in spaces such as tunnels and underground parking garages will pose a great challenge to the positioning of autonomous vehicles. (iii) *Inefficiency*. Sensors are incapable of detecting traffic jams or accidents a few blocks away because of their limited view. Furthermore, they can only be used partially and always have some blind spots. Therefore, the shortcomings of one sensor need to be remedied by equipping several more sensors, leading to a growing trend of the number of sensors in autonomous vehicles. The self-driving car developed and tested by Waymo has 6 LIDAR sensors; Uber's Ford Fusion has 7 LIDARs, 7 Radars and 20 cameras; Volvo's autonomous car has one LIDAR, 10 Radars and 7 cameras [6]. However, as the core sensor of autonomous vehicle, LIDAR is far from cheap. Velodyne as the leader in LIDAR market has launched HDL-64E LIDAR that costs a whopping $75,000 and the higher-performance VLS-128 LIDAR, which is expected to be more expensive. In short, the persistent pursuit of high precision and expensive sensors is inefficient, costly and even endless.

At this point, networking and communication technologies can greatly make up for sensor deficiencies, and are more reliable, feasible and efficient to promote the information interaction, ultimately greatly improve the security of autonomous vehicles. They have the following desired features. Firstly, information shared in real time among numerous vehicles such as locations, speeds and road states, can be adopted as the input of the perception layer without much consideration of environmental factors, thus making the perception range of the vehicle more extensive and reducing the demand for sensors. Secondly, the information mentioned above can also be used by the planning layer to facilitate accurate path planning and avoid the potential danger earlier. Thirdly, these technologies not only own high commercial values such as service for entertainment applications and advertisement delivery, but also bring the management convenience to the government sectors such as promoting the dissemination of public information, broadcasting traffic management directive and emergencies, and monitoring vehicle operating status. Consequently, the final form of autonomous driving will be a perfect combination of autopilot and vehicle communications, which has aroused world-wide attentions. Represented by American ASTM/IEEE, Japan's ISO/TC204 and European CEN/TC278, the international standards organizations have carried out the work on the formulation of the DSRC (Dedicated Short Range Communications) standard [7]. IEEE has developed the 802.11p protocol mainly used for wireless vehicle communications. Chinese domestic enterprises have formulated the LTE-V [8] protocol for intelligent connected vehicles. Furthermore, studies on the upcoming 5G vehicle networks are in full swing.

Given tons of pioneering works towards networking and communications in autonomous driving, to our best knowledge, existing reviews and surveys on this topic, although paving the way for the development of vehicle communications, are either narrow [9]–[13] or outdated [14]–[16] or not primarily focus on autonomous vehicles [17]–[19]. In light of this, we aim at providing an up-to-date and comprehensive survey of the networking and communication technologies available for autonomous driving as well as presenting the relevant challenges and suggestions, enabling both researchers and beginners to keep abreast of the latest global achievements in this field and to produce a quick and overall mastery, so as to further promote the development of autonomous driving.

The rest of this paper is organized as follows: Section II describes the intra-vehicle networking and communication technologies divided into two ways: wired and wireless. Inter-vehicle networking and communication technologies are investigated in Section III. New trends of communication technologies in autonomous driving are presented in Section IV. In Section V, we summarize the mainstream verification technologies. Later, in Section VI, we present some crucial challenges. Finally, Section VII concludes the paper.

II. Intra-Vehicle Networking and Communications

Intra-vehicle networking and communications as the basis of autonomous driving can realize the transmission of status information and control signals among sensors, actuators and electronic units in the autonomous vehicle, combine the wired and wireless technologies to form an extensible connection backbone structure, and actualize advanced functions such as state perception, motion control and fault diagnosis in a centralized system. In this section, we'll review the state-of-the-art of intra-vehicle networking and communication technologies that are already in use on autonomous vehicles or have the potential to be used.

A. Intra-Vehicle Networking

1) Wired Interconnection: Wired interconnection is the main way of exchanging information and coordinating control among diversified electronic components in today's autonomous vehicle's on-board network. There are two forms of wired interconnection currently used in vehicles. The first is that different messages are transmitted on different wires, i.e., the more types of information, the more data wires and pins of ECUs (Electronic Control Unit). Most traditional electrical systems adopt this single point-to-point communication mode. However, if autonomous vehicles marked by a great many electronic components and a large amount of data transmission use this method, the complex wire harness will not only undoubtedly create a huge wiring system and increase the weight of the bodywork, but also inevitably bring lots of difficulties in the wiring of the whole vehicle. The second form is to exchange all information among control units via data bus. In this way, the number of wires on autonomous vehicle can be greatly reduced, the wiring of the whole vehicle is able to be greatly simplified, and the sharing of ECUs' data can be realized. Therefore, the second manner is suitable for autonomous vehicles with numerous electronic components and massive intra-vehicle real-time data to be transmitted.

Several typical data bus wired interconnection technologies are used in current autonomous vehicles, such as Controller Area Network (CAN), Local Interconnect Network (LIN), FlexRay, Media Oriented System Transport (MOST) and Ethernet that will be detailedly introduced in Section II-B1. In general, the intra-vehicle networking technologies in autonomous driving used vary depending on information type, cost and efficiency considerations. For example, CAN is widely used in autonomous car's powertrain and body control fields. FlexRay, with prominent determinism and fault-tolerant capability, is usually used to support chassis control, communication backbones, and security critical applications. The cost of LIN is relatively low, so it is often used in places where high network performance is non-essential, such as transmission of small serial control messages. MOST is far from cheap and usually used to transmit infotainment data. Therefore, the existing autonomous vehicle's intra-vehicle wired networks show significant heterogeneity due to the different technologies used in different functional areas. For example, the autonomous vehicle Tesla Model S/X/3 adopt hybrid wiring diagram and use CAN, LIN and 100 Mbps Ethernet via a 6 port switch [20], while the autonomous Audi A-8 D5 uses the data bus system consists of CAN, LIN and MOST [21]. A hybrid wiring diagram of the autonomous vehicle's intra-vehicle networking is shown in Fig. 2. We'll detailedly introduce the wired interconnection technologies in Section II-B1.

2) Wireless Interconnection: With the escalating complexity of autonomous vehicle design: (i) The intra-vehicle sensors and ECUs are gradually increasing; (ii) The internal wiring harness becomes extremely intricate; (iii) Wire materials and wiring layout design turn more costly; (iv) The weight of the autonomous vehicle is getting heavier, putting more pressure on driving control system (e.g., steering system and brake system) and consuming more energy; (v) The deployment of wires becomes limited, for example, it is not appropriate to use the wired structure for intra-vehicle communications on steering wheel and tire parts; (vi) The intra-vehicle space will become more crowded.

Traditional wireless technologies are used to establish wireless connections between personal electronic products and the infotainment systems on-board. Besides, if massive data produced by multitudinous sensors, actuators or ECUs in autonomous vehicles can be transmitted wirelessly, the need for wires and the weight of autonomous vehicle's bodywork will be greatly reduced, the energy will be saved, and the sensors will be able to be integrated into various parts of the autonomous vehicle that cannot be wired. Subsequently, the endurance of autonomous vehicle and the flexibility of intra-vehicle communications can all be enhanced. Therefore, wireless interconnection method is a potential alternative to the intra-vehicle wired interconnection in autonomous driving. Several representative wireless technologies that have been used or may be widely deployed in autonomous vehicles in the future are summarized in Section II-B2.

B. Intra-Vehicle Communications

1) Wired Interconnection Technologies:

- *CAN* (Controller Area Network) is a kind of asynchronous serial bus network with low cost, high reliability and relatively low bandwidth developed by Robert Bosch GmbH to solve the data exchange problem in modern automobile. It is a main standard of European automobile manufacturing industry and has been widely used in automotive electronics systems such as powertrain, chassis and body electronics, while great limits are found in infotainment systems. The traditional CAN based on event triggering can be divided into CAN HS (High Speed) with data transmission rate of up to 1 Mb/s and CAN LS (Low Speed) between 40 and 250 Kb/s. In order to meet the needs of real-time vehicle control and dense message transmission, the traditional CAN is combined with the time trigger mechanism to produce TTCAN (Time-Triggered CAN). TTCAN [22] defines different

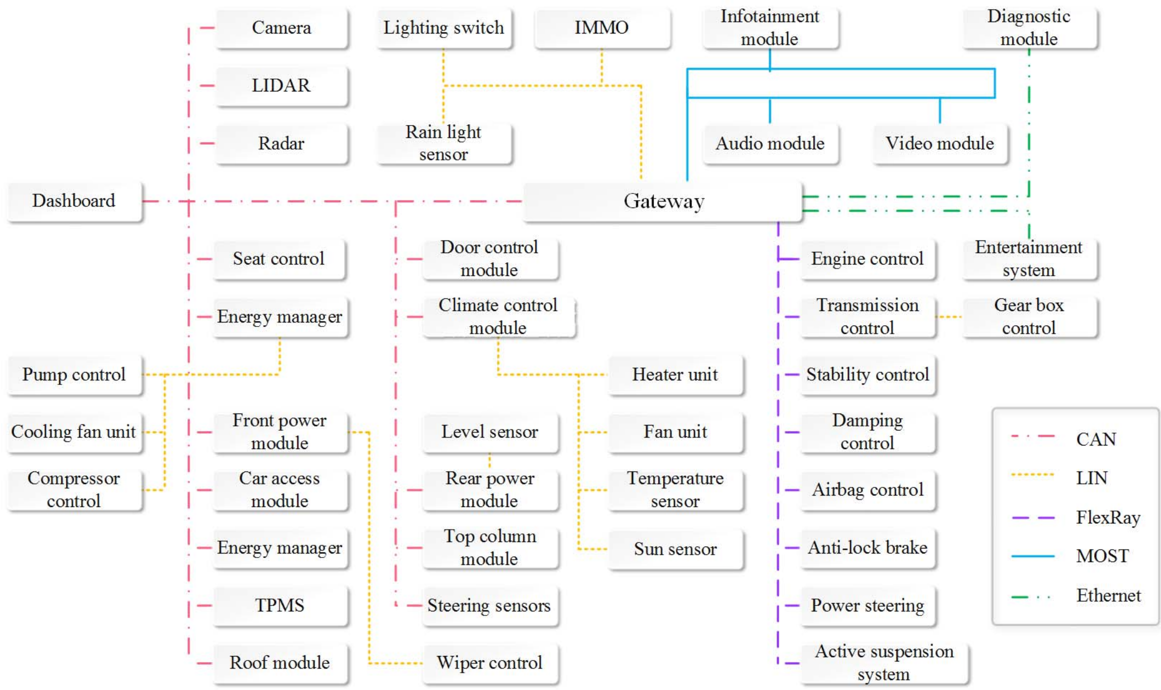


Fig. 2. Illustration of a hybrid wiring scheme for autonomous vehicles' intra-vehicle networking. CAN is mainly used for control modules and sensor connection. LIN is often used for modules that do not require high network performance. FlexRay is usually used in real-time or security-related applications and MOST in infotainment modules. Ethernet is applied for fault diagnose module and also involved in entertainment systems. Furthermore, gateway is used to connect different types of buses.

time slots for different information on the bus, thus avoids the bus arbitration and ensures the real-time information. Nevertheless, it has problems for the system working with dynamic value changing real time requirement [23]. Consequently, a new FTTCAN (Flexible Time-Triggered CAN) protocol is proposed [24]. Numerous world famous automobile manufacturers such as Volkswagen, Benz, BMW, Porsche, Rolls-Royce are already using CAN bus to realize the data communication of automobile internal control system. Audi A-8 D5, the world's first level 3 autonomous production vehicle, uses CAN in its drive system and adaptive cruise control system [21]. Tesla Model S/X/3 with autonomous driving level 2.5 also adopt CAN in their powertrain and body control [4]. In the top competition "DARPA Urban Challenge" of driverless industry, famous autonomous vehicles "Junior" from Stanford University and "Talos" from Cambridge University all applied CAN bus in its intra-vehicle network [1].

- *LIN* (Local Interconnect Network) is an open source protocol and a cheaper supplement to CAN developed in the late 1990s by Audi, BMW, Chrysler, Volkswagen and Volvo. It has the characteristics of low cost and low speed (less than 20 Kb/s), and is often used in lights, door locks, electric seats and other parts where network performance requirements are not high. The autonomous car Audi A-8 D5 and Tesla Model S/X/3 all use LIN for simple low speed devices such as air conditioner and seat heaters [4], [21].
- *FlexRay* is a new communication standard physically communicates over two separate buses (each having a data rate of 10 Mb/s) developed by BMW, Philips, Freescale and Bosch. It adopts time-triggered mechanism and has the advantages of high bandwidth and excellent fault-tolerant performance. Moreover, it provides flexible configuration to support various topologies such as linear bus, star and hybrid topologies. Compared with CAN, FlexRay has higher cost and can be used in power systems and security applications with strict performance requirements. For example, autonomous Audi A-8 D5 adopts FlexRay for distributed control and safty-related systems.
- *MOST* (Media Oriented System Transport) is an expensive multimedia network technology with the maximum bandwidth up to 150 Mb/s specially designed for vehicular infotainment systems. It adopts ring topology and transmits data through optical fibre. Supported by BMW, Chrysler, HARMAN/BECKER and SMSC, MOST has been used in myriad high-end vehicles such as BMW 7 Series, Mercedes E Series and the new autonomous car Audi A-8 D5 for infotainment system.
- *IDB*-1394 (Intelligent transport system Data Bus) with the transmission rate up to 400 Mb/s based on IEEE 1394 is specially designed for vehicle entertainment applications that require high bandwidth [23]. However, MOST is supported by more manufacturers including some software developers than IDB-1394 and is still the mainstream standard in multimedia transmission.

- *D2B* (Digital Data Bus) is a networking protocol based on optical fibre communication technology with transmission rate up to 11.2 Mb/s designed for multimedia (e.g., digital audio and video frequency). D2B is driven by C&C Electronics in the U.K. and has been accepted by Mercedes Benz and Jaguar [25].
- *LVDS* (Low Voltage Differential Signaling) is a high-speed standard with the bandwidth of 655 Mb/s based on twisted pair copper cables and an attractive option for intra-vehicle multimedia transmission in autonomous driving. Although not specifically developed for automotive applications, LVDS has many advantages inside the vehicle, such as low power and great immunity to electromagnetic interference (EMI) [26].
- *Ethernet* is a common used communication technology in the Local Area Network (LAN) field because of its benefits of low cost, high speed and flexibility. Besides, it has wide range of prospects in autonomous vehicles. The gradually increasing number of electronic products and the complexity of intra-vehicle network structure in autonomous driving lead to the demand for faster and more flexible communication technologies. Thereafter, 100BASE-T1 becomes IEEE's newly defined on-board Ethernet standard, using two twisted-pair wires to provide the transmission rate of 100 Mb/s [27]. The communication protocol supported by traditional intra-vehicle network is relatively unitary, while the on-board Ethernet can support many kinds of protocols or applications such as AVB (Audio/Video Bridging), TCP/IP, DoIP (Diagnostic over IP), SOME/IP (Scalable service-Oriented MiddlewarE on IP) simultaneously [28]. In "DARPA urban challenge", numerous well-known autonomous vehicles applied Ethernet to their car body. For example, Ethernet interfaces are used to deliver sensor data to the on-board computers for most devices in "Talos" from Cambridge University, and provide serial connections for the low-level hardware and sensors in "Little Ben" [1]. Tesla Model S/X/3 also adopt Ethernet for instrument cluster, diagnose port and gateway.
- *PLC* (PowerLine Communication) is a technology that uses existent power infrastructure to transmit data and electricity simultaneously. It adopts dedicated modem to modulate the data signal and then loads the signal into the powerline for communication. Besides, the coupler is used to separate the power supply voltage and the transmitted data to ensure that the data can be coupled to the powerline while the strong electricity on the powerline can be transmitted normally. Traditional electronic devices on vehicles have at least two connections: one for data transmission and the other for power supply. In complex cabling autonomous vehicles, it will be useful to transmit electricity and data over the same wire, thus reduce autonomous vehicle's body weight, save space and cut cost at the same time. Strobl *et al.* [29] use PLC to realize Ethernet in automobile network and put forward Ethernet-PLC-bridges built upon the SIG60 automotive narrowband PLC (NB-PLC) transceivers from Yamar Electronics Ltd. Moreover, PLC is a kind of harsh transmission medium with strong impulse noise, which will seriously deteriorate the autonomous vehicle's intra-vehicle transmission performance. Toward this end, Ling *et al.* [30] focus on typical vehicular noise model in PLC channel, while Xu *et al.* [31] propose a data transmission scheme supporting raptor coding for different traffic classes in intra-vehicle PLC systems. Simulation results all demonstrate their superiority in the high noise PLC environment. Although there are still lots of challenges to be addressed, PLC is a potential intra-vehicle interconnection solution that can be used in autonomous vehicles with more complex wire harness and electronic components than traditional cars.

