WIRELESS COMMUNICATIONS FOR AUTOMOTIVE APPLICATIONS

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ROHDE&SCHWARZ

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CONTENTS

1 INTRODUCTION

In the past decades, wireless communications has evolved from a circuit-switched voice call service to a ubiquitous communications network. Automotive is not just a service application any more, but has grown into a large vertical tenant of new applications and services in the automotive domain.

One pillar of modern society is mobility. Conveyance of goods and passengers is essential for a prospering economy. The growing affluence in many developing as well as industrialized countries is becoming apparent through the increase in individual mobility. The increase in transportation system efficiency through traditional road building often reaches its limits in terms of land consumption and lack of public acceptance. Engineers and scientists are looking for processes and technologies to enhance traffic flow through sophisticated traffic management. The established intelligent transportation system (ITS) ITS-G5 is expected to avoid traffic congestion and increase overall traffic efficiency. End-to-end digitization from single vehicles to road infrastructure and backend servers provides the basis for continuous traffic flow control and management. Technological progress in the automotive industry towards automated driving and development of advanced driver assistance systems (ADAS) is propelling the fully digital transportation system. The Cooperative ITS (C-ITS) transportation system enables all road users including pedestrians to communicate and cooperate with each other, and promises to increase efficiency and reduce road traffic fatalities and serious injuries. Reducing road traffic accidents is the primary goal of government agencies around the globe.

A mobile communications system is required that supports the reliable exchange of road traffic data even in scenarios where road users are traveling at high speed.

Two major motivations and objectives are driving the technology evolution: enhanced comfort in vehicles thanks to sophisticated entertainment services and safety-related applications. Especially the latter is advancing several communications technologies such as the eCall introduction and the first direct communications scenarios.

Policymakers and the automotive industry are striving to improve vehicle safety. A new technology enables vehicles to directly communicate with each other and/or roadside units. Devices such as smartphones, backpacks and bicycles will include technology to communicate with vehicles. These devices would alert drivers to the presence of a bicyclist in the road or a pedestrian in a crosswalk in order to greatly reduce the number of pedestrian-related injuries/fatalities. These direct communications systems are known by many different acronyms/initials (e.g. V2V, V2I, DSRC, ITS-G5, C-ITS, C2C, C2x).

New communications paths like the "sidelink" introduced in Release 12 of the 3GPP specifications offer new connection scenarios such as V2X where "x" stands for "everything" in the communications path. There are motivational aspects to enhance road safety thanks to a sophisticated communications network as well as vertical applications on the horizon to make driving more comfortable in the future. Thus, we may contemplate that the next "smart" phone is the "smart" vehicle.

3GPP Long Term Evolution (LTE) Release 14 specifies the vehicle-to-everything (V2X) communications service. This feature sets the starting point for the evolution of applications not previously supported by mobile communications technology. Release 15 contains the definition of enhanced V2X communications scenarios and Release 16 links cellular based V2X communications to 5G NR radio technology, offering much greater flexibility, higher data rates, lower latency, QoS-driven connectivity and future-proof deployments of direct communications. These technology enhancements are paving the way for ubiquitous and future-proof connectivity.

Beside direct communications, UE-to-network communications or V2N represents the continuation of the traditional communications path. The technology evolution from LTE via LTE-Advanced up to 5G New Radio offers the full flexibility and usability of all network based communications services. Applications range from existing solutions for traffic information updates through new and enhanced entertainment methods such as augmented or virtual reality in vehicles.

This white paper describes the technical aspects of wireless communications with a focus on the automotive application segment. The objective is to outline the differences between the two communications paths, i.e. the network-oriented path and direct mode communications.

Chapter 2 describes vertical automotive communications applications based on network and direct mode communications. Chapter 3 discusses general aspects of wireless communications including mobility aspects, security aspects and technology aspects (e.g. eCall) relevant to the automotive industry. Chapter 4 presents some of the details behind the network based communications technologies LTE and 5G. With the introduction of the sidelink enabling direct device mode, new communications scenarios are possible.

Chapter 5 describes major Release 14 and 15 LTE-V2X technology aspects as well as the new sidelink based on 5G NR specified in Release 16.

Chapter 6 presents certain test and measurement aspects and methodologies to ensure proper operation, interworking and interoperability between devices as well as correct deployment and implementation of radio technologies.

Future vehicles will contain multiple domain controllers. Fig. 1 provides an overview of a connected vehicle. Radar and lidar systems support sensing, road awareness and cruise control up to full autonomous driving. The Society of Automotive Engineers (SAE) defines the level of automation on a scale from 0 (no automation at all) to 5 (full automation) in the SAE J3016 [Ref. 1] document. Autonomous vehicles require independent autonomous driving control systems. Communications based technologies can support control decisions. However, vehicle cruise control cannot entirely depend on communications since communications can be interrupted. Connectivity based infotainment is a key aspect in future vehicle development. There are services supporting cruise control itself such as navigation info and traffic awareness messages, but also entertainment services such as web-browsing in the vehicle or video on demand. Multiple electronic control units (ECU) support various tasks and communicate with each other via automotive Ethernet. The importance of electromagnetic compatibility (EMC) will increase due to the integration of multiple electronic systems within the vehicle. Rohde&Schwarz provides a wide range of test solutions for all vehicle based applications.

Fig. 1: Vehicle architecture with domain controllers

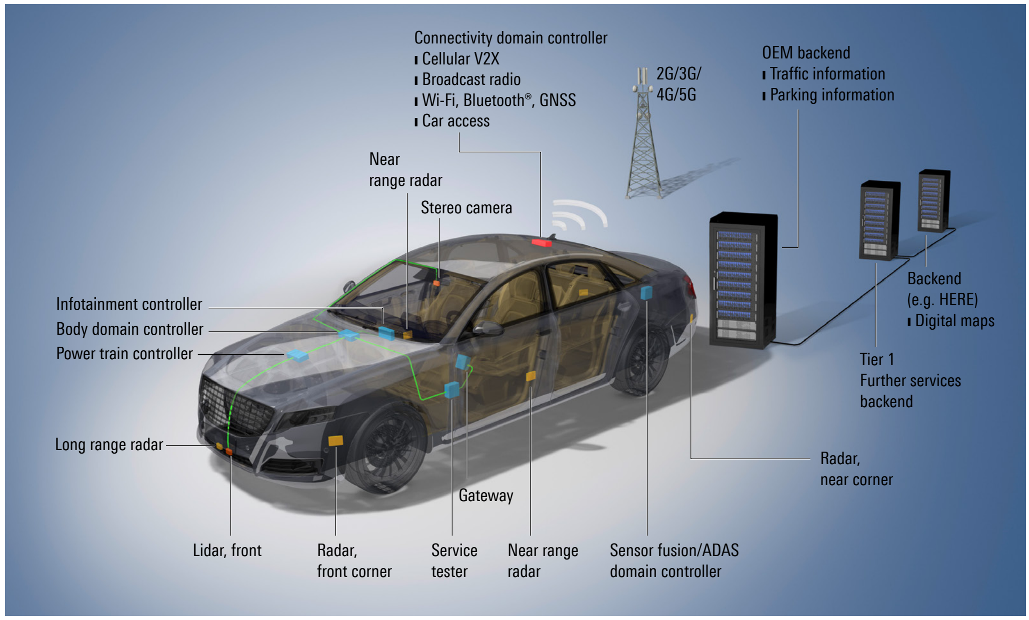
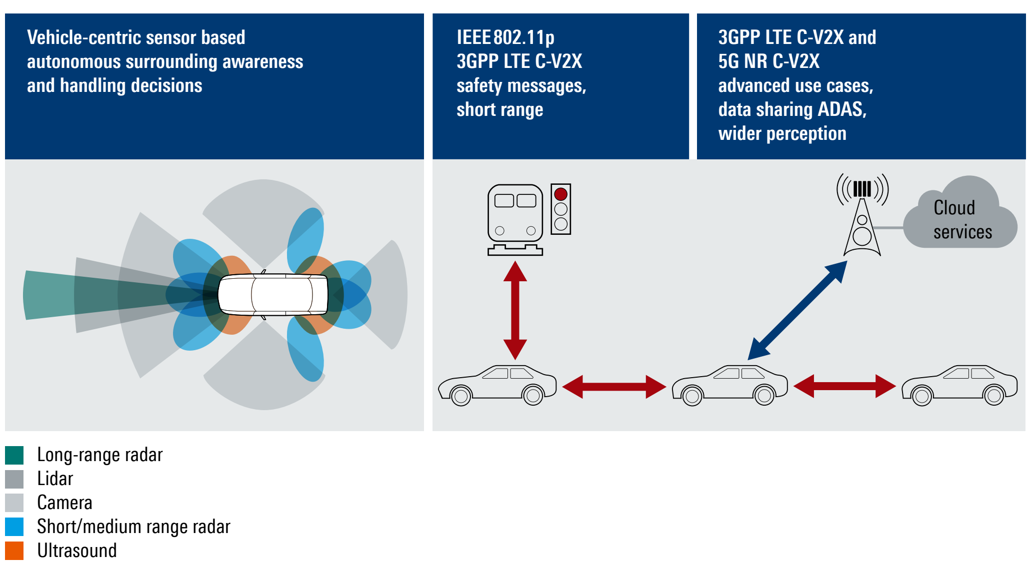


Fig. 2 illustrates vehicle based sensor awareness versus automotive communications. The general deployment concept relies on both elements in a complementary manner. Vehicle based communications do not aim to replace sensor based awareness systems. A radar sensor will always take its own images and make decisions independent of communications content. Due to space constraints, this white paper focuses on the right side of this figure, i.e. the communications technologies. Further details on radar and sensor awareness can be found in [Ref. 47].

Fig. 2: Vehicle-centric sensor awareness versus automotive communications

AUT communications evolution: two complementary domains

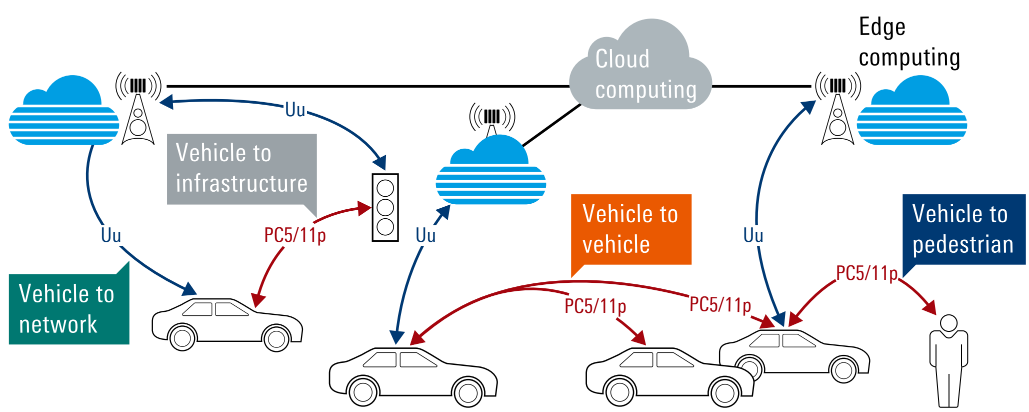


2 USE CASES AND SCENARIOS

The term intelligent transportation system (ITS) is a general expression encompassing technologies that make traffic smarter. Communications make this initiative a reality. Vehicle based connectivity and V2X describe connection scenarios between a vehicle and "everything". TS 23.287 defines V2X communications as communications to support vehicle-to-everything (V2X) services leveraging Uu and/or PC5 reference points. V2X services are realized by various types of V2X applications, e.g. vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I) and vehicle-to-network (V2N).

Fig. 3 shows some typical examples and connection use cases. Communications take place between the vehicle and the LTE or 5G network via the Uu interface (V2N) or the air interface between a base station (eNB or gNB) and a user device (UE). The technology aspects for this network based communications scenario are described in Chapter 4. The IEEE 802.11p standard introduced a radio technology that allows ad-hoc communications between devices, i.e. combining the radio interface with higher layer application protocols, especially the message types that can be exchanged. The term dedicated short-range communications (DSRC) is originally derived from the USA and indicates a combination of the IEEE 802.11p radio link with a higher layer application such as IEEE 1609. With its intelligent transportation system communications (ITS-G5), the European Telecommunications Standards Institute (ETSI) has specified a counterpart to DSRC with major similarities, especially on the application layer. With Releases 12 to 16, 3GPP introduces and updates the PC5 interface allowing direct device-to-device communications. PC5 represents a reference point including a radio link that is defined as a sidelink and a protocol structure on top of it. Many publications have referenced such direct communications using cellular technologies as C-V2X, with the most well-known examples being V2V, V2P or V2I. Note that the term V2I may correspond to either V2N Uu interface communications or V2I using the PC5 interface. There are two types of roadside units (RSU), i.e. base station and device. In addition, since there is no general consensus in the industry, one may also consider V2N to be part of C-V2X communications. Technology details for C-V2X direct communications based on 3GPP Release 14 up to later releases including the 5G NR sidelink are presented in Chapter 5.

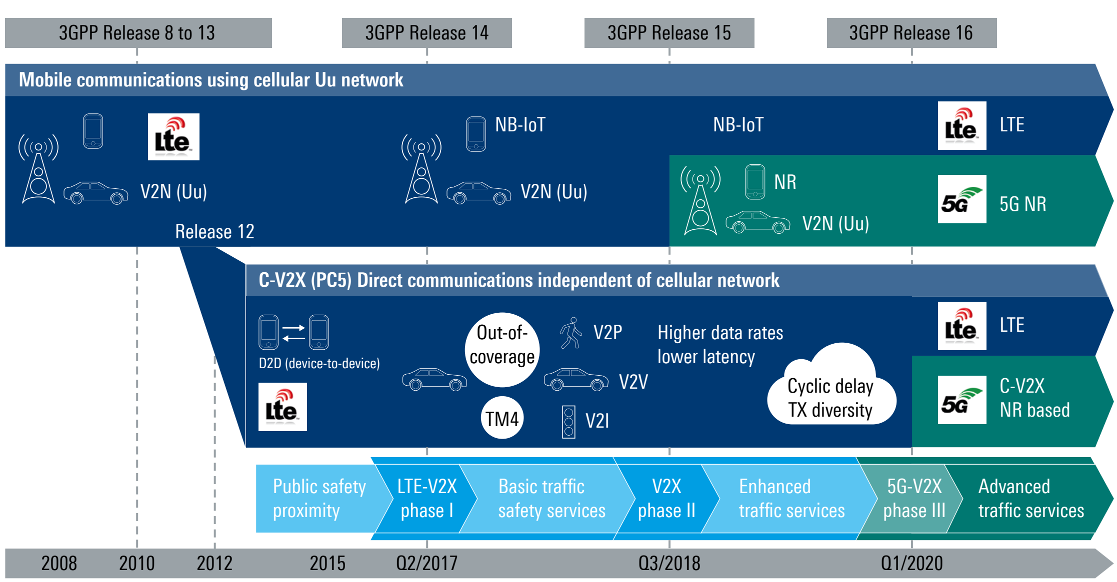
Fig. 3: Vehicle to everything (V2X) infrastructure and examples



To achieve a better understanding of the evolution of cellular technology, Fig. 4 provides an overview of the 3GPP standards and the corresponding timeline. The figure is divided into an upper part describing network based communications and a lower part describing direct communications. Based on 3GPP Release 8, the introduction of LTE, a network based connection between a vehicle based modem as the client and a data network as the server is offered for automotive services. Typical services are e.g. navigation system support with real-time traffic updates and vehicle entertainment services. Further specification releases offer enhancements to radio interface techniques such as carrier aggregation, enhanced MIMO, dual connectivity and the introduction of machine type communications. NB-IoT, as introduced in 3GPP Release 13, focuses on low data rate applications with enhanced coverage and improved energy efficiency or battery time. Some sensor based automotive applications use NB-IoT as the data carrier. With 3GPP Release 15, the new 5G NR technology was introduced. It allows vehicle based modems to communicate with data networks over the 5G NR network. Benefits include 5G NR technology enhancements such as higher data throughput, lower latency and a more reliable connection. More details on network based communications technologies from 3GPP Release 8 to 16 are provided in Chapter 4.

With the introduction of the PC5 interface, 3GPP Release 12 started a new approach, enabling direct communications between two devices. This was first motivated by public safety services, i.e. mission-critical communications enabling direct communications between devices when no cellular coverage is available. Note that the term PC5 represents the interface between two devices including the radio part and protocol structure. The term sidelink is only used to describe radio interface characteristics. 3GPP Release 14 extends the PC5 technology to automotive use cases and applications. New transmission modes (TM3 and TM4) are introduced for scenarios in which a base station allocates radio resources on the sidelink or two devices use random preconfigured resources. Release 15 introduces technology enhancements for the PC5 interface such as carrier aggregation, antenna diversity or higher order modulation schemes. The radio technology for the PC5 interface according to 3GPP Release 15 is still LTE. With 3GPP Release 16, additional services and applications based on a 5G NR PC5 interface are introduced. The technology details for the PC5 interface from 3GPP Release 14 to 16 are explained in Chapter 5.

Fig. 4: Cellular mobile communications technology evolution based on 3GPP

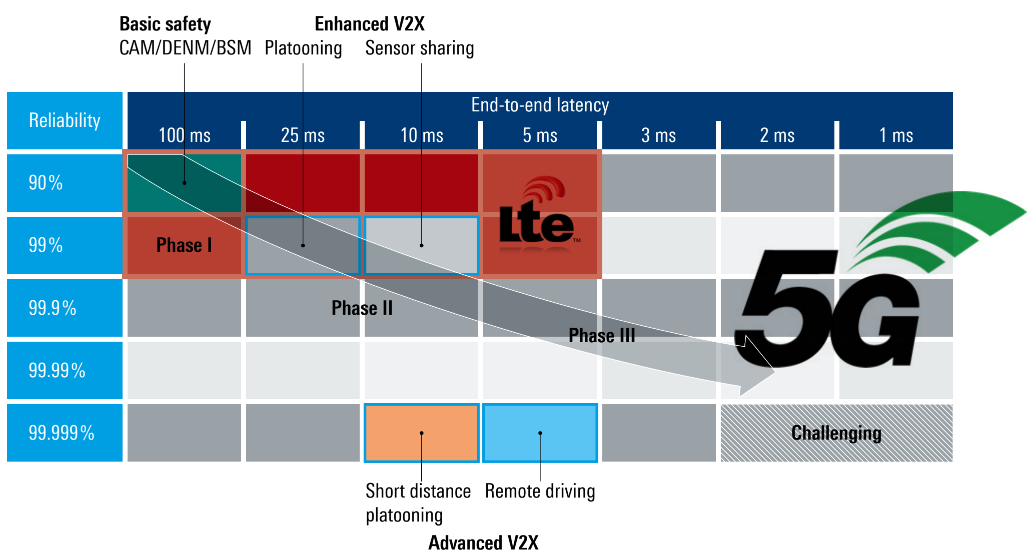


2.1 Connectivity scenarios

The idea of connected vehicles has existed since the evolution of vehicles and communications technologies and there are various ideas as well as applications. It is difficult to present all of the scenarios discussed in the industry and it is even harder to structure these scenarios in a timeline and requirement list. Beside standardization bodies such as the IEEE and 3GPP, there have been industry activities such as 5GAA [Ref. 70] or even national road safety activities. Common terms in these activities are advanced driver assisted system (ADAS) or intelligent transportation system (ITS). There is an abundance of papers published on various vehicle scenarios, e.g. [Ref. 2], [Ref. 7], [Ref. 8], [Ref. 40] and [Ref. 46].

In a timeline approach, we can see that the first motivation behind services and applications is the enhancement of road or vehicle safety. But in addition to vehicle safety, traffic management is an important use case for ITS. Traffic management focuses on providing updated local information, maps and other relevant messages limited in space and/or time. It is anticipated that this will, among other things, reduce the number of traffic jams, which will result in time savings for drivers and less pollution from carbon emissions from idling vehicles.

Fig. 5: 3GPP standard improvements



The evolution of applications and scenarios using the PC5 interface for V2X services is divided into three different phases by the 3GPP [Ref. 81]:

- Phase I, 3GPP Release 14 based, supports direct V2X communications, distributes random and reservation based resource usage to exchange basic traffic safety information between vehicles and other devices such as RSU, pedestrians, etc.
- Phase II, 3GPP Release 15 based, supports direct V2X communications of low latency, high data rate links to exchange data for enhanced automotive applications
- Phase III, 3GPP Release 16 based, introduces direct V2X communications using the 5G NR radio technology and supports broadcast, groupcast and unicast communications for advanced automotive applications

For a better understanding of the technology evolution, some vehicle and communications based services and applications are listed with respect to the technology evolution from LTE Release 8 to 16, covering both directions, network based communications (V2N) and direct communications (V2X) [Ref. 71].

One method of clustering the various applications and use cases is according to the time-line, while another method is application-specific. Application-specific clustering splits services into a safety feature related set and a driving comfort feature set.

Safety features range from traffic warning and basic safety messages like the China Day One Use Cases [Ref. 48] through sensor sharing and maneuver cooperation. Comfort features start from simple vehicle based web browsing setups through voice recognition and VR/AR application for high-end advanced entertainment systems.

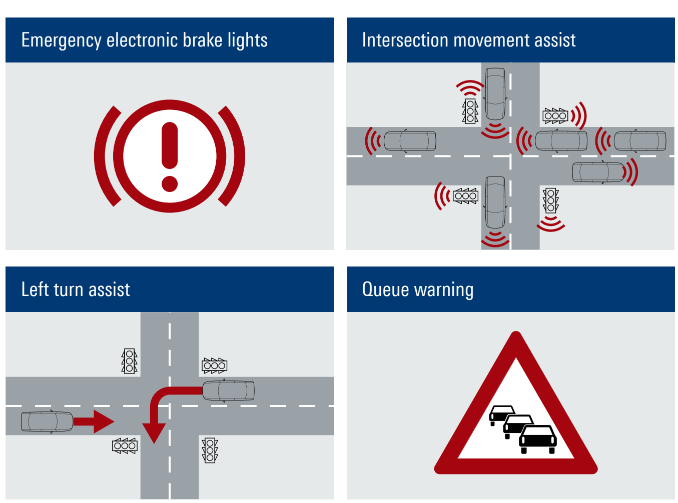
On a timeline perspective, we currently see many existing vehicle based applications implemented by the industry that communicate with a vehicle as the UE. These include communications scenarios via an OEM backend for services such as:
- Traffic information, e.g. traffic jam awareness
- Parking information
- Charge state
- Digital maps, e.g. dynamic routing

eCall and NGeCall are separate technologies, driven by governments and enabling an automatic emergency call to reduce the reaction time of first responders. eCall uses GSM as underlying radio technology, and next generation eCall is based on LTE to ensure future-proof operation. Further details on eCall are given in Chapter 3.6 and [Ref. 13], [Ref. 15] and [Ref. 38].

Updates and enhancements of the LTE technology known as LTE-Advanced offer updated vehicular based services such as voice recognition, audio and video streaming as well as sensor networks using the machine type communications technologies LTE-M and NB-IoT.

With 3GPP Release 14, support for direct V2X communications is introduced into the wireless communications standards. Scenarios are motivated by an enhanced safety mindset, allowing distributed random and reservation based resource usage to exchange basic traffic safety information:
- V2V safety use case, see e.g. China Day One Use Cases
- Road work warnings or hazardous road conditions
- Collaborative awareness
- Extended visual horizon

Fig. 6: LTE-V2X phase I scenarios (Release 14)



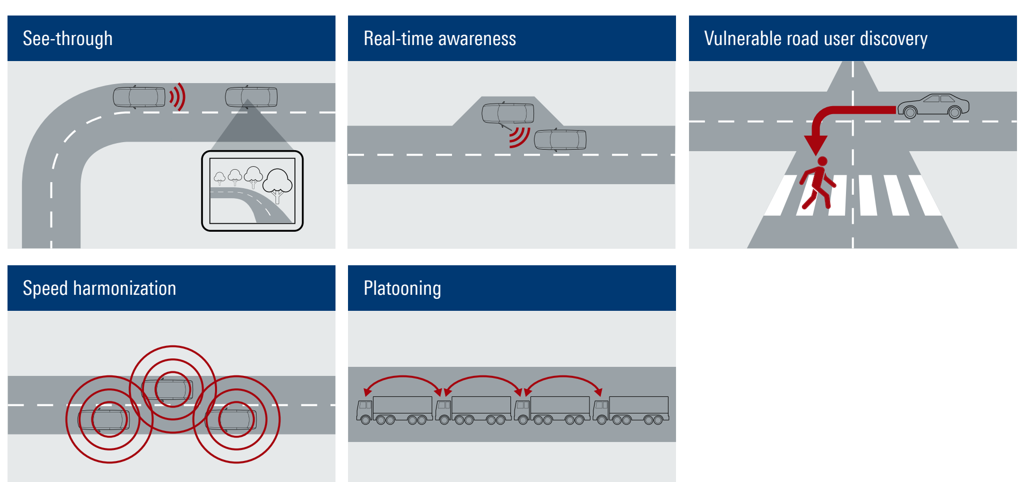
The People's Republic of China decided to introduce LTE-V2X based on 3GPP Release 14 as the technology for vehicular based direct communications scenarios. Certain V2X scenarios are defined in the document CSAE0053 [Ref. 48] containing "China Day One Use Cases":

No.	Category	Communications mode	Application name	Abbreviation
1	Safety	V2V	Forward collision warning	FCW
2	Safety	V2V/V2I	Intersection collision warning	ICW
3	Safety	V2V/V2I	Left turn assistant	LTA
4	Safety	V2V	Blind spot warning/lane change warning	BSW/LCW
5	Safety	V2V	Do not pass warning	DNPW
6	Safety	V2V-Event	Emergency brake warning	EBW
7	Safety	V2V-Event	Abnormal vehicle warning	AVW
8	Safety	V2V-Event	Control lost warning	CLW
9	Safety	V2I	Hazardous location warning	HLW
10	Safety	V2I	Speed limit warning	SLW
11	Safety	V2I	Red light signal violation warning	RLVW
12	Safety	V2P/V2I	Vulnerable road user collision warning	VRUCW
13	Efficiency	V2I	Green light optimal speed advisory	GLOSA
14	Efficiency	V2I	In-vehicle signage	IVS
15	Efficiency	V2I	Traffic jam warning	TJW
16	Efficiency	V2V	Emergency vehicle warning	EVW
17	Informataiment/telemetics	V2I	Vehicle near-field payment	VNFP

With phase two in LTE-V2X communications based on 3GPP Release 15, the technology introduces support for low latency, high data rate links to exchange data for enhanced automotive applications:

- See-through
- Cooperative driving
- Platooning support
- Tele-operated support

Fig. 7: LTE-V2X phase II scenarios (Release 15)



Release 15 introduced 5G NR as a new technology offering tremendous flexibility, a flexible network infrastructure supporting QoS control and maintenance along with sophisticated capabilities such as beamforming on the air interface. In the automotive world, this enables the introduction of enhanced entertainment systems, augmented and virtual reality, and big data uploads [Ref. 71]. On a large-scale horizon, the 5G NR core network inherits the ownership of massive machine type communications (nMTC) such as LTE-M or NB-IoT, and thus applications requiring a large scale internet of things will be enabled as well [Ref. 2].

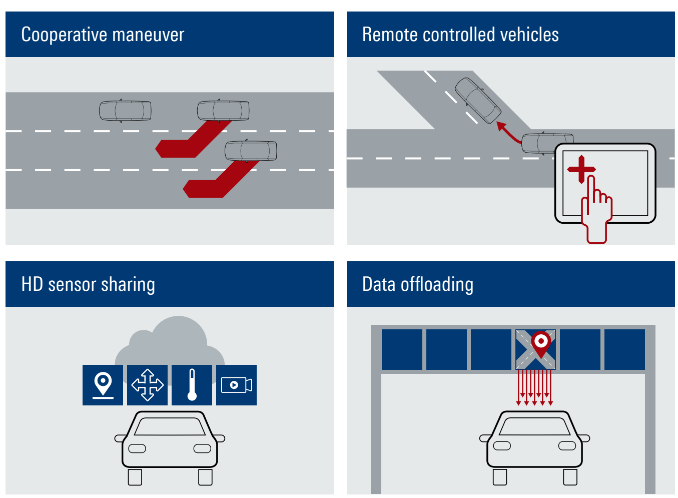
3GPP Release 16 introduces several technology aspects of 5G NR to the direct communications path with NR-V2X. Beside high flexibility, low latency and high data rates on the sidelink, support for broadcast, groupcast and unicast communications for advanced automotive applications allows:

- Improved software updates over the air
- Extended raw sensor data
- Enhanced intention information

This evolution is aligned with a further increase in the data rates due to mmWave and new spectrum usage.

