Vehicular Communications: A Network Layer Perspective

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***Abstract*—Vehicular communications, referring to information exchange among vehicles, infrastructures, etc. have attracted a lot of attentions recently due to its great potential to support intelligent transportation, various safety applications, and on-road infotainment. In this paper, we provide a comprehensive overview of recent research on enabling efficient and reliable vehicular communications from the network layer perspective. First, we introduce general applications and unique characteristics of vehicular communication networks and the corresponding classifications. Based on different driving patterns, we categorize vehicular networks into manual driving vehicular networks and automated driving vehicular networks, and then discuss the available communication techniques, network structures, routing protocols, and handoff strategies applied in these vehicular networks. Finally, we identify the challenges confronted by the current vehicular networks and present the corresponding research opportunities.**

***Index Terms*—Vehicular communications; manually driven vehicles; autonomous vehicles; routing protocols; handoff strategies; communication technologies.**

I. INTRODUCTION

In the last decade, vehicular communication networks have attracted tremendous interest not only from academia and industry but also from goverments. Via enabling vehicles to exchange information with other vehicles (i.e., vehicle-to-vehicle, V2V) and infrastructures (i.e., vehicle-to-infrastructure, V2I), vehicular communications can support a variety of applications, including intelligent transportation and safety management [1], [2]. However, due to high mobility and complicated communication environment, it is very challenging to provide efficient and reliable vehicular communications to satisfy different requirements, especially, higher reliability and lower latency. In our previous work, we have provided a comprehensive survey on vehicular communications from the perspective of the physical layer [3]. In this paper, we provide a survey from the network layer perspective.

Owing to the advances in sensor technologies, wireless communications, computational power, and intelligent control, a new driving pattern, named automated driving, has been gradually applied in vehicles. According to the SAE International's Standard J3016 [4], vehicles can be classified into six distinct levels of autonomy, as shown in Table I. Vehicles with level 0 and 1 autonomy are referred to as manually driven vehicles in this paper. Manual driving vehicular networks (MDVNETs), referring to communications among manually driven vehicles, are one of the main applications of vehicular networks and have been widely considered in the existing works [5]. MDVNETs can help manually driven vehicles to improve the traffic safety and provide infotainment services to drivers and passengers [2].

Vehicles with level 4 and 5 autonomy are referred to as autonomous vehicles (AVs). It is expected that no human actions or interventions are required for an AV that can automatically navigate a variety of environments, other than setting the destination and starting the system. In other words, people can be relieved from driving stress [6], [7]. Moreover, AVs are considered as a good solution for increased safety, velocity, convenience, and comfort with reduced energy consumption [7]. Despite the attractive advantages of AVs, how to ensure the autonomous driving system to be safe enough to completely leave humans' actions and interventions presents significant challenges. Being "safe" means at least the AVs can correctly execute vehicle-level behaviors, such as obeying traffic regulations and dealing with road and roadside hazards [6], [8]. On the other hands, there are several works indicating that inter-vehicle information plays an important role for AVs' "safe", in which, helpful information, either via onboard sensors or vehicular communications, is needed for the collision avoidance and cooperative driving among AVs [9]. Therefore, it enables advanced features, such as "platooning", and alerts AVs of real-time mapping information and surrounding environments, such as other AVs and potential hazards [10]. Thus, automated driving vehicular networks (ADVNETs), used for wireless communications among AVs, have been regarded as another important application of vehicular networks.

In addition to MDVNETs and ADVNETs, another important category of vehicular networks is heterogeneous driving vehicular network (HDVNET). Recently, vehicles with level 2 and 3 autonomy have been generated and begun to be test-driven on the roads. Table I shows that vehicles with level 2 and 3 autonomy may be completely controlled either by the automated driving system (ADS) or the driver in different road environments. Moreover, with AVs gradually prevailing on roads, scenarios where AVs and manually driven vehicles move on roads simultaneously will be more common. In order to achieve information sharing between manually driven vehicles and AVs or among vehicles with level 2 and 3 autonomy, HDVNET is essential.

Existing studies have demonstrated that several potential wireless communication technologies can be applied to vehicular networks: dedicated short-range communications (DSRC)

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Table I
SIX DISTINCT AUTONOMY LEVELS OF ON-ROAD VEHICLES [4]

Autonomy levels	Narrative defination
0 - No Driving Automation	The entire dynamic driving task (DDT) is performed by the driver, even when the DDT is enhanced by active safety systems.
1 - Driver Assistance	The driving automation system executes the sustained and specific operational design domain (ODD) of either the lateral or longitudinal vehicle motion control subtask, while the driver is expected to perform the remainder of the DDT.
2 - Partial Driving Automation	The ADS executes the sustained and specific ODD of both the lateral or longitudinal vehicle motion control subtask, and the driver completes the object and event detection/response subtask and supervises the driving automation system.
3 - Conditional Driving Automation	The sustained and specific ODD is performed by the ADS, while the DDT fallback-ready user is receptive to intervene requests from ADS and responds appropriately to DDT performance-relevant system failures in other vehicle systems.
4 - High Driving Automation	The sustained and specific ODD is performed by ADS of the entire DDT and DDT fallback, and a user has no need to respond to intervene requests.
5 - Full Driving Automation	The sustained and unconditional ODD is performed by an ADS of the entire DDT and DDT fallback, and a user has no need to respond to intervene requests.

[11], cellular network technologies [12], [13], Wi-Fi [14], White-Fi [15], infrared (IR) [16], and visible light communications (VLC) [17]. Through using one of these technologies or their combination, a variety of data generated by vehicles can be shared successfully to support different applications. However, in addition to the fundamental physical layer issues discussed in our previous work [3], there are many network layer issues that should be taken into account to enable efficient and reliable vehicular communications. Different types of communications techniques may fit in different vehicles in different environments. How to specify the ways that different communication entities exchange information with each other is a key to achieve efficient and reliable information dissemination, which refers to designing efficient routing protocols [18]. How to select network for executing information sharing when two or more communication technologies are available, i.e., developing corresponding handoff strategy, will determine the general network performance, such as delay [19].

There have been several excellent survey papers on vehicular communications, such as [13], [18], [19], [20], focusing on the network layer issues in MDVNETs. In this paper, we present a comprehensive overview of recent research on enabling efficient and reliable vehicular communications both in MDVNETs and ADVNETs. We start with general applications and unique characteristics of vehicular networks and the corresponding classifications. Then, we discuss recent research from a network layer perspective for both MDVNETs and ADVNETs. Specifically, for MDVNETs, we analyze the advantages and disadvantages of different communication technologies and introduce the routing protocols and handoff strategies. For ADVNETs, we summarize the communication structures designed for ADVNETs with different traffic management strategies, and then discuss two short-range communication technologies, i.e., IR and VLC. This survey also identifies the main challenges and potential solutions for the coming application scenarios, such as HDVNETs.

The remained of this paper is organized as follows. In Section II, the general applications and unique characteristics of vehicular networks are introduced. In Section III, we present four different communication technologies and address the routing and handoff issues for MDVNETs. Communication structures and two short-range communication technologies for ADVNETs are provided in Section IV. In Section V, we identify the main challenges and discuss the potential solutions. Finally, we conclude this paper in Section VI.

II. VEHICULAR NETWORKS

In this section, we present vehicular networks which support information exchange among vehicles without considering driving patterns. We will first introduce the applications of vehicular networks and then describe the unique characteristics of vehicular networks. Note that in-vehicle communications, which refer to wired or wireless communications between an on-board unit (OBU) and one or multiple application units (AUs) in a vehicle [21], are not considered here. Moreover, the mentioned AVs should be distinguished from autonomous robots, unmanned aerial vehicles, and unmanned underwater vehicles even if many communication technologies introduced here can be directly applied there.

