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# Infotainment and road safety service support in vehicular networking: From a communication perspective[☆]

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ABSTRACT

Vehicular ad hoc networking is an emerging technology for future on-the-road communications. Due to the virtue of vehicle-to-vehicle and vehicle-to-infrastructure communications, vehicular ad hoc networks (VANETs) are expected to enable a plethora of communication-based automotive applications including diverse in-vehicle infotainment applications and road safety services. Even though vehicles are organized mostly in an ad hoc manner in the network topology, directly applying the existing communication approaches designed for traditional mobile ad hoc networks to large-scale VANETs with fast-moving vehicles can be ineffective and inefficient. To achieve success in a vehicular environment, VANET-specific communication solutions are imperative. In this paper, we provide a comprehensive overview of various radio channel access protocols and resource management approaches, and discuss their suitability for infotainment and safety service support in VANETs. Further, we present recent research activities and related projects on vehicular communications. Potential challenges and open research issues are also discussed.

## 1. Introduction

Vehicular transportation is one of the crucial means of transportation around the world. Regardless of its convenience, there are more than one million human casualties due to vehicle crashes worldwide every year [1]; therefore, road traffic safety remains a big concern in our daily life. Over the years, governments and automotive industries have been working together to improve road traffic safety through various intelligent transportation system (ITS) initiatives. For example, in October 2008, the United States Department of Transportation laid out an aggressive goal of reducing vehicle crashes by 90% by 2030 [2]. Similar efforts have also been made in Europe and Asia [3,4]. To realize the vision of accident-free transportation, automobile manufacturers have been striving to assemble vehicles with sophisticated hardware components (such as sensors and cameras) and software programs (such as image recognition) [5]. Various active and passive safety measures intended to reduce the number and severity of accidents are also implemented in today's vehicles (e.g., GM OnStar automatic crash response system [6]).

To further enhance transportation safety, communication-based safety applications empowered by vehicular ad hoc networking have recently attracted a lot of attention from industry and academia [7,8]. Via inter-vehicle communications, drivers can be informed of crucial traffic information such as treacherous road conditions and accident sites by

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communicating with each other and/or with the roadside infrastructure. With better knowledge of traffic conditions, it is plausible that the problem of accidents can be alleviated. Traffic monitoring and management can also be facilitated by vehicular communications (e.g., vehicle platooning [9,10]) so as to elevate traffic flow capacity and improve vehicle fuel economy. On the other hand, convenience and commercial in-vehicle applications are envisioned to be supported in future automobiles, for example, live video streaming, file sharing, remote vehicle diagnostics, traffic jam notification, mobile office, advertisement, and gaming [11–13]. Clearly, these on-the-road data and entertainment services can greatly increase vehicle occupants' productivity, satisfaction, and/or comfort. In short, communication-based automotive applications are promising in providing safer and more fuel efficient use of vehicles, increasing vehicle throughput on the road (i.e., vehicles per lane per hour), and supporting diverse in-vehicle infotainment applications.

### *1.1. Architecture of vehicular networking*

Vehicular ad hoc networks (VANETs) belong to a general class of mobile ad hoc communication networks with fast-moving nodes (i.e., vehicles). In specific, a VANET consists of (1) on-board units (OBUs) built into vehicles and (2) roadside units (RSUs) deployed along highways/sidewalks, which facilitates both vehicle-to-vehicle (V2V) communications between vehicles and vehicle-to-infrastructure (V2I) communications between vehicles and RSUs. An illustration of a functional VANET architecture is given in Fig. 1. Via wireless communication links, each vehicle communicates with nearby vehicles in a highly dynamic ad hoc networking environment. Traffic-related information can be exchanged via V2V communications (e.g., through periodic beaconing) to allow drivers to be better aware of surrounding traffic conditions. In case of emergency, event-driven messages can be generated and disseminated to the vehicles in the zone of danger (or zone of relevance, ZOR) [14]. Peer-to-peer applications such as information sharing and gaming can also be supported through V2V communications.

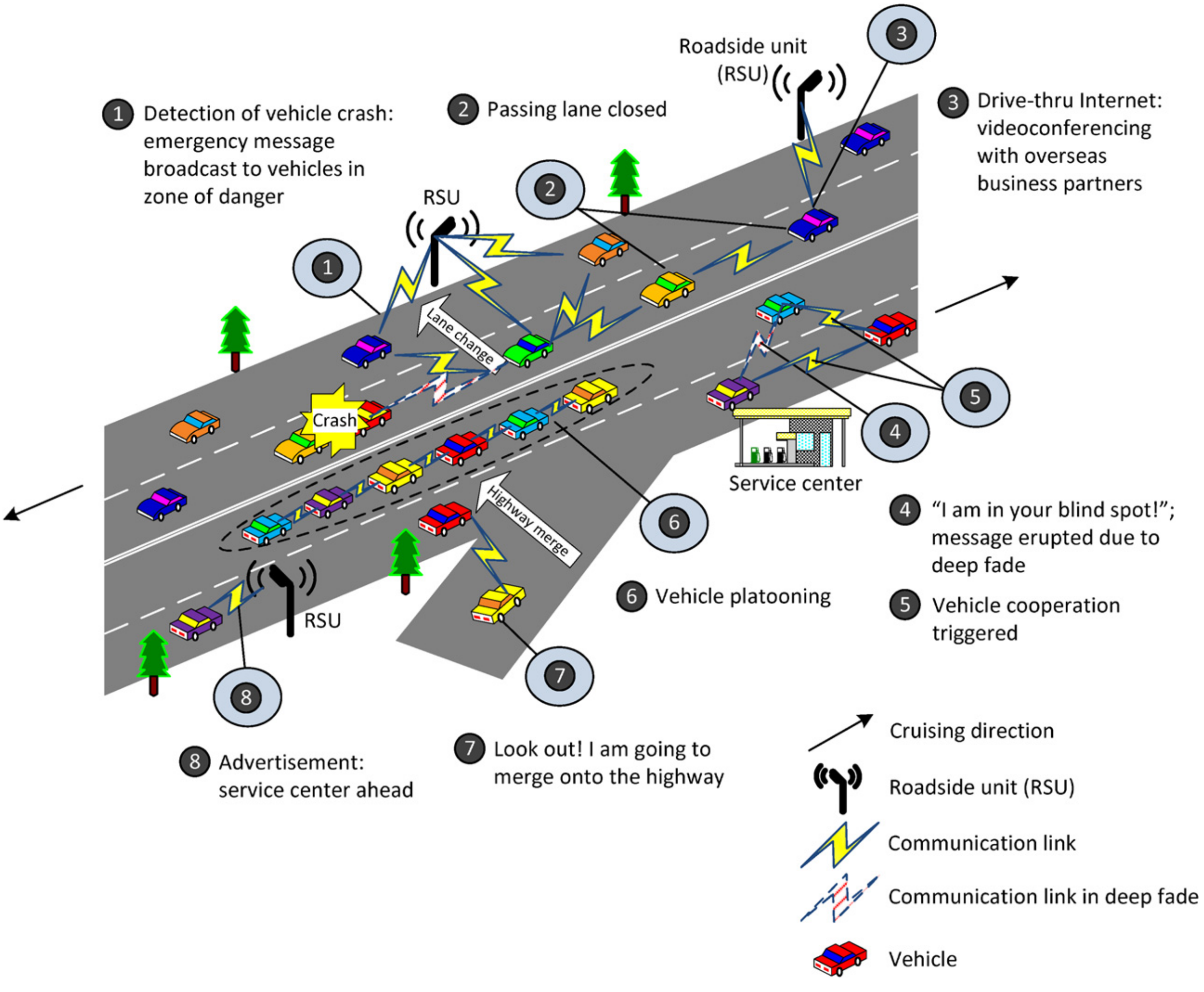

**Fig. 1.** An illustration of a VANET.

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In the presence of RSUs, not only can road and traffic conditions (e.g., sharp turns ahead) be broadcast to a driver, but *drive-thru* Internet access (e.g., [15]) can also be made possible for other occupants in the vehicle. Information from a remote data server can be delivered to a vehicle through the Internet backbone, and vice versa. Further, the communication service area can be enlarged with the RSUs in place. Through V2I communications, infotainment services (such as advertisements, parking lot availability, and automatic tolling) can also be provided with ease.

To enable communication-based safety and infotainment services, the Federal Communications Commission (FCC) in the United States has allocated 75 MHz of licensed spectrum at 5.9 GHz as the dedicated short range communication (DSRC) band for ITSs [11]. In Europe, different frequency bands are used for vehicular communications, for instance, unlicensed frequency band at 2010–2020 MHz is used in Fleetnet [16]. Recently, the European Telecommunications Standards Institute (ETSI) has also allocated a radio spectrum of 30 MHz at 5.9 GHz for ITSs. To increase spectrum utilization and improve quality-of-service (QoS) (e.g., network throughput, packet dropping rate, end-to-end delay, fairness, etc.), multiple channels are expected to be employed in vehicular communications. Location information of vehicles is generally available, thanks to the global positioning system (GPS). End-to-end paths for information delivery can then be established via location-aware V2V and/or V2I transmission. In short, this emerging vehicular networking paradigm is expected to enable a plethora of communication-based automotive applications in the near future, ranging from seamless inter-vehicle video streaming to road traffic monitoring to collision warning/avoidance.

