Heterogeneous Vehicular Networking: A Survey on Architecture, Challenges, and Solutions

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***Abstract*—With the rapid development of the Intelligent Transportation System (ITS), vehicular communication networks have been widely studied in recent years. Dedicated Short Range Communication (DSRC) can provide efficient real-time information exchange among vehicles without the need of pervasive roadside communication infrastructure. Although mobile cellular networks are capable of providing wide coverage for vehicular users, the requirements of services that require stringent real-time safety cannot always be guaranteed by cellular networks. Therefore, the Heterogeneous Vehicular NETwork (HetVNET), which integrates cellular networks with DSRC, is a potential solution for meeting the communication requirements of the ITS. Although there are a plethora of reported studies on either DSRC or cellular networks, joint research of these two areas is still at its infancy. This paper provides a comprehensive survey on recent wireless networks techniques applied to HetVNETs. Firstly, the requirements and use cases of safety and non-safety services are summarized and compared. Consequently, a HetVNET framework that utilizes a variety of wireless networking techniques is presented, followed by the descriptions of various applications for some typical scenarios. Building such HetVNETs requires a deep understanding of heterogeneity and its associated challenges. Thus, major challenges and solutions that are related to both the Medium Access Control (MAC) and network layers in HetVNETs are studied and discussed in detail. Finally, we outline open issues that help to identify new research directions in HetVNETs.**

***Index Terms*—Vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), heterogeneous networks, long term evolution (LTE), dedicated short range communications (DSRC).**

ABF	Adaptive Broadcast Frame
AC	Access Category
ACK	Acknowledgement
AIFS	Arbitration Interframe Space
AMC	Adaptive Modulation and Coding
CAM	Cooperative Awareness Message
CCH	Control Channel
CELL-DCH	CELL Dedicated Channel
CELL-FACH	CELL Forward Access Channel
CELL-PCH	CELL Paging Channel
CH	Cluster Head
CN	Core Network
CQI	Channel Quality Indicator
CRP	Contention-based Reservation Period
CSMA	Carrier Sense Multiple Access
CTS	Clear-To-Send
CW	Contention Window
D2D	Device-to-Device
DEN	Decentralized Environmental Notification
DMMAC	Dedicated Multi-Channel MAC
DOT	Department of Transportation
DS-CDMA	Direct Sequence Code Division Multiple Access
DSRC	Dedicated Short Range Communication
eMBMS	Evolved Multimedia Broadcast and Multicast Service
eNB	Evolved NodeB
EDCA	Enhanced Distributed Channel Access
EDCAF	Enhanced Distributed Channel Access Function
GW	Gateway
GI	Guard Interval
HetVNETs	Heterogeneous Vehicular NETworks
HLL	Heterogeneous Link Layer
I2V	Infrastructure-to-Vehicle
ICI	Inter-Carrier Interference
ITS	Intelligent Transportation System
LTE	Long Term Evolution
MAC	Medium Access Control
MBMS	Multimedia Broadcast and Multicast Services
MBSFN	MBMS Single Frequency Network
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
OBU	On-Board Unit
OVSF	Orthogonal Variable Spreading Factor
PCF	Point Coordination Function
QCI	QoS Class Identifier
QoS	Quality of Service
RAN	Radio Access Network
RRC	Radio Resource Control

Manuscript received May 21, 2014; revised November 21, 2014 and March 16, 2015; accepted April 28, 2015. Date of publication June 1, 2015; date of current version November 18, 2015. This work is funded in part by National Science Foundation of China (No. 61331009), the National High-Tech R&D Program (863 Program 2015AA01A705), National Key Technology R&D Program of China (No. 2015ZX03002009-004), Fundamental Research Funds for the Central Universities (No. 2014ZD03-02) and China Scholarship Council.

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Digital Object Identifier 10.1109/COMST.2015.2440103

RSSI	Received Signal Strength Indicator
RSU	Roadside Unit
RTS	Request-To-Send
SC	Service Center
SCH	Service Channel
SF	Spreading Factor
UE	User Equipment
URA-PCH	URA Paging Channel
UTC	Universal Coordinated Time
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANETs	Vehicular Ad Hoc NETworks
VE	Vehicle Equipment
WAVE	Wireless Access in Vehicular Environments
WBSS	WAVE Basic Service Set
WCDMA	Wideband Code Division Multiple Access
WHO	World Health Organization
WiMAX	Worldwide Interoperability for Microwave Access
WSA	WAVE Service Advertisement
WSMP	WAVE Short Message Protocol

I. Introduction

IN recent years, traffic congestion and accidents, as well as environmental pollution caused by road traffic and fuel consumption have become important global issues. Both developing and developed countries are plagued by traffic problems. High traffic accident rates claim huge losses of life and property. As reported by the World Health Organization (WHO), more than 100 million people die in traffic accidents worldwide, and the resultant economic losses are up to $500 billion each year [1]. Moreover, traffic congestion in urban areas decreases the efficiency of transportation systems, and hence hinders economic growth. Thus, both safety and efficiency of current transportation systems have room for significant improvements.

Vehicular networks are designed to provide information exchange via Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. It is reported that over 50% of interviewed consumers are highly interested in the idea of connected cars, 22% of whom are willing to pay $ 30 $\sim$ 65 per month for value-added connectivity services while on the road [2]. In 1999, FCC allocated 75 MHz (from 5.850 GHz to 5.925 GHz) bandwidth for Dedicated Short Range Communication (DSRC) in vehicular environments. The U.S. Department of Transportation (DOT) estimated that V2V communications based on DSRC can reduce up to 82% of all road crashes in U.S., potentially saving thousands of lives and billions of dollars [3]. Meanwhile, much attention has been paid to the applicability of mobile cellular networks to support vehicular services, which can provide wide coverage and high data rate services to vehicular users.

However, both DSRC and mobile cellular networks have their own limitations when used in vehicular environments. In particular, DSRC was initially designed for short-range communications without the need of pervasive roadside infrastructure. On the other hand, although mobile cellular networks can provide wide geographical coverage, they cannot efficiently support real-time information exchange for local areas. On the contrary, emerging heterogeneous networks not only have the ability of providing wide-area coverage to all vehicles in large-scale networks, but also supports real-time safety messages distribution in local areas in order to reduce traffic accidents. Therefore, Heterogeneous Vehicular NETworks (HetVNETs), which integrate DSRC with cellular networks, may well support the communications requirements of the Intelligent Transportation System (ITS). Recently, the Qualcomm Snapdragon automotive development platform, which supports not only Long Term Evolution (LTE) but also IEEE 802.11p for DSRC, was released to enable auto manufactures, suppliers and developers to rapidly innovate, test and deploy vehicular applications [4]. It is obvious that the HetVNET is emerging quickly in the market. Many research challenges arise in designing such a heterogeneous network, ranging from offering efficient proper channel access to Quality of Service (QoS) provision. Since vehicular networks are one of the emerging topics in wireless communications, we believe that a detailed classification and description of design approaches are useful to the interested reader.

Existing survey papers on vehicular networks focus mostly on either the overview of the ITS or a single network [2], [5]–[11]. For example, standardization efforts as well as ITS projects are introduced in [5], highlighting their scope and objectives for different countries and areas. The challenges and solutions of using DSRC for vehicular communications are discussed in [6]. A comprehensive survey of Vehicular Ad Hoc NETworks (VANETs) is presented in [9], [10]. After introducing the architecture of VANETs, the authors describe in detail the unique characteristics of VANETs, and give a brief introduction to the considered protocol stacks in VANETs. In [12], authors discuss the communications techniques and protocols used in vehicular environments that aim to reduce fuel consumption, gas emissions and traffic congestion. State-of-the-art wireless solutions for vehicle-to-other connectivity, i.e., vehicle-to-sensor, vehicle-to-vehicle, vehicle-to-Internet and vehicle-to-road infrastructure connectivity, and potential challenges are discussed in [11]. Worldwide Interoperability for Microwave Access (WiMAX) networks have been proposed to be used for vehicular communications to tackle the coverage problem in VANETs [13]. Moreover, the capability of LTE supporting vehicular applications is briefly assessed in [2]. World's leading experts held a seminar to discuss various issues of "Inter-Vehicle Communications" in Dagstuhl Castle, Germany [14]. Besides presenting key outcomes and performance results, they also shed light on new research directions and challenges for next generation vehicular networks. As stated in [14], the HetVNET is an important and timely topic, which was largely motivated by the fact that each type of the current wireless network offers their unique benefits, but also has individual drawbacks. Therefore, different from existing surveys in the literature, this paper focuses specifically on various services that can be provisioned by heterogeneous vehicular networks. On the basis of a service and user case analysis, a generic HetVNET framework is proposed after discussing various candidate networking techniques. Several typical application scenarios are then studied under our proposed framework as examples. Moreover, key solutions and challenges of the Medium

TABLE I
SAFETY SERVICES AND USER CASES REQUIREMENTS

Safety Services Category	User Cases	Communication Mode	Security/ Reliability Requirements	Usage	Minimum Frequency of Periodic Messages	Maximum Latency
Category I: Vehicle status warning	Emergency electronic brake lights	Time limited periodic broadcast on event	High/High	Warn a sudden slowdown of the following vehicle	10 Hz	100 ms
	Abnormal condition warning	Time limited periodic broadcast on event	High/High	Warn the abnormal vehicle state	1 Hz	100 ms
Category II: Vehicle type warning	Emergency vehicle warning	Periodic triggered by vehicle mode	High/High	Reduce emergency vehicle's intervention time	10 Hz	100 ms
	Slow vehicle warning	Periodic triggered by vehicle mode	High/High	Improve the traffic fluidity	2 Hz	100 ms
	Motorcycle warning	V2X co-operative awareness	High/High	Collision avoidance	2 Hz	100 ms
	Vulnerable road user Warning	V2X co-operative awareness	High/High	Collision avoidance	1 Hz	100 ms
Category III: Traffic hazard warning	Wrong way driving warning	Time limited periodic broadcasting on event	High/High	Wrong way driving warning	10 Hz	100 ms
	Stationary vehicle warning	Time limited periodic broadcasting on event	High/High	Avoid succession of collisions	10 Hz	100 ms
	Traffic condition warning	Time limited periodic messages broadcasting/authoritative message triggered	High/High	Reduce the risk of longitudinal collision on traffic jam forming	1 Hz	100 ms
	Signal violation warning	Temporary messages broadcasting on event	High/High	Reduce the risk of a stop/traffic violation	10 Hz	100 ms
	Roadwork warning	Temporary messages broadcasting on event	High/High	Reduce the risk of accident at the level of roadwork	2 Hz	100 ms
	Decentralized floating car data	Time limited periodic broadcasting on event	High/High	Improve safety and traffic fluidity	10 Hz	100 ms
Category IV: Dynamic vehicle warning	Overtaking vehicle warning	V2X co-operative awareness	High/High	Reduce the risk of accident	10 Hz	100 ms
	Lane change assistance	V2X co-operative awareness	High/High	Active road safety	10 Hz	100 ms
	Pre-crash sensing warning	Broadcast of pre-crash state	High/High	Accident impact mitigation	10 Hz	50 ms
	Co-operative glare reduction	V2X co-operative awareness	Medium/ Medium	Avoid the frontal collision	2 Hz	100 ms

Access Control (MAC) and networking layers in HetVNETs are identified. In addition, we present several open HetVNET research issues for future investigations.