The objective of NR-V2X technology is to extend (and not replace) the existing LTE-V2X technology by offering advanced services. Basic safety-related direct communications will be technology-agnostic and 3GPP Release 16 allows the network to control both the NR-V2X sidelink and the LTE-V2X sidelink [Ref. 45].

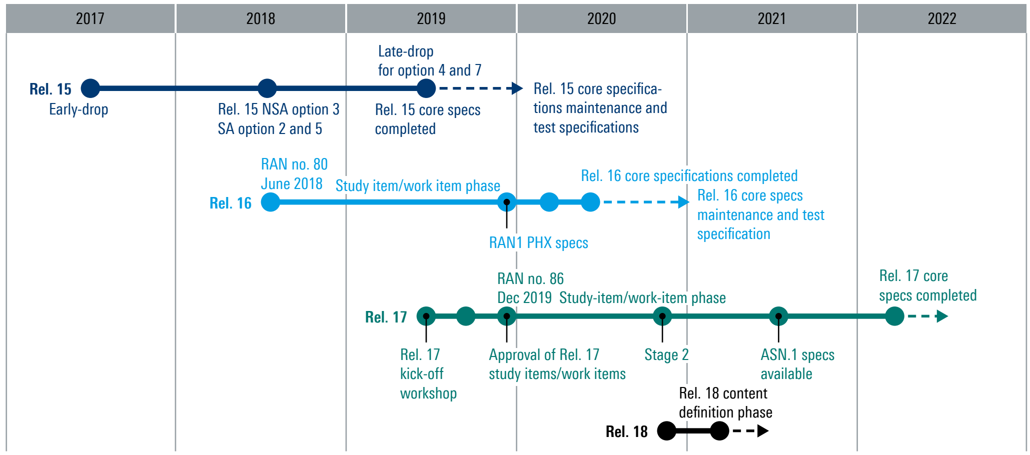
Fig. 8: NR-V2X phase III scenarios (Release 16)



2.2 3GPP standardization aspects and national initiatives

The main driver behind the LTE and 5G NR technologies is the 3rd Generation Partnership Project standard organization (3GPP; see www.3gpp.org for further details). 3GPP publishes technology aspects in releases. A release contains a set of technology functions. Corrections are possible in later updates. LTE was standardized with 3GPP Release 8, while later updates known as LTE-Advanced are included in 3GPP Releases 9 to 14, and LTE updates and enhancements are also included in 3GPP Release 15 and beyond. With 3GPP Release 15, 5G NR was introduced and the next updates are included in 3GPP Releases 16 and 17. The current timeline from summer 2020 shows that 3GPP Release 15 is more or less completed, while 3GPP Release 16 is approaching completion. Finalization of 3GPP Release 17 is expected in spring 2022.

Fig. 9: Timeline 3GPP standard evolution



With the introduction of 3GPP Release 14 direct communications for vehicular applications, there are now two radio technologies supporting direct communications with a focus on vehicular communications: 3GPP LTE-V2X and IEEE 802.11p. There is still no consensus on which technology should be applied and if there will be any preference at all [Ref. 3], [Ref. 70], [Ref. 71]. Several governments and companies choose LTE-V2X as the underlying radio access technology for national activities and regulations concerning automotive communications. These national activities selected LTE-V2X direct communications as the radio access technology, but different protocol layers are discussed depending on the geographical regions/countries.

A similar objective between these regions is obvious, i.e. the transfer of safety messages with a slightly different protocol stack. An important aspect is the technology-agnostic agreement across the world's regions regarding similar applications. Chapter 5 provides details on the various direct communications technologies for V2X, but on the application layer, there seems to be a consensus among them. In Fig. 10, the application layer represents the application across the three major regions applying V2X safety-related features. These messages can be transferred either via DSRC/ITS-G5 using the IEEE 802.11p radio layer or via C-V2X using the 3GPP LTE-V2X/NR-V2X radio layer [ETSI TS 102637-3], [IEEE 802.1], [ETSI EN 302637-3].

Fig. 10: Enhanced road safety initiatives based on regions

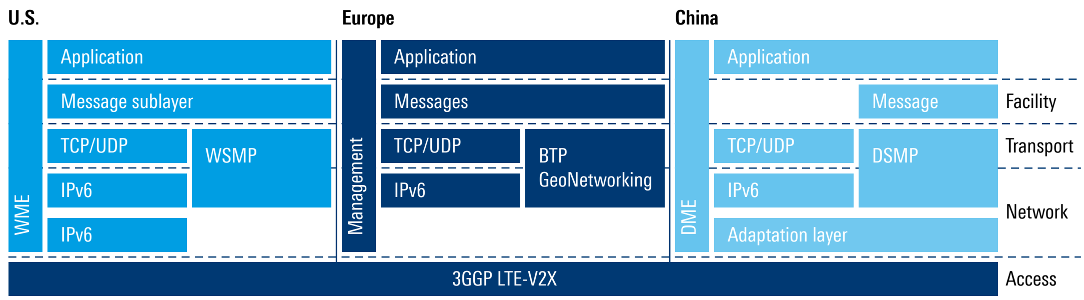
Application layer

Message type USA	Message type Europe	Message type China
Basic safety message (BSM) Vehicle status information, optional event flags (SAE J2735, SAE J2945)	**Cooperative awareness message (CAM)** Vehicle status information (ETSI EN 302637-2) **Decentralized environment notification (DENM)** Information about specific event (ETSI EN 302637-3)	**Basic safety message (BSM)** Vehicle status information (T/CSAE 53-2017))
End-to-end latency: 20 ms to 500 ms Message repetition: 1 Hz to 10 Hz	Range: 300 m to 1 km Speed: 250 km/h (absolute), 500 km/h (relative)	

In a more detailed protocol layer description including the underlying RAT, Fig. 11 indicates the application protocol layers across these three world regions based on cellular V2X, i.e. LTE-V2X [ETSI EN 303613].

Fig. 11: Vehicle based direct C-V2X communications for enhanced road safety

Regional protocol stacks



3 TECHNOLOGY ASPECTS OF WIRELESS COMMUNICATIONS FOR AUTOMOTIVE APPLICATIONS

3.1 Cellular networks and mobility aspects

This chapter will provide an overview of wireless communications functions and help understand the holistic picture of wireless communications systems with a focus on the automotive vertical application. Readers familiar with the fundamentals of cellular networks can skip this chapter, while readers not familiar with the general aspects of cellular networks may also consult [Ref. 64]. Communications networks have changed from classic telephone networks offering a voice call between two entities to today's data networks supporting a wide range of communications services.

Take a look at wireless communications from a vehicle perspective. How do cellular standard based communications in the vehicle behave? Do we need to switch them on or is this done automatically when starting the engine? How does such a device detect a cellular network? Assuming some mobility of the vehicle, how does this affect the radio connection of the device to the network? Another important question is whether a radio link is always established, and if not, what are the procedures to establish and release the radio link? Other aspects concern identification of a device or user. For the automotive world, location based services play a very important role. How can wireless communications assist with positioning methods? These questions are also related to security aspects, such as how to ensure that no one exploits another user's identity and how to avoid eavesdropping on the radio interface?

Networks are similar in the way that they are all packet-switched data networks. In the internet domain the network helps to establish a client-server connection. A client requests data packets that are provided and delivered by a server. Since the introduction of GSM, wireless communications systems have clearly distinguished between the subscriber or subscription to a network and the device itself. This has reasons that are important due to security aspects, but also for commercial aspects, e.g. it is possible to buy a new mobile device without needing to change the network operator subscription. The subscriber information such as the identity, security credentials for authentication and encryption as well as optional information influencing the network selection is stored on the familiar subscriber identity module (SIM). In the past, the SIM was provided as separate hardware, e.g. on a UICC chip card, but today there are implementations like the eSIM where the SIM is emulated electronically and content can be provided over the air via a secure connection. The device itself is designated as the mobile equipment (ME) and together, the SIM and ME are known as user equipment (UE) [TS 23.002]. In wireless communications, the subscriber is identified with the international mobile subscription identity (IMSI) and the device itself has an international mobile equipment identity (IMEI). Note that for subscriber privacy protection, the IMSI or IMEI number are in most cases not directly sent over the air interface; a temporary identity is used instead. A network is typically described with the term public land mobile network (PLMN), representing the case of a public operator with terrestrial infrastructure offering radio communications services. On the network side, there are identifiers like the mobile country code (MCC) indicating the country, the mobile network code (MNC) indicating the network operator ID, a location, routing or tracking area code (LAC or TAC) and a cell identity (CI).

A radio link is always directional and the direction from the base station to the UE is known as the downlink, while the direction from the UE to the base station is known as the uplink. To separate between the downlink and uplink directions, duplex modes are needed. Frequency division duplex (FDD) separates the uplink and downlink into frequency bands and time division duplex (TDD) separates them into time units. The radio resource needs to be assigned to multiple users, a principle that is known under the term multiple access. Three mechanisms are known: Frequency division multiple access (FDMA) where multiple users use frequency-separated resources, time division multiple access (TDMA) where time-separated resources are used, and UMTS technology with a mechanism where radio resources employ separate code channels which is known as code division multiple access (CDMA). [TS 25.101], [Ref. 9], [Ref. 10]

3.1.1 Network architecture and functions

During the evolution of wireless communications, there have been tremendous changes within the network architecture as well as in its functional behavior and network components and entities. This chapter provides an overview of the main functions. For a thorough introduction to the architectural and functional behavior, consult the relevant literature.

First, we divide a wireless communications network into a radio access network (RAN) using a certain radio access technology (RAT) and a core network or backhaul network. The network architecture consists of entities such as hardware components supplying certain functions. While in 2G or 3G the relation between the function and the corresponding network entity was more static, later generations (especially 5G) introduce terms such as network function virtualization where network functions can be implemented and executed at certain entities and places. As its major services, a network offers radio access, connection setup and release, and data communications. The radio resource management function covers the radio access technologies, the air interface and all relevant signaling to allow proper radio connection handling, starting from radio connection setup through radio connection maintenance and radio connection release, in addition to certain mobility aspects such as handover or cell reselection. This is described in a wireless network as the access stratum (AS) layer. Access and mobility management is the function in the network that controls and stores information on the subscriber's location and availability status. It is responsible for proper data network access, especially security-related processes such as subscriber authentication and authorization. Registration procedures encompass the storage of a subscriber's identity in the network and linking it to a region where this subscriber is located, which is known as the location area or tracking area. A third function is connection control or session management. This function is related to the data connection, starting from circuit-switched voice connection via packet-switched data connection up to flexible and dynamic connections with quality of service (QoS) control. Especially in later generations like 5G, QoS parameters such as the ensured throughput, priority handling, expected error ratio or latency are becoming more important and allow more advanced services, especially in the automotive sector. Session management uses a terminal identifier to address the device; common values are the well-known telephone number MSISDN or the IP address allocation. In a wireless network, mobility and session management are described as the non-access stratum (NAS). [TS 24.301], [TS 24.501]

A user device (UE) connects via a radio link to a base station that is further connected to the backhaul network. We distinguish between the radio technology and the protocol layers controlling and maintaining the radio access. The term base station typically describes the hardware including the transmit and receive entity, while in the protocol world terms like NodeB (eNB or gNB) represent a kind of anchor point within the infrastructure diagram. How to explain the term "cell"? Assuming a radio signal is transmitted from a TX antenna, this radio signal differs from other radio signals by either its radio technology or by its reference or pilot signals. Thus, a receiver can detect these reference signals and measure their power levels. We can say that a radio cell spans the geographical area where the radio signal from this particular TX entity provides the strongest signal power, i.e. the cell coverage area. A network operator deploys base stations fulfilling its coverage requirements and dimensions the capacity of the cell according to the expected traffic.

3.1.2 UE operating modes and protocol stack

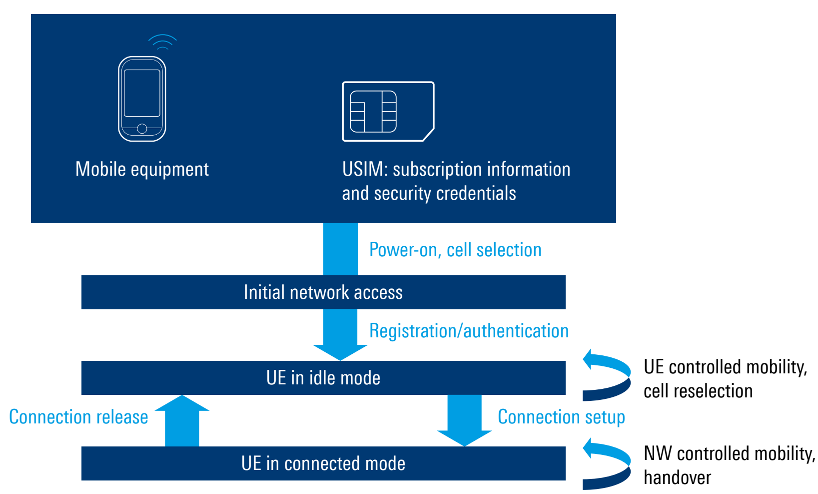
In simplified terms, a UE can be in three different operating modes:

Power-off mode (or "airplane" mode): In this state, there is no UE registration with the network, i.e. no data connection is possible and the network has no (or only the last) location information for the particular UE. Network-originated connection setup is not possible.

Idle or registered mode: This is the mobility management state where the UE is registered in the cellular network. This means the UE must monitor and update the system information broadcast via the radio cells, the UE knows about the random access channel if a mobile-oriented connection is needed, and the UE monitors the paging channel if a network-oriented connection is going to be established. Via the system information, the UE knows about the neighboring cells and the rules for cell reselection. Thus, in idle mode the UE mobility decisions are up to the UE and are indirectly controlled by the network.

Connected mode: This is the situation where a radio connection is established between the UE and the network, thereby enabling data transfer. In connected mode, higher layer protocols (RRC) control and maintain the proper functioning of the radio connection. Device mobility is supported by requesting measurement data from the UE that serves as the basis for deciding whether to keep the radio connection in the current serving cell or hand it over to a better suited neighboring cell. Thus, in connected mode the UE mobility is fully controlled by the network.

Fig. 12: UE modes and procedures

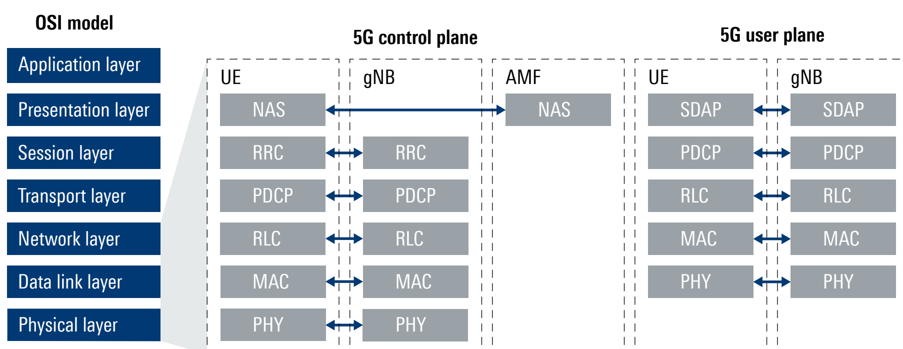


Note that the UE operating modes are more complex in real networks (see [TS 24.008]). For example, there are intermediate operating modes where the UE and network keep registration information but the radio connection is suspended. [Ref. 20]

Communications between two network entities is based on a protocol structure. Readers not familiar with protocols should think of a protocol as a standard set of rules allowing electronic devices to communicate with one another. These rules include what type of data may be transmitted, what commands are used to send and receive data, and how data transfers are confirmed. We should briefly mention the well-known open system interconnection (OSI) model in which communications is based on seven protocol layers [Ref. 50]. In wireless communications systems, the protocol layers responsible for radio link operation are layers 1 to 3. In the vertical direction, we can distinguish between protocol layers for user data communications (U-plane) and signaling control (C-plane). An example is shown for the 5G NR protocol structure in Fig. 13.

The 5G NR physical layer or radio interface handles aspects of radio communications such as the bandwidth, waveform, modulation schemes, transmit power, etc. The MAC and RLC layers ensure proper data transfer over the radio interface. This includes functions such as configuration of transportation blocks, forward and backward error correction, acknowledgment and (optionally) priority settings. Layer three represents the control layer, divided into the radio resource control (RRC) or access stratum, and mobility and session control known as the non-access stratum (NAS). In 5G, the user plane has two further protocol layers known as PDCP and SDAP. In brief, their functional behavior ensures a proper data connection in mobility scenarios such as handover, secure communications based on ciphering and integrity protection as well as control and maintenance of the quality of service (QoS). Today's modern communications systems such as LTE and 5G are all packet-switched, i.e. they use the internet protocol (IP) as the transport layer protocol for worldwide communications. Note that the presentation layer (e.g. graphical user interface) and application layer are typically not governed by standardization organizations such as the 3GPP (for the sake of completeness, we should mention one well-known exception: the speech codec for voice communications) [TS 36.300].

Fig. 13: OSI reference model and 5G NR control and user plane structure



3.2 Cell selection, reselection and connection mobility

The transition from power-on mode to idle mode is an important procedure in all wireless communications standards and is known as initial access. It is slightly different for each radio technology. The objective of this section is to describe the general principle. See e.g. [TS 38.304] for further details. As the initial capability when first powered on, we may assume that the UE acts as a receiving device, especially a frequency-selective power meter. Consequently, the UE starts a spectrum sweep and scans the frequency bands trying to detect the power levels of relevant signals. These synchronization signals have a very high autocorrelation function so they can be detected quickly and unambiguously. The frequency channel or radio technology that the UE searches first is configured either via the SIM card profile (e.g. preferred networks and technologies), or it is determined based on the SIM storage which indicates the last network the UE was connected to. Detection of these synchronization signals reveals the presence of a radio network. The content of these signals allows synchronization in time and frequency. Then, the UE must acquire system information broadcast on a common control channel such as the network identity, random access channel information, paging information and information for mobility procedures, to name a few examples. After receiving the minimum set of system information (and assuming the cell is not barred for this particular UE access class), the UE sends a random access message to establish a signaling connection. This signaling connection is used to execute the registration procedure. In detail, the registration procedure contains a signaling radio connection establishment, a UE capability exchange, the setup for a security context for authentication and authorization, and finally, the exchange of registration and session request information intended to establish a mobility and session management context. After successful initial access and registration, the UE enters idle mode. In idle mode, the UE needs to regularly update the system information and monitor the paging channel for mobile-terminated connection setup. The cell that is monitored by the UE is known as the serving cell.

A mobility scenario is a situation in which a UE moves from one cell to a neighboring cell. This applies to idle mode and to connected mode. More complex mobility scenarios can include an RAT change from one cell to another and even a PLMN change. The serving cell change can either be controlled by the network (handover) or by the UE (cell reselection).

Cell reselection describes the process in which a UE in idle mode detects that another cell is better than the current serving cell and decides to change the service cell. However, what does "better" mean in this context? We need to define some rules for this procedure. In RATs, every cell broadcasts via its system information the RF resources of possible neighboring cells and rules for cell reselection. An example of such a reselection criterion can involve the definition of a power threshold. When a received reference signal power value (RSRP) of a neighboring cell becomes stronger than the RSRP of the existing serving cell, the UE considers the neighboring cell as the new "best server" or serving cell. Other rules are defined for quality criteria, e.g. the new "best server" has to provide better quality (e.g. SNR) than the current serving cell. The system information provides priority rules and criterion details as well as reselection details for inter-RAT cell selection or inter-PLMN cell selection.

In connected mode, the mobility procedure is different. The major difference is that the network is responsible for the decisions. To provide the network with channel status information (CSI), the UE sends measurement reports to the base station. The content of such measurement reports is e.g. the power levels of neighboring cells, the power and quality of the current serving cell, and the interference status. Advanced CSI includes aspects such as a rank indicator for spatial multiplexing support, CSI reports supporting sophisticated interference detection methods, or precoding matrix identifiers for enhanced beamforming mechanisms. Further details on such enhanced CSI are provided in [Ref. 20]. Research activities outside the scope of 5G include investigation of predictive reporting, e.g. a vehicle knows its location and links it with connection history data such as the conclusion that the vehicle is on the daily route to the workplace and reports to the current serving cell that a handover is likely to happen soon. Now the serving cell may start communicating with the neighboring cell to pre-reserve resources.

3.3 Connection-related procedures

This section does not provide a detailed description of air interface procedures. Instead, the intention is to offer a concise overview of the relevant procedures to understand the basics of wireless communications. Further details can be found in relevant literature.

Radio frequency (RF) is a sparse resource that should be used efficiently. Thus, the network manages the multiple access. Initial access or connection setup procedures require transmission of an initial radio signal or control message in the uplink direction. For this purpose, the network reserves a radio resource known as the random access channel (RACH). Access policies for the RACH along with configuration details are sent via system information to the UEs. There is a distinction between two access schemes: Contention based access where a collision between multiple UEs accessing the radio interface is possible and has to be resolved, and contention-free access where the network preallocates resources for the RACH. The content of the first message, e.g. in 5G the RRCSetupRequest sent on the RACH channel, is the UE random identity and an establishment cause. One example for the information field establishment cause is "emergency call", which signals the priority of the connection to the network at the earliest instance.

In the mobile-terminated direction, the network offers a paging channel in the downlink direction where it sends the UE identities to trigger network-originated calls. This causes transmission of a setup request message on the RACH with establishment cause values set to e.g. "answer to paging".

RAT technologies such as LTE and 5G NR provide comprehensive support for various data connections inheriting different data transfer profiles. Profile parameters such as the ensured or peak bit rate, priority classes, expected or tolerated error ratio, and latency requests are summarized under quality of service (QoS). During connection setup, higher layer protocols (e.g. SDAP in 5G NR) negotiate and configure such a QoS profile for each data flow between the UE and network [TS 23.501].

A radio cell spans a certain geographical region and sizes can range from small indoor cells up to outdoor umbrella cells with dimensions in the dozens of kilometers. Release 17 discusses a work item for non-terrestrial networks where a base station can either be airborne or satellite based. To reduce interference to neighboring cells and to reduce the energy consumption within the UE, the base station will control the transmit power of the UE. RAT distinguishes between absolute power control information (e.g. a control message indicating the absolute power in dBm) or relative power control (e.g. transmit power control commands with content "up" or "down").

RF resources are assigned in time and frequency units, e.g. the term resource block in LTE and 5G. We know that radio waves travel at the speed of light, for example a signal needs approx. 3.3 µs to travel 1 km. This causes delayed signal reception equal to twice the propagation path and may result in interference to the following time slot. Countermeasure involve control information known as a timing advance, where the base station orders the UE to advance its transmission in the uplink direction to compensate for this propagation delay [TS 38.211]. One side effect is that the timing advance can now be used for radio technology based positioning technologies.

3.4 Security aspects

Cybersecurity is one of the major buzzwords in the wireless world and covers a wide range of issues. This white paper only provides a basic introduction to cybersecurity aspects.

Security in cellular networks mainly concerns the important functions of ciphering, authentication and integrity protection. A security framework model is part of the standard that fulfils these requirements and provides a security architecture and a trust model supporting the following major aspects:

Ciphering is encryption of communications content between two entities to avoid eavesdropping. In the recent evolution, ciphering has been enhanced by providing encryption for user and control data and by extending the encryption range from the air interface to the inclusion of backhaul connections as well. Note that the 3GPP standards only specify ciphering for connections within the 3GPP specified network. Higher application layer ciphering would be up to the implementation of the application layer itself. For example, if a carmaker has a service application where the vehicle provides status updates to the application server, this connection needs to be encrypted end-to-end by policies of the respective company.

Integrity protection verifies the origin of the data or control information to avoid man-in-the-middle attacks.

Authentication is defined as the process or action of proving or showing something to be true, genuine or valid. From a digital perspective, this is the process or action of verifying the identity of a user or process. Authentication in cellular networks uses a symmetrical procedure, i.e. the whole authentication process is simplified to the comparison of whether a symmetric key that exists on both sides leads into concordance. On the UE side, the security credentials are stored in the USIM card. This can either be an application in a tamper-proof section of an integrated circuit card UICC or, in an alternative that is attractive for the automotive world, the SIM card credentials can be enabled over the top into an electronic SIM (eSIM). The latter allows configuration of flexible user profiles, especially assuming a vehicle is sold internationally in different countries.

Subscriber privacy should be protected to avoid abuse of a subscriber's location information. However, this is not an easy task since wireless technologies need to send subscriber identities over the air interface. As the latest technology, 5G protects the subscriber identity in that temporary identifiers are used for random access and paging messages, and the UE only sends a concealed identifier to the network. The permanent identifier SUPI is de-concealed by the home network operator only and this information is provided in an encrypted inter-operator communications link. Further information on security aspects in wireless communications can be found in literature, e.g. [Ref. 8], [Ref. 20], [Ref. 30], [Ref. 31], [Ref. 49], [TS 33.401], [TS 33.501].

3.5 Positioning

Location based services or positioning play an essential role in wireless communications, especially in the automotive sector. This is even mandatory in some situations. For example, some governments mandate position information in combination with emergency calls (a prominent example is the E911 rule in USA), or the eCall technology sets the location information as a mandatory part of the emergency data call. Beside the mandated positioning requirement derived from public safety aspects, positioning methods are also important in commercial applications. One well-known example involves navigation services. In fact, we doubt whether there are any modern cars sold today without a navigation system. With 3GPP Release 9, several features were introduced into LTE technology to support positioning methods. There are various ways to describe and distinguish positioning technologies and methodologies. First, one may distinguish where the location is calculated and if assistant information is provided. For example, the network may assist with positioning control information (network-assisted) and enable the UE to calculate its position (UE based). Conversely, the UE may report measurement information to the network, enabling it to calculate the location (network based). A very detailed explanation of positioning methods in cellular networks is provided by [Ref. 88].

One distinction can also be the communications protocols for location based services. A well-known concept is the introduction of secure user plane location (SUPL) where the location information is sent over a user plane traffic channel. The advantage is that this concept has no impact on the UE protocol implementation. The opposite is the introduction of radio technology specific protocols for location information control exchange and their implementation into the UE stack. Two well-known examples are the LTE based location positioning protocol (LPP) [TS 37.355] and the 5G NR based positioning protocol (NPPa) [TS 38.455].

The last distinguishing factor for location services is the type of positioning method, depending on what radio signal is the basis for location calculation. One type is based on global navigation satellite services (GNSS) and the other type is based on wireless radio technologies. The distinction relates to the complexity of the implementation and the location accuracy that can be obtained, as well as whether the location calculation is performed in the UE itself or whether the UE assists with measurements to support location calculation in the network.

