CHAPTER 7

Vehicle-to-Everything (V2X) Communications

The concept of connected car has recently emerged, which provides new services to drivers via wireless communications that is considered as one of the most distinctive features of next generation vehicles. Vehicles wirelessly connected to other vehicles and pedestrians within proximity can identify the possibility of collisions by exchanging information such as speed, direction and their location. The vehicles can also communicate with a network entity in charge of traffic control so that they can be informed of weather, and road hazards or receive guidance on the speed and route for traffic flow optimization. The automotive industry is evolving toward connected and autonomous vehicles that have the potential to improve safety and to reduce traffic congestion while reducing the environmental impacts of the vehicles. A key enabler of this evolution is vehicle-to-everything (V2X) communications, which allows a vehicle to communicate with its surroundings, other vehicles, pedestrians, road-side equipment, and the Internet. Using V2X, critical information can be exchanged among vehicles to improve situation awareness and to avoid accidents. Furthermore, V2X provides reliable access to the vast information available in the cloud. For example, real-time traffic reports, sensor data, and high-definition mapping data can be shared and accessed, which are useful not only for improving today's driving experience, but also will be essential for navigating self-driving vehicles in the future.

V2X communications enables the exchange of information between vehicles and between vehicles and other nodes (infrastructure and pedestrians). The 3GPP Rel-12 device-to-device communication served as the basis for the V2X work in Rel-14. In Rel-14, 3GPP specified cellular V2X (C-V2X) communications with two complementary transmission modes: direct communications between vehicles and network communications. 3GPP Rel-16 focuses on continuation of LTE-based cellular V2X and tries to address advanced use cases. These include vehicle platooning, enhanced vehicle to infrastructure features, extended sensors, advanced driving (to enable semi-automated or fully-automated driving), and remote driving. C-V2X users can benefit from the existing widely-deployed cellular infrastructure. However, since the availability of cellular infrastructure cannot always be guaranteed, C-V2X defines transmission modes that enable direct communication using the sidelink channel over the PC5 interface.

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This chapter provides a technical overview of LTE-based V2X standards as of 3GPP Rel-15 and further provides insights into the emerging NR-based V2X technologies in 3GPP Rel-16 that are expected to accelerate the realization of advanced V2X communications and to improve transportation and commute experience. The NR-based V2X is required to enable very high throughput, high reliability, low latency, and accurate positioning use cases beyond the basic safety features provided by LTE-based V2X services. Some of the use cases will involve 5G working in tandem with other technologies, including cameras, radar, and light detection and ranging (LIDAR)[1] The Rel-16 C-V2X includes use cases such as advanced driving categories identified in 3GPP, ranging/positioning, extended sensors, platooning, and remote driving.

7.1 General Aspects and Use Cases

The V2X communications enable the vehicles to exchange data with each other and the infrastructure, with the goal of improving road safety, traffic efficiency, and the availability of infotainment services. V2X communications, as defined in 3GPP, consist of four use cases; namely, vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P), as shown graphically in Fig. 7.1. It is implied that

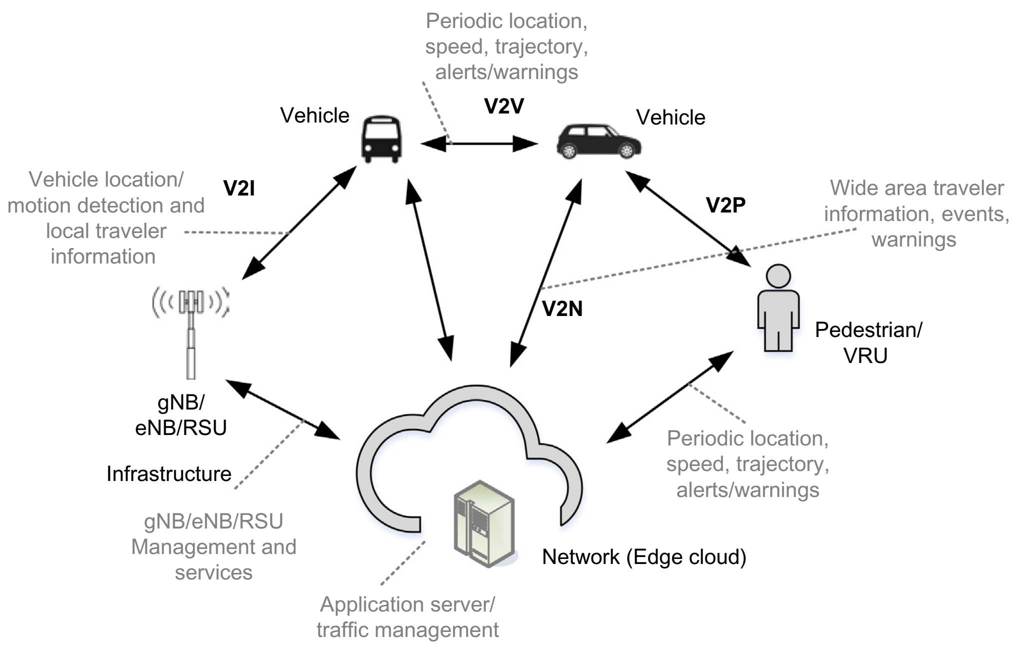

Figure 7.1
Illustration of various V2X use cases [1,9,13,14].

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[1] Light detection and ranging is a remote sensing method used to examine the surface of the earth.

these wireless connections are generally bidirectional; that is, the V2I and V2N also allow the infrastructure to send messages to the vehicles. The V2V and V2P transmissions are typically based on broadcast capability between vehicles or between vehicles and vulnerable road users, for example, pedestrians and cyclists, for providing information about location, velocity, and direction to avoid accidents. The V2I transmission is between a vehicle and a road-side unit (RSU). The V2N transmission is between a vehicle and a V2X application server which is in the cloud. An RSU may be used to extend the range of a V2X message received from a vehicle by acting as a forwarding node. The V2I may include communication between vehicles and traffic control devices near road work sites. V2N may include communication between vehicle and the server via 4G/5G network, such as for traffic operations.

There are two prominent V2X technologies available today, which have been designed to operate in 5.9 GHz intelligent transportation systems (ITS) spectrum. The IEEE 802.11p standard, which is commonly referred to as dedicated short-range communication (DSRC) and ITS-G5 in the United States and Europe, respectively, was developed as an extension of IEEE 802.11a standard. IEEE 802.11p specification was completed in 2012 and uses a half-clocked version of IEEE 802.11a, leveraging a radio technology that is over two decades old and was originally developed for wireless Ethernet cable replacement and not for high-speed mobile applications. IEEE 802.11p performance results indicate its limited range and unreliable large-scale field performance, derived from susceptibility to congestion and lack of minimum performance guarantees, which would limit its usefulness. Most of the present-day cars are equipped with several active sensors, including camera, radar, and LIDAR, which compel the V2X wireless sensor to provide longer range and reliability, especially in non-line-of-sight (NLoS) scenarios where other vehicles and buildings obstruct the vehicle's vision systems. In the meantime, 3GPP has continued to evolve LTE device-to-device (D2D) technology, specified as part of Rel-12, and to optimize it for automotive applications in Rel-14, also referred to as C-V2X communications, over proximate radio interface (PC5) or sidelink and/or the LTE Uu interface. The C-V2X incorporates LTE's mobility support and further extends the baseline standard for automotive applications, while learning from IEEE 802.11p issues and shortcomings. The C-V2X includes both direct communications and network-based communications. Fig. 7.2 shows various scenarios for sidelink and direct link communications where UEs are located in-coverage and out-of-coverage of a cell.

The future transportation technologies will include connected and intelligent vehicles, which can cooperate with each other and a transportation infrastructure that can provide safer and more convenient commute/travel experience. A wide range of use cases that require longer range or higher throughput can be supported with LTE-based/NR-based V2X communications. C-V2X is the technology developed in 3GPP and is designed to operate in the following two modes:

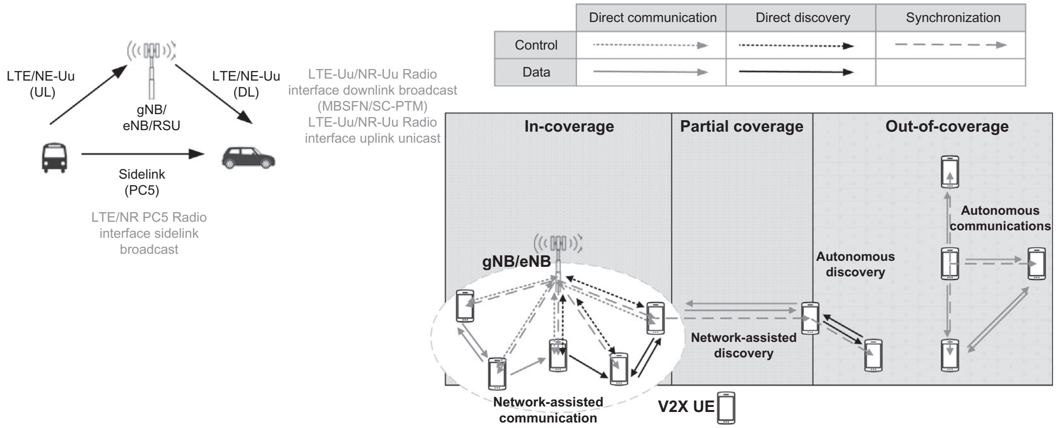

Figure 7.2
Various V2X scenarios [12–14].

- *Device-to-device:* This mode is sidelink communication between two or more devices without network involvement.
- *Device-to-network:* This mode uses the traditional cellular links to enable cloud services as part of the end-to-end solution by means of network slicing architecture for vertical industries.

Some key performance metrics for low-latency local communications that are addressed by LTE-based V2X as part of Rel-14 include support of vehicle speeds up to 160 km/h and relative speeds of 280 km/h; extended range to provide the driver(s) with sufficient response time (e.g., 4 seconds); message sizes for periodic broadcast messages between two vehicles/UEs with payloads of 50–300 bytes and for event-triggered messages up to 1200 bytes; and maximum latency of message transfer of 100 ms between two UEs and 1000 ms for messages sent via a network server [27]. In subsequent releases, more stringent requirements for latency, range, speed, reliability, location accuracy, and message payloads have been specified in order to support more advanced use cases. For example, NR-based V2X systems are expected to provide end-to-end latency between vehicles of less than 5 ms and guarantee more than 99% reliable packet delivery within a short-to-medium range (80–200 m).

RSUs are the new network nodes that are part of the LTE-based V2X communications system. These entities can be co-located with eNBs or operate in standalone mode. The V2I communication mode allows RSUs to monitor traffic-related conditions, such as traffic signals and tolls and subsequently notify the surrounding vehicles. The evolution path for LTE-based V2X is going to exploit the NR features and to provide ubiquitous coverage as the 5G technologies are designed and deployed. 3GPP evolved V2X (eV2X) has identified several new use cases/applications as follows [1,21,25,26]:

- *Platooning:* In this scenario, vehicles (dynamically) form a platoon while moving together in the same direction. Vehicles in the platoon obtain information from the leading vehicle for managing the platoon. Platooning allows the vehicles to form a tightly coordinated group with significantly reduced inter-vehicle distance, thus increasing road capacity and efficiency. It also improves fuel efficiency, reduces accident rate, and enhances productivity by allowing the drivers to perform other tasks. Vehicles within a platoon must be able to frequently exchange information (e.g., to share information such as vehicle's speed and direction) and to send event notifications such as the intent for braking or acceleration. There are several aspects of platooning that must be supported through reliable V2V communications such as joining and leaving a platoon; that is, to allow a vehicle to signal its intention to join or to leave a platoon at any time while the platoon is active, and to support additional signaling in order to complete join/leave operations; announcement and warning to indicate formation and existence of the platoon so that nearby vehicles can select to join the platoon or to avoid disruptions to the platoon; steady-state operation group communication to support the exchange of platoon management messages and further to indicate braking, acceleration, road selection, change of platoon leader, etc. Given the small target inter-vehicle distance while the vehicles are traveling at relatively high speed, V2V communication must be able to support reliable and secure message exchange to ensure effective and safe platooning operation. The following are some key V2V communication requirements in order to support platooning [13,14]:
  - 25 ms end-to-end communication latency among a group of vehicles (10 ms for the highest degree of automation[2]).
  - 90% message reliability, and 99.99% for the highest degree of automation relative longitudinal position accuracy of less than 0.5 m is required.
  - 10−30 messages per second during broadcasting.
  - Dynamic communication range control to improve resource efficiency given the varying platoon size, and to limit message distribution for privacy reasons.
- *Advanced driving:* Vehicle/RSU shares data that is collected through local sensors with nearby vehicles, allowing the vehicles to coordinate their paths and to avoid accidents. Advanced driving enables semi-automated or fully automated driving. Each vehicle shares its intention to change path and speed with vehicles in proximity, thus inter-vehicle distance adjustments are required. The key requirements for communication between two vehicles employing advanced driving mechanisms include:
  - Large system bandwidth to support burst transmission of large data packets
  - 10 ms latency for highest degree of automation
  - 99.99% message reliability for highest degree of automation

[2] In an autonomous vehicle scenario, the vehicle's on-board computers are fully capable of performing all driving operations on their own, with no human monitoring or intervention.

- *Extended sensors:* Extended sensors enable the exchange of raw or processed data (e.-g., cameras, radar, LIDAR) gathered from vehicle sensors or live video images among vehicles, road site units, devices of pedestrian, and V2X application servers. The vehicles can increase the knowledge of the environment/road conditions beyond of what their own sensors can detect and have a broader and holistic view of the driving conditions. The sensor data that a vehicle can share ranges from photo of a road hazard to real-time video stream. The availability of sensor data from multiple separate sources enhances situation awareness of the vehicles and pedestrians, and thus improves road safety. Extended sensors further enable new features such as cooperative driving and precise positioning, which are necessary for autonomous driving.
- *Remote driving:* Enables a remote driver or a V2X application to operate a remote vehicle for those passengers who cannot drive by themselves or remote vehicles located in dangerous environments. For a case where route variation is limited and routes are predictable, such as public transportation, driving based on cloud computing can be used. High reliability and low latency are the main requirements of this use case. Remote driving enables the remote control of a vehicle by a human operator or by a cloud-based application, via V2N communication. There are several scenarios that can leverage remote driving, including:
  - Provide a fallback solution for autonomous vehicles. An example is during the initial autonomous vehicle deployment when a vehicle is in an unfamiliar environment and has difficulty navigating.
  - Provide remote driver services to the youths, elderly, and others who are not licensed or able to drive.
  - Enable fleet owners to remotely control their vehicles. Examples including moving trucks from one location to another, delivering rental cars to customers, and providing remotely driven taxi services.
  - Enable cloud-driven public transportation and private shuttles, all of which are particularly suitable for services with predefined stops and routes. Remote driving can reduce the cost of fully autonomous driving for certain use cases because of the less stringent technical requirements (e.g., smaller number of in-vehicle sensors and less computation requirements for sophisticated algorithms). The following are V2X requirements for supporting remote driving:
    - Data rate up to 1 Mbps downlink and 25 Mbps in the uplink.
    - Ultra-high reliability at 99.999% or higher [similar to ultra-reliable and low-latency communication (URLLC) use case].
    - End-to-end latency of 5 ms between the V2X application server and the vehicle.
    - Support vehicular speeds of up to 250 km/h.

  Remote control will be required when an obstacle blocks an autonomous driving vehicle, rendering it unable to decide about a pathway or approach to safely navigate around it. Examples of obstacles include lanes that are blocked due to a recent accident, double-parked cars not allowing the vehicle to pass without crossing the ingress/egress yellow lines, or unexpected situations where the vehicle is unable to determine a safe action or a way forward. When the vehicle encounters such conditions, it will stop or find a minimum risk position and then will request assistance from a remote control operator to take control and navigate around the obstacle. The remote controller would need to understand the obstacle and determine the path that the vehicle must take. In this case, the controller will utilize the photos or streaming sensor information (e.-g., video, LIDAR, radar) that has been made available by the vehicle. Once cleared of the obstacle, the video stream to the controller will stop and the vehicle reasserts full control toward destination.

NR V2X is not intended to replace the services offered by LTE V2X, rather it is expected to complement LTE V2X for advanced V2X services and to support interworking with LTE V2X. From 3GPP RAN technology development point of view, the focus and scope of NR V2X is to target advanced V2X applications. However, this does not imply that NR V2X capability is necessarily restricted to advanced services. It is up to the regional regulators, car manufacturers, equipment vendors, and automotive industry, in general, to deploy the technology suited for their intended services and use cases. NR V2X is planned as 3GPP V2X phase 3 and would support advanced services beyond those supported in Rel-15 LTE V2X. The advanced V2X services would require enhancing the NR baseline system and developing a new NR sidelink to meet the stringent requirements of the new use cases. NR V2X system is expected to have a flexible design to support services with low latency and high reliability requirements, considering the higher system capacity and extended coverage enabled by the baseline NR system. The flexibility of NR sidelink framework would allow easy extension of NR system to support the future development of further advanced V2X services. More specifically, the NR V2X enhancements include the following areas [11]:

- *Sidelink design:* Identify technical solutions for NR sidelink to satisfy the requirements of advanced V2X services, including support of sidelink unicast, sidelink groupcast, and sidelink broadcast; study NR sidelink physical layer structure and procedure(s); study sidelink synchronization mechanism; study sidelink resource allocation mechanism; and study sidelink L2/L3 protocols.
- *Uu enhancements for advanced V2X use cases:* Evaluate whether Rel-15 NR Uu and/or LTE Uu interfaces could support advanced V2X use cases and identify enhancements, if any, that are needed to meet advanced V2X use cases.
- *Uu-based sidelink resource allocation/configuration (LTE V2X mode 3 and mode 4):* Identify necessary enhancements of LTE Uu and/or NR Uu to control NR sidelink through the cellular network and further identify the necessary enhancements of NR Uu to control LTE sidelink from the cellular network.

- *RAT/interface selection for operation:* Study if additional mechanisms are required to decide whether LTE PC5, NR PC5, LTE Uu, or NR Uu should be utilized for operation.
- *Quality of service (QoS) management:* Study technical solutions for QoS management of the radio interface (including Uu and sidelink) used for V2X operations.
- *In-device coexistence:* Study the feasibility of the coexistence mechanisms when NR sidelink and LTE sidelink technologies are implemented in the same vehicle for the non-co-channel scenarios such as advanced V2X services provided by NR sidelink while coexisting with V2X service provided by LTE sidelink in different channels.
- *Sidelink operating bands:* Sidelink frequency bands include both unlicensed ITS bands and licensed bands in FR1 and/or FR2. The target is to have a common sidelink design for both FR1 and FR2.

