

Chapter 2

Architecture of Heterogeneous Vehicular Networks

2.1 Background

Due to the high mobility of vehicles and the dynamic topology changes of Vehicular Ad hoc NETWORK (VANET), it is difficult to provide satisfied ITS services only through a single wireless network. Consequently, by integrating different wireless access networks such as LTE and DSRC, the HetVNET is expected to be a good platform that can meet various demanding communications requirements of ITS services. In this chapter, we first present a framework of the HetVNET [1]. Several HetVNET candidate communications techniques are then discussed for comparison purposes.

2.2 Framework of Heterogeneous Vehicular Networks

As illustrated in Fig. 2.1, an 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, and switching. In this book, we focus only on the RAN. In the 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 [2–4]. V2V allows for short- and medium-range communications among vehicular users, offering low deployment costs and supporting low-latency message delivery. V2I enables vehicles to connect to the Internet for information dissemination and infotainment via a roadside Base station (BS). Various candidate wireless access technologies can be used to support V2I and V2V communications subject to specific requirements.

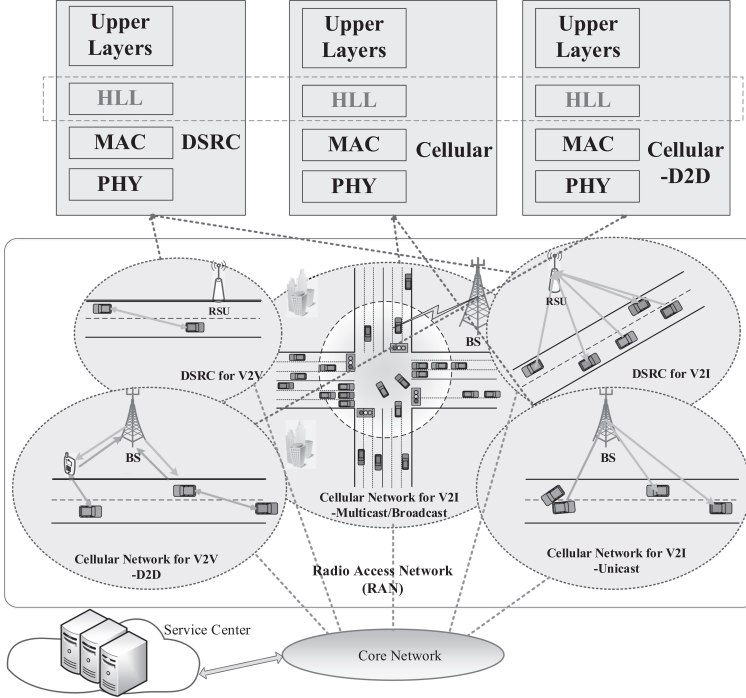


Fig. 2.1 Illustration of the unified HetVNET framework

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.

One of challenges in HetVNETs is to support a dynamic and instant composition of different networks, and to allow operators to utilize radio resources in an efficient and flexible manner. Towards this end, as illustrated in Fig. 2.1, 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 among different networks. These functions facilitate efficient link-layer inter-working among multiple networks. There exists a trade-off between the performance and exchange overhead of the HetVNET, which depends on the possible operational time scale of the HLL. The main objectives of the HLL functions are to enable the global management of network resources, and to meet the QoS requirements of safety/non-safety services by facilitating the coordination among various radio networks.

Since physical layer techniques and network layer protocols for different systems often have their own 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 [5]. 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, Medium access control (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 of resources across slices results in a 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 restricted to either LTE or DSRC through the access control function at the HLL with the knowledge of traffic loading 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 [6], which can be either bandwidth-based or resource-based [7]. Then, virtual radio resource allocation (VRRA) can be implemented to map between the physical and virtual links, allowing for dynamic allocation of radio resources to different systems [8].

2.3 V2I Communications

V2I communications aim to connect vehicles to the infrastructure located on the roadside. Since the infrastructure of cellular networks has been widely deployed in the past decades, it is economical to utilize cellular networks to support V2I communications [9, 10]. Another solution is to use DSRC, which is based on the IEEE 802.11p/1609 wireless access in vehicular environments (WAVE) protocols [11].