2) Wireless Interconnection Technologies:

- *Bluetooth* 5.0 is the latest Bluetooth version issued in 2016 with the advantages of power saving, low cost, low delay, long effective connection distance and AES-128 encryption. Its maximum throughput is 24 Mb/s, suitable for transmitting audio streams (e.g., connecting wireless speakers and headphones). It also has the potential to be used in autonomous car's electronic components connection to eliminate complex wiring problems and reduce bodywork weight. Mirza and Khan [32] propose a low cost and low energy communication scheme between sensor nodes and ECUs based on Bluetooth Low Energy (BLE), as well as compare the BLE and CAN bus for intra-vehicle communication. The results show that compared with CAN bus, BLE has less current consumption, higher communication efficiency and lower cost.
- *ZigBee* is a LAN protocol based on IEEE 802.15.4 standard characterized by close range, low complexity, low power consumption and low data rate. It uses unlicensed frequency bands (868 MHz, 915 MHz, and 2.4 GHz) to provide wireless connections with data rate at 250 Kb/s and can be embedded in a variety of devices. ZigBee also has the potential to connect the autonomous car's electronic components for control, monitoring and state reading. Parthasarathy *et al.* [33] introduce the research results of Volvo GTT in the field of vehicular wireless sensors, as well as present a practical design method for intra-vehicle wireless sensor networks. They carry out a series of extensive experiments to determine the feasibility and usability of integrating the network into vehicle electrical systems. With 2.4 GHz IEEE 802.15.4 radio, almost universal coverage is achieved, and the gateway performs best in the central and rear chassis areas.
- *UWB* (Ultra WideBand) is a carrier-free communication technology, which transmits data using nanosecond to microsecond nonsinusoidal narrow pulses. By transmitting quite low power signals over a wide spectrum, a typical UWB platform can have a transmission rate of 480 Mb/s at a distance up to 3 meters and 110 Mb/s at up to 10 meters [34]. MB-OFDM (MultiBand-Orthogonal Frequency Division Multiplex) technology can be adopted as its modulation scheme. In addition, huge bandwidth enables UWB to resist

TABLE I
COMPARISONS FOR POTENTIAL INTRA-VEHICLE WIRED INTERCONNECTION TECHNOLOGIES IN AUTONOMOUS DRIVING

Network	CAN	LIN	FlexRay	MOST	IDB	D2B	LVDS	Ethernet
Maximum data rate	1 Mb/s	19.2 Kb/s	20 Mb/s	150 Mb/s	400 Mb/s	11.2 Mb/s	655 Mb/s	100 Mb/s
Topology	Linear Bus, Star, Ring	Linear Bus	Linear Bus, Star, or Hybrid	Ring	Linear Bus, Star, Ring	Ring	Point-to-Point	Linear Bus, Star
Cost	Medium	Low	High	High	High	High	High	Medium
Main use	Low Bandwith Control, Real Time Control, Safety Applications	Low Bandwith Control	Real Time Control, Safety Applications	Multimedia Transmission	Multimedia Transmission	Multimedia Transmission	Multimedia Transmission	Multimedia Transmission
Medium	Twisted Pair	Single Wire	Twisted Pair / Optical Fibre	Optical Fibre	Optical Fibre	Optical Fibre	Twisted Pair	Twisted Pair

multipath fading and signal power attenuation, providing robust communication at low transmission power and high communication rates [35]. Thus, UWB is a suitable technology for autonomous vehicle's intra-vehicle wireless interconnection. Based on the time-series analysis of the data of vehicles moving at different speeds on different types of roads, Demir and Ergen [36] present a time-variation model for UWB channels beneath the chassis of vehicles. Similarly, from the point of view of frequency domain, Chandra *et al.* [37] analyze the channel transfer function of vehicular UWB channel and propose an autoregressive process to model the channel frequency transfer function of intra-vehicle UWB links.

- *WiFi* (Wireless Fidelity) is a high-speed wireless communication technology that provides a rich bandwidth to transmit multimedia data standardized by IEEE 802.11. Its maximum data rate in IEEE 802.11ac standardized in 2013 is 1 Gb/s. In autonomous intra-vehicle environment, WiFi can be used to connect the infotainment systems, wearable devices or electronic equipments. However, if Bluetooth and ZigBee technology are used for intra-vehicle wireless interconnection, WiFi signals will interfere their performance [38].

C. Discussions

As research into autonomous driving goes further, autonomous vehicles need to install more sensors, actuators and ECUs, making the automotive electronics become increasingly complicated. This situation requires an advanced intra-vehicle networking technology with higher bandwidth support and system compatibility. CAN bus, which is widely used at present, has outstanding reliability, real-time and flexibility. However, neither its communication distance nor its communication rate can be compared with Ethernet, which supports many kinds of communication protocols and has impressive system compatibility, interoperability and strong ability to share resources. In addition, Ethernet is easy to connect with Internet, form network, and interface with computers and servers, leading to its suitability to solve the problems of intra-vehicle networking for future autonomous driving. Comparisons for intra-vehicle wired interconnection technologies are shown in Table I and an intuitive contrast diagram of these technologies about cost and transmission rate is displayed in Fig. 3.

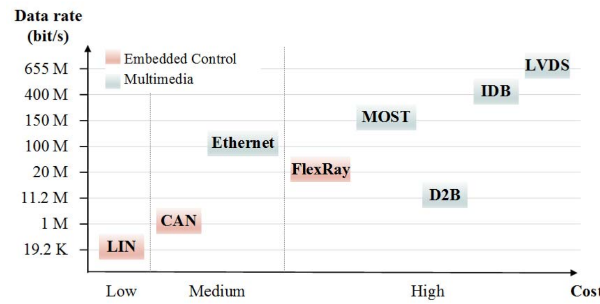


Fig. 3. Distribution of intra-vehicle interconnection technologies under cost and data rate.

To help readers better understand the level of autonomous driving, here we depict the SAE standard for autonomous vehicles released by the Society of Automotive Engineers (SAE) in 2014 [2]. In this standard, level 1 is driver assistance, which has an automation of specific function, such as Adaptive Cruise Control (ACC) or Automatic Emergency Braking (AEB). Level 2 is partial driving automation, which begins to take over lateral and longitudinal vehicle motion control, such as the combination of Cooperative Adaptive Cruise Control (CACC) and Lane Trace Control (LTC). Level 3 is conditional driving automation, which forms a complete control system including a set of central data, driving decision and driving planning, and possesses comprehensive intervention auxiliary functions including automatic acceleration, braking and steering, such as Traffic Jam Pilot (TJP). Level 4 is high driving automation, where all driving operations can be performed by autonomous vehicle in restricted area or environment without human intervention. Level 5 is full driving automation and a truly driverless phase, in which all functions are handled by the autopilot system. Most of the existing advanced autonomous cars remain at level 3, with the human safety guard sitting in the driver's seat and taking over the car at any time.

Table II displays the intra-vehicle interconnection technologies used in several autonomous vehicles in industry and academia. We can see the applications of Ethernet

TABLE II
EXAMPLES OF INTRA-VEHICLE INTERCONNECTION TECHNOLOGIES IN AUTONOMOUS DRIVING

	Autonomous Vehicles	Technologies	Applications	Autonomous Driving Level (SAE)
Industry	Tesla Model S/X/3	CAN	Powertrain, body fault tolerant, chassis, stability control, fast charge	Level 2.5
		LIN	For simple low speed devices, such as steering wheel controls, seat heaters	
		Ethernet	Instrument cluster, main display, diagnostic port, gateway	
	Audi A-8 D5	CAN	Drivetrain, comfort/convenience, display and control, diagnosis	Level 3
		LIN	For simple low speed devices, such as air conditioner, roof module	
		FlexRay	Distributed control, safety-related systems	
		MOST	Infotainment system	
Academia	Talos (MIT, Cambridge)		Prototype vehicle: Land Rover LR3	Level 3
		Ethernet (Retrofitted)	Deliver sensor data to the computers, offers electrical isolation, RF noise immunity, reasonable physical connector quality, variable data rates, data multiplexing, scalability, low latencies and large data volumes	
	Little Ben (University of Pennsylvania)		Prototype vehicle: Toyota Prius	Level 3
		Ethernet (Retrofitted)	Provide serial connections to the vehicle's low-level hardware and sensors	

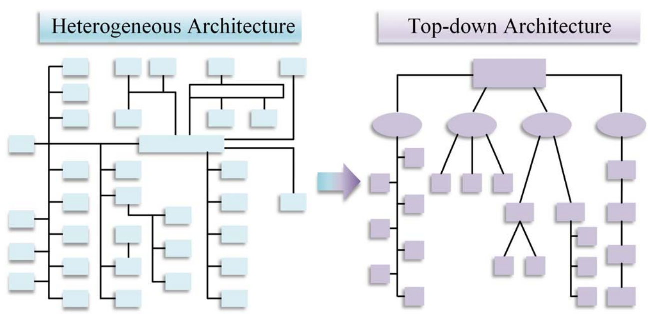


Fig. 4. The possible evolution of autonomous vehicles' intra-vehicle networking, from current heterogeneous architecture to future top-down architecture.

in the intra-vehicle network of autonomous vehicles. Industrial autonomous cars include Tesla's model S/X/3 and Audi A8 D5. Tesla's autopilot is positioned at level 2.5, since it's smarter than level 2 but doesn't reach level 3. For example, after the driver hit the turn-light, Tesla's autopilot can realize the operation of automatic change of track. Audi A8 D5 is the first volume production model to reach SAE level 3 on a global scale. Academic autonomous vehicles include "Talos" from the Cambridge team and "Little Ben" from the University of Pennsylvania in "DARPA Urban Challenge". Both vehicles are modified from prototype cars. Note that each camp has its own advantages and disadvantages. The strong point of academia is artificial intelligence technology, however, it lacks experience in automobile engineering. On the contrary, traditional car enterprises retain the advantages of the entire industry chain, high product safety and reliability, but weak in the emerging technologies.

As shown in Fig. 2, the left side of Fig. 4 and Table II, the intra-vehicle networking structure of existing autonomous vehicles shows significant heterogeneity. For example, CAN is mainly used in body control, LIN is usually used for small serial control message transmission with low bandwidth, FlexRay is often used for real-time security control, MOST for multimedia information transmission, and Ethernet is applied for diagnosis module, etc. Thus, various communication technologies with different rates and transmission modes form a more complex heterogeneous network inside autonomous vehicles than traditional vehicles. This heterogeneity comes from the development of intra-vehicle networking and the consideration of economy, leading to the difficulties of maintainability, expansibility and flexibility of the protocol and topology combination. Since autonomous vehicles have more advanced and varied functions, the hierarchical top-down architecture start from scratch proposed by Hank *et al.* [39] at the right side of Fig. 4 is possible to be more suitable for future self-driving cars and is worth studying. In this architecture, the application domain is connected through the data channel, ECUs are structured in a layered architecture, and Ethernet is applied as backbone bus to connect the various application domains and sub-networks.

As one of the potential intra-vehicle technologies, PLC is able to transmit electricity and data over the same wire as well as reduce vehicle weight and cost simultaneously. Thus, application of PLC in autonomous car body deserves further consideration. In addition, wireless interconnection can greatly reduce the need for wires and the weight of the autonomous vehicle's bodywork, save energy, and improve the flexibility of intra-vehicle communications, making wireless interconnection a promising intra-vehicle networking scheme. It also should be noticed that although some wireless communication technologies, such as WiFi and UWB, can provide high bandwidth and do not need copper wires to transmit information, antennas, special chips and other wireless modules are needed to be installed. Whether they are cheaper than wired communication technologies is not clear. Furthermore, the complex electromagnetic environment may affect the performance of wireless communications. Therefore, the wireless interconnection scheme in autonomous driving still need more in-depth research.

III. INTER-VEHICLE NETWORKING AND COMMUNICATIONS

As explained in Section I, due to the limitations of sensors and autonomous vehicle's dependence on environmental information, the inter-vehicle networking and communications is of particular importance and can greatly benefit the perception, planning and interaction of autonomous driving. The main control of traditional vehicles is in the hands of human beings, and the information obtained through the vehicle networks is mostly used for display, prompt, or multimedia entertainment. However, the driving process of autonomous vehicle is partly or wholly determined by the autopilot system, which relies on a large amount of real-time data from sensors and inter-vehicle communications, leading to the requirement for more secure, reliable and high-speed communication technologies. Firstly, in Section III-A, we introduce the autonomous vehicle's inter-vehicle networking form, i.e., VANET, and the promising Information-Centric Networking (ICN) architecture that is conducive to the information dissemination in autonomous driving. Then, we illustrate the clustering that can improve the scalability and reliability of VANET to meet the requirements of the autonomous vehicle networks, and show the effective autonomous vehicle management scheme, i.e., platooning. In addition, in Section III-B, we present the potential inter-vehicle communication technologies in autonomous driving, including low power technologies, IEEE 802.11 family technologies and base station driven technologies. Several auxiliary technologies are also mentioned in this section.

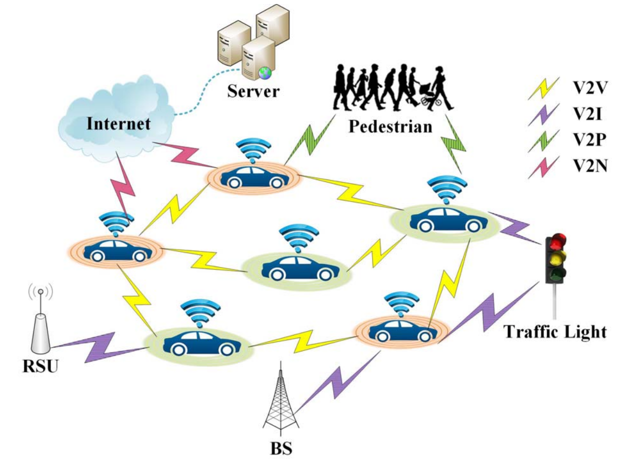


Fig. 5. Description of VANET for autonomous vehicles. V2V refers to the direct communication between vehicles. V2I is the connection between vehicles and infrastructures. V2P is the mutual communication between vehicles and pedestrians. V2N connects vehicles to the Internet.