For groupcast V2X communication, the following radio-layer enhancements are considered to improve sidelink communication performance in distributed resource allocation mode:

- Group radio-layer feedback
  - When transmitter node sends a sidelink transmission/message to a group of UEs, the UE that has not successfully received physical sidelink shared channel (PSSCH) sends a NACK on physical sidelink control channel (PSCCH) resource reserved by the transmitter for acknowledgment.
- Group radio-layer (re-)transmission
  - If the UEs in a group detect a NACK from at least one of the group members, the UEs can retransmit successfully the received packet on a resource that can be either reserved by the UE which is failed to receive or by the original source of transmission. Note that for groupcast communication, the same principles of sensing and resource selection as well as resource reservation can be reused. The group radio-layer feedback and (re-)transmissions can be developed using the same sidelink channel access and resource selection mechanisms.

The latency of V2X systems is categorized into transmission time interval (TTI) dependent and TTI-independent, depending on whether the latency is proportional to or independent of the transmission time interval of the radio air-interface [15]. Each data transmission, that is, control signaling, scheduling, HARQ (re-)transmission, and so on, consumes at least one TTI. The V2X services can be categorized into three groups: (1) safety-related services, (2) non-safety-related services, and (3) automated driving-related services. The safety-related services handle real-time safety messages, such as warning messages (e.g., abrupt brake warning message) to reduce the risk of car accidents. In this type of services, timeliness and reliability are the key requirements. On the other hand, non-safety-related services are intended to optimize the traffic flow on the road so that travel time is reduced. Therefore,

Table 7.1: Performance requirements of different V2X use cases [1].

Use Case	V2X Mode	End-to-End Latency	Reliability	Data Rate per Vehicle (kbps)	Communication Range
Cooperative awareness	V2V/V2I	100 ms to 1 second	90–95%	5–96	Short-to-medium
Cooperative sensing	V2V/V2I	3 ms to 1 second	> 95%	5–25,000	Short
Cooperative maneuver	V2V/V2I	< 3–100 ms	> 99%	10–5000	Short-to-medium
Vulnerable road user	V2P	100 ms to 1 second	95%	5–10	Short
Traffic efficiency	V2N/V2I	> 1 second	< 90%	10–2000	Long
Tele-operated driving	V2N	5–20 ms	> 99%	> 25,000	Long

these services enable more efficient driving experience with no stringent requirements in terms of latency and reliability. For the safety-related services, if we consider the frequency of periodic messages (e.g., from 1 to 10 messages/second) and the reaction time of most drivers (e.g., from 0.6 to 1.4 seconds), then the maximum allowable end-to-end latency must not exceed 100 ms. In fact, depending on the service type, the latency requirement may even be less than 100 ms (e.g., 20 ms for a pre-crash sensing warning). In addition to these types of services, automated driving-related services are being developed as a key transformation in the automotive industry. These services require more rigorous latency limits, data rates, and positioning accuracy. Therefore, the latency requirements for automated driving-related services are more stringent than those required for safety-related services. For example, automated overtaking or high-density platooning services have a 10 ms latency requirement. Table 7.1 lists the V2X use cases and the corresponding latency and data rate requirements [15].

V2V communication is conceptually based on D2D communications that was specified as part of proximity-based services (ProSe) in 3GPP Rel-12/Rel-13. The D2D feature provided public safety UEs the option to communicate directly. As part of ProSe, a new D2D interface (designated as PC5 interface or sidelink) was defined, which has been subsequently enhanced for vehicular use cases, specifically addressing high-speed (up to 250 km/h) and high node-density scenarios. Therefore, some fundamental modifications to PC5 have been made, including additional reference symbols to support high Doppler frequencies associated with relative speeds of up to 500 km/h and high frequency bands (e.g., 5.9 GHz ITS band being the main target) [1,24].

In order to support distributed scheduling, a sensing mechanism with semi-persistent transmission has been introduced. The C-V2V traffic from a device is mostly periodic in nature. This was utilized to sense congestion on a resource and estimate future congestion on that resource. Based on this estimation, the resources are reserved in advance. This technique optimizes the use of the channel by enhancing resource separation between transmitters that are using overlapping resources. The design is scalable for different bandwidths. There are

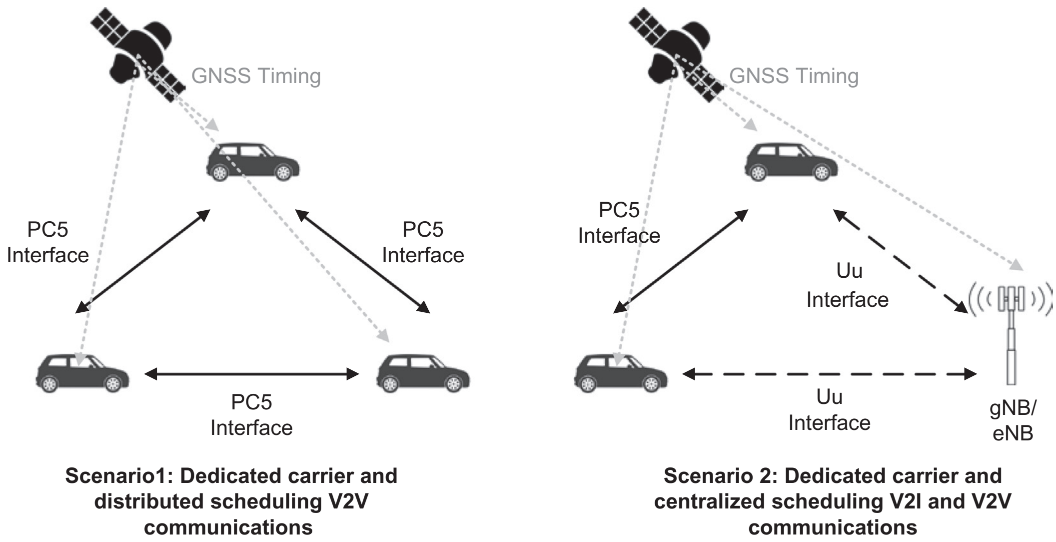

Figure 7.3
LTE V2X use cases and scheduling options [1].

two high-level deployment scenarios that are currently defined, as illustrated in Fig. 7.3. Both scenarios use a dedicated carrier for V2V communications, meaning that the target band is only used for PC5-based V2V communications. In both use cases, global navigation satellite system (GNSS) is used for time synchronization. In the first scenario, the scheduling and interference management of V2V traffic is supported based on distributed algorithms (referred to as mode 4) implemented between the vehicles. As we mentioned earlier, the distributed algorithm is based on sensing with semi-persistent transmission. Furthermore, a new mechanism where resource allocation is dependent on geographical information is introduced. Such a mechanism counters near-far effect arising due to in-band emissions. In the second scenario, the scheduling and interference management of V2V traffic is assisted by eNBs (referred to as mode 3) via control signaling over the Uu interface. The eNB assigns the resources that are used for V2V signaling in a dynamic manner.

The goal of the next-generation V2X communication is to enable accident-free cooperative automated driving by efficiently using the available roadways. To achieve this goal, the communication system will need to enable a diverse set of use cases, each with a specific set of requirements. The V2X feature was initially introduced with IEEE 802.11p and supported a limited set of basic safety services. IEEE 802.11 group has initiated a new project called IEEE 802.11bd which is tasked to enhance IEEE 802.11p and develop similar features as NR V2X, while backward compatible to IEEE 802.11p [28]. 3GPP Rel-14 V2X supported a wider range of applications and services, including low-bandwidth safety

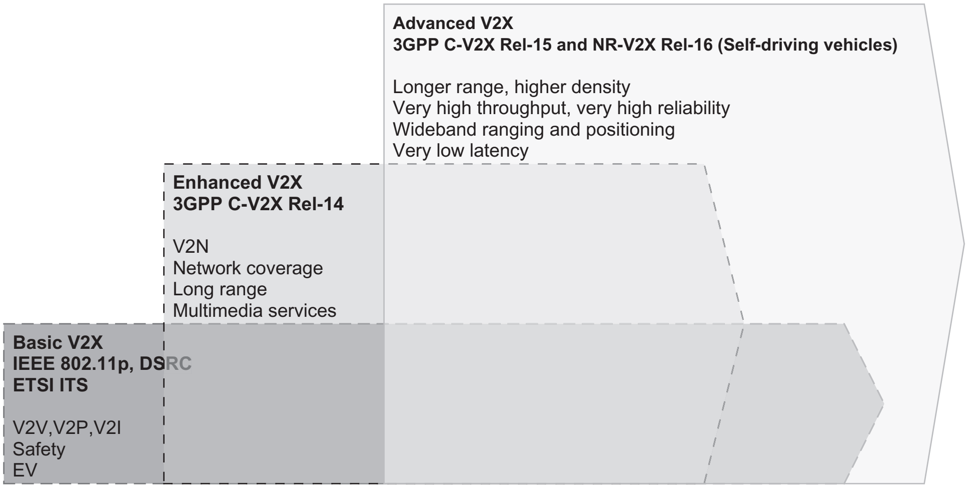

Figure 7.4
V2X technology evolution [13,14,25].

Table 7.2: High-level comparison of attributes for DSRC, LTE V2X, and NR V2X [13,14].

Features	DSRC/IEEE 802.11p	Rel-14 LTE C-V2X	(5G) (Rel-15/16) C-V2X
Out-of-network operation	Yes	Yes	Yes
Support for V2V	Yes	Yes	Yes
Support for safety-critical uses	Yes	Yes	No
Support for V2P	Yes	Yes	Yes
Support for V2I	Limited	Yes	Yes
Support for multimedia services	No	Yes	Yes
Network coverage support	Limited	Yes	Yes
Global economies of scale	No	Yes	Yes
Regulatory/testing efforts	Yes	Limited	No
Very high throughput	No	No	Yes
Very high reliability	No	No	Yes

applications and high-bandwidth applications such as infotainment. 3GPP Rel-15 and 16 enable even more V2X services by providing longer range, higher density, very high throughput and reliability, accurate positioning, and ultra-low latency. Fig. 7.4 summarizes these features and shows the evolution of V2X technologies and how IEEE 802.11p, LTE-based, and NR-based V2X may coexist over time. Table 7.2 compares DSRC, Rel-14 C-V2X, and 5G C-V2X key features at a high level. The analysis of radio link performance of LTE V2X and IEEE 802.11p indicates that the likelihood of successful delivery of warning messages between two vehicles both equipped with LTE V2X (PC5) is notably greater than utilizing IEEE 802.11p technology under the same test conditions.

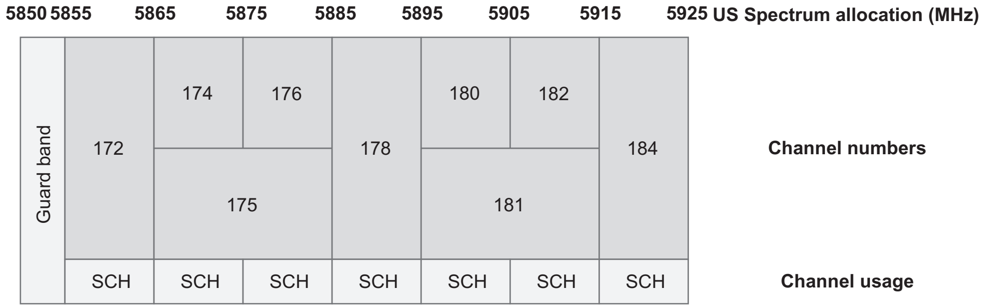

Figure 7.5
DSRC channel arrangement in the United States [13,14].

7.2 Spectrum Allocation

Some DSRC-based systems have been deployed or are expected to be deployed in 5.9 GHz band or in 700 MHz band. As shown in Fig. 7.5, the United States allocation divides the entire 75 MHz ITS band into seven non-overlapping 10 MHz channels, with 5 MHz reserved as the guard band. There is one control channel (CCH), corresponding to channel number 178 and six service channels (SCHs) for the DSRC in this band. The pair of channels (174 and 176, and 180 and 182) can be combined to form a single 20 MHz channel in either channel 175 or channel 181, respectively. Channel 172 is reserved exclusively for critical public safety communications, while channel 184 is reserved for high-power public safety use cases. The remaining channels can be used for non-safety applications. The V2X spectrum demands highly depend on environment (vehicle density, applications, traffic model, etc.), radio access technology, and target communication range and performance metrics.

System-level analysis shows that approximately 20−30 MHz of bandwidth is needed in typical highway scenarios for target range of 300−320 m based on LTE V2X sidelink communication [10]. Discussions on ITS spectrum allocation adjustments in low and high bands are in progress to allocate new spectrum for V2X as follows (see Fig. 7.6):

- *Low-band:* Potential use of 5.925−6.425 GHz in addition to 5.855−5.925 GHz.
- *High band:* Frequency allocation above 6 GHz in Europe may be updated—center frequency of ITS band may be shifted to 64.80 GHz and extended to 2.16 GHz of bandwidth (to avoid overlapping with two IEEE 802.11ad channels and to increase ITS bandwidth).

In the quest for increased network capacity, reduced cell sizes and the use of wider system bandwidths (whether contiguous or via carrier aggregation) have been actively investigated in the past decade. The use of mmWave spectrum for sidelink communications is believed to have several advantages for V2I communication, wherein transitory, high data rate

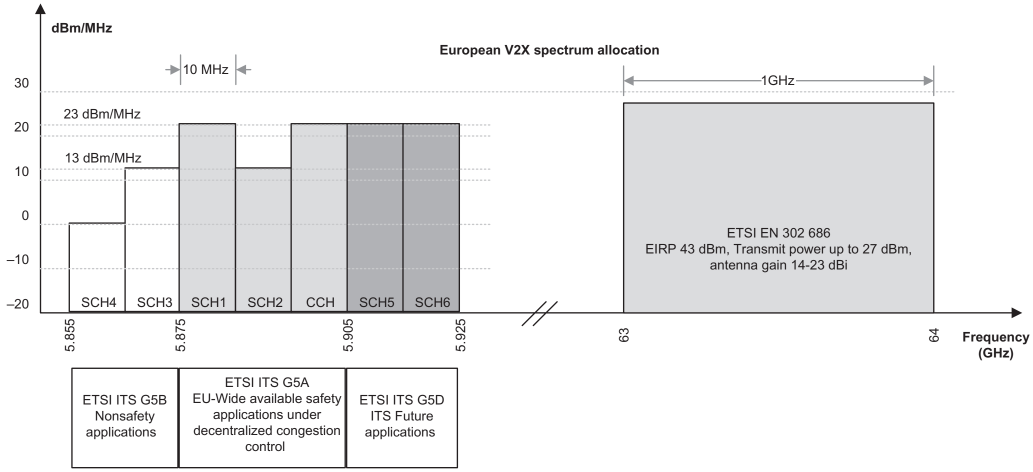

Figure 7.6
Region-specific ITS spectrum allocation in Europe [24,25].

connection can be established between vehicle and nearby base stations (small cells) to exchange delay-insensitive data (e.g., map updates and infotainment data in the downlink, and collected traffic and sensor information for large-scale traffic monitoring in the uplink); and for directional V2V communication for supporting specific use cases, such as communication between adjacent vehicles in a platoon. Although mmWave communication is very attractive from the data throughput perspective, it creates challenges for the physical layer. Due to high propagation loss (path loss) and its susceptibility to shadowing, the use of mmWave bands is deemed suitable for mainly short range (a few hundred meters) and point-to-point LoS communications. Furthermore, since the Doppler spread is linear function of the carrier frequency, the amount of Doppler spread in the 60 GHz band will be $10-30\times$ of that in $2-6$ GHz band. Radio signals used for communication with the cellular network and between vehicles can also be used for position estimation. The achievable positioning accuracy can be significantly higher in 5G networks relative to legacy LTE networks due to higher signal bandwidths and dense network deployments, which enables LoS communication with a high probability. Estimation of the relative position between vehicles is directly useful for certain use cases such as platooning, but can also serve as input to the cellular network in order to improve the estimation of vehicles' absolute position [16].

Global ITS spectrum is currently under further study within ITU-R Working Party 5A.[3] This study is considered essential in improving the safety and efficiency of roads and highways. Specifically, the ITU World Radio communication Conference 2015 (WRC-15) adopted a

3 ITU-R Study Group 5 (SG 5) Working Party 5A (WP 5A): Land mobile service excluding IMT; amateur and amateur-satellite service https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5a

resolution to include a new agenda item in the WRC-19[4] to conduct studies on technical and operational aspects of evolving ITS implementation using existing mobile service allocations.

7.3 Network Architecture and Protocol Aspects

7.3.1 Reference Architecture

LTE-based V2X operates in two modes: direct connection via sidelink and via the network. In the direct communication, the UE uses the LTE PC5 interface, which is based on 3GPP Rel-12 ProSe. The D2D communication in LTE operates over the sidelink channel in two different modes. In the first mode, the resources are allocated by the network (i.e., eNB). Devices that intend to transmit will send a request to the network for resource allocation, and the network subsequently allocates the resources and notifies the device. This mode requires additional signaling for every transmission, thus increasing transmission latency. In the second operation mode, devices select the resource autonomously. The autonomous mode reduces latency, but some issues related to possible collisions and interference may arise. Optimization of resource allocation procedures has been considered with emphasis on the autonomous mode due to its lower latency. Further enhancements to accommodate high-speed/high-Doppler, high-vehicle density, improved synchronization, and decreased message transfer latency have been studied. This mode is suitable for proximal direct communications over short distances and for V2V safety applications that require low latency; for example, advanced driver-assistance systems or situational awareness. This mode can work in and out-of-network coverage (see Fig. 7.2).

Network-based communication uses the LTE Uu interface between the vehicle (i.e., the UE) and the eNBs. The UEs send unicast messages via the eNB to an application server, which in turn re-broadcasts them via evolved multimedia broadcast multicast service (eMBMS) for all UEs in the relevant geographical area. This mode uses the existing LTE radio access and is suitable for latency-tolerant use cases (e.g., situational awareness, mobility services). It is possible to deploy the network-based mode in an operator licensed spectrum, while the direct PC5-based mode can be deployed in unlicensed spectrum.