2.3.1 Cellular-Network-Based V2I Communications

Cellular networks offer two transmission modes for V2I communications, namely unicast and multicast/broadcast. Unicast can be used for both uplink and downlink message distributions, which is point-to-point communications between a vehicle and the BS, also known as the Evolved nodeB (eNB). On the other hand, multicast/broadcast is exclusively used for the distribution of downlink messages, which

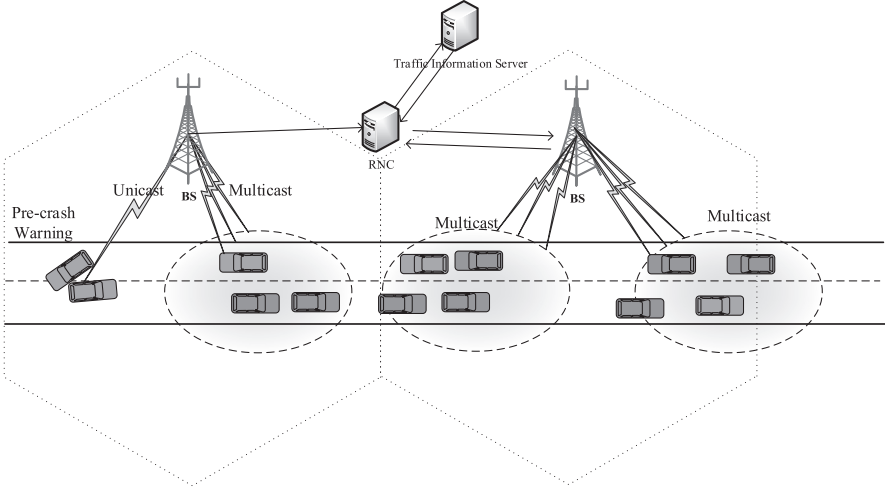


Fig. 2.2 Example of multicast/broadcast by BSs in the HetVNET

refers to point-to-multi-point transmission. In the broadcast scenario illustrated in Fig. 2.2, the traffic information server may distribute the safety messages of “pre-crash warning” to different broadcast areas via MBMS [12]. Each broadcast area consists of multiple cells configured by mobile operators.

2.3.1.1 WCDMA for V2I

Wideband code-division multiple access (WCDMA) is one of the most successful cellular systems. It is based on the direct sequence code-division multiple access (DS-CDMA) technique, where 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. This unique code distinguishes between each physical channel in a WCDMA system. The radio resource control (RRC) defines protocols that describe which processes should be active in a vehicle equipment (VE), and whether a common or dedicated/shared channel is used [12]. In accordance with the inactive and active statuses of VEs, the sub-states can be classified as RRC idle and RRC connected, respectively, as illustrated in Fig. 2.3. Typically, an inactive VE stays in the RRC Idle state, which is a power saving state with little signaling traffic. As 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 paging 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 2 s), the VE transits to the CELL_FACH, which