### *1.2. Potential applications of VANETs*

Potential applications in a vehicular environment can be divided into three main categories [17,18], namely, (1) infotainment delivery, (2) road safety, and (3) traffic monitoring and management:

- *Infotainment delivery*: The gist of infotainment applications is to offer convenience and comfort to drivers and/or passengers. For example, Fleetnet [16] provides a platform for peer-to-peer file transfer and gaming on the road. A real-time parking navigation system is proposed in [19] to inform drivers of any available parking space. Digital billboards for vehicular networks are proposed in [20] for advertisement. Internet access can be provided through V2I communications; therefore, business activities can be performed as usual in a vehicular environment, realizing the notion of mobile office [21]. On-the-road media streaming between vehicles also can be available [22,23], making long travel more pleasant.
- *Road safety*: Safety applications are always paramount to significantly reduce the number of accidents, the main focus of which is to avoid accidents from happening in the first place. For example, TrafficView [24] and StreetSmart [25] inform drivers through vehicular communications of the traffic conditions in their close proximity and farther down the road. Vehicle platooning is another way to improve road safety. By eliminating the hassle of changing lane and/or adjusting speed, platooning allows vehicles to travel closely yet safely together [9]. Fuel economy can also benefit from reduced aerodynamic drag[1] as a vehicle headway is tightened (e.g., the spacing can be less than 2 m [26]). Together with adaptive cruise control assisted by V2V communications, the problem of vehicle crashes due to human error can be alleviated.[2]
- *Traffic monitoring and management*: Traffic monitoring and management are essential to maximize road capacity and avoid traffic congestion. Crossing intersections in city streets can be tricky and dangerous at times. Traffic light scheduling can facilitate drivers to cross intersections. Allowing a smooth flow of traffic can greatly increase vehicle throughput and reduce travel time [27]. A token-based intersection traffic management scheme is presented in [28], in which each vehicle waits for a token before entering an intersection. On the other hand, with knowledge of traffic conditions, drivers can optimize their driving routes, whereby the problem of (highway) traffic congestion can be lessened [29].

In this paper, we present how vehicular networking and communication technologies can support in-vehicle infotainment and road safety services, mainly focusing on research challenges, issues, and techniques at the link layer of the VANET protocol stack. For research issues at the network layer such as routing protocols and load balancing techniques, interested readers are referred to [30,31] and the references therein.

### *1.3. Research challenges in VANETs*

In order to support diverse on-the-road applications in a vehicular environment, efficient and effective VANET-specific radio resource management strategies are required, including capacity enhancement, interference control, call admission control (CAC), bandwidth reservation, packet loss/delay reduction, medium access control (MAC), packet scheduling, fairness assurance, etc. Despite the fact that vehicles (nodes) are organized mostly in an ad hoc manner, VANETs are quite different from traditional mobile ad hoc networks (MANETs) in terms of the network architecture, user mobility pattern, energy constraint, and real-life application scenario. It has been demonstrated that directly applying the existing approaches designed for MANETs to large-scale VANETs with fast-moving vehicles can be ineffective and/or inefficient [32]. To achieve

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[1] In fluid dynamics, aerodynamic drag refers to forces that oppose the relative motion of an object through the air.

[2] In vehicle platooning, the maximum relative speed between vehicles is limited due to a very small headway, which greatly reduces the impact of a crash even in the case of extreme accelerations or decelerations [26].

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success in a vehicular environment, it is imperative to devise new yet effective strategies tailored for VANETs. Following are some of key research challenges in VANETs:

- *Frequent link disconnections*: Ascribed to high mobility of vehicles, the topology of a VANET changes rapidly from time to time, causing intermittent communication links. Unlike nodes in MANETs, vehicles generally travel at much higher speeds, especially on highways (i.e., over 100 km/h). As such, network resources allocated to vehicles can become futile due to frequent link disconnections between a source and a destination [33]. Suppose a sender travels at 120 km/h (or 75 miles/h) while its corresponding receiver travels at 100 km/h (or 62 miles/h) in the same direction, and the transmission range is 300 m [11]. The communication between both vehicles can last only for about a minute. Should the vehicles travel in opposite directions, a communication link can exist for less than 5 s. Thus, connectivity analysis and mobility-aware resource management are important.
- *Highly dynamic spatial–temporal traffic conditions*: The vehicle density of a VANET can vary from very small (e.g., in rural areas) to very large (e.g., in a traffic jam). The vehicle traffic flow at one location can also be highly dynamic, primarily contingent upon the time of the day [34]. Addressing the issue of a fast-varying spatial–temporal traffic condition is certainly imperative yet challenging. Particularly in the early stage of VANET deployment, it is anticipated that only a small fraction of vehicles are VANET-enabled. Such low vehicle participation can possibly exacerbate the problem of frequent network fragmentation, whereby the reachability (or effective diameter) of a VANET is capped. Another concern is the impact of dynamic traffic variations on wireless channel impairments such as slow and fast fading. A vehicular environment can exhibit fast fading in situations with a low vehicle density, where vehicles can travel at a very high speed. Slow fading, on the other hand, can be experienced in situations with a high vehicle density such as in a traffic jam. Channel conditions can vary greatly in both spatial and temporal domains and, therefore, adaptive channel access protocols with resistance to channel impairments are of main importance.
- *Heterogeneity of data dissemination*: VANETs are expected to support a wide range of road safety and infotainment applications. Generally speaking, road safety applications require low latency and high reliability, whereas throughput, packet loss, resource utilization, and fairness are common performance measures for infotainment applications. In light of heterogeneous information services, channel access protocols and network resource allocation strategies should be adaptive to ensure efficient, orderly, and fair communications among all the vehicles on the road. In VANETs, it is clear that safety-related (infotainment) messages should be assigned high (low) priority. Devising an effective and efficient communication approach to guarantee vehicle safety yet offer quality infotainment services in a highly dynamic vehicular environment is necessary.

It should be noted that link-layer protocols and techniques alone cannot completely solve the aforementioned VANET-specific technical challenges. A holistic solution should be formulated by considering the features of different layers in the VANET protocol stack. Here, this paper is intended to provide an overview on MAC-layer channel access protocols and resource management techniques, whereby some of the research challenges in VANETs can be dealt with or at least alleviated to a certain degree.

### 1.4. Unique characteristics of VANETs

Despite their research challenges presented in Section 1.3, VANETs possess network unique characteristics on which we can leverage. Three important characteristics of VANETs are given as follows:

- *Somewhat predictable network topology*: Although vehicles in VANETs move at a very high speed, the movement of each vehicle is restricted to thoroughfares such as highways and city streets. With the knowledge of roadway geometry, the mobility pattern of vehicles can be predicted (within a certain time interval) to a certain extent. For example, at an intersection, a vehicle can go straight, left turn, left right, or make a U-turn, if allowed. In MANETs, on the other hand, nodes can move freely in an open space, since there is no restriction on mobility. With a relatively predictable network topology, traffic load estimation in VANETs can be facilitated; yet, how to exploit this VANET-specific mobility information is of great interest.
- *Availability of location information*: Satellite navigation systems are becoming more prevalent in vehicular transportation these days. It is expected that future automobiles will be equipped with a GPS receiver, in which vehicle occupants can locate themselves (with an error up to a few meters). Making good use of location information in communication service provision not only can reduce delivery latency of message dissemination (i.e., for road safety services) but can increase system throughput (i.e., for infotainment services).
- *No strict energy consumption constraints*: Minimizing power consumption has been one of the key objectives in MANETs with battery-powered wireless nodes [35]. Energy-efficient protocols are, therefore, crucial to not only increase the lifespan of an MANET but also improve throughput performance. In VANETs, however, communication transceivers mounted in vehicles do not have strict energy consumption constraints. The rationale is that a power supply is usually ample (in comparison with battery-powered handsets) when a vehicle is running on fuel. In addition, the processing capability of a vehicle is expected to be relatively more powerful than that of a nomadic/mobile user in MANETs. Sophisticated algorithms of high performance can be implemented in a vehicular environment.

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### 1.5. Paper organization

In this paper, we present a systematic overview of a number of communication solutions for infotainment and road safety service support in VANETs. The remainder of this paper is organized as follows. In Sections 2 and 3, we provide a comprehensive study on various radio resource management approaches for on-the-road service support from both perspectives of a user and a system, respectively. In Section 4, recent research projects on VANETs are presented. In Section 5, open research issues are discussed. Finally, concluding remarks are given in Section 6.

General readers can focus on Sections 2.1 and 3.1 to grasp basic understandings of the research issues on user-level channel access and system-level resource management, respectively, and then proceed to Sections 4–6. For detailed discussions on infotainment and road safety service support from a communication perspective, interested readers are referred to Sections 2.2, 2.3, 3.2, 3.3, and the references therein.