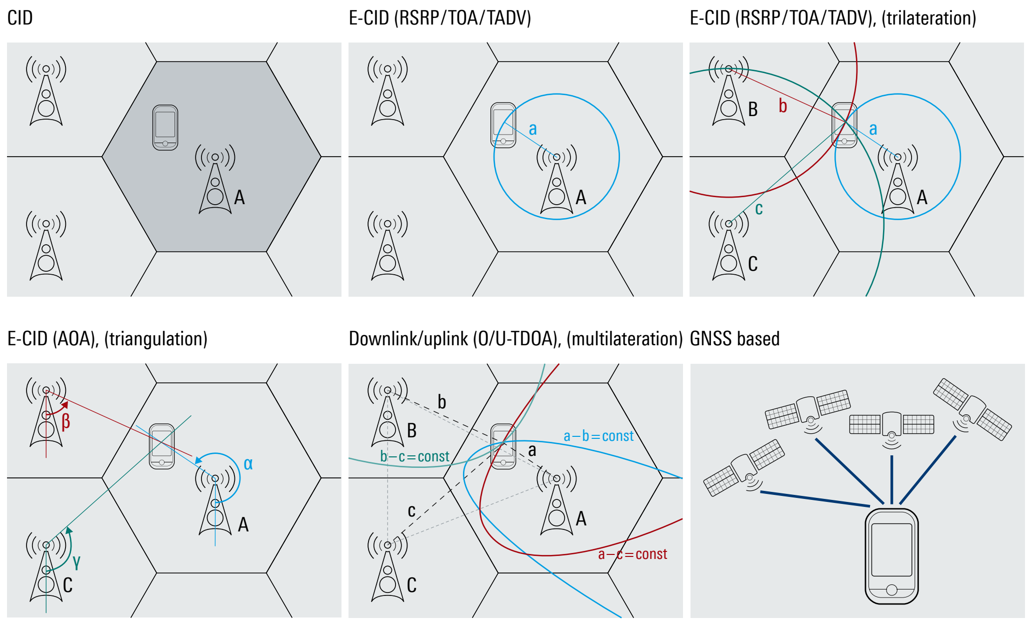
3.5.1 GNSS based positioning

These methods use GNSS systems such as GPS, Galileo, GLONASS or BeiDou to calculate the location of a device. Vehicle based emergency call services (e.g. eCall or NGeCall) require a satellite based positioning method and the vehicle location is a relevant component of such an automated emergency call. GNSS support in the end-user device requires a chipset for GNSS technology and a radio frontend covering the satellite frequency ranges. If the position is calculated based on GNSS, what is the role of the wireless technology? Drawbacks (besides the extra hardware requirement) are that GNSS based location services may not work properly in indoor situations such as a road tunnel as well as a probable long time to first fix. When contemplating the system details of a GNSS briefly, we understand that there are several satellites needed to provide coverage all over the globe and in addition, there is a large distance from earth to satellite. As one example, the GPS system consists of a total of 24 satellites in six orbital planes with four satellites on each plane. Their altitude is approx. 26 560 km. One drawback, resulting from the high path attenuation leading to very low RX power, is the low data rate since the channel bandwidth is low. Assuming a satellite receiver is turned on without any prior information, it would have to scan for all possible satellites. The duration until the first position is calculated is described as the time to first fix (TFF). GPS transmits at a rate of 1500 bit per 30 s. In the worst case, given as a cold start, it may take a maximum of about 12 minutes to execute a full quest and obtain the required signaling information from the available satellites. Wireless communications technologies introduced the idea of assisted GNSS (A-GNSS) where the LTE or 5G radio technology provides information about the available satellites. It is assumed that initial access to the LTE or 5G network is faster. This typically takes several seconds and via the signaling connection, the network can send assisted satellite information (i.e. A-GPS) to the UE directly. Two specific signaling protocols support such an exchange of location-relevant control information: the location positioning protocol (LPP) introduced with 3GPP Release 9 and the NR positioning protocol (NPPa) introduced with 3GPP Release 16. To enhance the location accuracy, additional methods such as differential GPS, where known errors at certain geographical positions are sent to the UE for correction purposes, are supported. The next generation of GNSS based positioning methods enhances the location accuracy based on technologies such as real-time kinematics (RTK) or hybrid methods where several location calculations are combined. Further information on how to test satellite based location services is provided in [Ref. 29], [Ref. 51], [Ref. 53].

3.5.2 Radio technology based positioning

As opposed to satellite based positioning methods, LTE Release 9 started with the definition of radio technology based methods. The advantage is that they do not require any extra hardware such as a GNSS receiver, but the drawback is that wireless radio is historically derived from communications systems and was not designed for location based services originally. There exist various methods differing in implementation complexity and location accuracy. Another distinction is whether the location calculation is UE based or network based. Fig. 14 gives an overview of several radio technology based methods. They can be based on LTE or 5G NR.

Fig. 14: Wireless radio and GNSS based positioning methods – overview



Cell identity positioning is a very simple positioning method with cell size accuracy. Every radio cell broadcasts a cell identity (besides the MCC and MNC) via system information. The UE reads this value, sends it to the network and via database query, the network operator provides the location information. A slightly more accurate positioning method involves usage of information such as the timing advance, received signal power or time of arrival. This leads to a kind of circle or circle extract as position information. For greater accuracy, these parameters can be measured at several neighboring cells and a kind of trilateration approach is now possible. With advanced antenna systems like the beamforming massive MIMO AAS used in 5G, the base station may measure the direction of arrival (DoA) or angle of arrival (AoA). The last method we wish to present, offering better accuracy but requiring a certain time measurement capability within the UE, is the observed time difference of arrival (OTDoA) measurement. In this approach, the UE measures the time difference between several downlink signals and reports these measurement results to a network based location server which computes the UE's location. In the opposite direction, the network can perform an uplink time difference of arrival measurement (UTDoA).

3.5.3 Outlook for positioning methods

Positioning methods are an evolving technology, and both the academic world and industry are conducting ample research to enhance the location based services of the future. Important fields of research include accuracy improvement for indoor and outdoor scenarios, speed of positioning acquisition and accuracy especially for autonomous vehicles, 3D location information acquisition and hybrid methods using multiple technologies to acquire location information in a less complex approach. In addition to absolute location calculation, relative location information, e.g. the distance between two vehicles, is considered as a topic for further discussion. With Release 16, 3GPP introduces positioning methods for 5G NR. Most of these methods seem to be a copy and paste from positioning methods introduced in 3GPP Release 9. There are A-GNSS methods for 5G NR using the LPP/NPP protocol to exchange satellite-related control information. Moreover, there are radio technology based methods such as the cell ID, angle of arrival measurement and OTDOA, a multilateration method, based on calculation of localization hyperbolas. For indoor accuracy optimization, hybrid methods such as a combination of 5G NR and WLAN or Bluetooth® are discussed. IEEE introduces with IEEE 802.15 or UWB a technology used in the automotive industry. Thanks to its ability to leverage accurate short-distance location information, UWB enables application scenarios such as wireless key opening of vehicle doors, child seat positioning, trailer attachment or general gesture control or haptic control within a vehicle [Ref. 52]. Bluetooth® is also expanding its application range in the vehicle environment. Bluetooth® 5 contains location acquisition technologies based on beamforming to enable very accurate short distance positioning [Ref. 42].

There is growing demand for high-precision positioning in the automotive industry for assisted driving and autonomous driving applications (ADAS). Real-time kinematics (RTK), which is well established for specialized applications (e.g. surveying), is now making its way into many more applications such as precision farming, road construction, etc. It is a differential positioning technique, where error sources get eliminated/minimized by double-differencing measurements between terrestrial reference stations whose geolocation is accurately known and a moving receiver ("rover"). The wide coverage of LTE networks enables large-scale delivery of required assistance data through broadcasting of system information. 5G is assumed to support this provisioning with even higher data rates. Precise point positioning (PPP) is a differential positioning technique in which satellite clock and orbit errors are calculated by a network of reference stations and distributed to the receiver as model parameters. Thus, there is no need for nearby terrestrial reference stations. The disadvantage is that acquisition takes a bit longer. RTK PPP positioning uses state space observation (SSR) parameters. SSR data combines the advantages of PPP and RTK: all parameters provided to rover, rover can decide whether to use PPP or RTK. Such high-precision location acquisition methods are affected by parameters such as multipath propagation, phase jumps due to signal blocking, or differential atmospheric delays representing the receiver independent part. However, there are also hardware-related influencing parameters such as the different ambiguity resolution algorithms, the RF frontend quality and antenna performance, and the quality of the correction data itself. To compensate such influences, inertial measurement units (IMU) containing sensors such as an accelerometer, gyroscope or other motion sensors can improve the performance significantly. [Ref. 51], [Ref. 53]

3.6 Automated emergency call in the car (eCall/ERA-GLONASS)

In May 2010, the UN General Assembly proclaimed the period of 2011 to 2020 as the decade of action for road safety. During this period, international measures are to be taken to effectively reduce the high number of fatalities and serious injuries due to road traffic. The European Union's contribution to this effort was to design eCall, an automatic emergency call system. The Commission as well as the European Parliament and Council have approved the initiative. There are several European standards by the ETSI summarized under the term eCall. Just to name one of them, CEN EN 16072 defines the Pan-European eCall operating requirements.

It stipulates that all new car and delivery vehicle models that come on the market in the EU after the cut-off date must support eCall operation.

What is eCall? eCall automatically contacts the emergency services in the event of a serious accident. The in-vehicle electronics determine whether or not a serious accident has taken place. Typically, eCall activation is linked to airbag deployment. However, it is up to the manufacturer to determine which sensors are integrated and according to which criteria. In addition, the system can also be activated manually to report an emergency that cannot be detected automatically – for example, when a passenger has an urgent health problem – or witnessing an emergency involving another vehicle.

Since eCall requires both a wireless communications connection and satellite positioning, even low-cost small cars will have to be delivered with this functionality ex works. Car manufacturers have the option of either integrating a pure eCall modem or equipping vehicles with eCall-compatible telematics units, which of course can also be used for infotainment purposes.

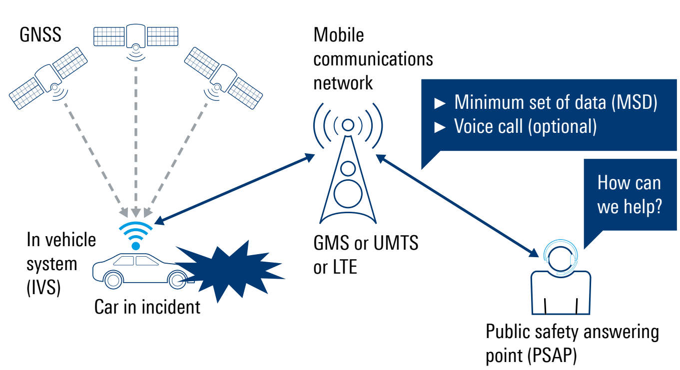
The eCall system consists basically of three components: the in-vehicle system (IVS, normally an integral part of the telematics system), the telephone network that is used for communications (wireless and fixed network) and the public safety answering point (PSAP). When activated, the system dials the standardized pan-European emergency number 112. A special flag that must be implemented by the network operator is transmitted with the signal to alert the called station that it is dealing with an eCall. Control is passed on to the PSAP, which asks the IVS to transmit the standardized 140 byte eCall minimum set of data (MSD). The MSD contains all essential information that rescue services require in order to respond appropriately: vehicle position and heading (important on highways), time of accident, vehicle type, engine and/or fuel type (important for the fire department), number of occupants (closed safety belts). Additional information is optional. The most important information is the position information in the MSD, thus location based service technologies like GNSS are needed and the device support for voice communications. The well-established in-band modem technology was chosen to transmit the MSD due to its extensive availability (GSM) and the prioritization of voice telephony. It sends the data as beeps over the voice channel like in the days of acoustic couplers for telephones. The data is decoded at the PSAP and displayed on the operator's console. Optionally on request, a voice connection is established between the operator and the vehicle so that the parties can interact directly. The IVS will accept the voice directly without further user action. [Ref. 13], [Ref. 63], [Ref. 72]

As eCall is based on the GSM radio technology and the lifecycle of a new car is in the range of > 10 years, 3GPP specified in later releases the eCall communications over UMTS. To ensure a future-proof technology over a much longer period, eCall evolves with 3GPP Release 14 into the next generation eCall (NGeCall). The general working principle stays untouched but as a major difference, the radio access technology used to convey the MSD is LTE instead of GSM. Thus, the voice call moves from circuit-switched to packet-switched and from single voice call to IP data. [Ref. 15], [Ref. 38]

NGeCall supports voice services in LTE (VoLTE), but voice services in LTE are controlled via an IP based signaling framework IMS (IP multimedia subsystem). With the IMS system, the minimum set of data (MSD) is sent in an SIP invite message during call setup. 3GPP Release 14 defines a flag network indicator for eCallOverIMS-Support to indicate that the LTE network supports NGeCall.

Fig. 15 provides an example of a manually or automatically initiated emergency call and transmission of an MSD from an IVS to PSAP via the LTE network using IMS for MSD transmission.

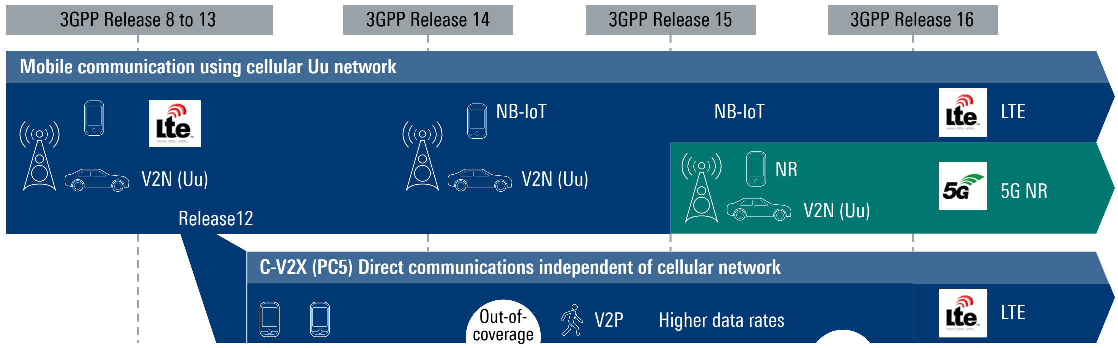
Fig. 15: Automated emergency call



Besides the European approach for standardization of a common vehicle based emergency system, the Russian Federation launched the ERA-GLONASS initiative, sponsored by the Federal Agency on Technical Regulating and Metrology. To name one standard of the whole set as an example, GOST R 54721 provides a general base service description of ERA-GLONASS. In principle, it operates (similar to eCall) either on GSM or UMTS, but with one major difference. In ERA-GLONASS, the emergency message data (MSD) can also be sent via the short message service (SMS) instead. Other differences involve the support for GNSS systems: an eCall IVS must also support Galileo (besides GPS) and an ERA-GLONASS IVS must support GLONASS as a GNSS positioning system. [Ref. 13], [Ref. 14], [Ref. 15], [Ref. 38]

4 NETWORK BASED COMMUNICATIONS FOR AUTOMOTIVE APPLICATIONS

Upper part of Fig. 4 (recapitulation)



Based on the upper part of Fig. 4, this section provides more details on network based radio access technologies. Due to space constraints, the details of GSM and UMTS technologies are not explained here but can be found in [Ref. 9], [Ref. 10]. In the evolution of wireless communications standards, there is a migration from voice-only communications to ubiquitous data networks offering multiple services with different requirements. In the automotive sector, the first devices were car based telephones allowing drivers to communicate via voice calls with other persons. Nowadays, there are communications systems such as entertainment entities or navigation systems that are connected via packet-switched data connections. With the introduction of 5G NR, there is greater emphasis on flexibility and new applications are possible.

4.1 Long Term Evolution (LTE)

In December 2004, the standardization group 3GPP started a technical study on Long Term Evolution (LTE) for UMTS. At that time, UMTS networks were rolled out worldwide and deployment of high speed downlink packet access was about to start. To ensure the competitiveness of UMTS for the coming years (10 years and beyond was targeted), the industry initiated work on UMTS long-term evolution concepts, with the objective to provide a perspective for UMTS towards a true mobile broadband technology: high data rate, low latency and packet-optimized. Given the long-term nature of the work, it was possible to deviate from existing technology paradigms and introduce completely new concepts for LTE as long as a migration story from UMTS was possible.

Obviously, LTE has to meet ambitious requirements in order to provide a real future-proof technology and live up to the expectations of the industry. The first part of the work in 3GPP was the definition of clear requirements that LTE would have to fulfil. These requirements were the baseline for the evaluation of new technology concepts, i.e. every new feature had to prove that it would contribute to the fulfilment of at least one of the requirements. Particularly network operators were providing input on these requirements; it was in their vital interest to ensure an attractive long-term perspective for their existing UMTS networks and to get a return on investment.

The requirements identified by the industry were captured in a technical report, 3GPP TR 25.913. Some major requirements are summarized in the following:

Packet-switched services
LTE is focusing solely on the packet-switched domain and is not supporting circuit-switched services any more. This includes support for voice services as voice over IP (VoIP) using the IP multimedia system (IMS) infrastructure. The commercial term is voice over LTE (VoLTE).

Data rate
The requirement for the peak data rates was initially set to values of 100 Mbps on the downlink and 50 Mbps on the uplink, assuming a 20 MHz spectrum allocation and two receive antennas/one transmit antenna at the terminal. Note that these values were actually even exceeded by LTE-Advanced technologies later.

Spectrum efficiency
The target for downlink spectrum efficiency is 3 to 4 times better than HSPA according to the 3GPP Release 6 specifications. The target for uplink spectrum efficiency is 2 to 3 times better than HSPA Release 6.

Latency
Latency is an important measure for the interaction time between the subscriber and the network. In LTE, the one-way transit time between a packet available at the IP layer in either the UE or radio access network and the availability of this packet at the IP layer in the radio access network/UE should be less than 30 ms. Moreover, the control plane latency should be low, e.g. to allow fast transition times of less than 100 ms from camped state to active state.

Bandwidth
There was a clear understanding from the beginning that LTE would operate in bandwidths up to 20 MHz and that scalable bandwidths should be supported allowing smaller values. While the values 5 MHz, 10 MHz, 15 MHz, 20 MHz were defined quite early, the smaller bandwidth values of 1.4 MHz and 3 MHz took a while to agree upon. They are important to allow operation of LTE in narrow spectral allocations; especially LTE-M for machine type communications uses the 1.4 MHz bandwidth for energy efficient implementations.

Interworking
LTE should interwork with existing UMTS and GSM/EDGE systems as well as with other "non-3GPP" systems.

Costs
Network operators expected LTE to become a cost-effective technology, regarding both capital and operational expenditures (CAPEX and OPEX), and also including considerations related to the backhaul. This requirement especially reflects the lessons learned from the UMTS deployment. Moreover, the migration from the 3GPP Release 6 UTRA radio interface and architecture to LTE should be possible with reasonable effort, and reasonable system and terminal complexity, cost and power consumption should be ensured. Another important requirement addresses the multivendor capability of all the interfaces specified, because network operators want to be flexible regarding the choice of their suppliers for different network entities.

Mobile speeds
LTE is optimized for low mobile speeds (0 km/h to 15 km/h), but higher mobile speeds should be supported as well, including a high speed train environment as a special case.

Duplex modes
Operation in paired (frequency division duplex (FDD) mode) and unpaired spectrum (time division duplex (TDD) mode) is possible.

Quality of service
End-to-end quality of service (QoS) should be supported. VoIP should be supported with at least as good radio and backhaul efficiency and latency as voice traffic over the UMTS circuit-switched networks.

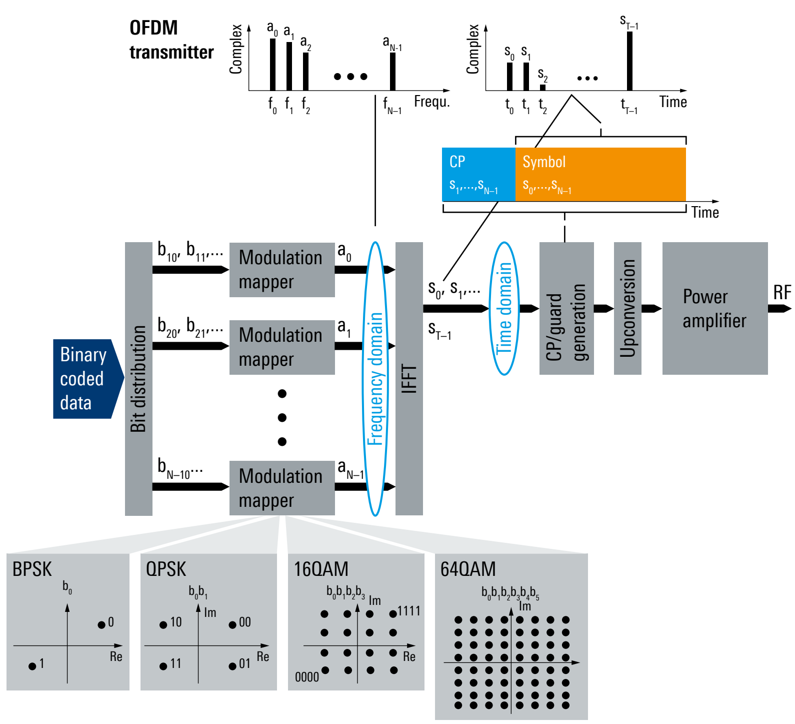
Network synchronization
Time synchronization of different network sites should not be mandated.

4.1.1 LTE radio interface aspects
LTE uses conventional OFDMA on the downlink. The basic principle is illustrated in Fig. 16 showing the example of a 5 MHz signal, but the scheme can be easily adapted to higher or lower bandwidths.

In an OFDM(A) system, the available transmission bandwidth is subdivided into subcarriers with equal spacing, which can be independently modulated with data symbols. In the time domain, OFDM symbols are transmitted which are separated by guard intervals to protect the symbols from intersymbol interference. These guard intervals are not DTX as this would increase the peak-to-average power ratio (PAPR). Instead, they repeat a section of the OFDM symbol in a copy and paste operation. This extension is described as cyclic prefix (CP) and the duration of the CP should have a length corresponding to the typical expected delay spread. In other words, the CP length is a design parameter of the expected cell size. On the transmitting end, an OFDM(A) signal is generated with an IFFT operation. Modulated data symbols are used as frequency bins for the IFFT and converted into time domain OFDM symbols. This also creates the inherent orthogonality of the subcarriers to each other, giving OFDM(A) its name. On the receiving end, an FFT operation is used to convert the time domain symbols back to the frequency domain.

The difference between OFDM and OFDMA lies in the scheduling. In OFDM, different users are scheduled in the time domain and always allocated the full available bandwidth. In OFDMA, users are scheduled in both the time and frequency domains, so that several users can share the available bandwidth.

Fig. 16: OFDMA signal generation as used in 3GPP EUTRAN Release 8



A particular benefit of OFDMA systems is the frequency-dependent scheduling feature which allows adaptation of the scheduling decisions in the frequency domain. For example, some subcarriers can be modulated with 64QAM, while others can be modulated with QPSK simultaneously in order to take into account frequency dependencies in the radio link quality.

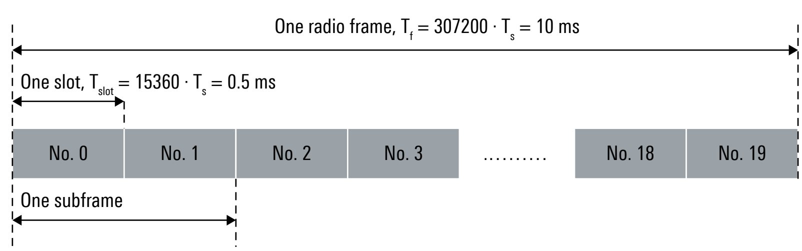
LTE uses similar radio access methods as the later generation 5G. For size reasons, refer to Fig. 26 showing a structure of a downlink resource grid for both FDD and TDD, where the x-axis shows the OFDM symbols in the time domain and the y-axis shows the subcarriers in the frequency domain. A resource element is formed by the combination of one specific OFDM symbol and one specific subcarrier. [Ref. 9], [Ref. 54]

The subcarriers in LTE have a constant spacing of Δf = 15 kHz. In the frequency domain, 12 subcarriers form one resource block corresponding to 180 kHz. The resource block is of special importance for the LTE scheduling because it is the smallest entity that can be scheduled in the frequency domain (on the downlink and uplink). This means that in the frequency domain, one terminal can receive or transmit on one resource block or integer multiples of one resource block only.

As in WCDMA, LTE is based on 10 ms radio frames. Such a frame structure plays an important role in general timing aspects, i.e. it indicates the positions of the control information and schedules traffic in the time domain. Two frame structure types are defined for LTE: frame structure type 1 for FDD mode and frame structure type 2 for TDD mode.

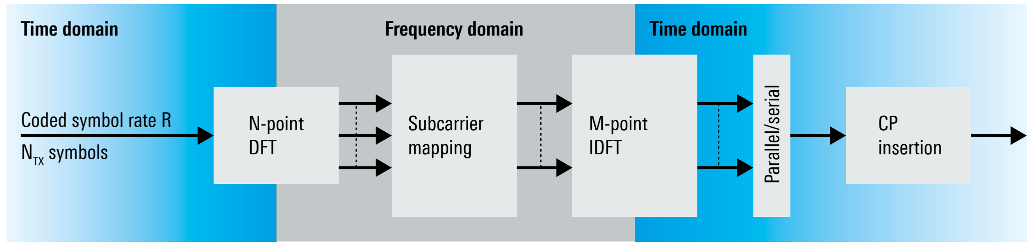
For frame structure type 1, the 10 ms radio frame is divided into 20 equally sized slots of 0.5 ms. A subframe consists of two consecutive slots so that one radio frame contains ten subframes. This is illustrated below (T_s expresses the basic time unit corresponding to 30.72 MHz).

Fig. 17: Frame structure type 1



In the LTE uplink, single carrier frequency division multiple access (SC-FDMA) is used. SC-FDMA can be best explained as a precoded OFDM scheme. Compare the signal generation chains for SC-FDMA in Fig. 18 and for OFDM(A) in Fig. 16. SC-FDMA signal generation is also based on an IFFT operation, but the modulated data symbols to be transmitted are not directly mapped to the IFFT. Instead, an DFT preprocessing (or "precoding") is first performed on the modulated data symbols and its result is input to the IFFT stage. For this reason, SC-FDMA is also referred to as DFT-spread-OFDM (DFT-s-OFDM) or, as previously noted, precoded OFDM.

Fig. 18: SC-FDMA signal generation chain



What is the benefit of an additional DFT stage in the terminal compared to a classic OFDM scheme? The answer is that SC-FDMA significantly reduces the peak-to-average power ratio (PAPR) of the signal. Signals with a high peak-to-average power ratio degrade the efficiency of the terminal's power amplifiers. Thus, the improvement provided by SC-FDMA is very beneficial for terminal manufacturers. The achieved reduction in the peak-to-average power ratio depends on the signal parametrization, e.g. the modulation scheme, and can be greater than 3 dB.

Due to similarities with the OFDM(A) signal generation chain, the parametrization of the LTE uplink and downlink is quite similar. This is also true for the uplink frame structure which similarly consists of 20 slots of 0.5 ms each, and one subframe consists of two slots.

4.1.2 LTE physical channels and physical signals

One major goal in the design of the LTE standard was to achieve a leaner protocol architecture, including less transport and logical channels. This also impacts the physical layer, producing less physical channel types compared to WCDMA. The LTE physical channel design has to reflect the focus on packet-oriented data transmission. Transmission of data packets in LTE is purely based on shared channels on the uplink and downlink because they are optimized for the bursty traffic characteristics of IP data services. The radio link can be dynamically shared among the different users in the cell depending on their varying traffic needs. No dedicated channels exist any longer in LTE (unlike the case of GSM and WCDMA where the circuit-switched connection was still part of the communications schemes).

The two figures below summarize the LTE physical channels and physical signals including a concise description. A physical signal is only defined inside the physical layer, supporting radio channel related procedures such as channel estimation and equalization, channel status information (CSI) acquisition and feedback or synchronization tasks. In contrast to the physical signal, the contents and structure of a physical channel are influenced by the higher layers. Such a physical traffic channel obtains the relevant data from a layer 2 transport channel inheriting a transport profile (like the question "how data is transferred") that contains multiplexed traffic derived from logical channels (like the question "what is transferred").

Fig. 19: Overview of LTE downlink physical channels and physical signals

LTE downlink physical channels	
Physical downlink shared channel (PDSCH)	carries user data
Physical downlink control channel (PDCCH)	carries control information (DCI: downlink control information)
Physical control format indicator channel (PCFICH)	indicates the format of the PDCCH (CFI: control format indicator)
Physical hybrid ARQ indicator channel (PHICH)	carries ACK/NACKs for uplink data packets (HI: HARQ indicator)
Physical broadcast channel (PBCH)	provides information during cell search, e.g. on system bandwidth
LTE downlink physical signals	
Primary and secondary synchronization signal	provides acquisition of cell timing and identity during cell search
Reference signal (RS)	enable channel estimation

Fig. 20: LTE uplink physical channels and physical signals

LTE uplink physical channels	
Physical uplink shared channel (PUSCH)	carries user data
Physical uplink control channel (PUCCH)	carries control information (UCI: uplink control information)
Physical random access channel (PRACH)	preamble transmission for initial access
LTE uplink physical signals	
Demodulation reference signal (DMRS)	enables channel estimation and data demodulation
Sounding reference signal (SRS)	enables uplink channel quality evaluation

The **physical downlink shared channel (PDSCH)** is used to carry downlink data on a time and frequency shared basis. The PDSCH contains DL user data, UE-specific higher layer control messages, system information blocks and paging. Frequency resource allocation is performed in units of resource blocks. The PDSCH uses a flexible modulation scheme depending on the actual SNR and a flexible coding scheme.

The **physical downlink control channel (PDCCH)** is used to carry downlink control information (DCI) primarily for scheduling DL transmissions on the PDSCH and UL transmissions on the PUSCH. The PDCCH always uses QPSK as its modulation scheme.

The **physical control format indicator channel (PCFICH)** indicates the size of the PDCCH as either one, two or three symbols.