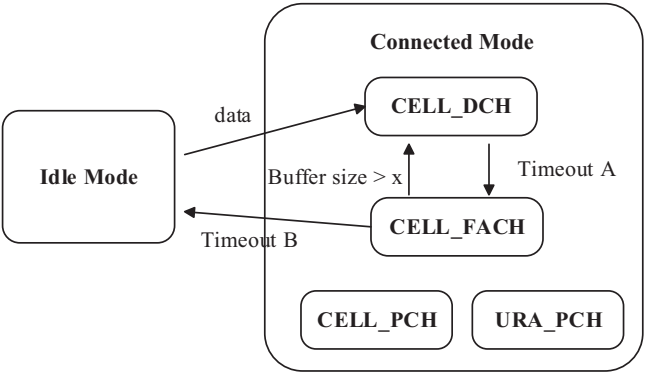


Fig. 2.3 Illustration of the WCDMA RRC states for V2I communications

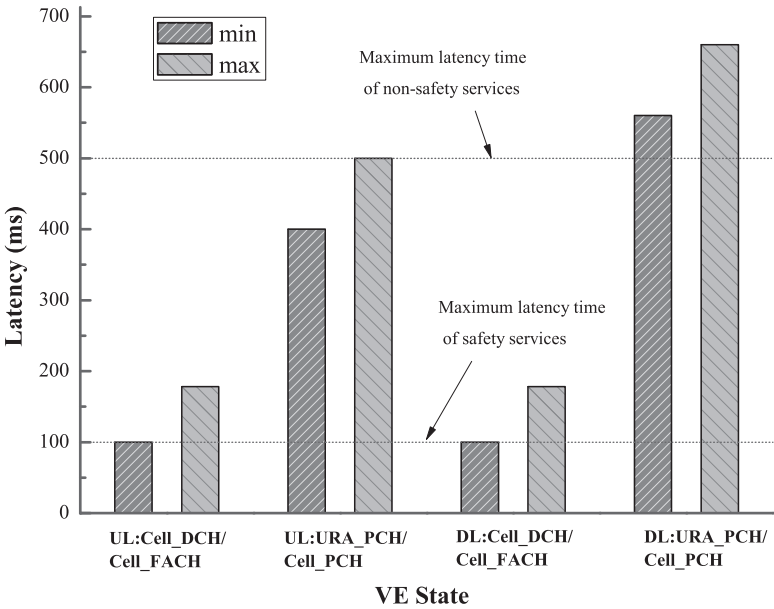


Fig. 2.4 Latency performances of WCDMA different RRC states

can be used to exchange control information and a 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 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 URA_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. Figure 2.4 shows the delivery

latency of the VE under different states in the WCDMA system. In the idle state, the connection setup requires $2 \sim 2.5$ s, which is not presented in Fig. 2.4. As can be seen from the figure, the delivery latency that the VE is in all the states is longer 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 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 latency is around 100–178 ms. When the VE is in the URA_PCH state, the latency is increased to 400 ~ 500 ms. The latency of unicast is 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 URA_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 be 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 that can be in CELL_DCH and CELL_FACH simultaneously becomes a major limiting factor for non-safety services in the WCDMA system.

2.3.1.2 LTE for V2I

As stated in [13], 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 supports a maximum mobile speed of 350 km/h. 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 [14]. 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 capable of providing 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 [12]. Besides, it also can provide a robust mechanism for mobility management. Experiments of trialing LTE in vehicles to support various applications, e.g., 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/h [15]. LTE can be particularly helpful at intersections by enabling a reliable exchange of cross-traffic assistance applications [14]. In [16], the authors analyze the applicability of LTE to vehicular safety communications at intersections. Their analysis shows that the LTE system can support the demand of transmitting approximate 1500 CAMs

per second per cell. Furthermore, the Evolved multimedia broadcast and multicast service (eMBMS) is an effective means to support multicast or broadcast services in highly dense vehicle environments.

Nevertheless, several problems need to be solved before LTE systems can be widely used for V2I communications [14]. Firstly, the MAC layer of LTE lacks an efficient scheduling mechanism for properly mapping the vehicular traffic features to the existing QCI and/or the new QCI definition. Secondly, when the eMBMS is employed to broadcast vehicular service messages, the signaling overhead resulting 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 affected by different levels of potential impact due to the introduction of new types of traffic, especially the heavy load ones [17].

2.3.2 DSRC-Based V2I Communications

Figure 2.5 illustrates the WAVE protocol in a DSRC network. In order to enable robust connections and fast setup for moving vehicles, the half-clocked mode with a 10 MHz bandwidth 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 [18]. 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 the overhead rarely exceeds 20 bytes. The minimum overhead associated with User Datagram Protocol (UDP)/Internet Protocol version 6 (IPv6) is 52 bytes. In addition, in the network and transport layers, the Internet Protocol version 4 (IPv4), Transmission Control Protocol (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 [11]. 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 a large room for improvement and enhancement in DSRC. Next, several problems of DSRC networks when used for V2I communications are discussed.

- **Sparse pilot design:** The dynamic V2I environment with large multipath delay spread and high mobility results in highly time-frequency selective vehicular communications channels. In a typical application scenario, 50 % coherence