LTE uses unicast and broadcast bearers for data transmission. Broadcast is applicable, if the mobile operator has deployed eMBMS. LTE can complement the short-range communication path for V2X provided by other technologies (e.g., DSRC/IEEE 802.11p). This type of broadcast transmission can potentially cover more vehicles in network coverage because the network can control the broadcast range, which is more suitable for the V2I/V2N type of services. Mobile operators can provide additional value-added services to subscribed drivers including traffic jams/blocked roads further ahead, real-time map/3D building/landmarks,

[4] World Radiocommunication Conference 2019 (WRC-19) https://www.itu.int/en/ITU-R/conferences/wrc/2019

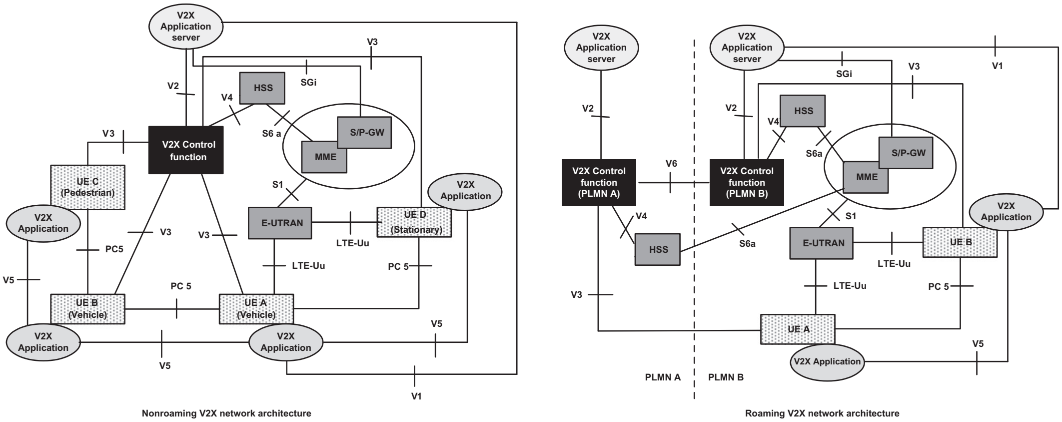

Figure 7.7
Roaming/non-roaming network architecture for LTE-based V2X communication [2].

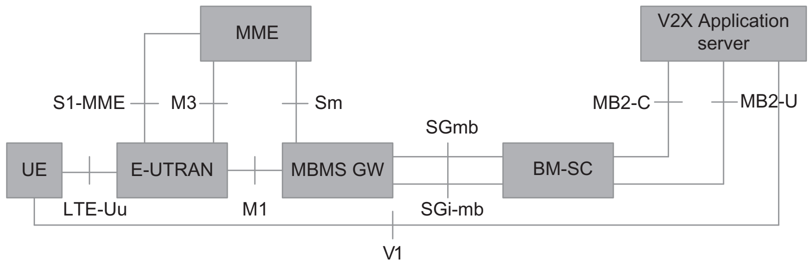

Figure 7.8
Reference architecture for eMBMS for LTE-Uu-based V2X communication via MB2 [2].

updates for the area, or suggested speed. These two operation modes may be used by a UE independently for transmission and reception; for example, a UE can use eMBMS for reception without using LTE-Uu for transmission. A UE may also receive V2X messages via LTE-Uu unicast downlink.

V2X application servers (e.g., for traffic management services) in different domains can communicate with each other to exchange V2X messages. The interface between V2X application servers and the methods of the exchange of messages between V2X application servers is out of scope of 3GPP specifications. ProSe discovery feature can be used by a V2X-enabled UE and it is up to UE implementation. The RSU is not an architectural entity, but an implementation option. The high-level roaming and non-roaming reference architectures for PC5 and LTE-Uu-based V2X communications are shown in Fig. 7.7.

Fig. 7.8 shows the high-level reference architecture with eMBMS for LTE-based V2X communication. The V2X application server may apply either MB2 or xMB reference points when managing eMBMS service-related information via a broadcast multicast service center (BM-SC),[5] where MB2 reference point provides the functionality related to group communication and xMB reference point provides an interface for any content and supports security framework between content provider and BM-SC.

In the V2X reference architecture, the V2X control function is a logical function that is used for network-related functionalities required for V2X. It is assumed that there is only one logical V2X control function in each public land mobile network (PLMN) that supports V2X services. If multiple V2X control functions are deployed within the same PLMN, then the method to locate the specific V2X control function, for example, through a database lookup, is not specified by 3GPP. The V2X control function is used to configure the UEs with necessary parameters for V2X communication. It is used to provide the UEs with network-specific parameters that allow the UEs to use V2X service in that PLMN. The V2X control function is also used to configure the UEs with parameters that are needed when the UEs are not served by an LTE network. The V2X control function may also be used to obtain V2X user service descriptions (USDs) so that the UEs can receive eMBMS-based V2X traffic through V2 reference point from the V2X application server. V2X control function may also obtain the parameters required for V2X communications over PC5 reference point, or from the V2X application server via V2 reference point. The V2X control function in home PLMN can be always reached, if home-routed configuration is applied for packet data network (PDN) connection (e.g., the P-GW is part of the home PLMN), when such function is supported by the home PLMN. In the case of local breakout (e.g., the P-GW is part of the visited PLMN), a V2X control function proxy can be deployed by the visited PLMN to support UE to home V2X control function logical connection, if inter-PLMN signaling is required. The UE is not aware of these transactions and it will not know which access point name (APN) can be used for communication with the V2X control function unless the specific APN information is configured in the UE indicating that this APN provides signaling connectivity between the UE and the home V2X control function. The V2X control function of the home PLMN is discovered through interaction with the domain name service (DNS) function [2].

The V2X application server supports receiving uplink data from the UE over a unicast connection and delivering data to the UE(s) in a target area using a unicast and/or eMBMS delivery mechanism as well as mapping of geographic location information to the appropriate target eMBMS service area identities for the broadcast. It is further responsible for mapping from geographic location information to the appropriate [target] E-UTRAN cell global identifier (ECGI), which is used to globally identify the cells. The

5 Broadcast multicast service center is an evolved multimedia broadcast multicast service network entity located in the core network and is responsible for authorization and authentication of content providers, charging, and overall configuration of the data flow through the core network.

V2X application server handles the mapping from UE provided ECGI to appropriate target eMBMS service area identities for the broadcast; provides the appropriate ECGI(s) and/or eMBMS service area identities to BM-SC, which is preconfigured with the local eMBMS information (e.g., Internet protocol (IP) multicast address, multicast source, common tunnel endpoint identifier); and is preconfigured with the local eMBMS IP address and port number for the user plane. The V2X application server is also in charge of sending local eMBMS information to the BM-SC; requesting BM-SC for allocation/de-allocation of a set of temporary mobile group identities; requesting BM-SC for activating/deactivating/modifying the eMBMS bearer; providing the V2X USDs so that the UE can receive eMBMS-based V2X traffic from V2X control function; providing the parameters for V2X communications over PC5 reference point to V2X control function; or providing the parameters for V2X communications over PC5 reference point to UE [2].

The reference points or network interfaces shown in Fig. 7.7 can be further described as follows [2]:

- *V1:* This reference point is between the V2X application in the UE and in the V2X application server, and it is not defined in 3GPP specifications.
- *V2:* This reference point is between the V2X application server and the V2X control function in the operator's network. The V2X application server may connect to V2X control functions belonging to multiple PLMNs.
- *V3:* This reference point is between the UE and the V2X control function in UE's home PLMN. It is based on the service authorization and provisioning part of the PC3 reference point. It is applicable to both PC5 and LTE-Uu-based V2X communication and optionally eMBMS and LTE-Uu-based V2X communication.
- *V4:* This reference point is between the home subscriber server (HSS) and the V2X control function in the operator's network.
- *V5:* This reference point is between the V2X applications in the UEs, and is not specified in 3GPP specifications.
- *V6:* This reference point is between the V2X control function in the home PLMN and the V2X control function in the visited PLMN.
- *PC5:* This reference point is between the UEs for direct communication over user-plane for V2X service.
- *S6a:* In case of V2X service, S6a is used to download V2X service-related subscription information to mobility management entity (MME) during E-UTRAN attach procedure or to inform MME subscription information in the HSS has changed.
- *S1-MME:* In case of V2X service, it is used to convey the V2X service authorization from the MME to eNB.
- *xMB:* This reference point is between the V2X application server (e.g., content provider) and the BM-SC.

- *MB2:* This reference point is between the V2X application server and the BM-SC.
- *SGmb/SGi-mb/M1/M3:* The SGmb/SGi-mb/M1/M3 reference points are internal to the eMBMS system.
- *LTE-Uu:* This reference point is between the UE and the E-UTRAN.

The V2N and communication via the network represent suitable applications for the network slicing. For instance, autonomous driving or safety/emergency services would require a URLLC network slice. Meanwhile, some infotainment services or personal mobility services would require either a best-effort slice or an eMBB. A vehicle can access different slices at the same time, with passengers watching a high-definition movie while a background application detects a road hazard and triggers an emergency message for the cars behind or nearby to slow down or stop to prevent an accident. Fig. 7.9 illustrates this scenario. The slices could come from one device or multiple devices. In the case of one device, 3GPP has defined that a given device can support up to eight different slices with a common access and mobility management function (AMF) for all slices and a session management function (SMF) per slice. In the example shown in Fig. 7.9, there are three network slices attached to the same device sharing the same AMF instance. The first slice is massive machine-type communication, which sends data to the core and the PDN. The second slice offers caching at the edge, while the third slice provides access to an edge V2X application.

The C-V2X can operate outside of network coverage using direct communication without requiring provisioning of a universal subscriber identity module (USIM). To enable USIM-less communication, automobile manufacturers will preconfigure the vehicle device with parameters necessary for out-of-network operation, including authorization to use V2X; a list of authorized application classes and the associated frequencies to use; radio parameters for use over the direct link; and configuration for receiving V2X messages via cellular

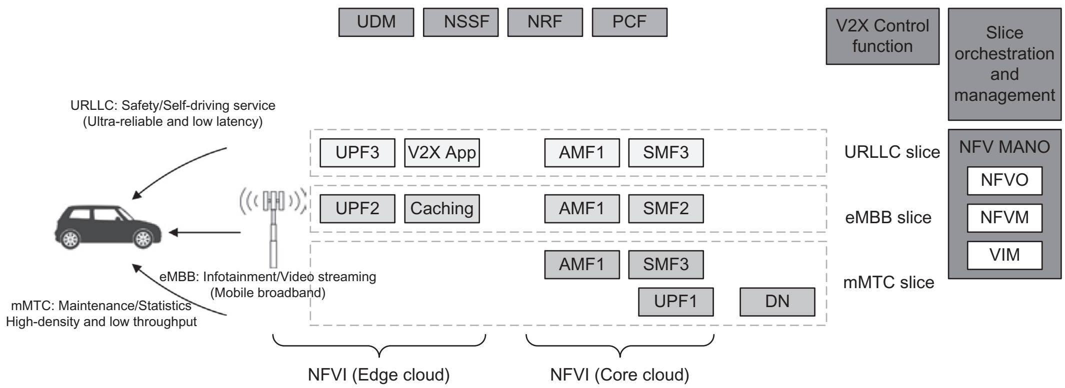

Figure 7.9
Example of NR V2X network slicing [13,14].

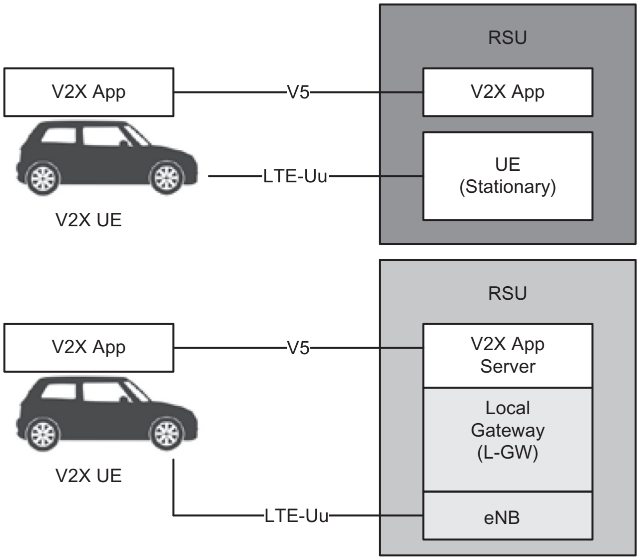

Figure 7.10
RSU implementation options [20].

broadcast (i.e., eMBMS). Direct USIM-less communication allows C-V2X to support critical safety services when network coverage is unavailable or if the vehicle does not have an active cellular subscription. These parameters can also be securely updated by the vehicle manufacturers or the mobile operators.

For V2I applications, the infrastructure that includes an RSU can be implemented in an eNB or a stationary UE. Fig. 7.10 shows two RSU implementation options and the functional entities in each case.

7.3.2 Sidelink and Radio Access Protocols

Sidelink communication is a mode of operation whereby UEs can communicate with each other directly over the PC5 interface. This operation mode is supported when the UE is served by an eNB/gNB or outside of the network coverage. The use of sidelink communication was originally limited to those UEs that were authorized for public safety operation; however, the application of sidelink communication was further extended to V2X services. In order to perform synchronization for out-of-coverage devices, the originating device may act as a synchronization source by transmitting sidelink broadcast control channel (SBCCH) and synchronization signals. The SBCCH carries the most essential system information needed to receive other sidelink channels and signals. In LTE V2X, the SBCCH is transmitted along with a synchronization signal with a fixed periodicity of 40 ms [6].

When the UE is in network coverage, the content of SBCCH are derived from the parameters signaled by the serving eNB. When the UE is out-of-network coverage and if it selects another UE as a synchronization reference node, then the system information is obtained from SBCCH transmitted by the reference node; otherwise, the UE uses preconfigured parameters. The system information block type 18 (SIB18) provides the resource information for the synchronization signal and SBCCH transmission. There are two preconfigured subframes every 40 ms for out-of-coverage operation. The UE receives the synchronization signal and the SBCCH in one subframe and transmits the synchronization signal and the SBCCH in another subframe, if it assumes the role of the synchronization node. The UE performs sidelink communication in subframes defined over the duration of sidelink control period. The sidelink control period is the time interval during which the resources are allocated in a cell for sidelink control information (SCI) and data transmission. Within the sidelink control period, the UE sends SCI followed by sidelink data. SCI indicates a physical layer identifier and resource allocation parameters; for example, modulation and coding scheme (MCS), location of the resource(s) over the duration of sidelink control period, timing alignment, etc. The UE performs transmission and reception over LTE-Uu and PC5 (without sidelink discovery gap) where Uu transmission/reception is the highest priority, followed by PC5 sidelink communication transmission/reception and then by PC5 sidelink discovery announcement/monitoring, which is considered the lowest priority. The UE further performs transmission/reception over Uu and PC5 (with sidelink discovery gap) starting with Uu transmission/reception for RACH, followed by PC5 sidelink discovery announcement during a sidelink discovery gap for transmission; non-RACH Uu transmission; PC5 sidelink discovery monitoring during a sidelink discovery gap for reception; non-RACH Uu reception; and PC5 sidelink communication transmission/reception [6].

The UE radio protocol structure for sidelink communication consists of user-plane and control-plane protocols. Fig. 7.11 shows the protocol stack for the user plane (the access

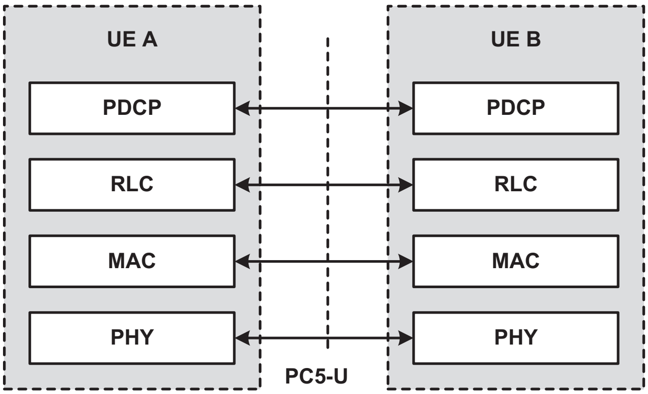

Figure 7.11
User-plane protocol stack for sidelink communication [6].

stratum protocol stack over PC5 interface), where packet data convergence protocol (PDCP), radio link control (RLC), and medium access control (MAC) sublayers, which are terminated at the other UE, perform similar functions defined for LTE protocols with some exceptions. The user plane corresponding to sidelink communication does not support HARQ feedback; uses radio link control (RLC) unacknowledged mode (UM) and the receiving UE must maintain at least one RLC UM entity per transmitting UE; a receiving RLC UM entity used for sidelink communication does not need to be configured before reception of the first RLC UM protocol data unit (PDU); and robust header compression (RoHC) unidirectional mode is used for header compression in PDCP for sidelink communication. A UE may establish multiple logical channels. In that case, the logical channel ID (LCID) included in the MAC subheader uniquely identifies a logical channel with one source layer-2 ID and destination layer-2 ID combination [7]. The parameters for logical channel prioritization are not configured. The access stratum is provided by ProSe per-packet priority (PPPP)[6] of the PDU transmitted over PC5 interface by higher layers. Note that there is one PPPP associated with each logical channel [6]. The user-plane protocol stack and functions are further used for V2X sidelink communication. In addition, for V2X sidelink communication, the sidelink traffic channel (STCH) is used. Non-V2X data (e.g., public safety) is not multiplexed with V2X data transmitted over the resources configured for V2X sidelink communication. The access stratum is provided by the PPPP of a PDU transmitted over PC5 interface by upper layers. The packet delay budget (PDB), which refers to the permissible latency of data packets transported between UE and P-GW, of the PDU can be determined from the PPPP. The low PDB is mapped to the high priority PPPP value. The existing logical channel prioritization based on PPPP is used for V2X sidelink communication [6].

The control-plane protocol stack for the sidelink broadcast channel (SL-BCH) is also used for V2X sidelink communication (see Fig. 7.12). A UE that supports V2X sidelink communication can operate in two modes for resource allocation: (1) scheduled resource allocation,

[6] In 3GPP Rel-13, ProSe per-packet priority (PPPP) was introduced to enable QoS differentiation across different traffic streams corresponding to different sidelink logical channels. PPPP has eight values ranging from one to eight, and each PPPP value represents the priority at which the associated traffic should be treated over the sidelink. Each data packet to be transmitted is assigned a PPPP value selected by the application layer. The UE then performs logical channel prioritization such that the transmission of the data associated with higher PPPP is prioritized. PPPP is also applied to transmission pool selection in the case of UE autonomous resource selection. The network can configure one or multiple PPPP for each transmission pool in the list of pools. Then, for each MAC PDU to transmit on the sidelink, the UE selects a transmission pool associated with the PPPP [2]. For downlink to sidelink mapping, which occurs when the relay UE receives traffic from the eNB, it identifies whether the packet should be relayed, by referring to the destination IP address of the packet. The relay UE then assigns a priority value called PPPP to the received packet to be relayed. The priority assignment is based on the mapping information representing the association between the QoS class identifier values of downlink bearers and the priority values. The QoS class identifier-to-priority mapping information is provisioned to the relay UE by the network.

which is characterized by the UE's need for radio resource control (RRC) connection establishment to transmit data and the UE's request for transmission resources from the eNB. The eNB schedules transmission resources for transmission of SCI and data. Sidelink semi-persistent scheduling (SPS) is supported for scheduled resource allocation; and (2) UE autonomous resource selection, which is characterized by the UE's self-selection of resources from resource pools and transport format selection to transmit SCI and data. In the latter case, if mapping between the zones and V2X sidelink transmission resource pools is configured, the UE selects V2X sidelink resource pool based on the zone in which the UE is located. The UE further performs sensing for (re)selection of sidelink resources. Based on sensing results, the UE (re)selects some specific sidelink resources and reserves multiple sidelink resources. The UE can perform up to two parallel and independent resource reservation processes. It is also allowed to perform a single resource selection for its V2X sidelink transmission [6].