A. Inter-Vehicle Networking

1) Characteristics: VANET (Vehicular Ad-hoc NETwork) is the application of traditional MANET (Mobile Ad-hoc NETwork) on traffic road, using V2X technologies including V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), V2P (Vehicle-to-Pedestrian) and V2N (Vehicle-to-Network) to form large networks in which vehicles become wireless nodes as shown in Fig. 5. It has the commonness of ad-hoc network, such as (i) autonomy and no fixed structure, (ii) multi-hop routing, (iii) dynamically changed topology, (iv) limited capacity and (v) superb scalability. Moreover, it owns numerous differences compared with MANET, some of which are even difficult to handle. For example, the distribution of vehicle nodes is restricted by the shape of the road, resulting in the limitation of network topology and capacity, as well as the frequent competition of wireless channels and the excessive concentration of traffic load.

When VANET is applied to the autonomous vehicle, it also has some superiorities: (i) autonomous vehicle nodes and roadside facilities have sufficient energy supply, favorable wireless communication capacity, computing ability and storage capability; (ii) autonomous vehicles in VANET can not only obtain their own position but also acquire abundant road information through lots of on-board sensors and information interaction; (iii) the movement of autonomous vehicles is more regular because of the fixed road shape and the possible orderly arrangement of autonomous vehicles (e.g., platooning).

2) ICN Architecture: At present, the design of inter-vehicle network is mostly end-to-end mode [40]. However, autonomous driving mainly depends on the content of information itself obtained from inter-vehicle communications such as real-time map or road conditions and no longer pays attention to their sources. Thus the end-to-end mode will not be able to meet the needs of the information dissemination performance in autonomous vehicle networks. Accordingly, ICN architecture in VANET addresses data directly by changing the addressing scheme, rather than using the location of the data [40]. It focuses directly on the data as the main entity of information dissemination and eliminates the IP address restriction. The data is hierarchically named and transmitted instead of being embedded into the conversation [41]. The resulting loosely coupled communication model is conducive to mobility support. Meanwhile, by caching in the network, the scalable and efficient data transmission can be achieved, the delay can be reduced, and mobile nodes can be easily managed [42]. Therefore, adopting ICN architecture in traditional vehicular networks can meet the requirements of high scalability and low delay of autonomous driving.

NDN (Named-Data Networking), also known as CCN (Content-Centric Networking), is one of ICN's important and widely accepted running prototypes, which can obtain data identified by the given name from potential providers [41]. Its name-based data retrieval and pervasive caching capabilities eliminate reliance on static locations and IP addresses, help to handle intermittent connections in traditional VANET, and can improve the reliability of autonomous vehicle networks [43]. Two kinds of packets are contained in NDN: interest packets (Interests) and data packets. The former is used to require the desired content while the later replys the corresponding data. Each node in autonomous vehicular NDN needs to maintain three data structures: (i) the Content Store (CS) cache contains data/contents, (ii) the Forward Information Base (FIB) manages the outgoing interfaces to forward the Interests, and (iii) the Pending Interest Table (PIT) keeps track of forwarded Interests in order to send the data packets back to the consumer [44].

Detailed examination and domain-specific comparison of ICN approaches in connected vehicles are provided in [40] and [41]. Zhu *et al.* [41] focus mainly on ICN's architecture design, caching, routing and forwarding, while Grewe *et al.* [40] also consider the safety mechanisms.

A prototype of V-NDN includes NDN daemon, NDN local faces, NDN network faces, link adaptation layer and location service is implemented under Ubuntu Linux 12.04 LTS in [45]. Its preliminary performance is assessed using ndnSIM [58] over NS-3, and the result reveals that the capability of the entire NDN system is improved when the number of vehicles interested in the same information increases. Besides, Yu *et al.* [55] propose an all-broadcast ICN architecture DT-ICAN (Delay Tolerant Information Centric Ad-hoc Network) for VANET to optimize the network performance by leveraging the epidemic Interests dissemination and the node-based Interests aggregation. In this architecture, the hierarchical naming [59] of ICN is used to segment files into chunks that named like applicationID/filename/chunkID. The network is able to use the name prefixes to judge the type of applications and associate the data with the properties of the application. Eventually, they use real San Francisco taxi traces generated by VANETMobiSim to evaluate DT-ICAN's performance. Simulation results show that the file retrieval rate can be promoted by 45% compared with the traditional multi-hop ICN.

Routing design theories in ICN architecture have attracted researchers' attention. For example, Guo *et al.* [42] propose a new ICN routing selecting algorithm ECRMLET (Efficient Content Routing Model based on Link Expiration Time), which has the following designs: (i) adding receive time and tolerance time to PIT; (ii) adding the LET (Link Expiration Time) algorithm to the content routing selection in FIB; (iii) adding the link availability probability as auxiliary information to ECRMLET. In addition, Yu and Gerla [47] consider two ICN-specific routing design options: caching policies and data source selection policies. Simulation in this work is conducted by QualNet 6.1, and radio propagation is modeled by CORNER [46].

To place valuable data nearby the autonomous vehicles or balance the network traffic, caching capacities are necessary for network nodes in ICN architecture [49]. A series of popular caching schemes in ICN such as copy with Probability (Prob), Leave Copy Down (LCD), Move Copy Down (MCD) [60], [61] are analyzed in [48] using Veins simulation framework. A cache content insertion policy named UG-Cache based on popularity utility gradient and distance is put forward in [50]. Simulation results show that UG-Cache can increase delivery rate and reduce average hop count of content delivery over other schemes such as Cache Everything Everywhere (CEE), Never Cache, Distance-Probabilistic (DistProb) [60], [61]. Besides, Grewe *et al.* [49] propose a proactive caching approach to improve the network performance by distributing the content with a minimal number of replicas one-hop away from the consumer, and Liu *et al.* [52] present a NDN-based collaborative caching scheme to relieve the disconnection problem caused by the mobility of vehicles.

Efforts have also been made to solve the Interests forwarding problem in ICN. Ahmed *et al.* [44] put forward a robust forwarder selection method to mitigate the Interests broadcast storm, while Liu *et al.* [53] present an improved NDN based forwarding strategy according to the nodes concern degree for named content. Moreover, Amadeo *et al.* [54] propose transport-level functions with related content segmentation and an Interests retransmission scheme that extend the NDN Interests format with an additional BITMAP field to indicate the missing packets.

Entertainment and multimedia transmission are indispensible parts of autonomous cars. Considering this aspect, Quan *et al.* [51] propose a cooperative cache solution based on ICN to improve the experience quality of multimedia streaming media service. In addition, a lightweight multipath selection strategy to guide the network system and adaptively adjust the forwarding mode for multimedia streaming is presented in [56].

As a new architecture that has not been widely applied in VANET for autonomous driving, ICN has brought lots of vulnerabilities that haven't been prevented yet. Signorello *et al.* [57] focus on the security challenges in future NDN-Enabled VANETs, such as cache poisoning attacks, Interests flooding attacks and privacy violation attacks by means of content names. Moreover, Chowdhury *et al.* [43] study two potential threats in autonomous vehicle networks based on NDN: false data dissemination and vehicle tracking. They propose a four-level trust model and an associated naming authentication scheme to detect false data, and use pseudonym scheme for anonymizing vehicle names and certificating issuing proxies to solve the vehicle tracking problem. These methods are successfully implemented on NDN platform using Raspberry Pi-based mini cars. Existing studies on ICN are summarized in Table III.

3) Clustering: Autonomous vehicles use a large number of real-time data obtained from inter-vehicle networking and communications for decision-making, which puts forward higher requirements for the reliability of networking technology. Therefore, clustering as an efficient organization structure is desired to meet the needs of autonomous vehicle networks, improve the scalability and reliability of VANET, and realize the distributed formation of hierarchical network structure [78]. The principle of clustering is to associate autonomous vehicles to clusters on the basis of special rules such as geographical location and vehicle speed. Several steps are needed for autonomous vehicles to participate in the clustering process, i.e., neighbourhood discovery $\rightarrow$ cluster head selection $\rightarrow$ affiliation $\rightarrow$ announcement $\rightarrow$ maintenance [78]. These autonomous vehicle nodes will be assigned different functions such as cluster member, cluster header and cluster gateway. Cluster members are common nodes without links between different clusters, while cluster header usually acts as the local coordinator for its cluster and executes the transmission arrangement [79]. A cluster gateway can access adjacent clusters and forward information between clusters [79].

The earliest survey of clustering algorithm in VANET is [80], some other surveys are also comprehensive like [81]–[83]. Sood and Kanwar [81] focus mainly on clustering techniques and cluster-based routing protocols, while Almheiri and Alqamzi [82] present several clustering algorithms classified according to different categories such as ID-based clustering, nodal degree-based clustering, mobility-based clustering, direction-based clustering,

TABLE III
SUMMARY OF EXISTING STUDIES ON ICN

Reference	Focus	Wireless Propagation Model	Mobility Model	Signal Attenuation Model	Popularity Model	Cache Replacement Policy	Simulator
Grassi *et al.* [45]	Prototype implementation	CORNER [46]	N/A	N/A	N/A	N/A	ndnSIM over NS-3
Yu *et al.* [47]	Routing	CORNER	Synthetic vehicle movement patterns	N/A	Zipf-like distribution model	N/A	QualNet 6.1, SUMO
Guo *et al.* [42]	Routing	Constant speed propagation delay model	IDM_LC	Friis propagation loss model	N/A	N/A	ndnSIM over NS-3
Modesto *et al.* [48]	Caching	N/A	N/A	N/A	Zipf-like distribution model	RR, LRU, LFU	Veins simulation tools, OMNeT++, SUMO
Grewe *et al.* [49]	Caching	Constant speed propagation delay model	Constant velocity mobility model	Nakagami attenuation process	N/A	LRU, FIFO, LFU	ndnSIM over NS-3
Modesto *et al.* [50]	Caching	N/A	N/A	N/A	Zipf-like distribution model	LFU	Veins simulation tools, OMNeT++, SUMO
Quan *et al.* [51]	Caching	N/A	Highway traffic model	N/A	N/A	N/A	ndnSIM over NS-3
Liu *et al.* [52]	Caching	N/A	N/A	N/A	N/A	N/A	ndnSIM over NS-3
Ahmed *et al.* [44]	Forwarding	N/A	N/A	N/A	N/A	N/A	NS-2, SUMO
Liu *et al.* [53]	Forwarding	N/A	N/A	Nakagami attenuation process	N/A	N/A	ndnSIM over NS-3
Amadeo *et al.* [54]	Retransmissions management	N/A	N/A	Nakagami attenuation process	Zipf-like distribution model	N/A	NS-2, VANETMobiSim
Yu *et al.* [55]	Disruption-tolerant	N/A	Intelligent driver model (IDM)	N/A	N/A	N/A	DT-ICANSIM in QualNet, VANETMobiSim
Song *et al.* [56]	Multimedia delivery	N/A	Manhattan mobility model	N/A	N/A	N/A	ndnSIM over NS-3, Emu NetDevice, VANETMobiSim
Signorello *et al.* [57]	Security	N/A	N/A	N/A	N/A	N/A	N/A
Chowdhury *et al.* [43]	Security	N/A	N/A	N/A	N/A	N/A	Raspberry Pi-based mini cars

leadership duration-based clustering and path loss-based clustering. Besides, Yang *et al.* [83] summarize the applications of clustering algorithms in VANET.

UAVs (Unmanned Aerial Vehicle) can also participate in the clustering of autonomous vehicles. Rossi *et al.* [63] propose an algorithm SCalE (Stable Clustering algorithm for vehicular ad-hoc networks) to facilitate the networking among clustered VANETs, UAVs and cellular base stations. Two features are considered in this algorithm: the vehicles behaviour for efficient selection of CHs (Cluster Head); a backup CH to maintain the stability of cluster structures. Simulation results verify that SCalE's performance on cluster stability is superior than Highest-Degree [84] and VMaSC (Vehicular Multihop algorithm for Stable Clustering) [85] algorithms. In addition, focusing on the influence of contents in vehicular communications, Zhang *et al.* [62] present a content aided clustering algorithm and an evolution game based cluster head selection algorithm for VANETs, as well as design a social network attributes based mobility model. Simulation results show that the proposed clustering algorithm can balance the loads of base stations and improve the user's QoE (Quality of Experience), and the head selection algorithm has good scalability and convergence.

With regard to the performance of clustered VANET, Prakaulya *et al.* [66] focus on packet delay time, packet delivery time, throughput and end to end delay through NS-2 simulator. The result reveals that the performance of IEEE 802.11p in the proposed model is better than that of IEEE 802.11. Morever, Peng *et al.* [67] analyze the transmission opportunity and capacity in cellular based clustered VANET with stochastic geometry tools in three scenarios, i.e., dynamic channel does not exists, dynamic channel exists, and dynamic channel exists with activated OSA (Opportunistic Spectrum Access) control.

4) Platooning: Autonomous vehicular platooning is a traffic management scheme and a form of cluster, in which autonomous vehicles are organized in the same lane to form a string [74], thus can reduce traffic jams, improve road safety, save the space of roads and make traffic more orderly. As shown in Fig. 6, each platoon is led by a leading autonomous vehicle; intra-platoon autonomous vehicles track each other in a train-like manner and at small interval from the vehicle in front [74].

Although platooning has lots of advantages, the maintenance of it is not easy. The realization of autonomous vehicular platooning requires not only information exchange among

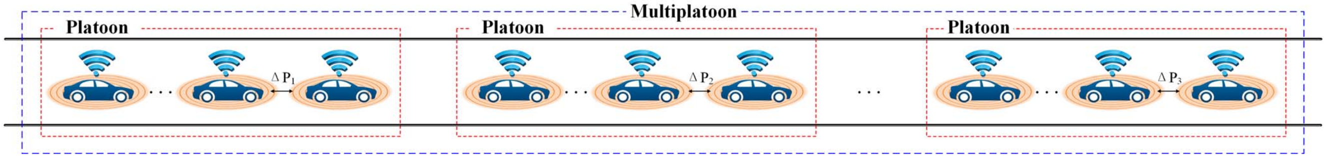


Fig. 6. Autonomous vehicular platooning is a traffic management strategy, in which autonomous vehicles are organized in the same lane to form a string. When the number of autonomous vehicles becomes large, it will be a better way to form a multiplatoon (a chain of platoons) rather than a large single platoon. ΔP_i means the fixed intra-platoon spacing between autonomous vehicles.

autonomous vehicles using communication technologies, but also the control system (e.g., the aforementioned CACC in Section II-C) using information collected by sensors and communication systems to coordinate autonomous vehicles' operations, maintain the target velocity, and control distance between vehicles. Focus on the communication aspect, Guo and Wen [70] demonstrate a closed-form methodology for autonomous vehicular platooning by introducing binary sequences for network access scheduling and using independent Bernoulli processes for the random packet dropouts modeling. Fernandes and Nunes [68] propose intra-platoon information management strategies and new algorithms to mitigate communication delays. Focus on the control aspect, Santini *et al.* [71] propose a consensus-based controller that can be reconfigured by control topology and test it by applying the real dynamics of vehicles in PLEXE [86], which is a mobility simulator that includes basic building blocks for platooning, and an extension for Veins simulation framework. However, due to the variability of autonomous vehicle's processing rate and wireless channel, the communication links between autonomous vehicles will inevitably be affected, resulting in time-varying delay [72], which can endanger the control system and the operation of the autonomous vehicular platooning. Therefore, control system must be robust to such wireless transmission delay, and can be optimized to alleviate the delay requirements for the communication system, thus improving the reliability of the wireless network. Toward this end, Zeng *et al.* [72], [73] propose a novel framework for optimizing the autonomous vehicular platoon's operation jointly considering the delay of the wireless V2V network and the stability of the autonomous vehicle's control system. They analyze the V2V communication links between consecutive vehicles in the platoon using stochastic geometry and queuing theory, propose two notions of control system stability for platooning, i.e., string stability and plant stability, and derive the SINR (Signal to Interference plus Noise Ratio) threshold to ensure them. Simulation results verify the effectiveness of the proposed joint control and communication framework, as well as show that the approximate reliability and the reliability lower bound of wireless network can be increased by 25% and 30% respectively.