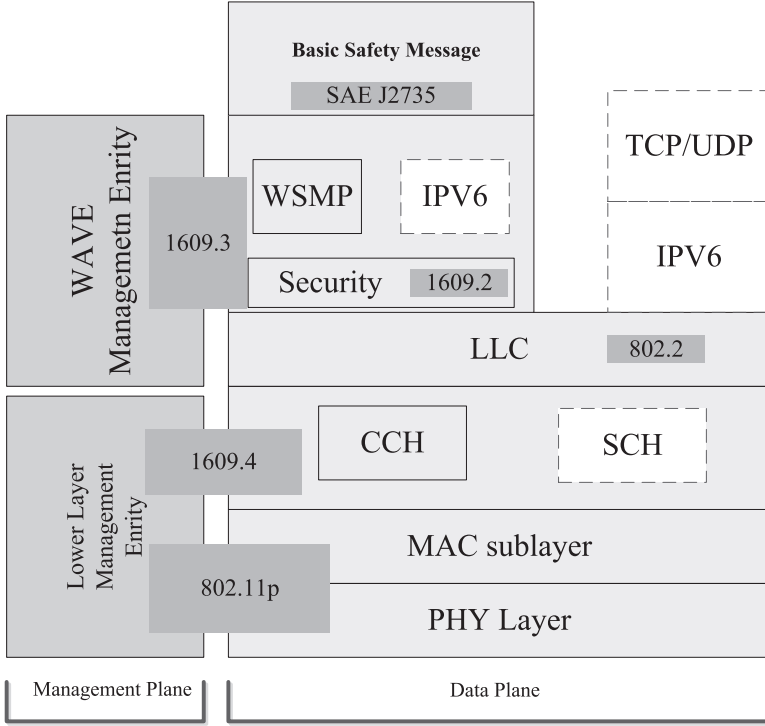


Fig. 2.5 Illustration of the WAVE protocol stack of DSRC networks

bandwidth is roughly in the order of 1 MHz, and 50 % of the coherence time can be as short as 0.2 ms [19]. Then, a typical packet transmission period in DSRC, i.e., approximately 0.5 ms with a packet size of 300 bytes, Quadrature phase shift keying (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 collisions increases rapidly with the number of vehicles in the network, resulting in large end-to-end latency and low channel utilization [20]. Therefore, channel congestion has to be dealt with so as to guarantee the QoS requirements of vehicular services. One approach is to reduce the number of transmitters to within the carrier sense range of each device [21, 22];
- **Unbalanced link:** Due to the different hardware configurations between the Onboard 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 m, while the range from the OBU to RSU is only up to 400 m. 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 [23, 24]. Then, communications quality deteriorates due to such “unbalanced links”; and

- **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 multiple RSUs. The OBU may create a WAVE basic service set (WBSS) with the first RSU it detects. 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 [23]. 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., 0xFFFFF, so that the 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 [11].

2.4 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. Extensive investigations and trials on V2V have been carried out with the objective of supporting traffic services, such as slow vehicle warning and abnormal vehicle status warning [25]. In this subsection, two candidate techniques for V2V communications are discussed in detail.

2.4.1 LTE D2D-Based V2V Communications

Device-to-device (D2D) communications underlaying a cellular network have been proposed as a means of taking advantage of the physical proximity of communicating devices in LTE systems [26, 27]. In the D2D mode, user equipments (UE) 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 [28], 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 m. 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 [29], the time remained for message transmission is only around 3 s. Thus, in many cases, the D2D discovery time is larger than that allocated for message transmission, which is not acceptable for delivering safety messages with strict QoS requirements.

2.4.2 DSRC-Based V2V Communications

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 still exist several challenges for using DSRC in V2V communications [30–32]. 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.

2.5 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 technique may be chosen according to their characteristics, and they can work together with the aid of the HLL. Two examples are given below to illustrate the applicability of HetVNETs to ITS services.

2.5.1 Urban Intersection Scenario

Figure 2.6 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 the 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 [33]. The traditional method

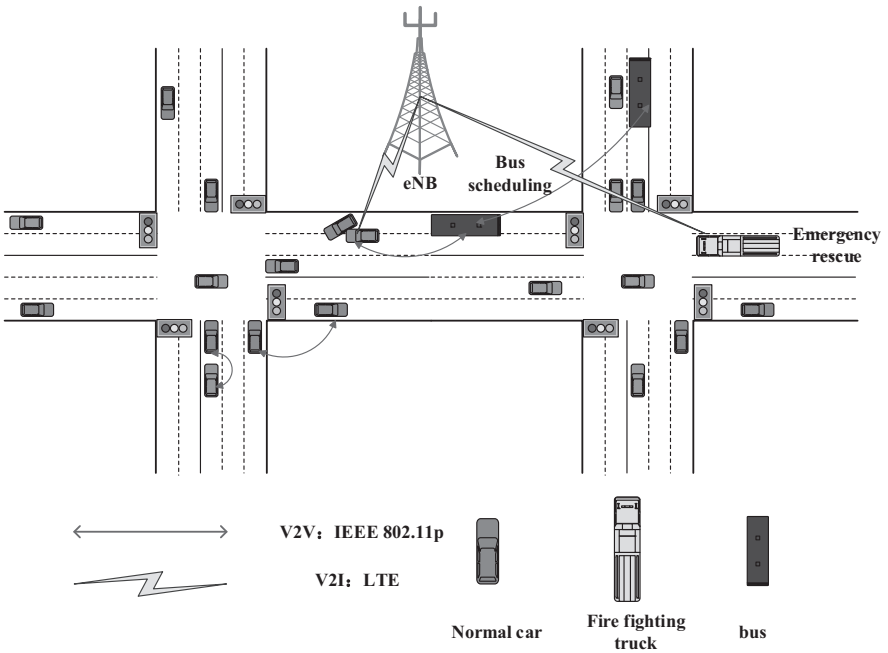


Fig. 2.6 Illustration of an urban intersection scenario

is that the witness sends the information to the eNB. A new method of notification may be like eCall [33], 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 is periodically sent by vehicles, the eNB can predict mobility via some prediction algorithm, e.g., road-topology-based [34] and behavior-based mobility prediction [35]. Then, in order 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.