The **physical broadcast channel (PBCH)** contains system information and is mapped on an a priori part of the channel to be detected easily. For flexible system information broadcasting, the decision in LTE is to divide the overall system information into various segments, so-called system information blocks (SIB). The PBCH contains the most important one, the master information block (MIB), while other SIBs are transferred via the PDSCH channel.

The **physical HARQ indicator channel (PHICH)** transmits the acknowledgment ACK/NACK feedback for a previous uplink data packet.

The **physical uplink shared channel (PUSCH)** is used to carry uplink data on a time and frequency shared basis. Resources on the PUSCH are scheduled as an uplink grant on the downlink control channel PDCCH. These grants also indicate the modulation and coding scheme as well as e.g. physical layer control information such as the TX power control.

The **physical uplink control channel (PUCCH)** provides a method to deliver uplink control information such as HARQ feedback, CSI reports, etc. in the uplink direction. This control information can also be multiplexed into the uplink traffic channel PUSCH if available.

The **physical random access channel (PRACH)** carries channel requests from a UE to the network and initiates the radio connection in the uplink direction. Policies on usage and configuration of the PRACH are sent via system information.

Further details on LTE physical channels and signals can be found in [Ref. 9] and [Ref. 54].

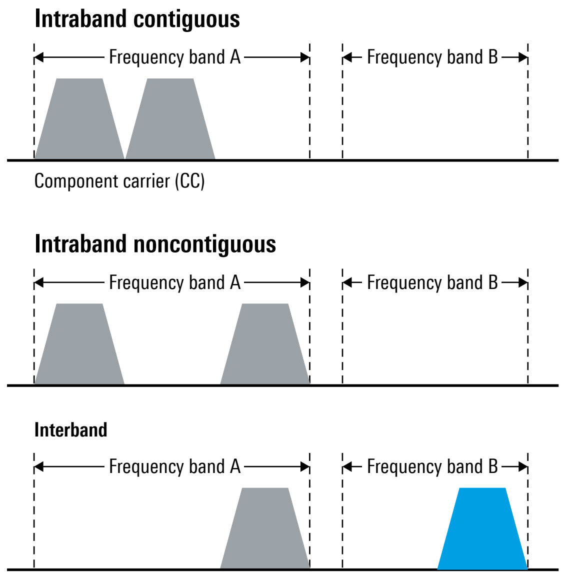
4.2 LTE-Advanced and LTE-A Pro

LTE is undergoing several extensions and updates in Releases 9 to 15 and there seems to be no stop in the evolution of this technology. This evolution is described using the terms LTE, LTE-A and LTE-A Pro for initial LTE, advanced LTE and more advanced LTE. Roughly speaking, we may cluster the various technology enhancements to LTE into the 5G service triangle (see Fig. 23). There are technology enhancements focusing on higher data throughput, while others leverage reliability aspects and machine type communications starts with LTE. In summary, LTE technology is a trailblazer for 5G NR. 3GPP Release 9 introduces aspects of positioning (see Fig. 14) and the idea of broadcasting, i.e. the term multimedia messaging and broadcast services (MBMS). MBMS represents a technology method by allocating RF resources in multiple cells to generate a broadcast area known as the MBMS single-frequency network (MBSFN). The term LTE-Advanced that accompanied 3GPP Release 10 indicates that this technology satisfies the IMT-Advanced requirements set by the ITU. LTE-A according to 3GPP Release 10 comprises essentially four features [Ref. 11]:

- ▶ Enhanced MIMO schemes allowing operation of up to 8x8 MIMO on the downlink and 4x4 MIMO on the uplink
- ▶ Enhanced intercell interference coordination (eICIC) introducing the capability to escape interference in the time domain, which is particularly important in heterogeneous network deployments
- ▶ Enhanced SC-FDMA, an improvement in the uplink transmission scheme to increase uplink capacity at the cost of increased linearity requirements for the end-user device transceiver
- ▶ Carrier aggregation (explained in more detail below)

LTE-A allows aggregation of up to five component carriers with up to 20 MHz of bandwidth to attain a total transmission bandwidth of up to 100 MHz. To assure downward compatibility, each carrier is configured to be 3GPP Release 8 compliant. Each of the aggregated component carriers can use a different bandwidth. In fact, one of the six supported bandwidths within LTE is allowed, i.e. 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz or 20 MHz. This is dependent on each network operator’s spectrum availability. Three carrier aggregation modes are possible within LTE-Advanced: intraband contiguous and noncontiguous as well as interband carrier aggregation (CA).

Fig. 21: LTE-Advanced carrier aggregation



The document [Ref. 12] lists and describes the LTE technology updates in Release 11. This evolution introduces aspects such as in-device coexistence which touch upon some of the radio cooperation aspects with LTE and WLAN, as well as inter-cell interference management and coordinated multipoint technologies (CoMP) for better efficiency, and enhancements for MBMS support and positioning methods.

4.2.1 LTE-Advanced Pro enhancements envisioned with Release 12 and Release 13

With the next enhancements in the LTE evolution starting with 3GPP Release 12, the term LTE-Advanced Pro is introduced. Details on these features can be found in [Ref. 16], [Ref. 17] and [Ref. 19]. These extensions are bringing to reality a very extensive set of new functionalities compared to LTE-Advanced:

LTE-WLAN aggregation (LWA), representing an enhancement of the previous aspect of WLAN offloading, where the LTE carrier could offload traffic into a WLAN radio channel. The drawback of these first implementations was a non-reversible offload concept, i.e. LTE could move traffic into WLAN but no reverse handover. To overcome these restrictions, LWA targets radio level integration with LTE serving as an anchor. The UE is configured by the eNB to utilize radio resources of both LTE and WLAN simultaneously. In simplified terms, we may understand the WLAN channel as an additional component carrier like in carrier aggregation scenarios.

Licensed assisted access (LAA) aggregates the licensed LTE carrier (serving as a mobility and signaling anchor – PCell) with SCell using the new LTE frame format over the unlicensed 5 GHz ISM band. It can be seen as a specific derivate of carrier aggregation to use additional spectral resources. In a later enhancement (Release 14), uplink transmission is also allowed on the ISM band.

Device-to-device (D2D) introduces direct communications between devices assisted by the network using sidelink transport and physical channels [TS 36.577]. The motivation behind D2D direct communications or proximity services (ProSe) is to support communications for public safety organizations [Ref. 6]. This feature paves the way for direct communications used for automotive connectivity with 3GPP Release 14 onwards (see Chapter 5 for more information).

Massive carrier aggregation, which extends carrier aggregation towards a higher number of aggregated bands and towards the use of unlicensed spectrum for mobile networking. Massive CA enables up to 32 CCs and thus theoretically provides up to 640 MHz of aggregated bandwidth for a single device, while still offering backwards compatibility with LTE Release 8 channel bandwidths. Massive CA can be combined with LAA to exploit spectrum in unlicensed bands.

Dual connectivity (DC), which provides a link combination scheme combining links from a primary and a secondary cell. Carrier aggregation is a layer 1 feature, increasing the overall bandwidth. Dual link combines two links, where a link consists of the physical layer and also higher layers. Thus, the complexity is higher since the RX entity has to run two concurrent protocol stacks. In contrast to carrier aggregation where both CCs have to be time-aligned and are typically sent from the same TX source, dual connectivity is a scheme allowing non-ideal backhaul for primary and secondary cell connectivity. The concept of dual connectivity culminates in the 5G NR technology where a radio connection using two radio links simultaneously is a default situation.

Machine type communications (MTC) enhancements (see study item [TR 36.888]) address low complexity MTC with a focus on defining a low complexity UE category type that supports reduced bandwidth (operation with 1.4 MHz), reduced transmit power, reduced support for downlink transmission modes, ultra-long battery life via power consumption reduction techniques and extended coverage operation (up to 15 dB). The concept of machine type communications evolves through the various releases of LTE. Starting with protocol aspects focusing on less energy consumption like long inactivity cycles (DTX and DRX) and reduced hardware capability, the standardization forum leverages the aspect of machine type communications. 3GPP Release 14 introduces a MTC extension supporting 5 MHz higher data rate operation for MTC devices.

Narrowband IoT (NB-IoT) as part of 3GPP Release 13 leverages the aspects of very low complexity, long battery standby times and enhanced coverage. The focus is on a typical sensor network where the UE as the sensor only sends sporadic traffic. To ensure proper reception, a high number of retransmissions can occur. NB-IoT is relevant for delay-tolerant traffic.

3D or full dimension MIMO (FD-MIMO), which allows directive antennas, or beamforming enhancing the horizontal beam steering. These mechanisms will be leveraged in 5G with further beamforming support.

4.2.2 LTE-Advanced Pro enhancements envisioned with Release 14 and Release 15

As an overview, we can sort the different technology features in the LTE releases from Release 12 onwards into the 5G triangle of services from Fig. 23. LTE technology features can also be headlined with enhanced mobile broadband (eMBB), massive machine type (mMTC) and ultra-reliable, low latency (uRLLC). Clearly, LTE serves as a trailblazer for the 5G evolution. The document [Ref. 19] describes details of the LTE updates in a more precise way.

Single cell point-to-multipoint (SC-PTM) covers the broadcast idea in a slightly different approach, focusing on machine type communications devices. The broadcast area now consists of a single cell area only and the radio resources for SC-PTM broadcast are assigned in a more flexible way. It is not a replacement or substitute for MBMS but instead leverages the multicast idea within a cell, e.g. for software updates to a group of devices. In the long-term evolution from LTE to 5G, the SC-PTM will be extended to multiple cells (MC-PTM) and leverage the aspect of multicast over a restricted geographic region versus the aspect of broadcast, e.g. FeMBMS.

Enhanced LAA (eLAA) extends the LTE and WLAN scheme LAA with permission to transmit in the uplink direction. This enables full dual connectivity-like capabilities for unlicensed spectrum. These ideas culminate in the introduction of NR-U with 3GPP Release 16 where 5G NR may use the unlicensed spectrum in ISM bands.

Enhanced LWA (eLWA) overcomes the restriction in LWA to use the WLAN channel in a unidirectional manner only. Additionally, it optimizes WLAN channel activation and release to support UE mobility.

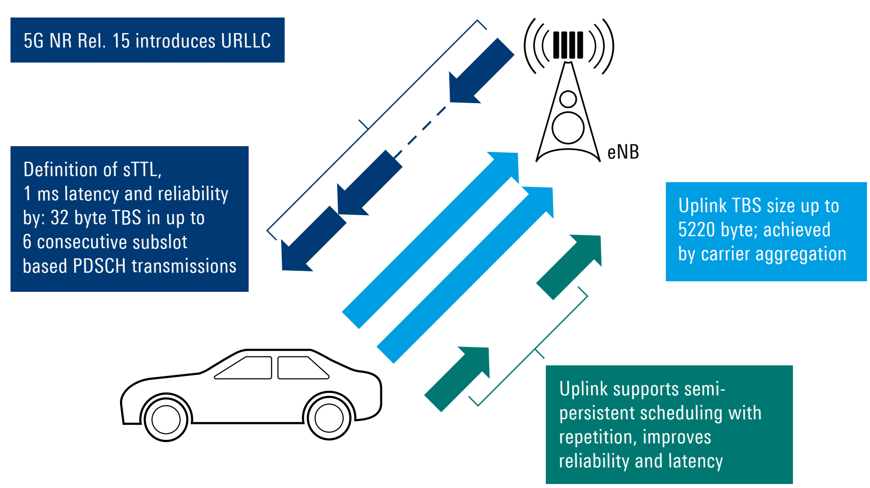
Vehicular-to-vehicular (V2V) extends the direct communications technology introduced in Release 12 D2D focused on public safety applications for automotive communications. Further details are found in Chapter 5.2 and [Ref. 45].

Latency enhancements on the control and user plane to shorten the transmit time interval (TTI) down to a single OFDMA symbol and more resource-efficient UL scheduling timing are some examples of proposed improvements targeting latency reduction.

Multiconnectivity enhances dual connectivity by providing multiple links for a UE where all of the configured multiple radio links can be active.

3GPP Release 15 introduces **5G New Radio** as a new wireless technology. Beside the 5G NR introduction, several LTE enhancements are described as well. The objective is to tackle the aspect of high reliability and low latency communications (HRLLC) in LTE. Fig. 22 describes LTE extensions focusing on automotive applications using the Uu interface. Latency reduction is achieved by designing a shortened TTI, and reliability improvements are obtained through automatic retransmissions and repetitions as well as a scheduling mechanism using semi-persistent scheduling. Another interesting feature for vehicle based communications is the uplink carrier aggregation scheme, boosting the possible data rate in the uplink direction and targeting applications such as sensor information uploads.

Fig. 22: LTE enhancements in Release 15 on the Uu interface for automotive applications



4.3 5G New Radio

3GPP Release 15 introduces 5G NR as a new wireless technology including the new air interface and the 5G core as an updated system. What is important to understand is that 5G NR should not replace or substitute LTE, but instead represents more of a technology evolution. Or alternatively, the evolution of LTE technology over the last releases has trailblazed the introduction of 5G NR. Some LTE features such as the broadcast concept FeMBMS, machine type communications (LTE-M and NB-IoT) or even the LTE radio and core network will present parts of the 5G system. In simplified terms, we may understand 5G NR as LTE plus much more. A more detailed description of 5G technology is available in a technology book from Rohde & Schwarz [Ref. 20]. With 5G, a paradigm change has happened in the wireless technology evolution. In a first step, 5G intends to focus on the services provided to users. In a second step, the technologies were elaborated to fulfill these service requirements. The services within the 5G scope can be categorized into three main types:

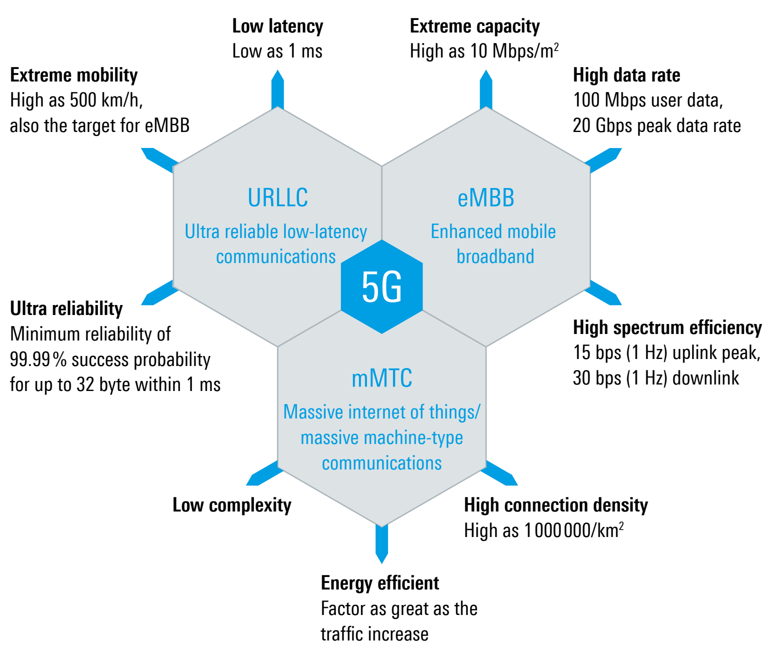
High data rate services should be designed to cater to the ever-growing demand for faster and higher-volume data access. This concept is a direct successor to the high data rate services provided by LTE (enhanced mobile broadband, eMBB).

Massive internet of things (IoT) should be an extension of the current IoT services, thus including nearly every machine communicating with other machines. This approach should open doors to major automation in every area of life (massive machine type communications, mMTC).

Ultra-reliable, low-latency services would involve new use cases in which small data exchanges can be realized to provide reliable and critical communications such as health monitoring (ultra-reliable, low-latency communications, URLLC).

In 2015, the International Telecommunication Union (ITU) defined the requirements in its **IMT vision for 2020 and beyond** for all upcoming services. These requirements can be categorized by considering the three main services eMBB, mMTC and URLLC. 3GPP has a standardization committee that is seeking to define a technology that fulfills the ITU requirements for submission to the ITU for approval.

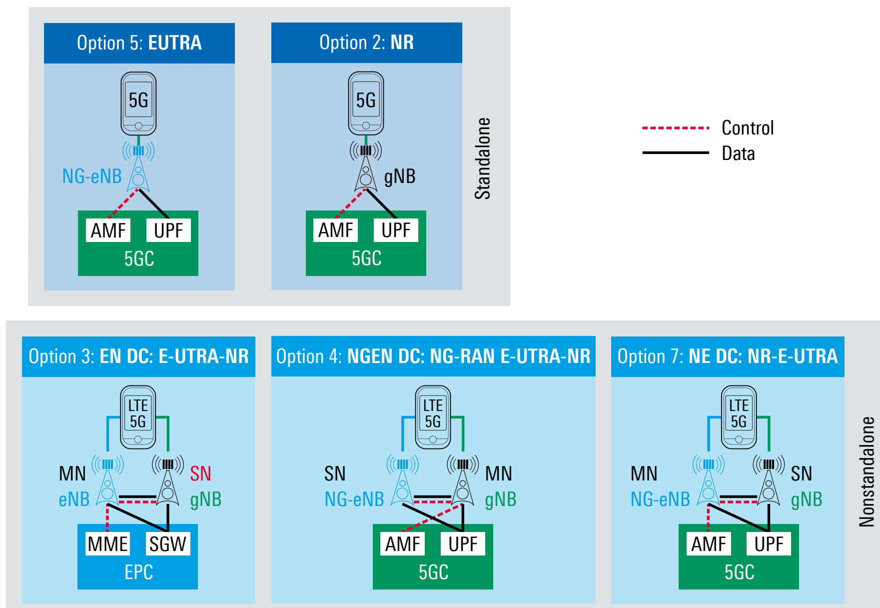
Fig. 23: ITU vision for IMT-2020 and beyond



4.3.1 5G NR connectivity scenarios and infrastructure aspects

5G NR is envisioned to enhance LTE functionality but not replace it. The possibility of the same core network connecting with various access networks results in several connectivity scenarios. The UE can be connected over LTE or over NR to the new 5GC (standalone connectivity options). Moreover, connectivity involving the cellular technologies has further evolved with an option for the connection to pass via more than one access technology at the same time (non-standalone connectivity options). The two most prominent 5G NR deployment and connectivity scenarios are standalone (SA) and non-standalone (NSA).

Fig. 24: Connectivity options (SA and NSA)



The background was prepared with LTE's dual connectivity (DC) concept, which allows the UE to connect simultaneously to two different base stations. The two base stations (xNB) are involved in a connection whose signals do not need to be time-synchronized and therefore are not required to be physically collocated.

In 3GPP Release 15, dual connectivity can involve two NR base stations (NR-DC) or one NR and one LTE base station (multiradio DC or MR-DC). Only LTE is considered for possible multiradio connectivity with NR.

4.3.2 5G NR physical layer aspects

5G is designed to support a variety of different services. The end-user data rate and system capacity have been further increased, and services have become much more diverse. In order to address the peak data rate and capacity requirements, 5G NR deploys a much higher bandwidth (up to 400 MHz per carrier) compared with 4G. Due to spectrum allocation, high bandwidth is only available at higher absolute frequencies. Consequently, 5G NR is designed for deployment in two main frequency ranges. FR1 comprises spectrum from 450 MHz to 7.125 GHz and FR2 from 24.25 GHz to 52.6 GHz.

To address the variable nature of services, physical layer design must support very high configuration flexibility. Although the waveform is still OFDMA based as was the case in LTE, there are certain fundamental differences which enable the required flexibility. A key difference compared to existing OFDMA based access schemes is the introduction of a so-called flexible numerology, i.e. the ability to use a number of different subcarrier spacing (SCS). In contrast to a fixed SCS of 15 kHz in LTE, 5G NR allows an SCS of 15 kHz, 30 kHz, 60 kHz, 120 kHz and 240 kHz. This leads to different symbol time durations since the SCS is inversely proportional to the symbol duration. Similarly, the number of symbols in a fixed time duration, e.g. the number of symbols within a 10 ms radio frame, is now variable. This flexible numerology is a key component for enabling a configurable air interface.

5G enables both FDD and TDD duplex schemes. Throughout the past generations (2G to 4G), FDD has been the dominant duplex scheme among the globally deployed networks, but with aspects like better channel reciprocity and dynamic load sharing, many 5G deployments will be TDD-specific. Especially FR2 deployments at mmWave do currently only support TDD duplex schemes.

The conceptual idea behind making OFDMA as flexible as possible with a different kind of parameterization entered into the standardization process. The result is the 3GPP 5G NR numerology based on CP-OFDMA, involving a kind of vertical orientation where one column represents one numerology consisting of the major parameters subcarrier spacing, symbol duration and cyclic prefix length.

Fig. 25: 3GPP 5G NR numerology based on CP-OFDMA

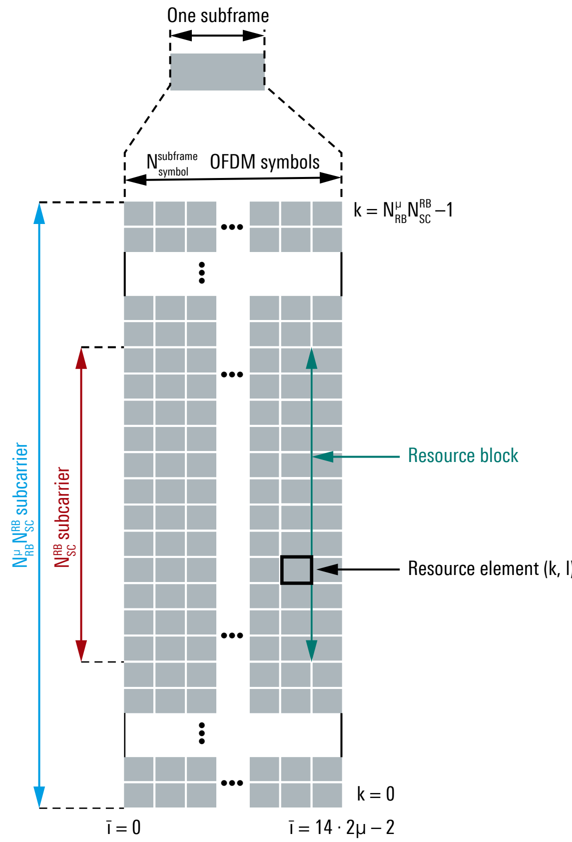
Subcarrier spacing (in kHz)	15	30	60	120	240
Symbol duration (in µs)	66.7	33.3	16.7	8.33	4.17
CP duration (in µs)	4.7	2.3	1.2 (normal), 4.13 (extended)	0.59	0.29
Maximum nominal bandwidth (in MHz)	50	100	100 for FR1, 200 for FR2	400	400
Maximum FFT size	4096	4096	4096	4096	4096
Symbols per slot	14	14	14, 12 (extended CP)	14	14
Slots per subframe	1	2	4	8	16
Slots per frame	10	20	40	80	160

5G NR uses physical resources in the time and frequency domain for resource allocation. A resource block includes 12 consecutive subcarriers in the frequency domain. Note that this represents a difference compared to EUTRAN where a resource block was defined as 12 subcarriers in the frequency domain and 6 or 7 OFDM symbols, depending on the cyclic prefix length, in the time domain. In 5G NR, the term resource block is only used in the context of the frequency domain. This is due to the flexible allocation of radio resources based on the OFDM symbol level only, i.e. mini-slot. This affects the symbol mapping that is performed first for frequency and then for time, enabling early decoding at the receiver, which is especially useful in the context of URLLC services. To obtain a two-dimensional definition of resources, the term resource grid was specified. Due to the increased flexibility and the introduction of OFDMA numerologies, TS 38.211 additionally defines the terms physical, common and virtual resource blocks.

For each 5G NR numerology and carrier, a resource grid is defined as being the product of the resource grid size specified as the number of resource blocks and the number of OFDMA symbols per subframe, starting at a common resource block indicated by higher layer signaling. Here, the idea is to divide the overall system bandwidth into multiple resource grids in order to benefit from using various 5G NR numerologies. Since the resource grid is defined by parameters such as reference point A, offset to SSB, etc. which are signaled in the system information, the configuration of such a resource grid can be interpreted as semi-static. To allow much greater flexibility and much more dynamic behavior, the possibility of bandwidth parts (BWP) was introduced.

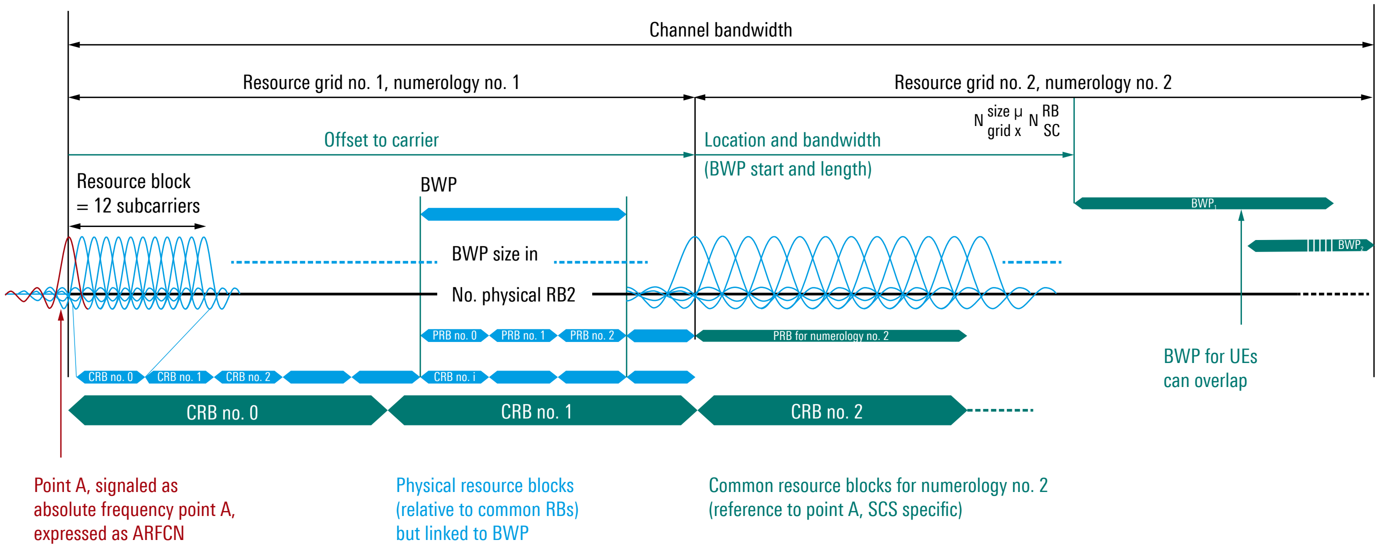
A resource element is defined (like in EUTRAN) as a complex value mapped onto a physical resource indicated by a subcarrier number and OFDM symbol number.

Fig. 26: 5G NR resource block and resource elements



One important aspect is related to the 5G NR introduction of very flexible bandwidth allocation, numerology usage and numerology switching capability. Since the resource grid details are specified and indicated via system information broadcast, changes are possible, but they are not very dynamic and can be considered as semi-static or even fully static within a cell. In other words, the resource grid provides a network-centric concept of allocating various 5G numerologies within the overall system bandwidth, while the bandwidth part (BWP) represents the UE-centric allocation of frequency and 5G numerology resources, allowing a much higher level of flexibility as well as more dynamic switching between them. A bandwidth part is a subset of contiguous resource blocks within a resource grid; thus, one bandwidth part uses one NR numerology. A UE is configured with an active BWP in both directions (UL and DL), both for FDD and TDD. There is no downlink reception of PDCCH/PDSCH and uplink transmission of PUSCH/PUCCH outside the allowed active BWP.