A. Vehicular Networks Applications

For moving vehicles, communication networks are usually designed for sharing information and supporting a large number of cooperative applications, which can be categorized into safety and non-safety applications.

Safety applications: Through sharing safety-related information [1], safety services can be provided, traffic accidents can be significantly reduced, and commuters' life, health, and property can be effectively protected. Once obtaining safety-related information from other vehicles, drivers can take actions in advance to enhance driving safety or be informed about unexpected dangerous situations to avoid traffic accidents [5]. One type of safety-related information is vehicle's traveling state information, such as, real-time position, speed, and direction. This type of information is not only important to assist drivers or automated driving systems in passing and changing lane and avoiding collision, but also a necessary condition for cooperative driving among AVs to maintain the string stability of platoons/convoys [22]. Another type of safety-information is event-driven safety information, e.g., emergency vehicle warning, traffic condition warning, and rear-end collision warning. Event-driven safety information, generated by certain vehicles involved in or discovering a dangerous situation (such as an emergency brake or sudden lane change), should be shared to help other vehicles obtain real-time situational awareness and detect possible dangers. As shown in Figure 1, sharing cooperation collision and rear-end collision warning information among vehicles can help avoid accidents in several scenarios [23].

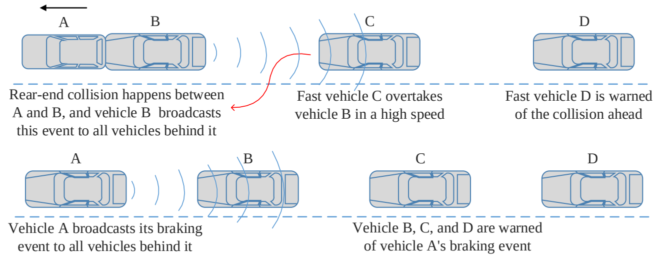

Figure 1. Examples for sharing event-driven safety information.

Non-safety applications: By sharing information among moving vehicles, value-added services, such as traffic management and infotainment support, can be provided to enhance the comfort of commuters. Similar to some safety applications, most of the traffic management applications are designed for reducing traffic jams to improve traffic flow and save travel time for commuters. For example, via sharing information about traffic monitoring and road conditions among moving vehicles, traffic management applications can be applied to help drivers reroute to their destinations and to improve the efficiency of traffic light schedules, and consequently reduce traffic jams [24]. Different from traffic management, infotainment-support applications are mainly focusing on providing traveler location-based services and entertainments. For instance, infotainment-support applications can provide location information, such as about fuel station, parking, restaurant, and hotel, to moving vehicles when the related services are required by drivers or passengers [25]. Furthermore, infotainment-support applications can also provide Internet access for moving vehicles to download multimedia entertainment information [26].

Despite the benefits of the above applications, the implementation of safety and non-safety applications has their own challenges. In a vehicular network with certain communication technology, all available spectrum resources can be used for either safety or non-safety applications. For safety applications, related information is with high priority in terms of transmission delay and reliability so that drivers can receive them and take the corresponding actions in time [25]. Moreover, due to high mobility, variable network density, and unstable topology in vehicular networks, meeting these requirements is sometimes very challenging [2], [11], [23], [27], [28]. It is for these reasons that safety applications are given higher priority over non-safety applications. Different from safety applications, most of the non-safety applications do not have stringent real-time requirements. However, how to reduce the delay and packet loss for non-safety information without impacting safety applications is important to improve the service quality of the non-safety applications, especially for some infotainment applications [26].

B. Vehicular Networks Characteristics

In vehicular networks, V2V communications are basically executed by applying the principles of mobile ad hoc networks (MANETs), namely, wireless communications are spontaneously created for data exchange. In addition to some characteristics similar to MANETs [29], such as self-organization and management, short to medium transmission range, omnidirectional broadcast, and low bandwidth, a vehicular network has its own unique characteristics due to its moving nodes. According to whether they are beneficial to information exchange or not, these characteristics are classified into detrimental and beneficial ones.

Detrimental characteristics: These characteristics, including high mobility, stringent delay constraints, and complicated communication environment, pose obstacles or challenges to vehicular networks.

1) High mobility: High moving speed of vehicles often results in frequently disconnected wireless communication links and then reduces the amount of effective communication time among vehicles. Furthermore, it also causes the network topology to change dynamically and further adds challenges to information exchange among vehicles.

2) Stringent delay constraints [18]: In some vehicular network applications, such as safety applications and some infotainment applications, information exchange is required to be successfully finished within a particular time limit to avoid traffic accidents and ensure the quality of infotainment services. Note that delay mentioned here is the maximum delay from the source to the destination, not average delay in vehicular networks.

3) Complicated communication environment: Vehicular networks are usually applied in three kinds of communication environment. The first one is one-dimensional communication environment, such as highway traffic scenario. Even though vehicles in highways always move faster than in other type of environment, one-dimensional environment is relatively simple due to the straightforward moving direction and relatively fixed speeds. The second one is two-dimensional communication environment. A typical example is urban traffic scenarios, which are more complex compared with highway scenarios [30]. Streets in most urban areas are often divided into many segments due to intersections. Therefore, for two moving vehicles in different road segments, a direct communication link may not exist due to obstacles around the intersections, such as buildings and trees. Moreover, there are always higher vehicle density in urban areas, which implies more communication links within communication range and significantly impacts the spectrum resource occupation probability. The last one is three-dimensional communication environment, such as viaducts [31]. For vehicles in a viaduct, communication links in different physical space layers make this type of environment the most complex.

Beneficial characteristics: These characteristics are beneficial to the wireless communications in vehicular networks, such as weak energy constraints and driving route prediction.

1) Weak energy constraints: Since vehicles always have sufficient energy, vehicular networks do not suffer from power constraints as in regular mobile communication networks. Moreover, vehicles can afford significant sensing and computing capabilities (including data storage and processing) since the sensing and communication devices can power themselves while providing continuous communications with other vehicles.

2) Driving route prediction: A vehicle is limited to moving on the road in usual circumstances, which makes it possible to predict the driving route for itself or even for other vehicles when the road map and vehicle speed information are available. Driving route prediction plays an important role in routing protocol design for vehicular networks, especially when addressing the challenges presented by high mobility.

Characteristics of vehicular networks are similar in both MDVNETs and ADVNETs. However, challenges presented by the above characteristics and how to address these challenges to meet application requirements are different for different types of vehicular networks. We will address these issues from the network layer perspective in the subsequent two sections.

III. MANUAL DRIVING VEHICULAR NETWORKS

Almost all current vehicles are manual driving and always move individually on the roads. For example, some drivers may accelerate suddenly to pass other vehicles or others may get used to low speeds. Thus, the impacts of high and heterogeneous mobility on the MDVNETs are significant. How to address the challenges caused by high and heterogeneous mobility and enable communications in different types of communication environment has attracted more and more attentions. In this section, we will discuss the existing works for MDVNETs. Specifically, we first introduce the available communication technologies for MDVNETs and then present routing protocols and handoff strategies.

A. Technologies for MDVNETs

In addition to the navigation system, most modern vehicles are fitted with DSRC, cellular, Wi-Fi, White-Fi etc., to enable vehicular networks to improve the driving experience and safety [32]. In the following, we review four widely applied communication technologies in MDVNETs. Note that, ultra-wide band (UWB) and Bluetooth, which can be used to support the in-vehicle communications or/and traffic conditions monitoring [33], [34], are not considered here.