The remainder of this survey is organized as follows. Firstly, an overview of several user cases and their associated QoS requirements for ITS applications are presented in Section II. Section III introduces a generic framework of HetVNETs, alongside several scenarios that consider various networking techniques. In Section IV, key issues and solutions for HetVNETs are given, mainly at the MAC and network layers. Open research issues and challenges of implementing HetVNETs are also discussed in Section V. Finally, conclusions are drawn in Section VI.

II. USER CASES AND REQUIREMENTS FOR SAFETY AND NON-SAFETY RELATED SERVICES

The main scope of this section is to summarize user cases and services for the deployment of the ITS. The system capabilities are then derived from an requirement analysis of these user cases and services. ITS services can be broadly categorized into safety and non-safety services as described in [2], [15]. The former disseminates real-time safety-related messages, e.g., various warning messages including abrupt brake warning messages, so as to prevent car accidents, while the latter is to optimize the flow of vehicles in order to reduce travel time and improve the road users' experience.

A. Safety Related Service and Use Cases

Safety services aim at reducing the risk of car accidents and decreasing the possibility of life losses for vehicular users. Timeliness and reliability are considered as highly demanding requirements for this kind of services. Table I lists the requirements for the user cases of safety services [16], [17]. The minimum frequency of periodic messages of the safety service varies from 1 Hz to 10 Hz, and the reaction time of most drivers ranges from 0.6 s to 1.4 s [18]. Thus, it is

TABLE II
NON-SAFETY SERVICE AND USER CASES REQUIREMENTS

Non-safety Services Category	User Cases	Communication Mode	Security/ Reliability Require-ments	Usage	Minimum Fre-quency of Peri-odic Messages	Maximum Latency
Category I: Traffic management	Regulatory/contextual speed limits	Authoritative message triggered by traffic management entity	High/High	Enhance the traffic efficiency/reduce the vehicles' pollution	1 Hz	N/A
	Traffic light optimal speed advisory	Periodic, permanent messages broadcasting	High/High	Traffic regulation at an intersection	2 Hz	100 *ms*
	Intersection management	Periodic, permanent messages broadcasting	High/High	Road safety and traffic regulation at an intersection	1 Hz	100 ms
	Co-operative flexible lane change	Periodic broadcasting messages	High/High	Enhancement of mobility efficiency	1 Hz	500 ms
	Electronic toll collect	I2V broadcasting and unicast full duplex session	High/High	Traffic fluidity at the toll collect	1 Hz	500 ms
Category II: Infotainment	Point of interest notification	Periodic, permanent messages broadcasting	Medium/ Medium	Driver and passengers comfort	1 Hz	500 ms
	Local electronic commerce	Duplex communication between RSU and Vehicles	High/High	Vehicle driver/passenger comfort	1 Hz	500 ms
	Media download	User access to Internet for multimedia download	Medium/ Medium	Passenger entertainment	1 Hz	500 ms
	Map download and update	Access to Internet for map download and update	Medium/ Medium	Efficiency and comfort	1 Hz	500 ms

reasonable to restrict the maximum latency time to be no more than 100 ms. For example, the maximum latency of pre-crash sensing warning is 50 ms. The communication mode and the user cases are also compared in Table I. The security and reliability requirements are very strict due to the characteristics of safety services. We mainly consider two message types used for safety services [15], i.e.,

- **Cooperative Awareness Message (CAM)**: CAMs are sent or broadcasted periodically to the area of interest mainly for road warning purposes, e.g., the user cases in Categories II as shown in Table I. The exchanged messages usually include the information on a vehicle's status, type, positions, speed and so on.
- **Decentralized Environmental Notification (DEN)**: DEN messages are usually triggered by special events, e.g., user cases in Categories I, III and IV in Table I. The purpose of DEN is to notify the vehicles in the area of interest of potential hazards.

B. Non-Safety Related Service and User Cases

Non-safety services are used primarily for traffic management, congestion control, improvement of traffic fluidity, infotainment, etc. The main objective of non-safety services is to enable a more efficient and comfortable driving experience. These services have no stringent requirements on latency and reliability [17]. As shown in Table II, non-safety services can be roughly classified into two categories, i.e., traffic efficiency and infotainment services. The former is to improve the traffic fluidity as well as offering secondary benefits not directly associated with traffic management [16]. For instance, due to efficient traffic scheduling, the travel time and fuel consumption can be reduced. The latter provides on-demand entertainment information to passing vehicles. Compared to safety services, non-safety services have different QoS requirements. For most non-safety services, the minimum frequency of periodic messages is 1 Hz, while the maximum latency is 500 ms. In special user cases such as optimal traffic-light speed advisory and intersection management, positioning accuracy is crucial, e.g., no more than 5 meters [16]. On the other hand, user cases such as local electronic commerce with monetary transactions require high-level security. For traffic efficiency services, broadcast messages have to be authoritative and endorsed by traffic management authorities.

Several wireless communication systems have been considered to support ITS services via V2V and V2I communications. Among them, LTE and DSRC technologies are front-runner candidates, and both are considered well suited for providing ITS services under the condition of low vehicle density [19], [20]. However, with an ever increasing number of vehicles, LTE networks are easily overloaded. Moreover, work in [19] shows that DSRC in conjunction with IEEE 802.11p exhibits poor performance in the event of a large number of vehicles. As a result, to remedy the drawbacks of existing vehicular networks, new ITS network architecture is needed in order to support various services under dense vehicular environments.

III. HETEROGENEOUS VEHICULAR NETWORKING ARCHITECTURE

Due to the high mobility of vehicles and the dynamic topology changes of VANETs, it is difficult to provide satisfactory ITS services only through a single wireless network. Therefore, by integrating different wireless access networks such as LTE and DSRC, HetVNETs are expected to be a good platform that can meet various demanding communications requirements of ITS services. In this section, we first present a framework of the HetVNET. Several HetVNET candidate communications techniques are then discussed for comparative purposes.

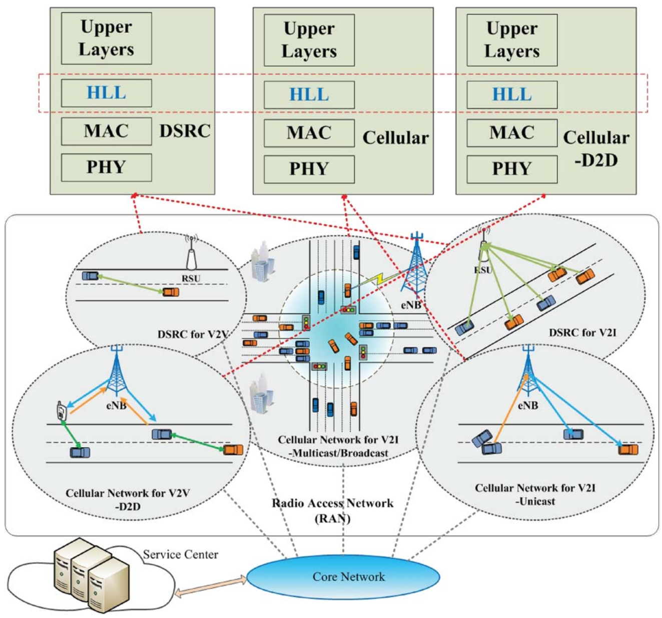

Fig. 1. Illustration of the unified HetVNET framework.

A. Framework

As illustrated in Fig. 1, a HetVNET is composed of three main components, namely a Radio Access Network (RAN), a Core Network (CN), and a Service Center (SC). Service providers can often supply a variety of services to vehicular users through the SC. The CN is a key component of the HetVNET because it provides many important functions, such as aggregation, authentication, switching and so on. In this paper, we focus only on the RAN. In a HetVNET, there are two types of communications links, i.e., V2V and V2I, which are similar to traditional vehicular networks supported by only a single communications technology [21]–[23]. V2V allows for short- and medium-range communications among vehicular users, offering low deployment costs and supporting short message delivery with low latency. V2I enables vehicles to connect to the Internet for information dissemination and infotainment via a roadside base station. Various candidate wireless access technologies can be used to support V2I and V2V communications depending on specific requirements. Thus, it is a challenging task to select an efficient and suitable radio access method that meets all distinct QoS requirements of desired services for vehicular users.

A key challenge HetVNETs face is to support a dynamic and instant composition of different networks, and to allow operators to utilize radio resources in an efficient and flexible way. Towards this end, as shown in Fig. 1, we introduce a new layer, namely the Heterogeneous Link Layer (HLL), which operates on the top of the MAC layer in each radio access network. The HLL enables unified processing, offers a unified interface to the higher layers, and can adapt to the underlying radio access techniques. In the proposed layer, we define specific functions for joint management of multi-radio resources and load sharing between different networks. These functions facilitate efficient link-layer inter-working among multiple networks. A trade-off between the performance and exchange overhead of the HetVNET should exist, which depends on the possible operational time scale of the HLL. The main objectives of the HLL functions are to enable global management of network resources, and to meet the QoS requirements of safety/non-safety services by facilitating coordination among various radio networks.

Since physical layer techniques and network layer protocols for different systems often have unique characteristics, a unified approach to enable cooperation among multiple systems is highly desirable. Through virtualization techniques, the physical wireless infrastructure and the radio resources in HetVNETs can be abstracted and isolated into a number of virtual resources, which are then shared by multiple parties through isolating each other [24]. Thus, our purpose is to introduce virtualization functions to the HLL for abstracting, slicing, isolating and sharing resources so that each wireless system in the HetVNET can be regarded as part of the entire network. However, the unique characteristics of different wireless systems, in terms of physical radio resources, MAC and network protocols, etc., make this task extremely complicated.