When the number of autonomous vehicles increases, it will be a better way to form a multiplatoon (a chain of platoons) rather than a large single platoon. To address this issue, Peng *et al.* [74] introduce a multiplatooning communication model, analyze the probability performance of intra- and inter-platoon communications based on Distributed Coordination Function (DCF), and study the communication performance of several typical multiplatooning application scenarios. They also analyze the probabilistic performance of IEEE 802.11p DCF and obtain the expressions of transmission attempt probability, packet collision probability, network throughput and packet delay in [87]. Fernandes and Nunes [77] consider that constant spacing between platoons' leaders is a foundation to attain high traffic capacity, and propose a set of algorithms to maintain constant spacing as well as allow autonomous vehicles to access the main track cooperatively: intra- and inter-platoon positioning management algorithm; platoon joining maneuvers management algorithm; extra spacing for secure maneuvering improvement algorithm. Simulation results show that these algorithms can achieve high traffic capacity values and avoid congestion. Furthermore, Peng *et al.* [75], [76] look at the resource allocation issues by numerical results. Existing studies on clustering, platooning and multiplatooning are summarized in Table IV.

5) Routing Protocol: Because of the dynamic change of VANET's topology, routing becomes a difficult problem. Numerous routing protocols for VANET have emerged in academia and can be mainly divided into five categories: (i) position based, (ii) topology based, (iii) cluster based, (iv) geocast based and (v) broadcast based. Summary of these routing protocols is shown in Fig. 7.

Position based routing protocols can use autonomous vehicle's location information provided by transmitting beacons within a certain interval of time [88] to transfer data to the nearest autonomous vehicle node greedily. These protocols have three main components, i.e., beaconing, location services and forwarding [89]. The main advantage of position based routing protocol is that global routing from source to destination is not required. Typical position based routing protocols are GPSR (Greedy Perimeter Stateless Routing) [90], A-STAR (Anchor-based Street and Traffic Aware Routing) [91] and VADD (Vehicle-Assisted Data Delivery) [92]. Furthermore, Kaur and Meenakshi [93] import the Bathinda city map to SUMO and use NS-2 simulator to analyze GPSR's and A-STAR's performance.

Topology based routing protocols can be classified as preactive, reactive and hybrid. Preactive routing protocols can store the routing information of all autonomous vehicle nodes in the routing table, and do not require the route discovery process. However, the maintenance of unused routes will lead to high network load and severe bandwidth consumption, thus reducing network performance [94]. Reactive routing protocols start route discovery process when required, and do not need periodic flooding. Nevertheless, its route finding latency is high. Hybrid routing protocols use preactive routing protocols in

TABLE IV
SUMMARY OF EXISTING STUDIES ON CLUSTERING, PLATOONING AND MULTIPLATOONING

	Ref.	Focus	Interface	Mobility Model	Density of Vehicles	Simulated Vehicle Speed	Simulator
Clustering	[62]	Content aided clustering	N/A	Social network attributes based mobility model	$11 * 11$ grid topology and 121 veh nodes	N/A	N/A
	[63]	Stable clustering	DSRC, LTE-A	Gipps car following model [64], Gipps lane-changing model [65]	Arrival rate: 30 veh/min, path length: 6 km	22 - 33 m/s	MATLAB
	[66]	Performance	DSRC	IDM_IM	4 - 33 veh/km^2	25 km/h (city), 120 km/h (highway)	NS-2
	[67]	Transmission	DSRC, LTE	Car following model	20 veh/km	N/A	MATLAB
					Platoon Size	**Spacing**	
Platooning	[68]	Information management	DSRC	IDM, Krauβ car-following model [69]	31 m	1 m	NS-3, MATLAB / Simulink, SUMO,
	[70]	Control	N/A	N/A	N/A	25 cm	Arduino cars
	[71]	Control	DSRC	N/A	8 and 16 vehs	15 m	PLEXE
	[72]	Joint communication and control	N/A	Highway traffic model	6 vehs	5-35 m	N/A
	[73]	Joint communication and control	N/A	Car following model	5 vehs	5-35 m	N/A
Multi-platooning	[74]	Performance	DSRC	IDM	5 vehs	N/A	N/A
	[75]	Resource allocation	LTE	N/A	5 platoons each has 20 vehs	Intra-platoon: 5 m, inter-platoon spacing: 40 m	N/A
	[76]	Resource allocation	LTE	N/A	5 platoons each has 20 vehs	Intra-platoon: 8 m, inter-platoon spacing: 40 m	N/A
	[77]	Positioning and cooperative behavior	DSRC	Car following model	65 platoons for a total of 520 vehs	Intra-platoon: 1 m, inter-platoon spacing: 61 m	MATLAB / Simulink, SUMO

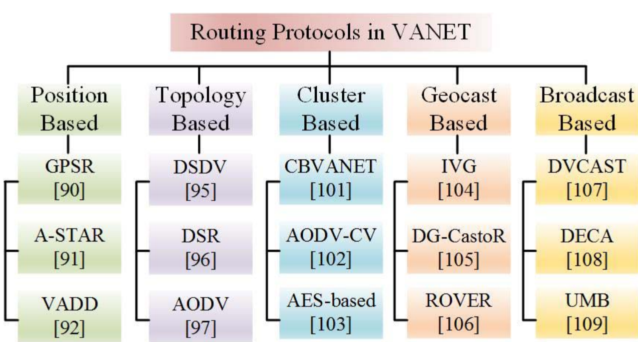


Fig. 7. Summary for five kinds of routing protocols, each of which gives three representative specific protocols.

intra-zone routing and reactive routing protocols in inter-zone routing [94], thus having the characteristics of both protocols. DSDV (Dynamic destination Sequenced Distance Vector) [95], DSR (Dynamic Source Routing) [96] and AODV (Ad-hoc On-demand Distance Vector) [97] are some of the topology based routing protocols. Moreover, the performance of AODV is analyzed in [98] and [99] using NS-2 simulator.

Cluster is a set of autonomous vehicle nodes with similar characteristics such as direction and velocity. Clustering has been introduced in Section III-A3 to satisfy the scalability and reliability requirements of autonomous vehicles in VANET. In cluster based routing, nodes select clusters by themselves, and cluster heads are responsible for broadcasting information to clusters. These routing protocols improve the packet delivery ratio, save the memory space, and are scalable and suitable for large networks [89], [100]. A number of cluster based routing protocols have been proposed such as CBVANET (Cluster Based Vehicular Ad-hoc NETwork) [101] and AODV-CV (Ad-hoc On-demand Distance Vector for Clustering maintenance in VANETs) [102]. An AES based security clustering routing for VANET is also put forward in [103].

The geocast based routing protocol belongs to the multicast routing protocol, and can use selective flooding to transmit information to all autonomous vehicle nodes in specified geographical areas (autonomous vehicles outside these areas will not be notified). It defines the destination area as ZOR (Zone Of Relevance) and the forwarding area as ZOF (Zone Of Forwarding). Autonomous vehicle nodes in ZOR are the destinations of packets and in ZOF are responsible for forwarding packets. Geocast based routing protocols have the advantages of decreasing packet overhead and thus reducing conflicts [94]. Some examples of geocast based routing protocol are IVG (Inter-Vehicle Geocast) [104], DG-CastoR (Direction-based GeoCast Routing) [105] and ROVER (RObust VEhicular Routing) [106].

Broadcast based routing protocols are common routing technologies in VANET. They can be used to disseminate information among autonomous vehicles and between autonomous vehicles and infrastructures. For example, traffic states, emergencies, weather conditions, even advertisements and public information can be spread by this kind of protocols. However, when network size becomes large, multitudinous nodes broadcast the packets simultaneously, resulting in packet collisions and causing broadcast storm. Some of the broadcast based routing protocols are DV-CAST (Distributed Vehicular broadCAST) [107], DECA (DEnsity-aware reliable broadCAsting) [108] and UMB (Urban Multi-hop Broadcast) [109].

B. Inter-Vehicle Communications

1) Low Power Technologies:

- *Bluetooth* is a low-cost, low power, open short-range wireless technology. Its modulation schemes include GFSK (Gaussian Frequency-Shift Keying), $\pi/4$-DQPSK (Differential Quadrature Phase Shift Keying) and 8DPSK (Differential 8-Phase Shift Keying). Sachan *et al.* [110] provide the analysis of these modulation schemes in terms of energy consumption. The data rate of Bluetooth ranges from 1 Mb/s to 24 Mb/s. The low-energy mode of Bluetooth 4.0 with power consumption of 0.5 mW adopts the simple modulation technique GFSK, which leads to low bit rate at only 1 Mb/s [111]. In Section II-B2, we have characterized the Bluetooth technology and discussed its applications in intra-vehicle networking and communications. Besides, it also own some potential out of the vehicle. In the early literature, experiments have been conducted to connect high-speed moving vehicles in ad-hoc networks using Bluetooth [112]. In addition, the application of Bluetooth communications in platooning for space control is studied, and a simple stochastic model of its delay distribution is established in [113]. Furthermore, Zheng *et al.* [114] analyze the communication reliability of Bluetooth for mobile vehicles and consider three data protection methods, i.e., 1/3FEC (Forward Error Correcting), 2/3FEC and ARQ (Automatic Repeat-reQuest) scheme. However, Bluetooth technology needs time to discover device and establish connection. It is not suitable for time sensitive autonomous vehicular applications. With the development of networking and communications, there have been many technologies that can replace Bluetooth to connect autonomous vehicles.
- *ZigBee* is a short distance, low power and low price wireless communication technology. Its transmission range is generally between 10 m and 100 m [115]. Most commercial ZigBee devices use the frequency band of 2.4 GHz; some also adopt 868 MHz in Europe, and 915 MHz in America and Australia. The BPSK (Binary Phase-Shift Keying) modulation scheme is used in the frequency bands of 868 MHz and 915 MHz with the data rates of 20 Kb/s and 40 Kb/s, respectively. Besides, 2.4 GHz band uses O-QPSK (Offset Quadrature Phase Shift Keying) with the data rate of 250 Kb/s [116]. Deep and Elarabi [117] propose a hardware ZigBee design by using verilog hardware description language, and demonstrate the building blocks of an energy efficient ZigBee transmitter, i.e., cyclic, redundancy check, symbol-to-chip block, bit-to-symbol block and O-QPSK modulator. Applications of ZigBee in intra-vehicle networking are introduced in Section II-B2. The following are the applications of ZigBee in inter-vehicle communications. Gheorghiu and Minea [118] present a vehicle identification prototype, using ZigBee as a solution to test V2I communications in laboratory conditions. Then, Priyanka and Kumar [119] propose the intelligent vehicle collision avoidance communication based on ARM (Advanced RISC Machine) and ZigBee. The later is used as a communication service provider between nodes. Besides, an algorithm for freeway vehicle distance measurement based on ZigBee technology is put forward in [120]. Although ZigBee has relatively low performance, it owns the characteristic of low cost and allows the simulation of complex protocols and scenarios [115]. Therefore, ZigBee can play an active role in the simulation research of autonomous vehicle's communication system.

2) IEEE 802.11 Family Technologies:

- *WiFi* is a high speed wireless communication technology commonly uses 2.4 GHz and 5.8 GHz frequency bands. The widely used IEEE 802.11n standard and the IEEE 802.11ac standard issued in 2013 all adopt MIMO (Multiple-Input Multiple-Output) and OFDM (Orthogonal Frequency Division Multiplexing) modulation technology [115]. IEEE 802.11n can support the modulation types of BPSK, QPSK and 16/64QAM (Quadrature Amplitude Modulation), and can reach the maximum transmission rate of 600 Mb/s, while IEEE 802.11ac can apply the modulation types of BPSK, QPSK and 16/64/256QAM, and its maximum transmission rate is up to 1 Gb/s. WiFi's applications in intra-vehicle communications have been introduced in Section II-B2. The following are researches of WiFi in inter-vehicle communications. Goel *et al.* [121] propose the WiFi based V2V communication for traffic information dissemination. Similarly, Viittala *et al.* [122] give an experimental evaluation of WiFi based V2V communication in the tunnel, such as mining vehicles work in a tunnel. In addition, Chou *et al.* [123] study the WiFi based V2I communication and compare it to WiMAX. The measurement results show that WiMAX can provide a longer communication range than WiFi, but its latency can be significantly greater than WiFi in a short distance. Furthermore, Jerbi and Senouci [124] use six vehicles to evaluate the performance of WiFi based V2V and V2I communication. WiFi can be used for applications such as information dissemination and Internet access in autonomous vehicle's communication system. Its upgraded technology, DSRC, is more widely used in vehicular communication systems, and will be introduced in the following.
- *DSRC* (Dedicated Short Range Communications) is a highly efficient wireless communication technology, which is specially designed for automotive applications. As shown in Fig. 8, the generation of DSRC technology based on three sets of standards. The first

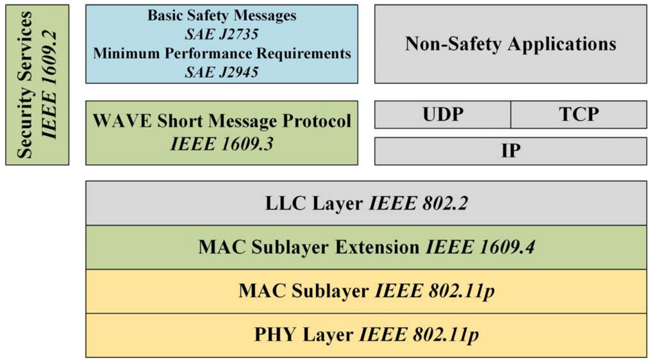


Fig. 8. Illustration of the DSRC protocol stack.