DSRC: It is a dedicated wireless communication technology used for exchanging information between vehicles and between vehicles and infrastructures over short to the medium range [11]. DSRC is based on the IEEE 802.11p, which is amended from the IEEE 802.11 Wi-Fi standard. As the only communication technology specifically designed for vehicular users, DSRC can provide

1) Designated licensed bandwidth: In October 1999, 75 MHz radio spectrum in the 5.9 GHz band was allocated to support the DSRC-based communications in intelligent transportation system (ITS) applications by the Federal Communications Commission (FCC) of the United States;
2) High reliability: DSRC-based wireless links can work in high mobility and harsh weather conditions, such as rain, fog, and snow;
3) Priority for safety applications: The total 75 MHz bandwidth is divided into one control channel (CCH) and six service channels (SCHs), each with 10 MHz bandwidth and 5 MHz guard band. Among these seven channels, safety applications are given priority over non-safety applications [35];
4) Security and privacy: Message authentication and privacy are provided by the IEEE 1609.2 standard [36].

Thanks to the above benefits, DSRC is regarded as a promising technology applied to support ITS applications, especially the safety-related ones [37]. However, DSRC also exposes some drawbacks. First, due to the limited spectrum resource, a broadcast storm may occur when disseminating safety information over a large area, especially in situations with high vehicle density. With the increase in the number of vehicles attempting to transmit in the same channel simultaneously, the packet delay and transmission collision probability will increase and the performance of DSRC will degrade [27], [38]. To address this problem, improved broadcast mechanisms, such as probabilistic flooding and clustering [27], [39], have been proposed and will be introduced in detail in Subsection III-B. Another obvious drawback in DSRC communications is poor and short-lived V2V and V2I connectivity. Short-lived V2V connectivity always occurs in the environment with low vehicle density, where the number of vehicles is too sparse to disseminate the information to all destination vehicles. Furthermore, due to the short radio transmission distance, i.e., around 300 m, DSRC can only provide short-lived V2I connectivity [40] if there is no pervasive roadside communication infrastructure. In order to improve the performance of vehicular networks, some medium and long-range communication technologies [27] can be commonly used.

Cellular: Nowadays, cellular networks are distributed over land areas, where each cell is served by a base station (BS), e.g., the evolved node B (eNB) in the long-term evolution (LTE) system. The key enabler of cellular-based vehicular networks is the LTE standard developed by the 3rd Generation Partnership Project (3GPP), which provides efficient information dissemination to user equipment [27]. Lots of academic research and field tests have indicated that cellular technologies, such as LTE technologies, possess great advantage in vehicular networks [40]. Specifically, benefited from the large coverage area of the eNB and high penetration rate, cellular technologies can provide relatively long-lived V2I connectivity [40]. Compared with other communication technologies, cellular technologies can potentially support several vehicles within a small region simultaneously due to its relatively high capacity. Furthermore, the channel and transport modes in cellular technologies, i.e., the dedicated/common modes and the unicast/broadcast/multicast downlink transport modes, can help reduce the transmission delay and improve the capacity for communication environment with high vehicle density [27]. Device-to-device (D2D) communications can provide short range direct links between two vehicle users to reuse the spectrum, and therefore mitigate the problems caused by the limited radio spectrum resources [12], [41].

Recently, cellular-based vehicular networks have been widely investigated [12], [40]. Due to the above mentioned advantages, cellular technologies are regarded as a promising alternative to DSRC for vehicular networks [40]. However, due to the current cellular data pricing model, the corresponding cost for data transmission in cellular-based vehicular networks is much higher than other communication technologies [14].

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On the other hand, in the dense traffic areas, the heavy data traffic-load generated by some vehicles may significantly challenge the cellular capacity and potentially affect the delivery of traditional cellular applications [40]. To address this challenge, millimeter-wave (mmWave) communications with advantages of multi-gigabit transmit ability and beamforming technique have been considered for the 5th generation (5G) cellular networks. For example, millimeter-wave communications are applied for sharing vehicles' massive sensing data in [42], where the beam alignment overhead has been reduced by configuring the mmWave communication links based on sensed or DSRC-based information.

Wi-Fi: It is a technology for wireless local area networks (WLANs) based on the IEEE 802.11 standards. It has been shown in [14], [43], [44] that Wi-Fi technology is an attractive and complimentary Internet access method for moving vehicles. Equipped with a Wi-Fi radio or Wi-Fi-enabled mobile devices, such as mobile phones, vehicles can access the Internet when they drive through the coverage of Wi-Fi access points. The obvious advantages of Wi-Fi technology include low per-bit cost, extremely widespread global deployments, and higher peak throughput, which are beneficial to some vehicular applications with a high data transmission rate, such as infotainment applications. However, due to the limited coverage of each Wi-Fi access point (AP) and high mobility of vehicles, Wi-Fi technology suffers from intermittent connectivity in vehicular networks. Thus, handoff schemes become particularly important to Wi-Fi technology in such a scenario [45]. Furthermore, instead of establishing the Wi-Fi-based inter-vehicle communications, Wi-Fi technology is considered as an complementary access method to offload delay tolerant data traffic [14], [43].

White-Fi: It is a term coined by the FCC of the United States to describe communications that allows unlicensed users to access the TV white space spectrum in the VHF/UHF bands between 54 and 790 MHz. Note that even though White-Fi is also referred to super Wi-Fi, it is not endorsed by the Wi-Fi Alliance or based on Wi-Fi technology. The progress of White-Fi technology has yielded many new insights into vehicular networks, which has motivated researchers to explore unlicensed spectrum to solve the spectrum-scarcity issue for vehicular networks. It has been shown in [15] and [46] that the White-Fi-enabled vehicular networks can improve the dissemination capacity by offloading a portion of data traffic from the DSRC band or cellular band to the TV band. Furthermore, different from the 2.4 GHz radio frequency used by Wi-Fi, TV white space spectrum is at lower frequency range and allows the signal to penetrate walls better and travel farther than the higher frequency range. Thus, White-Fi technology can provide relatively long range communications to improve transmission efficiency. For example, applying White-Fi for long-distance dissemination to avoid multi-hop transmission can reduce the transmission delay of some safety-related information [46]. However, White-Fi-enabled vehicular communications generate potential interference to incumbent TV band users, which may bring challenges to protect the incumbent services. Moreover, due to the unlicensed characteristic of TV band, vehicular networks and other existing wireless networks are all allowed to co-exist. Vehicle users may experience interference caused by other networks, and therefore impact the service quality of some vehicular applications [47].

Multiple technologies interworking: It has been shown that single technology applied in vehicular networks always has its own limitations as discussed before. Thus, instead of establishing the *homogeneous MDVNETs* that support vehicular communications by a single communication technology, the aforementioned advantages and shortcomings of DSRC, cellular, Wi-Fi, and White-Fi have motivated the works on establishing heterogeneous MDVNETs [13], [26], [48]. In *heterogeneous MDVNETs*, vehicular communications are supported by at least two kinds of communication technologies, example of a heterogeneous MDVNET in an urban area is illustrated in Figure 2, where V2X refers to vehicle-to-everything communications, including V2V and V2I communications. A typical heterogeneous MDVNET is the interworking of the DSRC and cellular technologies, where cellular-based communications can act as 1) a backup for traffic data when DSRC-based multihop links are disconnected in sparse vehicles situations, 2) a long-range Internet access method, and 3) a powerful backbone network for control message dissemination [13]. Other types of heterogeneous MDVNETs include the interworking of the Wi-Fi and cellular technologies [43], interworking of the DSRC and White-Fi technologies [46], and interworking of the DSRC, Wi-Fi, and cellular technologies. Even though multiple technologies interworking can make the best use of the advantages and bypass the disadvantages of each single technology, how to select the applicable technology for each communication link and achieve seamless handoff among different technologies are still challenging.