A UE does not establish and maintain a logical connection to receiving UEs before one-to-many sidelink communication. Higher layer protocols establish and maintain a logical connection for one-to-one sidelink communication, including ProSe UE-to-network relay operation. The control plane functions for establishing, maintaining, and releasing the logical connections for unicast sidelink communication are shown in Fig. 7.12.

Sidelink discovery is defined as the procedure used by the UE supporting sidelink discovery to find other UE(s) in its proximity, using LTE direct radio signals via PC5 (see Fig. 7.13). Sidelink discovery is supported regardless of whether the UE is within network coverage or out-of-coverage. The service was originally limited to ProSe-enabled public safety UEs to perform sidelink discovery when they were out-of-network coverage where the allowed operating frequency was preconfigured in the UE, and is used even when UE is out-of-network coverage in that frequency. The preconfigured frequency is the same frequency as

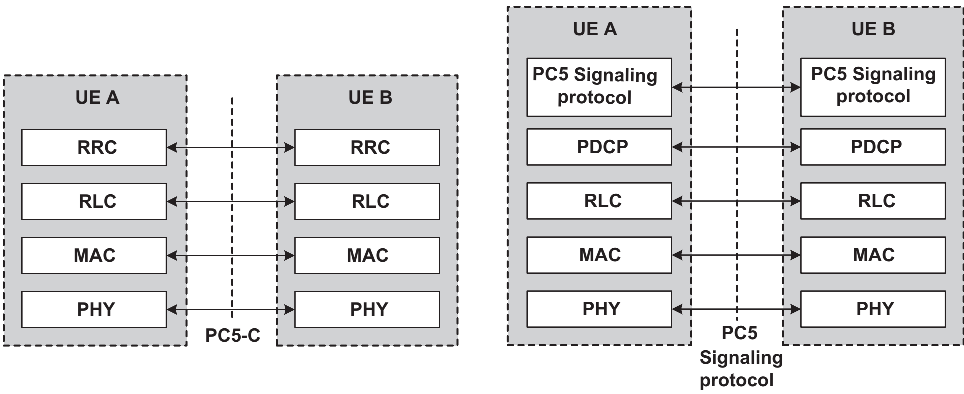

Figure 7.12
Control-plane protocol stack for sidelink broadcast and unicast transmissions [6].

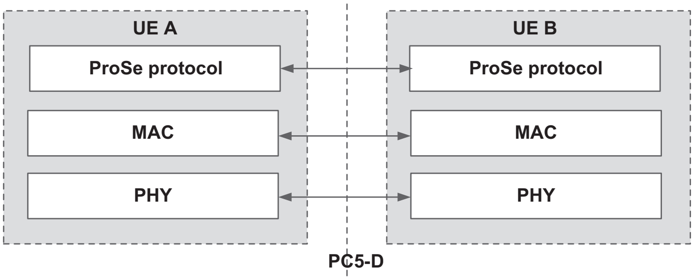

Figure 7.13
PC5 interface for sidelink discovery [6].

the public safety ProSe carrier[7] [6]. The AS protocol stack for sidelink discovery consists of only MAC and PHY. The AS layer interfaces with upper layer (ProSe protocol) where the MAC sublayer receives the discovery message from the upper layer (ProSe protocol). The IP layer is not used for transmitting the discovery message. The MAC layer determines the radio resource to be used for announcing the reception of the discovery message from upper layer and further generating the MAC PDU carrying the discovery message and sending the MAC PDU with no MAC header to the physical layer for transmission in the predetermined radio resources [7]. The content of discovery message is transparent to the access stratum, over which no distinction is made for sidelink discovery models and types; however, higher layer protocols detect whether the sidelink discovery notification is related to public safety. A UE can participate in announcing and monitoring of discovery message in both RRC_IDLE and RRC_CONNECTED states following eNB configuration, where the UE announces and monitors its discovery message subject to the half-duplex constraint. In order to perform synchronization, the UE(s) participating in announcing of discovery messages may act as a synchronization source by transmitting SBCCH and a synchronization signal based on the resource information allocated for synchronization signals provided in SIB19. There are three range classes. The upper layer authorization provides applicable range class of the UE. The maximum allowed transmission power for each range class is signaled in SIB19. The UE uses the applicable maximum allowed transmission power corresponding to its authorized range class. This sets an upper limit on the configured transmit power based on open-loop power control parameters.

7.4 Physical Layer Aspects

V2X communications enable information exchange between vehicles and between vehicles and the infrastructures and/or pedestrians. The information exchange will provide the

[7] Public safety ProSe carrier is the carrier frequency used for public safety sidelink communication and public safety sidelink discovery.

vehicles with more accurate knowledge of their surroundings, resulting in improved traffic safety. Some efforts were made in recent years to deploy V2X communications using IEEE 802.11p. However, IEEE 802.11p uses a carrier sense multiple access scheme with collision avoidance which may not be able to guarantee stringent reliability levels and network scalability as the traffic increases. As an alternative, 3GPP LTE Rel-14 included support for V2X communications. The LTE-based V2X physical layer improves the link budget relative to IEEE 802.11p. In addition, it can improve the reliability, under certain conditions, by adding redundant transmission per packet. The C-V2X standard includes two radio interfaces. The LTE-based Uu radio interface supports vehicle-to-infrastructure communications, while the PC5 interface supports V2V communications based on LTE-based sidelink communications. LTE sidelink (or D2D communication) was originally introduced in Rel-12 for public safety, and included two modes of operation: mode 1 and mode 2 (see Fig. 7.14). Both modes were designed with the objective of prolonging the battery life of mobile devices at the cost of increased latency. Connected vehicles require highly reliable and low-latency V2X communications; therefore, modes 1 and 2 are not suitable for vehicular applications. 3GPP Rel-14 introduced two new communication modes (modes 3 and 4) specifically designed for V2V communications (see Fig. 7.15). In mode 3, the cellular network selects and manages the radio resources used by vehicles for their direct V2V communications. In mode 4, vehicles autonomously select the radio resources for their direct V2V communications. In mode 4, the UE (the vehicle) can operate without cellular coverage; therefore, this is considered the baseline V2V mode since safety applications cannot depend

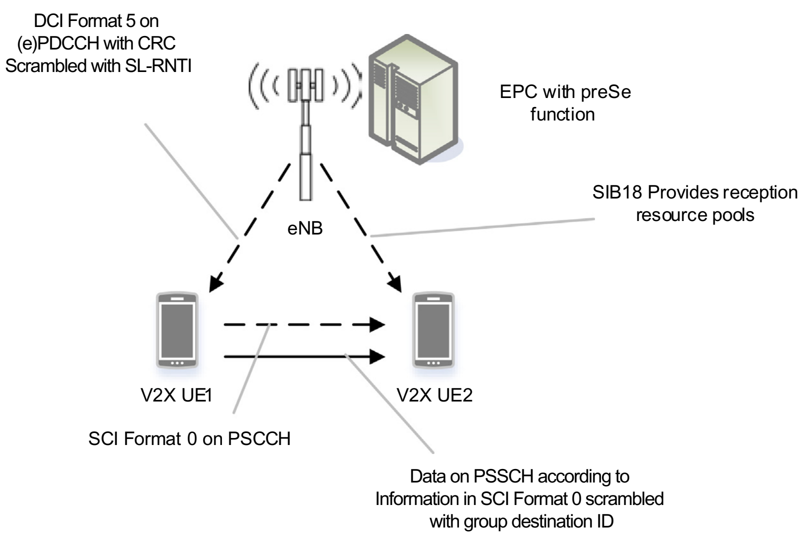

Figure 7.14
Scheduling transmission resources for direct communication, mode 1 [18,19].

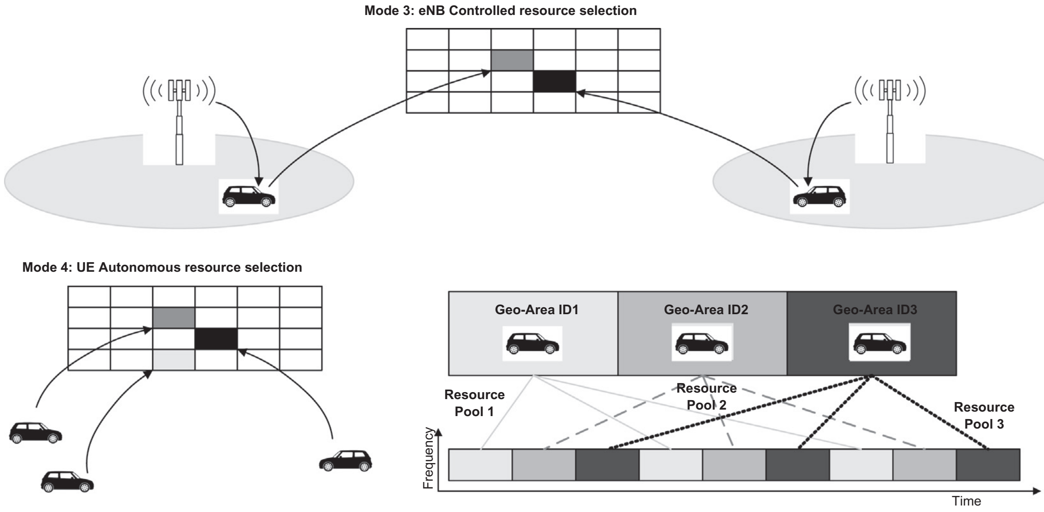

Figure 7.15
Illustration of LTE V2X modes 3 and 4 operation [25].

on the availability of cellular coverage. Mode 4 includes a distributed scheduling scheme for vehicles to select their radio resources and includes the support for distributed congestion control. In mode 3, the vehicle reports its location and coordinates to assist the eNB in scheduling, whereas in mode 4, the vehicle location information can be used to restrict sidelink resource selection (to enable spatial reuse in a distributed system).

The C-V2X utilizes LTE uplink multiple access scheme (SC-FDMA), and supports 10 and 20 MHz channels. Each channel is divided into subframes, resource blocks (RBs), and subchannels. Subframes are 1 ms long. The resource block is the smallest unit of frequency resources that can be allocated to a user. It is 180 kHz wide in frequency (12 subcarriers with 15 kHz subcarrier spacing). The C-V2X defines subchannels as a group of RBs in the same subframe, and the number of RBs per subchannel can vary. Subchannels are used to transmit data and control information. The data is transmitted in the units of transport blocks (TBs) over PSSCH, and the SCI messages are transmitted over PSCCH. A TB contains a full packet to be transmitted; for example, a beacon or cooperative awareness message. A node that wants to transmit a TB must also transmit its associated SCI, which is also referred to as a scheduling assignment. The SCI includes information such as the MCS that is used to transmit the TB, the number of RBs, and the resource reservation interval for SPS. This information is critical for other nodes to be able to receive and decode the TB; thus the SCI must be correctly received. A TB and its associated SCI must always be transmitted in the same subframe. The overall LTE-based V2X sidelink physical layer processing is shown in Fig. 7.16.

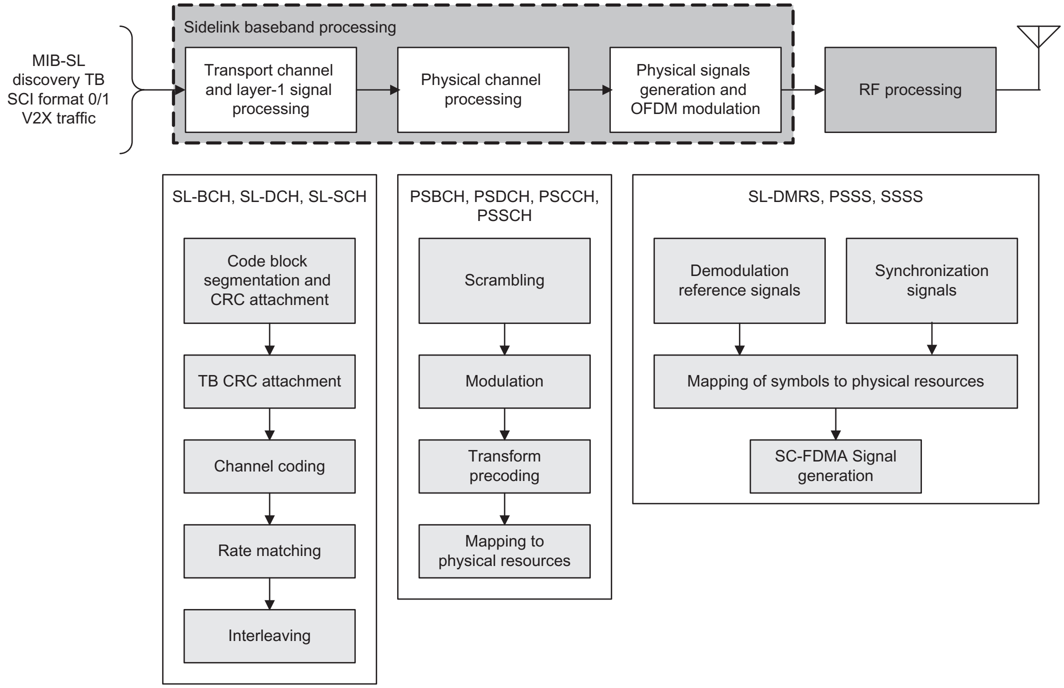

Figure 7.16
LTE V2X sidelink physical layer processing [17,22].

The C-V2X specifies two subchannelization schemes, as shown in Fig. 7.17: (1) adjacent PSCCH + PSSCH, where the SCI and TB are transmitted in adjacent RBs. For each SCI + TB transmission, the SCI occupies the first two RBs of the first subchannel utilized for the transmission. The TB is transmitted in the RBs following the SCI, and can occupy several subchannels depending on its size. It will also occupy the first two RBs of the following subchannels; and (2) non-adjacent PSCCH + PSSCH, where the RBs are divided into pools. One pool is dedicated to transmit only SCIs, and the SCIs occupy two RBs. The second pool is reserved to transmit only TBs and is divided into subchannels. The TBs can be transmitted using QPSK or 16QAM modulation, whereas the SCIs are always transmitted using QPSK. The C-V2X uses turbo coding with normal cyclic prefix. There are 14 OFDM symbols per subframe, and four of these symbols are dedicated to the transmission of demodulation reference signals (DM-RS) in order to improve robustness against the Doppler effect at high speeds. The reference signals are transmitted in the third, sixth, ninth, and twelfth symbol of the subframe. The maximum transmit power is 23 dBm, and the standard specifies a sensitivity-power-level requirement at the receiver of −90.4 dBm and a maximum input level of −22 dBm [17].

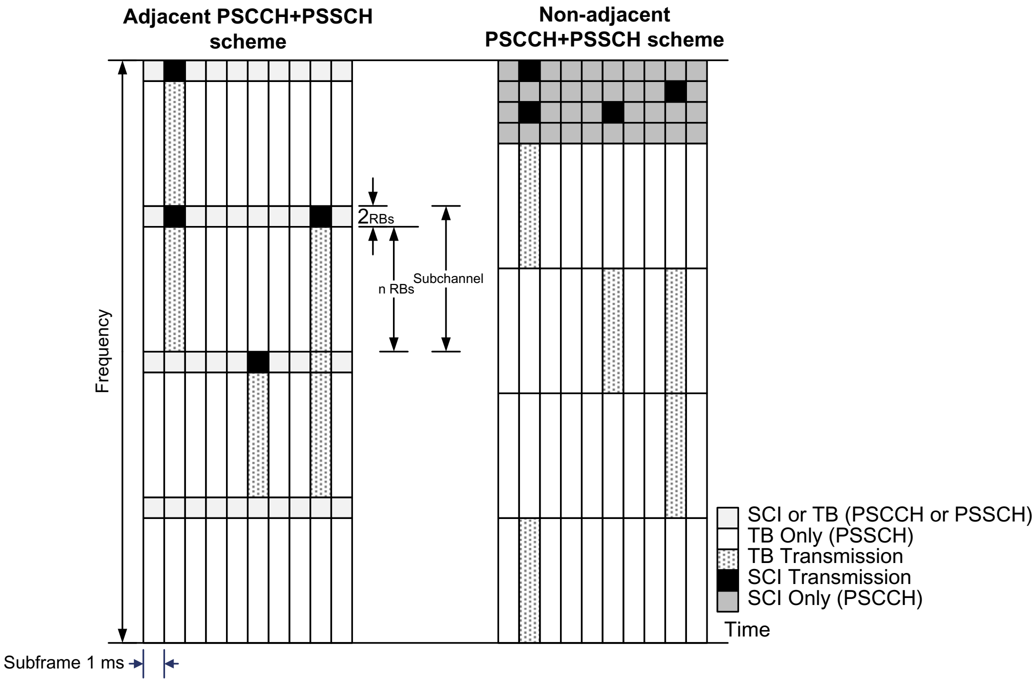

Figure 7.17
C-V2X frame structure and resource allocation schemes [17].

Vehicles communicate using sidelink or V2V communications in mode 4 and autonomously select their radio resources, independent of cellular coverage. When the vehicles are under cellular coverage, the network decides how to configure the V2X channel and informs the vehicles through the sidelink V2X configurable parameters. The message includes the carrier frequency of the V2X channel, the V2X resource pool, synchronization references, the subchannelization scheme, the number of subchannels per subframe, and the number of RBs per subchannel. When the vehicles are not within the cellular coverage, they utilize a preconfigured set of parameters to replace the sidelink V2X configurable parameters. However, the standard does not specify a specific value for each parameter. The V2X resource pool indicates which subframes of a channel are utilized for V2X. The rest of the subframes can be utilized by other services. The standard includes the option to divide the V2X resource pool based on geographical areas. In this case, vehicles in an area can only utilize the pool of resources that have been assigned to those areas (see Table 7.3).

Sidelink transmissions use the same basic transmission scheme as the uplink; however, sidelink is limited to single-cluster transmission for all sidelink physical channels. Furthermore, sidelink uses one symbol gap at the end of each sidelink subframe. For V2X sidelink communication, PSCCH and PSSCH are transmitted in the same subframe (see Fig. 7.18). The

Table 7.3: Characteristics of LTE V2X transmission schemes [20].