Virtualization can be implemented at different levels, ranging from the spectrum level through to the physical radio resource unit, which determines the flexibility of radio resource utilization. Virtualization at a higher level may reduce the flexibility of virtualization, while better multiplexing resources across slices and resulting in more feasible implementation. However, this may lead to less efficient use of resources and less strict isolation between different systems. For example, in spectrum-level slicing, resource sharing between the LTE and DSRC systems emphasizes on the data bearer instead of the physical layer technique. A vehicular user may be associated with either the LTE or DSRC system through the access control function at the HLL with the knowledge of traffic loads and resource usage of different systems. On the other hand, when wireless virtualization is implemented at a lower level with a different definition of slices, the effect may be opposite. It is possible that the physical resources that belong to one or more wireless systems are virtualized and split into virtual resource slices [25], which can be either bandwidth-based or resource-based [26]. Then, Virtual Radio Resource Allocation (VRRA) can be implemented to map between the physical and virtual links, dynamically allocating radio resources to different systems [27].

B. V2I Communications

V2I communications provide a connection with the infrastructure located on the roadside. Since the infrastructure of cellular networks has been widely deployed for the past decades, it is economically efficient to utilize cellular networks to support V2I communications [20], [28]. Another solution is to use DSRC, which is based on the IEEE 802.11p/1609 Wireless Access in Vehicular Environment (WAVE) protocols [3].

1) Cellular Networks: Cellular networks offer two transmission modes, namely unicast and multicast/broadcast, which can be utilized for V2I communications. Unicast can be used for both uplink and downlink message distributions, which is point-to-point communications between a vehicle and the base station, also known as the Envolved NodeB (eNB). On

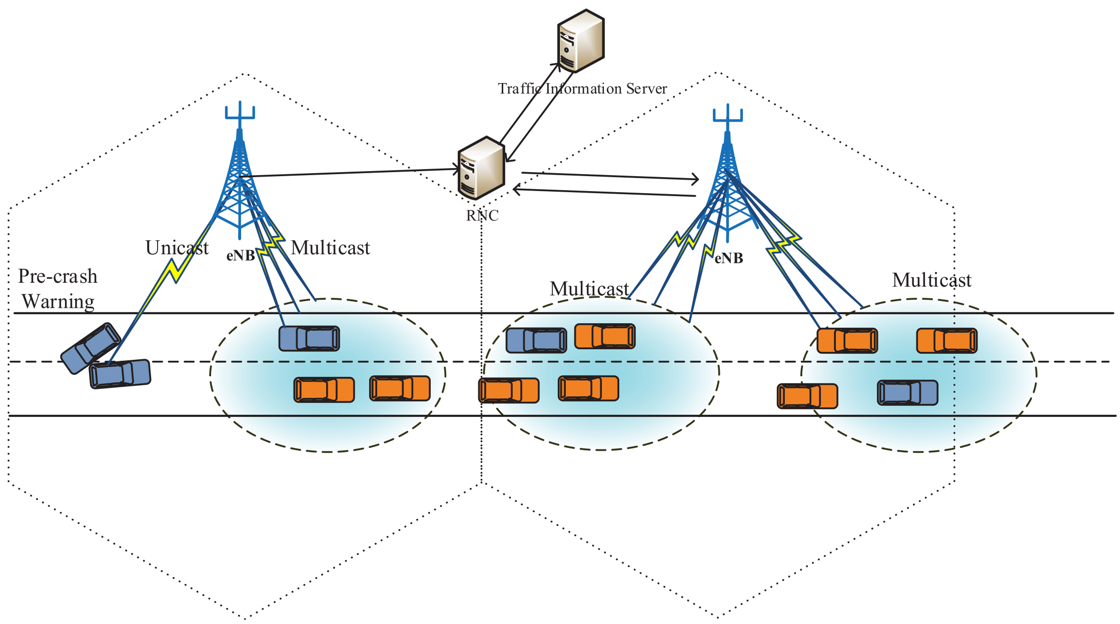

Fig. 2. Multicast and broadcast examples of eNBs in the HetVNET.

the other hand, multicast/broadcast is exclusively used for the distribution of downlink messages, which is point-to-multi-point transmission. In the broadcast scenario illustrated in Fig. 2, the Traffic Information Server may distribute the safety messages of "Pre-crash warning" to different broadcast areas via Multimedia Broadcast and Multicast Services (MBMS) [15]. Each broadcast area consists of multiple cells, which are configured by mobile operators.

a) WCDMA for V2I: Wideband Code Division Multiple Access (WCDMA) is one of the most successful cellular techniques. It is based on the Direct Sequence Code Division Multiple Access (DS-CDMA) technique, in which the signal of a physical channel is spread over wide bandwidth through multiplying with a certain channelization code, e.g., the Orthogonal Variable Spreading Factor (OVSF) code. Thus, the unique code distinguishes each physical channel in a WCDMA system. The Radio Resource Control (RRC) defines protocol states that describe which processes should be active in a Vehicle Equipment (VE), and whether a common or dedicated/shared channel is used [15]. In accordance with the inactive and active statues of VEs, the sub-states can be classified as RRC idle and RRC connected, respectively, as illustrated in Fig. 3. Typically, an inactive VE stays in the RRC Idle state, which is a power saving state with little signaling traffic. For the RRC connected state, there are four different sub-states, i.e., the CELL Dedicated Channel (CELL-DCH), CELL Forward Access Channel (CELL-FACH), CELL Paging Channel (CELL-PCH) and URA Pagin Channel (URA-PCH). When a dedicated channel is allocated to a VE, i.e., in the CELL_DCH, messages can be transmitted and received with minimal latency. After a certain inactive period A (usually two seconds), the VE transits to the CELL_FACH, which can be used to exchange control information and small amounts of user data. When the buffer in the VE or RNC exceeds a certain threshold (i.e., about 220 bytes on the uplink), the VE sends an RRC measurement report and

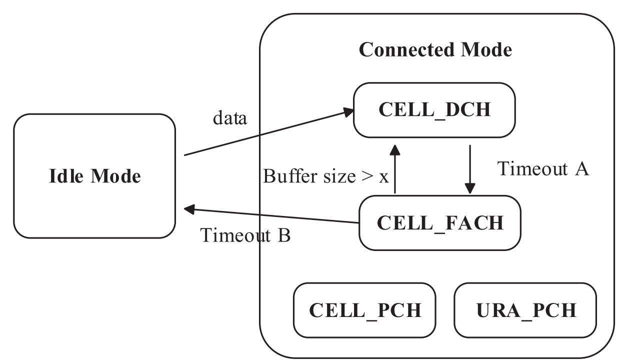

Fig. 3. Illustration of the WCDMA RRC states for V2I communications.

thus initiates a channel type switch to the CELL_DCH. In the CELL_PCH, the VE sends regular cell updates and thus becomes known at the cell level. The URAC_PCH state is similar to that of the CELL_PCH, except that the VE sends URA updates instead of cell updates.

However, there are still a few technical challenges that remain to be solved, when applying WCDMA to V2I communications. Fig. 4 shows the delivery latency of the VE under different states in WCDMA systems. In the idle state, the connection setup requires 2 $\sim$ 2.5 s, which is not presented in Fig. 4. As can be seen from the figure, the delivery latency that the VE is in all the states is larger than the allowed maximum latency for safety services, i.e., 100 ms. This means that the WCDMA system cannot well support safety services in vehicular communications. On the other hand, in most scenarios, the performance of the WCDMA system can nearly meet the latency requirement of non-safety services, i.e., no more than 500 ms. For example, if the VE is in the CELL_DCH or CELL_FACH state, the delivery latency is around 100 to 178 ms. When the VE is in the URAC_PCH state, the latency is increased to 400 $\sim$ 500 ms. The delivery latency of unicast is

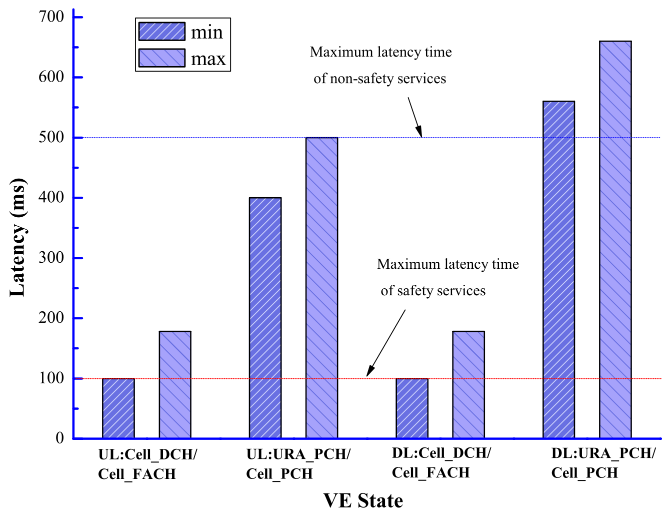

Fig. 4. Latency performances of WCDMA for different RRC states.

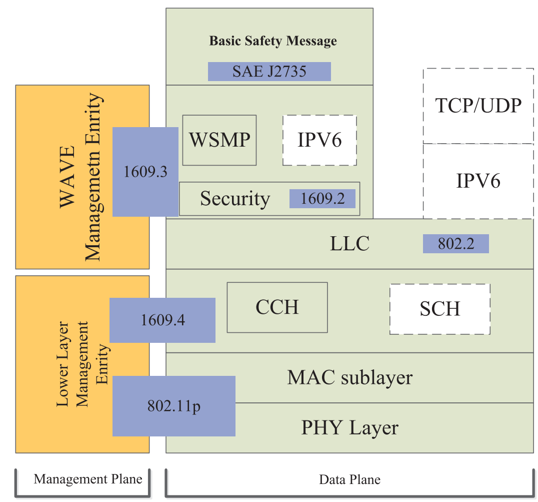

Fig. 5. Illustration of the WAVE protocol stack of the DSRC network.

similar to that of the above case. For VEs in the CELL_DCH or CELL_FACH state, the delay is similar to that of uplink transmission. For VEs in URAC_PCH, channel switching requires 300 ms. Furthermore, the paging procedure takes another 160 ms. Providing that the VEs are permanent in the CELL_DCH or CELL_FACH state, the delivery latency for most non-safety services may not the bottleneck. In fact, the capacity of the WCDMA system is limited, in which a large number of VEs cannot always remain connected, i.e., in the CELL_DCH or CELL_FACH sub-state. Therefore, the number of VEs simultaneously in CELL_DCH and CELL_FACH becomes a major limiting factor for non-safety services in the WCDMA system.

b) LTE for V2I: As stated in [29], LTE can provide uplink data rates up to 50 Mbps, and downlink data rates up to 100 Mbps with a bandwidth of 20 MHz, and support a maximum mobile speed of 350 km per hour. The flat architecture of the LTE system is attributed to the low transmission latency, e.g., the theoretical round-trip time is lower than 10 ms, and the transmission latency in the RAN is up to 100 ms [2]. Therefore, LTE is envisioned to well support V2I communications. Especially, in the initial deployment stage of vehicular networks, LTE is expected to play a crucial role in supporting vehicular services. This could first take place in rural areas, where the vehicle density is low.