is IEEE 1609, entitled "Wireless Access in Vehicular Environment" (WAVE), a network layer standard that defines the architecture and flow of the network, as well as controls application and security features [115]. The second is SAE J2735 and SAE J2945 [7], which regulates the content and structure of the information. The third is IEEE 802.11p, which draws lessons from the characteristics of 802.11a and 802.11e, and defines the physical (PHY) layer and Media Access Control (MAC) layer standard. Vivek *et al.* [125] implement the DSRC stack on a Linux system and port it on Gateworks development board. The experimental results show that the proposed developed stack performs better than ARADA stack (commercial platform for V2V and V2I application development) in terms of packet loss. In addition, DSRC uses OFDM technology and supports BPSK, QPSK, 16/64QAM modulation types. It can provide high-speed data transmission up to 54 Mb/s as well as ensure low latency and low interference in communication links. DSRC works at the exclusive traffic safety spectrum 5.850-5.925 GHz, which is divided into one central CCH (Control CHannel) and six SCHs (Service CHannels). CCH is used to transmit traffic safety messages, while SCH is adopted to transmit data in various applications [126]. DSRC communication system mainly composes three parts: (i) OBU (On Board Unit), (ii) RSU (Road Side Unit), and (iii) special short-range wireless communication protocols. In the communication system of autonomous vehicle, OBU places on the vehicle corresponds to the mobile terminal and contains a device capable of communicating with other autonomous vehicles or infrastructures [127]. RSU in the communication system mainly refers to the roadside communication equipment and performs a number of functions, including transmitting and receiving application data from autonomous vehicles, and providing Internet access to them [127]. Both OBU and RSU provide two-way transmission of information. To mention first, for autonomous vehicle's perception module, full scene reconstruction of objects using 3D point cloud, 2D images and V2V 3D information to accomplish robust perception of the environment is of great importance. Thus, Maalej *et al.* [128] design a multimodal framework for autonomous vehicle's object detection, recognition and mapping according to the fusion of data from LIDAR, camera and DSRC-based V2V communication, in order to enrich the learning of the 3D autonomous vehicle surroundings. Secondly, Yuan *et al.* [129] set up a DSRC system to build a recording link between the autonomous vehicle's local sensor data and the remote vehicle information using position information, and provide a track-based correlation method using an interacting multiple model estimator with a sequential multiple hypothesis test. They also analyze the proposed DSRC system in real traffic environment, i.e., two highway sections in California, and obtain promising performance. Thirdly, Ye *et al.* [130] study the data transmission problem between vehicles in 802.11p-based VANET and use network coding to provide analytical results for the steady state dissemination velocity. Moreover, Librino *et al.* [131] design different multi-hop forwarding strategies in congested IEEE 802.11p vehicular networks as well as assess their effectiveness of delivering fresh situational information to surrounding vehicles. Lastly, two different models, i.e., the extension of Rényi's packaging model and the Markovian point process, are proposed to approximate the noise and interference ratio, bit error rate and frame error rate [132]. Numerous research teams have given close attention to the performance of DSRC. Tong *et al.* [133] propose a new mathematical approach based on queuing theory and stochastic geometry to model the performance and characteristics of IEEE 802.11p. Specially, they use the Matérn hard-core type-II process to derive the backoff counters' temporal states. Simulation results show that the proposed model performs well in a wide range of network densities. For the similar purpose, Giang *et al.* [132] aim at two main performance quantities of IEEE 802.11p-based VANET, i.e., the mean number of simultaneous transmitters and the distribution of the distance between them, and propose two models, i.e., an extension of the Rényi's packing model and a Markovian point process to approach the two quantities. Furthermore, Zhao *et al.* [134] analyze the similarities and differences between IEEE 802.11p and IEEE 802.11a/e, and implement an approximate IEEE 802.11p communication platform using the existing IEEE 802.11a hardware. Quite a few autonomous driving application scenarios are based on DSRC technology. Cooperative localization is of great significance for autonomous driving, while DSRC based V2V communication has great potential to improve the cooperative localization capability of GNSSs (Global Navigation Satellite Systems). Thus, in [135], a new robust Cubature Kalman Filter (CKF) integrating GNSS with DSRC is proposed to improve the performance of data fusion in uncertain sensor observation environments. For the similar purpose, assume that the vehicle is equipped with IEEE 802.11p wireless interface, Cruz *et al.* [136] use a two-stage Bayesian filter to track the position of the vehicle and establish a robust DSRC-based location system to provide useful location information. Moreover, evaluating and characterizing the behavior of surrounding autonomous vehicles, such as yaw rate, acceleration and absolute velocity, is critical to ensure the safety and travelling comfort of autonomous driving [137]. Toward this end, Shin *et al.* [137] study the effects of wireless communication (DSRC) on integrated risk management based autonomous vehicle, and derive the steering angle and longitudinal acceleration for ensuring the safety of the subject vehicle based on the probabilistic prediction of object vehicle using multi-sensor (V2V/Radar) fusion. In the aspect of automobile entertainment, Sarakis *et al.* [127] discuss the network architecture and protocol stack based on IEEE 802.11p to support the wide entertainment applications in VANET. Lots of existing researches admit the perturbing elements of DSRC and try to find effective solutions to alleviate them. For example, IEEE 802.11p does not have enough training symbols in time domain and pilot subcarriers in frequency domain to accurately estimate the fast changing V2V channel [138]. Thus, Li *et al.* [138] propose a new scheme "Tentpoles", which uses a small number of data symbols and subcarriers to track and estimate V2V channel changes under the protection of a strong error-correcting code. To verify this scheme, they use a combination of simulation and real signal based experiment. In addition, due to the lack of validation technology in IEEE 802.11p standard, ensuring the reliability of communication is a great challenge [139]. Gholibeigi *et al.* [139] focus on the on-demand error recovery of multi-hop broadcast vehicular communication, and analyze a receiver oriented reliability mechanism modeled by absorbing Markov model and probabilistic graphical model. Furthermore, under V2I and V2V communications, the influence of imperfect channel state information is especially serious in high mobile IEEE 802.11p systems [140]. Therefore, a single or multiple user collaboration inter-vehicle cooperative channel estimation in V2I environment is proposed in [140]. DSRC technology is strongly supported by the U.S. Department Of Transportation (DOT). Based on the analysis of traffic accidents from 2004 to 2008, the U.S. DOT came to the following conclusion: the use of V2X system can reduce 4.5 million collision accidents (81% of the total number of multiple vehicle collisions) [7]. Thereafter, in December 2016, the U.S. DOT planned to pass mandatory legislation to enable all light vehicles in the United States to install DSRC technology on 2023 [141], followed by Europe and Japan. Besides, GM and Toyota are supporters of DSRC technology, and suppliers such as NXP have launched V2X system solutions based on DSRC technology. At 2014 International Consumer Electronics Show (CES) in the United States, Ford showed its DSRC-based V2V communication system and said that this system was much more powerful than sensor technology and would be the basis for future autonomous cars [142]. As one of the IEEE 802.11 family technologies, DSRC owns the characteristics of short distance and low delay. It can be used for V2V communications in autonomous driving such as collision warning, but it has limitations in the high-speed movement scenario. Besides, RSUs are needed to be established. Therefore, with the continuous development of autonomous driving, the requirements of transmission distance and bandwidth become more and more obvious, which will bring great challenges to DSRC technology. The base station driven technologies have wider range of coverage and larger bandwidth, and they do not need special roadside equipment and special spectrum. Therefore, the base station driven technologies described below are very competitive in autonomous vehicle's communication systems.

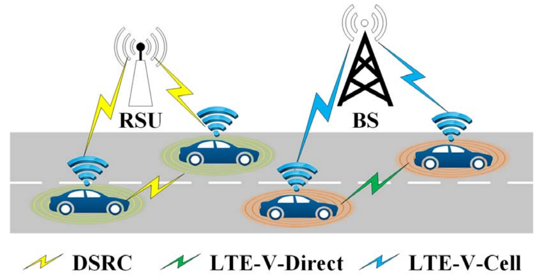


Fig. 9. Illustration of the communication modes for DSRC and LTE-V. LTE-V has two working modes: LTE-V-Direct and LTE-V-Cell.

3) Base Station Driven Technologies:

- *WiMAX* (Worldwide Interoperability for Microwave Access) is the interface standard for IEEE 802.16 Ethernet and has some potential in autonomous vehicle's inter-vehicle communications. It adopts MIMO and OFDMA (Orthogonal Frequency Division Multiple Access) technologies, and supports BPSK, QPSK, and 16/64QAM modulation schemes [143]. The transmission distance of WiMAX is up to 50 kilometers and the peak download rate can reach 128 Mb/s. Traffic analysis for VANET using WAVE and WiMAX technologies is done in [144], and NCTUns simulator [145] is used to calculate the delay for different packet length over base stations. However, WiMAX's equipment development lags behind, and its mobile access is not particularly ideal, thus we just list it as a possible and referential technology in autonomous driving.
- *LTE-V* (Long Term Evolution for Vehicle) is a proprietary protocol for inter-vehicle communications based on LTE cellular network. It uses SC-FDMA (Single-Carrier Frequency-Division Multiple Access) and OFDMA modulation technologies, and can support 10 MHz and 20 MHz channels. Each channel is divided into subframes, resource blocks and subchannels. Subframe is 1 ms long, resource block is 180 KHz wide in frequency and is the smallest unit of frequency resources that can be assigned to autonomous vehicles, and subchannel is a group of resource blocks in the same subframe to transmit data and control information [146]. The data can be transmitted through the physical side link shared channel in transport blocks, which use the modulation schemes QPSK and 16/64QAM. As shown in Fig. 9, it has two working modes: (i) LTE-V-Direct and (ii) LTE-V-Cell.

LTE-V-Direct modifies the physical layer of TD-LTE (Time-Division LTE), adopts mesh topology and provides direct V2V communication independent of the cellular network to support low delay and high reliability road safety applications [147]. LTE-V-Cell is a centralized mode of LTE-V, adopts star topology and uses the existing cellular base stations to support high bandwidth and large coverage. LTE-V-Direct and LTE-V-Cell are capable of complementing each other and collecting data effectively. Heartbeat messages can be transmitted directly by LTE-V-Direct and information entertainment services can be provided by LTE-V-Cell [8]. Autonomous vehicles are able to use LTE-V-Direct to obtain information from surrounding vehicles directly and LTE-V-Cell to improve the reliability of vehicle connections in the case of low vehicle density. Molina-Masegosa and Gozalvez [146] present an overview of the LTE-V supporting side links using LTE's direct interface PC5. Besides, they analyze the performance of LTE-V-Direct under the Highway Fast (60 vehicles/km at 140 km/h) and Highway Slow (120 vehicles/km at 70 km/h) scenarios [148]. Moreover, Shi *et al.* [149] provide an application-oriented performance comparison between 802.11p and LTE-V in real world environment, as well as build a probability model to evaluate the communication performance. The message broadcasting mechanism of autonomous vehicle is vulnerable to broadcast storm and message flooding, resulting in unpredictable long forwarding delay. Chang *et al.* [150] propose an efficient emergency message forwarding approach AFCS (Adaptive Forwarding message and Cooperative Safe driving) to solve this problem in LTE-V. Its performance is evaluated by numerical results compared to the flooding-based broadcast approach [151], the dynamic transmission-range assignment approach [152], the trajectory-based data forwarding for light-traffic [153], and the vehicle routing of the packet error rate with considering delay time [154]. In addition, to determine an optimal flood strategy and minimize the number of broadcasts, in [155], Lien and Chen investigate a function validated by Monte Carlo simulation for LTE-V to determine an optimal flood strategy and obtain the broadcast efficiency under a given range. To design power allocation strategy for each vehicle while motivating other vehicles to forward the data in LTE-V, Zhang *et al.* [147] model the data transmission in the uplink scenario of vehicular network as an equalization scheme with equilibrium constraints, and adopt multi-level water-filling algorithm [156] at the vehicle transmitter for power allocation. Besides, in the high-speed V2X scenario, the Carrier Frequency Offset (CFO) greatly affects the performance of the signal transmission due to the Doppler effect. To solve this problem, Xie and Zhao [157] propose a Comb-DMRS (Comb type Reference Signal DeModulation sequence) based joint CFO estimation scheme for LTE-V systems and use tracking algorithm to improve the robustness. The simulation results show that the proposed scheme has lower complexity and better effect compared with other joint schemes based on CP (Cyclic Prefix) and DMRS. Moreover, for autonomous vehicular platooning communication, Yu *et al.* [158] establish V2V transmission according to LTE-V specification and simulate end-to-end throughput and delay profiles to compare different platooning system configurations. Numerical results show that the LTE-V system is hard to support the highest degree automation under shadowing effects in autonomous vehicular platooning, which requires communication enhancement in 5G networks. Compared with DSRC, LTE-V is based on cellular communication system. Thus, it can reuse the existing cellular infrastructure and has a wider coverage. In addition, because base stations can participate in the coordination of resource allocation, LTE-V's anti-jamming ability is greatly improved, especially in the traffic-intensive condition. LTE-V also has better support for high-speed autonomous driving scenario, the relative speed can be supported up to 500 km/h [163]. Comparisons between the existing standard DSRC and the ongoing standard LTE-V are shown in Table V. LTE-V receives strong support from telecom operators and has significant implications for autonomous driving. At the 3GPP 73rd meeting in September 2016, the first phase of LTE-V standard was formally frozen in Release 14 [148]. Members of the 5GAA (5G Automotive Association), including Intel, Huawei, Qualcomm, Audi, BMW and Daimler, are among the industry leaders working to boost the LTE-V industry. LTE-V is now based on 4G technology to achieve the vehicle communication. In the future, it can evolve smoothly to 5G.

TABLE V
COMPARISONS BETWEEN THE EXISTING STANDARD DSRC AND THE ONGOING STANDARD LTE-V

	DSRC	**LTE-V**
Development	First-mover and more mature verification time	Still in the early stage
Resource Selection	CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance)	SPS (Semi-Persistent Scheduling)
Infrastructure	Additional investments in network infrastructure are required [159]	No need to invest in new roadside facilities
Coverage	Narrow	Wide
Bandwidth	Low	High
Spectrum	Narrow	Wide
QoS	Lack of stringent QoS (Quality of Service) provisioning [160]	Comprehensive QoS support [161]
Future	Lack of a clear plan for future strengthening of standards [162]	Strong momentum

4) Auxiliary Technologies:

- *HetVNET* (Heterogeneous Vehicle NETwork)'s emergence is due to the difficulty of using a single wireless access technology to provide satisfactory services in vehicular networks. Each technology has its own shortcomings, for example, DSRC is originally designed for short-range communications without considering the infrastructures already deployed; although cellular network covers a large area, it might not effectively supports real-time information exchange because of the delay caused by the centralized control. At this time, HetVNET can be used to integrate different types of wireless access technologies and support real-time message dissemination to meet various communication requirements for autonomous driving. To begin with, Zheng *et al.* [164] put forward the concept of HetVNET for autonomous driving and an improved protocol stack to meet the communication requirements of secure and non-secure services. The specific types of messages necessary to support autonomous vehicles are also defined, i.e., Periodic State Messages (PSM) and Action-Triggered Messages (ATM) [164]. After that, several typical autonomous driving schemes, including highway free flow, highway synchronized flow and urban intersection, are considered and studied in detail. Similarly, in [165], they review the wireless network technology used in HetVNET, including WCDMA (Wideband Code Division Multiple Access), LTE and DSRC, and present a HetVNET framework using various wireless network technologies, which includes three main components: a Service Center (SC), a Core Network (CN), and a Radio Access Network (RAN). The requirements and use cases of secure and non-secure services are summarized, and various applications of typical scenarios such as urban intersection scenario and expressway scenario are described. In view of the basic technical requirements of multi-mode communication in heterogeneous vehicular telematics, a dynamic and adaptive network selection method is proposed to ensure the efficient utilization and fair distribution of HetVNET resources [166]. This selection method is inspired by the cellular gene network, which enables the terminal to dynamically select the appropriate access network according to various QoS requirements and available network conditions. Céspedes and Shen [167] study the seamless provision of mobile Internet access and general IP services over HetVNET, and propose a hybrid scheme that allows seamless communications among device passengers, in-vehicle networks and public transport users in the system. Besides, in order to facilitate video streaming applications, a heterogeneous architecture based on the semi-Markov decision process with the roadside infrastructure supported by cellular base station and cognitive radio is proposed in [168]. Recently, the Qualcomm Snapdragon automotive development platform, which supports not only LTE, but also IEEE 802.11p, has been released to automakers and developers [169]. Thus, we can conveniently innovate, test and deploy on-board applications. Future HetVNET is able to support high bandwidth demand, large coverage and time sensitive business, as well as guarantee the QoS requirements of security services [170]. However, the diversity of wireless access technologies makes it difficult to integrate these different wireless technologies into one device, and a large amount of wireless network infrastructures and spectrum resources may be wasted [171]. Eventually, the successful architecture of HetVNETs must allow for growth, scalability, and combination of fresh technologies [170].