B. Routing Protocols

A routing protocol establishes a path/route between a source and a destination (or a group of destinations), decides to forward the information, and acts in maintaining the route or recovering from route failure. Based on the applied transmission strategies in MDVNETs, we can classify the routing protocols into unicast, multicast, broadcast, and cluster-based routing protocols, as shown in Figure 3.

Unicast Routing Protocol: It refers to a one-to-one transmission from one communication entity to another. In MDVNETs, the main goal of unicast is to transmit packets from a single source vehicle to another single destination vehicle via single/multi-hop wireless communications, by either using a "hop-by-hop" mechanism or "store-and-forward" one [49]. The main difference between these two mechanisms is whether the intermediate vehicles forward the received packets immediately or carry them until the corresponding routing algorithm makes a forward decision [50]. Unicast routing protocols can be performed in two ways: greedy and opportunistic.

In greedy unicast routing protocols, the source vehicle forwards packets to its outermost neighbors (the next hop intermediate vehicles), and then the intermediate vehicles forward these packets to its outermost neighbors (the second hop intermediate vehicles) until these packets are received by the destination vehicle [51]. That is, the forward decisions in the greedy-based unicast routing protocols are made based on vehicles' geographic information. It has been shown in [51] that the greedy-based unicast routing protocols are well working in some simple communication scenarios when "hop-by-hop" mechanism is used, such as for vehicles in straight traffic roads. However, for urban areas that always have lots of

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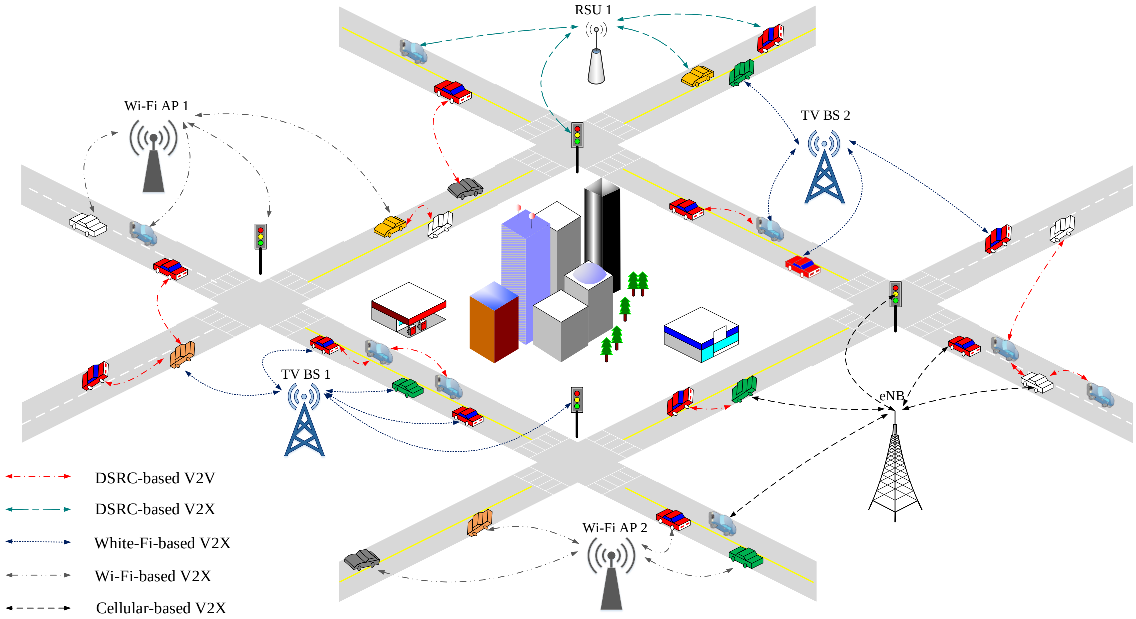


Figure 2. Illustration of a heterogeneous MDVNET in an urban area.

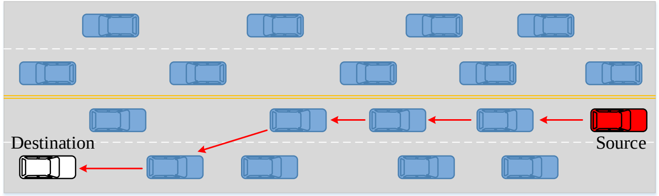
intersections, greedy store-and-forward routing protocols are more suitable to support delay-tolerant non-safety applications [52]. For example, by exploiting the availability of map information, they can reduce the communication delay through choosing the next hop based on the information about physical location, velocity, direction [53], dynamic traffic density, and curve-metric distance to the destination [52], etc.

Opportunistic unicast routing protocols support wireless networks to operate in scenarios with frequent disconnections, such as vehicular networks. In opportunistic unicast routing protocols, data packets from the source are delivered to the destination opportunistically, where

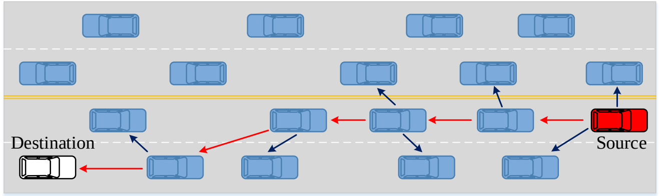
1) The intermediate vehicles should have the ability to store-and-carry the received packets and perform in a "store-and-forward" manner;
2) Forward decisions are made independently for vehicles in different regions, to deliver the packets eventually with little or no location information of the destination;
3) Multiple copies of the source packets may be transmitted in parallel to increase the probability of at least one copy of the packets being delivered.

The major challenges in designing unicast routing protocols include how to efficiently share this essential information, reduce the communication delay and packet losses, and deal with the routing conflict when there are a large number of unicast routing requests.

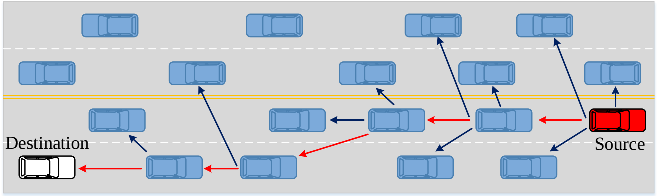
Multicast Routing Protocol: It is a one-to-many or many-to-many group communication where packets from the source are addressed to a group of destinations simultaneously. It has been demonstrated in [54], [55] that multicast routing protocols are essential to inter-vehicle communications among a group of vehicles in some situations, such as roadblocks, traffic congestion, calamities, and geographic advertising. The most classical and familiar multicast routing protocols are geocast, which are also special forms of multicast used for MANETs, where the group of destinations are identified by their geographical locations. The geocast protocol can



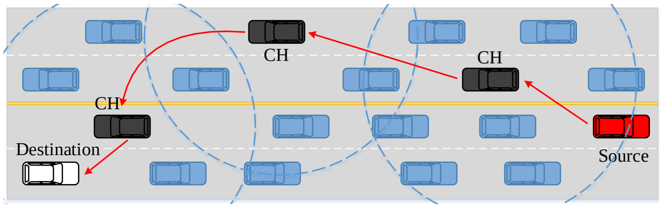
(a) Unicast



(b) Multicast



(c) Broadcast



(d) Cluster-based

Figure 3. Illustration of four categories of routing protocol in MDVNETs.

be improved by considering more and different information, such as mobility and connection information of vehicles [55], and vehicle trajectories [56]. The main goal is to address the challenges caused by network disconnection, mobility uncertainty, and redundant packets, and therefore design more efficient multicast protocols. Another important issue in designing multicast routing protocols is security, namely, how to make sure only authorized vehicles can be involved in the related communications and provide the confidentiality of the communications among an authorized group of vehicles. To address this issue, group key management schemes have been proposed with or without the assistance of infrastructure [57].