Fig. 27: Resource grid, BWP and carrier bandwidth



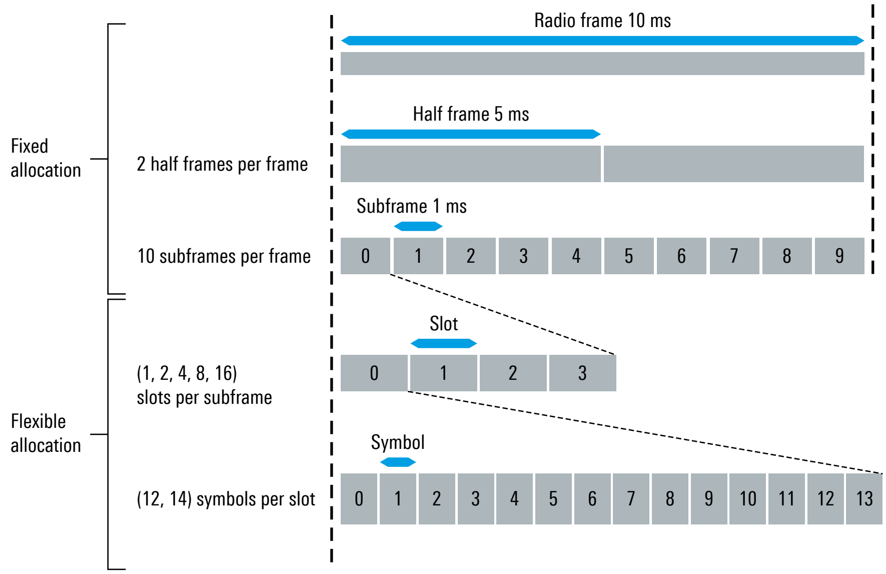
A major difference between NR and former standards is the flexibility of the frame structure. Certain service scenarios such as ultra-reliable, low latency communications (URLLC) and transmission at mmWave frequencies can require shorter slot or subframe structures in order to decrease the latency or enable faster UL and DL switching for immediate HARQ feedback. NR frames consist of a fixed frame length and subframe length, but with flexible allocations underneath.

The radio frames have a length of 10 ms for both the DL and UL. Each radio frame consists of ten subframes of 1 ms duration each. The first five and the last five subframes form a half-frame.

There are (1, 2, 4, 8, 16) slots in a subframe and (12, 14) consecutive OFDM symbols in a slot. The number of slots per subframe depends on the 5G numerology or the SCS. The number of symbols per slot depends on the length of the cyclic prefix (CP). In 5G NR, two CP lengths are defined: a normal and an extended CP length. Extended CP, used for 60 kHz SCS only, results in 12 symbols per slot. Basically, the default use case of 14 symbols corresponds to the number of symbols per slot for the normal cyclic prefix. Fig. 28 shows the frame structure and subframe structure.

In alignment with the 5G NR numerologies, there is a fixed allocation part, i.e. a time period that has a constant length like a radio frame, half-frame and subframes. On the other hand, there is a flexible allocation like a slot and symbol that support different timing.

Fig. 28: Frame structure in 5G NR (e.g. slot structure for SCS 60 kHz)



Physical channels in 5G NR

Physical channels are used to transport information over the radio channel and are characterized by their function as well as by RF aspects such as the modulation scheme, reference signal mapping, transmit power, coding, etc. There are physical channels that carry higher layer information as well as physical channels that are terminated in the physical layer. The nomenclature for the physical channels in 5G NR corresponds in a straightforward manner to the nomenclature in LTE, explained in brief in the previous chapter 4.1.2.

The physical channels defined on the downlink are:

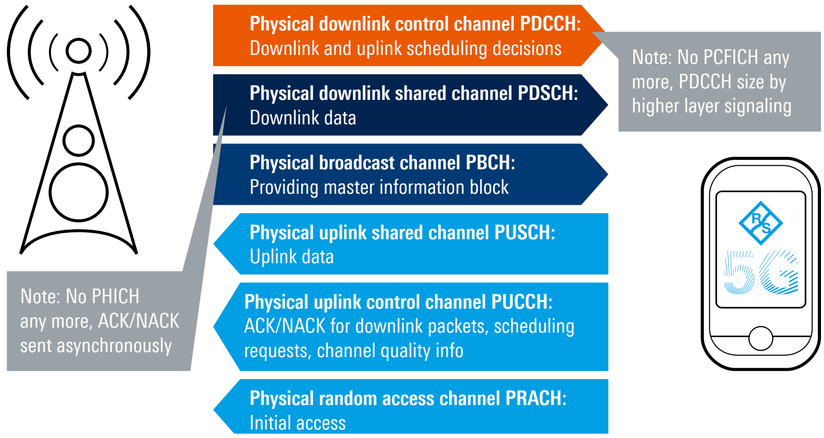
- ▶ Physical downlink shared channel (PDSCH)
- ▶ Physical downlink control channel (PDCCH)
- ▶ Physical broadcast channel (PBCH)

The physical channels defined on the uplink are:

- ▶ Physical random access channel (PRACH)
- ▶ Physical uplink shared channel (PUSCH)
- ▶ Physical uplink control channel (PUCCH)

These physical channels resemble those from EUTRAN, and only the channels PHICH and PCFICH have been eliminated. The HARQ operation has been updated to a more flexible configuration performed by the network vis-à-vis the UE in relation to the timing of the scheduling transport block and the corresponding acknowledgments (ACK/NACK). Moreover, the format of the downlink control channel (PDCCH) is now indicated by layer 3 procedures.

Fig. 29: Overview of the 5G NR physical channel structure



Further details on the content and behavior of 5G NR physical channels is given in [Ref. 20].

In addition to the physical channels providing services to higher layers, 5G NR defines a number of additional physical signals. These signals are used by the physical layer, but they do not carry information originating from the higher layers. The main purpose of the physical signals is related to synchronization aspects, channel estimation, tracking and beam identification for beamforming optimization, and channel status reporting. The following UL physical signals are defined in TS 38.211, chapter 6.1.2:

- Demodulation reference signals (DMRS) for PUSCH and PUCCH
- Phase tracking reference signals (PTRS) for PUSCH
- Sounding reference signal (SRS)

For the DL, the following downlink physical signals are defined:

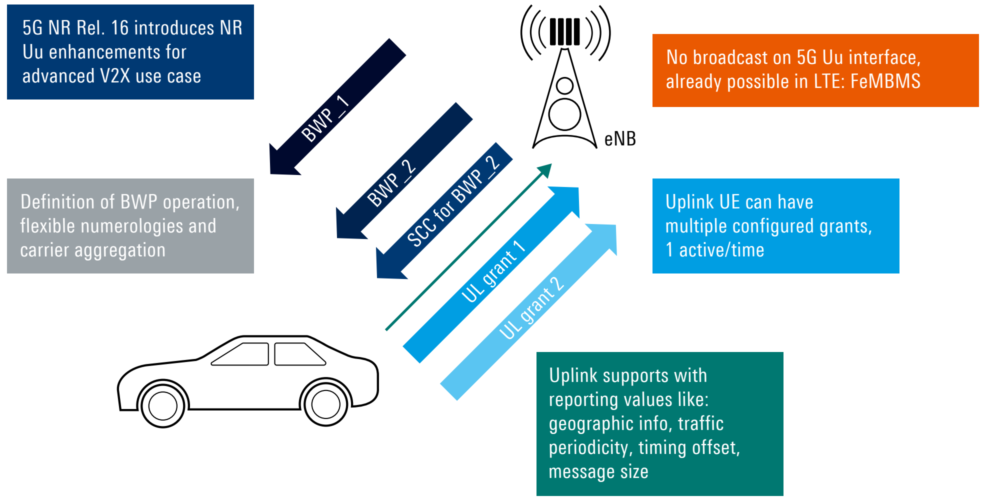
- Demodulation reference signals (DMRS) for PDSCH, PDCCH and PBCH
- Phase tracking reference signals (PTRS) for PDSCH
- Channel-state information reference signal (CSI-RS)
- Tracking reference signals (TRS)
- Primary synchronization signal (PSS)
- Secondary synchronization signal (SSS)

Due to space constraints, further details on physical layer aspects as well as procedures and signaling details of 5G NR will not be given in this document, but can be found in literature, e.g. [Ref. 20].

As an example of 5G NR as a living technology, the next Release 16 will contain several new features. One important feature set for the automotive industry is the introduction of NR-V2X direct communications as discussed in Chapter 5.4.

Besides the introduction of new connection scenarios, some updates and enhancements to the existing Uu interface are defined. From Release 16, it is possible to combine carrier aggregation across component carriers with different numerologies, to configure the uplink grant with more than one grant and to support the network scheduler with enhanced measurement and feedback in the uplink direction.

Fig. 30: NR enhancements in Release 16 on Uu interface for automotive applications

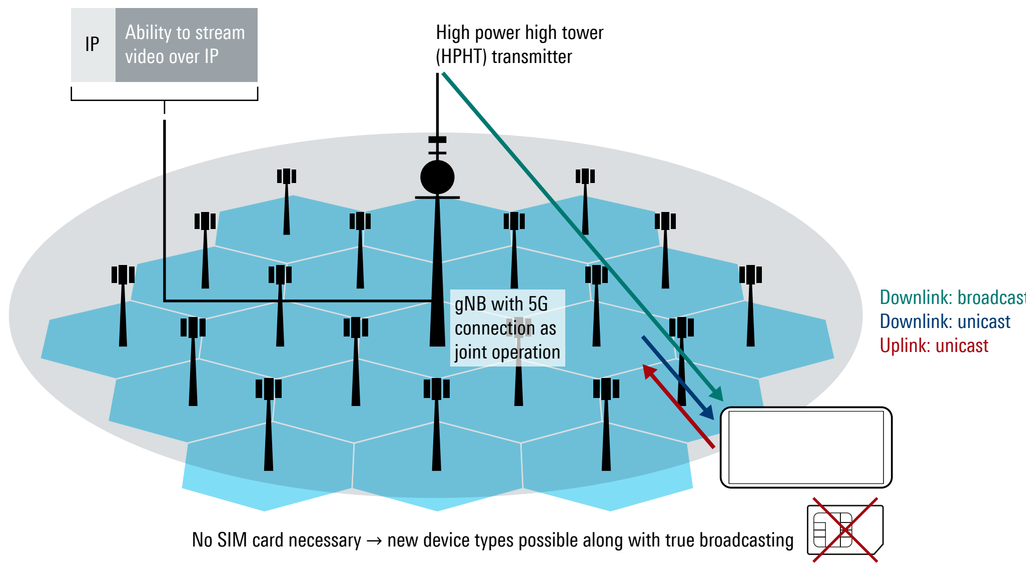


4.4 5G broadcasting

Needless to say, the idea of broadcasting is not new and is already a traditional application in the automotive world since FM radio is available in nearly every vehicle. If this is the case, then what is the relationship between traditional radio or TV broadcasting and cellular radio? Each has its own objectives: A broadcast operator may envision cooperation with a cellular network operator to extend its user base and introduce interactivity via a feedback channel. Cellular network operators see the challenge of non-linear streaming causing a high traffic load and may use broadcasting to offload traffic, address a wider range of users and allow much greater coverage. In the automotive domain, there is the idea of sending relevant data such as software updates to automotive entities, and emergency warnings or video streaming via a broadcast mode to improve the entire system efficiency. In LTE Release 9, the 3GPP introduced enhanced multimedia broadcast and message services (eMBMS). The main drawback is the lack of a business case. The eMBMS resources are in-band with a fixed allocation within an LTE carrier.

In Release 14, 3GPP introduced further enhanced MBMS (FeMBMS). This technology is based on the LTE radio interface with the objective of introducing a true broadcast mode. FeMBMS targets an overlay network concept using high power high tower (HPHT) transmitters. The carriers are in the lower frequency range (sub 1 GHz), providing cell sizes of about 100 km. Due to the in-band signaling method, there is no need for network registration. Devices do not even require a SIM card to register to an LTE or 5G network; reception only is possible. Nevertheless, a device with a network connection can apply FeMBMS as a kind of supplementary downlink (SDL) and interactivity is possible. Since the protocol layers place the broadcast traffic into IP packets, the ability to stream video over IP is following the industry trends.

Fig. 31: 5G broadcasting using a high power high tower overlay network



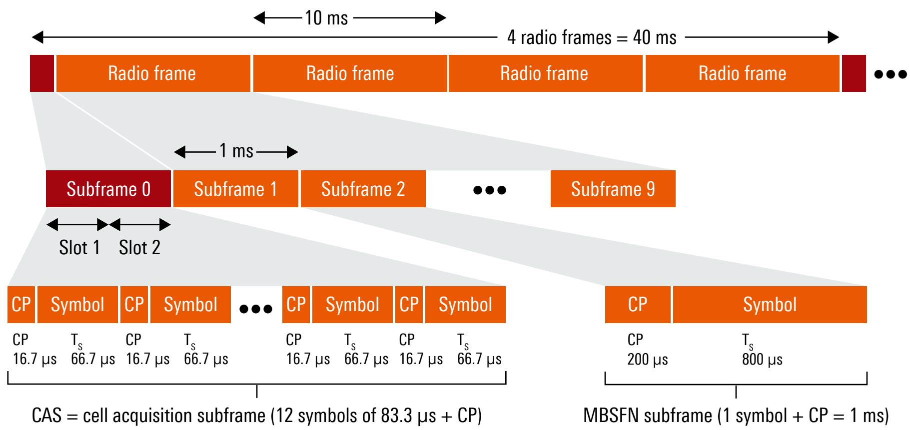
The physical layer of FeMBMS follows the 5G numerology concept, CP-OFDMA with a subcarrier spacing of 1.25 kHz, aligned with the numerology as shown in Fig. 25. The symbol duration lasts 800 µs with a long cyclic prefix duration of 200 µs allowing cell sizes of approx. 100 km. Similar to LTE and 5G NR, the frame duration is equal to 10 ms and broadcast traffic is delivered using MBSFN subframes containing one symbol in each slot. The idea is to jointly transmit the MBMS traffic in a time-synchronized single-frequency network (SFN) where several HPHT transmitters can span a wide coverage area. Unlike broadcast standards such as DVB-T or ATSC, implementation of FeMBMS is feasible for the 5G baseband chipset directly. The advantage is that a device does not require a second chipset for combined reception of cellular traffic and broadcast traffic.

Content providers deliver broadcast traffic to a broadcast multicast service center (BMSC) that performs encoding (e.g. MPEG-2) and multiplexing of various transport channels with control information. The multimedia broadcast multicast service (MBMS) gateway delivers a time-synchronized data stream, allowing single-frequency networks (SFN) to the transmitting entities. Such an entity can either be an eNodeB in case of LTE eMBMS or a HPHT transmitter in case of FeMBMS broadcast. Since FeMBMS may operate as a true broadcast in standalone mode without an accompanying cellular network connection, time synchronization information is delivered via an in-band cell acquisition subframe (CAS). Concerning the infrastructure components BMSC and MBMS-GW, they operate independently of the 5G infrastructure components and represent a perfect complement from either side. Thus, real deployments of FeMBMS may be implemented by broadcast operators or TV operators.

In Release 16, the FeMBMS concept is renamed to LTE based 5G terrestrial broadcast. There is research underway to support convergence of the traditional broadcast concept with traditional unidirectional communications. For example, several OFDMA numerologies besides 1.25 kHz are discussed to support broadcasting under various circumstances, ranging from high velocity rural areas through smaller city district indoor coverage. Another research activity involves the concept of dynamic or temporary generation of multicast areas, like a multicell point-to-multipoint transmission.

With LTE based 5G terrestrial broadcast, a combination of traditional broadcasting and cellular networks is feasible. Spectrum can be shared in a very efficient way as traffic can either be distributed non-linearly on cellular networks or linearly on broadcast networks to multiple users. This allows automotive applications ranging from real-time traffic information updates (like the FM radio traffic news) through more sophisticated services like software updates to vehicles and service-related traffic broadcasts. Further information on traditional broadcast technologies like DVB can be found in [Ref. 23], [Ref. 24].

Fig. 32: FeMBMS physical layer frame and symbol structure



With over 80 years of experience in broadcast and media, Rohde & Schwarz supports the industry with a new cost-effective end-to-end solution [Ref. 39] that is compliant with the 3GPP standard. This solution is intended to help network operators deliver better quality of service and higher quality of experience, all with reduced costs. Further information on 5G broadcasting can be found in [Ref. 24] and [Ref. 43].

5 DIRECT COMMUNICATIONS TECHNOLOGIES FOR AUTOMOTIVE APPLICATIONS

Cooperative ITS (C-ITS) is a transportation system in which all road users cooperate with each other, including pedestrians and fixed infrastructure components like roadside units (RSU). C-ITS promises to increase efficiency even further and additionally reduce road traffic fatalities and serious injuries. Reducing the severity of injuries in road traffic accidents is an ambitious intention declared by several government agencies around the globe. One confusing aspect involves the various terms found under the common roof of an intelligent transportation system. To shed some light here, we will first separate the radio technology aspects from the application layer (see Fig. 10). Then, we will distinguish the proposing entity, e.g. regional initiatives like in the USA, EU or China (see Fig. 11) and also standardization bodies like the IEEE or 3GPP. The objective of this chapter is to examine some of the details of the radio technologies used for direct communications.

Connecting vehicles via vehicular ad-hoc networks (VANET) represents an early attempt to support safety-related applications such as accident warnings, crash notifications and cooperative cruise control [Ref. 1], [Ref. 35] and [Ref. 55]. With VANET, a vehicle functions as a router or network node, and neighboring vehicles are allowed to communicate with each other via vehicle-to-vehicle (V2V) communications, helping to improve driving safety. Vehicles can also communicate with roadside infrastructure via vehicle-to-infrastructure (V2I) communications to collect road and traffic-related information. These communications links are enabled by the radio layer of dedicated short-range communications (DSRCs) or cellular-enabled direct vehicle-to-everything (C-V2X) communications.

IEEE 802.11p defines a WLAN technology derivate operating in the 5.9 GHz band and supporting direct communications between vehicular devices.

Release 14 specifies the sidelink or PC5 interface leveraging the direct vehicle-to-everything (V2X) communications service. This feature sets the starting point for the evolution of applications not previously supported by mobile communications technology and paves the way for ubiquitous and future-proof connectivity in the automotive domain. LTE-V2X in Release 14, termed phase I, is mainly designed to carry vehicle status and environment information in the aim of exchanging safety-related information. Phase II, enhanced direct V2X (eV2X) introduced in Release 15, is intended to support applications such as cooperative perception. Phase III, expected to be standardized in Release 16, will introduce the 5G New Radio (NR) concept into direct V2X communications, while phase I and II still remain LTE technology. It is important to understand the evolution, e.g. phase III does not replace phase I or II of C-V2X communications. Furthermore, it represents an extension from LTE-V2X extended to NR-V2X.

5.1 Dedicated short-range communications (DSRC)/ITS-G5

Communications technologies are the basis for intelligent transportation systems. In a first step, we will consider the relevant radio technology but also the application layers. DSRC and ITS-G5 contain the IEEE 802.11p based radio technology enabling direct device to device communications combined with application layer protocols. The difference is that DSRC is driven by the USA while ITS-G5 is a European initiative. From 3GPP Release 14 onwards, the application layer of DSRC/ITS-G5 may also use cellular direct communications radio technology such as LTE-V2X. In this manner, vehicle applications are tending to become more radio interface technology agnostic.

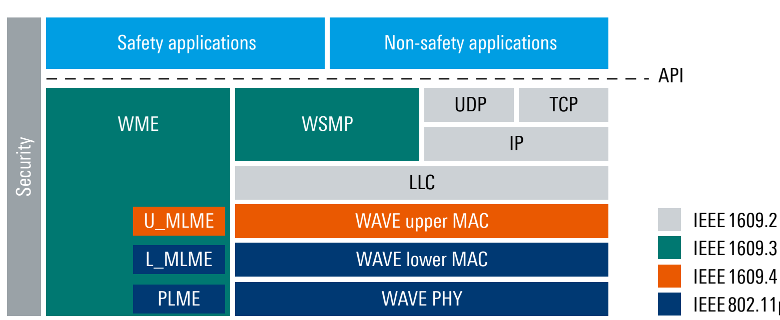
This chapter briefly introduces the technology and physical layer aspects of IEEE 802.11p. Further details can be found in the IEEE 802.11 standard and [Ref. 21] and [Ref. 55].

We will begin with some basic terms and definitions. In the IEEE 802.11 standard, the term access point is used for the infrastructure side and the term station corresponds to the terminal or UE in the cellular RAT language.

The IEEE 802.11 standard body has published an amendment to the existing WLAN specification series IEEE 802.11 known as IEEE 802.11p that is intended to support vehicular device direct communications. The IEEE 802.11p WAVE standardization process, defined for higher layers in IEEE 1609, originates from the allocation of the dedicated short-range communications (DSRC) spectrum band in the United States in 1999 and the effort to define the technology for usage in the DSRC band. In 1999, the US Federal Communication Commission allocated 75 MHz of spectrum at 5.9 GHz to be used exclusively for vehicle-to-vehicle and infrastructure-to-vehicle communications. The same spectrum is now becoming technology agnostic and possible implementations of LTE-V2X or 5G NR-V2X are targeting the same band. IEEE 802.11p should not be considered as a complete and standalone standard. WAVE is the acronym for wireless access in vehicular environment. Overall, V2X communications should allow safety applications as well as non-safety applications.

Fig. 33: DSRC standards and communications stack

[Ref. 56]



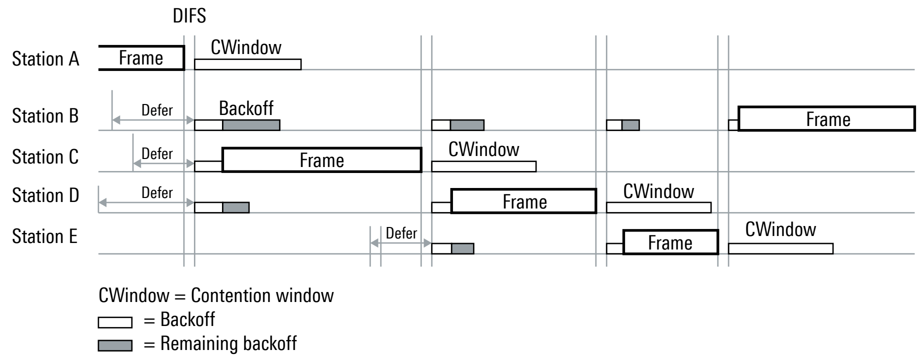
As shown in Fig. 33, IEEE 802.11p WAVE is only part of a group of standards related to all layers of protocols for DSRC based operations [Ref. 56]. The IEEE 802.11p standard is limited by the scope of IEEE 802.11, which is a MAC and PHY level standard for working within a single logical channel [IEEE 802.11]. This is an important difference compared to C-V2X technologies as their specification perimeter encompasses all protocol layers, even in the direct communications mode. All knowledge and complexities related to the DSRC channel plan and operational concept are covered by the upper layer IEEE 1609 standards. The IEEE 1609.4 standard providing application layers is placed above IEEE 802.11p and enables operation of upper layers across multiple channels, without requiring knowledge of PHY parameters.

While the service and scenario details applicable by the ITS systems (especially at the higher layers) vary depending on regional/regulatory issues, all of these systems plan IEEE 802.11p for the MAC and PHY layers. An important decision concerning application layers is the similarity of the services between C-V2X and DSRC. Comparing the applications in Fig. 33 and Fig. 10, we can see that the basic safety message set is the main application for both direct mode communications technologies. For real deployments, the industry is discussing dual protocol stack implementations, especially for fixed sites like RSU.

IEEE 802.11p is part of the WLAN standard family and supports communications via an ad-hoc network or a connection to basic service set infrastructure. Real-world examples are a home router for WLAN access in an apartment (infrastructure based) and a connection between two smartphones via tethering mode (ad-hoc communications). The infrastructure approach in WLAN for setup of a small network is based on a basic service set (BSS) involving a group of stations anchored by an access point. Communications between stations uses the WLAN radio link and the frequency carrier typically lies in an unlicensed ISM band. Several BSS can be interconnected logically into one extended service set (ESS) by the system administrator, which is the case in larger environments, e.g. conference centers. The most interesting aspect for vehicular communications is the possibility for WLAN technology to set up an ad-hoc network. General WLAN technologies support the setup of an independent BSS (IBSS) between several stations into an ad-hoc network. The challenge is to reduce the complexity and overhead that comes about with the generation of such an IBSS, especially for V2X communications. For example, IEEE 802.11p changes the WLAN concept of the frame using the serving set identification (SSID) since it would have too much signaling overhead. In IEEE 802.11p, there is a so-called WAVE mode allowed, permitting a station to transmit and receive data frames with a wildcard ID, independent of any BSS numbering. This represents a major change on the MAC layer between the IEEE 802.11a standard and its derivate IEEE 802.11p designed for automotive applications. The WAVE standard introduces a new BSS type, WAVE BSS (WBSS). A station forms a WBSS by first transmitting an on-demand beacon. A WAVE station uses the permanent beacon, which uses the beacon frame to advertise a WAVE BSS. It contains all the necessary information for receiver stations to understand the services offered in the WBSS in order to decide whether to join. If the RX entity decides to join the WBSS, it obtains all relevant information to request membership in this ad-hoc WBSS from the advertisement. In other words, a station can decide to join and complete the joining process of a WBSS by only receiving a WAVE advertisement with no further interactions [Ref. 56]. Note that this represents a major difference to C-V2X where ad-hoc direct communications are used, but most sidelink operations are scheduled via a base station.

To join such a WBSS, a station sends or receives data frames with this specific WBSS ID and it ceases membership when its MAC layer stops sending or receiving frames. With no members, a WBSS stops existing, thus there is no always-on signal and typically we do not speak about network radio coverage. The MAC layer of IEEE 802.11p uses an enhanced distributed channel access (EDCA) method which uses carrier sense multiple access with collision avoidance (CSMA/CA). It corresponds to a "listen before talk" mechanism. The IEEE 802.11p access method can briefly be summarized as follows: A station wanting to send a data frame first monitors the radio channel for activity. This is done through energy detection (ED) or power sniffing resulting in a clear channel assessment (CCA). After transmission of a frame, the station enters a contention phase (contention window) where no transmission is allowed. To avoid collisions between two consecutive data frames, the standard defines a distributed interframe space (DIFS) within a slot. When a station detects that the channel is busy, it starts a random backoff timer. After expiry of the backoff timer and channel clearance is indicated, the station may transmit a data frame. An example with multiple stations accessing the radio channel with individual backoff timers and contention windows is given in Fig. 34 [IEEE 802.11].

Fig. 34: IEEE 802.11p channel access with backoff procedure



As mentioned above, IEEE 802.11p is derived from the WLAN standard IEEE 802.11a. Comparing the physical layer parameters, some value derivation is obvious. In simplified terms, the timings from IEEE 802.11a are scaled by a factor of two in IEEE 802.11p to provide better resilience against an increased delay spread since IEEE 802.11p is designed to operate at higher velocity and larger distances. It is obvious that vehicles move at higher speeds than pedestrians and V2V communications is mainly not indoors. In detail, the carrier spacing and bandwidth are reduced by a factor of two which results in twice longer symbol duration. The cyclic prefix (CP) duration is also doubled, which allows compensation for larger delay spreads and makes it more suitable for outdoor environments.

The main system parameters of IEEE 802.11p [IEEE 802.11] are given in the table below.

IEEE 802.11p physical layer parameters

IEEE 802.11p physical layer parameters	Values
System bandwidth	10 MHz
Subcarrier spacing	156.25 kHz
Number of subcarriers	52
Number of data subcarriers	48
Number of pilot subcarriers	4
Symbol duration	8 µs
Guard time	1.6 µs
Modulation schemes	BPSK, QPSK, 16QAM, 64QAM
Code rate	1/2, 2/3, 3/4 convolutional code
Frame size	100 byte or 1500 byte
Peak data rate	7.69 Mbps (100 byte frame size)
Peak data rate	23.08 Mbps (1500 byte frame size)

In addition to the physical layer amendments, IEEE 802.11p defines receiver enhancements to cope with cross-channel interference as well as improved transmission masks to reduce the channel interference.