## 2. On-the-road service support in VANETs: from a user's perspective

### 2.1. Research issues

Generally speaking, MAC is essential in wireless communication systems to define the way of how wireless nodes should contend for and share network resources. Without proper MAC-layer coordination, packet collisions can occur, thereby reducing throughput, increasing packet dropping rates, and making poor use of the scarce radio resources. In case of imminent traffic accidents, failure in delivering emergency messages to target vehicles in a timely manner can lead to catastrophic consequences. Despite the fact that there exists a very rich body of research work on MAC protocols in the literature [35–37], most of them are not suitable for a vehicular environment due to the unique network characteristics and design objectives of VANETs. On the other hand, since VANETs are likely to be permanently deployed, system-level resource management is imperative. In particular, efficient network planning and effective system performance enhancement techniques should be developed, whereby the performance of both infotainment and safety services can be maximized. In this section, we provide an overview on various channel access candidates for on-the-road service support in VANETs from an end-user's perspective, while system-level resource management from a system's (service provider's) perspective is discussed in Section 3. Since VANETs are expected to support different types of infotainment and safety applications, here we further divide the channel access candidates according to their underlying design objective and methodology into two categories: (1) thin infotainment service support; and (2) rich infotainment and safety service support. Notice that *thin* infotainment applications refer to non-real-time traffic and real-time traffic without stringent QoS requirements, while *rich* infotainment applications require fine-grain QoS support. Fig. 2 gives a taxonomy of existing communication approaches for on-the-road service support discussed in the following.

In wireless communication systems, QoS performance metrics can be classified into three categories [38]: (1) bit-level QoS; (2) packet-level QoS; and (3) call-level QoS. Different applications usually require different degrees of QoS satisfaction at different levels. For example, real-time applications (such as voice conferencing) are delay-sensitive, where their packets should be transmitted within a delay bound with a low packet dropping rate but can tolerate a high bit error rate. By contrast, data applications (such as peer-to-peer file sharing) are mostly delay-insensitive, but require very high transmission accuracy (i.e., a low bit error rate). Since this paper focuses on MAC-layer channel access and resource management, we are interested in packet-level QoS performance metrics such as throughput, packet dropping rate, packet collision, delay, delay jitter, and fairness.

### 2.2. Thin infotainment service support

One minimal requirement of MAC for thin infotainment applications in VANETs is to support best-effort services such as advertisement, web browsing, and file sharing. Best-effort MAC protocols are desired for low-cost VANETs with

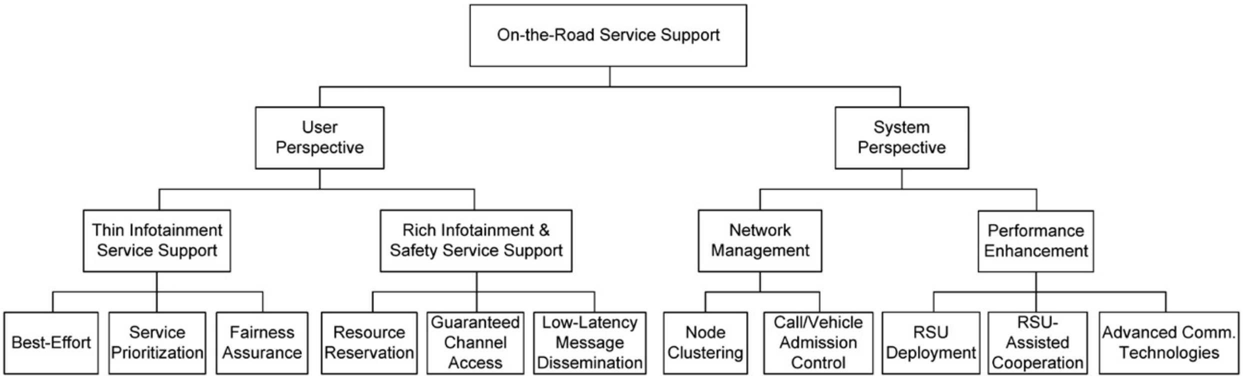

**Fig. 2.** Taxonomy of existing communications approaches for on-the-road service support in VANETs.

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homogeneous information services. In the presence of heterogeneous information services, service differentiation is vital by assigning different priorities to different traffic types. For example, video streaming service is assigned high priority, whereas email service is assigned low priority. To guarantee a fair share of resources distributed to every vehicle, fair channel access protocols are necessary.

### 2.2.1. Best-effort channel access

The design goal of best-effort channel access is throughput increase, where packet collisions should be kept to a minimum. To support best-effort services, IEEE 802.11a (or IEEE 802.11b) is the most widely employed standard in wireless local area networks (WLANs) [39]. In light of its popularity, this legacy MAC protocol has been endorsed and adopted in the DSRC standard for wireless access in a vehicular environment (WAVE), referred to as IEEE 802.11p [40]. Note that IEEE 802.11p standard also adopts enhanced distributed channel access originally specified in IEEE 802.11e, to be discussed in Section 2.2.2. The medium access method in both DSRC and IEEE 802.11a standards is based on the notion of carrier sense multiple access (CSMA). In specific, if a channel is sensed free, a vehicle transmits its packets; otherwise, it defers its packet transmission. The caveat of applying CSMA to large-scale multi-hop wireless networks such as VANETs is the problems of hidden terminals (which cause transmission collisions) and exposed terminals (which unnecessarily suppress radio frequency reuse), thereby causing system performance degradation [36]. To improve throughput in VANETs, a request-to-send (RTS)/clear-to-send (CTS) handshake can be employed. This RTS/CTS dialogue is often used before the actual information exchange. A sender first sends an RTS frame to a receiver. Upon successful reception of the RTS frame, the receiver replies with a CTS frame. All neighboring vehicles hearing either the RTS or CTS frame defer their packet transmission. As such, the hidden and exposed terminal problems can be alleviated. Many MAC protocols following the aforementioned medium access mechanism have been proposed in the literature, for example, CSMA with collision avoidance (CSMA/CA) [39], floor acquisition multiple access (FAMA) [41], and receiver-initiated multiple access with simple polling (RIMA-SP) [42]. To mitigate the problem of inter-symbol interference due to a large delay spread caused by the transmission medium, the symbol duration used in the aforementioned best-effort channel access schemes can be increased (e.g., the symbol duration in the IEEE 802.11p/WAVE standard is doubled compared to the legacy IEEE 802.11a standard for WLANs [40]).

Another effective way to avoid packet collisions in VANETs is through signal jamming. In receiver-initiated busy tone multiple access (RI-BTMA) [43], a receiver transmits an out-of-band busy tone signal during the process of packet reception. The busy tone not only can act as an acknowledgement to a sender's transmission, but also can stop potential hidden terminals from transmitting. In hindsight, busy-tone aided MAC has not been as popular as its CSMA-based counterparts, since energy consumption is one of the key issues in most traditional wireless networks such as MANETs and sensor networks. As discussed in Section 1.4, vehicles do not have strict energy consumption constraints; thus, busy-tone aided MAC protocols can be viable candidates for practical implementation in VANETs.

Being the first MAC protocol with random access proposed for packet radio networks, (slotted) ALOHA has recently been suggested as a potential MAC candidate for VANETs (e.g., in Fleetnet [16]). To enhance throughput, reservation-ALOHA (R-ALOHA) [44] allows vehicles to reserve certain timeslots for their packet transmission, reducing the overhead introduced by subsequent channel contention. Reliable R-ALOHA (RR-ALOHA) [45,46] further improves R-ALOHA by eliminating the notorious hidden terminal problem. In the RR-ALOHA protocol, each vehicle disseminates its transmission schedule to all the vehicles in its two-hop neighborhood. One drawback of RR-ALOHA is that a great deal of signaling overhead is needed for every vehicle to maintain up-to-date information of the transmissions of its two-hop neighbors. Nonetheless, the idea of bandwidth reservation suggested in RR-ALOHA is a cornerstone towards fine-grain QoS assurance for rich infotainment applications, to be discussed in Section 2.3.1.

In short, all of the aforementioned CSMA-based, busy tone-aided, and ALOHA-like MAC protocols can be applied to VANETs with low- and moderate-speed vehicles; yet, applying these protocols to highly mobile vehicles can be ineffective due to severe channel impairments, and more research is needed to address the issue of high mobility. Besides, priority is not considered in the best-effort channel access protocols. To facilitate service differentiation in VANETs with heterogeneous information traffic, packet transmission prioritization is indispensable, meaning that higher (lower) priority is assigned to more (less) important traffic classes, discussed in Section 2.2.2.

### 2.2.2. Service prioritization

One way to achieve service differentiation is to prioritize the channel access for various traffic types. In the IEEE 802.11e standard [47], an enhanced distributed channel access (EDCA) scheme is used in order to grant *statistical* priority. In fact, the EDCA mechanism is implemented in the MAC extension layer of the IEEE 802.11p/WAVE standard [11]. Different traffic flows are classified into different access categories (ACs). Traffic in a higher-priority AC is assigned a smaller contention window size and shorter arbitration inter-frame space (AIFS). Suppose there are $K$ traffic classes. Traffic class $j$ $(1 \le j \le K)$ is assigned an AIFS value AIFS[$j$], where AIFS[1] $<$ AIFS[2] $< \cdots <$ AIFS[$K$]. As such, those higher-priority packets are more likely to win a contention, realizing the notion of service differentiation. The dynamics of channel access in EDCA are shown in Fig. 3. Although diverse infotainment services can be efficiently differentiated, EDCA is shown to be ineffective in supporting delay-sensitive applications (e.g., interactive gaming and safety message dissemination, to be discussed in Section 2.3) due to the randomness of its binary backoff mechanism [36]. Recently, a number of research works have been presented to enhance the performance of EDCA for VANETs. In [48], a polling-based MAC protocol is proposed to alleviate the problem of priority reversal. Proposed in [49] is a distributed beaconing scheme to facilitate the topology control and link-level synchronization