Broadcast Routing Protocol: It uses a one-to-all communication method to transfer a message from a single source to all receivers simultaneously. For vehicular networks, broadcast is an important routing method, which is usually used to discover nearby neighbors, propagate useful traffic information to other vehicles to support safety-related and cooperative driving applications, and disseminate the aforementioned essential information for unicast or multicast methods. The availability and practicability of broadcast are beyond doubt. Nevertheless, two major problems should be considered when designing a broadcast protocol for vehicular networks, especially for DSRC-based vehicular networks: broadcast storm and disconnected network problem.

A broadcast storm usually occurs in the communication environment with redundant broadcasting packets and high vehicle density, especially when multiple vehicles attempt to transmit packets simultaneously. When a broadcast storm is occurring, transmission among neighboring vehicles may experience frequent channel contention and packets collisions. There are a number of works to address this issue for vehicular networks. In [58], three distributed broadcast suppression techniques have been proposed, where a vehicle rebroadcasts the received broadcasting packets with certain probability. In these three techniques, the rebroadcast probability for each vehicle depends on the distance between this vehicle and the sender, i.e., only global positioning system (GPS) information or packet received signal strength (RSS) information from vehicles within one-hop area is required. Besides the distance information, other information has been also used to select rebroadcast vehicles, such as local topology information [59] and spatial distribution information [60]. Furthermore, advanced techniques are applied in recent proposed broadcast protocols. Such as in [39], network coding is used to reduce the number of transmissions, and therefore reduce redundant broadcasts.

The disconnected network problem is another major problem for each type of routing protocol in vehicular communications. Similar to unicast and multicast routing protocols, store-and-forward method is usually applied in broadcast protocols to address the disconnected network problem. For example, by integrating rebroadcast vehicle selection and store-and-forward, a distributed multihop broadcast protocol has been proposed in [59], which can not only handle both broadcast storm and disconnected network problem but also operate in different traffic environments, including extreme scenarios with dense or sparse vehicles.

Cluster-based Routing Protocol: It is a routing method by grouping vehicles into different sets (clusters) according to some rules, selecting a vehicle from each set to be a cluster-head (CH), and the rest called cluster members (CMs). Note that, unicast, multicast, and broadcast are three types of fundamental routing protocols that can be used to describe all routing methods in vehicular networks. Cluster-based routing protocol is a combination of unicast, multicast, and broadcast. For example, in the same cluster, CMs unicast packets to their CH, the CH broadcasts packets to all its members and multicasts packets to road infrastructures or other CHs, and road infrastructures unicast packets to one CH or multicast packets to CHs within its coverage [20].

Existing research results have indicated that clustering can improve the scalability and reliability of routing protocol in vehicular networks, by grouping vehicles based on information about relative velocity and spatial distribution. Due to the hierarchical characteristics, the cluster-based routing protocol is especially suitable for multi-hop vehicular networks with large scale and heterogeneous communication technologies [27], [61], [62]. In heterogeneous MDVNETs, cluster-based routing protocol can make the selection process of communication technologies simplified and effective. For example, in a cluster-based heterogeneous MDVNETs with the interworking of DSRC and cellular technologies, a simple way to select communication technologies for each link is that the CMs communicate with the CH by using DSRC and the CHs communicate with the eNB by using cellular technologies [27]. This way can minimize the number of vehicles communicating by using cellular technologies, and therefore reduce the cost of vehicular networks and the overload of cellular networks.

Despite the advantages of cluster-based routing protocols, an important issue should be considered when designing a cluster-based routing protocol, i.e., the stability of cluster membership. The cluster member stability, usually represented by residence times of cluster, relates to cluster-head selection mechanism and can be analyzed by a stochastic mobility model [63]. For example, in order to improve the stability of cluster membership, lots of information should be considered when selecting CHs, such as geographic position information of vehicles [61], the relative space position relations between vehicles and the center of the cluster [62], and the relative velocity between a vehicle with its neighboring vehicles [27]. Table II summarizes unicast, multicast, broadcast, and cluster-based routing protocols in terms of specific examples, elementary information, mobility pattern, communication model, application type, and hierarchical topology.

C. Handoff Strategies

In MDVNETs, handoff is a major issue for efficient and reliable vehicular communications. Vehicles often move in and out of the communication ranges of other vehicles and infrastructures, resulting in frequently disconnected V2V and V2I communication links and dynamically changing network topology. Handoff strategies aim to provide seamless communications for vehicles in MDVNETs while reducing financial cost, handoff latency, and packet loss, etc., and have attracted lots of attentions in the past few years. There are two types of handoff strategies: horizontal handoff and vertical handoff, depending on whether the same or different wireless access technologies are used.

Horizontal handoff: It is used for transferring a data transmission session from one point of attachment to another when the same wireless access technology is applied in both

Table II
COMPARISONS OF ROUTING PROTOCOLS IN MDVNETS

Routing type	Specific examples	Elementary information	Mobility pattern	Communication model	Application type	Hierarchical topology
Unicast	GyTAR [52]	Traffic density & Curvemetric distance	City	V2V	Safety & Comfort applications	No
	VADD [53]	Location & Velocity & Direction	Highway & City	V2V & V2I	Delay tolerant	No
	ETCoP [64]	Mobility & Local topology	City	V2V & V2I	Delay tolerant	No
Multicast	IVG [54]	Location & Velocity & Direction	Highway	V2V	Safety	No
	GeoMobCon [55]	Mobility & Contact	Highway	V2V	Delay-tolerant	No
	TMC [56]	Trajectories	City	V2V	For public vehicles	No
Broadcast	DV-CAST [59]	Local location & velocity	Highway	V2V	Safety	No
	DADCQ [60]	Location	Highway & City	V2V	NA	No
	[39]	Location & Velocity	Highway & City	V2V	NA	No
Cluster	VMaSCLTE [27]	Relative velocity	Highway	V2V & V2I	Safety	Yes
	PPC [61]	Location & Vehicle priority	Highway	V2V	NA	Yes
	[62]	Local location & direction	Highway & City	V2V & V2I	NA	Yes

points of attachments [13]. There are three scenarios where horizontal handoff is required in MDVNETs, i.e.,

1) For V2V communications in vehicular ad hoc networks, horizontal handoff is required for data transfer when the neighboring vehicles change, and is performed by rerouting to construct a new routing path to the destination vehicle [19];
2) For D2D-based V2V communications in cellular-based MDVNETs, horizontal handoff is required to provide continuous communication services when the proximity services (PreSe)-enabled vehicle moves across the cell boundary [65]; and
3) For V2I communications in infrastructure-based homogeneous MDVNETs, horizontal handoff is required to transfer a vehicle's data transmission session, such as Internet video streaming session, from one infrastructure to another when the vehicle moves between both infrastructures' coverage ranges [13], [66]. For example, the handover controller proposed in [66] combines the centralized and distributed control mechanisms to improve the efficiency of channel resources and support the handover operation for V2I communications.