5.1.1 IEEE 802.11p enhancements in IEEE 802.11bd

Like other radio technologies, IEEE 802.11 can also be considered as a living specification. In the most recent WLAN applications, we see technology enhancements accompanying the introduction of the IEEE 802.11ax standard as the successor of IEEE 80211n or IEEE 802.11ac, marketed as Wi-Fi 6. A similar evolution is also happening with the vehicle derivate IEEE 802.11p. IEEE has started a task group to work on enhancements of the IEEE 802.11p MAC and PHY layer concept. This amendment is known as IEEE 802.11bd enhancements for next generation vehicular communications [IEEE 802.11bd]. The main design goals are [Ref. 3]:

- Backward compatible and interoperable with IEEE 802.11p
- Two times higher throughput measured at MAC layer
- Higher reliability by reducing packet collisions and improving performance under high Doppler shift conditions
- Support for device target speed of 250 km/h
- Range improvement by a factor of two compared to IEEE 802.11p

IEEE 802.11bd physical layer parameters

IEEE 802.11bd physical layer parameters	Values
System bandwidth	10 MHz or 20 MHz
Subcarrier spacing	156.25 kHz
Number of subcarriers	52 or 108
Number of data subcarriers	48
Number of pilot subcarriers	4
Symbol duration	8 µs
Guard time	1.6 µs or 3.2 µs
Modulation schemes	BPSK, QPSK, 16QAM, 64QAM and 256QAM
Code rate	1/2, 2/3, 3/4 or 5/6 LDPC coding
Frame size	100 byte or 1500 byte
Peak data rate	8 Mbps (100 byte frame size)
Peak data rate	30.09 Mbps (1500 byte frame size)

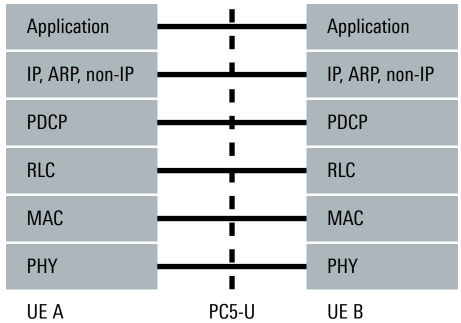
Higher data rates can be achieved by adopting some of the existing PHY technologies such as introduction of LDPC coding, multi-antenna technologies MIMO, higher order 256QAM modulation and 20 MHz bandwidth support. In order to improve the range, dual carrier modulation (DCM) and range extension modes can be adopted from IEEE 802.11ax.

5.2 LTE-V2X based direct communications

With Release 14, the 3GPP extended the concept of direct communications from D2D proximity services solely for public safety to V2X, direct communications between vehicles, pedestrians and infrastructure components like roadside units (RSU). These major services include the cooperative awareness message (CAM) and the decentralized environmental notification message (DENM) exchange among vehicles and others (V2X). The V2X system reference architecture design refers to the system model specified for 3GPP proximity based services (ProSe) specified in Release 12. New standardized interfaces, reference points and functions supplement the previous architecture to offer UEs communications services to carry user data from the V2X application and V2X application server. The 3GPP LTE-V2X specification is strongly motivated by the assumption that V2X applications are at least in part replicated from the existing C-ITS dedicated short-range communications (DSRC), WAVE and ITS-G5 (see Fig. 10). Furthermore, 3GPP LTE-V2X is able to carry IP data traffic as well as other data traffic.

Direct C-V2X communications based on LTE-V2X uses the PC5 interface for evolved universal terrestrial radio access (EUTRA), supporting direct communications scenarios such as V2V, V2I and V2P. The PC5 interface describes the radio link known as sidelink and the corresponding protocol structure. The protocol stack related to the user plane (UP) of the V2X communications through the PC5 interface is shown in Fig. 35.

Fig. 35: Communications protocol stack related to the user plane



There is also a control plane protocol stack using a PC5 signaling protocol on top of the PDCP protocol layer. Further details are available in [Ref. 4]. This white paper also provides further details on the user plane, control plane and communications channels.

5.2.1 User plane, control plane and communications channels

5.2.1.1 User plane

The physical layer handles signal transmission and reception including functions such as signal processing, data modulation and demodulation, applies adaptive channel coding to the data in the process of transmission, adjusts the output power, adapts the radio frequency and performs time synchronization [TS 36.201]. Data is transmitted on physical sidelink channels. V2X communications exploits a 10 MHz or 20 MHz frequency bandwidth at 5.9 GHz in radio frequency band 47. Licensed band operations are possible as well.

The MAC sublayer [TS 36.321] operates the hybrid automatic repeat request (HARQ) protocol, performs packet scheduling and resource selection with regard to packet prioritization, and applies packet filtering to further process PDUs intended for this particular UE. SDUs are multiplexed to the transport channels as well as demultiplexed when operating data reception (RX).

The RLC sublayer [TS 36.322] takes care of in-sequence delivery of SDUs and offers SDU segmentation and reassembly protocol services in addition to SDU concatenation. Service from the ARQ protocol, usually provided by the RLC sublayer to the preceding sublayer, is not supported in the case of V2X communications. Data is transmitted on logical channels.

The PDCP sublayer [TS 36.323] separates communications protocol layers related to non-3GPP applications from the ones offering the standard 3GPP data transmission service. It offers header compression and provides an application protocol specific transmission service. The PDCP sublayer has supported transmission of non-IP data since Release 14, which in particular is important for operating C-ITS applications.

5.2.1.2 Control plane

The communications protocol stack specified for the CPL differs from UPL in the radio resource control (RRC) sublayer. The protocol service offered from the PDCP sublayer is not required for control data transmission.

The radio resource control (RRC) sublayer [TS 36.331] offers the broadcast communications service. Specified RRC messages carry system information to manage communications, configure protocol services and adapt the radio parameters to the specific requirements. For further details on the V2X control plane, see [Ref. 4].

5.2.1.3 Communications channels

The following two logical channels are provided by the MAC to the RLC sublayer for V2X communications [TS 36.322]:

- ▶ Sidelink broadcast control channel (SBCCH) to carry control plane-related data units or layer 3 control messages
- ▶ Sidelink traffic channel (STCH) to carry user plane-related data units

The SBCCH and STCH are mapped to the subsequently defined point-to-multipoint transport channels provided by the PHY layer [TS 36.300]:

- ▶ Sidelink broadcast channel (SL-BCH) to carry higher layer control data
- ▶ Sidelink shared channel (SL-SCH) to carry user data

Transmissions on these transport channels may experience high interference power from parallel data transmission by nearby UEs when using autonomous resource selection. SL-SCH only supports HARQ soft-combining with a maximum of one retransmission. HARQ is not applied to data carried on SL-BCH. The transport channels are then mapped to physical channels on the PHY layer [TS 36.300]:

- ▶ Physical sidelink broadcast channel (PSBCH) to carry higher layer control data
- ▶ Physical sidelink shared channel (PSSCH) to carry user data

Control information to announce the time and frequency physical resource allocation is transmitted on the following channel:

- ▶ Physical sidelink control channel (PSCCH)

The transmission service to carry data on physical sidelink channels exploits single carrier frequency division multiple access (SC-FDMA), which is the known waveform from the V2N LTE uplink, and applies quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) with a maximum order of 16, i.e. 16QAM.

The PHY layer protocol entity applies robust QPSK at all times to transmit data related to control information on the PSCCH and PSBCH [TS 36.211]. In contrast, user data transmitted on the PSSCH exploits the adaptive modulation schemes QPSK and 16QAM. The UE operates SC-FDMA because V2X communications through the PC5 interface is permitted in-coverage as well. When frequency division duplexing (FDD) or time division duplexing (TDD) is used for communications through the Uu interface, then communications through the PC5 interface occurs in the uplink (UL) part of the frequency spectrum. Communications through the PC5 interface exploits TDD. The eNB is presumed to cope better with additional signal interference exhibited when performing UL data transmission at the same time as data is carried through the PC5 interface.

5.2.2 Synchronization in out-of-coverage V2X scenarios

Accurate frequency and time synchronization is essential especially in time division multiple access (TDMA) and frequency division multiple access (FDMA) systems. Traditional wireless communications systems typically use the base station as the timing reference. However, some networks, especially TDD networks, also require inter-node B time alignment. There are challenges with the introduction of PC5 interface direct communications especially in situations where no coverage is provided by a node B.

Time misalignment may result in intersymbol interference (ISI) and intercarrier interference (ICI), which can degrade system performance. Timing advance, applied to data transmission in the UL direction to ensure signal orthogonality in mobile networks at the eNB, cannot be operated in out-of-coverage scenarios. When a UE is permitted to access the wireless channel from the distributed MAC for point-to-multipoint data transmission, the signal propagation time to every receiver remains unknown. This makes it even more important to align signal transmission to the slot and subframe (SF) boundary. The frame timing of the sidelink follows the structure known from network based LTE (see Fig. 17).

The maximum time difference before ISI may occur is limited to the length of the cyclic prefix (CP). The CP is inserted in orthogonal frequency division multiplex (OFDM) symbol transmission to achieve signal orthogonality even if the transmitter and receiver are not very well synchronized.

Correction of the carrier frequency compensates for imperfect oscillator calibration and additional frequency offset due to temperature drift. LTE-V2X exploits the sidelink synchronization signals (SLSS) on the PHY layer [TS 36.211] and the master information block SL V2X (MIB-SL-V2X) [TS 36.331] message on the RLC sublayer to achieve time and frequency synchronization.

A UE obtains information on time and frequency synchronization from signals received from global navigation satellite systems (GNSS), an eNB or from a nearby UE. The standard distinguishes direct from indirect synchronization [TS 36.331]:

- GNSS: The UE is synchronized to GNSS (direct) or to a nearby UE that achieves time and frequency synchronization from GNSS (indirect)
- eNB: The UE is synchronized to an eNB (direct) or to a nearby UE that is synchronized to an eNB (indirect)
- UE: The UE is synchronized to a nearby UE that obtains no synchronization information either directly or indirectly from eNB or GNSS

The synchronization sources and preference order are preconfigured for the UE or temporarily configured through control messages delivered by the eNB.

Fig. 36: Direct and indirect eNB synchronization including synchronization reference UE (SyncRefUE) established in V2X scenarios with partial coverage

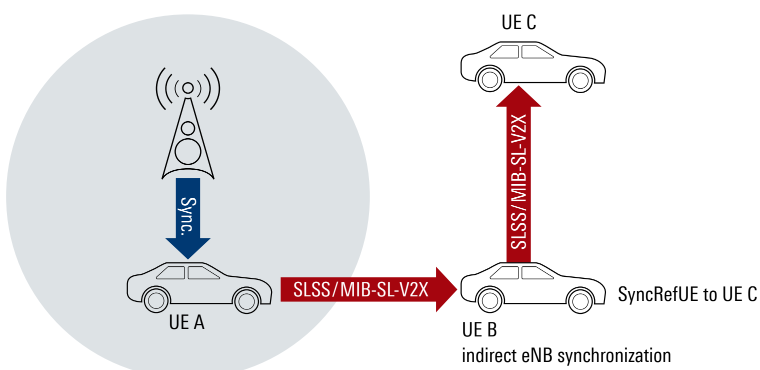
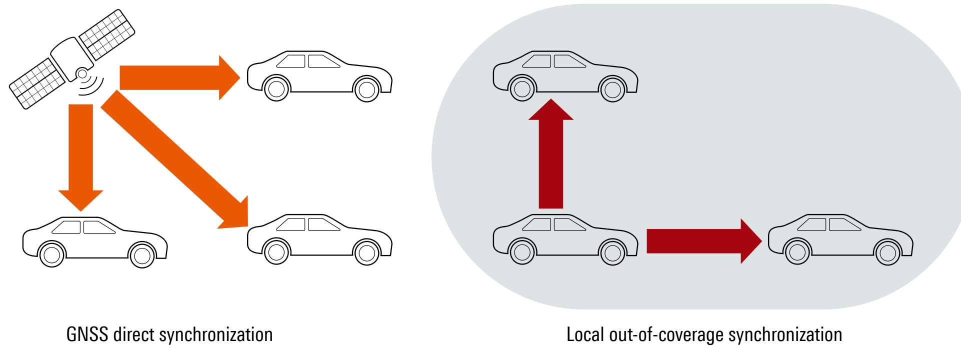


Fig. 36 shows the partial coverage scenario with time reference to the eNB. UE A, assumed in network coverage, receives direct synchronization information provided by the eNB. This UE is directly synchronized to an eNB and configured to forward synchronization information to nearby UEs, possibly not in network coverage.

UE B, not in signal detection range from the eNB and out-of-coverage, receives an SLSS and MIB-SL-V2X message from UE A, provided for indirect eNB synchronization. UE C, out-of-coverage, detects the SLSS sent by UE B and is permitted to use UE B as the synchronization reference UE (SyncRefUE).

LTE-V2X communications should be possible in scenarios without network coverage. Resource scheduling is performed according to transmission mode 4 (TM4; see Fig. 38) and the timing reference can either be the GNSS when in coverage or a nearby UE (see Fig. 37).

Fig. 37: Direct GNSS synchronization and local out-of-coverage synchronization



5.2.2.1 Sidelink synchronization signals and information

The SLSS is a sidelink-specific sequence consisting of two signals:

- Primary sidelink synchronization signal (PSSS) established from the Zadoff-Chu sequence
- Secondary sidelink synchronization signal (SSSS) (maximum length sequence)

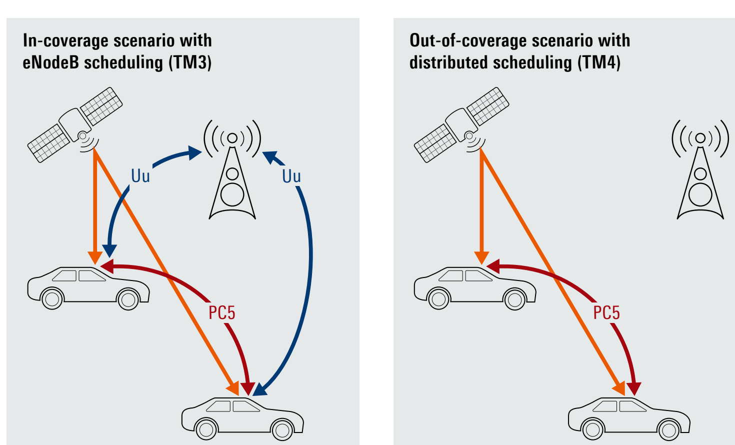
PSSS and SSSS carry implicit information about the synchronization source considered for time and frequency adjustment. Specified values are assigned to the sidelink synchronization signal identifier (SLSSID) that indicates the specific synchronization source (GNSS, eNB or out-of-coverage).

A UE offering synchronization information to nearby UEs is supposed to serve as a synchronization reference. In addition to the SLSS, this UE provides further parameter values by carrying RLC messages on the SL-BCH. The information provided relates to the standardized MIB-SL-V2X [TS 36.331] and includes the SF number, whether the UE is in coverage or out-of-coverage, and the operated frequency bandwidth. This information supports UEs in selecting the reference source according to the configured prioritization when seeking synchronization.

5.2.3 Physical resources and resource assignment

The physical layer carries data between a transmitting and receiving entity. The introduction of the sidelink concept with the different synchronization aspects requires the definition of resources and resource allocation methods. Resource scheduling depends on the coverage situation of the UE. LTE-V2X offers two transmission modes (TM) for resource allocation either by the serving eNodeB or by indirect scheduling as shown in Fig. 38.

Fig. 38: Transmission modes TM3 and TM4 for radio resource allocation

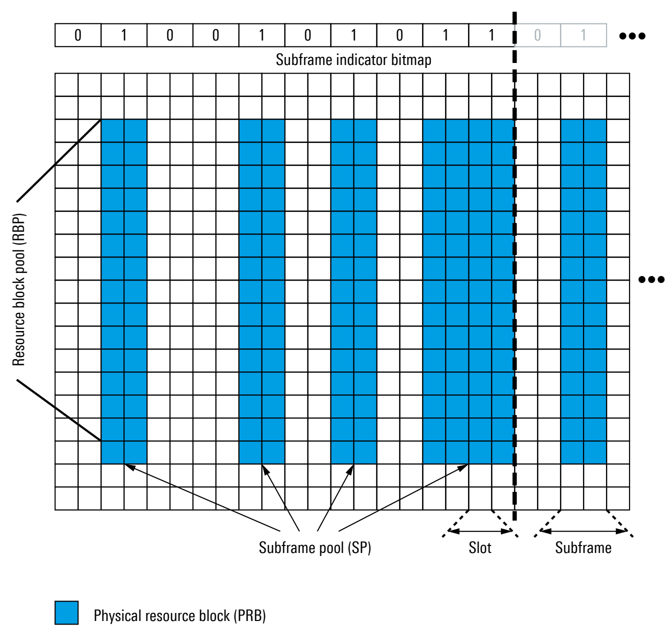


5.2.3.1 Resource pool (RP)

A UE that intends to operate PC5 sidelink communications allocates specific time and frequency resources in terms of physical resource blocks (PRB) to carry control and user data. Resource allocation on the sidelink follows the allocation principle of network based LTE. PC5 sidelink communications is permitted in PRBs either configured through control messages provided by an eNB or preconfigured for the UE. All subframes (SF) offering PRBs intended for PC5 sidelink communications constitute the subframe pool (SP). Based on the concept of subframe pools combined with meticulous planning, an operator can mitigate inter-cell interference.

A subframe indicator bitmap specifies the subframe pool. The indicated SFs in the SP reoccur periodically at an interval equal to the length of the subframe indicator bitmap.

Fig. 39: Resource pool and subframe indicator bitmap

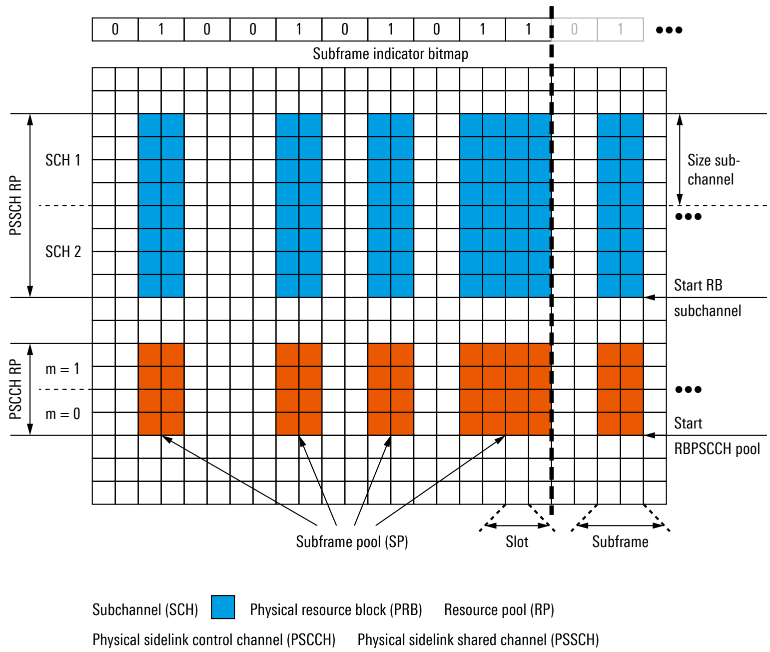


PRBs offering time and frequency resources for PC5 sidelink communications are stated in the resource block pool (RBP). The RBP is assigned to UEs through sidelink control information 1 (SCI 1), obtained from decoded control data received on the PSCCH. SCI 1 indicates PRBs allocated for user data transmission in that SF. RBP and SP constitute the resource pool (RP). Several RPs are provided to the UE and are specifically assigned for data transmission (TX) and data reception (RX) to maintain half-duplex operation.

5.2.3.2 Subchannels

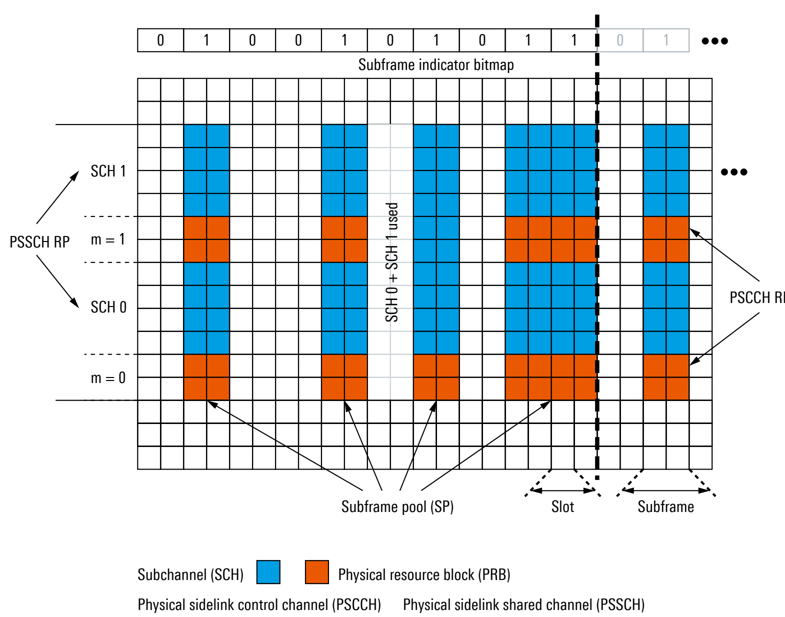
PRBs from the RBP that cover adjacent radio frequencies establish subchannels (SCH). The UE identifies SCHs from control information provided as part of the network configuration. The specific SCH allocation is further notified by SCI 1.

Fig. 40: SCHs provide time and frequency resources using subchannels



The subchannel concept in LTE supports non-adjacent or adjacent allocation.

Fig. 41: PSSCH subchannels for adjacent PSCCH configuration



These parameters define the PSSCH RP:

- StartRBSubChannel: addresses the first PRB of the SCH
- SizeSubChannel: number of PRBs within the SCH
- NumberofSubChannels: number of SCHs established in the subframe specified in the SP

5.2.3.3 Sidelink channel structure and resource assignment

Three physical channels are involved in the data exchange using the radio interface and in the resource assignment procedure, PSCCH, PSSCH and PBCH. To support successful data transmission, LTE-V2X applies the acknowledgment and retransmission procedure HARQ, known from LTE.

PSCCH

PRBs from the RP are specifically assigned to carry control data related to the PSCCH. Four constant and contiguous PRBs are provided per SF to carry one SCI 1 message. These PRBs are allocated either adjacently or non-adjacently to the corresponding notified PRBs carrying user data on the PSSCH. When the UE is configured to operate non-adjacent PSCCH transmission, the additional parameter provided to the UE specifies the following:

- StartRBPSCCHPool: addresses the first PRB of the PSCCH RP

If control data is transmitted adjacent to PRBs intended to carry user data on the PSSCH, information about PRBs is directly obtained from the introduced parameter StartRBSubChannel.

PSSCH

A UE with V2X user data ready to send allocates PRBs from the PSSCH RP in terms of one SCH. There is always a direct relationship between the SCI 1 transmitted on the PSCCH and the allocation for PSSCH operation. Granting access permission to multiple (but contiguous) SCHs is feasible. SCHs as well as PRBs offering time and frequency resources adequate to carry control data are indexed in ascending order. As a result, the UE implicitly knows the SCH from the corresponding PSSCH transmission.

PSBCH

Specific subframes are continuously allocated in recurring synchronization periods every 160 ms. These subframes, known as synchronization subframes, are not notified by any RP; they are indicated through an additional parameter set:

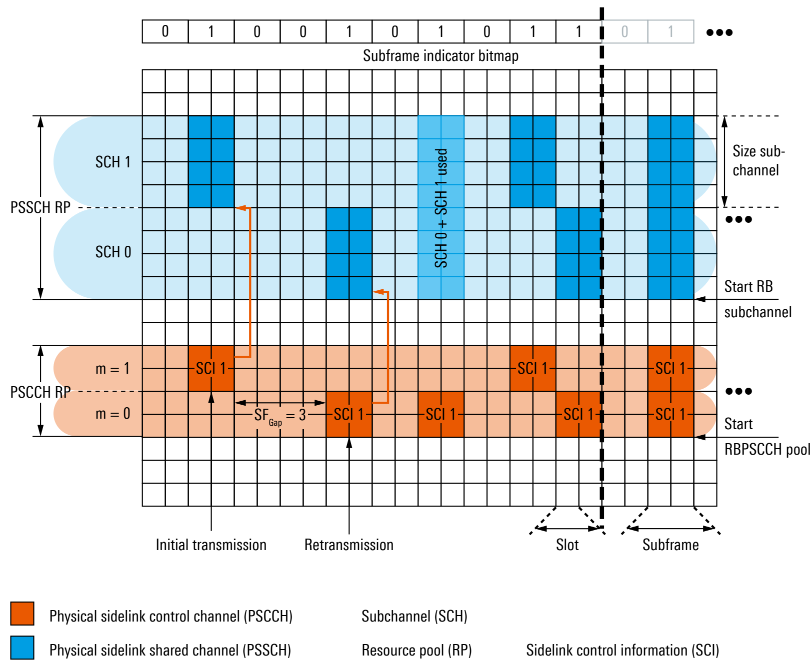
- SyncOffsetIndicator: parameter set either provided by the eNB or preconfigured for the UE to identify time and frequency resources related to the synchronization subframe

Radio signals received on the PSBCH are subject to signal interference if nearby UEs intend to serve at the same time as SyncRefUE. The SyncRefUE selects one SyncOffsetIndicator from the set of three to decrease the probability of continuously recurring signal interference.

Hybrid automatic repeat request (HARQ)

A UE configured to support HARQ soft-combining on the SL-SCH selects PRBs from the RBP for message retransmission on the PSSCH. The number of subframes between initial and retransmission is indicated by the parameter subframe gap (SF gap) carried in the SCI1 on the PSCCH. The HARQ protocol service is not provided for data transmission on the PSBCH. Note that this mechanism corresponds to an automatic retransmission. There is no explicit HARQ feedback in LTE-V2X based on Release 14.

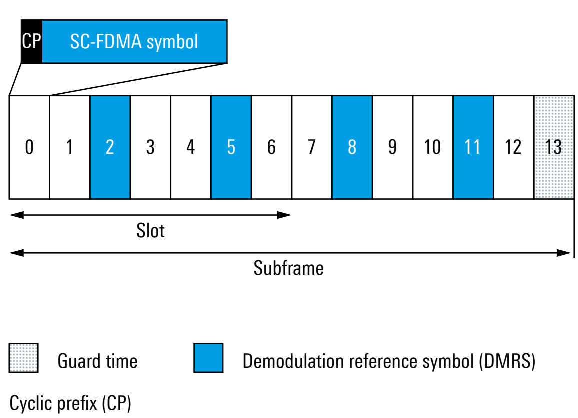
Fig. 42: ARQ initial transmission and retransmission, assuming non-adjacent PSCCH configuration



5.2.3.4 Slot structure

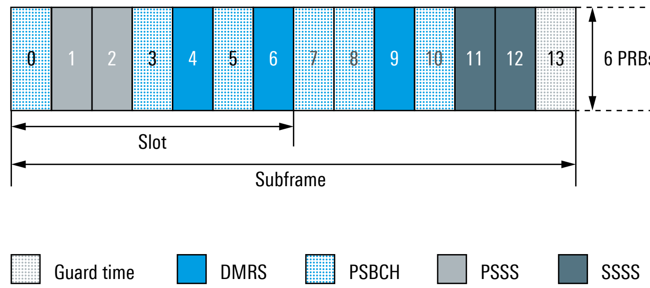
PC5 sidelink communications adopts the general LTE 1 ms subframe structure.
14 SC-FDMA symbols per subframe, 7 per 0.5 ms slot, are modulated to subcarriers. The normal CP with length 4.7 µs is applied to every SC-FDMA symbol [Ref. 4]. No distinction is made between the channels PSSCH, PSCCH and PSBCH. Two additional demodulation reference symbols (DMRS), compared with 3GPP Release 12, are inserted into subframes in order to compensate for radio signal interference caused by Doppler shifts that is expected particularly in V2X scenarios. Consequently, the sidelink subframe contains four DMRS symbols, and with reference to the figure below, SC-FDMA symbols 2, 5, 8 and 11 carry DMRS when radio signal transmission relates to PSCCH and PSSCH operation.

Fig. 43: Slot structure for PSSCH and PSCCH



When radio signal transmission refers to the PSBCH (Fig. 44), then three DMRSs are carried in SC-FDMA symbols 4, 6 and 9 [Ref. 4]. The last SC-FDMA symbol remains unused in all cases in order to leave ample time to switch the transmitter from signal transmission to reception. SLSSs are modulated to subcarriers associated with the central six PRBs of the synchronization subframe. More specifically, PSSS is carried in SC-FDMA symbols 1 and 2, while SSSS is carried in SC-FDMA symbols 11 and 12.

Fig. 44: Slot structure for the synchronization subframe



5.3 LTE-V2X direct communications (Release 15)

In Release 15, LTE-V2X phase II introduces technology features targeting additional V2X use cases such as advanced driving support, collaborative perception, extended sensors and probably vehicle platooning scenarios (see also Fig. 7). The major difference compared to phase I is the requirement for higher data rates on the sidelink and shorter reaction times. Newly introduced technology features for the sidelink support these requirements:

TX diversity

Known from LTE, TX diversity represents a transmission scheme using two TX antennas providing a diversity gain. With the two transmit antennas, the transmitting entity applies a space-time block coding scheme to gain additional redundancy and therefore a diversity gain with the advantage that this TX diversity does not require any feedback from the RX entity.

Higher order modulation schemes

The ability to use 64QAM on the sidelink increases the overall achievable data throughput, but also requires a better signal-to-noise ratio (SNR). The impact is a slight change in the SCI message to adjust the adaptive modulation information to this newly introduced modulation scheme.