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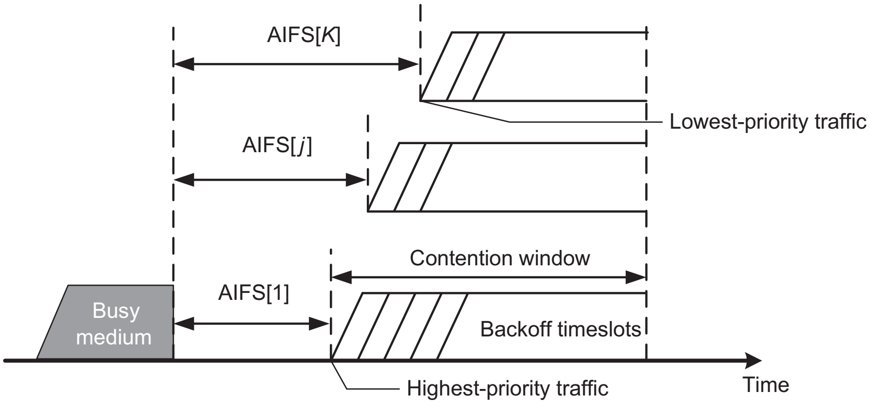

**Fig. 3.** Channel access for different traffic types in EDCA.

in VANETs. VMESH [50] adopts the EDCA mechanism but employs multiple channels for packet transmission, thereby enhancing system throughput. In general, the problem of optimal channel allocation is NP-hard, even in static wireless networks [51,52]. In large-scale VANETs with fast-moving vehicles, how to allocate channels such that frequency reuse can be maximized in a distributed fashion remains an open research issue. A hybrid MAC protocol is proposed in [23] to provide opportunistic access for streaming media and contention-based access for best-effort traffic in VANETs.

To guarantee near-absolute service differentiation in VANETs supporting multimedia applications with different QoS requirements, a control-theoretic packet scheduling tailored for vehicular communications is proposed in [53]. The packet scheduling is formulated as an optimal control problem with respect to the characteristics of VANETs. QoS differentiation is parametric, which can be achieved simply by solving a constrained quadratic optimization problem iteratively. This control-based scheduling approach can also be implemented on top of the existing EDCA mechanism in the IEEE 802.11p/WAVE standard to support delay-sensitive traffic. The only pitfall is that solving an optimal control problem can be computationally expensive. In a highly dynamic vehicular environment, whether or not employing control-based packet scheduling for service differentiation is preferred needs further investigation.

As seen, packet prioritization is necessary to achieve service differentiation in VANETs with heterogeneous information flows. With no consideration of fairness, some low-priority services can be starved in the presence of too many high-priority services. To lessen the problem of transmission starvation, fairness assurance should be taken into consideration when designing a channel access protocol.

### 2.2.3. *Fairness assurance*

Fairness is an important performance measure to gauge how fairly network resources are shared by wireless nodes. It is well-known that the IEEE 802.11a (CSMA/CA) MAC protocol cannot achieve satisfactory fairness performance, due to its binary exponential backoff mechanism [54]. In VANETs with substantial disparity in vehicle speed and hence connection lifetime, the fairness performance of the IEEE 802.11p/WAVE MAC protocol designed for VANETs is anticipated to be even worse. To alleviate the unfairness problem, one feasible solution is to adjust the parameters in the backoff procedure such as the size of a contention window. A CSMA/CA-based MAC protocol for VANETs with fairness consideration is proposed in [55]. This protocol leverages the fact that vehicles traveling at a higher (lower) speed have less (more) time to access the channel. To assure fairness, the contention window size of each vehicle should hinge upon its velocity. In other words, the higher the velocity of a vehicle, the smaller its contention window size. A similar approach is proposed in [56], in which vehicles with less remaining connection time are assigned higher priority for channel access. This packet scheduling approach also takes into account the mobility of vehicles, the number of user requests, and the staleness of traffic data. On the other hand, fuzzy logic can be used to devise fair channel access protocols of low computational complexity. Proposed in [57] is an adaptive contention-based MAC protocol driven by a set of fuzzy logic rules in order to improve fairness among vehicular nodes.

In brief, best-effort channel access is essential to enable basic infotainment service without QoS requirements. Service differentiation is required to prioritize heterogeneous thin infotainment applications. To fairly distribute resources to every vehicle, channel access protocols with fairness consideration are needed. Nonetheless, to achieve fine-grain QoS (e.g., a low packet dropping rate) for rich infotainment applications and guaranteed access for life-critical road safety applications with stringent delay demands, MAC-layer resource reservation is fundamental. Plus, the availability of location information in a vehicular environment can be leveraged to better support road safety applications.

## 2.3. *Rich infotainment and road safety service support*

In addition to thin in-vehicle infotainment services, future VANETs are expected to support a variety of rich infotainment and road safety applications, ranging from interactive gaming to accident avoidance warning. These applications have

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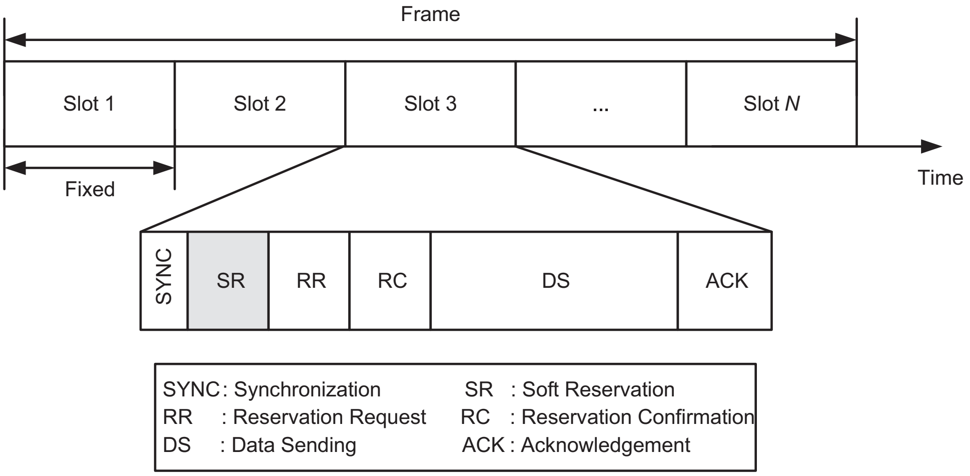

**Fig. 4.** Frame structure of SRMA/PA.

stringent QoS requirements such as delivery latency and reliability, meaning that the channel access methods presented in Section 2.2 are no longer applicable. To all intents and purposes, resource reservation is the rudimentary yet core element to the success in fine-grain QoS assurance (in terms of packet dropping rate and message dissemination latency) for rich infotainment and safety service support. To further guarantee the effectiveness of road safety measures, contention-free channel access should be granted for periodic traffic-related message dissemination, while reliable end-to-end packet transmission with minimal latency should be provided for highly delay-sensitive life-critical emergency messages.

### 2.3.1. *Resource reservation via contention*

Channel contention is a commonly used way to realize resource reservation [36]. If its reservation request is acknowledged, a vehicle can reserve a certain amount of resources (e.g., bandwidth, frequency channels) for its subsequent packet transmission. In soft reservation multiple access with priority assignment (SRMA/PA) [58], resources can be reserved by both real-time traffic and non-real-time traffic through successful contention attempts. Unlike RR-ALOHA where there is no service differentiation, the SRMA/PA protocol allows higher-priority traffic sources (i.e., with real-time packets) to seize the resources already reserved by lower-priority traffic sources (i.e., with non-real-time packets). The frame structure of SRMA/PA is depicted in Fig. 4. This soft reservation approach is shown promising in effectively capping a packet dropping rate for real-time traffic via resource reservation and supporting service differentiation via traffic prioritization. The SRMA/PA protocol is fully distributed yet requires accurate time synchronization. Since future automobiles are expected to be equipped with a positioning system (such as the GPS) which facilitates accurate time synchronization, SRMA/PA can be a viable solution for rich infotainment service support. On the other hand, sustainable resource reservation is particularly important but challenging in highly dynamic VANETs with frequent link disconnections. To improve link connectivity, a dynamic transmission-range-assignment (DTRA) algorithm driven by traffic flow theories is proposed in [59]. With the knowledge of vehicle density, each vehicle can adjust its transmission range to prolong its link connection, thereby improving the sustainability of resource reservation.

In general, resource reservation via contention has been shown promising in providing fine-grain QoS support in terms of packet dropping to real-time traffic such as rich infotainment services. This methodology, however, can be less effective in supporting life-critical road safety applications. Highly delay-sensitive traffic-related messages should be guaranteed access as per request such as periodic beaconing for *active safety*, and disseminated without access latency such as emergency message dissemination for *passive safety*.[3]

### 2.3.2. *Guaranteed channel access*

To achieve active safety, contention-free channel access is necessary, whereby traffic-related messages can be broadcast reliably to the vehicles of interest. With collision-free periodic beaconing, each vehicle can update and monitor the status of its neighboring vehicles such as position, speed, and acceleration. To realize contention-free guaranteed channel access, centralized resource reservation approaches tailored for active road safety have been proposed in the literature [60,61]. In [60], a controlled vehicular Internet access protocol with QoS support (CVIA-QoS) is proposed to first guarantee the QoS requirements (such as packet loss and delay demands) of real-time traffic (i.e., rich infotainment and safety applications) and

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[3] In automotive industry, road safety measures can be classified into two groups: (1) active safety (e.g., turn signals) and (2) passive safety (e.g., airbags). Here, we adopt a similar classification for road safety service support in VANETs from a communication perspective. The gist of communication-based *active* safety measures is to avoid crashes from happening in the first place via contention-free periodic beaconing, whereas that of communication-based *passive* safety measures is to keep the damage of an (imminent) accident to a minimum via efficient emergency message dissemination.