2.5.2 Expressway Scenario

In the expressway scenario, there are generally two types of traffic flows, i.e., the free and synchronized flows as shown in Fig. 2.7a and b, respectively. These two vehicle flows may switch to each other.

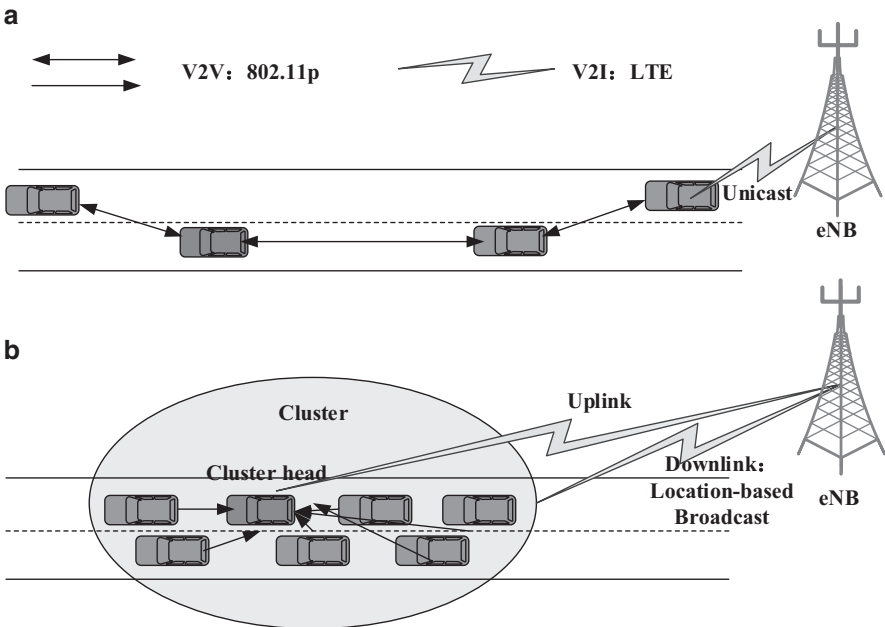


Fig. 2.7 Illustration of an expressway scenario. (a) Free flow. (b) Synchronized flow

- **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 communications. However, in specific environments, e.g., in a tunnel, 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 [36]; and
- **Synchronized flow:** The traffic density of a synchronized flow is much higher, meaning that broadcast messages are likely to be flooded. Due to traffic jam, vehicle speeds are low, and the random behavior of vehicles can be modeled by a car-following behavior, meaning that the radio links among vehicles become relatively static. With the aid of DSRC, clustering mechanisms may be an efficient information dissemination method. The 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 aggregate 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 [37]. For the downlink, the multicast of the LTE network can be used to distribute messages.

2.6 Summary

Since a single wireless communications network, either DSRC or LTE, cannot well satisfy the QoS requirements of ITS services, we propose an HetVNET framework. Several candidate techniques, e.g., DSRC and LTE cellular networks, are discussed and summarized in Table 2.1. As can be seen from the table, 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.

Table 2.1 Advantages and challenges of candidate techniques for the HetVNET

Communications	LTE/LTE D2D	DSRC
V2I Communica- tions	Advantages: • Large coverage • Robust mechanisms 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 delays in disseminating messages • Prone to overloaded in high density environments	Advantages: • Easy deployment and low costs • Suitable for local message dissemination, i.e., traffic signal, parking information, etc. 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 Communi- cations	Advantages: • High spectral efficiency • High energy efficiency • Efficient scheduling on D2D resources Challenges: • Interference between D2D pair and other users • Peer and service discovery is time consuming • Serious performance degradation in high vehicle speed	Advantages: • Easy deployment and low costs • Ad-hoc mode • Overhead of WSM messages is low Challenges: • Sparse pilot design • Serious channel congestion with a large number of vehicles • Adjacent band leakage in multi-channel operations • Broadcast storm and hidden node problems

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