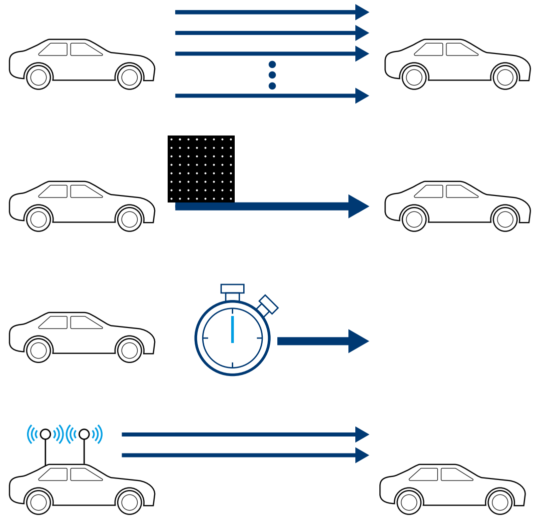
Shorter processing time

Traffic scenarios require lower latency. A method defined in Release 15 is the reduction of the maximum time between layer 1 packet arrival and resource selected for transmission from 20 ms to 10 ms. Note that there is no change in the physical layer timing; it is still based on the LTE subframe structure of 1 ms. The advantage is faster processing time on layer 2.

Carrier aggregation

In Release 10, LTE-Advanced introduced the mechanism of carrier aggregation (see also Fig. 21) to support higher data rates by using more bandwidth. Multiple component carriers are aggregated. Release 15 allows carrier aggregation on the sidelink with a maximum of eight PC5 carriers in both transmission modes, TM3 and TM4.

Fig. 45: LTE-V2X enhancements overview



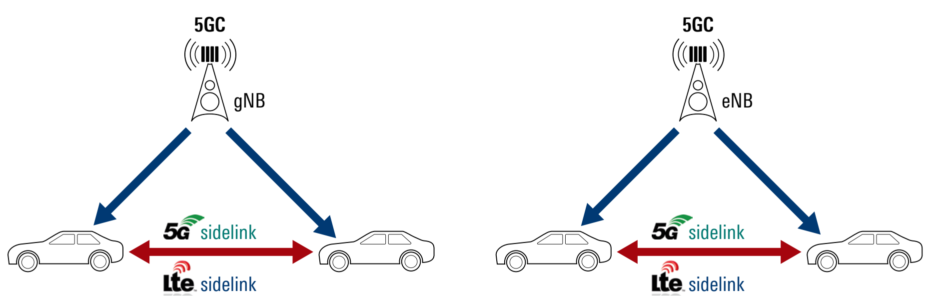
5.4 NR-V2X direct communications (Release 16)

Direct communications C-V2X introduced with 3GPP Release 14 and extended with Release 15 evolves with Release 16 to introduce 5G NR technology on the PC5 interface. According to the 3GPP connectivity scenario timeline (see Chapter 2.1), this V2X phase III targets more complex advanced traffic scenarios such as remote driving, high density platooning, cooperative maneuvers including intention sharing and advanced sensor data sharing. These services require strong support of the URLLC in the ITU services (see Fig. 23). The NR sidelink should cover ultra-reliable, low-latency and high data rate communications. One important aspect is backward compatibility with C-V2X based on 5G NR to C-V2X based on LTE Release 14 and Release 15. This is a complementary technology and not a replacement. Major technology aspects are the introduction of the PC5 interface or sidelink using flexible 5G NR radio characteristics such as flexible numerologies, flexible resource scheduling allowing varying packet sizes, flexible synchronization allowing network independent communications, and a flexible frame structure coping with varying speed and radio propagation environments while remaining future-proof (see also Chapter 4.3). The main objective within the 3GPP standardization organization is to design a sidelink to meet the requirements of advanced V2X services [TR 38.885]. This includes sidelink unicast, sidelink groupcast or multicast, and sidelink broadcast with overall QoS support. Sidelink unicast allows direct communications between two entities enabling reliable and latency-critical communications such as sensor sharing or dense platooning, and is designed for transmission of small data packets. Sidelink broadcast enables unidirectional communications one to many, e.g. advanced information services or safety-related information. Sidelink groupcast or multicast offers the advantage compared to broadcast of allowing reliable communications with a feedback concept based on HARQ operation. The specification work covers aspects such as flexible sidelink physical layer structures and procedure(s), the sidelink synchronization mechanism, the sidelink resource allocation mechanism and sidelink layer 2/layer 3 protocols. Flexible sidelink framework structures allow varying packet sizes and resource sharing between latency-critical or latency-tolerant traffic, and introduce a future-proof concept to allow future updates of the channel framework and slot structure. Sidelink resource allocation enables network or non-network based usage of radio resources (similar to LTE-V2X; see Fig. 38) and usage of frequency resources in the ISM bands or licensed bands in either FR1 or FR2. Resource allocation on the sidelink follows a two-stage resource allocation mechanism [TS 38.321]. The objective is to foster flexible resource scheduling for unicast, groupcast or broadcast with probable carrier sensing steps and to enable the possible introduction of new scheduling mechanisms for future releases at a later time. The sidelink layer 2 and layer 3 protocols introduce distance-dependent scheduling of data packets and corresponding acknowledgments and support network based scheduling of sidelink as well as direct communications network independent scheduling. NR-V2X uses either the time reference of a base station providing radio coverage, a GNSS system or a sidelink UE in case neither the network nor GNSS provide coverage. A more sophisticated QoS management concept leverages the various QoS profiles on radio interfaces Uu and PC5 to optimize V2X operations. To ensure secure communications, the NR-V2X sidelink applies an integrity check and authentication mechanism [TS 23.501].

An extended channel structure on the NR-V2X sidelink enhances the LTE-V2X sidelink and supports data transmission over the PC5 interface with greater flexibility. Besides various OFDMA numerologies, a dynamic resource allocation scheme, spatial multiplexing scheme (MIMO) and non-constant HARQ timing leverage the sidelink flexibility and spectral efficiency. Even if NR-V2X first targets frequency range 1 (FR1), especially LTE band 47 in the 5.9 GHz frequency range, further extensions into FR2 are likely. Besides licensed bands, the 5G sidelink may operate in unlicensed ISM bands.

TR 38.885 describes certain technology items to be considered in the Release 16 standardization phase. One proof of both flexibility and backward compatibility is the infrastructure support for sidelink operation in either way. There are enhancements of the LTE Uu and NR Uu interface to control the NR sidelink from the cellular network, i.e. either the eNB or gNB may allocate 5G sidelink resources. In addition to the eNB assigning resources on the LTE-V2X sidelink, 3GPP Release 16 contains gNB enhancements of the NR Uu to allocate the LTE-V2X sidelink. 5G NR standalone operation is, from a 3GPP perspective, considered as the first priority, but sidelink operation is also supported with 5G networks operating in NSA mode and multiconnectivity; see [TR 38.885] for these various deployment scenarios.

Fig. 46: NR and LTE-V2X connection modes



Enhancements of **LTE Uu and 5G NR Uu** to control **5G NR sidelink** from the cellular network
Enhancements of **5G NR Uu** to control **LTE sidelink** from the cellular network
5G NR sidelink shoud cover **ultra-reliable** and **high data rate** communications

To summarize the 5G sidelink technology aspects, we classify the various methods into four major clusters:

- Unicast, groupcast and broadcast transmission on the sidelink. Especially unicast and groupcast communications require a redesign of the physical channel architecture. This includes e.g. a two-stage scheduling concept for efficiency improvements and a sidelink feedback control channel to deliver HARQ decoding feedback and channel status information from the RX entity to the TX side
- Low latency support with features such as a self-contained slot structure where acknowledgments can be sent within the same slot as the data message and a grant-free scheduling operation on the sidelink. To leverage higher reliability, sidelink resources for automatic retransmission can be scheduled with the initial scheduling

- Enhanced collision avoidance strategies and use of a two-stage scheduling concept to be future-proof. Carrier sensing periods as "listen before talk" mechanisms to obtain channel clearance and a sophisticated resource pool and subchannel concept to schedule sidelink resources with low collision probabilities. The division of the scheduling into a common part and a second part within the traffic channel outlines a future-proof concept
- Full flexibility of the physical layer and protocol layer. Allowance of several numerologies enhances the spectral efficiency and an adaptive reference signal concept (DMRS) supports connection setups with different velocities of the communications entities. As in network based 5G NR, the PC5 interface fully supports QoS and management procedures to enable various QoS flows with different parameters between V2X entities. Authentication and integrity check methods ensure secure sidelink communications

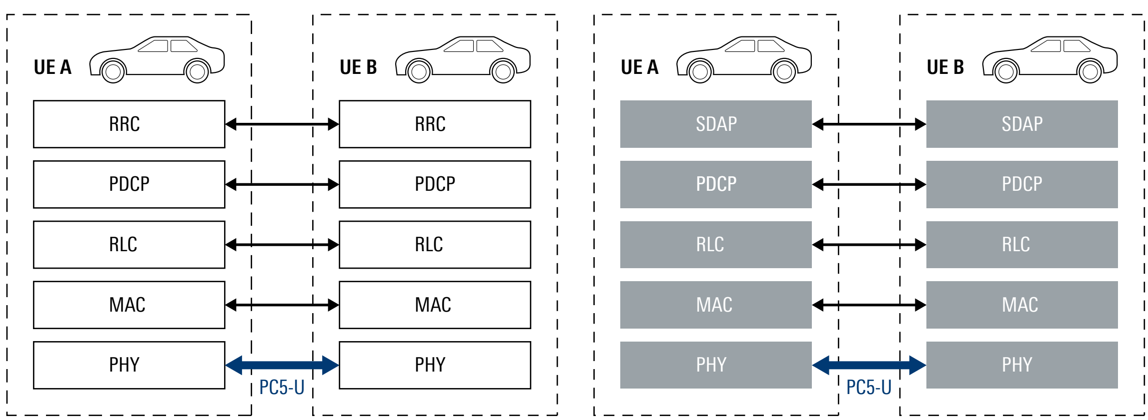
5.4.1 5G NR PC5 interface and sidelink

The PC5 interface is the interface used for direct communications between two entities (most likely, direct C-V2X connection scenarios). The term PC5 encompasses the air interface introduced as the sidelink and the protocol layer structure for both the control plane (CP) and user plane (UP). Both protocol layers have similar functions to the 5G NR Uu interface protocol layer [TS 23.287].

The PC5-C protocol stack for control message exchange over the PC5 interface consists of the layers NAS, RRC, PDCP, RLC, MAC and physical layer.

The PC5-U protocol stack for user data exchange over the PC5 interface consists of the layers SDAP, PDCP, RLC, MAC and physical layer. PC5-U is agnostic to the higher application layers, e.g. data transfer based on IP or non-IP is possible.

Fig. 47: PC5 interface for direct V2X communications; control and user plane



Sidelink describes the radio channel between two V2X UEs

The major difference compared to the LTE based PC5 protocol structure is the introduction of the service data application protocol (SDAP) [Ref. 20], [TS 37.324]. With the SDAP, the communications modes broadcast, groupcast and unicast are managed, and additionally, this protocol layer supervises quality of service aspects. It maps a QoS flow to sidelink radio bearers (SLRB). The packet data convergence protocol (PDCP) handles some security aspects such as encryption and ensures reliable communications by offering a sidelink packet duplication and duplicated discard function [TS 38.323]. The RLC main functions are data packet segmentation and reassembly as well as a discard function for broadcast scenarios [TS 38.322]. The MAC layer manages the three communications modes broadcast, multicast and unicast due to transport channel configuration and multiplexing [TS 38.321]. To ensure reliability, the PC5 interface in 5G introduces the HARQ concept, allowing the receiving entity to send acknowledgments.

Sophisticated HARQ operation on the sidelink introduces a range determination or zone concept as shown in Fig. 49. In addition, the PC5 MAC layer supports functions such as prioritization, data buffering and scheduling request transmission. The physical layer of sidelink offers functions such as flexible numerologies, RF transmission and reception supporting spatial multiplexing up to two layers, synchronization and resource scheduling.

5.4.1.1 PC5 connection and QoS aspects on PC5

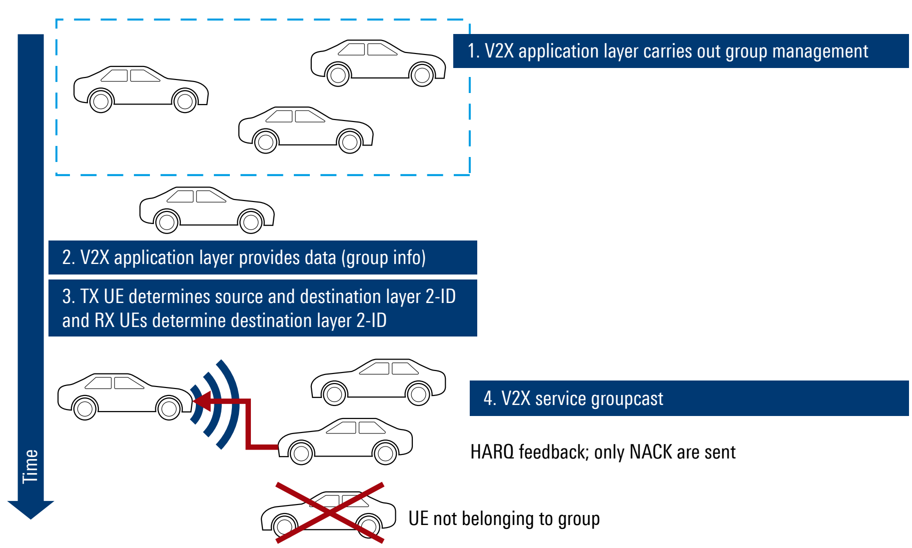
For direct C-V2X communications, the PC5 interface reference point can either be LTE based or 5G NR based. The UE settings or network configurations influence the RAT selection. V2X communications over the PC5 reference point supports roaming scenarios via a serving network and inter-PLMN operations, e.g. when the UE is in a serving network but the application server resides in the HPLMN. V2X communications over the PC5 interface is possible when the UE is in coverage of either LTE or 5G, and is also possible when no network coverage exists. Via protocol messages, sidelink communications can be established, maintained and released. It operates in the three modes broadcast, groupcast or unicast and inherits a QoS profile. In addition, a zone concept depending on the device location allows flexible and signaling-efficient temporary generation of multicast groups. To address the RX and TX sides in all three communications modes, a layer 2 ID is used as source and destination ID.

Since 5G NR supports QoS at a very sophisticated level in the entire system, the PC5 interface for V2X services provides an update to QoS management. For NR based PC5, [TS 23.287] defines a QoS model similar to the one used on the Uu interface. The major differences are the configuration of QoS profiles depending on the communications mode unicast, groupcast or broadcast and the introduction of a new QoS parameter determining the range between the TX and RX entities. TS 23.287 defines QoS flows, QoS identities, QoS modes and QoS parameters such as the ensured bit rate, delay, error rate or priority. Two V2X entities establish a PC5 link that owns one or multiple QoS flows and each QoS flow is identified by a PC5 QoS flow identifier (PFI). Allowing greater flexibility, the QoS flow parameters can be configured individually or similar to the 5QI term, default QoS parameters described as PC5 5QI QoS parameters (PQI) can be used.

5.4.1.2 PC5 groupcast mode

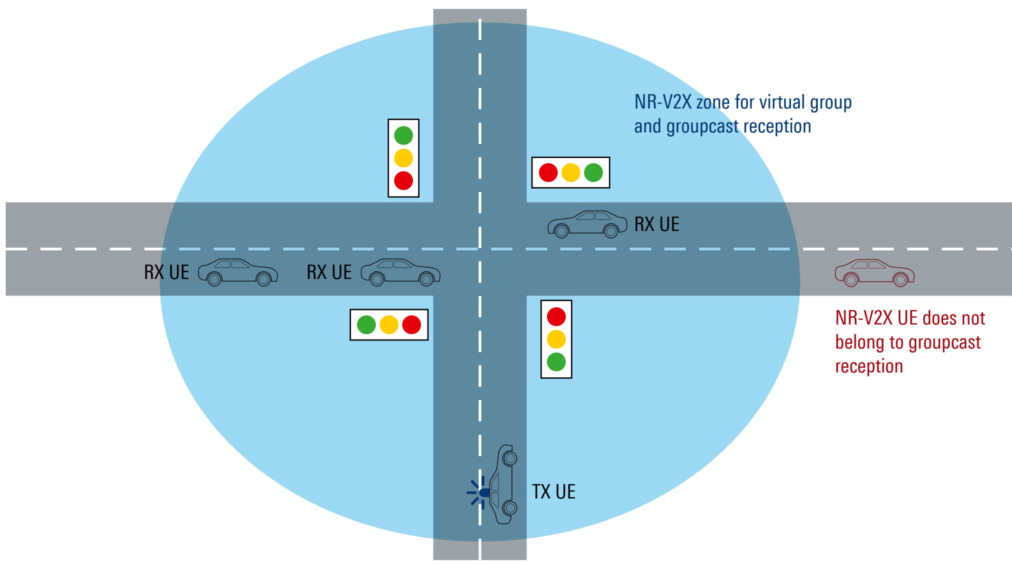
The groupcast or multicast mode on the sidelink represents a new communications mode compared to LTE-V2X sidelink communications. The connection setup consists of four major signaling steps, only slightly different from the broadcast mode establishment procedure. Note that those signaling steps do not directly correspond to a message transfer.

Fig. 48: Procedure for groupcast mode V2X communications over the PC5 interface



The advantage or motivation for the introduction of the groupcast on top of broadcast communications is the reliability aspect. A groupcast message transfer comes together with an acknowledgment (at least the NACK is sent), thus a TX entity may retransmit the message if at least one member of the virtual group indicates a decoding error, leading to higher reliability. Group management is triggered by the V2X application. This includes membership aspects for UEs belonging to that group, addressing names and QoS profiles. As an enhancement, such a virtual group can be set up based on location, i.e. the range. In other words, membership in such a virtual group depends on the distance between the TX and RX UEs. As an advantage, time-consuming signaling procedures such as connection setup and release can be leapfrogged. As an example in Fig. 49, we want to exchange collision warning information when an emergency vehicle approaches a road crossing. Thus, via groupcast a message is sent to a group consisting of all vehicles within a certain range. This range is also the decision criterion when it is time to leave such a virtual group. If a vehicle is far away from the road crossing, there is no longer any need to receive such a collision warning message.

Fig. 49: Zone concept for range dependent message transfer in 5G NR-V2X



How does a UE know its zone or range? The 5G NR concept is to divide the worldwide geographic map into zones. Each zone is defined based on its longitude and latitude parameters. Based on GNSS location services, a UE knows its relationship to a relevant zone. A receiving entity can easily decide based on this zone concept in addition to the sidelink identifier whether a groupcast message is considered to be valid or not.

In the transmitting UE, the V2X application layer provides the data unit to lower layers, possibly associated with group-specific QoS and V2X application requirements. Both the TX and RX entities need to determine the proper destination layer 2 ID for groupcast and the source layer 2 ID. At the last stage in the procedure, the transmitting UE sends the V2X service data using the source layer 2 ID and the groupcast destination layer 2 ID. To reduce the signaling overhead in groupcast HARQ feedback, 3GPP introduced a single frequency combined feedback principle, i.e. multiple RX UEs may send their NACK information on the same radio resource using a CDM multiplexing scheme.

Besides groupcast, the NR-V2X sidelink supports unicast communications between two V2X entities and broadcast. The broadcast mode is similar to the LTE-V2X communications mode and unicast allows direct communications with a certain QoS profile and HARQ support to leverage reliability. Unicast mode allows transmission of variable data packets, thus V2X communications supports everything from single message exchange through a full “dialogue”. Further information on NR-V2X broadcast and unicast is provided in [Ref. 45].

5.4.2 NR sidelink physical layer aspects

5G NR-V2X introduces the term sidelink as the radio resource that is used to exchange data in a direct communications scenario between two V2X entities. The following figure presents a concise overview of the physical layer differences over 3GPP Releases 12 to 16 for the sidelink.

Fig. 50: Physical layer details of sidelink over 3GPP Releases 12 to 16

Parameter	LTE D2D (Release 12)	LTE-V2X (Release 14)	LTE-V2X (Release 15)	5G V2X (Release 16/17)
Frequency	all bands possible (e.g. FirstNet 700 MHz)	target: 5.9 GHz	target: 5.9 GHz	target: 5.9 GHz, FR1 and FR2
Waveform	DFT-s-OFDM	DFT-s-OFDM	DFT-s-OFDM	CP-OFDM
Subcarrier spacing	15 kHz	15 kHz	15 kHz	NR numerologies, 15/30/60/120 kHz
Cyclic prefix	normal and extended	normal	normal	normal and extended (only 60 kHz SCS)
Modulation	QPSK, 16QAM	QPSK, 16QAM	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM, 256QAM
Channel coding	turbo code	turbo code	turbo code	LDPC (data) and polar (signaling) codes
Time scheduling	1 subframe ≙ 1 ms	1 subframe ≙ 1 ms	1 subframe ≙ 1 ms	1 slot, flexible slot duration, slot aggregation possible
Number of DMRS symbols per TTI	2 per subframe	4 per subframe	4 per subframe	2 to 4 per slot
Data/control multiplex	TDM	FDM	FDM	TDM and FDM
HARQ	–	–	–	RX UE reports to TX UE, TX UE reports to gNB
MIMO	single layer	single layer	TX and RX diversity	up to 2 layers
Retransmissions	4 (by default)	up to 2	up to 2	up to 32 (configurable and resource reservation)
Communications type	groupcast, broadcast	broadcast	broadcast	unicast, groupcast, broadcast
Carrier aggregation	no	no	up to 8 CCs	no
Peak throughput	approx. 7 Mbps	approx. 32 Mbps	approx. 72 Mbps	approx. 200 Mbps (256QAM)

One major difference compared to the sidelink in LTE-V2X is the possible wider channel bandwidth of up to 100 MHz in NR-V2X. The NR sidelink inherits similar characteristics known from the 5G NR radio interface: It is configured in time and frequency units and the smallest element is a resource element describing one OFDM symbol on one subcarrier. Like an NR radio cell, a resource grid spanning a certain bandwidth given as a number of resource blocks and using one 5G numerology configures transmission on the sidelink radio resource. The exact configuration parameters for the sidelink resource grid are similar to the resource grid definition for 5G NR on the uplink or downlink corresponding to a 5G NR cell. The frequency position of the sidelink resource grid uses the point A [Ref. 20] (Fig. 27) as the frequency position identifier and the higher layer parameter absoluteFrequencyPointA-SL indicates the point A for sidelink transmission/reception. The starting position for one specific resource grid using a certain numerology is given by the higher layer parameter offsetToCarrier-SL. A sidelink resource grid uses a certain carrier bandwidth for one subcarrier spacing configuration μ. It is provided by the higher layer parameter subcarrierSpacing-SL given by the higher layer parameter carrierBandwidth-SL. The sidelink resource scheduling concept for a UE uses the UE-specific bandwidth part concept as explained later [TS 38.211].

The sidelink time configuration is defined in frames, slots and symbols using the same values as the 5G Uu interface; see Fig. 28 (e.g. slot structure for SCS 60 kHz). The granularity of the resource allocation is one slot. The sidelink frame has a duration of 10 ms and is divided into slots. The number of slots depends on the 5G numerology, i.e. the subcarrier spacing and ranges from 1 to 8 for the sidelink. There can be 14 OFDM symbols in one slot if the cyclic prefix is of normal length. For the extended CP duration, only 12 OFDM symbols are allowed. The sidelink uses CP-OFDM as the access waveform with either the normal or extended cyclic prefix length and defines the resource grid and bandwidth parts based on the known flexible 5G NR numerologies (see Fig. 25). The 5G NR sidelink is not targeted at one single band like ISM band n47, but can also use additional frequency bands especially at higher frequency ranges. Thus, flexibility is available to adjust the waveform to the characteristics of the radio channel through selection of the appropriate numerology. At lower frequencies, a narrower SCS facilitates the equalization effort and at higher frequencies, a wider SCS reduces the impact of phase noise. These flexible numerologies enhance the overall achievable spectrum efficiency. Consequently, the objective is to permit multiple numerologies on the sidelink.

If the sidelink operates in FR1, the 15 kHz, 30 kHz and 60 kHz subcarrier spacings are permitted and if the sidelink operates in FR2, only the 60 kHz and 120 kHz subcarrier spacings. The extended cyclic prefix is only allowed with 60 kHz SCS to reduce the overall complexity.

5.4.2.1 Bandwidth part for the sidelink

Like the 5G NR Uu interface, there is a bandwidth part defined for the NR sidelink and the BWP operates on one specific numerology within a certain resource grid on that particular sidelink. The bandwidth part presents a UE-specific temporary frequency allocation for idle and connected mode, i.e. a UE active on a sidelink expects transmission and reception only in its active bandwidth part.

In a licensed carrier, the SL BWP is defined separately from BWP for Uu. The same SL BWP is used for both TX and RX as the sidelink operates in TDD mode. Only one SL BWP is active in a carrier for in-coverage as well as of out-of-coverage connections. There is no higher layer signaling exchanged on the sidelink for activation and deactivation of SL BWP.

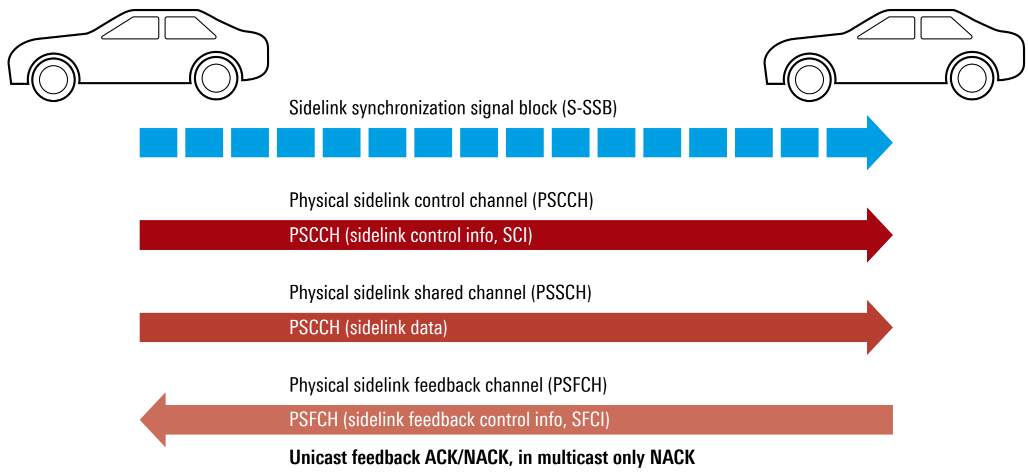
To allow multiple connections and avoid collisions, the 5G NR sidelink uses the concepts of resource pools and subchannels [TR 38.885], similar to LTE-V2X (see Fig. 39). A high level of flexibility is obtained on the sidelink due to allowance of multiple numerologies as well as the flexible time configuration. Each resource pool is (pre)configured within a SL BWP. Mapping of physical channels onto the sidelink follows a flexible time allocation. Thus, it is possible to give the sidelink channels a flexible starting position and also a flexible time duration.

5.4.2.2 Sidelink physical channels

A sidelink physical channel corresponds to a set of resource elements carrying information originating from higher layers. The following sidelink physical channels are defined [TS 38.211]:

- ▶ Physical sidelink shared channel, PSSCH
- ▶ Physical sidelink broadcast channel, PSBCH
- ▶ Physical sidelink control channel, PSCCH
- ▶ Physical sidelink feedback channel, PSFCH

Fig. 51: NR sidelink physical channels



The sidelink operates in TDD mode. The physical channels on the sidelink are present in a time and frequency structure accompanying or relating to one another. As a major difference compared to LTE-V2X Release 14, the sidelink scheduling follows a two-stage procedure. First, the PSCCH schedules PSSCH resources via SCI format 0_1 information and secondly, the PSSCH itself contains SCI format 0_2 information for further decoding information [TS 38.214]. To improve the latency and reliability, there are scheduling control and sidelink data channels sent in one direction and the sidelink feedback channel is likely sent in the same slot in the opposite direction. To allow flexibility, the start symbol and the length of the PSSCH are controlled by higher layers. For synchronization purposes, especially in non-coverage sidelink scheduling, a PSBCH channel delivers synchronization signals via the S-SSB and sidelink system information.