In general, LTE networks are able to provide high capacity with wide coverage. For instance, LTE can support up to 1200 vehicles per cell in rural environments with a uplink delay under 55 ms and one CAM per second [15]. Besides this, it also can provide a robust mechanism for mobility management. Experiments of trialing LTE in vehicles to support various applications such as infotainment, diagnostics and navigation, have been carried out. The results show that the LTE system is able to provide a data rate of 10 Mbps with a speed up to 140 km per hour [30]. LTE can be particularly helpful at intersections by enabling a reliable exchange of cross-traffic assistance applications [2]. In [31], the authors analyze the suitability of LTE for vehicular safety communications at intersections. The analysis shows that the LTE system can support a demand of transmitting approximate 1500 CAMs per second per cell. Furthermore, the Evolved Multimedia Broadcast and Multicast Service (eMBMS) is an effective way to support multicast or broadcast services in high density vehicle environments.

Nevertheless, several problems need to be solved before LTE systems can be widely used for V2I communications [2]. Firstly, the MAC layer of LTE lacks efficient scheduling mechanisms for a proper mapping of vehicular traffic features to the existing QoS Class Identifier (QCI) and/or the new QCI definition. Secondly, when the eMBMS is employed to broadcast vehicular service messages, the signaling overhead resultant from the subscribing and joining procedures to the multicast service is overly large. Thus, it is essential to design lightweight joining/leaving procedures for dynamic groups of vehicles. The challenge is how to ensure transmission efficiency while reducing the overhead. Meanwhile, traditional applications offered by LTE networks may be subject different levels of potential impact due to the new kind of traffic especially in the heavy load cases [32].

2) DSRC: Fig. 5 illustrates the WAVE protocols in DSRC networks. In order to achieve robust connections and fast setup for moving vehicles, the half-clocked mode with the 10 MHz bandwidth option in the physical layer, termed IEEE 802.11p, is employed. Considering the characteristics of vehicular environments, the Enhanced Distributed Channel Access (EDCA) mechanism in IEEE 802.11e with small modifications is adopted to satisfy the strict QoS requirements of the MAC layer [33]. In order to meet the requirements of vehicular communications, a suite of standards are defined by the IEEE 1609 Working Group for DSRC networks, i.e., 1609.4 for Channel Switching, 1609.3 for Network Services including the WAVE Short Message Protocol (WSMP), and 1609.2 for Security Services. In order to avoid the packetization overhead, the minimum WSM overhead is 5 bytes, and even with optional extensions it will rarely exceed 20 bytes. The minimum overhead associated with UDP/IPv6 is 52 bytes. In addition, at the network and transport layers, IPv4, TCP and UDP are also employed on the top of the stack. The SAE J2735 Message Set Dictionary standard specifies a set of message formats that support a variety of vehicle-based applications [3]. DSRC networks can operate well under sparse nomadic deployment with stationary channels. However, vehicular communications may take place over severe frequency-selective multipath and fast fading channels, as well as in densely populated environments. Therefore, there is large room for improvement and enhancement for DSRC. Next, several problems of DSRC networks when used for V2I communications will be discussed.

- **Sparse pilot design**: The dynamic V2I environment with alarge multipath delay spread and high mobility results in highly time-frequency selective vehicular communication channels. In typical application scenarios, 50% coherence bandwidth is estimated roughly in the order of 1 MHz, and 50% of the coherence time can be as short as 0.2 ms [6]. Then, a typical packet transmission period in DSRC, e.g., approximately 0.5 ms with a packet size of 300 bytes, QPSK modulation, and a code rate of 1/2, is larger than the coherence time. Moreover, the inter-spacing between two pilot subcarriers defined in IEEE 802.11p, i.e., 2.4 MHz, is larger than the coherence bandwidth. Thus, such a sparse pilot design is insufficient to accurately estimate the channel state information. The only way is to improve the receiver performance at the expense of implementation complexity.
- **Channel congestion**: When the Carrier Sense Multiple Access (CSMA) mechanism is employed at the MAC layer of the DSRC network, the probability of collision increases rapidly with the large number of vehicles in the network, resulting in large end-to-end latency and low channel utilization [19]. Therefore, channel congestion has to be dealt with so as to guarantee QoS requirements of vehicular services. One of the approaches is to reduce the number of transmitters to within the carrier sense range of each device [34], [35].
- **Unbalanced link**: Due to the different hardware configurations between the On-Board Unit (OBU) in the vehicle and the Roadside Unit (RSU), the coverage areas of the OBU and RSU are obviously different, causing the so-called "unbalanced link" problem. For example, the reliable radio communications range from the RSU to OBU is up to 1,100 meters, while that from the OBU to RSU is only up to 400 meters. Thus, the OBU may commence data transmission after moving into the broadcast range of an RSU, even at a distance that is too far for the RSU to receive data from the OBU [36], [37]. Then, communications quality deteriorates due to such "unbalanced links".
- **Prioritization and service selection**: This situation only arises in the overlapped coverage area of multiple RSUs. When an OBU moves into such an overlapped area, various services are provided by different RSUs. The OBU may create a WAVE Basic Service Set (WBSS) with the first RSU it hears. It may switch to another RSU only if that RSU is advertising a service with a higher priority. If the services from the other RSUs have lower priorities compared with the first one, the OBU does not create a WBSS with any other RSUs, and may miss any service channel messages or services offered by the other RSUs [36]. The wildcard WBSS is an efficient method to resolve this problem. In the event of overlapped coverage, an RSU can configure its Basic Service Set Identification (BSSID) with wildcard BSSID, i.e., 0xFFFFFF, so that OBUs already in a WBSS can still receive frames, and do not miss any services offered by the other RSUs which use the wildcard BSSID [3].

C. V2V Communications

V2V communications refer to direct connection between vehicles. It aims at minimizing traffic accidents and improving traffic efficiency. Accidents caused by slow vehicles or non-sight vehicles may be avoided by exchanging information on velocity, acceleration, and vehicle status with neighboring vehicles. Intensive investigations and trials on V2V have been carried out with the objective of supporting traffic services such as slow vehicle warning, abnormal vehicle status warning and so on [38]. In this subsection, two candidate techniques for V2V communications are discussed in detail.

1) LTE D2D: Device-to-device communications underlaying a cellular network has been proposed as a mean of taking advantage of the physical proximity of communicating devices in LTE systems [39], [40]. In the D2D mode, User Equipment (UE)s in close proximity can directly communicate with each other. As a candidate technique supporting V2V in HetVNETs, D2D communications in LTE face several challenges.

Since D2D communications links share the same radio resources with other links in the LTE network, interference is a major issue when employing D2D in HetVNETs. For example, in the FDD system, when a D2D link uses downlink resources, the donor eNB may cause severe interference to the D2D pair. Moreover, the interference from neighboring cells is another problem facing D2D communications. On the other hand, if a D2D pair uses uplink resources, the receiving end of the D2D pair may suffer strong interference from a cellular UE using the same uplink resources.

Most D2D devices in LTE systems are usually static or of low speed mobility. However, vehicles usually move in medium or high speeds, which may severely degrade the performance of D2D communications. Specifically, existing peer and service discovery of D2D communications does not work well in vehicular environments. In the D2D mode, before any two vehicles can directly communicate with each other, they need to first discover the existence of its peer, which is a time-consuming procedure. As specified in [41], the discovery period usually is set to 1, 2, 5, or 10 s. Since the survival time of available connectivity between two vehicles is very short in vehicular environments, it is very difficult for the existing D2D discovery mechanism to meet the strict QoS requirements of safety services. Taking as an example the safety user case of hard-braking warning, we assume that two vehicles move at a speed of 120 km/h (i.e., 33.3 m/s) along the same direction with an inter-vehicle spacing of 30 meter. If the front vehicle starts hard-braking with a deceleration of 4 m/s^2 and the reaction time of the rear vehicle's driver is about 1.5 s [42], the time remained for message transmission is only around 3 s. Thus, in many cases, the D2D discovery time is larger than the time allocated

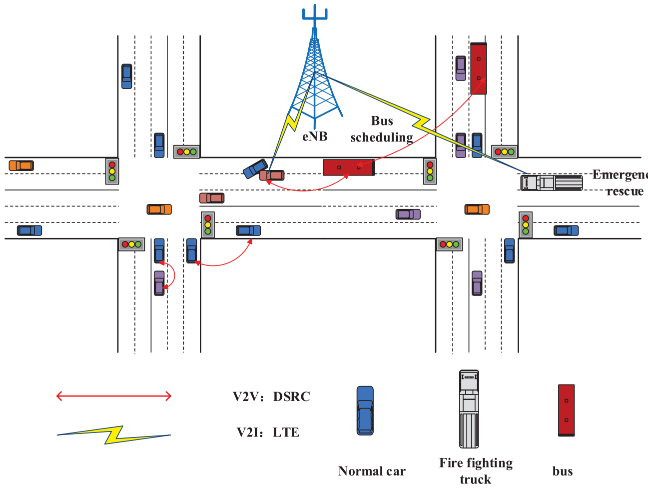

Fig. 6. Illustration of an urban intersection scenario.

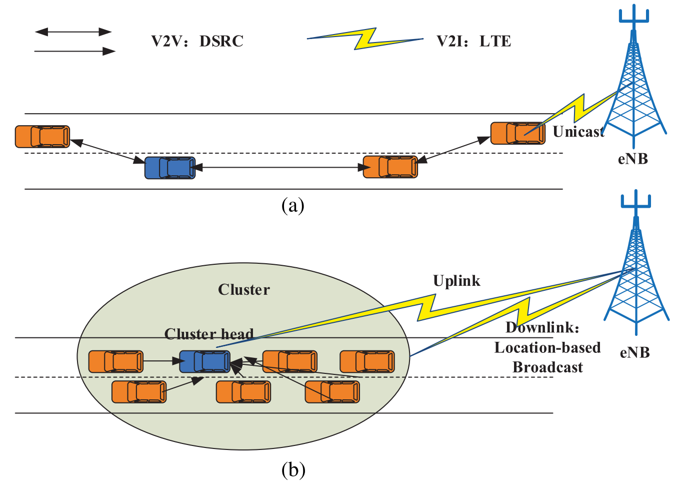

Fig. 7. Illustration of an expressway scenario. (a) Free flow. (b) Synchronized flow.

for message transmission, which is not acceptable for delivering safety messages with strict QoS requirements.

2) DSRC: DSRC has been shown to be effective in supporting both safety and non-safety services in V2V communications. Firstly, V2V communications usually employ a decentralized approach, in which the network is autonomous and needs no external infrastructure to organize itself. Secondly, since both entities in V2V communications are vehicles, there is no aforementioned "unbalanced link" problem in V2I communications. Furthermore, V2V communications based on DSRC do not interfere with cellular networks due to the use of different frequency bands. However, there are still several challenges for using DSRC in V2V communications [5], [8], [43]. For example, in a densely populated vehicular environment, collisions occur so frequently attributed to the limitation of the CSMA mechanism that the overall performance significantly deteriorates.