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then maximize throughput by allocating any remaining bandwidth to best-effort traffic. Similar to CVIA-QoS, proposed in [61] is another controlled channel access protocol called coordinated external peer communication (CEPEC). Thanks to the salient features of IEEE 802.16 employed, it is shown that CEPEC is of low complexity and can be used to support delay-sensitive safety applications. Nonetheless, the aforementioned research work focuses on V2I communications. To enable guaranteed channel access in V2V communications, token ring-based MAC can be employed to broadcast traffic-related messages periodically without contention. Proposed in [62] is an example of a token ring-based MAC protocol designed for V2V communications to support safety and infotainment services. In the proposed protocol, any ring member detecting a traffic accident broadcasts an emergency message to other members in the token ring. Time is partitioned into MAC frames, the first (second) portion of which is dedicated to safety-related message dissemination (non-safety applications). If the channel is sensed free at the beginning of an MAC frame (i.e., free of accidents), a token holder can transmit its packets and pass the token to its successor; otherwise, its data transmission is suspended, the corresponding driver is warned of potential danger, and a new token is circulated around the token ring to inform all the drivers of the accident. It is shown that this token ring-based MAC protocol can promptly and reliably deliver safety-related messages. However, only homogeneous channel access is considered, meaning that all vehicles are treated with equal importance; in practice, some vehicles are more vulnerable to crashes (e.g., due to their location, their cruising direction, their braking ability, drivers' aggressiveness, etc.), where risk awareness with respect to road safety should be taken into account. In [63], a risk-aware channel access strategy is proposed, in which different risk levels gauging the degree of potential danger are assigned to different vehicles in their close proximity (e.g., in a token ring or cluster). Vehicles with a high risk level will react to an (imminent) accident first. Through channel access prioritization, the proposed risk-aware MAC protocol is shown effective in minimizing message delivery latency and the damage of pileup accidents (i.e., passive safety measures); however, how to accurately determine a risk factor for every vehicle can be challenging in practice.

In addition to resource reservation in the temporal domain, network resources can also be reserved for vehicles according to their geographic location. In [64], a location-aware MAC protocol is proposed for inter-vehicle communications. In specific, a thoroughfare is divided into cells such that only one vehicle can occupy one cell at a time (see Fig. 5). Each vehicle acquires a unique CDMA (code division multiple access) code based on its current location. Since the location of each vehicle is unique, resource reservation and hence periodic traffic-related message broadcasting can be efficiently performed. Thanks to its robustness, CDMA-based channel access has been considered as a viable candidate for communication-based active safety measures (e.g., a prototype of a CDMA-based VANET is presented in [65]). Despite the fact that safety messages can be disseminated without delay, one obvious drawback of employing the CDMA technology to support rich infotainment applications in VANETs is signal spreading, lowering the effective data rate of each individual packet transmission. Power control is also necessary to alleviate the near–far problem (i.e., multiuser interference) in CDMA systems [66]. In VANETs without a dedicated centralized controller, it can be difficult to achieve efficient and effective power control. Further studies on the suitability of CDMA for VANETs supporting rich infotainment applications are needed. On a different note, the frequency of both traffic-related message broadcasting and spatial resource reservation should be contingent upon road and traffic conditions. To address the issue of dynamic resource reservation, a situation-adaptive beaconing scheme is proposed in [67]. The study reveals that, to maintain a certain level of road safety, the rate of periodic beaconing should be adaptive according to the movement of each vehicle and its surrounding vehicles. Nevertheless, to meliorate the effectiveness of traffic safety and rich infotainment service support, more research studies on adaptive spatial–temporal resource reservation are required.

All in all, with guaranteed channel access, contention-free periodic beaconing can provide drivers with knowledge of vehicular activities in their proximity. Numerous communication-based active safety measures can be enabled by effective periodic beaconing, including cooperative collision warning, highway merge assistant, blind spot warning, and cooperative adaptive cruise control. However, transmission delay can still be incurred in most of the aforementioned contention-free protocols due to link-layer access overhead. Besides, due to high vehicle mobility, the zone of danger (ZOR) can be quite large (e.g., collisions on highways). In case of an imminent traffic accident, effective multi-hop message delivery schemes with low latency are required.

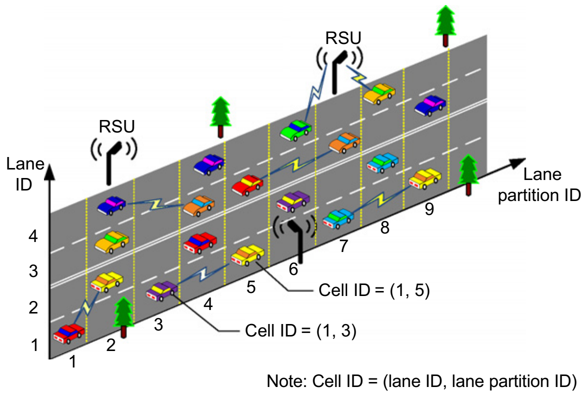

**Fig. 5.** Spatial resource reservation via location-aware channel access [64].

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### *2.3.3. Low-latency message dissemination*

Today's vehicles are equipped with a number of active safety measures for accident avoidance such as vehicles' headlamps, signals, mirrors, brakes, and steering. Mostly ascribed to human errors, road accidents are unavoidable and thus, passive safety measures such as seatbelts, airbags, and collapsible steering columns play an essential role in protecting vehicle occupants during a crash. Likewise, communication-based active safety measures such as periodic beaconing discussed in Section 2.3.2 can only warn drivers early of potential risks. Should a vehicle crash be imminent and inevitable, communication-based passive safety measures are essential for damage control so as to limit the impact of a pileup accident and reduce injury severity. Since the most critical performance measure for communication-based passive road safety applications is delivery latency, emergency messages should be disseminated with no or very low delivery delay. In light of high vehicle mobility, the ZOR can be quite large (e.g., with a radius of a kilometer or more), where low-latency multi-hop message dissemination strategies are strongly desired. An effective way to realize passive safety is the use of a dedicated channel for emergency message dissemination. An example of employing a dedicated channel for event-driven safety applications is described in [33], where a multi-channel token ring-based channel access protocol is proposed. Once an accident is detected, a ring founder node quickly broadcasts an emergency message to its ring members on a dedicated channel. As conceived, emergency safety messages can be disseminated promptly with no access latency. To minimize the gap between the time instants that an accident occurs and that it is detected, pre-crash warning suggested in [68] can be employed. If a crash is unavoidable, the vehicle of interest broadcasts a pre-crash warning signal to its neighboring vehicles, whereby the nearby drivers can have more time to react and plausibly avoid a fatal pileup accident. Illustrated in Fig. 6 is the mechanism of a pre-crash warning system for passive safety measures. Suppose Driver 1 realizes that an accident is inevitable and brakes at the position of zero. Without any pre-crash warning, Driver 2 and Driver 3 will slam on the brakes only after seeing the brake lights of the first vehicle, resulting in a 3-vehicle pileup accident. On the contrary, employing a pre-crash warning system can reduce the severity of a pileup accident, as only the first two vehicles will be involved in a crash (See Fig. 6). Also, the earlier the drivers are warned of imminent vehicle crashes, the less severe the accidents can be. To increase the range of communications, power control can be used, where higher transmit power levels are reserved for emergency message dissemination. Since emergency messages are broadcast with guaranteed channel access, more drivers can be reached with an enlarged transmission range, realizing effective passive safety. Due to the limitation of a transmission range (i.e., the maximum transmit level is upper-bounded), it is expected that not all the vehicles in the ZOR can be informed immediately of an imminent accident, posing a potential danger of a pileup accident. To efficiently disseminate emergency messages to the vehicles in the ZOR, vehicle location and vehicle mobility should be taken into account. In other words, location-aware event-driven message broadcasting protocols are required in order to promptly alert all the potentially affected drivers to trouble ahead. In [69], an intelligent message broadcast protocol is proposed to effectively and efficiently