- *SDN* (Software Defined Network) is a new network innovation architecture, virtualization implementation and design framework, which has great potential for complex network management of autonomous driving. Its core technology, OpenFlow, realizes the flexible control of network traffic by separating the control plane from the data plane, thus making the network more intelligent. SDN allows independent deployment of control, processing entities and traffic forwarding [172]. Besides, its logical centralized control enhances the service efficiency of resources [172], and its programmability makes the network more flexible [173]. A great deal of research has been done on SDN, which can be used in autonomous driving. Firstly, Peng *et al.* [174] propose a new architecture combining Multiple-access Edge Computing (MEC) with SDN, which can be adopted for flexible resource management and effective resource utilization to guarantee the performance of information interaction among autonomous vehicles. Similarly, Liu *et al.* [172] present an extensible SDN architecture supported by MEC, which integrates different types of access technologies and provides reliable communication services according to precise application requirements. The tight coupling control and data plane in traditional network greatly increase the complexity and cost of network management. Therefore, a SDN-based vehicular network architecture is proposed to solve this problem, which separates the control plane from the data plane, configures heterogeneous switches in a unified manner, and reduces traffic aggregation and distribution delays [175]. After that, Zheng *et al.* [170] propose a soft-defined HetVNETs by integrating SDN and radio resource virtualization into LTE system, as well as a delay optimization scheme for wireless resource scheduling according to stochastic learning. Furthermore, using the global information collection and network control ability of SDN, the adjacent autonomous vehicles can cluster adaptively according to the real time road conditions and form a 5G VANET [176].

C. Discussions

The sensors' intrinsic shortcomings such as limited perception range and restricted use in special conditions result in the demand for future autonomous vehicles to form the inter-vehicle network to enhance the information interaction as well as the perception and planning capacity. The inter-vehicle networking technology for autonomous driving is VANET, which has lots of superiority when applied to autonomous driving such as autonomous vehicle nodes equipped with various sensors have good perception ability, sufficient energy supply, favorable wireless communication capacity and computing ability. Autonomous vehicles depend on the content of information itself rather than on its source, while ICN architecture for VANET can just fit this application environment. Besides,

TABLE VI
COMPARISONS FOR POTENTIAL WIRELESS COMMUNICATION TECHNOLOGIES FOR AUTONOMOUS DRIVING

Technology	Spectrum	Standard	Bit rate	Modulation	Range	Modes	Delay
UWB	3.1-10.6 GHz	IEEE 802.15.3a	>10 Mb/s	MB-OFDM	<10 m	N/A	N/A
WiFi	2.4-2.4835 GHz, 5.150-5.850 GHz	IEEE 802.11n	600 Mb/s	MIMO, OFDM	<100 m	STA, AccessPoint, Monitor, IBSS, WDS, Mesh	Seconds
	5 GHz	IEEE 802.11ac	1 Gb/s	MIMO, OFDM			
Bluetooth	2.4-2.485 GHz	IEEE 802.15.1	1-24 Mb/s	GFSK, π/4-DQPSK, 8-DPSK	<100 m	Active, Sniff, Hold, Park	3-10 s
ZigBee	2.4 GHz, 868 MHz, 915 MHz	IEEE 802.15.4	250 Kb/s, 40 Kb/s, 20 Kb/s	BPSK, O-QPSK	<100 m	N/A	30 ms
DSRC	5.850-5.925 GHz	IEEE 802.11p	<54 Mb/s	OFDM	<1 km	Active, Passsive	100 ms
WiMax	2.5 GHz	IEEE 802.16	128 Mb/s	MIMO, OFDMA	<50 km	PMP, Mesh	10 ms
LTE-V	N/A	LTE-V	1 Gb/s	MIMO, OFDMA, SC-FDMA	<2 km	LTE-V-Cell, LTE-V-Direct	50 ms
5G	600 MHz-6 GHz, 24-86 GHz	N/A	10 Gb/s	Massive MIMO, NOMA	<2 km	N/A	1 ms
VLC	430-790 THz	IEEE 802.15.7	500 Mb/s	OOK, VPPM	<100 m	N/A	Very low

clustering is needed to realize the distributed formation of hierarchical VANET structure and improve its scalability and reliability. Moreover, as a traffic management scheme and a form of cluster, autonomous vehicular platooning can also be used to reduce traffic jams, improve road safety, save the space of roads and make traffic more orderly.

For inter-vehicle communication technologies, Table VI gives detailed comparisons. Bluetooth, ZigBee, WiFi and WiMAX have been very popular in the field of vehicle networks in the past few years and rarely used lately, thus, we just gave a brief introduction to these technologies. However, their existence and potential for future development can not be denied. DSRC and LTE-V are already two major standards in automotive networking community. On one hand, DSRC has the characteristics of short distance and low delay, however, limitations can be found in high-speed autonomous driving scenario, and RSUs are needed to be established. On the other hand, LTE-V can reuse existing cellular infrastructures and has a wider range of coverage as well as better support for high-speed movement. In addition, DSRC is a pioneer of automotive communication standards, which has more mature verification but no clear future strengthening plan, while LTE-V is still in progress and has relatively strong momentum. Existing studies on DSRC, LTE-V are summarized in Table VII. It should be noted that the "dimension" column in Table VII is defined according to the direction of the traffic flow. If the authors only consider the vehicles moving in the same or exactly opposite direction, the dimension will be defined as 1-D; if the vehicles moving at a plane or at an intersection is considered, the dimension will be defined as 2-D.

Which technology will dominate the autonomous vehicle's future, governments, telecom operators, automobile manufacturers all play significant parts. Different countries have different national conditions. It is possible that communication technologies will change with the region. Besides, in future autonomous vehicle networks, it might be difficult to use one single communication technology to satisfy different service requirements. Thereafter, coexistence can meet different needs. Thus in Section III-B4, HetVNET has been introduced for integrating different types of communication technologies to meet various communication requirements of autonomous driving. Besides, as a new network innovation architecture, SDN has great potential for complex autonomous vehicle network management. More new trends of communication technologies in autonomous driving are described in the next section.

IV. NEW TRENDS OF COMMUNICATION TECHNOLOGIES IN AUTONOMOUS DRIVING

A. *The Emerging 5G Technology*

5G (5th Generation mobile networks) is not only a new access technology, but also a user-centric network concept. Its goal is to use all available and envisioned technologies to provide a unified platform and multiple services to customers instead of changing the existing communication architectures (e.g., LTE) [182]. Intel CEO Brian Krzanich said that future driverless cars will consume about 4,000 GB data a day [183]. In autonomous driving, the real-time transmission of sensor data and location data, the uploading and downloading of massive information in the cloud, and even the transmission of entertainment video and advertisements, all require higher network bandwidth and lower network delay. Besides, autonomous vehicles can be very close to each other and travel at extremely high speeds. Thus, the communication requirements of autonomous driving are more stringent than those of traditional vehicles, whether in terms of delay, reliability, scalability or mobility. At this point, 5G technology uses the existing LTE frequency range (600 MHz to 6 GHz) and millimeter-wave bands (24-86 GHz), and adopts the NOMA (Non-Orthogonal Multiple Access) technology to improve the spectral efficiency. It can support 256/1024QAM modulation format and control end-to-end communication delay within 10 milliseconds, as well as meet the communication requirements of autonomous driving at rate of more than 10 Gb/s for low mobility, and 1 Gb/s for high mobility with speed from 350 to 500 km/h [184]–[186]. In the following we'll introduce the key technologies in 5G.

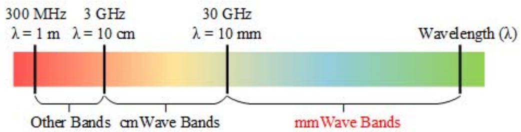
- *Millimeter-wave:* Millimeter-wave (mmWave) travels through frequencies between 30 and 300 GHz with the

TABLE VII
SUMMARY OF EXISTING POTENTIAL STUDIES ON DSRC, LTE-V AND 5G FOR AUTONOMOUS DRIVING

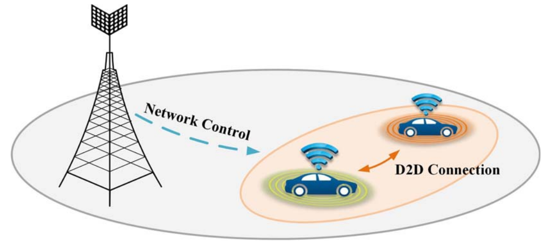
Reference	Technology	Focus	Scenario	Dimension	Type	Verification
Maalej *et al.* [128]	DSRC	Environment learning	N/A	N/A	V2V	Kitti vision benchmark suite
Yuan *et al.* [129]	DSRC	Object matching	Two highway sections	1-D	V2V	Realworld experiment
Ye *et al.* [130]	DSRC	Data dissemination	Highway	1-D	V2I	Simulation
Liu *et al.* [135]	DSRC	Localization	Road network covering 9 signalized intersections	2-D	V2V	Simulation by Paramics
Cruz *et al.* [136]	DSRC	Localization	Three-lane urban road	1-D	V2V	Realworld experiment
Shin *et al.* [137]	DSRC	Risk management	Subject vehicle deceleration, subject vehicle lane change	1-D	V2V	Simulation by MATLAB / Simulink and CarSim
Sarakis *et al.* [127]	DSRC	Entertainment	Spacious parking lot, uncongested road, moderately congested three-lane highway	2-D	V2V, V2I	Realworld experiment
Tong *et al.* [133]	DSRC	Safety communications	Highway	1-D	V2V	Simulation by NS-2
Giang *et al.* [132]	DSRC	Performance	Straight road or highway	1-D	V2V	Simulation by NS-3
Zhao *et al.* [134]	DSRC	Performance	Road lined with buildings and trees	1-D	V2V	Hardware experiment
Librino *et al.* [131]	DSRC	Forwarding	Multi-hop vehicle configuration in a linear arrangement	1-D	V2V	Simulation by MATLAB
Li *et al.* [138]	DSRC	Channel estimation	Expressway oncoming, expressway same direction, urban canyon oncoming	1-D	V2V	Simulation by MATLAB and real signal based emulation experiments
Yang *et al.* [140]	DSRC	Channel estimation	Highway	1-D	V2I	Simulation
Chang *et al.* [150]	LTE-V	Broadcast	K-lane highway	1-D	V2V	Simulation by VanetMobiSim
Lien *et al.* [155]	LTE-V	Broadcast	N/A	N/A	V2X	Monte Carlo simulation
Zhang *et al.* [147]	LTE-V	Power allocation	Three-lane road	1-D	V2X	Simulation by MATLAB
Xie *et al.* [157]	LTE-V	CFO estimation	N/A	N/A	V2V	Simulation by MATLAB
Shi *et al.* [149]	LTE-V	Performance	Two roads and an intersection with built obstacles	2-D	V2V	Realworld experiment
Yu *et al.* [158]	LTE-V	Performance	Highway	1-D	V2V	Simulation by NS-3 and SUMO
Ge *et al.* [177]	5G	Small-cell	Urban road	1-D	N/A	Numerical analysis
Cao *et al.* [178]	5G	Resource allocation	Highway	1-D	V2V	Simulation by OMNeT++
Ge *et al.* [179]	5G	Network architecture	N/A	N/A	V2V, V2I	Simulation
Wang *et al.* [180]	5G	Cell-less communications	Road	1-D	V2V	Simulation
Eiza *et al.* [181]	5G	Video reporting service	N/A	N/A	V2V	Analysis

wave length from 1 to 10 mm [187] as displayed in Fig. 10a. Multitudinous sensors on autonomous vehicles can produce a large amount of data per second to be shared among multiple vehicles, leading to an urgent need for wireless transmission over gigabit level, which is difficult to be realized by existing standards. By increasing the bandwidth of the spectrum, mmWave can achieve super-high speed wireless data transmission of multi-gigabit-per-second that can meet the communication requirements of autonomous driving from real-time sensor data such as 3D image of the LIDAR and high-definition video of the camera, to infotainment multimedia stream [188]. In addition, due to that the wavelength of mmWave is in the millimeter class, a large number of antennas can be encapsulated in small space, thus providing the possibility of achieving highly directional beamforming capabilities [189].

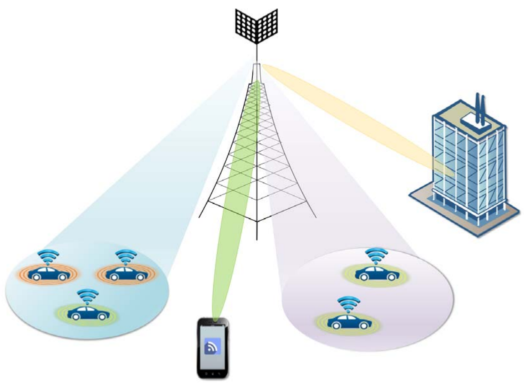
- *Beamforming:* In beamforming technology, base stations have multiple antennas and can automatically adjust the phase of each antenna to form the superposition of the electromagnetic wave at the receiving point [190], thus improving the intensity of the received signal. Large scale antenna array equipped with hundreds of antennas at the base station is able to modulate the beams of dozens of target receivers and transmit dozens of signals simultaneously [191]. Each antenna only needs to transmit signals with small power, thus avoiding the use of expensive power amplifiers and reducing the cost of hardware. Due to the law of large numbers, the channel becomes better, and the process of debilitating depth can be greatly simplified [191]. mmWave has rich bandwidth but strong attenuation, while massive MIMO with beamforming can complement its shortcoming. Beamforming can concentrate the mmWave's power in one direction, providing a transmission range of more than 130 m at 385 Mb/s and more than 79 m at 2 Gb/s [111]. It is of great significance to the communication of autonomous vehicles. On onehand, directional transmission is helpful for



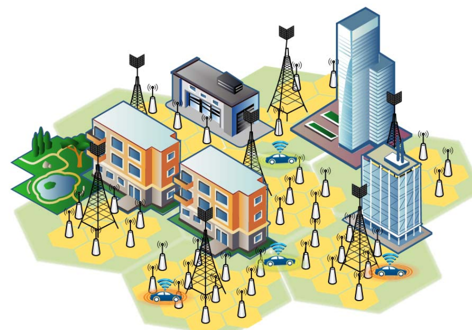
(a) Distribution of mmWave bands in the spectra.



(b) D2D communication in 5G.



(c) A base station with multiple antennas can simultaneously construct different beams for multiple target users or autonomous vehicles using beamforming technology.



(d) 5G small-cell is much smaller in shape, coverage and transmit power than traditional macro cell and will be densely distributed in the city.