D. Typical Application Scenarios

Each candidate technique for either V2I or V2V communications has its own advantages and disadvantages. For different application scenarios in HetVNETs, any candidate techniques may be chosen according to their characteristics, and they can work together with the aid of the HLL functions. Two examples are given below to illustrate the feasibility of HetVNETs for ITS services.

1) Urban Intersection Scenario: Fig. 6 depicts a safety driving user case in an urban intersection scenario. Under this scenario, DSRC is used for the communications between vehicles, i.e., V2V communications, while LTE is employed to provide connections between vehicles and the eNBs, i.e., V2I communications. The following cases (but not limited to) have to be considered for safety driving in such an urban intersection:

- **Collaboration between vehicle and eNB**: Pedestrians and obstacles are detected and reported to the eNB by vehicles or pedestrians. There are several methods to report roadwork, obstacles, and accidents to the eNB [1]. The traditional method is that the witness sends the information to the eNB. A new method of notification may be like eCall [1], which is the most important road safety efforts made under the European Union's eSafety initiative. Based on the information (speed, direction, or target destination) that are periodically sent by vehicles, the eNB can predict mobility via some prediction algorithm, e.g., road-topology-based [44] and behavior-based mobility prediction [45]. Then, in order to to avoid traffic congestion or accidents, the eNB can broadcast existing dead zones to the vehicles that may go through its coverage area.
- **Collaboration between vehicles**: The front vehicle is able to inform the following vehicles of sharp stops, and thus avoids the rear-end problem. Moreover, vehicles involved in a car accident may broadcast the occurrence of such an event so as to prevent further collisions; and
- **Traffic light management**: The duration of a traffic signal can be intelligently adjusted to pass high priority vehicles, such as fire-fighting trucks and buses.

2) Expressway Scenario: In the expressway scenario, there are generally two types of traffic flows, i.e., free and synchronized flows as shown in Fig. 7(a) and (b), respectively. These two vehicle flows may switch to each other.

- **Free flow**: In this flow, the number of vehicles in the HetVNET is small, and the interactions among vehicles are infrequent. Therefore, vehicles move with high speeds and the network topology changes rapidly so that the radio links are unreliable. In this case, the mobile cellular network such as the LTE system is preferred for V2I communication. However, under specific environments, e.g., in tunnels, the received signal from the eNB is not of high quality at the vehicles. Then, the vehicles may help one another through multi-hop DSRC transmission before connecting to the eNB eventually [46]; and
- **Synchronized flow**: The traffic density of a synchronized flow is much higher, meaning that broadcast messages

TABLE III
ADVANTAGES AND CHALLENGES OF CANDIDATE TECHNIQUES FOR THE HETVNET

Communications mode	LTE/LTE D2D	DSRC
V2I Communications	**Advantages:** • Large coverage • Robust mechanism for mobility management • High downlink and uplink capacity • Centralized and flat architecture • High-efficiency eMBMS **Challenges:** • Lack of efficient scheduling schemes for ITS services • Users in the idle state cause high delay in disseminating messages • Easily overloaded in high density environments	**Advantages:** • Easy deployment and low costs • Suitable for local message dissemination i.e., traffic signal, parking information **Challenges:** • Sparse pilot design • Serious channel congestion with a large number of vehicles • Unbalanced link • Prioritization and service selection • Broadcast storm and hidden node problems
V2V Communications	**Advantages:** • High spectrum efficiency • High energy efficiency • Efficient scheduling on D2D resources **Challenges:** • Interference between D2D pair and other users, • Peer and service discovery is time-consuming, • High speed of vehicles seriously degrades the performance	**Advantages:** • Easy deployment and low costs • Ad-hoc mode • The overhead of WSM message is low **Challenges:** • Sparse pilot design • Serious channel congestion with large number of vehicles • Adjacent band leakage in multi-channel operation • Broadcast storm and hidden node problems

are likely to be flooded. Due to traffic jam, vehicle speeds are low, and the random behaviour of vehicles can be modelled by a car-following behaviour, which means the radio links among vehicles become relatively static. With the aid of DSRC, clustering mechanisms may be an efficient information dissemination method. Vehicles within the transmission range of DSRC form a cluster, and a Cluster Head (CH) is elected via a certain algorithm. Then, on the V2I uplink, the CHs aggregates the data of their cluster members before forwarding it to the eNB via LTE. In this way, the overall LTE traffic can be reduced compared to separate transmissions by individual vehicular users [47]. For the downlink, the multicast of the LTE network can be used to distribute messages.

E. Summary

Since a single wireless communication network, either DSRC or LTE, can not well satisfy the QoS requirements of ITS services, we propose a HetVNET framework instead. Several candidates, e.g., DSRC and LTE cellular networks, are discussed and summarized in Table III. It can be seen that LTE is much more suitable for V2I communications than DSRC. On the contrary, DSRC is more practical for V2V communications than LTE D2D. The collaborations between heterogeneous networks are essential for HetVNETs.

IV. MAC AND NETWORKING DESIGN CHALLENGES IN HETVNETS

There exist a large number of issues to be addressed in the HetVNET. In this section, we restrict our discussions to only those related to MAC and networking designs.

A. Multi-Channel Access

A vehicular network has to guarantee safety-related applications first before providing other data services. Safety-related applications, such as the collision avoidance alert, urgent brake alert, and roadside hazards warning, require instant message delivery with a short delay, which should not be interfered with non-safety related applications. Therefore, DSRC with low end-to-end delay is preferred to be used among vehicles. One Control Channel (CCH) is assigned to transmit critical messages such as safety warning, while six Service Channels (SHs) are used for various data service applications, such as point of interest notification, and map downloading and updating. Moreover, an efficient multi-channel MAC scheme is essential to guaranteeing the QoS requirements of safety-related applications.

1) Multi-Channel in the WAVE Protocol: IEEE 1609.4 defines a management extension to MAC, which allows a system with one or more radios to effectively switch among them. We give a brief overview of the multi-channel operation in IEEE 1609.4, followed by a discussion of existing problems.

a) Multi-channel in IEEE 1609.4: Fig. 8 illustrates the channel switching mechanism defined in IEEE 1609.4, which enables multiple vehicle nodes with simultaneous alternating operations on the CCH and an SCH. As safety-related applications usually require a broadcast rate of about 10 Hz, a Sync Interval is set to 100 ms. A Synchronization (Sync) Interval is comprised of a CCH Interval and a SCH Interval, each lasting for 50 ms in the alternating access mode. Vehicles are synchronized with the Universal Coordinated Time (UTC) obtained from sources like GPS. This approach separates flows of data traffic with distinct QoS requirements. High priority

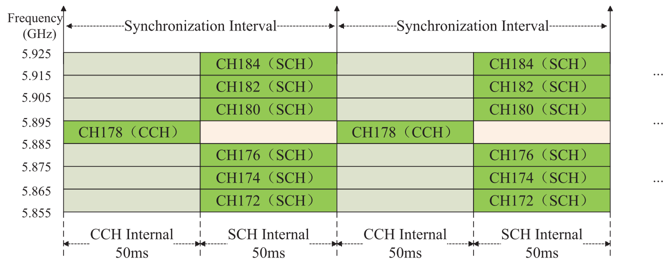

Fig. 8. Illustration of the channel switching mechanism in IEEE 1609.4.

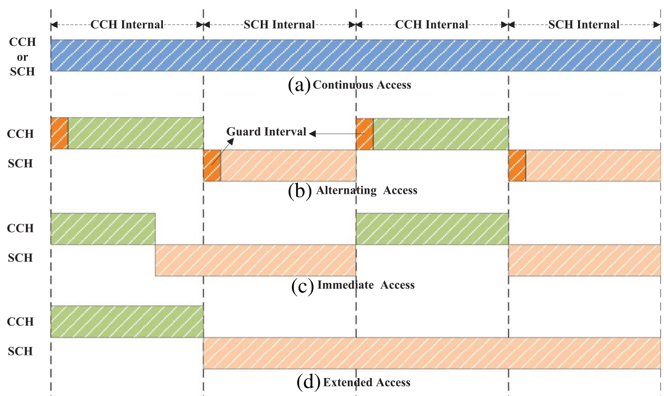

Fig. 9. Illustration of channel access methods in IEEE 1609.4.

data such as the "Heartbeat" broadcast messages and WAVE Service Advertisement (WSA) frames, are delivered during the CCH interval, while non-safety packets are sent during the SCH interval.

As illustrated in Fig. 9, there are four types of channel access methods, i.e., continuous access, alternating access, immediate access and extended access. Accounting for the radio switch delay and timer drift among different vehicles, a Guard Interval (GI) is inserted at the beginning of each channel interval, which is usually 4 ms. Data transmission may not start until the GI reaches the end. During the GI, no transmission is allowed, and the wireless medium is flagged as busy to the MAC layer. Thus, a random back-off procedure is invoked after the GI expires to prevent heavy collisions caused by multiple switching devices attempting to transmit simultaneously at the end of the GI. However, when a large number of vehicles have buffered data, collisions are difficult to avoid [48].

Channel switching is designed to support data exchanges involving one or more switching devices with concurrent alternating operations on the CCH and an SCH. This allows, for example, a single-PHY device access to high priority data and management traffic during the CCH interval, as well as high layer traffic during the SCH interval. The continuous access option is rarely used, since it misses the information from either the SCH or CCH. Under normal conditions, the basic option, i.e., the alternative access, is adopted. For services that need to transmit a large amount of data, the extended access becomes a better choice since it improves the transmission rate of the SCH. The immediate access is suitable for emergency services due to its immediate switch feature.

b) Problems in IEEE 1609.4: The existing channel access methods of IEEE 1609.4 suffer from a few drawbacks, i.e., [48], [49],

1) Channel utilization degrades with an increasing number of vehicles, because more collisions occur due to the CSMA-based MAC scheme applied;
2) The round-robin concurrent channel switching scheme in IEEE 1609.4 may cause the so-called start-of-interval collision flooding problem. During the CCH interval, OBUs that want to send IP data have to wait until an SCH Interval. Therefore, they tend to transmit messages at the beginning of the SCH interval simultaneously, causing many potential collisions;
3) Due to vehicle mobility, the hidden node problem is more severe with a dynamic vehicular topology than in traditional static environments;
4) Frequent Request-to-Sent (RTS)/Clear-to-Sent (CTS) exchanges may result in a relatively large overhead; and
5) Due to the limited communications time and the non-association strategy of IEEE 1609.4, an OBU or RSU cannot maintain a status table of its neighbors, making it very difficult and inefficient to implement node-by-node channel access scheduling.