Vertical handoff: It is used for transferring a data transmission session from one point of attachment to another when two different wireless access technologies are applied in these two points of attachments [13]. Different from horizontal handoff, vertical handoff only occurs in heterogeneous MDVNETs and is required to maintain communication connection for data transfer when a vehicle moves out of the coverage area of one type of network to another, or is an optional and efficient method to benefit the users or networks when a vehicle moves in an overlapping area of two or more types of networks. Since overlapping areas of different networks are very common in heterogeneous MDVNETs, vertical handoff as an optional method is mainly discussed in this context. Vertical handoff could be triggered by different reasons, such as user-centric handoff triggers, network-centric ones, and their combination.

The user-centric handoff triggers include QoS and financial cost. The QoS for each vehicle user is generally based on the common communication performance metrics, such as end-to-end delay, throughput, outage probability, and packet loss. Different networks can provide vehicular users with different QoS. For example, when vehicles make a handoff decision with a probability based on the maximum transmission rate, their throughput can be improved. In [67], an efficient proxy mobile IPv6 (E-PMIPv6) handoff scheme has been proposed to guarantee session continuity in urban scenario, which eliminates packet loss and reduces handoff latency and signaling overhand. Applying different technologies results in different financial costs for vehicle users, such as subscription fees required by cellular technology and fees for RSUs placement and management. Vehicles can calculate handoff probability based on the costs of different networks. Therefore, network cost normalization method is important to this trigger. For example, in [68], distributed optimal vehicle handoff (VHO) algorithms have been proposed to minimize the packet end-to-end delay and the cost of data traffic transmission.

The network-centric handoff triggers include network throughput maximization, fairness balancing, and load balancing. In [69], a fast network selection scheme has been proposed to balance throughput and fairness, where vehicles select an access network according to a coalition formation game method. In [70], by optimizing a combined cost function of the battery lifetime of mobile nodes and load balancing over infrastructures, a VHO decision algorithm has been proposed to balance the overall load among all infrastructures and maximize the collective battery lifetime.

In network-centric handoff triggers, handoff decisions are usually made based on the centralized calculating results and, therefore, abundant computing ability and data storage resources are important. Even though infrastructures in heterogeneous MDVNETs are strong enough to handle data computing and storing, cloud computing has been utilized to provide anytime and anywhere data processing and storing for

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some network-centric handoff triggers, such as the fast cloud-based network selection scheme in [69]. Moreover, software defined network controller is also utilized in heterogeneous MDVNETs, where the handover strategy is combined with OpenFlow to make smoother handover decisions [71]. Security is another important issue when performing handover since the security key needs to be changed for different connections. Thus, some works have been done to address this issue. For example, in a multihop-authenticated proxy mobile IP scheme proposed in [72], the concept of symmetric polynomials has been used for key generation at the mobile and relay routers for authentication.

IV. AUTOMATED DRIVING VEHICULAR NETWORKS

Autonomous vehicles open the door for fleet management and coordinative driving. According to the traffic management strategy applied in ADVNETs, we classify ADVNETs into free ADVNETs, convoy-based ADVNETs, and platoon-based ADVNETs, as shown in Figure 4. In free ADVNETs, AVs move independently under the control of the computerized autopilots [9]. In convoy-based ADVNETs, AVs that move on multiple lanes and with the same direction are grouped into a convoy, where lateral and longitudinal controls are conducted by all AVs in the convoy on a distributed basis to maintain the pre-set inter-vehicle spacing and align velocity. Convoy can be regarded as an extension of platoon [73]. In the platoon-based ADVNETs, with the centralized control of the leader vehicle (the first vehicle of the platoon), AVs move cooperatively with the same steady velocity and keep a steady inter-vehicle spacing one after another. Platoon-based management strategy can not only reduce energy consumption and exhaust emission by minimizing air drag due to the streamlining of AVs, but also increase the driving safety by cooperative driving among vehicles [74]. Note that, platoon-based structure can be also considered in MDVNETs [11], where manually driven vehicles may spontaneously form a platoon, i.e., one vehicle follows another one for easy driving. However, since the probability that several manually driven vehicles move spontaneously with a platoon structure is too small, the existing works related to platoon-based MDVNETs are considered as cluster-based MDVNETs, where the first vehicle of one platoon, i.e., the leader vehicle, acts as the CH, and others, i.e., member vehicles, are CMs.

Different from MDVNETs, the impacts of high mobility and complicated communication environment on the ADVNETs are more significant due to the following reasons:

1) Nodes in ADVNETs, i.e., AVs, are self-driving without human's actions and interventions and have more stringent delay constraints and higher reliable packet delivery requirement to ensure the safety of AVs [8], especially for intersection environments;
2) More types of safety-related information are required for AV applications, resulting in challenging data load in ADVNETs; and
3) Management and allocation of computing resources are more complicated, where both sensory and communication information should be processed for AVs.

In order to improve the safe navigation of AVs and efficiency of information exchange, research and testing on ADVNETs have attracted a great deal of attentions. In this section, existing works related to ADVNETs will be discussed. Specifically, we first present different communication structures designed for ADVNETs, and then, we introduce the related communication technologies used for sharing this information.

A. Communication Structures

Communication structures indicate the communication pair or group of AVs for sharing different types of information. Different communication structures are designed for different types of ADVNETs.

In free ADVNETs, one of the main communication structures is broadcast-based V2V communication, i.e., each AV broadcasts its information to the neighboring vehicles [9], [75], [76]. For example, in [75], a collision-avoidance algorithm is proposed to prevent collision in intersections, where an AV broadcasts information about collision to AVs within its communication range once it moves in a critical region, and therefore avoiding endless waiting in the intersection. To avoid collision in the usual road environment, a broadcast-based communication structure is designed, which can adjust the communication range of each AV accordingly for different scenarios in [9]. Another communication structure is V2I communication in infrastructure-based scenarios, where infrastructures are used for collecting and broadcasting information from or to AVs.

Convoy has been introduced by AutoNet[1] 2030 in [73] to support cooperative driving among AVs on multiple lanes. At least two kinds of communication structures are considered in convoy-based ADVNETs, i.e., broadcast-based V2V communication structure for sharing information to enhance the cooperative maneuvering and V2I communication structure to improve efficiency of traffic management [8].

For platoon-based ADVNETs, in addition to ensuring safe driving of each AV, another major challenge is maintaining the string stability of platoons, i.e., ensuring that inter- and intra-platoon spacing errors do not amplify upstream from AV to AV and from platoon to platoon. In addition to the information mentioned in Subsection II-A, velocity and acceleration information of the leader and preceding vehicles is also required to share with all member vehicles and the following vehicle, respectively, to maintain string stability of the platoon [77]. Thus, more communication structures are considered in platoon-based ADVNETs, including:

1) Intra-platoon communication structure [78], used for sharing information among AVs within the same platoon, can be further classified into three ones: leader-to-member (or member-to-leader) communication structure for sharing information between the leader vehicle and one of member vehicles [22], two-adjacent communication structure for sharing velocity and acceleration information [77], [79], and platoon-based multicast communication structure for improving the communication efficiency.
2) Inter-platoon communication structure is designed for sharing information among AVs within different platoons, such as sharing collision information from one platoon to its following platoons.

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[1] AutoNet system consists of infrastructure and cooperative vehicles, where the cooperative vehicles refer to the vehicles that are able to sense surrounding information and communicate with other cooperative vehicles for exchanging perception and commands to enable automated maneuvering.