Item	Transmission Characteristics	
	Uu Interface	PC5 Interface
Operating frequency range	All bands specified in 3GPP TS 36.101 support operation with the Uu interface, except band 47 Bands for Uu interface when used in combination with PC5 Band 3: Uplink 1710–1785 MHz Downlink 1805–1880 MHz Band 7: Uplink 2500–2570 MHz Downlink 2620–2690 MHz Band 8: Uplink 880–915 MHz Downlink 925–960 MHz Band 39: 1880–1920 MHz Band 41: 2496–2690 MHz	For Rel-14 Band 47: 5855–5925 MHz
RF channel bandwidth	1.4, 3, 5, 10, 15, or 20 MHz per channel	10 or 20 MHz per channel
RF transmit power/EIRP	Maximum 43 dBm for eNB Maximum 23 or 33 dBm for UE	Maximum 23 or 33 dBm
Modulation scheme	Uplink: QPSK SC-FDMA, 16QAM SC-FDMA, 64QAM SC-FDMA Downlink: QPSK OFDMA, 16QAM OFDMA, 64QAM OFDMA	QPSK SC-FDMA, 16QAM SC-FDMA
Forward error correction scheme	Convolutional coding and turbo coding	Convolutional coding and turbo coding
Data transmission rate	Uplink: From 1.4 to 36.7 Mbps for 10 MHz channel Downlink: From 1.4 to 75.4 Mbps for 10 MHz channel	From 1.3 to 15.8 Mbps for 10 MHz channel
Scheduling	Centralized scheduling by eNB	Centralized scheduling or distributed scheduling
Duplex method	FDD or TDD	TDD

sidelink physical layer processing of transport channels differs from uplink transmission in two aspects: (1) scrambling in physical sidelink discovery channel (PSDCH) and PSCCH processing is not UE-specific and (2) 64QAM and 256QAM modulation schemes are not supported for the sidelink. The PSCCH is mapped to the sidelink control resources and indicates resource and other transmission parameters used by a UE for PSSCH. For PSDCH, PSCCH, and PSSCH demodulation, reference signals similar to uplink DM-RS are transmitted in the fourth symbol of the slot in normal cyclic prefix and in the third symbol of the slot for extended cyclic prefix. The sidelink DM-RS sequence length equals the size (number of subcarriers) of the assigned resources in the frequency domain. For V2X sidelink communication, reference signals are transmitted in the third and the sixth symbol of the first slot and the second and the fifth symbol of the second slot in normal cyclic prefix. For PSDCH and PSCCH, the reference signals are generated based on a fixed base sequence, cyclic shift, and orthogonal cover code. For V2X sidelink communication, cyclic shift for PSCCH is randomly selected in each transmission [6].

For in-coverage operation, the power spectral density of the sidelink transmissions is determined by the eNB. For measurement on the sidelink, the following basic UE measurement quantities are defined [18,19]:

- *Sidelink reference signal received power (S-RSRP)* is defined as the linear average over the power contributions [in (Watts)] of the resource elements that carry DM-RSs associated with physical sidelink broadcast channel (PSBCH), within the six middle-band PRBs of the relevant subframes. The reference point for the S-RSRP is the antenna connector of the UE. The reported value must not be lower than the corresponding S-RSRP of any of the individual diversity branches, if receive diversity is utilized by the UE.
- *Sidelink discovery reference signal received power (SD-RSRP)* is defined as the linear average over the power contributions (in [Watts]) of the resource elements that carry DM-RSs associated with PSDCH for which CRC has been validated. The reference point for the SD-RSRP is the antenna connector of the UE. If receive diversity is used by the UE, the reported value will be lower than the corresponding SD-RSRP of any of the individual diversity branches.
- *PSSCH reference signal received power (PSSCH-RSRP)* is defined as the linear average over the power contributions [in (Watts)] of the resource elements that carry DM-RSs associated with PSSCH, within the PRBs indicated by the associated PSCCH. The reference point for the PSSCH-RSRP is the antenna connector of the UE. If receive diversity is used by the UE, the reported value must not be lower than the corresponding PSSCH-RSRP of any of the individual diversity branches.
- *Sidelink reference signal strength indicator (S-RSSI)* is defined as the linear average of the total received power [in (Watts)] per SC-FDMA symbol observed by the UE only in the configured subchannels over SC-FDMA symbols $(1, 2, \ldots, 6)$ of the first slot and SC-FDMA symbols $(0, 1, \ldots, 5)$ of the second slot of a subframe. The reference point for the S-RSSI is the antenna connector of the UE. If receive diversity is used by the UE, the reported value should not be lower than the corresponding S-RSSI of any of the individual diversity branches.

In the sidelink, there is no HARQ feedback and retransmissions are always performed in a predefined/configured manner. Measurement gaps and sidelink discovery transmission during a sidelink discovery gap for transmission are of higher priority than HARQ retransmissions, and whenever a HARQ retransmission collides with a measurement gap or sidelink discovery transmission during a sidelink discovery gap for transmission, the HARQ retransmission does not take place.

Vehicles (or the UEs) select their subchannels in mode 4 using the sensing-based SPS scheme specified in Rel-14 [6]. A vehicle reserves the selected subchannel(s) for several consecutive reselection counter packet transmissions. This counter is randomly set between

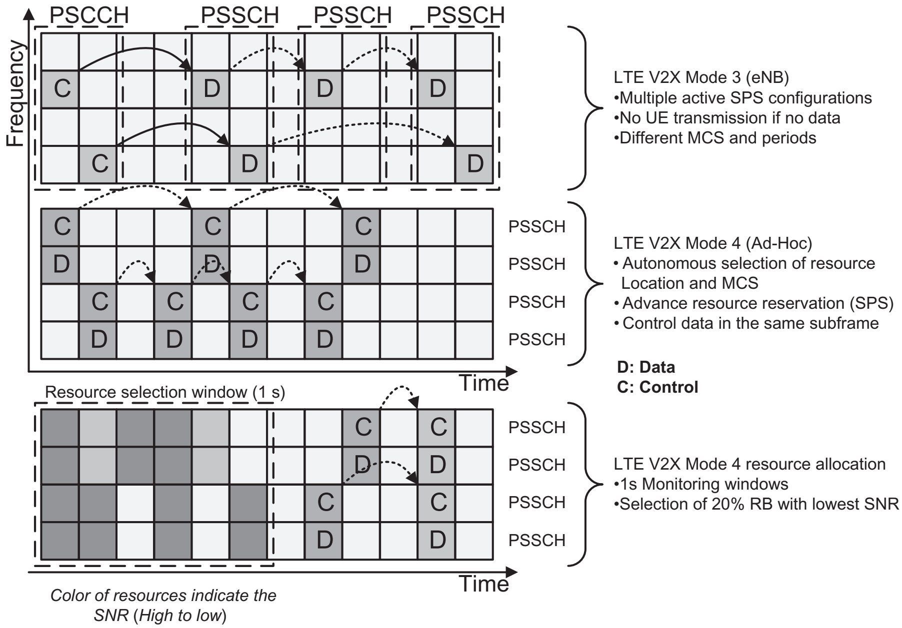

Figure 7.18
Comparison of LTE V2X modes 3 and 4 [25].

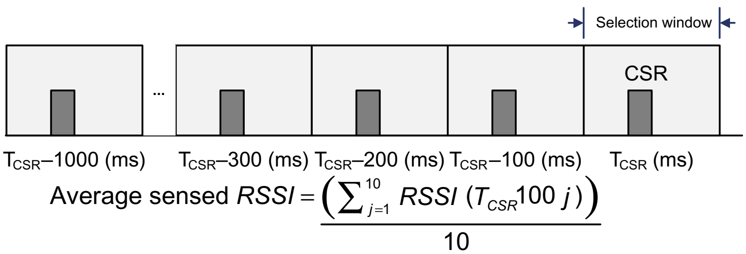

Figure 7.19
Calculation of the average RSSI of a candidate resource [17].

5 and 15, and the vehicle includes its value in the SCI. After each transmission, the reselection counter is decremented by one. When it is equal to zero, new resources must be selected and reserved with probability $(1 - p)$ where the UE/vehicle can set the value of p between 0 and 0.8. New resources also need to be reserved, if the size of the packet to be transmitted does not fit in the subchannel(s) previously reserved. The reselection counter is randomly chosen every time that new resources are reserved. Packets can be transmitted every 100 subframes or in multiples of 100 subframes with a minimum of one packet per subframe. Each UE/vehicle includes its packet transmission interval in the resource reservation field of its SCI. The semi-persistent reservation of resources and the inclusion of the

reselection counter and packet transmission interval in the SCI would help other vehicles to estimate the [potentially] unused subchannels when making their own reservation, resulting in reduced risk of packet collision.

Let us assume that a vehicle needs to reserve new subchannels at time $T_{reservation}$. It can reserve subchannels between $T_{reservation}$ and the maximum latency of 100 ms. This interval is referred to as the selection window (see Fig. 7.19). Within the selection window, the vehicle identifies candidate single-subframe resources (CSR) to be reserved by all groups of adjacent subchannels within the same subframe where the SCI + TB information to be transmitted would fit. The vehicle analyzes the information it has received in the previous 1000 subframes before time instant $T_{reservation}$ and creates a list of permissible CSRs.

LTE V2X mode 4 provides an option for each packet to be transmitted twice to increase the reliability. The sensing-based SPS scheme randomly selects a CSR from a candidate list for the redundant transmission of the SCI + TB. 3GPP Rel-14 includes a variant of the sensing-based SPS scheme for pedestrian-to-vehicle communications, where pedestrians broadcast their presence using mobile devices. Since the sensing process increases the battery consumption, the standard provides an option to only sense a fraction of the 1000 subframes (1000 ms) before $T_{reservation}$. The mobile devices can only select CSRs in the sensed subframes using the sensing-based SPS scheme. LTE V2X supports two types of sidelink transmission: (1) single shot without resource reservation and (2) multi-shot with resource reservation. Both types of transmission follow sensing and resource selection procedure. The timing diagram for LTE V2X mode 4, dedicated sensing and resource selection, is illustrated in Fig. 7.20 with sensing (1000 ms) and resource (re)-selection (up to 100 ms) windows. The concept of sensing and resource reservation is further depicted in Fig. 7.21.

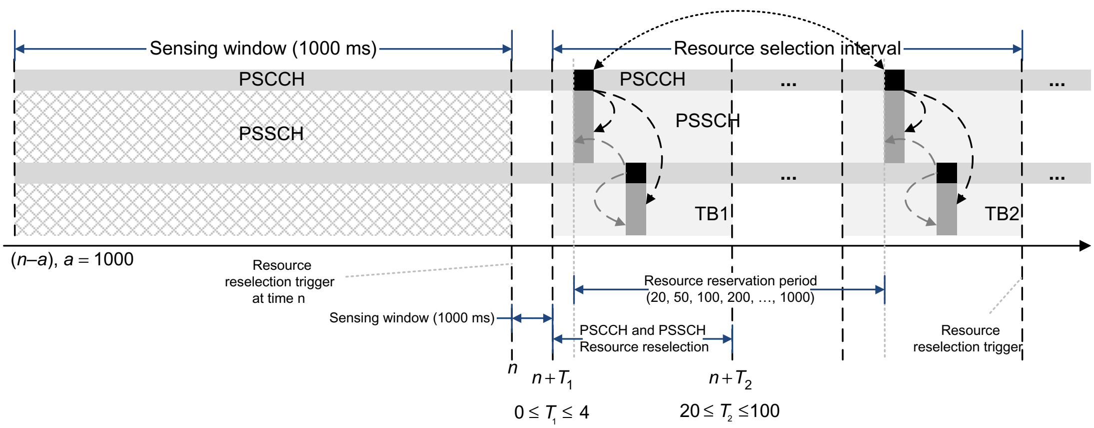

Figure 7.20
Mode 4 UE autonomous sensing and resource selection [25].

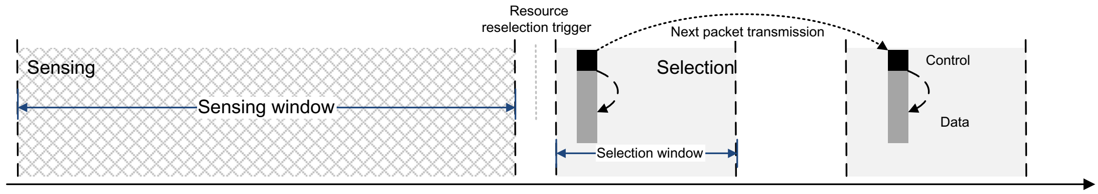

Figure 7.21
Sensing and resource reservation for collision avoidance in LTE V2X [6].

Vehicles also communicate using sidelink or V2V communications in mode 3. However, the selection of subchannels is managed by the base station and not by each vehicle as opposed to mode 4 (see Fig. 7.18). Mode 3 is only available when vehicles are within the network coverage. 3GPP has defined network architecture enhancements to support V2X. One of these enhancements is the V2X control function that is used by the network in mode 3 to manage radio resources and to provide vehicles with the sidelink V2X configurable parameters. Mode 3 utilizes the same subchannel arrangements as defined for mode 4. Vehicles using mode 3 must also transmit an associated SCI/TB, and the transmission of the SCI/TB must take place in the same subframe. In contrast to mode 4, the standard does not specify a resource management algorithm for mode 3. Each operator can implement its own algorithm that should fall under one of two categories: (1) Dynamic scheduling where the vehicles request subchannels from the eNB for each packet transmission, which increases the signaling overhead, and delays the packet transmission until vehicles are notified of their assigned subchannels; and (2) SPS-based scheduling where the base station reserves subchannels for the periodic transmissions of a vehicle. However, in contrast to mode 4, the eNB decides how long the reservation should be maintained and it can activate, deactivate, or modify reservation of subchannels for a vehicle. The vehicle must inform the eNB of the size, priority, and transmission frequency of its packets so that the eNB can semi-persistently reserve the appropriate subchannels. This information must be provided to the eNB at the start of a transmission, or when any of the traffic characteristics (size, priority, and frequency) change [17].

Vehicles operating in mode 3 can be supported by different cellular operators. To enable their direct communication, 3GPP has defined an inter-PLMN architecture that can support vehicles subscribed to different PLMNs to transmit over different carriers. In this case, vehicles must be able to simultaneously receive the transmissions of vehicles supported by other PLMNs on multiple carriers. Therefore, each PLMN broadcasts in the sidelink V2X configurable parameters the necessary information so that the subscribed vehicles can receive the packets transmitted by other vehicles supported by different PLMNs. In an alternative scenario, the vehicles may be supported by different PLMNs sharing the same carrier, where each PLMN is assigned a fraction of the resources of the carrier. The standard does not

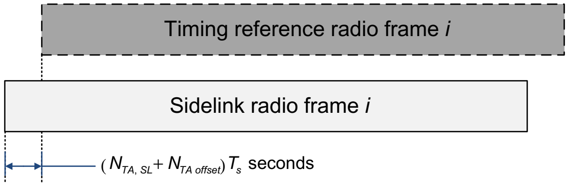

Figure 7.22
Sidelink timing alignment [3].

specify how the resources should be allocated among the PLMNs, but introduces a coordination mechanism (through the V2X control function) between PLMNs to avoid packet collisions [17].

The frame timing synchronization is an important consideration. Transmission of the ith sidelink radio frame from the UE starts at $(N_{TA,SL} + N_{TA\ offset})T_s$ seconds before the start of the corresponding timing reference frame at the UE (see Fig. 7.22). The UE is not required to receive sidelink or downlink transmissions earlier than $624T_s$ following the end of a sidelink transmission. The parameter $N_{TA,SL}$ differs between channels and signals where $N_{TA,SL} = N_{TA}$ for PSSCH in sidelink transmission mode 1 and 0 otherwise [3].

7.4.1 Sidelink Physical Resources and Resource Pool

In LTE-based sidelink communication, physical layer transmissions are organized in the form of radio frames with duration $T_{frame} = 10$ ms, each consisting of 20 slots of duration $T_{slot} = 0.5$ ms. A sidelink subframe consists of two consecutive slots. A physical channel or signal is transmitted in a slot and is described by a resource grid of $N_{RB}^{SL} N_{sc}^{RB}$ subcarriers and N_{symbol}^{SL} SC-FDMA symbols. The sidelink bandwidth is equal to the uplink bandwidth $N_{RB}^{SL} = N_{RB}^{UL}$ if the cell-selection criterion is satisfied for a serving cell having the same uplink carrier frequency as the sidelink; otherwise, a preconfigured value is used. The sidelink cyclic prefix is configured independently for type 1 discovery, type 2B discovery, sidelink transmission mode 1, sidelink transmission mode 2, control signaling, and PSBCH as well as synchronization signals. The configuration is done per resource pool for discovery, sidelink transmission mode 2, and control signaling. The PSBCH and synchronization signals always use the same cyclic prefix value. Normal cyclic prefix is only supported for PSSCH, PSCCH, PSBCH, and synchronization signals for a sidelink configured with transmission mode 3 or 4 [3].

Each resource element in the resource grid is uniquely defined by the index pair $\left\{(k,l)|k = 0,\ldots,N_{RB}^{SL} N_{sc}^{RB} - 1;\ l = 0,\ldots,N_{symbol}^{SL} - 1\right\}$ in a slot where the first and the second indices represent the frequency and time, respectively. The resource elements that are not used for transmission of a physical channel or a physical signal in a slot are set to zero.

A physical resource block (PRB) is defined as $N_{symbol}^{SL} = 7$ or 6 (extended cyclic prefix) consecutive SC-FDMA symbols in the time domain and $N_{sc}^{RB} = 12$ consecutive subcarriers in the frequency domain. A PRB in the sidelink consists of $N_{symbol}^{SL} \times N_{sc}^{RB}$ resource elements, corresponding to one slot in the time domain and 180 kHz in the frequency domain [3]. The relationship between the PRB number n_{PRB} in the frequency domain and resource elements (k, l) in a slot is given by $n_{\text{PRB}} = \lfloor k/12 \rfloor$.

A key concept in LTE-based sidelink communication is the resource pool, which defines a subset of available subframes and RBs for either sidelink transmission or reception. Sidelink communication is a half-duplex scheme and a UE can be configured with multiple transmit resource pools and multiple receive resource pools. The resource pools are configured semi-statically by RRC signaling. When data is sent using a resource pool, the actual transmission resources are selected dynamically from within the pool using one of the two following modes:

- Transmission mode 1, where the serving eNB identifies the resources via downlink control information (DCI) format 5 that has to be sent to the transmitting UE. This mode requires the UE to be fully connected to the network; that is, in RRC_CONNECTED state.
- Transmission mode 2, where the transmitting UE self-selects the resources according to certain rules aimed at minimizing the risk of collision. This mode can be used when the UE is in connected state, idle state, or out of network coverage.