2) Improved Multi-channel MAC for Vehicular Networks: IEEE 802.11p/1609.4 provides only basic ways of multi-channel operations for vehicular communications. Due to the above problems, much attention has been paid to improve the access performance. In general, there are three types of schemes for reducing the collisions of safety messages and improving data service efficiency. Details are given as follows.

a) Type I—Dedicated time slots: A typical scheme to make safety messages more reliable is to dedicate specific resources to safety related data [50]. For example, in Dedicated Multi-Channel MAC (DMMAC) [50], the channel access time is equally divided into multiple Sync Intervals, each of which consists of a CCH interval (CCHI) and an SCH interval (SCHI) of the same length. Unlike IEEE 1609.4, the CCHI can be further divided into an Adaptive Broadcast Frame (ABF) and a Contention-based Reservation Period (CRP). Moreover, the ABF consists of multiple time slots, which are dynamically reserved by an active vehicle for contention-free delivery of safety messages or other control messages. The slot reservation process is decentralized, similar to Reliable R-ALOHA. This provides collision-free and delay-bounded transmissions for safety applications under various traffic conditions.

b) Type II—Coordinator-based: In dense traffic vehicular networks, a central coordinator managing the local network, similar to the Point Coordination Function (PCF) in IEEE 802.11, can help improve efficiency and performance. In [28], an RSU maintains several tables, which contain information of vehicles associated with the RSU and service requirements of these vehicles, and polls each vehicle one by one in a collision-free period during the CCH interval. A Multi-Channel Token Ring Protocol (MCTRP) is designed in [51]. The founder, which initiates a ring, collects and broadcasts emergency messages to other rings, while a vehicle that wants non-safety

TABLE IV
IMPROVED MULTI-CHANNEL MAC PROTOCOLS

Category	Scheme name	Coordinated	Ad-Hoc	SR	MR	Directional	Asynchronous	Safety	Non-safety
Type I - Dedicated time slots	DMMAC [50]	-	√	√	-	-	-	√	-
Type II - Coordinator-based	MCTRP [51]	-	√	-	√	-	-	√	√
	CBMCCP [52]	√	-	-	√	-	-	√	√
	CMMP [53]	√	-	-	√	-	-	-	√
Type III - Contention-based	MCBS [54]	-	√	-	√	-	-	√	-
	EMcMAC [55]	-	√	√	-	-	-	√	√
	QVCI [56]	-	√	√	-	-	√	√	-
	VMMAC [57]	-	√	√	-	√	√	-	-
	CROCS [58]	-	√	√	-	-	-	-	√

data exchange has to wait until the token is passed to it. In the Cluster-based Multichannel Communications Protocol (CBMCCP) [52], the elected Cluster Head (CH) functions as an coordinator to collect/deliver real-time safety messages within its own cluster, and to forward consolidated safety messages to neighboring CHs. A CH vehicle also controls channel assignment for non-real-time data transmission. In another cluster-based MAC scheme dubbed the Cluster-based Multi-Channel MAC Protocol (CMMP) [53], the CH manages the channel status and periodically broadcasts a channel usage list. Before data transmission, each vehicle sends Request Channel Assignment (RCA) in the CCH to the CH in order to obtain available channel resources, which is determined by the cluster head in consideration of the received requests and channel usage condition.

c) Type III—Contention-based: This type includes diverse contention-based MAC schemes. In order to reduce collisions and increase channel utilization, the Multi-Channel Beaconing Service (MCBS) is proposed, where the service period is divided into the collision detection and collision avoidance phases [54]. Each vehicle sends beacons with a predefined transmission interval specified by the lifetime of a beacon in the collision detection phase. After receiving a beacon, each vehicle updates its neighbor table and calculates the probability of a collision. After identifying a potential collision risk, the collision avoidance phase is invoked. In the second phase, it designs a dedicated bi-directional communications process between vehicles. The main objective of the MCBS is to provide benefits for vehicles in critical situations without interfering with the communications of their neighbors. In [55], the Enhanced Multichannel MAC (EMcMAC) protocol is proposed, where Extended Transmission is designed that allows nodes to extend their services in an SCH interval to the CCH interval. Safety messages have to be transmitted twice. It greatly improves throughput while still guaranteeing the dissemination of safety message. In [56], a CCH interval is further divided into the safety and WSA intervals. Parameters including the CCH/SCH intervals and the minimum contention window size are dynamically adjustable to ensure high saturation throughput and prioritized transmission of critical safety information. In addition, spacial diversity and cognitive radio techniques can also be used to enhance channel utilization [57], [58].

3) Summary: Table IV summarizes several MAC schemes for improving the performance in terms of latency and channel utilization for vehicular communications. Different protocols have various requirements on the OBU, e.g., a Single Radio (SR) device or Multi-Radio (MR) device. In a dense vehicular environment, the reservation and coordination process may result in considerable overhead with the **Type I** and **Type II** schemes. On the other hand, with an increasing number of vehicles, collisions become more severe for the **Type III** scheme. Therefore, regarding MAC schemes in the HetVNET, more efforts are needed to cope with the dense vehicle condition. Thanks to the introduction of the HLL in HetVNETs, channel congestion may be improved. For example, when a service request arrives at the HLL, the HLL may allocate it to one of the suitable wireless systems.

B. Broadcast/Multicast Protocols

Broadcast/Multicast services are important in vehicular networks, e.g., road vehicle safety, road navigation support, periodic beacon broadcast, emergency messages dissemination, etc. Therefore, efficient broadcast mechanisms are crucial to minimizing the rate of accidents, enhance traffic efficiency, and improve the travel experience of vehicular users.

Vehicular environments have their unique characteristics in comparison to other wireless networking environments. In a vehicular network, power supply is abundant and mobility trajectory is predictable, which are conducive to implementing broadcast/multicast services [59]. However, there are also several performance-limiting factors such as the large-scale network size, high mobility condition, dynamic network topology, and unreliable connectivity [43].

1) MBMS in LTE: LTE can support high-quality multicast and broadcast transmission via the eMBMS functions in the CN and RAN [2]. It is capable of sending data only once to a set of users registered to the offered service, instead of sending it to each node individually. In the LTE system, the transmission of eMBMS data packets is coordinated among a group of tightly synchronized cells, which transmit identical signals on exactly the same time and frequency resources. The signals from these cells are combined over the air, resulting in an increased signal strength. From the terminal perspective, all signals appear to be transmitted from a single large cell. Such a transmission mode is known as the MBMS Single Frequency Network (MBSFN) operation [15].

The eMBMS can be one of possible solutions for the distribution of vehicular services. Traffic management, safety-related and infotainment services can be more efficiently supported by eMBMS in lieu of unicast. In order to guarantee reliable multicast services to each MBMS subscriber, a conservative approach is used for data rate selection. As a consequence, Adaptive Modulation and Coding (AMC) is provided on a group basis, and system performance is constrained by the user with the worst channel conditions, resulting in increased user dissatisfaction [60]. On the other hand, efficient broadcast and multicast delivery of data may facilitate the development of new services and reinforce the transmission capability of current ITS services.

2) Challenges and Solutions for eMBMS in LTE: Challenges exist when applying eMBMS to message dissemination in HetVNETs. Firstly, since service data are sent by multiple eNBs, the propagation delay experienced at the vehicular user may be large. To tackle this issue, an extended cyclic prefix is defined for the eMBMS configuration in LTE, in which only 12 instead of 14 OFDM symbols can be transmitted per sub-frame. Moreover, the LTE system is highly susceptible to Inter-Carrier Interference (ICI) in high mobility scenarios due to large Doppler spreads. Thus, low carrier frequencies such as 800 MHz with relatively smaller Doppler spreads are recommended for vehicular services supported by the LTE system. On the other hand, thanks to high mobility, vehicles frequently subscribe to and join in multicast services on a per-user basis. Thus, the signaling overhead increases rapidly. In order to deal with this issue, a dedicated MBMS carrier for downlink only transmission has been proposed in [15].

3) Broadcast Protocol in DSRC: A DSRC system is designed for safety broadcast services. However, when vehicular density is high, the successful message reception probability in IEEE 802.11-based broadcast can be lower than 30% under saturation conditions [61]. Thus, several challenges remain for existing broadcast protocols to offer reliable and timely services, i.e.,

a) Hidden node problem: The RTS/CTS handshake protocol is a mechanism proposed to circumvent the hidden node problem. However, broadcast packets have more than one destination, and the RTS/CTS and Acknowledgement (ACK) packets may cause packet storms at the transmitter. Thus, the RTS/CTS handshake is not well suited for broadcasting as it is conductive to a more severe hidden node problem than unicast.

b) Fixed size of contention window (CW): The lack of an ACK mechanism causes the inability to determine whether a message delivery is successful or not. Thus, regardless of the delivery status, it is impossible to change the CW size for broadcast once the original size is decided. This is the major reason of congestion in broadcast, resulting in a significant reduction in channel utilization [62].

c) Limited lifetime of safety messages: In a vehicular network, beacons carry not only broadcast information, but also a vehicle's status information. Thus, a beacon contains data from the OBU such as the vehicle speed and location. Due to the highly dynamic network topology, beacon messages are useful only for a limited time [63]. If such a message cannot be transmitted before the next beacon is generated, the information it contains becomes invalid. Therefore, this brings in more strict requirements when the broadcast mechanism is adopted in the vehicular network.

d) Broadcast storm problem: The broadcast storm is a well-known problem, caused by excessive retransmissions [7]. In vehicular networks, this may happen when vehicles try to send information packets related to traffic events. To keep the information alive, each vehicle receiving the messages attempts to flood or forward the same packets to all the other vehicles within its coverage range via the CCH/SCH channel. This leads to large end-to-end latency and low channel utilization. The circumstance becomes worse when the vehicle density is high.