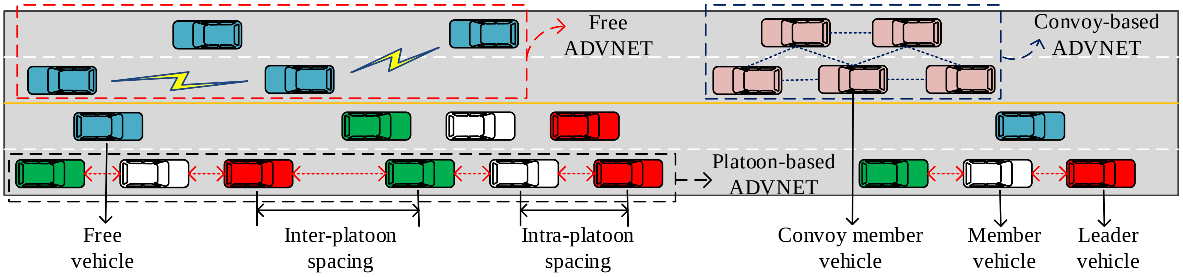

Figure 4. Illustration of normal and platoon-based ADVNETs.

Similar to the free ADVNETs, infrastructures would play the control role either for networks or platoons in most of platoon-based ADVNETs. Hence, infrastructures are usually considered to relay information for AVs in infrastructure-based environments [80], [81].

B. Technologies for ADVNETs

Several communication technologies have been considered to be applied in ADVNETs, including the ones that have been widely applied in MDVNETs, i.e., DSRC [9], [82], cellular [83], Wi-Fi [84], and White-Fi [85], and other short-range communication technologies, such as infrared and VLC. Among them, most of the long-range communications in ADVNETs and communications in the free ADVNETs are usually supported by the DSRC and cellular technologies, such as in [9], [82], [83]. Since the advantages, disadvantages, and challenges of DSRC, cellular, Wi-Fi, and White-Fi have been introduced in Section III, we will focus on the infrared and VLC in this subsection, which have been proposed mainly for ADVNETs even if they can be also used for MDVNETs.

Infrared (IR): It is one of the earliest technologies that uses light invisible to human, i.e., infrared light, to enable wireless communications on a line-of-sight (LOS) basis. It has been indicated in [16], [86] that infrared communication has high directionality, high confidentiality, and harmlessness. Considering roads are usually in line, communications among AVs can be achieved by an inexpensive infrared laser. Furthermore, the wavelength of infrared communications is much shorter than other wireless communications while it is with a potential of 1 Gbps data communication speed. Therefore, it is optimal for sharing large-volume data, such as multimedia entertainment information among AVs. Infrared lights have been used to measure the intra-platoon spacing to assist the gap control in [86]. However, infrared communications can only be used in some special scenarios, such as for two-adjacent communication structure in platoon-based ADVNETs, since the infrared light can only carry shorter than 10 meters and do not penetrate obstacles [86]. Furthermore, weather conditions are another challenge for infrared communications. Thus, in order to take the advantages while addressing related challenges, infrared communications are always combined with other communication technologies, such as DSRC, to support AVs' applications [16].

Visible light communications: It is a type of communication through visible light. Compared with other types of wireless communications, VLC have the following special importance advantages:

1) 360 Terahertz of license-free bandwidth within visible light spectrum can be tapped for wireless communications while avoiding interference from radio frequency (RF) signals. Therefore, it can address the scarcity of current RF spectrum to support the ever-increasing mobile data traffic demand. For example, VLC are used to backup DSRC communications to reduce the packet loss resulted from congestion in high vehicle density scenarios [87];
2) Existing research about VLC has shown that a very high data communication speed can be achieved by VLC (i.e., multiple Gbps in research and around 100 Mbps in IEEE 802.15.7 standard);
3) Low data rate transmission at 1000 and 2000 meters have been demonstrated for VLC, and a 50-100 meters communication range can be typically provided for vehicular networks. Moreover, by reusing existing lighting infrastructure to support communication, VLC can be deployed easily and inexpensively [17].

The above advantages have motivated works on tapping VLC for ADVNETs. For example, the feasibility of using VLC for sharing information among platoon members to support platoon control has been proposed in [88]. Similar to infrared communications, VLC signals cannot penetrate through most obstacles. Therefore, they can be only used for communications between two vehicles with LOS.

It should be noted that IR and VLC technologies can not only be used to support communications in ADVNETs but also in MDVNETs. For example, IR has been used in tolling applications [89]. Based on the light emitting diode (LED) headlamp, a demonstration system that uses VLC to support V2V communications has been proposed in [90].

V. CHALLENGES AND OPPORTUNITIES

Even though there has been a large amount of existing research for vehicular networks and many industrial products can be used to support vehicular communications, achieving efficient and reliable vehicular communications to support practical ITS applications still faces many challenges. Next, we will discuss the major challenges and opportunities.

A. Heterogeneous Driving Vehicular Networks

With the rapid development and gradual maturity of the autonomous driving technologies, AVs will prevail on the roads in the near future, resulting in scenarios where AVs and manually driving vehicles move on the roads simultaneously. In order to achieve information sharing among manually driving and autonomous vehicles, a HDVNET, consisted of both MDVNETs and ADVNETs, is in immediate need. That said, due to the vastly different QoS requirements and affecting factors of ADVNETs and MDVNETs as discussed in Section IV, the design of HDVNETs faces significant challenges, which will be discussed in this section.

It has been indicated that cooperative driving with ADVNETs is a promising technology to improve safe driving of AVs, especially in intersection scenarios. For example, through sharing real-time positions, velocity, and desired driving lane information among AVs within the same platoon, cooperation based safety driving patterns can be designed to help AVs to safely cross the intersection without traffic lights in [91]. However, how to help AVs and manually driven vehicles to cross intersections safely remains to be unsolved. In such scenarios, manually driven vehicles have to be controlled by drivers, resulting in human factors, and therefore, challenging the cooperative driving of AVs. Thus, designing an efficient and suitable communication scheme, i.e., scheduling which kind of information should be shared by which vehicle, to achieve cooperative driving of AVs and improve safe driving of manually driven vehicles is desired for some scenarios such as intersections.

In HDVNETs, AVs and manually driven vehicles have different information requirements both in message types and QoS requirements, which result in complex message structure. In [92], a novel beacon scheduling algorithm has been proposed to guarantee the reliable and timely dissemination of two types of beacon messages in HDVNETs, i.e., event-driven safety messages for manually driven vehicles and periodic beacon messages for cooperative driving of AVs. However, in most HDVNETs scenarios, message types are more complex than the one that has been considered in [92]. For example, when a special infotainment service (e.g., video) is required for vehicles in platoon-based HDVNETs, event-driven safety messages, periodic messages, and video information need to be shared to guarantee the string stability of platoon while ensuring the QoS requirement of this infotainment service. Moreover, the driving patterns of vehicles with level 2 and 3 autonomy need to be adjusted dynamically, which results in complicated road environment and challenges the adjustment of message structure. Hence, efficient communication structures and message dissemination schemes are required for different HDVNETs scenarios.

B. Security Issue

In addition to the security issue discussed in Subsection III-C for MDVNETs [93], there are further privacy and security related concerns in ADVNETs and HDVNETs [94]. To support autonomous navigation, AVs need to monitor the environment and collect detailed video/sound/sensor data, which renders them to potential privacy infringers [95]. Also, AVs should periodically share various types of information with other AVs to support cooperative driving, e.g., real-time positions, velocity, and acceleration. Enabling the availability of these types of information may comprise privacy of drivers or passengers. The adversaries can extract privacy information (such as where they are, where they frequently visit, and driving behavior-based insurance) about drivers, eavesdrop valuable information about the platoon/convoy, and falsify data to benefit themselves, e.g., in road toll collection [95], [96].