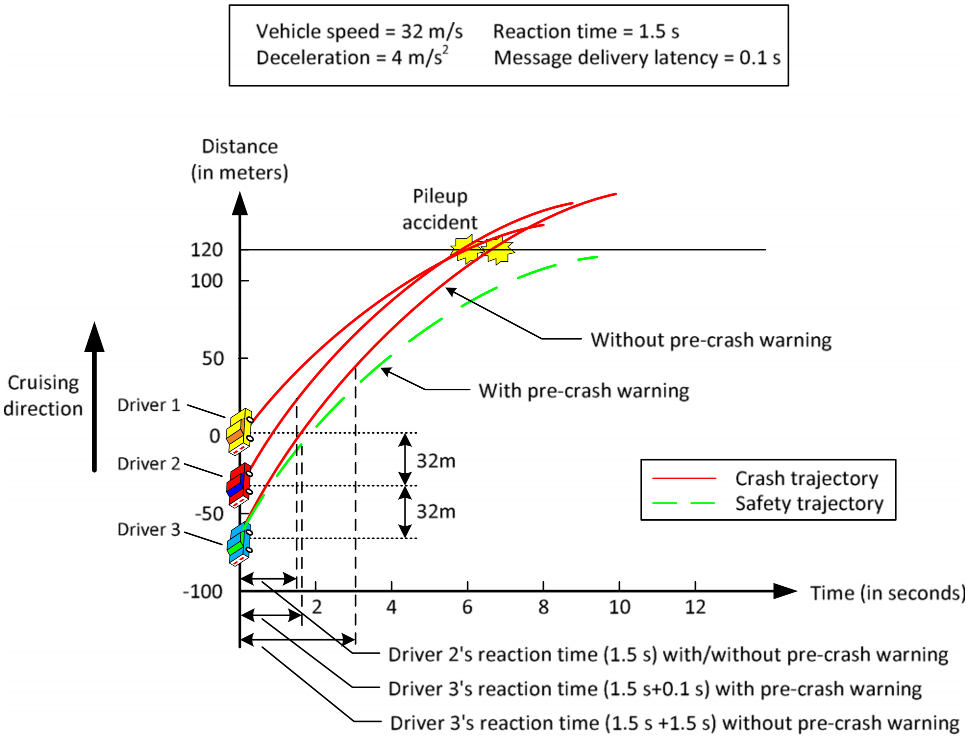

**Fig. 6.** An illustration of a pre-crash warning system.

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disseminate emergency messages to the target vehicles in danger. Consider an unidirectional traffic flow (e.g., an eastbound highway, a one-way street). The direction of emergency message dissemination should be opposite to the flow of traffic. In the proposed location-aware MAC protocol, before disseminating an emergency message, a vehicle first checks whether or not any vehicle traveling behind is broadcasting the same emergency message so as to alleviate the problem of message flooding. Similar to [69] is a vehicular self-organizing MAC (VeSOMAC) protocol proposed in [70], where multi-hop message delivery latency is capped. To further minimize the delay of end-to-end message delivery, system-level clustering is strongly desired. As discussed in Section 3.2.1, inter-cluster communications can be performed among clusterheads or clustergateways, thereby greatly expanding the range of communications in a timely fashion. Frequency reuse can also be fostered by node clustering, facilitating rich infotainment service support.

In a nutshell, resource reservation is vital in supporting rich infotainment and road safety services in VANETs. Periodic beaconing via guaranteed channel access is imperative to inform drivers of the traffic conditions in their close proximity for active safety. Since a split-second delay can cause a serious traffic accident and human causalities, low-latency multi-hop message dissemination is critical to control the damage caused by an imminent crash for passive safety. Nonetheless, to guarantee the efficiency and effectiveness of user-level channel access, system-level resource management is indispensable, to be discussed in Section 3.

## 3. On-the-road service support in VANETs: from a system's perspective

### 3.1. Research issues

In Section 2, we have discussed how diverse infotainment and safety services can be supported from a user's perspective. Without well-executed system-level resource management, those proposed channel access solutions can be less effective or even futile. For example, a CAC mechanism administers call admission and call rejection in order to support the QoS (e.g., throughput, packet dropping, fairness, etc.) of new calls and existing calls in the system. No matter how efficient an underlying user-level channel access protocol can be, without effective CAC, too many (few) calls would be admitted, causing many packet collisions (resource underutilization) and degrading system performance. In this section, we tackle two key issues of on-the-road service support in VANETs from a system's perspective: (1) network management and (2) performance enhancement.

At the system level, the main goals of a service provider are to maximize the number of customers (i.e., maximize its revenue) and improve road safety for vehicle occupants (i.e., reduce human causalities). To cut cost and speed up deployment, decentralized control in vehicular networking is preferred, where data exchange can be facilitated by means of node clustering. On the other hand, increasing the number of high-priority traffic sources (e.g., rich applications) in the system can decrease the performance of low-priority traffic sources (e.g., thin applications) [71], giving rise to the need of admission control. Apart from conventional CAC, the notion of *vehicle admission control* (*VAC*) is also of great importance in a vehicular environment. In essence, CAC is to guarantee the QoS of new and ongoing infotainment applications. By contrast, VAC monitors and controls traffic conditions such as vehicle density and traffic flow in a certain area at a given time based on a desired level of road safety. In other words, effective VAC can cap the number of traffic accidents and realize active road safety. To cope with an ever increasing global demand for vehicular applications, system performance enhancement for both infotainment and safety service support is strongly desired to further boost user satisfaction, while honing road safety measures in terms of delivery latency and communication reliability. The system performance of VANETs can be elevated by way of optimal RSU deployment, beneficial node cooperation, and advanced communication technologies.

### 3.2. Network management

#### 3.2.1. Node clustering

To effectively manage large-scale wireless networks, node clustering has been shown promising in balancing system performance and complexity [72,73]. In specific, a wireless network is divided into a number of clusters, and some wireless nodes located geographically close to each other (e.g., 1-hop neighbors) are grouped into the same cluster. As perceived, any changes in a cluster membership only require an information update locally (i.e., in the corresponding clusters) rather than globally (i.e., the entire network). The overhead of message exchange can then be lessened, facilitating network stability and scalability. In the presence of clusterheads, transmission collisions can be eliminated through contention-free packet scheduling, thereby effectively minimizing packet delay and utilizing scarce radio resources. By the same token, traffic-related data exchange can be better coordinated (i.e., active safety measures), and emergency messages can be disseminated to the ZOR more efficiently (i.e., passive safety measures). Although there already exists a large body of research studies on clustering for wireless networks (e.g., wireless mesh networks [74], wireless sensor networks [75]), new clustering approaches specifically designed for VANETs are imperative due to their unique networking attributes. Besides, how clusterheads are elected and whether clusterheads are necessary in highly mobile VANETs remain challenging research problems. In [76], a node clustering algorithm is proposed for effective message dissemination in VANETs. Considering each vehicle equipped with two transceivers, safety messages are broadcast periodically within (among) clusters over contention-free (contention-based) channels using the first transceiver, while non-safety messages (i.e., infotainment applications) are transmitted on a separate channel using the second transceiver. Their results show that a clustered VANET can achieve low delivery latency for safety messages and high throughput for non-safety applications. Similar to [76], reported in [77] is

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another cluster-based approach for vehicles using a single transceiver for safety and infotainment service support. To further improve the effectiveness of node clustering in VANETs, human attributes should be taken into account. An interesting clustering algorithm is proposed in [78], considering vehicular dynamics and drivers' intentions as the metrics of cluster formation. The proposed algorithm is demonstrated promising in terms of cluster lifetime and message delivery latency. In [14], traffic flow theories are employed to evaluate the delay performance of emergency message dissemination in clustered VANETs under three realistic traffic scenarios. It is shown that, ascribed to the robust cluster structure, the delivery latency of event-driven emergency message dissemination can be upper bounded. In [22], peer-to-peer relaying and node clustering are jointly considered, aiming to increase the successful delivery rate of message dissemination. Channel allocation in clustered VANETs is studied in [79] to improve the rate of successful data exchange and increase channel utilization. In the presence of multiple channels, the methodology of tax-based channel allocation pioneered in [74] can be employed for effective interference control. Node clustering and channel allocation can also benefit from vehicle platooning [10]. Nonetheless, how to devise a joint node clustering and effective channel allocation algorithm tailored for QoS-sensitive VANETs needs further investigation. In a highly mobile vehicular environment, clusters can be short-lived, undermining the effectiveness of inter- and intra-cluster message dissemination. For the sake of system performance, more research efforts are needed to aim at the stability of clusters in VANETs.

### 3.2.2. *Call/vehicle admission control*

In wireless networks with limited radio resources, there is a natural tradeoff among different network design objectives such as increasing throughput, minimizing packet loss, and maintaining fairness [80]. There is a lot of research work aiming at balancing different performance objectives in VANETs (e.g., tradeoff between packet dropping and fairness assurance [81]); yet, CAC is vital to effectively guarantee the QoS such as throughput, delay, and fairness of infotainment applications for both new calls and ongoing calls already in service [71]. In [82], a new call admission criterion based upon the expected amount of data to be transmitted is proposed for VANETs. A lexicographical max–min algorithm with respect to the new admission metric is devised to determine whether or not a new call can be admitted. In [83], a CAC problem is formulated as a utility maximization problem, whereby service differentiation and reliable data delivery can be supported at the same time. On the other hand, roadways can vary from one location to another, for example, from a multi-lane road to a single-lane load. Also, a vehicle needs to be within a proximity in order to connect to other vehicles within its transmission range. Thus, CAC in VANETs should take roadway geometric features into account. Call admission with the consideration of realistic thoroughfares is addressed in [84]. A call admission condition is contingent upon the availability of radio resources and spatial–temporal traffic variations. On a different note, CAC can be performed either in a centralized manner or in a distributed manner. In centralized CAC, since global information is usually required, call admission/rejection can be performed by an RSU or a clusterhead. In distributed CAC, each vehicle initiates or delays a call based on its local knowledge, its movement route, and traffic load statistics over the route at the time. Centralized CAC generally results in better system performance than distributed CAC at the cost of complexity. On the other hand, which network entities should perform CAC also depends on an application-specific scenario. For example, consider video streaming from a remote site to a vehicle via an RSU. CAC should be performed by an RSU that checks if such a call admission would violate the QoS support of existing calls in session. However, a peer-to-peer data session can be initiated by a vehicle in a distributed manner, even in the presence of RSUs. Therefore, whether centralized CAC or distributed CAC is used highly depends upon an application scenario, a desired level of system performance, and computational complexity.