There are two types of resource pools: (1) reception resource pools and (2) transmission resource pools. These are either signaled by the eNB for the in-coverage cases, or preconfigured for the out-of-coverage scenarios. Each transmission resource pool has an associated reception resource pool in order to enable bidirectional communication. However, within a cell, there may be more reception resource pools than transmission resource pools, allowing reception from the UEs in the neighboring cells or from the UEs that are out-of-coverage. Fig. 7.23 illustrates the LTE V2X resource pool structure.

A sidelink direct communication resource pool is configured semi-statically using layer-3 signaling. The physical resources (subframes and RBs) associated with the pool are partitioned into a sequence of repeating hyper frames known as PSCCH periods or alternatively referred to as the scheduling assignment period or sidelink control period. Within a PSCCH period, there are separate subframe pools and RB pools for control (PSCCH) and data (PSSCH). The PSCCH subframes always precede those for PSSCH transmission. This is analogous to the symbol layout of the physical downlink control channel and physical downlink shared channel OFDM symbols within a single downlink subframe, where the control region precedes the data subchannel. The PSCCH carries SCI messages, which describe the dynamic transmission properties of the PSSCH that follows. The receiving UE

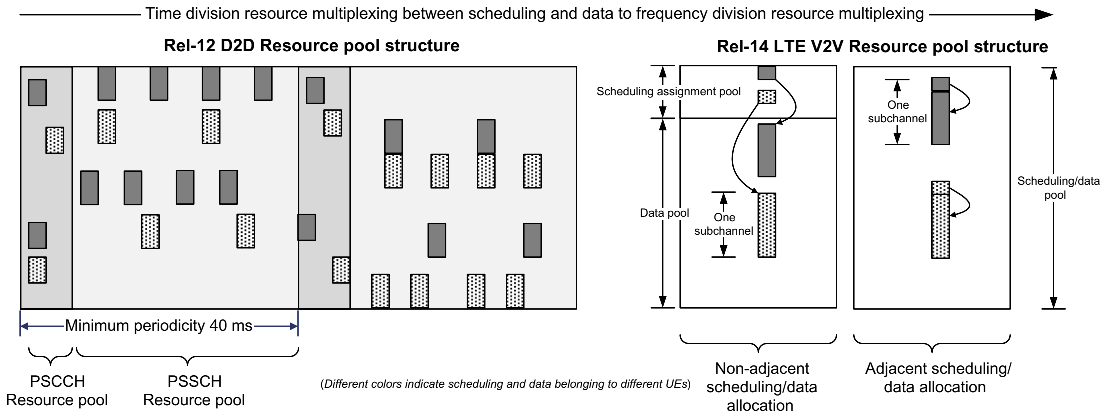

Figure 7.23
LTE V2X resource pool structure [13,14].

searches all configured PSCCH resource pools for SCI transmissions of interest. A UE can be a member of more than one sidelink communications group.

For PSSCH, the number of current slot in the subframe pool $n_{ss}^{PSSCH} = 2n_{ssf}^{PSSCH} + i$, where $i \in \{0, 1\}$ is the number of current slot within the current sidelink subframe $n_{ssf}^{PSSCH} = j \bmod 10$, where j is equal to the subscript of l_j^{PSSCH} for sidelink transmission modes 1 and 2, respectively; and $i \in \{0, 1\}$ is the number of the current slot within the current sidelink subframe $n_{ssf}^{PSSCH} = k \bmod 10$ in which k is equal to the subscript of t_k^{SL} for sidelink transmission modes 3 and 4. The last SC-FDMA symbol in a sidelink subframe is used as a guard period and is not used for sidelink transmission [3,5].

7.4.2 Sidelink Physical Channels

7.4.2.1 Physical Sidelink Shared Channel

In LTE-based sidelink communication, the processing of the sidelink shared channel (SL-SCH) follows the procedures for LTE downlink shared channel processing with some differences as follows: (1) data arrives at the channel coding unit in the form of a maximum of one TB in every transmission time interval; (2) in the step of code block concatenation, the sequence of coded bits corresponding to one TB after code block concatenation is referred to as one codeword; and (3) physical uplink shared channel (PUSCH) interleaving is applied without any control information in order to apply a time-first rather than frequency-first mapping, where $C_{mux} = 2\left(N_{symb}^{SL} - 1\right)$. For SL-SCH configured by higher layers for V2X sidelink, $C_{mux} = 2\left(N_{symb}^{SL} - 2\right)$ is used [3,5] (Fig. 7.24).

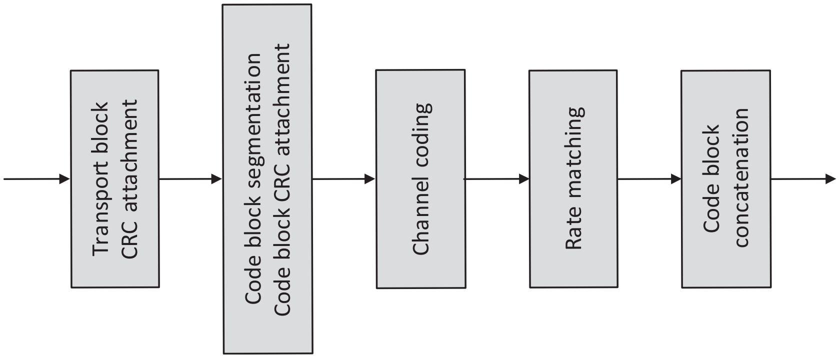

Figure 7.24
Transport block processing for PSSCH [4].

The PSSCH processing begins with the scrambling of the block of bits $b(0),\ldots,b(N_{bit}-1)$, where N_{bit} is the number of bits transmitted on the PSSCH in one subframe. The scrambling sequence generator is initialized with $c_{init}=n_{ID}^{X}2^{14}+n_{ssf}^{PSSCH}2^{9}+510$ at the start of each PSSCH subframe. For sidelink transmission modes 1 and 2, $n_{ID}^{X}=n_{ID}^{SA}$ is the destination identity obtained from the sidelink control channel, and for sidelink transmission modes 3 and 4 $n_{ID}^{X}=\sum_{i=0}^{L-1}p_i 2^{L-1-i}$ with p and L equal to the decimal representation of CRC on the PSCCH transmitted in the same subframe as the PSSCH [3]. The output of the scrambling function is modulated using QPSK or 16QAM modulation and layer-mapped assuming a single antenna port [3]. Transform precoding is then performed with M_{RB}^{PSSCH} and M_{sc}^{PSSCH} parameters followed by precoding for single antenna port transmission.

The block of complex-valued modulated symbols $z(0),\ldots,z(M_{symb}^{p}-1)$ are power-adjusted using the scaling factor β_{PSSCH} and sequentially mapped to PRBs on antenna port p starting with $z(0)$ allocated for PSSCH transmission. The resource elements (k,l) used for the latter frequency-first mapping should not be designated for transmission of reference signals, starting with the first slot in the subframe. Resource elements in the last SC-FDMA symbol within a subframe are counted in the mapping process but not used for transmission. If sidelink frequency hopping is disabled, the set of PRBs used for transmission is given by $n_{PRB}=n'_{VRB}$, where n'_{VRB} is given in [3]. If sidelink frequency hopping with predefined hopping pattern is enabled, the set of PRBs used for transmission is given by the SCI associated with a predefined pattern such that only inter-subframe hopping is used. The number of subbands $N_{sb}\in\{1,2,4\}$ is configured by RRC signaling. The parameters $N_{RB}^{HO}\in\{0,\ldots,110\}$ is given by higher layers; $n_s=n_{ss}^{PSSCH}$ where n_{ss}^{PSSCH} is given in [3]; and $CURRENT\_TX\_NB=n_{ssf}^{PSSCH}$. The pseudo-random sequence generator is initialized at the start of each slot with $n_{ss}^{PSSCH}=0$ and the initialization value $c_{init}\in\{0,1,\ldots,503,510\}$ is determined by *hoppingParameter-r12* RRC parameter; the quantity n_{VRB} is replaced by n'_{VRB}; and for sidelink transmission mode 1, $N_{RB}^{UL}=N_{RB}^{SL}$, for sidelink transmission mode 2, $N_{RB}^{UL}=M_{RB}^{PSSCH\_RP}$ where $M_{RB}^{PSSCH\_RP}$ in given in [5]; the quantity n_{PRB} is replaced by n'_{PRB}; and the physical RB to use for transmission $n_{PRB} = m^{PSSCH}_{n'_{PRB}}$ with m^{PSSCH}_{j} given in [3].

7.4.2.2 Physical Sidelink Control Channel

As we mentioned earlier, the SCI messages are transmitted over PSCCH in LTE-based sidelink communication. The fields defined in the SCI formats below are mapped to the information bits a_0 to a_{A-1} such that each field is mapped in the order in which it appears in the description, with the first field mapped to the lowest order information bit a_0 and each successive field mapped to higher order information bits.

There are two SCI formats for transmission of the SCI content as follows [4]:

- *SCI format 0* carries 1-bit frequency hopping flag; RB assignment and hopping resource allocation $\lceil \log_2 [N^{SL}_{RB}(N^{SL}_{RB}+1)/2] \rceil$ bits where for PSSCH hopping N_{SL_hop} most significant bits (MSBs) are used to obtain the value of $\tilde{n}_{PRB}(i)$ and $\left(\lceil \log_2 (N^{SL}_{RB}(N^{SL}_{RB}+1)/2) \rceil - N_{SL\_hop} \right)$ bits provide the resource allocation in the subframe. For non-hopping PSSCH, $\left(\lceil \log_2 (N^{SL}_{RB}(N^{SL}_{RB}+1)/2) \rceil \right)$ bits provide the resource allocation in the subframe. The SCI format 0 further includes 7-bit time resource pattern; 5-bit modulation and coding; 11-bit timing advance indication; and 8-bit group destination ID.
- *SCI format 1* is used for the scheduling of PSSCH and carries 3-bit priority; 4-bit resource reservation; frequency resource location of initial transmission and retransmission $\lceil \log_2 (N^{SL}_{subchannel}(N^{SL}_{subchannel}+1)/2) \rceil$ bits; 4-bit time gap between initial transmission and retransmission; 5-bit modulation and coding; 1-bit retransmission index; and a number of reserved bits to adjust the size of SCI format 1 to 32 bits. The reserved bits are set to zero.

The block of bits $b(0), \ldots, b(N_{bit}-1)$, where N_{bit} is the number of bits transmitted on the physical sidelink control channel in one subframe are scrambled with the scrambling sequence generator initialized to $c_{init} = 510$ at the start of each PSCCH subframe and then QPSK-modulated. Layer mapping with single antenna port and transform precoding are performed on complex-valued modulated symbols. Transform precoding is performed similar to LTE uplink with M^{PUSCH}_{RB} and M^{PUSCH}_{sc} parameters replaced by M^{PSCCH}_{RB} and M^{PSCCH}_{sc} values, respectively. For transmission on a single antenna port, precoding is defined by $z^{(0)}(i) = y^{(0)}(i)$, where $i = 0, 1, \ldots, M^{layer}_{symb} - 1$ and $y^{(0)}(i)$ denotes the transform-precoded complex-valued symbols.

The block of complex-valued symbols $z(0), \ldots, z(M^{p}_{symb} - 1)$ are multiplied by β_{PSCCH} in order to adjust the transmit power and are sequentially mapped, starting with $z(0)$, to the PRBs on antenna port p that have been assigned for transmission of PSCCH. The latter frequency-first resource mapping must avoid resources that are designated to transmission of reference signals, starting with the first slot in the subframe. Resource elements in the last SC-FDMA symbol within a subframe are considered in the mapping process but are not used for transmission.

The radio resources for direct communication can be selected by the device autonomously or will be scheduled by the network. In case the device has acquired SIB18 and has further a passive connection with the network in RRC_IDLE, the device would select radio resource from the broadcast resource pool in SIB18. Similar to direct discovery case, a UE would have to transit to the RRC_CONNECTED state when no valid (transmit) resource pool are provided by SIB18. In this case, a ProSe UE information indication is sent by the terminal to the network, indicating the intent to use the direct communication capability. In response, the network will assign a sidelink radio network temporary identifier (SL-RNTI) to the device. The network then uses the SL-RNTI and the downlink control channel to assign a transmission grant to the device with the new defined DCI format 5. The DCI format 5 is used for scheduling of PSCCH and contains some SCI format 0 fields that are used for scheduling of PSSCH. The DCI format 5 information fields include 6-bit resource indication for PSCCH; and 1-bit transmit power control command for PSCCH and PSSCH, as well as SCI format 0 fields including frequency hopping flag; RB assignment and hopping resource allocation; and time resource pattern [5]. Similarly, the DCI format 5A is used for scheduling of PSCCH, containing some SCI format 1 fields to schedule PSSCH. The DCI format 5A information fields include 3-bit carrier indicator; the lowest index of the subchannel allocation to the initial transmission $\lceil \log_2(N^{SL}_{subchannel}) \rceil$ bits as well as SCI format 1 information fields including frequency resource location of initial transmission and retransmission; time gap between initial transmission and retransmission; and 2-bit sidelink index [this field is present only for TDD uplink/downlink configuration 0−6]. When DCI format 5A CRC is scrambled with sidelink semi-persistent scheduling V-RNTI (SL-SPS-V-RNTI[8]), it would further include 3-bit sidelink SPS configuration index and 1-bit activation/release indication [4].

For sidelink transmission mode 1, if a UE is configured via RRC signaling to receive DCI format 5 with the CRC scrambled by the SL-RNTI, the UE is required to decode PDCCH/ePDCCH according to the combination defined in Table 7.4. For sidelink transmission mode 3, if a UE is configured by higher layers to receive DCI format 5A with the CRC scrambled by the SL-V-RNTI or SL-SPS-V-RNTI, the UE must decode the PDCCH/ePDCCH according to the combination defined in Table 7.4, and it is not expected to receive DCI format 5A with size larger than DCI format 0 in the same search space that DCI format 0 is defined.

The PSCCH carrying SCI format 0 is transmitted in two subframes within the configured resource pool occupying only one RB pair. The 7-bit time resource pattern determines

[8] Semi-persistently scheduled sidelink transmission for V2X sidelink communication, which is used for activation, reactivation, deactivation, and retransmission.

Table 7.4: PDCCH/ePDCCH configured by various RNTIs [5].

DCI Format	Search Space
DCI format 5	For PDCCH: Common and UE-specific by C-RNTI For ePDCCH: UE-specific by C-RNTI
DCI format 5A	For PDCCH: Common and UE-specific by C-RNTI For ePDCCH: UE-specific by C-RNTI

which subframes are used for transmission of PSSCH. A subframe indicator bitmap of variable length is defined, where the length of this bitmap depends on the duplex mode; i.e., FDD or TDD, and in case of TDD which UL/DL configuration is used. In case of FDD, the bitmap is 8 bits long. Up to 128 different time resource patterns define how these 8 bits are used. The RB allocation for PSSCH follows the same principles defined for LTE Rel-8 while interpreting the RB assignment and hopping allocation information provided by SCI format 0. The information is transmitted four times. For mode 2, the device would autonomously select resources from the transmission resource pool provided in SIB18. If a device is out-of-coverage, it can only autonomously select resources from a preconfigured resource pool.

Transmissions in PSSCH follow a time resource pattern, which is a subframe indication bitmap with fixed length N_{TRP} (e.g., eight subframes) repeated over the length of PSSCH, to identify which subframes are used by a transmitting UE. Each time resource pattern is identified by an index I_{TRP} corresponding to the predefined subframe indication bitmap. In order to mitigate the throughput degradation due to inter-cell/inter-user interference, each transmission on PSSCH is performed with four HARQ processes without feedback. Thus, each TB transmission on PSSCH requires four subframes to be carried. In other words, in the case of PSSCH, different parameters are used to specify the time and frequency resources. This differs from PSCCH, which signals the subframes and PRB to be used by a single value.

The subframes associated with PSSCH transmission are indicated by the time resource pattern index I_{TRP}. This index is used to look up a bitmap from a set of tables, with the choice of table depending on the duplexing mode. The selected bitmap is denoted by $\left(b'_0, b'_1, \ldots, b'_{N_{TRP}-1}\right)$ where N_{TRP} is 6, 7, or 8 depending on the table. This bitmap is repeated to form an extended bitmap $\left(b_0, b_1, \ldots, b_{L_{PSSCH}-1}\right)$ where $b_j = b'_{j \bmod N_{TRP}}$ covers the entire PSSCH subframe pool. The subframes used for PSSCH transmission are selected by l_j^{PSSCH} values in this extended bitmap to obtain the final subframe set denoted by $\left(n_0^{PSSCH}, n_1^{PSSCH}, \ldots, n_{N_{PSSCH}-1}^{PSSCH}\right)$, where N_{PSSCH} value is a multiple of 4, and denotes the number of subframes that can be used for PSSCH transmission in the PSCCH period. This is consistent with the fact that each TB transmitted within this interval will be sent four times using the fixed HARQ redundancy version sequence (0,2,3,1) [5].

7.4.2.3 Physical Sidelink Discovery Channel

In LTE-based sidelink communication, the processing of the SL-DCH follows the downlink shared channel with the following differences: (1) data arrives at the channel coding unit in the form one TB per each transmission time interval; (2) in the step of code block concatenation, the sequence of coded bits corresponding to one TB after code block concatenation is referred to as one codeword; and (3) PUSCH interleaving is applied without any control information in order to apply a time-first rather than frequency-first mapping such that $C_{mux} = 2\left(N_{symb}^{SL} - 1\right)$. The block of bits $b(0), \ldots, b(N_{bit} - 1)$, where N_{bit} is the number of bits transmitted on the PSDCH in one subframe, are scrambled with the scrambling sequence generator initialized with $c_{init} = 510$ at the start of each PSDCH subframe and then QPSK-modulated. The layer mapping, transform precoding, precoding, and the mapping to the physical resources are similar to PSCCH processing described earlier.

7.4.2.4 Physical Sidelink Broadcast Channel

Fig. 7.25 shows the processing stages of SL-BCH transport channel in LTE-based sidelink communication. The broadcast channel data in a TB is processed through channel coding module, which includes CRC attachment to the TB, channel coding, and rate matching. Since the latter processing is in the uplink direction of LTE, following the rate matching, LTE PUSCH interleaving is used without multiplexing with control information. A time-first rather than frequency-first mapping is applied, where $C_{mux} = 2\left(N_{symbol}^{SL} - 3\right)$. For SL-BCH configured by higher layers for V2X sidelink, $C_{mux} = 2\left(N_{symbol}^{SL} - 2\right) - 3$ is used. The entire TB containing the sidelink broadcast channel is used to calculate the 16-bit CRC. Information bits inclusive of the attached 16-bit CRC are encoded using tail biting convolutional code (i.e., a TBCC with constraint length 7 and coding rate 1/3) and rate matched.