Since the final driving decisions in cooperative driving are made based on the shared information, security attacks either on the communication channel or sensor tampering significantly impact the safe driving [97]. Ensuring AVs' privacy and protecting communications from message falsification, message eavesdropping, radio jamming, and tampering attacks is important to cooperative driving. However, the algorithms used for current wireless communication security may not work well for ADVNETs and HDVNETs since lower latency is required by communications in cooperative driving of AVs. Moreover, due to the spontaneous short-lived interactions among moving vehicles, it is cumbersome to authenticate the interacting vehicles using traditional authentication factors. In order to reduce the end-to-end delay while guaranteeing the information privacy and security, group authenticated algorithms can be considered, especially for communications among vehicles within the same platoon or convoy, as well as for vertical handoff in heterogeneous ADVNETs and HDVNETs. For cluster-based MDVNETs and platoon/convoy-based ADVNETs, performing efficient mutual authentication in the formation stage of cluster/platoon/convoy and when a new vehicle is applying to join them, can reduce the impacts of authentication on information sharing in each cluster/platoon/convoy.

C. Machine Learning for Vehicular Communications

Recent advances in artificial intelligence have been widely regarded as the major driving force behind the trends of autonomous driving and the emerging ADVNETs investigated in Section IV. However, we have not included discussions on artificial intelligence for vehicular communications due to the page limit. In fact, artificial intelligence has been widely studied for intelligent transportation. Machine learning, in particular, has been proposed for general wireless networks [98], [99], [100] and to address the special requirements of vehicular communications [101], [102], [103]. For example, a novel deep-learning based method has been proposed in [104] to infer the traffic flow information from multiple sources of data for a wide variety of intelligent transportation related applications. A deep reinforcement learning approach has been proposed in [102] for dynamic centralized orchestration of networking, caching, and computing for vehicular networks whereas a distributed vehicular resource management scheme has been developed in [100] based on deep reinforcement learning. Besides, a fuzzy Q-learning based vertical handoff strategy for heterogeneous vehicular networks has been devised in [105], which ensures seamless mobility management without prior knowledge on handoff behavior.

Despite the strong potentials of applying machine learning in vehicular networks, as demonstrated by the above initial efforts, a number of challenges still remain. For instance, vehicular networks exhibit substantial differences from where machine learning has been traditionally applied (e.g., computer vision and speech recognition) including strong dynamics in wireless channels, network topologies, traffic flow, etc. How to efficiently learn and robustly predict such dynamics based on historical data for the benefit of reliable communications is still an open issue. In addition, data are naturally generated and stored across multiple units in the vehicular network, e.g., vehicles, road side units, and remote clouds. It is particularly interesting to investigate whether traditional centralized machine learning algorithms can be adapted to work efficiently in a distributed manner. In particular, the overhead incurred by information sharing for collective intelligent decision making in learning-enabled vehicular networks needs to be explicitly taken into account. Another major consideration is that most current state-of-the-art learning algorithms, especially deep learning, involves heavy use of high-performance computing facilities, such as power graphics processing units (GPUs). Such strong computational power is hardly available aboard vehicles and because of the strict end-to-end latency requirements of vehicular networks, leveraging powerful servers housed remotely will be rather limited. As a result, special treatment is needed to trim down the complexity of various learning algorithms to make them applicable in vehicular networks. We refer interested readers to [101] for detailed discussions on the challenges and opportunities of applying machine learning in vehicular networks.

D. SDN for Vehicular Communications

As an emerging network paradigm, software defined networking (SDN) has been increasingly applied to integrate multiple wireless communication technologies to support vehicular communications [106], [107], [108]. In SDN, through decoupling the control plane from data plane, the deployment of control, processing entities, and traffic forwarding can be permitted independently, and therefore, significantly simplifying network management to enable programmable and flexible for vehicular networks. Moreover, resource utilization can be improved by the logically centralized controller. Due to the potential benefits brought by SDN, some SDN-enabled architectures have been proposed in existing researches. For example, a SDN-based architecture has been proposed for vehicular communications in [106], in which, bandwidth resources are managed in a centralized way to provide an agile configuration capability. In [108], a SDN-based application-layer scheme has been proposed to manage the available bandwidth resources from both cellular and Wi-Fi networks. However, implementing SDN-enabled vehicular architecture is still challenging in practices. In SDN-based architectures, the SDN controllers make control decisions based on a globe view over the network. That is, some incentives should be provided by the network to motivate vehicles to transfer information to SDN controllers for obtaining the globe view [107]. Moreover, it is of important to protect the SDN controllers from threats to ensure the security of the network globe view information.

E. Other Issues

Due to the technology of self-driving, ADVNET/HDVNET can be regarded as a typical convergence of the cloud computing and Internet of things (IoT) [109]. From the macro aspect, cloud computing provides map service (e.g., high-definition map) and information about road conditions to AVs to support safe navigation. From the micro aspect, the real-time moving states (e.g., direction, speed, and acceleration) of AVs are determined based on the sensed dynamic road surrounding information and the communicated information from other vehicles.

There are some other issues that should be considered in MDVNETs, ADVNETs, and HDVNETs. Firstly, mmWave and VLC communication technologies have been considered to support vehicular networks [42], [87], [90]. However, how to address the potential issues caused by high mobility and harsh weather conditions still needs further investigation and test. Moreover, in heterogeneous vehicular networks with one of or both of mmWave and VLC communication technologies, finding a criterion for network selection among mmWave/VLC and other communication technologies is not an easy work. Secondly, to achieve efficient cooperative driving, information management and cooperative control should be considered globally in ADVNETs and HDVNETs, which results in complicated allocation issue among storage and computing resources of each vehicle, especially in scenarios with heterogeneous QoS requirements. Thirdly, with the increase of vehicle users and mobile data traffic demand, the limitation of resources (including communication, computing, and storage resources) is a critical issue. In addition to the interworking of two communication technologies, enabling two or more communication technologies can be contributed while it also makes the resource allocation more complicated. A promising technology can be applied to address this issue is multi-access edge computing (MEC), which can not only enable multiple communication technologies but also move the computing and storage resources to base stations to enable computing and storing capabilities at the edge of core networks. Such that, combining with SDN-enabled controllers, efficient resource management can be achieved, hot information (e.g., maps and some hot videos) can be cached in the MEC servers to reduce the communication time, and some computing tasks of AVs can be offloaded to the MEC serviens.

VI. CONCLUSIONS

In this paper, we have provided a comprehensive survey of vehicular communications from the network layer perspective, including communications in MDVNETs and ADVNETs. Advantages and disadvantages of different communication technologies for these two types of vehicular networks have been analyzed. Due to high mobility and complicated communication environment, challenges confronted with vehicular networks are different when supporting different applications. Recent research works addressing these challenges have been discussed, including routing protocols for exchanging different messages, efficient handoff strategies to benefit users or networks, and suitable communication structures according to the applied traffic management strategies. We have further identified several main under-explored issues in MDVNETs, ADVNETs, and HDVNETs, and suggested some potential solutions.

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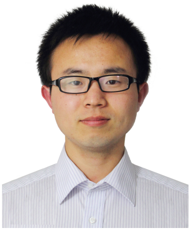

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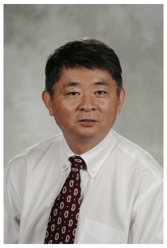

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