The idea of considering roadway geometry can be employed in VAC for active road safety measures. According to the City of York Council, England [85], traffic accidents happen more often in a congested traffic road (e.g., during peak traffic periods). In other words, the higher the vehicle density, the more likely the traffic accidents occur. Thanks to traffic flow theories, vehicle density can be easily estimated [59], whereby traffic control by means of traffic lights, stop signs, speed bumps, and other flow management policies can be enacted accordingly. Unlike CAC mainly for infotainment service support, VAC is critical for active safety measures; however, the issue of VAC has been given little attention. A joint call-vehicle admission criterion is also of great interest in VANETs, taking into consideration vehicle density, vehicle mobility, relative vehicle location, frequency reuse pattern, and roadway geometry. More research studies are needed to design an effective and efficient call-vehicle admission control mechanism for integrating infotainment and road safety service support.

## 3.3. *Performance enhancement*

### 3.3.1. *RSU deployment*

Optimal RSU deployment is an effective way to greatly enhance the performance of VANETs. Deploying RSUs strategically along highways or city streets not only can alleviate the infamous problem of frequent network fragmentation, but also can facilitate efficient and reliable message dissemination for infotainment services and improve road safety. Important traffic information such as treacherous road conditions can be disseminated to inform drivers early of potential risks ahead (e.g., sharp turns, icy roads, construction sites). Several RSU-assisted safety applications have been identified by the Vehicle Safety Communication (VSC) project conducted by the U.S. National Highway Traffic Safety Administration [86]. One example of active safety applications is curve speed warning (see Fig. 7). In this application, RSUs broadcast messages to vehicles approaching curves. The delivered information can include curve location, curve speed limits, curvature, bank, and road surface condition, whereby drivers can be warned early of potential danger. In addition, with RSUs, delivery latency and

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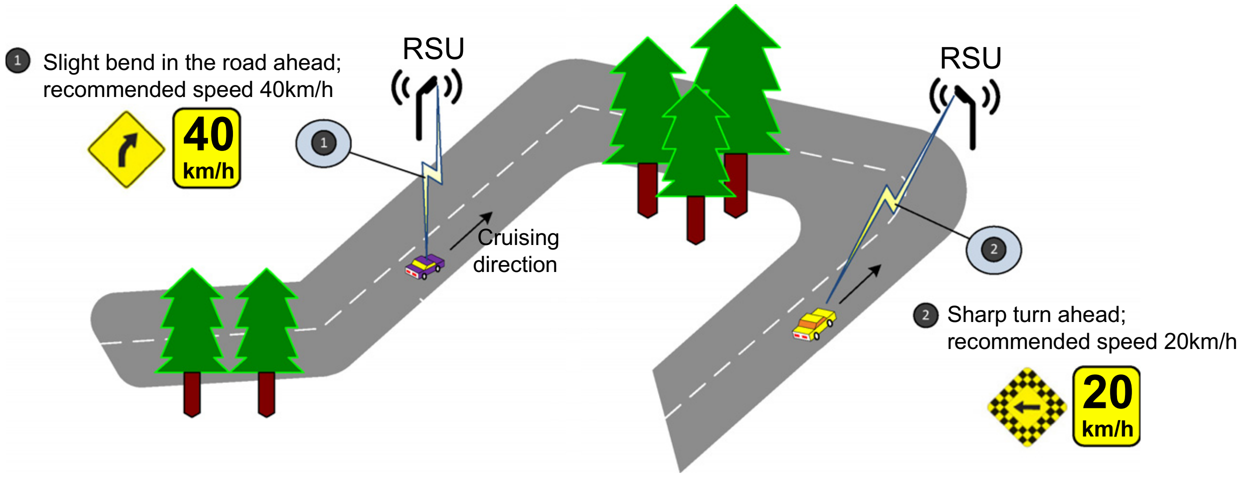

**Fig. 7.** Curve speed warning.

communication reliability can be improved due to the enlarged coverage area. In [87], it is shown that, by carefully placing RSUs, the delivery ratio of successful message dissemination can be increased by up to 13%. Formulated as an (NP-hard) optimization problem, an RSU deployment problem can be solved by genetic algorithms (GAs) (e.g., in [88]) or greedy approaches (e.g., in [89]) so as to optimize link reliability and delivery latency. With improved reliability and delay performance, the effectiveness of road safety applications can be increased, plausibly lowering the vehicle collision rate. In practice, RSUs should be placed at traffic accident black spots[4]; however, determining a traffic accident black spot can be difficult, and more cross-disciplinary efforts are needed. Regarding infotainment service support in a vehicular environment, on the other hand, the issue of optimal RSU deployment has not been well addressed in the literature. Reported in [90] is one of the few attempts to optimally place RSUs for infotainment service support in VANETs. It can be shown that, with the optimal RSU deployment, the end-to-end communication delay can be minimized, while system throughput increased. In [91], an analytic framework based on the theory of effective bandwidth is proposed to study the impact of the number of RSUs on delivery latency. The proposed framework is useful in determining the minimum number of RSUs required to guarantee a statistical end-to-end delay bound for message dissemination. Another RSU placement approach for throughput maximization in VANETs is proposed in [92], taking into consideration highway mobility patterns and realistic path-loss models. The proposed approach takes advantage of adaptive modulation and coding to further increase system throughput. To expand a service area, virtual access points can be employed as relays to increase the rate of successful message delivery [93]. In fact, the introduction of virtual access points resembles the concept of node cooperation. In VANETs with fast-moving vehicles, partner (relay node) selection can be challenging, and a new node cooperative resource allocation strategy for VANETs is indispensable, to be discussed in Section 3.3.2. Despite their potential in elevating system performance, the aforementioned RSU deployment approaches ignore the impact of severe Doppler spread due to high vehicle mobility (i.e., small-scale fading effects). Field tests are necessary to evaluate the actual performance and practicality of the proposed solutions. In addition, only a single service type is considered; therefore, directly applying the proposed approaches to VANETs with heterogeneous services (e.g., rich infotainment applications) can be ineffective in provisioning packet-level QoS such as packet dropping rate and throughput. Further, network connectivity analysis (e.g., in [94]) is necessary to gauge the effect of frequent network fragmentation on system performance and hence facilitate effective RSU deployment. In short, a generic RSU deployment framework with the consideration of safety concerns, heterogeneous traffic types, resource reservation, vehicle mobility, vehicle density, and roadways is needed.

### *3.3.2. RSU-assisted cooperation*

Recently, distributed node cooperation has drawn a plethora of attention from industry and academia [95]. Since the signal transmitted by a source node can be overheard by other nodes in a wireless environment, the source and its partner(s) can jointly process and transmit their information by forming a virtual antenna array. Beneficial node cooperation has been shown promising in increasing the system throughput [96,97] and/or improving the transmission accuracy [95]. RSU-assisted node cooperation is particularly useful in supporting safety applications. Due to high mobility of vehicles, communication channels are susceptible to fast fading, whereby reliable links cannot be guaranteed [98]. Thus, active safety measures governed by contention-free periodic beaconing approaches discussed in Section 2.3 can fail at times when poor channel conditions arise. Likewise, in case of an accident, event-driven emergency messages cannot be disseminated to a target ZOR efficiently if the link between a source and its destination is in deep fade, weakening the effectiveness of passive

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[4] A traffic accident black spot is a place over which traffic accidents have historically been concentrated.

safety measures. By employing diversity-based cooperation protocols, link reliability can be greatly improved [99,100]. With appropriate detection techniques, an additional diversity order can be attained in time-varying wireless channels [101], further meliorating the level of communication reliability. In [102], a cooperative relaying approach based on space-time block coding is proposed for multi-hop VANETs. It is confirmed that beneficial cooperation can greatly improve the system performance in terms of successful message delivery ratio, latency, throughput, and link reliability. Diversity performance of RSU-assisted cooperation is analyzed and optimized in [103]. The results show that link reliability can be improved by up to four-fold in a high signal-to-noise-ratio (SNR) regime (i.e., diversity order of four). On the contrary, achieving spatial multiplexing via node cooperation for infotainment service enhancement can be a challenging task. One obvious hurdle is the uncertainty of a communication link between a source and its partner(s). Two cooperative protocols for infotainment delivery are proposed in [13,104]. In both approaches, a vehicle initiates message exchange with an RSU and triggers node cooperation with its neighboring vehicles for a throughput increase. Nonetheless, the issue of partner selection is not addressed properly, where the throughput requirement and availability of partners should be taken notice of. On the other hand, beneficial cooperation among vehicles can improve inter-vehicle communication reliability. Due to high mobility, however, channel estimation errors are inevitable [101], undermining the effectiveness of vehicle cooperation. In the case of non-altruistic vehicle cooperation, cooperative transmission is not always advantageous over ordinary direct transmission [105]. Determining whether and when vehicle cooperation is beneficial is required. How to incorporate platooning into vehicle cooperation in VANETs is also of great interest and yet needs further research.