4) Improved Broadcast Protocols for DSRC: The main objective of broadcast protocols is to provide reliable packet transmission with minimum latency, maximum throughput, and low communications overhead. In accordance with the number of broadcast hops, broadcast protocols can be broadly classified into one-hop broadcast and multi-hop broadcast protocols. They can also be divided into centralized and decentralized broadcast protocols based on the presence or absence of a centralized broadcast node. In this subsection, from the viewpoint of factors that may impact on the forwarding decision, we classify broadcast/multicast protocols into the following categories, i.e., road segmentation-based, link-based, and threshold-based.

a) Road segmentation-based method: Since rapid changes in network topology and node movement in vehicular networks, it is difficult to determine which node is used to forward packets based only on the topology. To tackle this issue, a multi-hop broadcast protocol, termed Urban Multi-hop Broadcast (UMB) is proposed in [64]. This protocol assigns the task of forwarding and acknowledging broadcast packets to only a single vehicle by dividing the road portion inside the transmission range into segments, and choosing the vehicle in the furthest non-empty segment without *a priori* topology information. To guarantee the reliability of multi-hop broadcast, an ACK packet is feedback to the forwarding vehicle, and a mechanism similar to the RTS/CTS handshake is also employed to avoid collisions due to hidden nodes. However, there is usually no Line-of-Sight (LoS) link between the vehicles nearby the intersection. To ensure broadcast in this situation, repeaters are installed at the intersection to disseminate messages omni-directionally [65]. In this way, packet delivery of high success and efficient channel utilization even with high packet loads are achievable with a fully ad-hoc intersection broadcast mechanism. However, none of these protocols have taken the link status into account when selecting the forwarding vehicle.

b) Link-based method: Various factors such as the link status can be considered in choosing a forward delivery node in multi-hop broadcast schemes, e.g., the Link-based Distributed Multi-hop Broadcast scheme (LDMB) [66]. This forward scheme is completely distributed without the need of any handshake. Each vehicle receiving an emergency message estimates its link status firstly, and then calculates the waiting time before forwarding this message. This scheme takes the link status into consideration, which is concerned mainly with the distance between the sender and receiver, transmission power, transmission rate, and vehicular traffic density. Compared with other multi-hop broadcast protocols, LDMB offers similar performance in reliability while enabling lower latency.

c) Threshold-based method: Aside from the link status, other factors such as speed deviation, message priority and vehicle density may also affect broadcast performance. A threshold can be yielded using various functions to determine whether a node should forward the broadcast message. In [67], a decision threshold function is designed, which simultaneously

TABLE V
SUMMARY OF BROADCAST PROTOCOLS IN HETVNETS

Technology	Category	Broadcast Protocol	Hand shake	Service	Target Deployment	Feature	Objectives
LTE	eMBMS [15]	eMBMS [15]	×	Safety and traffic efficiency services	Highway, urban	Centralized architecture, mobility management, high capacity and large coverage	Reinforce the transmission capability, support low-delay communications
DSRC	Road-segmentation -based method	UMB [64]	√	Not mentioned	Urban, nonline-of-sight intersection	Need repeaters installed at the intersection	Solve the hidden terminal, broadcast storm, reliability problems
		AMB [65]	√	Not mentioned	Urban, nonline-of-sight intersection	Vehicle as repeater at the intersection	Solve the hidden terminal problem, broadcast storm, reliability problems
	Link-based method	LDMB [66]	×	Emergency /safety services	Not mentioned	Link status is considered	Reinforce reliability, reduce transmission delay
	Threshold -based method	DADCQ [67]	×	Not mentioned	Highway, urban	Adaptive to node density and distribution, channel quality	Improve reachability and reduce bandwidth consumption
		HMB [68]	√	Safety services	Highway	Passive forwarder selection and acknowledgment	Solve the broadcast storm, hidden node, and reliability problems
		Stochastic Broadcast [69]	×	Not mentioned	Not mentioned	Adjust the retransmit probability according to node density	Reduce overhand, improve reachability and bandwidth utilization

adapts to the number of neighbors, the node clustering factor and the Rician fading parameter. In [68], vehicles make their own decisions to forward and acknowledge received packets without the knowledge of any topology information. The decision is made according to the distance from the source, the Received Signal Strength Indicator (RSSI) of messages, the speed deviation between the sender and forwarder, and the priority of the received messages. However, the performance is still dependent on vehicle density. To solve this problem, a stochastic broadcast scheme is proposed in [69] as an efficient solution to the data dissemination problem. It instructs nodes to rebroadcast messages with a retransmission probability. Unfortunately, choosing a proper retransmission probability is not a simple task. Towards this end, the similarity between stochastic broadcast and the theory of continuum percolation is demonstrated, and the crucial percolation threshold (about 4.5 neighbors on average) in continuum percolation is obtained. Then, the retransmission probability is adjusted so that the apparent density of the network approaches the critical threshold for ensuring greater success with minimum bandwidth.

5) Summary: Reliable packet transmission with minimum transmission delay is the main challenge in designing multi-hop broadcast schemes for HetVNETs. Besides, channel utilization and signal overhead must be taken into account. Meanwhile, many issues, such as the hidden terminal and broadcast storm problems, need to be addressed urgently. In this subsection, we investigate some existing multi-hop broadcast protocols for vehicular networks based upon three groups, i.e., the road segmentation-based, link-based, and threshold-based methods, as shown in Table V. Most of the above protocols solve only part of these issues with some limitations. For example, topology information is imperative for the road segmentation-based method. However, accurate topology information is difficult to obtain in vehicular environments. Fast moving vehicles have difficulties in accurately estimate the link quality, which impacts on the performance of the link-based method. With regards to the threshold-based method, vehicle density is a performance bottleneck. Furthermore, the performance and problems when eMBMS is applied in vehicle networks have also been discussed. The signalling overhead due to frequent joining in and leaving eMBMS services and the larger propagation delay caused by multiple-eNBs coordinated broadcast have to be dealt with. How to take advantage of both DSRC and LTE while tackling these challenging issues is still a hard “nut” to crack.

C. Resource Allocation and QoS Support

Resource allocation schemes are designed to meet QoS requirements of the safety and non-safety services in vehicular networks. The EDCA mechanism is proposed in the IEEE 802.11x series of standards, while the QoS Class Identifier (QCI) and bearer selection are designed for cellular networks. However, there is a lack of efficient resource allocation schemes in HetVNETs to date. In this subsection, we will discuss the solutions and performances using the two network technologies, i.e., LTE and DSRC.

1) QCI in LTE: QoS support is enabled in LTE networks by a packet scheduler, which is located at the eNB and responsible for radio resource management, as shown in Fig. 10. The packet scheduler selects which traffic flows to serve and allocates corresponding radio resources depending on the QoS requirements of each traffic, as specified by the QCI. Then, based on the feedback Channel Quality Indicator (CQI), an appropriate Modulation and Coding Scheme (MCS) is chosen to transmit traffic data. The main difference among the scheduling schemes lies in their distinct optimization objectives, e.g., the throughput maximization, end-to-end latency minimization, interference-limited [70], service-oriented schemes [71], etc.

a) Existing problems in scheduling schemes: LTE can be used to support vehicular services with different scheduling schemes, such as the Round Robin (RR), maximum Carrier-to-Interference ratio (C/I), and Proportional Fairness (PF) schedulers. The performances of different scheduling strategies under various vehicular environments are evaluated in [20], where

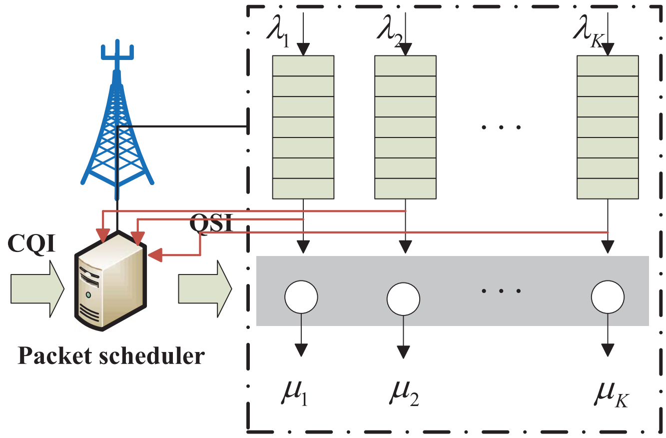

Fig. 10. Illustration of the packet scheduler in LTE.

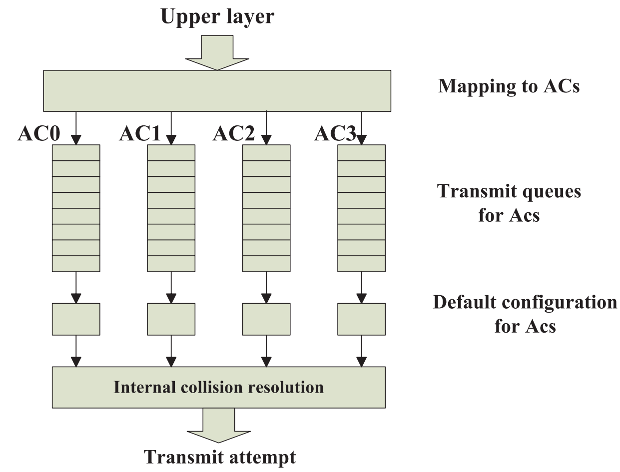

Fig. 11. Illustration of EDCA in DSRC.

voice, video and safety traffic coexists in the same network. Safety services can be well supported in the rural or low density environments. However, in the urban or high density environments, LTE suffers from large latency and high packet loss rates attributed to insufficient resources, and can be easily overloaded if periodic messages are sent every 100 ms [72]. Furthermore, ITS data streams are usually bursty and comprise small chunks of data such as vehicle status messages, causing the vehicle users to frequently switch between the connected and idle states [73]. Thus, an excessive amount of signaling overhead is generated so that the LTE network may suffer from heavy congestion in the control channels.

b) Improved solution to QCI: A simple way to guarantee QoS requirements is to reduce the transmission frequency. The number of vehicles per cell that can be served increases to 1200 from 190, when the transmission frequency of CAM messages decreases from 10 to 1 Hz [15]. Another way to reduce the overall volume of traffic messages in highly dense vehicular environments is to amalgamate or classify messages before transmission. The basic idea is that the vehicles within a certain range amalgamate messages based on their content. A scheme integrating cellular automatic clustering with an interest ontology of users is proposed in [28], which can achieve substantial improvements in the lifetime of interest groups, increasing throughput and reducing communications overhead in vehicular environments.

Since traditional scheduling schemes in LTE are not straightforwardly applicable to vehicular services, existing LTE scheduling schemes need to be improved so as to satisfy the QoS requirements in vehicular environments. The first issue is how to map vehicular services to the LTE QoS classes. It is concluded in [2] that DENs should be handled with the highest priority, although no QCI mapping is suggested. To remedy the drawbacks of dynamic and persistent scheduling, semi-adaptive scheduling is proposed, which uses both scheduling methods, i.e., persistent scheduling for the initial transmission and dynamic scheduling for retransmissions [74].

In addition, cross-layer scheduling is suitable for tackling these issues in LTE networks. In a strictly layered design, opportunistic communications cannot be exploited sufficiently [75]. A upper layer is unable to make sufficient use of the indicators of a low layer without a cross-layer design. For instance, a TCP sender may mistaken packet errors over a wireless link for an indicator of network congestion [76]. Transmission parameters can be dynamically adjusted according to cross-layer information such as the channel quality, queue status and traffic priority.