The block of bits $b(0), \ldots, b(N_{bit} - 1)$, where N_{bit} is the number of bits transmitted on the PSBCH in one subframe, are scrambled so that the scrambling sequence generator is initialized at the start of every PSBCH subframe with $c_{init} = N_{ID}^{SL}$ and then QPSK-modulated. Layer mapping with single antenna port and transform precoding are performed on

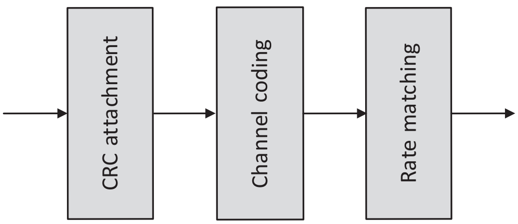

Figure 7.25
Physical sidelink broadcast channel processing [4].

complex-valued modulated symbols. Transform precoding is performed similar to LTE uplink with parameters M_{RB}^{PSBCH} and M_{sc}^{PSBCH}. For transmission on a single antenna port, precoding is defined by $z^{(0)}(i) = y^{(0)}(i)$, where $i = 0, 1, \ldots, M_{symb}^{layer} - 1$ and $y^{(0)}(i)$ denotes the transform-precoded complex-valued symbols. The block of complex-valued symbols $z(0), \ldots, z(M_{symb}^{p} - 1)$ are multiplied by an amplitude scaling factor β_{PSBCH} in order to adjust the transmit power, and sequentially mapped to PRBs on antenna port p. The PSBCH utilizes the same set of RBs as the synchronization signal. The frequency-first mapping to the PRBs would avoid resources designated for transmission of reference signals or synchronization signals, starting with the first slot in the subframe. The resource element index k is determined by $k = k' - 36 + N_{RB}^{SL} N_{sc}^{RB}/2, \quad k' = 0, 1, \ldots, 71$ since the last symbol of the subframe is used as a gap and not used for transmission.

7.4.3 Sidelink Physical Signals

7.4.3.1 Demodulation Reference Signals

In LTE V2X, the DM-RSs associated with PSSCH, PSCCH, PSDCH, and PSBCH are transmitted similar to LTE PUSCH with different parameters and antenna ports. The set of physical RBs used in the mapping process are identical to the corresponding PSSCH/PSCCH/PSDCH/PSBCH transmission. As shown in Fig. 7.26, for sidelink transmission modes 3 and 4 on PSSCH and PSCCH, the mapping uses symbols $l = 2, 5$ for the first slot in the

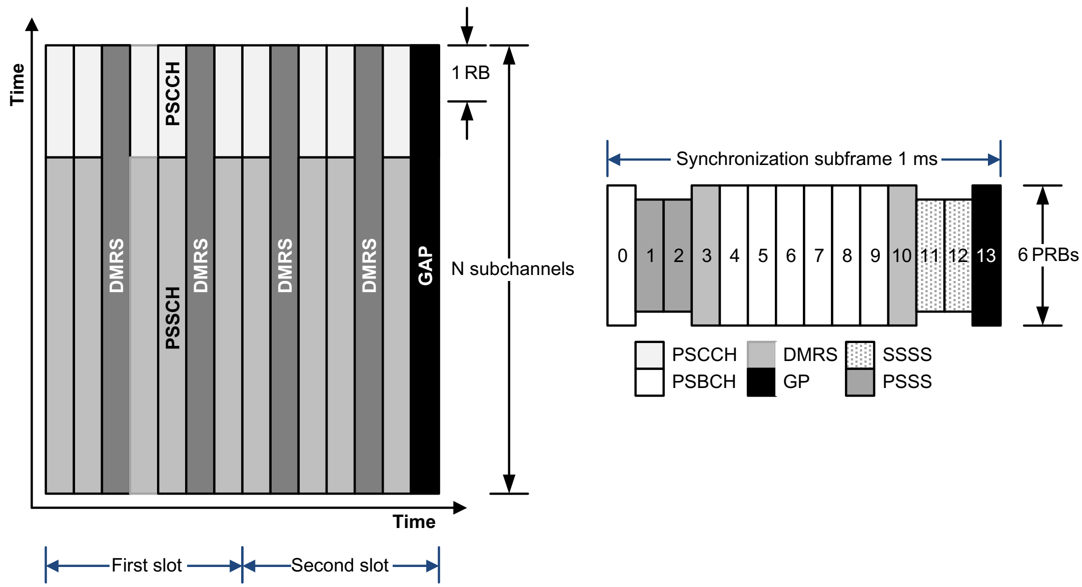

Figure 7.26
C-V2X frame structure and location of various physical channels and signals [3].

subframe and symbols $l = 1, 4$ for the second slot in the subframe. For sidelink transmission modes 3 and 4 on PSBCH, the mapping uses symbols $l = 4, 6$ for the first slot in the subframe and symbol $l = 2$ for the second slot in the subframe. For sidelink transmission modes 1 and 2, the pseudo-random sequence generator used for scrambling is initialized at the start of each slot where $n_{ss}^{PSSCH} = 0$, whereas for sidelink transmission modes 3 and 4, the pseudo-random sequence generator is initialized at the start of each slot where $n_{ss}^{PSSCH} \bmod 2 = 0$. For sidelink transmission modes 3 and 4, the quantity n_{ID}^{X} is equal to the decimal representation of the CRC on PSCCH transmitted in the same subframe as PSSCH according to $n_{ID}^{X} = \sum_{i=0}^{L-1} p_i 2^{L-1-i}$ with parameters p and L defined in [3].

7.4.3.2 Synchronization Signals

Time and frequency synchronization are important aspects of cellular communication for interference management and mitigation, which are further extended to V2X communication. A V2X-enabled device first needs to determine if it is in coverage of the network. A device is defined to be in-coverage based on signal quality measurement using the RSRP measurement performed on the downlink synchronization signals. When the measured RSRP values are above a specific threshold, the device considers itself in coverage and uses the base station downlink synchronization signals for timing and frequency alignment. This threshold is defined as part of broadcast system information. If the received signal quality measurement falls below the threshold, the device would start transmission of sidelink synchronization signals (SLSS) and the PSBCH. These signals have a periodicity of 40 ms. Assuming the device cannot detect an eNB, due to possibly being out-of-coverage, the device starts looking for SLSS from other devices and performs signal quality measurements (S-RSRP) on those synchronization signals. The SLSS comprise a primary sidelink synchronization signal (PSSS) and a secondary sidelink synchronization signal (SSSS). The PSSS and SSSS are both transmitted in adjacent time slots in the same subframe (see Fig. 7.26). The combination of both signals defines a sidelink ID (SID), similar to the physical cell ID transmitted in the downlink. The SIDs are split into two sets. The SIDs in the range of $\{0, 1, \ldots, 167\}$ are reserved for in-coverage, whereas the SIDs $\{168, 169, \ldots, 335\}$ are used when the device is out-of-coverage. The subframes to be used as radio resources to transmit SLSS and PBSCH are configured by higher layers and no PSDCH, PSCCH, or PSSCH transmissions are allowed in these subframes. The resource mapping is slightly different for normal and extended cyclic prefix. Fig. 7.27 shows the mapping for normal cyclic prefix. In the frequency domain, the inner six RBs are reserved for SLSS and PSBCH transmission. More specifically, a physical layer sidelink synchronization identity is represented by $N_{ID}^{SL} \in \{0, 1, \ldots, 335\}$, divided into two sets consisting of identities $\{0, 1, \ldots, 167\}$ and $\{168, 169, \ldots, 335\}$. The PSSS is transmitted in two adjacent SC-FDMA symbols in the same subframe. Each of the two sequences $d_i(0), \ldots, d_i(61), i = 1, 2$ is used for the PSSS in the two SC-FDMA symbols with root index $u = 26$ if $N_{ID}^{SL} \leq 167$ and $u = 37$, otherwise. The sequence $d(n)$ used for the primary synchronization signal is derived from a frequency

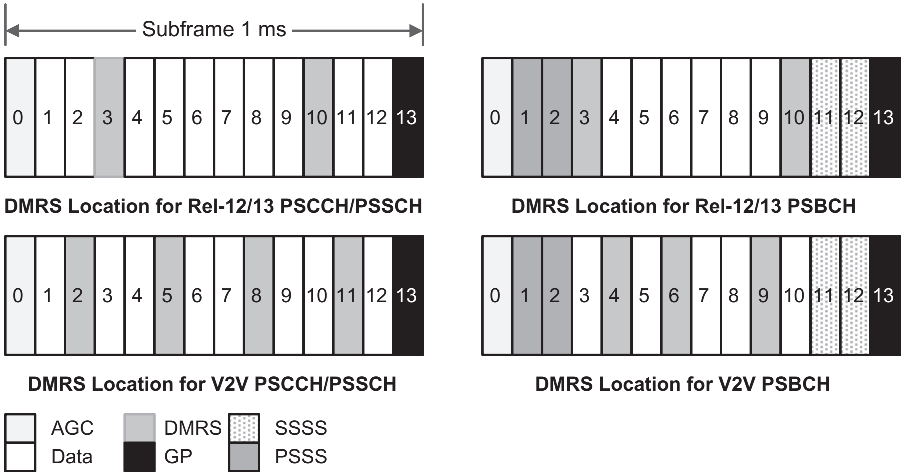

Figure 7.27
LTE V2X sidelink frame structure.

domain Zadoff-Chu sequence according to $d_u(n) = \exp\left[-j\pi un(n+1)/63\right] \forall n = 0, 1, \ldots, 30$ and $d_u(n) = \exp\left[-j\pi u(n+1)(n+2)/63\right] \forall n = 31, 32, \ldots, 61$, where u denotes the Zadoff-Chu root sequence index [3]. The sequence $d_i(n)$ is multiplied with an amplitude scaling factor of $\sqrt{72/62}\beta_{PSBCH}$ and mapped to resource elements on a single antenna port in the first slot of the subframe according to $a_{k,l} = d_i(n) \forall n = 0, \ldots, 61; k = n - 31 + N_{RB}^{SL} N_{sc}^{RB}/2$ with $l = 1, 2$ (normal cyclic prefix) and $l = 0, 1$ (extended cyclic prefix).

The SSSS is transmitted in two adjacent SC-FDMA symbols in the same subframe. Each of the two sequences $d_i(0), \ldots, d_i(61) \forall i = 1, 2$ is used for the SSSS. The sequence $d(0), \ldots, d(61)$ used for the second synchronization signal is an interleaved concatenation of two length-31 binary sequences. The concatenated sequence is scrambled with a scrambling sequence given by the primary synchronization signal assuming subframe 0 with $N_{ID}^{(1)} = N_{ID}^{SL} \mathrm{mod} 168$ and $N_{ID}^{(2)} = \lfloor N_{ID}^{SL}/168 \rfloor$ for transmission modes 1 and 2, and subframe 5 for transmission modes 3 and 4 [3]. The sequence $d_i(n)$ is multiplied with the amplitude scaling factor β_{SSSS} in order to adjust the transmit power and mapped to resource elements on a single antenna port in the second slot in the subframe according to $a_{k,l} = d_i(n) \forall n = 0, \ldots, 61; k = n - 31 + N_{RB}^{SL} N_{sc}^{RB}/2$ with $l = 4, 5$ (normal cyclic prefix) and $l = 3, 4$ (extended cyclic prefix) [3].

7.5 Layer 2/3 Aspects

The LTE layer-2 functions are divided into three sublayers: MAC, RLC, and PDCP. Fig. 7.28 depicts the layer-2 structure for the LTE-based sidelink. In this figure, the service access points (SAP) for peer-to-peer communication are marked with circles at the interface

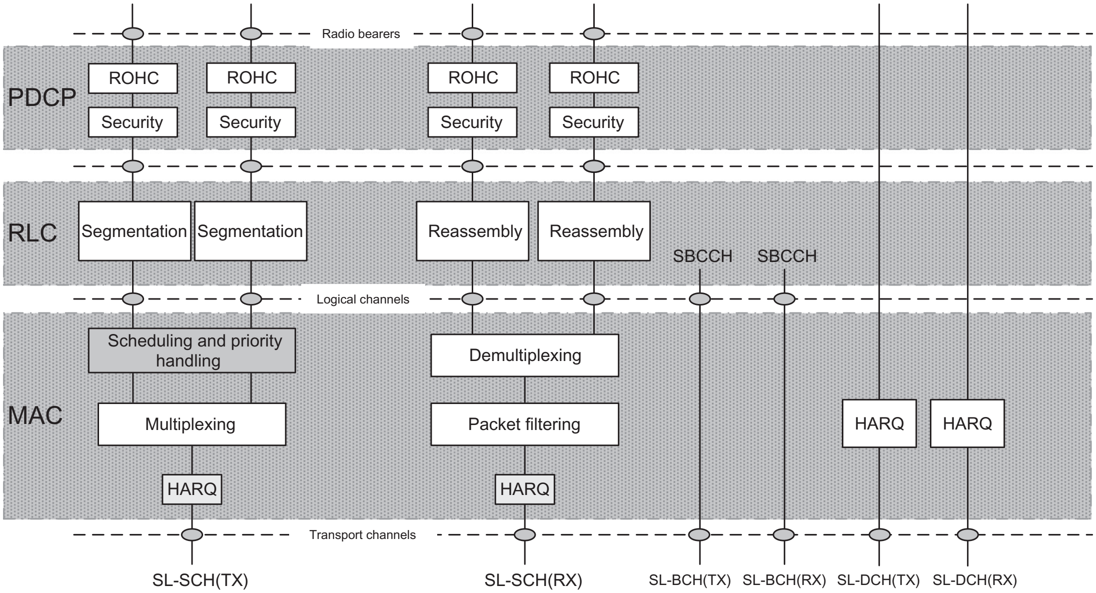

Figure 7.28
Layer-2 structure for sidelink [6].

between sublayers. The SAP between the physical layer and the MAC sublayer provides the transport channels. The SAPs between the MAC sublayer and the RLC sublayer provide the logical channels. The multiplexing of several logical channels (i.e., radio bearers) on the same transport channel is performed by the MAC sublayer. In sidelink communications, only one TB is generated per TTI. The sidelink specific services and functions of the MAC sublayer include radio resource selection and packet filtering for sidelink communication and V2X sidelink communication [6].

MAC sublayer provides different types of services that are represented by logical channels, where each logical channel is defined by the type of information it conveys. The logical channels are generally classified into two groups: (1) control channels (for the transfer of control-plane information) and (2) traffic channels (for the transfer of user-plane information), as shown in Fig. 7.29. The SBCCH is a sidelink logical channel for broadcasting sidelink system information from one UE to another UE(s). STCH is a point-to-multipoint channel, for transfer of user information from one UE to another UE(s). This channel is used only by sidelink communication-capable UEs and V2X sidelink communication-capable UEs. Point-to-point communication between two sidelink communication-capable UEs is also realized with an STCH.

As shown in Fig. 7.29, STCH logical channel can be mapped to SL-SCH transport channel and SBCCH logical channel can be mapped to SL-BCH transport channel. Sidelink

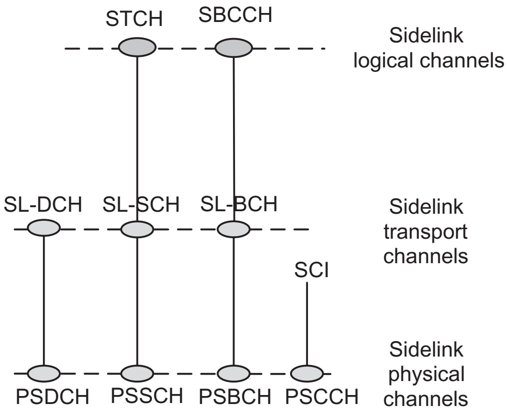

Figure 7.29
Mapping between sidelink logical, transport, and sidelink physical channels [6].

transport channels include SL-BCH, which is characterized by a predefined transport format; SL-DCH that is characterized by a fixed size, predefined format, and periodic broadcast transmission, as well as support for both UE autonomous resource selection and scheduled resource allocation by the eNB. It is subject to collision risk due to support of UE autonomous resource selection; however, no collision is expected when UE is allocated dedicated resources by the eNB. It further supports HARQ combining, but there is no support for HARQ feedback. The sidelink transport channels further include SL-SCH, which has similar characteristics as the SL-DCH, as well as support for dynamic link adaptation by varying the transmit power, modulation, and coding [6]. In the sidelink, no HARQ feedback is used and the retransmissions are always performed in a predefined/configured number. Furthermore, the measurement gaps and sidelink discovery transmission during a sidelink discovery gap for transmission are of higher priority than HARQ retransmissions; that is, whenever a HARQ retransmission collides with a measurement gap or sidelink discovery transmission during a sidelink discovery gap for transmission, the HARQ retransmission does not happen.

One of the functions of the RRC sublayer is broadcasting the system information. Both LTE RRC states, RRC_IDLE and RRC_CONNECTED, support sidelink transmission and reception; sidelink discovery announcement and monitoring; and V2X sidelink transmission and reception. The *SystemInformationBlockType18* contains information related to sidelink communication; *SystemInformationBlockType19* contains information related to sidelink discovery; and *SystemInformationBlockType21* contains information related to V2X sidelink communication. The LTE RAN uses SL-RNTI and SL-V-RNTI to identify sidelink communication scheduling and V2X sidelink communication scheduling, respectively [6].

In order to assist an LTE base station in providing sidelink resources, a UE in RRC_CONNECTED state may report geographical location information to the serving eNB. The eNB can configure the UE to report the complete UE geographical location information based on periodic reporting via the existing measurement report signaling. Geographical zones can be configured by the eNB or preconfigured. When zones are (pre-)configured, the area is divided into geographical subdivisions using a single fixed reference point; that is, geographical coordinates (0,0), length and width. The UE determines the zone identity by means of modulo operation using length and width of each zone, number of zones in length, number of zones in width, the single fixed reference point, and the geographical coordinates of the UE's current location. The length and width of each zone, number of zones in length, and number of zones in width are provided by the eNB when the UE is in-coverage, and preconfigured when the UE is out-of-coverage. The zone is configurable for both in-coverage and out-of-coverage. In an in-coverage scenario, when the UE uses autonomous resource selection, the eNB can provide the mapping between zone(s) and V2X sidelink transmission resource pools via RRC signaling. For out-of-coverage UEs, the mapping between the zone(s) and V2X sidelink transmission resource pools can be preconfigured. If the mapping between zone(s) and V2X sidelink transmission resource pool is (pre-)configured, then the UE selects transmission sidelink resources from the resource pool corresponding to the zone where it is presently located. The zone concept is not applied to exceptional V2X sidelink transmission pools as well as reception pools. Resource pools for V2X sidelink communication are not configured based on priority.