### 3.3.3. *Other advanced communication technologies*

Advanced communication technologies are commonly used in wireless networks to enhance system performance. For example, the multiple-input–multiple-output (MIMO) technology can be employed to enhance system capacity (for infotainment service support) and diversity performance (for road safety service support). As shown in [106], however, the MIMO channel model in VANETs is quite different from that in a conventional wireless network (e.g., Jakes' model [107]) due to high mobility of scatterers (i.e., other vehicles). Thus, new MIMO approaches targeted for VANETs with fast-moving vehicles are needed. On the other hand, employing directional antennas can reduce transmission collisions and foster frequency reuse. An example of a directional MAC protocol is described in [108]. Since the movement of vehicles is restricted to thoroughfares, it is expected that directional antenna-based communication protocols can be viable candidates for practical implementation. Recently, the concept of *network coding* has emerged and drawn a lot of attention due to its prominence in tremendously improving system performance [109]. By employing network coding-based information dissemination, it can be shown that the system performance in terms of throughput and latency can be greatly enhanced [110]. Furthermore, cognitive radio networks have been extensively investigated as a promising solution to spectrum congestion and low spectrum utilization by licensed (primary) users [111]. Effective channel exploration and channel exploitation techniques (e.g., [112]) can be employed to improve resource utilization of a VANET. However, as the license exempted (secondary) users can only share the leftover radio resources after the primary users, ensuring service quality to the secondary users in a VANET is difficult due to the randomness in resource availability.

To sum up, system-level resource management is important for a VANET supporting diverse road safety and infotainment applications. Node clustering can be a potential approach to manage large-scale VANETs with decentralized control. CAC is critical in providing fine-grain QoS support to new calls and protecting the ongoing calls in service, whereas VAC is indispensable in administering traffic volume to achieve active road safety. Optimal RSU deployment and beneficial node cooperation are promising to enhance system performance. Advanced communication technologies such as MIMO, directional antennas, network coding, and cognitive radio can also be incorporated into V2V and/or V2I communications to further augment the effectiveness of VANETs. Nonetheless, more research studies are needed to evaluate the effectiveness of the aforementioned system-level resource management approaches in challenging VANETs with fast-moving vehicles.

## 4. Related research projects

As wireless technology advances, vehicular communication has stimulated a number of research activities around the globe, striving to realize the vision of ITSs. Early research projects on inter-vehicle communications can date back to 1980s. Coordinated highway driving was introduced by the Association of Electronic Technology for Automobile Traffic and Driving (JSK) in Japan [113]. In the 1990s, similar ITS initiatives were found in two major European projects, PROMETHEUS and DRIVE [114], aiming to improve traffic efficiency. Around the same time, research activities on vehicular communications were caught up in the United States. In 1997, an eight-vehicle platooning system was successfully demonstrated by the California Partners for Advanced Transit and Highway (PATH) in San Diego [26]. This demonstration reveals that, via V2V communications, vehicles can operate in a tight yet safe coordination, resulting in a significant improvement in vehicle throughput and road safety. Similar demonstrations on vehicle platooning were also conducted in the late 1990s in Europe (e.g., [9]) and early 2000s in Japan (e.g., DEMO 2000 [115]). Despite the fact that the technique of vehicle platooning is considered feasible, more research studies and tests are needed before this functionality can be securely equipped in today's vehicles.

On the road safety front, a European project named PReVENT [116] has been launched in order to develop and demonstrate preventive safety applications and technologies. The prominent feature of PReVENT is that, not only can it provide drivers with an increased horizon, but its accident avoidance mechanism can also be fully automated without the need of manual maneuvers. Other European road safety-related projects include COMeSafety [117], SAFESPOT [118], SeVeCOM [119], and

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COOPERS [120]. Recently, the Research and Innovative Technology Administration (RITA) of the United States Department of Transportation (DOT) has launched a campaign (also known as Transportation Vision for 2030), aiming to drastically reduce traffic accidents [2]. The DOT focuses on both V2I and V2V communication technologies for safety applications. The Car-to-Car Communication Consortium (C2C-CC) [121] driven by many European automobile manufacturers (e.g., Audi, BMW, Fiat, Opel, Volkswagen, etc.) focuses on the development and release of an open standard for cooperative ITSs, including road safety and traffic efficiency.

To increase the comfort and convenience of vehicle occupants, infotainment service support has been considered in several recent research projects. For instance, a European research project is launched with an emphasis on the development of Cooperative Vehicle-Infrastructure Systems (CVIS). To enable continuous V2V and V2I communications, the CVIS are expected to support a variety of convenience and commercial applications as well as safety applications. Fleetnet [16] is a German research project, and its objective is to develop a platform for V2V communications to provide both comfort services (e.g., Internet access) and safety applications (e.g., cooperative driving). Network on Wheels (NOW) [122] is another research project based in Germany. The main NOW objective is to develop communication protocols for infotainment and active safety service support. A testbed for functional tests and demonstrations is also implemented in the NOW to evaluate the performance of VANETs. To further enrich driving experience, an in-vehicle system called TracNet [123] has been introduced to provide Internet access to vehicle occupants.

The untapped potential of vehicular communications has sparked a number of collaborative initiatives for on-the-road infotainment and safety service support. As synergy on VANETs among government, automotive industry, and academia continues to grow, so will innovative research projects to identify and capitalize on lucrative new markets for VANETs.

## 5. Open research issues

### 5.1. Integration of road safety and infotainment applications

In VANETs supporting road traffic safety and infotainment applications, it is certain that safety messages should always be assigned the highest priority and guaranteed resource access, as discussed in Section 2. In large-scale VANETs, however, traffic conditions (i.e., traffic load and road terrain) and user demands (i.e., desired infotainment category and satisfaction level) can vary greatly in both the spatial and temporal domains. Deterministic channel access protocols are less effective to provide fine-grain QoS support such as throughput, packet dropping, and fairness for safety and infotainment services. Adaptive resource reservation approaches tailored for highly dynamic VANETs supporting different combinations of on-the-road applications are indispensable.

### 5.2. VANET/LTE internetworking

Merging VANETs with cellular systems has recently gained a lot of attention [124,125]. The reason behind this hybrid VANET/LTE networking paradigm is that, in the early stage of VANET deployment, only a small fraction of vehicles equipped with OBUs can perform computing and communications on the road. Together with peculiar VANET-specific features such as high vehicle mobility, frequent network partitioning in a vehicular environment is inevitable. One viable option to improve the network connectivity in VANETs is via the assistance of a well-established cellular system as a complementary network (e.g., communications architecture for land mobile, CALM [125]). It has been shown that cellular system-aided VANETs can greatly facilitate message dissemination in terms of message delivery ratio, outperforming pure VANETs with sparsely placed vehicles [124]. Devising effective and efficient resource management approaches tailored for integrated VANET/LTE networks, however, needs further investigation.

### 5.3. Privacy and security issues in VANETs

Wireless networks are generally susceptible to various kinds of security and privacy threats such as modification attacks and relay attacks [29,126,127]. Obviously, any malicious behavior of vehicle occupants can cause fatal consequences to other drivers and passengers on the road. Unlike MANETs, the security and privacy issues in VANETs become more challenging due to the unique networking attributes such as the mobility pattern of fast-moving vehicles. On one hand, privacy preservation is imperative such that the sensitive information of a user, for example, the name of a driver/passenger, a license plate, etc., is protected. On the other hand, authorized parties such as police officers should be able to reveal the identities of message senders in case of emergency (e.g., to identify victims and witnesses) and criminal investigation (e.g., to locate hit-and-run drivers). Security and privacy issues of VANETs, however, have been given little attention [29]. How to design an effective, reliable, and secure VANET-specific communication solution to support infotainment and safety applications is essential [126,127]; yet, more in-depth research study is needed.

### 5.4. Traffic flow-theoretic approaches

As discussed in [14,59], traffic flow theories developed by civil engineers lay out insightful guidelines to the design and modeling of VANET-related communication problems. Civil engineering research not only provides rigorous mathematical models to describe the behavior of vehicle traffic (e.g., vehicle platooning, vehicle passing, intersection crossing), but also provides realistic traffic flow models for different types of roadways (e.g., highways, city streets, single lane, multiple lanes). Traffic flow theories have been researched for many decades and proven consistent with the real traffic measurements. How to optimize the system performance of VANETs by means of traffic flow-theoretic approaches needs further investigation.

### 5.5. Mobility models and parameters

An accurate mobility model with tunable system parameters (e.g., vehicle speed, drivers' aggressiveness) reflecting a realistic vehicular environment is desired in performance evaluation and design of any communication protocols for VANETs. For example, mobility information has been utilized to improve fairness on the MAC layer [128]. In the literature, many research studies have been undertaken so as to provide a close-to-reality mobility model for VANETs [129,130]; however, those proposed models are suitable for only a small number of scenarios (e.g., communication-aided lane change). Realistic mobility models for VANETs should incorporate the unique features of a vehicular environment such as highly dynamic spatial–temporal road and traffic variations, which requires further research study.

## 6. Conclusions

As vehicular transportation has become an integrated part of our daily routine, there is a growing demand for inter-vehicle communications and in-vehicle computing. VANETs consisting of OBUs and RSUs can realize V2V and V2I communications. This emerging vehicular networking paradigm is considered promising, enabling a wide spectrum of new on-the-road applications including safety, convenience, and comfort services. Due to the unique network characteristics and application-oriented objectives, most existing channel access protocols and resource management approaches designed for traditional wireless networks are ill-suited for highly dynamic VANETs with fast-moving vehicles. To achieve success in a challenging vehicular environment, devising VANET-specific communication strategies is necessary. This paper is intended to shed light upon infotainment and road safety service support from a communication perspective. We have studied the suitability of various user-level channel access protocols and system-level resource management approaches for the QoS support of diverse infotainment and road safety applications. A number of related research projects and open research issues have also been identified and discussed.

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