Fig. 10. Ilustration of 5G features including (a) mmWave, (b) D2D, (c) small cell, and (d) massive MIMO with beamforming.

positioning in high speed autonomous driving environment [111]. On the other hand, beamforming achieves concurrent transmission by Space-Division Multiple Access (SDMA), which effectively separates electromagnetic waves between different autonomous vehicles in space and reduces mutual interference. As shown in Fig. 10c, in practical applications, using mmWave and smart antenna array, beamforming technology can be adopted to construct directional signal, as well as track and transmit to high speed target over long distance, which meets the requirements of autonomous driving.

- *D2D:* As an important technology for 5G shown in Fig. 10b, D2D (Device-to-Device) technology allows physically approximal autonomous vehicles to communicate directly with each other via a licensed cellular band, thus greatly improves spectral efficiency. It can achieve high data rate and long transmission range, as well as support large-scale high-definition video stream transmission [192]. Therefore, D2D is suitable for real-time communication of autonomous vehicles that exchange a large amount of information and travel at high speed. Due to the contention nature of CSMA/CA mechanism adopted in traditional DSRC, vehicles have to spend time on backoff. For example, if the transmission time of some packets is long (result in the suspension of backoff counter), or retransmission is allowed to improve the reliability of data transmission, the waiting time might be longer [178]. Contrarily, D2D communications are contention free, thus can reduce the above mentioned time delay, and further meet the real-time requirements of autonomous vehicles. However, D2D technology also has lots of challenges, one of which is the interference management problem caused by channel reuse between D2D and cellular users. The effective methods to solve this problem include: transmission power management, advanced coding strategies, and interference avoiding MIMO techniques [193].
- *Small-cell:* Small-cell is much smaller in shape, coverage and transmit power than traditional macro cell as shown in Fig. 10d. In the foreseeable future, the driving distance between autonomous vehicles will be smaller, and the distribution of autonomous vehicles will be extremely dense. In hot spot areas, especially in vehicle-intensive urban area, small-cell can implement frequency multiplexing in a smaller range and assist macro cell to ease the rush. In addition, small-cell will offer high-speed wireless access by reducing the distance between the autonomous vehicles and the access points, as well as provide coverage in remote areas.

A lot of research has been done on the emerging 5G technology. Wang *et al.* [180] propose a 5G vehicular network communication scheme that adopts software-defined cloudlet for scheduling management and performing transmission. Similarly, Ge *et al.* [179] present a vehicular network based on 5G SDN, including a fog unit to cover the vehicle flexibly as well as avoid frequent handover between vehicles and roadside units. Its transmission delay and throughput are analyzed and the results show that the transmission delay of the proposed scheme is minimum. They also derive the cooperation probability and coverage probability of 5G cooperative small-cell network and give the vehicle handover rate and vehicle overhead ratio in [177] based on the distance between the vehicles and the cooperative small-cell base stations. Wymeersch *et al.* [194] consider that the specific signal characteristics of 5G is conducive for vehicle positioning and summarize the development process of cellular positioning as well as 5G mmWave positioning. Furthermore, Eiza *et al.* [181] propose a new system model for 5G enabled vehicle networks, which is propitious to reliable, secure and privacy aware real-time video reporting services. Summary of these studies are shown in Table VII.

B. Computing Technologies

Due to the limited storage and computing capabilities of autonomous vehicle's on-board terminals, computing technologies are needed to deal with tasks that are difficult for autonomous cars to accomplish themselves. The powerful cloud can be used to process computation-intensive tasks for autonomous driving. However, this method need high bandwidth to transmit raw data and will cause increased latency over the communication link between autonomous vehicles and the cloud. Thus the cloud is suitable for long-term and non-real-time autonomous driving assignments, examples include large-scale model training, generation and updating of high-precision maps, massive data storage and simulation. Updates can also be obtained from the cloud when autonomous vehicles are not in use. Besides, autonomous vehicles need to make fast decisions on their control, perform path planning, process the perceptual data in real time and take driving action accordingly, while edge computing, as one of the 5G technologies and the extension of cloud computing to edge networks [195], can provide adjacent services for a variety of time-sensitive processing requirements, and is suitable for handling real-time tasks of autonomous vehicles such as perception analysis and sensor data fusion [196], [197].

For cloud computing, a new model named VANET-Cloud applied to VANET is proposed and various transportation services are reviewed in [198]. In order to improve network capacity and system computing capability, Yu *et al.* [186] propose a new vehicular network model supported by 5G, which extends the original Cloud Radio Access Network (C-RAN) to integrate local cloud service to form the enhanced C-RAN. The management and allocation of cloud resources are operated using matrix game theory, and the Nash equilibrium solution is obtained by using Karush-Kuhn-Tucker (KKT) nonlinear complementarity approach [186]. Moreover, Salahuddin *et al.* [199] propose a novel RSU cloud with the architecture consisting of traditional and specialized RSUs using SDN to instantiate, replicate and/or migrate services, and construct an Integer Linear Programming (ILP) problem with the method of reconfiguration cost analysis to model the scheme.

With regard to edge computing, Tareq *et al.* [200] demonstrate the ultra-reliable, low-latency V2I wireless communications with edge computing, thereinto, cellular small base stations with edge computing capability can reduce end-to-end service latency by processing local requests for autonomous vehicles. They propose a new algorithm for jointly optimizing the association and bandwidth allocation between autonomous vehicles and small base stations in order to maximize the reliability of V2I networks. Simulation results show that the proposed algorithm is superior to the traditional cell association scheme in terms of service reliability and latency. Then, a series of "edge-up" SDN designs with particular emphasis on the most critical functions of delay control to support possible wireless applications for the next generation advanced drive machines are put forward in [10]. Liu *et al.* [201] propose a new four-tier urban traffic management architecture, which combines VANETs, 5G networks, SDN, and MEC technologies. Hou *et al.* [202] present an overview of potential capability for vehicular fog computing paradigm and analyze its capacities in four scenarios, i.e., employing *moving* and *parked* vehicles as infrastructures for *communication* and *computation*. In addition, the existence of multiple resources, the high dynamic nature of the autonomous vehicle networks and the limited memory of the local server, all bring challenges to resource management. To combat this problem, a resource management scheme based on fuzzy logic under fog computing platform is proposed in [203], which adopts MATLAB and mobility traces generator VANETMobiSim in the simulation.

C. Simultaneous Wireless Information and Power Transfer

Future autonomous vehicles are likely to be electric vehicles. This is first because electric vehicles are easy to operate accurately and react quickly without the need to consider complex mechanical controls. Secondly, the autonomous vehicles adjust their speed frequently according to information obtained from sensors and vehicular networks. Cars that use gasoline rely on mechanical brake to dissipate energy into heat, while most of the deceleration of electric vehicles is done through energy recovery, and the cost of energy consumption for electric autonomous cars is much lower. Thirdly, low-carbon travel is more environmentally friendly and in line with people's attitudes. Therefore, Simultaneous Wireless Information and Power Transfer (SWIPT) will become a very promising communication mode for the high electric consumption autonomous driving in the future [204].

SWIPT is a technology that can transmit information and power to terminal devices simultaneously in Radio Frequency (RF) signals. This is similar to the previous introduction in Section II-B2 for PLC, which is a promising autonomous vehicle's intra-vehicle communication technology that carries both information and power through wired connections. However, because of the different sensitivity of information decoding and energy harvesting, different receiving structures are needed. Typical SWIPT architectures include time switching and power splitting [205]. Time switching architecture is that each receiving antenna periodically switches between the information decoder and the energy harvester, while in power splitting architecture, the received signal is divided into two separate signal streams, one is sent to the information decoder and the other is sent to the energy harvester [206].

SWIPT has received a lot of attention from academia. Perera *et al.* [205] and Huang *et al.* [206] all provide comprehensive overviews of the latest technologies in SWIPT, as well as some useful research challenges and suggestions. Thereinto, Huang *et al.* [206] present a SWIPT-supported power allocation mechanism for D2D communications using game theory to illustrate the importance of the application of SWIPT. Li *et al.* [207] study the design of V2X-SWIPT optimal secure beamforming in MISO (Multiple-Input Single-Output) communication network with multi-antenna energy vehicular receivers. Their goal is to maximize the minimum harvested energy of vehicular receivers. Both energy signals and artificial noise are used to facilitate efficient wireless energy access. Wang *et al.* [208] propose a joint power allocation and splitting scheme for SWIPT to optimize the power allocation at transmitter and the power splitting at receiver over doubly-selective channels in vehicular communications system. Simulation results show that compared with the existing dynamic power splitting scheme, the performance of the proposed scheme is obviously improved. SWIPT is a meaningful technology for autonomous vehicle, however, the literature on this field is few and worthy of further study.

D. Visible Light Communications

Visible Light Communication (VLC) is a new wireless transmission technology which uses visible light (380-780 nm) as information carrier and can provide 1000 times more bandwidth than RF communication [209]. It uses fluorescent lamps or Light-Emitting Diodes (LED) to transmit messages at frequencies ranging from 430 THz to 790 THz [210]. In VLC technology, the data can be modulated to the instantaneous power of light by On-Off-Keying (OOK) and Variable Pulse Position Modulation (VPPM). At the receiving end, light sensing components such as photodetectors or cameras are used to extract data [211]. The IEEE 802.15.7 standard released in 2011 defines the PHY layer and the MAC layer for short-range wireless optical communication using visible light. However, this standard lacks the latest technological development in the field of optical wireless communication [212].

In the near future, as autonomous vehicles' demand for wireless networks continues to grow, there will be less and less RF spectrum available, thus the potential of VLC can be highlighted. Besides, as the number of autonomous vehicles increases and the distance between autonomous vehicles shrinks, their distribution will become more and more dense, while heavy use of RF communication technologies may endanger people's health [213]. VLC is different from multitudinous existing RF technologies owing to its radiation-free, with people's increasing pursuit of health, VLC undoubtedly has a great merit and selling point to be applied in autonomous driving. LED lights are widely distributed in streets and autonomous vehicle bodies, it can be expected that VLC is suitable for roadside traffic information broadcasting or emergency warning.

The development of VLC needs effective experimental research. Takai *et al.* [214] introduce a vehicle optical V2V communication system based on VLC, including LED transmitter, camera receiver and a special CMOS image sensor. They test the prototype system in real scenes from daytime to nighttime, various vehicle internal data and image data are successfully sent and received. Also considering the transmission of multimedia data, Narmanlioglu *et al.* [215] demonstrate the possibility of capturing VLC video transmission by a vehicle forward camera using off-the-shelf equipment through outdoor experiment. Besides, Abualhoul *et al.* [216] present the application of VLC technology in autonomous vehicular platoon, and propose a outdoor prototype which can be used as vehicle taillight system. They use a Cycab Simulink model to analyze the impact of this VLC system on the platoon's performance. The results show that vehicles using VLC system need less time to adjust their speed to the preceding vehicle than those vehicles that are only based on perception.

Lee *et al.* [217] provide an analog channel model for the application of VLC in ITS (Intelligent Transportation System) and model the usage scenario by using CATIA V5 tool [218] and LightTools [219] software. Furthermore, Uysal *et al.* [220] evaluate the performance of a typical V2V VLC system that has realistic automative light sources, and consider the measured headlamp beam pattern as well as the impact of road reflected light. However, the research on VLC for autonomous driving is still in its infancy and needs the joint efforts of the academia and industry.

E. Deep Learning

Deep learning technology uses a cascade of multiple layers of nonlinear processing units to extract features from large-scale and high-dimensional datasets [221]. It has important applications in autonomous driving's traditional computer vision field since the abundant information from sensors such as LIDAR, Radar and camera is difficult to model manually. For example, through deep learning, autonomous driving systems can accurately identify roads, pedestrians, obstacles, etc., in order to make the right decision. However, in the future autonomous driving, deep learning technology will have brighter prospects whether in bodywork or in networking and communications.

To mention first, the edge computing we have already introduced in Section IV-B can reduce the data analysis delay for autonomous vehicles. Thus, Ferdowsi *et al.* [221] propose a distributed edge computing structure with deep learning by endowing the edge equipment with powerful computer vision and signal processing function in ITS. The preliminary results show that this edge analytics architecture with deep learning algorithms can make ITS more reliable and safer. In addition, they demonstrate the application of deep learning in edge analytics and mobile sensing, for example, multimodal RBM (Restricted Boltzmann Machines) for heterogeneous data integration, CNN-LSTM (Convolutional Neural Networks-Long-Short Term Memory) for path planning and autonomous control, CNNs and vehicular communication for platoon control, RNN (Recurrent Neural Networks) for driver behavior prediction, as well as GAN (Generative Adversarial Networks) and LSTM for the security of ITS.

TABLE VIII
PROMISING COMMUNICATION TECHNOLOGIES USED IN PARTIAL FUNCTIONS OF AUTONOMOUS DRIVING

Partial Functions of Autonomous Driving	**Inter-vehicle Technologies**	**Type**	**Coverage**	**Reliability**
Real-time sensory data exchange, such as LIDAR and HD camera's data	WiFi, ZigBee, DSRC, LTE-V-Direct, **5G D2D**, VLC	V2V	Small	High
Feedback identifiable objects and signs	WiFi, ZigBee, WiMax, DSRC, LTE-V-Cell, **5G**, VLC	V2I	Small	High
Access cloud	WiFi, ZigBee, WiMax, DSRC, LTE-V-Cell, **5G**, VLC	V2I	Large	Best effort
Vehicle identification	WiFi, ZigBee, DSRC, LTE-V-Direct, **5G D2D**, VLC	V2V	Small	High
Emergency warning	WiFi, ZigBee, DSRC, LTE-V-Direct, 5G D2D, **VLC**	V2V	Small	High
Distance control	DSRC, LTE-V-Direct, **5G D2D**, VLC	V2V	Small	High
Cooperative precise localization	WiFi, ZigBee, WiMax, DSRC, LTE-V, **5G**, VLC	V2V/V2I	Large	High
Road hazard warning	WiFi, ZigBee, WiMax, DSRC, LTE-V-Cell, **5G**, VLC	V2I	Large	High
Remote diagnosis	WiFi, ZigBee, WiMax, DSRC, LTE-V, **5G**, VLC	V2V/V2I	Large	High
3D map download	WiFi, ZigBee, WiMax, DSRC, LTE-V-Cell, **5G**, VLC	V2I	Large	Best effort
Roadside real-time traffic information broadcast	WiFi, ZigBee, WiMax, DSRC, LTE-V-Cell, 5G, **VLC**	V2I	Large	High
Multimedia information download	WiFi, ZigBee, WiMax, DSRC, LTE-V-Cell, **5G**, VLC	V2I	Large	Best effort

Due to the autonomy of autonomous vehicles and their needs for massive information in real time, network traffic control becomes a key problem. Fadlullah *et al.* [222] summarize the most advanced deep learning architectures and algorithms related to network traffic control systems. Besides, they propose the appropriate input and output characterizations of heterogeneous network traffic, and consider a supervised deep neural network system consists of multiple hidden layers [223]. In this work, the greedy hierarchical training method is applied to initialize the deep learning system, and the reverse support algorithm to fine-tune the system. C++/WILL [224] is adopted to provide preliminary simulation results, which prove the feasibility of the proposed deep learning system for improving heterogeneous network control.

Deep learning also has potential to solve routing problems in autonomous vehicles. Mao *et al.* [225] study the new opportunities of deep learning in packet processing, and transfer computing needs from rule based routing to deep learning based high throughput packet processing routing. They also use C++/WILL as the simulation framework. Furthermore, Kurosawa *et al.* [226] present an anomaly detection scheme based on dynamic training method, which updates the training data periodically.