2) EDCA in DSRC:

a) MAC sublayer in DSRC: QoS support in DSRC is based on an EDCA MAC sublayer protocol, which originates from IEEE 802.11e with some modified transmission parameters. EDCA provides a distinguishing distributed channel access mechanism to guarantee QoS requirements. It defines four Access Categories (ACs) to support data traffic with different priorities as illustrated in Fig. 11 (b). Each transmission queue for a corresponding AC operates as an independent DCF station (STA) with the Enhanced Distirbuted Channel Access Function (EDCAF) to contend for Transmission Opportunities (TXOP) using its own default EDCA parameters.

The default EDCA parameters include the Arbitration Interframe Space (AIFS), $CW_{\max}$, and $CW_{\min}$. The AIFS is used to indicate the priority of an AC's access to the channel. The smaller the AIFS, the higher the chance of transmission. Meanwhile, the CW size can be selected between the difference of $CW_{\max}$ and $CW_{\min}$. The shorter the CW size, the higher the chance of accessing to the channel. A short CW size also means that data can be transmitted with potentially lower end-to-end latency.

b) Existing problems in EDCA: The validation and performance improvement of the EDCA mechanism has attracted interest from both industry and academia alike. A simple way of performance evaluation is to validate the performance without considering the dynamic density of vehicles [77]–[79]. A delay model that can predict throughput is proposed in [77]. However, as mentioned in [77], this model is proven to be inaccurate for throughput prediction in semi-saturated scenarios. To improve on the accuracy of analyzing the transmission probability, the concept of the contention zone is introduced to the analytical model proposed in [78]. Due to computational complexity, only two ACs are taken into account without consideration of internal collision. Furthermore, a 3-D Markov-chain-based analytical model considering four ACs is studied in [79], which is also of high computational complexity. Based upon the results achieved by the above analytical models, a wide consensus has been reached that EDCA provides an effective service differentiating mechanism, which is well suited for distributing emergency messages. However, with an increasing number of vehicles in the network, the collision probability becomes higher so that performance decreases rapidly.

Another analytical approach is to take the dynamic vehicular environments into account [80], [81]. The analytical performance of message dissemination is studied for dynamic vehicular environments in [80]. In this model, event-driven safety and periodic messages are both considered, in which the former messages have a higher priority than the latter ones. In [81], an analytical model for the performance evaluation of safety message dissemination in vehicular ad-hoc networks is presented in consideration of two priority classes. The analysis shows that the probability of a receiving vehicle being exposed to potential interference and collision increases with the transmission range, which is especially true in the case of highly dense traffic.

c) Improved EDCA: The main approaches to reducing the collision probability include: (i) reduce the number of transmitters within the carrier sense range; and (ii) use a collision-free reservation mechanism.

For (i), a typical solution is to adjust the transmission power of the devices, reducing the number of the devices synchronously counting down. Moreover, either decreasing the periodicity of the safety messages or increasing the carrier sense threshold is also an efficient way to avoid collision [6]. The main challenge is how to improve channel utilization while ensuring the dissemination of safety messages. Thus, a novel mechanism focusing on the back-off mechanism and an adaptive CW is proposed in [82], which tries to strike an elegant balance between collision and expired beacons. In addition, a distributed congestion control mechanism is designed in [83], in which each vehicle can sense the channel load and dynamically adjust its transmission parameters in stead of using fixed configurations.

The approaches in (ii) use some reservation mechanism or Time Division Multiple Access (TDMA)-based systems. A TDMA-based system assigns individual time slots to each user so as to achieve collision-free transmission of data. The difference among mechanisms in (ii) rests on how to assign the time slots. Moreover, Spacial Division Multiplexing (SDM) can also be used, where a road is divided into sections and within each section a TDMA scheme is specially mapped. Each vehicle uses different time slots according to which section it belongs to [84]. A potential remedy for congestion control, namely Self-organizing Time Division Multiple Access (STDMA), is presented in [85], in which a vehicle accesses to its time slots depending on its position and neighbor's information. If all time slots are occupied within the selection interval of a vehicle, it may reuse the slot used by a far-away vehicle. In [86], a novel data dissemination strategy is designed from the scheduling perspective to address the unavoidable collision problem, which assumes that there is a Central Server (CS) to schedule radio resources with real-time knowledge of the varying topology. However, serious interference may arise in the reuse scheme. In conclusion, the TDMA-like system is likely used for safety messages dissemination.

3) Summary: Due to the unique characteristics of vehicular communications, e.g., high vehicle mobility, unreliable connectivity, and fast topology changes, existing schemes in either LTE or DSRC cannot well satisfy the QoS requirements of vehicular services. Several solutions and protocols have been proposed to improve the QoS performance of vehicular communications. Future work may focus on solutions and protocols based on cross-layer cooperation and optimization for HetVNETs. For example, Cognitive Radio (CR) technology has emerged as a promising technique to enhance the utilization of radio channels by sensing vacant channels [87], [88]. To efficiently make use of all radio resources in HetVNETs, it is essential to implement radio resource management among all the systems at the HLL. The HLL may play an important role in coordinating and operating for different purposes, e.g., spectrum, load and congestion control in HetVNETs.

V. Open Issues

This section presents some future research directions for HetVNETs, especially those closely related to heterogeneity. Addressing these open issues is vital to alleviating the restrictions imposed by heterogeneity.

Inter-System Handover Issues: Since a HetVNET consists of various wireless networks, e.g., WCDMA, LTE and DSRC, vehicular users may frequently switch among different networks due to their fast movement. It is desired that a vehicle always keeps connected with the most suitable network. Handover is imperative to achieve continuous seamless transmission in HetVNETs. Traditional handover mechanisms for cellular networks are mostly centralized, which are not well suited for the hybrid-distributed vehicular architecture. Also, the handover decision usually depends on a single threshold, affected by a number of factors such as the network load, receiving signal strength, channel conditions, and so on. However, it lacks an appropriate model for mapping a number of these parameters to the threshold. Furthermore, the handover of vehicular users is more frequent than cellular users, resulting in an excessive signaling overhead. Therefore, the main challenge in designing an effective handover strategy in HetVNETs is to strike an elegant trade-off among QoS requirements, implementation complexity and signaling overhead.

Big Data Issues: All participants in an ITS act as data generators, yielding huge volumes of data, e.g., beacon messages, warning messages, and so on. For instance, most commuters may like to socialize with other commuters or watch popular movies in the car or bus during the long and boring commuting time, which would generate huge volumes of data and requests. With millions of miles of roads, millions of vehicles as well as drivers collecting data over the years, the sheer number of data points is extrodinary. Thus, how to exploit this big data in HetVNETs has drawn much attention. However, the methods, models and algorithms for big data that are used today may not work well for HetVNETs. In general, big data are physically and logically decentralized, but virtually centralized [89]. In order to achieve an effective balance between information processing and data transmission, advanced data processing and mining techniques are required to find, collect, aggregate, process, and analyze information in HetVNETs. There is much more work to be done.par

Cooperation Issues: Due to vehicle mobility, wireless links for vehicular communications are unreliable and of limited capacity. Thus, minimizing end-to-end latency and maximizing throughput are key issues in HetVNETs. Spatial diversity has been shown to be effective in enhancing energy efficiency and improving spectral efficiency in vehicular networks [90]–[92]. However, the multiple antennas technique is not employed in DSRC, and equipping vehicle nodes with multiple antennas may not always be practical. As an alternative solution, cooperative communications can reap the benefits of spatial diversity gains so as to increase link capacity. For example, due to the unstable features of the wireless channel, the data download volume of an individual vehicle per drive-through is quite limited. In order to solve this problem, a cooperative Drive-through Internet scheme, dubbed ChainCluster, is proposed to select appropriate vehicles to form a linear cluster on the highway [93]. The cluster members then cooperatively download and share the same content of information, increasing the probability of successful content download. Current studies have shown that: i) cognitive radio technology provides more opportunities for cooperative communications; ii) the performance of link scheduling with an appropriately selected transmission mode is better than purely relying on one single transmission mode; and iii) cooperative Multiple Input Multiple Output (MIMO) techniques provide attractive benefits for vehicular networks [90], [94]. Schemes such as link adaptation, relay selection and radio resource management in cooperative communications are important for improving system performance. The optimization problem in cooperation is usually NP-hard and computationally intractable. The main issue is how to balance between performance and complexity.

Cross-Layer Design Issues: HetVNETs are expected to support a wide variety of safety and non-safety related services such as web browsing, file transfers and video streaming. As opposed to the traditional wireless and wired environments, the highly dynamic vehicular environment causes some serious concerns. For example, the communications channel is more prone to unpredictability, and connectivity of counterparts is easy to break. Hence, stringent and diversified QoS requirements of ITS services are hard to be met by traditional layered designs. Correspondingly, there has been increased attention to exploiting significant interaction among various layers of the protocol stack for performance enhancement [95]–[98]. The main challenge is how to design the upper layer functions based on the feedback from lower layers. At the same time, the implementation complexity of the system needs be taken into account.

Vehicular Cloud Networking (VCN) Issues: As computing and communication technologies have been rapidly developed, the vehicles with powerful computing abilities are advocated to be regarded as service providers rather than being only service consumers. As a result, the concept of Vehicular Cloud Computing (VCC) has been proposed, that jointly makes use of computation, communication and storage resources in vehicle equipments [99], e.g., on-board computer/communication devices or mobile user equipments arrived by passengers. In general, services in the VCC system can be divided into four types according to the function of the resources, i.e., “Network-as-a-Service (NaaS),” “Storage-as-a-Services (StaaS),” “Sensing-as-a-Service (SaaS),” and “Computation-as-a-Service (CaaS).” Differently from the traditional cloud computing system, the VCC system has its unique features [100]. For example, one of them is the variability of the available computation resources in Vehicular Clouds (VCs). Due to the uncertainty of the vehicle behavior, i.e., vehicles may randomly join or leave VCs, the resources in VCs are time varying. Another obvious feature is the heterogeneity of VCs resources. Vehicles are produced by different vendors and thus have inherently different computation resources. Therefore, there are lots of problems in vehicular cloud networking needed to be solved.

VI. Conclusion

This paper aims to illustrate that wireless communication networks can be efficiently used to provide ubiquitous ITS applications with guaranteed QoS. Moreover, the requirements of safety and non-safety services are summarized and compared. Based on the framework of the HetVNET, we discussed current wireless networking technologies for vehicular communications in detail. The discussions on different protocols relating to both the MAC and network layers emphasize on the feasibility and efficiency of the HetVNET. It is concluded that the HetVNET with LTE for V2I communications and DSRC for V2V communications is one of the best solutions for supporting vehicular services, in which collaboration between various communications infrastructure is required.

There are still many on-going research efforts that are being undertaken to identify more efficient techniques for vehicular communications systems. Moreover, several open issues, e.g., handover, big data, cooperation, cross-layer design, and vehicular cloud computing, have been suggested for the future mass deployment of HetVNETs.

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