For V2X sidelink transmission, during handover, transmission resource pool configurations including exceptional transmission resource pool for the target cell can be signaled in the handover command to minimize the transmission interruption. In this way, the UE may use the V2X sidelink transmission resource pools of the target cell before the handover is completed, if either synchronization is performed with the target cell in case eNB is configured as synchronization source or synchronization is performed with GNSS in case GNSS is configured as synchronization source. If the exceptional transmission resource pool is included in the handover command, the UE uses randomly selected resources from the exceptional transmission resource pool, starting from the reception of handover command. If the UE is configured with scheduled resource allocation in the handover command, then it continues to use the exceptional transmission resource pool while the timer associated with the handover is running. If the UE is configured with autonomous resource selection in the target cell, it continues to use the exceptional transmission resource pool until the sensing results on the transmission resource pools for autonomous resource selection are available. For exceptional cases (e.g., during radio link failure, during transition from RRC_IDLE to RRC_CONNECTED, or during change of dedicated V2X sidelink resource pools within a cell), the UE may select and temporarily use resources in the exceptional pool provided in serving cell's SIB21 message or in dedicated signaling based on random selection. During cell reselection, the RRC_IDLE UE may use the randomly selected resources from the exceptional transmission resource pool of the reselected cell until the sensing results on the transmission resource pools for autonomous resource selection are available [6].

To avoid interruption in receiving V2X messages due to delay in acquiring reception resource pools broadcast from the target cell, synchronization configuration and reception resource pool configuration for the target cell can be signaled to RRC_CONNECTED UEs in the handover command. For RRC_IDLE UE, it is up to UE implementation to minimize V2X sidelink transmission/reception interruption time associated with acquisition of SIB21 message of the target cell.

A UE is considered in-coverage on the carrier used for V2X sidelink communication, whenever it detects a cell on that carrier. If the UE that is authorized for V2X sidelink communication is in-coverage on the frequency used for V2X sidelink communication or if the eNB provides V2X sidelink configuration for that frequency (including the case where the UE is out-of-coverage on that frequency), the UE uses the scheduled resource allocation or UE autonomous resource selection according to eNB configuration. When the UE is out-of-coverage on the frequency used for V2X sidelink communication and if the eNB does not provide V2X sidelink configuration for that frequency, the UE may use a set of transmission and reception resource pools preconfigured in the UE. The V2X sidelink communication resources are not shared with other non-V2X data transmitted over sidelink. An RRC_CONNECTED UE may send a *sidelink UE information* message to the serving cell, when it wishes to establish V2X sidelink communication in order to request sidelink resources [6].

If the UE is configured by upper layers to receive V2X sidelink communication and V2X sidelink reception resource pools are provided, then the UE will receive sidelink communication on the allocated resources. The reception of V2X sidelink communication on different carriers or from different PLMNs can be supported by incorporating multiple receivers in the UE. For sidelink SPS, up to eight SPS configurations with different parameters can be configured by the eNB and all SPS configurations can be simultaneously active. The activation/deactivation of SPS configuration is signaled via PDCCH by the eNB. The existing logical channel prioritization based on PPPP is used for sidelink SPS. The UE can provide supplementary information to the eNB which configures the reporting of such information for V2X sidelink communication. The latter information includes traffic characteristic parameters (e.g., a set of preferred SPS interval, timing offset with respect to subframe 0 of the SFN 0, PPPP and maximum TB size based on the observed traffic pattern) related to the SPS configuration. The UE supplementary information can be reported regardless of whether SPS is configured. Triggering of UE supplementary information transmission is implementation specific. For instance, the UE can report its supplementary information when a change in estimated periodicity and/or timing offset of packet arrival occurs. The scheduling request mask per traffic type is not supported for V2X sidelink communication. The serving cell can provide synchronization configuration for the V2X sidelink carrier. In this case, the UE follows the synchronization configuration received from serving cell. If no cell is detected on the carrier used for V2X sidelink communication and the UE does not receive synchronization configuration from serving cell, the UE follows preconfigured synchronization procedure. There are three possible synchronization nodes; that is, eNB, UE, and GNSS. In case GNSS is configured as synchronization source, the UE utilizes the universal time and the (pre)configured direct frame number (DFN) offset to calculate DFN and subframe number. If the eNB timing is configured as synchronization reference for the UE in order to perform synchronization and conduct downlink measurements, the UE follows the cell associated with the acquired frequency when in-coverage. The UE can indicate the current synchronization reference type to the eNB. One transmission pool for scheduled resource allocation is configured, considering the synchronization reference of the UE.

For controlling channel utilization, the network can indicate how the UE adapts its transmission parameters for each transmission pool depending on the channel busy ratio (CBR). The UE measures all configured transmission resource pools including the exceptional resource pool. If a resource pool is (pre)configured such that a UE always transmits PSCCH and PSSCH in adjacent RBs, then the UE measures PSCCH and PSSCH resources together. If a resource pool is (pre)configured such that a UE may transmit PSCCH and the corresponding PSSCH in non-adjacent RBs in a subframe, then PSSCH resource pool and PSCCH resource pool are measured separately. A UE in RRC_CONNECTED state can be configured to report CBR measurement results. For CBR reporting, periodic reporting and event-triggered reporting are supported. Two reporting events are introduced for event-triggered CBR reporting. In case PSSCH and PSCCH resources are placed non-adjacently, only PSSCH resource pool measurement is used for event-triggered CBR reporting. In case PSSCH and PSCCH resources are placed adjacently, CBR measurements of both PSSCH and PSCCH resources are used for event-triggered CBR reporting. Event-triggered CBR reporting is triggered by overloaded threshold and/or less-loaded threshold. The network can configure which of the transmission pools the UE needs to report [6,8].

A UE (regardless of its RRC state) performs transmission parameter adaptation based on the CBR. If PSSCH and PSCCH resources are placed non-adjacently, only PSSCH pool measurement is used for transmission parameter adaptation. However, if PSSCH and PSCCH resources are placed adjacently, CBR measurements of both PSSCH and PSCCH resources are used for transmission parameter adaptation. When CBR measurements are not available, the default transmission parameters are utilized. The exemplary adapted transmission parameters include maximum transmission power, range of the number of retransmissions per TB, range of PSSCH RB number, range of MCS, and the maximum limit on channel occupancy ratio. The transmission parameter adaption applies to all transmission resource pools including exceptional resource pools [5,6].

In V2X sidelink communication, sidelink transmission and/or reception resources including exceptional resource pool are provided via dedicated signaling, SIB21 message, and/or preconfiguration for different frequencies in both scheduled resource allocation and UE autonomous resource selection scenarios. The serving cell may signal only the frequency on which the UE should acquire the resource configuration for V2X sidelink communication. If multiple frequencies and associated resource information are provided, then it is up to UE to select a frequency among the permissible frequencies. The UE does not use preconfigured transmission resource, if it detects a cell providing resource configuration or inter-carrier resource configuration for V2X sidelink communication. An RRC_IDLE UE may prioritize the frequency that provides cross-carrier resource configuration for V2X sidelink communication over other choices during cell reselection. If the UE supports multiple transmission chains, it may simultaneously transmit on multiple carriers via PC5. In that case, a mapping between V2X service types and the suitable V2X frequencies is configured by upper layers. For scheduled resource allocation, the eNB can schedule a V2X transmission on a frequency based on the sidelink buffer status report, in which the UE includes the destination index uniquely associated with a frequency reported by the UE to the eNB in *sidelink UE information* message [6,8].

The UE may receive the V2X sidelink communication of other PLMNs. The serving cell can directly signal the resource configuration for V2X sidelink communication in an inter-PLMN operation or indirectly via the frequency on which the UE may acquire the inter-PLMN resource configuration. Note that the V2X sidelink communication transmission in other PLMNs is not permissible. When uplink transmission overlaps in time domain with V2X sidelink transmission on the same frequency, the UE prioritizes the latter over the former, if the PPPP of sidelink MAC PDU is lower than a (pre-)configured PPPP threshold; otherwise, the UE prioritizes the uplink transmission over the V2X sidelink transmission. When uplink transmission overlaps in time domain with V2X sidelink transmission in different frequency, the UE may prioritize the V2X sidelink transmission over the uplink transmission or may reduce uplink transmission power, if the PPPP of sidelink MAC PDU is lower than a (pre-)configured PPPP threshold; otherwise, the UE prioritizes the uplink transmission over the V2X sidelink transmission or reduces V2X sidelink transmission power. However, if uplink transmission is prioritized by upper layer or random-access procedure is performed, the UE prioritizes uplink transmission over any V2X sidelink transmission irrespective of the sidelink MAC PDU's PPPP [6].

Resource pool for transmission of a pedestrian UE (P-UE) may be overlapped with resources dedicated for V2X sidelink communication. For each transmission pool, the resource selection mechanism (i.e., random selection or partial sensing-based selection) is configured. If the P-UE is configured to choose either random selection or partial sensing-based selection for a transmission pool, then it is up to the UE to select a specific resource selection mechanism. If the eNB does not specify a random selection pool, the P-UEs that only support random selection cannot perform sidelink transmission. In exceptional resource pool, the P-UE uses random selection. The P-UE can send *sidelink UE* *information* message to indicate that it requests resource pools for pedestrian-related V2X sidelink transmission. It is not mandatory for P-UE to support zone-based resource selection. The P-UE reports whether it supports zone-based resource selection as part of UE capability signaling. The P-UEs do not perform CBR measurements; however, they may adjust the transmission parameters based on the default transmission parameter configuration, which can be provided to the P-UE via RRC signaling [6].

The LTE V2X messages can be delivered in unicast mode via non-guaranteed bit rate (non-GBR) or GBR bearers. To meet the QoS message delivery requirements for V2X services, a non-GBR QoS class identifier (QCI) value and a GBR QCI value are used. For broadcast V2X messages, single-cell point-to-multipoint or multimedia broadcast single frequency network transmission can be used. The reception of downlink broadcast V2X messages on different carriers/PLMNs can be supported by having multiple receiver chains in the UE. A GBR QCI value is used for the delivery of V2X messages over eMBMS bearers [6].

7.6 LTE/NR V2X Security

3GPP LTE has one of the most advanced security mechanisms among all wireless technologies and NR V2X will continue to maintain very high standards for V2X security. 3GPP has been developing capabilities that will benefit V2X, starting with enhancements in LTE to support V2X use cases. 5G will evidently support more advanced use cases; therefore, two requirements are particularly important: (1) the need for direct, ad hoc, broadcast, secure communication without any a priori configuration of security by the network and (2) management of identities for user privacy from the network or other third parties. There are two types of LTE transport-level security mechanisms: (1) LTE security protecting the UE signaling and communications with the LTE network, and (2) LTE D2D or ProSe communications security. LTE security uses a symmetric keying scheme for data protection between the UE and the network. For user-plane data, only confidentiality (encryption) is applied; there is no integrity protection on application-layer messages exchanged with the network. For ProSe/D2D communications, each group of devices conduct one-to-many, confidentiality protected data transfers. This is done using a group symmetric key, which is provisioned by the network to all member devices. There is no integrity protection on the user data and, because the key is shared by all, there is no way to positively identify which of the group members has sent the data.

V2X sidelink communication uses the following identities [6]:

- *Source layer-2 ID:* Identifies the sender of the data in the sidelink and V2X sidelink communications. The source layer-2 ID is 24 bits long and is used together with destination layer-2 ID and LCID for identification of the RLC UM entity and PDCP entity in the receiver.

- *Destination layer-2 ID:* Identifies the target of the data in the sidelink and V2X sidelink communications. For sidelink communication, the destination layer-2 ID is 24 bits long which is split in the MAC sublayer into two bit strings. The first bit string is the least significant bit part (8 bits) of destination layer-2 ID and is forwarded to physical layer as group destination ID. This identifies the target of the intended data in SCI and is used for filtering of packets at the physical layer. The second bit string is the MSB part (16 bits) of the destination layer-2 ID which is carried within the MAC header. This is used for filtering of packets at the MAC sublayer. In the case of V2X sidelink communication, destination layer-2 ID is not split and is carried within the MAC header.

No access stratum signaling is required for group formation and to configure source layer-2 ID, destination layer-2 ID and group destination ID in the UE. These identities are either provided by higher layer or derived from identities provided by higher layer. In case of groupcast and broadcast, the ProSe UE ID provided by higher layer is used directly as the source layer-2 ID and the ProSe layer-2 group ID provided by higher layer is used directly as the destination layer-2 ID in the MAC sublayer. In the case of one-to-one communications, the ProSe UE ID provided by higher layer is used directly as the source layer-2 ID or the destination layer-2 ID in the MAC sublayer. In the case of V2X sidelink communication, higher layer provides source layer-2 ID and destination layer-2 ID.

5G network security is still under development by 3GPP for device-to-network communications. The C-V2X security was not updated with Rel-15. However, the enhancements developed for network access and associated security aspects will apply to the network-enabled mode of communication. As for the direct mode of operation, the security design for the Rel-14 C-V2X is expected to remain unchanged, namely specifying the reuse of the application-level security already defined by IEEE for DSRC systems.

In particular, LTE Rel-14 does not support vehicle identity privacy when it sends V2X traffic via the network. Architectural changes would be required to support user/vehicle anonymity from the operator. It is expected that 5G core network will enable network mode V2X operation privacy. 5G security is going to define device-to-network authentication methods and transport; specify provisioning and storage of 3GPP credentials for devices; and specify network functions and protocols necessary for secure device operation within the operator network. The V2X architecture relies on the security relationship between device and its home operator network. In addition, secondary authentication schemes can support industrial and virtual private networks that wish to deploy their own authentication methods and credentials, thus it is possible to deploy public key infrastructure (PKI)[9]

[9] A public key infrastructure (PKI) is a set of rules, policies, and procedures needed to create, manage, distribute, use, store, and revoke digital certificates and manage public key encryption. In cryptography, a PKI is an arrangement that binds public keys with respective identities of entities. The binding is established through a process of registration and issuance of certificates at and by a certificate authority.

security, where devices use a digital certificate to authenticate themselves to the network and vice versa. 5G security design is being developed to achieve the following goals [23]:

- Enhanced subscriber/device privacy: This is an improvement over LTE in that the new subscriber permanent identifier (SUPI) is never allowed to be transmitted over the air. Instead, the sensitive part of the SUPI is sent over the radio link protected against spoofing and tracking, which was not the case with the 3G/4G international mobile subscriber identity.
- Enhanced security support at the network level, along with capability for flexible authentication and authorization schemes: A new network function is specified, known as security anchor function (SEAF), which maintains the security anchor deep in a network (in a physically secure location). The SEAF also provides flexibility in deploying other network entities such as AMF and SMF. In Rel-15, the SEAF is co-located with the AMF.
- Support various types of devices that have different security capabilities and requirements: Secondary authentication enables support for non-3GPP access links and sessions authorized by third-party servers, such as for industrial IoT, V2X, and automation. This functionality is related to the access control for network slices. For example, various IoT devices may require different credential provisioning and authentication methods. The details for this type of industrial scenarios are being investigated.
- Support user data and signaling encryption and integrity protection: These features are essential for a secure system. A new feature is data path integrity protection, which may be especially important for certain new services such as industrial IoT. There is also the potential for the user-plane security to be terminated in the network instead of the base station.
- Separate device credential management and access authentication from data session setup and management: This split results in a separate security context between device and the AMF which is used for mobility management. A different security context is established for session management, between device and the SMF, used to authorize access of the device to specific services; for example, network slices or specific data networks such as enterprise networks. This new type of access control employs a separate and flexible authentication and authorization procedure; for example, extensible authentication protocol (EAP).[10]
- Support secure slicing: There could be several services instantiated as a network slice, each with different security requirements. The access to a slice is granted based on the primary authentication and subscription information, but this authorization is carried out

[10] Extensible authentication protocol (EAP), defined in IETF RFC 5247, is an authentication framework frequently used in wireless networks and point-to-point connections which provides an authentication framework for transport and usage of keying material and parameters generated by EAP methods. Each protocol that uses EAP defines a method to encapsulate EAP messages within that protocol's messages.

by the respective SMF. Therefore, the access security is contained within that network slice and does not rely on the AMF, which may serve multiple slices that may have different security requirements. Moreover, an attack mounted on one slice does not result in an increased risk for an attack on a different slice of the same network.

In a nutshell, what 5G security is trying to achieve is increased user privacy, robustness to cyber-attacks on the network, and better device hardware security. These goals can be achieved with stronger authentication/authorization schemes between device and network, both radio access and core network functions, secure credential provisioning and storage on device, and new network functions that support device-to-network communications security.

Cellular-based V2X systems treat latency as the most important performance metric because the level of protection decreases as the delay in receiving safety information increases. While the delay in non-mission-critical applications may be tolerated to some extent, delayed information in V2X communications could result in serious automobile accidents and injuries. The volume of traffic in V2X communication is much smaller than other applications in cellular systems. Sensing information or safety notifications transmitted via a V2X link can be carried in small packets, thus high-speed data transmissions are less important in V2X systems. The device-to-core network (AMF) signaling is integrity- and confidentiality-protected. The device link to the radio access network is also protected for both signaling and data traffic. The V2X system can leverage the 5G system security for vehicle device authorization, authentication, and access to the network.

7.7 Implementation and Deployment Considerations

The DSRC would require the deployment of tens of thousands of RSUs embedded or attached to roadway infrastructure to enable an effective network along the country roads. This would be a challenge in rural areas considering the vast distances involved. State highway administrations and other highway authorities would be responsible for deploying, managing, and operating the RSUs and the associated infrastructure network and interconnections such as fiber or copper backhaul. After considering how to map each V2V service to different 3GPP technologies, the conclusion is that Rel-14 is only used for basic safety, while NR-based V2X is used for advanced services to avoid duplication or replacement of LTE-based Rel-14 functionalities. Therefore, it is expected that in the beginning of the V2X service deployment, there will be LTE-based Rel-14 V2X devices which later evolve into dual-mode UEs that support both LTE and NR V2X services.

Several V2X use cases require vehicles to communicate with an infrastructure. The DSRC security relies on a public key infrastructure that distributes and manages digital certificates for vehicles. This means that vehicles need to have access to this infrastructure, which in the case of DSRC is provided via the RSUs. The RSU may also be used by vehicles to communicate with the V2X application server. Owing to various factors, the deployment of RSUs might be limited. It is therefore unrealistic to expect the provision of ubiquitous coverage of roadways via DSRC equipment in near future. One challenge with the deployment of V2X technologies is that there is uncertain business incentive for network providers. In the United States, where V2V deployments may be mandated, there is still lack of clarity regarding the plan to implement the infrastructure that would utilize the balance of the channels, and which entities should manage the security network functions. Since government funding has been a driving force for many V2X pilot programs, it is unclear if commercial business models can be applied to accelerate infrastructure deployment or if deployments will be managed by the governments. In some regions, the government agencies are mainly promoting pilot projects in order to benefit the economy of cities and regions by improving traffic efficiency, reducing emissions, and minimizing the risk of crashes. With C-V2X, mobile operator involvement can make additional, commercially motivated services available. The beneficiaries of these can be both subscribers and road operators.

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