F. Discussions

In this section, we have introduced the new trends of communication technologies in autonomous driving. Firstly, the emerging 5G technology, which promises to provide ubiquitous connectivity as well as ultra-reliable and low-latency transmissions, can meet the communication requirements of autonomous driving. Then, both cloud computing and edge computing are of great significance for autonomous vehicles to provide powerful storage and computing capabilities. Edge computing can be used for time-sensitive tasks, and cloud computing is suitable for long-term tasks. SWIPT as a technology that can transmit information and power simultaneously has great potential for future electric autonomous vehicles, while with the scarce RF spectrum resources, VLC has attracted lots of attention due to its wide spectrum range, harmless to human body, and the broad distribution of LED lights. Last but not least, deep learning technology can not only be adopted in the traditional aspects such as computer vision of autonomous vehicles, but also become a new direction in autonomous vehicle networks. Table VIII summarizes the functions of autonomous driving and the corresponding possible technologies that can be used. Words in bold type are our recommended technologies. We can see that emerging technologies have great potential for the foreseeable future and will be more in line with the requirements of autonomous driving, thus they deserve to be studied in depth.

V. VERIFICATION METHODOLOGIES

A. Simulators

The research of autonomous driving's networking and communications needs a lot of experimental support. Doing real-world experiments may cost a great deal of human or material resource, and can even be a waste of time before technologies are mature. Accordingly, the simulator plays an important role in this field. Vehicle networking and communications generally needs two kinds of simulator, that is, the network simulator and the traffic simulator. Network simulators are used to test the performance of network applications and protocols, while traffic simulators are used to generate vehicle tracks. There are also simulators that combine network simulators and traffic simulators to make them easier for researchers to use. This section summarizes the mainstream simulators in the scope of this paper. The summary of these simulators is given in Table IX.

1) Network Simulators: NS-2 (Network Simulator, version 2) is an object-oriented network simulator and essentially a discrete event simulator that provides important simulations of wired and wireless network transport, routing and multicast. Its code is written in C and OTcl. The results of its simulation can be demonstrated using a network animation simulator (nam). Although both NS-2 and NS-3 are written by C, NS-3 is not an extension of NS-2, but a new simulator. In NS-3, simulation scripts can be written in C or Python rather than OTcl. One of NS series's best advantages is open source and free.

Qualnet is a commercial software with high cost rooted in the U.S. Department of DARPA global mobile

TABLE IX
SUMMERY OF MAINSTREAM SIMULATORS FOR NETWORKING AND COMMUNICATIONS IN AUTONOMOUS DRIVING

Simulator	Type	Officially Supported Wireless Technology	Simulation Language	Supported OS	GUI	Open Source
NS-2 [228]	Network Simulator	WiFi, Cellular, Satellite	C++, OTCL	Windows+cygwin, Linux, macOS, FreeBSD, Solaris	×	✓
QualNet [229]		WiFi, LTE, WiMAX, UMTS, ZigBee, GSM	C, C++	Windows, Linux, macOS, FreeBSD, Solaris	✓	×
NS-3 [230]		WiFi, LTE, WiMAX	C++, Python	Windows+cygwin, Linux, macOS, FreeBSD, Solaris	×	✓
OMNeT++ [231]		Through external models	C++, NED	Windows, Linux, macOS	✓	✓
MATLAB [232]	Traffic Simulator	N/A	MATLAB	Windows, Linux, macOS	✓	×
VANETMobiSim [233]		N/A	XML	Windows, Linux	✓	✓
SUMO [234]		N/A	XML	Windows, Linux, macOS	✓	✓
Veins [235]	Integrated Simulator	N/A	N/A	Windows, Linux, macOS	✓	✓

communications program, both its simulation speed and accuracy have significant advantages over other emulators. In addition, Qualnet has a predecessor named GloMoSim, which is free and open source [235].

OMNeT++ (Objective Modular NETwork testbed in C++) is also a free and open source modular component-based multiprotocol network simulator that owns a powerful graphical interface and has a commercial version named OMNEST.

2) Traffic Simulators: MATLAB is a commercial mathematical software produced by MathWorks Inc. and a quite general platform that can be used in traffic simulation.

VANETMobiSim, written by java, is an open source vehicle movement simulator that can generate multiple forms of movement paths. Its modeling includes V2V and V2I relationships, and combines parking signs, traffic lights and the activity-based macro-mobility with human mobility dynamics [236]. In addition, it allows users to generate trips based on their own assumptions or activity behavior, and is able to configure the path between the start point and the end point according to the Dijkstra algorithm [236].

SUMO (Simulation of Urban MObility) is also a powerful mobile simulator written in C. It can import real tracks from real map databases, such as building, mark point and lane count, to realize spatially continuous and discrete traffic flow simulation [237]. Moreover, SUMO-GUI is the graphical interface tool with the same function as SUMO.

3) Integrated Simulator: Veins (VEhicles In Network Simulation) is a simulator that combines the traffic simulator SUMO with the network simulator OMNeT++ and provides many modern features in programming, especially a full-featured WAVE model, leading to the more accurate results [12].

B. Real-World Experiments

On one hand, testing and evaluating networking and communication technologies in real scenarios can be especially difficult and may cost a lot of money and resources. On the other hand, practice is the only criterion to test truth, studying networking and communications only by simulation is nowhere near enough. Therefore, it is necessary to use real scenes to verify the research problem.

For example, in [129], a DSRC system is established to provide inter-vehicle wireless communication, and two roads in California, namely, the Highway 101 in Sunnyville and Mountain View and the Highway 17 between Los Gatos and Scotts Valley, are selected for real-world experiment [129]. Two vehicles equipped with DSRC are used for testing, i.e., a 2012 Mercedes-Benz C-Class as a remote vehicle, and a 2011 Mercedes-Benz E-Class as a host vehicle. In this experiment, data transmitted by DSRC is connected to embedded computer by Ethernet, Radar data is collected by CAN bus, and two types of GPS sensor devices are used to evaluate the quality of location data and their impact on fusion performance [129]. In addition, Shi *et al.* [149] provide an application-oriented performance comparison between 802.11p and LTE-V in real world environment conducted at National Intelligent Connected Vehicle Pilot Zone, in Jiading District, Shanghai. The experiment involves two vehicles, Changan CS75 and MG GS, two kinds of communication devices, i.e., CWAVE-Original from Nebula Link to implement 802.11p and IEEE 1609 series, and a prototype of LTE-V communication equipment device from Datang Telecom Technology. Moreover, Dong *et al.* [238] concentrate on the innovations of the 5G-enabled smart collaborative vehicle network architecture. They performs extensive experiments in various real-world scenarios, including the 4th Ring Road of Beijing usually with traffic jams, and Datong-Xian HSR (High-Speed Railway) located in the northwest of China that has high-speed trains run at speeds up to 300 km/h. Thereinto, the experiments on the real HSR simulates the frequent handover among femtocells with a total running time of 42 minutes.

VI. CHALLENGES AND OPEN ISSUES

A. Strict Requirements

The main control of traditional vehicles is in the hands of human beings. Human drivers are responsible for observing complex traffic environment, as well as operating vehicles directly according to their own judgement and traffic regulations. At this time, the information obtained through the vehicle networks is mainly used for display, prompt or multimedia entertainment, and can only be seen as an assistant function. Even if the information is tampered or stolen, the damage to cars and people may not be great. However, the driving process of the autonomous vehicle is partly or wholly determined by the autonomous driving system, which relies on the status of the autonomous vehicle collected in real time by sensors and communication modules, such as road condition and high-precision maps, for decision-making and control. In this way, a second delay may lead to serious accidents, thus putting forward more stringent requirements for more secure, more reliable and faster communication and networking technologies in autonomous driving.

B. Network Management

With the rapid development of networking and communication technologies, not only are people increasingly dependent on networks, but also the devices or autonomous vehicles around them. The communication technologies and elements of network composition will become extremely complex, thus bringing great difficulties to network management. More intensive infrastructures and faster autonomous vehicles result in frequent handover problems, leading to the continual interaction among vehicles or between vehicles and infrastructures and causing serious interference. Furthermore, rapid growth of mobile data and networking devices around the world result in the inadequacy of network capacity shared among people, autonomous vehicles and other objects, which will also bring about the competition of network resources.

SDN is extensible, flexible to realize centralized management, and will be a key solution to solve the autonomous vehicle's network management problem. The initial development of deep learning in autonomous vehicle networks is also beneficial to the control of network traffic. Moreover, resolvent for the frequent handover between vehicles and roadside facilities can refer to the advanced research on UDN (Ultra-Dense Network). In short, the network management problem still needs the academic circles to study more deeply.

C. Computing System

The development of autonomous driving needs the combination of sensor technologies, transmission technologies and data processing technologies, which is a convergence of multi-source information, leading to the requirement for virtualization, mass storage and computing capabilities.

Universally, in order to serve autonomous vehicles from different geographical locations, the cloud computing data center is located in the core network. However, it is far away from the end user, resulting in the problems of high latency, network congestion and low reliability. Subsequently, edge computing mainly uses the equipment in the edge network, such as traditional network devices and specially deployed local servers. Although the resource capacity of these devices is much smaller than that of a data center, their large number can make up for this shortage. Edge nodes are closer to end users and have smaller network delay as well as more timely response, while driverless safety and low delay are closely linked, a second earlier may be able to reverse an accident. Therefore, in the future, edge computing can be used as a supplement of cloud computing, while clouds can be responsible for large amounts of computing or long-term storage tasks. The two can form a system of mutual benefits.

Most of the existing researches focus on single computing technology. Nevertheless, future autonomous vehicles need the common development of cloud computing and edge computing to form a system in which several computing technologies coexist and complement each other.

D. Development of Standards

Autonomous driving has prominent cross-industry and cross-field attributes. However, its development is in the primary stage, its business model is in a state of ambiguity, and there still exists gaps between various fields. Commercial vehicle manufacturers, Internet companies, telecom operators, governments and other public institutions have not yet achieved effective integration. Manufacturers without uniform standards for hardware, software and technologies are at war, which is a stumbling block to communications among vehicles.

Only standardization is able to promote the development of technologies, boost the integration of different fields, and realize the real development of networking and communications in autonomous driving. Therefore, a cross-field cooperation mechanism should be set up to establish a relatively complete industry standard system for autonomous vehicles.

E. Security Issues

This paper focuses mainly on the research of networking and communications in autonomous driving and not too much involves the security aspects. Security issues are of utmost importance in every time and everywhere, especially when it comes to autonomous driving, which is closely related to human life. The problem arose when autonomous vehicles were hooked up to the network. At the 2015 Black Hat Conference, two U.S. cyber security experts announced the details of the remotely intruded Jeep Cherokee using the vulnerability of intelligent vehicle system. They cracked the on-board multimedia system and penetrated into the wireless network operator Sprint's internal network, as well as found all Jeeps with loopholes. They eventually invaded the vehicle's CAN bus through the multimedia controller and could send any command over the CAN bus.

The operation of autonomous vehicles is completely controlled by the internal system without human intervention. Hackers can spread viruses and Trojans through the network, as well as use the wireless network attack means to assault autonomous vehicles, such as brute force crack and packet capture. Consequently, not only will people's privacy information be stolen, autonomous vehicles will even be remotely controlled, but the entire autonomous vehicle network may also be paralyzed, resulting in a series of tragedies. Therefore, it is particularly important to isolate the bottom layer of the autonomous vehicle and speed up the research of driverless firewall. In this way, if hackers invade into the autonomous vehicle, the underlying information may not be obtained and the autonomous vehicle will not be controlled. In addition, rich supply of data in autonomous vehicle networks can be transmitted encrypted. However, the reliability of these data will become a new problem, for example, generation of false information will bring great risks to the entire network. Thus, the research of novel data encryption technology in autonomous vehicle network will also become a huge challenge. Furthermore, block chain technology has the characteristics of non-tampering and anonymity but traceability. It is a feasible solution to autonomous vehicle data security problems and deserves in-depth research in autonomous driving.

Compared with traditional vehicles, autonomous vehicles have more abundant and advanced functions, such as dynamic path planning, real-time driving task customization, and even adaptive scene mode switching. Because of the limited on-board storage and processing capacity, autonomous vehicles will be more dependent on the cloud or edge. For example, model training, simulation, and perception analysis. Therefore, in terms of security, data storage, authentication, network transmission and virtualization are all important and worthy of study.

F. Information Transmission Priority

As the number of future autonomous vehicles increases and the distance between autonomous vehicles shrinks, their distribution will become increasingly dense, and the amount of messages to be propagated will become extremely large. Since the channel bandwidth is limited and the driving process of autonomous vehicle is primarily determined by the autonomous driving system, the priority of the transmitted information needs to be carefully defined to ensure that autonomous vehicles can obtain timely access to information that is important to them. Information propagated by future autonomous vehicle networks may include: periodically broadcast messages, such as the location of the surrounding vehicles and real-time motion status; warning messages on dangerous events, such as vehicle runaway warning and abnormal road conditions warning; emergency messages, such as signals from ambulances or police cars. In many cases, although the warning or emergency information is urgent, too much emphasis on the transmission of these messages will greatly weaken the transmission of environmental information, which is also the cornerstone of autonomous driving. Therefore, the priority of various information transmissions needs to be weighed carefully.

G. Data Sharing

Information obtained through the traditional vehicle networks is mainly used for assistant function. Even primary autopilot requires only the interaction between adjacent autonomous vehicles, such as the autonomous driving level 2 function CACC we mentioned in Section II-C that uses communication technologies to adaptively control the distance from the car in front. Besides, multimedia infotainment in traditional vehicle networks depends largely on service providers. Future autonomous vehicle networks need numerous autonomous vehicles to participate in data sharing in order to collect more real information and make more accurate decisions, thus it depends on the number and popularity of autonomous vehicles. If autonomous vehicles are not widespread and the number of connected autonomous vehicles is limited, the information sharing rate will be low, which is a great challenge to the communications of autonomous driving.

VII. Conclusion

This paper has investigated the networking and communication technologies in autonomous driving to promote the perception and planning ability of existing autonomous vehicles relying solely on sensors. However, few of relevant literatures and concepts are specifically designed and proposed for autonomous vehicles, which are more complicated and have more interactive information as well as more stringent requirements than traditional cars, thus we have come up with lots of technologies that are suitable for or have been used in autonomous vehicles.

We have carried out a retrospective and forward-looking study on the networking and communications in autonomous driving from two aspects: intra- and inter-vehicle. Firstly, the intra-vehicle network as the basis of autonomous driving can simplify the wiring, facilitate the sharing of data among the on-board systems and improve the driving efficiency by connecting the electronic components of the vehicle. On one hand, the data bus wired interconnection mode has a wide range of applications in the field of autonomous vehicles. On the other hand, Ethernet, once used only for traditional local area network, has been applied to autonomous car bodies; power-line communication and wireless interconnection technologies are also worthy of academic attention. Secondly, the inter-vehicle network is the focus of this paper divided into low power technologies, 802.11 family technologies, base station driven technologies and other auxiliary technologies. Among them, DSRC and LTE-V are specially designed for cars, nevertheless, more practical tests are needed. Thirdly, we have introduced the new trends of communication technologies that bring opportunities for the networking and communications in autonomous driving, such as 5G, computing technologies, SWIPT, VLC, and deep learning. Finally, we have summarized the verification methods as well as the challenges and open issues, which are convenient for researchers to refer to and carry out further studies.

Anyhow, networking and communications for autonomous driving still have a long way to go and require the joint efforts of academia and industry.

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