5.4.2.3 Physical sidelink shared channel (PSSCH)

The physical sidelink shared channel transfers user data and the second part of the sidelink control information (SCI) on the sidelink radio interface. It represents a unidirectional physical channel and is accompanied by a control channel PSCCH in the same direction and a feedback control channel PSFCH in the opposite direction. The PSSCH uses a flexible bandwidth given in a number of resource blocks within the active BWP. It uses an adaptive modulation and coding scheme (AMC) and optionally uses spatial multiplexing transmission with a maximum of two layers of transmission. Resource blocks used for PSSCH must be within the resource pool only. The modulation schemes QPSK, 16QAM and 64QAM are mandatory for every V2X UE, while 256QAM depends on the UE capability and can optionally be activated by higher layers. The channel coding scheme is LDPC for data and polar codes for control information. For operation regarding PSSCH, a UE performs either transmission or reception in a slot on a carrier. For demodulation purposes, there are DMRS within the PSCCH; one important aspect is the flexible number of DMRS per slot. There can be two, three or four DMRS symbols within one slot, supporting link adaptation and Doppler shift compensation depending on the UE velocities (see Fig. 53).

5.4.2.4 Physical sidelink control channel (PSCCH)

The physical sidelink control channel is an in-band channel to transmit the sidelink control information (SCI), part one. To allow greater flexibility, the SCI is divided into two parts: format 0_1 as stage 1 and format 0_2 as stage 2. The PSCCH carries the first part, SCI stage 1 and the PSSCH multiplexes the second part, SCI stage 2. In comparison to the data channel, the control channel PSCCH offers less flexibility. The modulation scheme is constant QPSK only, the coding scheme is polar codes and there is no spatial multiplexing allowed, thus only one layer transmission. For demodulation purposes, there are DMRS within the PSCCH [TS 38.211].

The PSCCH shares the same time resource as the PSSCH, but is mapped onto different subcarriers within one subchannel only. Allowing greater reliability for sidelink control, a UE can be provided with two or three symbols in a slot, signaled as timeResourcePSCCH. This supports an automatic retransmission concept. In the frequency domain, the PSCCH is located in the first subchannel configured for PSSCH with a variable number of PRBs, signaled as frequencyResourcePSCCH.

5.4.2.5 Physical sidelink broadcast channel (PSBCH)

The physical sidelink broadcast channel is part of the S-SSB for synchronization purposes and carries sidelink-specific control information. As it is common control information, signal generation follows a constant procedure. The mapping on time and frequency resources is depicted in Fig. 56. All symbols within the PSBCH are QPSK-modulated and no spatial multiplexing is permitted. The S-SSB has the same numerology as PSCCH/PSSCH on that carrier, and an S-SSB should be transmitted within the bandwidth of the configured BWP. The PSBCH conveys information related to synchronization such as the direct frame number (DFN), indication of the slot and symbol level time resources for sidelink transmissions, in-coverage indicator, etc. [Ref. 45].

5.4.2.6 Physical sidelink feedback channel (PSFCH)

The physical sidelink feedback channel (PSFCH) supports unicast and groupcast communications over PSSCH as it conveys sidelink feedback control information (SFCI). The content of the SFCI is ACK/NACK information to leverage reliability and when applying the self-contained slot structure with immediate feedback (see Fig. 54), it reduces the overall latency. There is a configurable time relationship between the PDU on the PSSCH and the corresponding HARQ feedback, ranging from within the same slot (self-contained) to several slots later. The PSFCH uses the same numerology and CP duration as the associated PSCCH and PSSCH channels. A sequence based PSFCH format with one bit as ACK/NACK is supported for unicast and groupcast. Content-wise, ACK and NACK are differentiated by applying different cyclic shifts of the same base sequence. To reduce collisions with other sidelink communications, the cyclic shift for ACK/NACK transmission in unicast mode also depends on the TX UE source ID [TS 38.213].

For unicast transmission, the situation is straightforward: There is only one TX UE and one RX UE, which sends ACK or NACK depending on the decoding result. Groupcast is slightly more difficult as there is one TX with multiple RX entities. The agreement to reduce the signaling load is to only transmit NACK information in groupcast situations. Like the analogy "no news is good news", an acknowledgment is indicated as silence. For NACK transmission in groupcast mode, two options are specified: option 1 reserves resources common to all group member UEs for NACK transmission and option 2 reserves group member specific NACK resources. As there is a high possibility that multiple UEs may send a NACK on the same configured resource, thus a collision situation, the NACK sequence will be spread with a CDM sequence. Nevertheless, the TX UE will retransmit when at least one RX UE sends a NACK; the feedback does not scale with the number of UEs.

Another important aspect of NR-V2X acknowledgment feedback is the relationship between the feedback information transfer and the range between the TX and RX entities. For example, a UE may properly decode a sidelink PDU, but will ignore it when the range information exceeds a given limit and will therefore suspend feedback transmission.

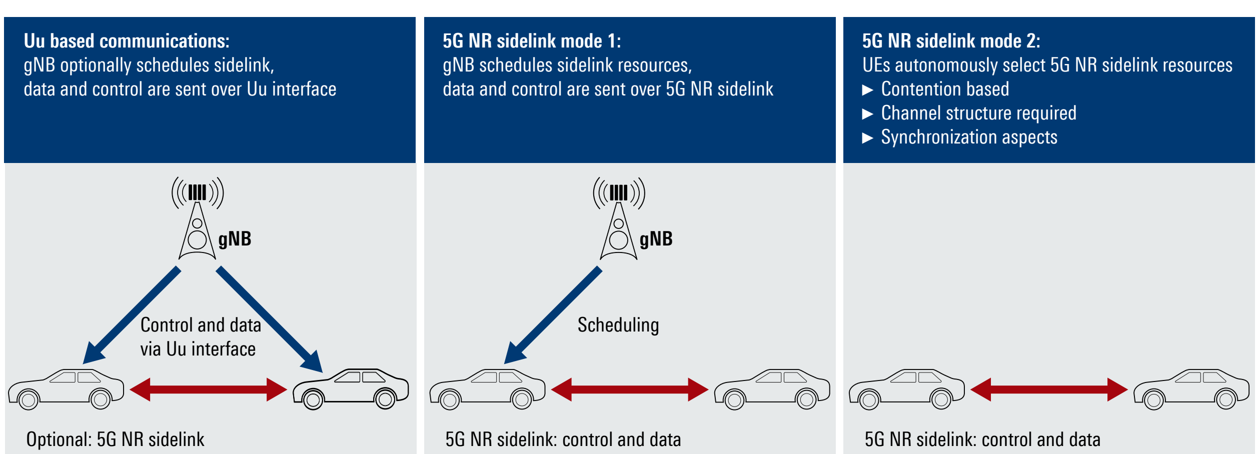
Every one, two or four slots, the last two symbols excluding the guard period (GP) symbol are able to accommodate the PSFCH.

5.4.3 NR-V2X physical resource scheduling

C-V2X traffic between two entities can be scheduled via the Uu interface (network based) or via the PC5 interface (direct mode). Scheduling of V2X traffic flow via the Uu interface corresponds to a vehicle-to-network-to-vehicle connection (V2N2V). In 3GPP Release 16, there are two scheduling methods defined for scheduling of V2X-related traffic on the sidelink [TS 38.214]. Sidelink scheduling mode 1 is network based, and the gNB uses DCI or a priori RRC scheduling to allocate radio resources on the sidelink. This assumes that at least one V2X UE is in coverage. A further distinction involves whether this scheduling is dynamic, semi-persistent with activation/deactivation commands, or directly configured by RRC. The dynamic grant procedure targets the scheduling of one PDU with the advantage of flexible PDU size. As a drawback, it requires sidelink connection setup beforehand such that this grant does not target low latency. Semi-persistent scheduling needs a priori higher layer configuration that can be dynamically activated or deactivated. Direct RRC resource scheduling addresses a kind of constant or periodic traffic flow. The latter, sometimes described as grant-free operation, leverages latency aspects.

Autonomous resource selection or sidelink scheduling mode 2 describes autarchic radio resource scheduling, supporting out-of-coverage operation. The two V2X UEs use a random selection based principle to establish sidelink communications using sidelink synchronization methods, sidelink sensing and sidelink physical channels TX and RX. From a UE perspective, mode 2 is the appropriate scheduling principle when the UE is without coverage. If the UE is in coverage, the gNB may either choose to use mode 1 or mode 2 allocation. TS 38.331 and TS 38.304 define several rules for when the UE is allowed to use sidelink resources. This includes in-coverage and out-of-coverage criteria, channel sensing thresholds and a pseudo random selection algorithm for how the UE should handle sidelink resources.

Fig. 52: NR-V2X traffic scheduling principles



One aspect differing from LTE-V2X is the time domain scheduling in the 5G NR sidelink. Assuming varying packet sizes, the NR sidelink allows aggregation of slots.

5.4.4 Sidelink physical signals

A sidelink physical signal corresponds to a set of resource elements used by the physical layer but does not carry information originating from higher layers. They play an essential role in maintaining the radio link as they support e.g. equalization, channel estimation, synchronization or power control.

The following sidelink physical signals are defined [TS 38.211]:

- Demodulation reference signals, DMRS used for demodulation purposes. These reference signals accompany any physical channel containing data to be demodulated, as there are PSCCH, PSSCH and PSBCH. Equalization and channel estimation rely on the DMRS signals as well as power control
- Channel-state information reference signal, CSI-RS used optionally for channel status acquisition. Like in 5G NR, the CSI-RS are configurable by the transmitter and support sophisticated channel status information acquisition methods. This will be essential when considering sidelink communications in higher frequency ranges (FR2) and directive antenna methods known as beamforming
- Phase tracking reference signals, PTRS used optionally for tracking and synchronization purposes on the sidelink. Mitigation of phase noise effects is possible; see [Ref. 20]. The activation of PTRS is possible only in FR2 in the current release
- Sidelink primary synchronization signal, S-PSS included in the S-SSB to provide a primary synchronization signal for initial sidelink synchronization. The S-PSS is part of the sidelink synchronization ID (SSID)
- Sidelink secondary synchronization signal, S-SSS included in the S-SSB to provide the secondary synchronization signal for initial sidelink synchronization. The S-SSS is part of the sidelink synchronization ID (SSID) [TS 38.331]

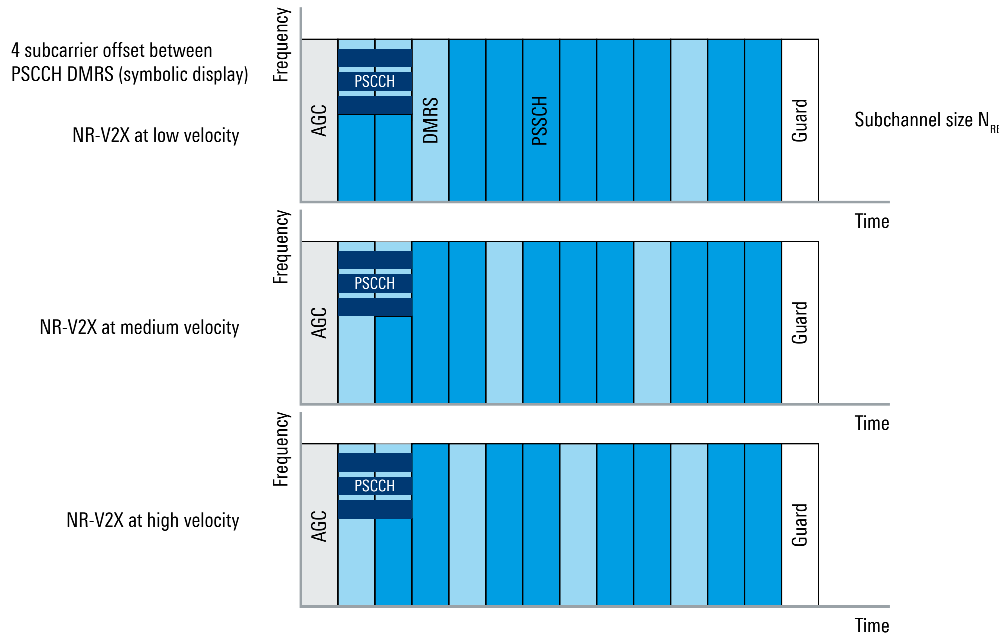
DMRS for PSSCH

To illustrate the great flexibility of the 5G sidelink, a few further details on the DMRS are presented here [TS 38.211]. The DMRS for PSSCH generally follows the structure of the PDSCH in 5G NR. The only difference is that the pseudo random sequence is based on a sidelink identity instead of the physical cell ID or UE ID.

The mapping of the DMRS on time and frequency resources is not that simple since the size and the start symbol of the PSSCH in the time domain are flexible. The size of the scheduling PSCCH is either two or three symbols and there can be multiple DMRS time patterns configured by higher layers. TS 38.211 contains a table indicating the various DMRS positions within a sidelink slot [Ref. 45].

NR-V2X needs to support various velocities, from situations like a static entity (e.g. RSU) up to situations where two vehicles pass one another on a highway in the opposite direction. The effect on the physical layer is the resulting Doppler shift, which depends on velocity and carrier frequency. A countermeasure to tackle Doppler shift is flexible configuration of DMRS symbols contained in an NR-V2X slot [Ref. 46]. The example in Fig. 53 shows a situation where one V2X slot contains 12 symbols for PSSCH and a duration of two symbols of PSCCH. For this case, TS 38.211 allows three different mapping possibilities for DMRS with either two, three or four symbols per slot depending on the velocity situation. The SCI first stage on the PSCCH indicates the exact number of DMRS symbols within the slot, allowing very fast link adaptation if radio conditions change rapidly [Ref. 56]. The example in Fig. 53 uses the first symbol for adaptive gain control (AGC) and the last symbol as guard.

Fig. 53: DMRS with various numbers and positions to support various velocities in NR-V2X



5.4.5 Sidelink slot structure

The 5G NR sidelink uses the time unit of one slot as the smallest granularity for the sidelink physical channels. No mini-slot operation is allowed on the sidelink, but it is possible to have a partial allocation of several symbols within one slot for the sidelink only. The remaining symbols may be used for Uu interface transmission on the uplink in case of shared band operation, they may be used for carrier sensing, or they are simply reserved for future use. The total duration of one slot depends on the numerology. To support high flexibility, there is a variable mapping scheme of PSSCH, PSCCH and PSFCH physical channels onto one slot. One technology aspect to improve the latency on the sidelink is the configuration of a self-contained slot. This represents the case where the PSCCH and PSSCH carry scheduling control and data in one direction and the PSFCH provides immediate feedback within the same slot. To allow RX-TX switching, a guard symbol is included whenever there is a switch in the duplex direction. Since the receiving UEs need to blind-detect the frequency resources used for PSCCH in a flexible manner and also since it does not have any a priori information on the TX power (assume an RX UE is in an obstructive environment), the first symbol may be used for automatic gain control (AGC) [Ref. 46]. Within a slot, the start symbol and the symbol duration containing sidelink data are configurable, besides the flexible RF resource given as a number of resource blocks. The consequence is a flexible data rate on the sidelink [TS 38.214]. Additionally as shown in Fig. 53, the slot contains a variable number of DMRS symbols.

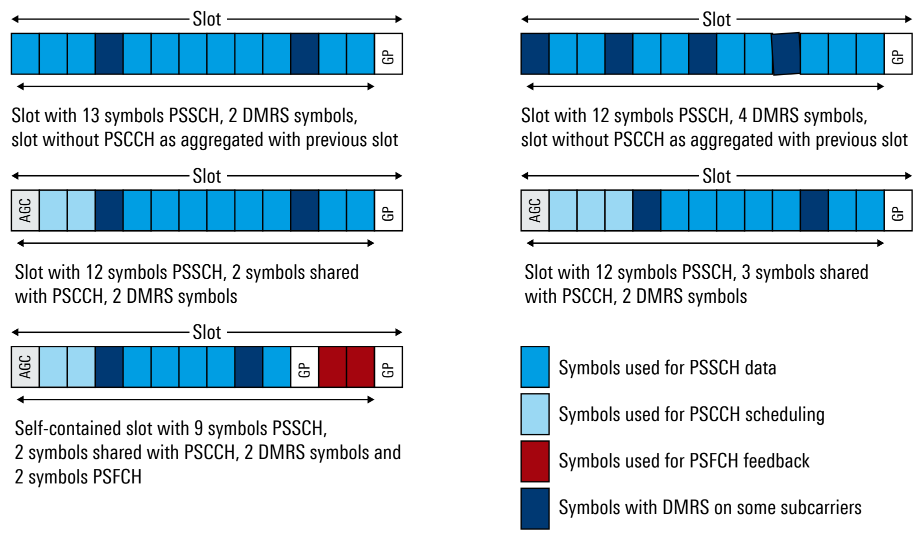
The number of PSSCH symbols within one slot ranges from 6 symbols to 13 symbols depending on the cyclic prefix duration, the size of the PSCCH and the sidelink slot configuration. The duration of the scheduling information on the PSCCH can be either two or three symbols and the content is repeated within these symbols. This automatic retransmission concept ensures better reception of the scheduling control information, leveraging the reliability aspect.

Since there are multiple slot configurations based on the high flexibility, Fig. 54 shows examples of the mapping of sidelink physical channels. The upper part of the figure shows a slot containing 13 symbols PSSCH. Thus, a focus on data throughput and time assignment via PSCCH is assumed in a previous slot that operates in aggregation mode with this slot. The difference between the left and right parts is the amount of DMRS signals within one slot. This represents a case of either high Doppler shift due to device mobility or low SNR situations.

In the middle part, the figure shows a situation where the scheduling channel and data channel are contained within the same slot. The difference between the left and right parts is the size of the PSCCH of either two or three symbols.

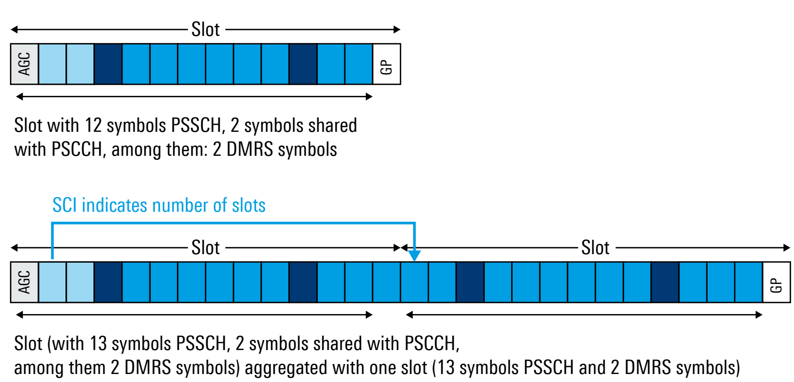
In the lower part, the figure presents the self-contained slot configuration with scheduling information, sidelink traffic and sidelink feedback within the same slot. Note that this configuration with 9 symbols PSSCH indicates the maximum size of PSSCH due to the need for guard symbols as TX-RX switching is required.

Fig. 54: Slot structure examples containing physical sidelink channels



Another advantage of NR-V2X compared to LTE-V2X is the possibility to aggregate slots for sidelink transmissions (see Fig. 55). This enables transmission of variable packet sizes stretched over one or multiple sidelink slots. The current numbers are one, two or four slots used for sidelink operation. Thus, it is possible for a sidelink slot to not contain a PSCCH scheduling channel. In this case, the time resource assignment indicates consecutive slots in the association between PSCCH and PSSCH.

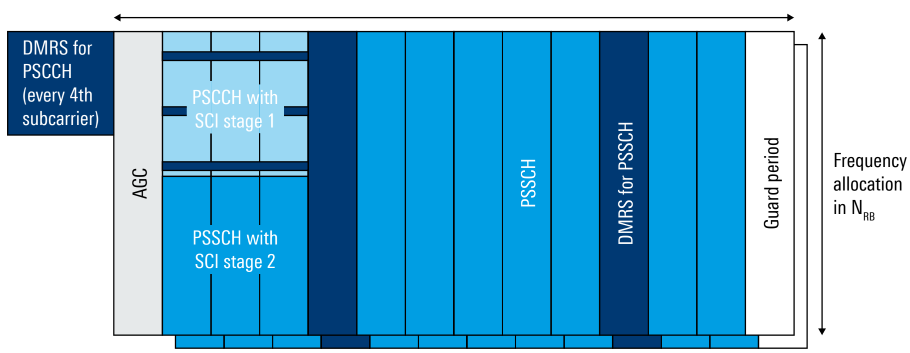
Fig. 55: Slot aggregation for sidelink



One important aspect is the separation of the sidelink control information into two parts: stage 1 and stage 2 SCI. Two major reasons are behind this decision. First, since the RX UEs will have to blind-detect relevant scheduled sidelink traffic in various frequency resource pools and subchannels and possibly also various control channel formats, the overall implementation complexity for the UE would be too high. Consequently, the control information is restricted to formats common to all UEs. The second reason is the requirement to remain future-proof. It will be easily possible to extend or replace the current Release 16 format for SCI stage 2 with a different SCI format in future releases.

The PSCCH shares the sidelink radio resources with the PSSCH. As one example of such a physical channel and SCI control information mapping, Fig. 56 below shows the slot structure without PSFCH feedback information and assuming 14 symbols per slot. A number of 12 symbols is used for PSSCH with 2 symbols DMRS and the PSCCH duration is set to 3 symbols. PSCCH and PSSCH share the same time domain symbols but not the same subcarriers. The PSSCH physical channel on the sidelink can operate in spatial multiplexing mode transmitting on two layers, but the PSCCH is only SISO. Also, the stage 2 SCI control information will only use the QPSK modulation scheme. Note that the frequency axis corresponds to the size of the subchannel and is only indicated symbolically in the figure.

Fig. 56: Sidelink slot structure with PSCCH, PSSCH and two-stage SCI information



5.4.6 Sidelink synchronization aspects and S-SS/PSBCH block details

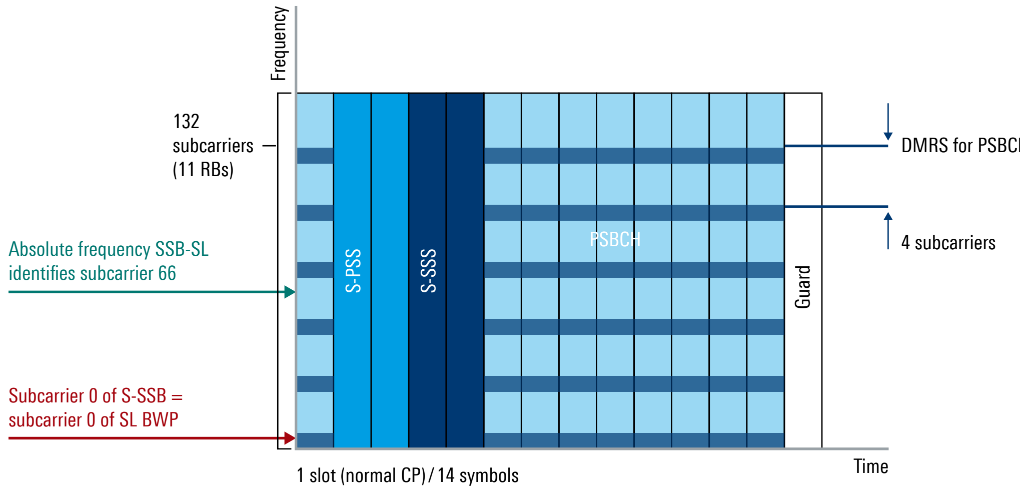
For synchronization purposes, the 3GPP standard defines the S-SS/PBCH block (also known as S-SSB) for the sidelink, similar to the SS/PBCH block of 5G NR [TS 38.211]. The S-SS/PBCH block consists of the physical signals S-PSS, S-SSS, DMRS and the physical channel PSBCH. S-SSB uses the same numerology, which includes SCS and CP length, as the control and data channels PSSCH and PSSCH for the given SL-BWP.

There can be normal or extended cyclic prefix length in the S-SS/PSBCH block and the number of symbols depends on the cyclic prefix length. If normal CP duration is used, there are 13 OFDM symbols used in one S-SS/PSBCH block, and otherwise 11 symbols. The last symbol is used as a guard interval, permitting a possible TX/RX switch at the receiving entity.

In the frequency domain, an S-SS/PSBCH block consists of 132 contiguous subcarriers. The higher layer information element (IE) absoluteFrequencySSB-SL indicates the frequency position of the center of the S-SS/PSBCH block. For demodulation purposes, the PSBCH contains DMRS mapped on every fourth subcarrier.

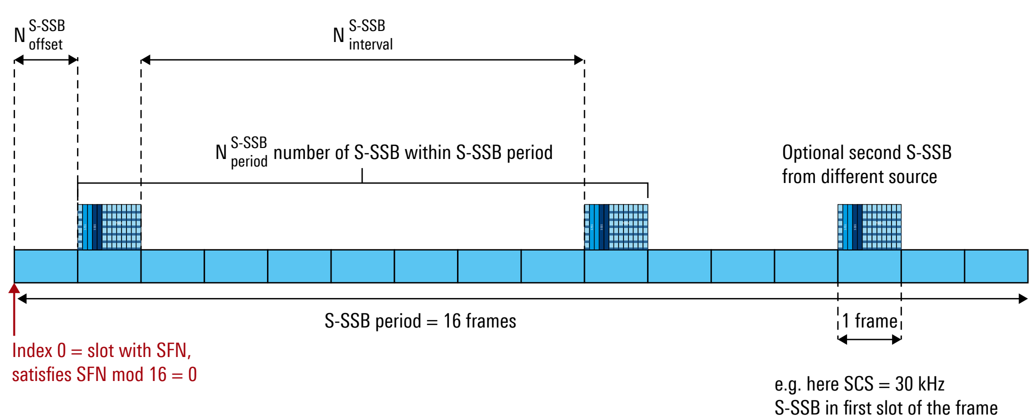
Fig. 57: S-SS/PBCH block structure

(here normal CP, 14 symbols)



For synchronization purposes on the sidelink, the standard defines an S-SSB period of 16 frames, e.g. 160 ms in total. This S-SSB period contains a number of S-SS/PSBCH blocks, provided by the parameter numSSBwithinPeriod-SL. Within the S-SSB period, the first S-SS/PSBCH block is included in the slot with slot offset timeOffsetSSB-SL to the start of the S-SSB period. At least the higher layer IE timeIntervalSSB-SL indicates the slot interval between S-SS/PSBCH blocks [TS 38.211]. Fig. 58 illustrates the timing relationships for sidelink synchronization with the example of 30 kHz SCS and a number of two S-SSB blocks per period with one frame offset and a second S-SSB from a different source.

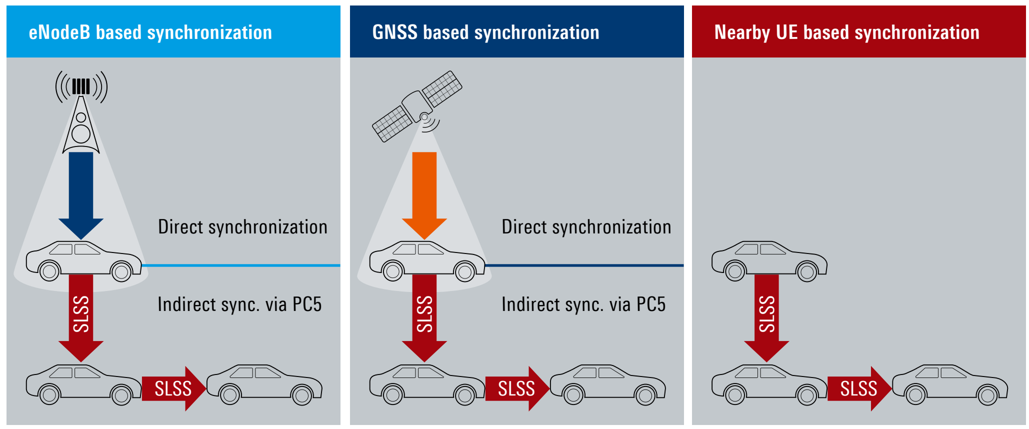
Fig. 58: S-SS/PBCH synchronization aspects



A UE that wants to transmit on the sidelink frequency and is capable of S-SSB transmission should transmit the sidelink synchronization information signal when it is either in partial coverage or out of coverage. Partial coverage here corresponds to a situation where the TX UE receives from its serving base station the trigger to transmit the S-SSB on the sidelink, possibly enabling time synchronization for other V2X UEs that are out-of-coverage. TS 38.331 defines the exact conditions that should be met, resulting in an S-SSB transmission.

The timing reference for sidelink operation behaves like the LTE-V2X sidelink. A UE can synchronize to GNSS, gNB or another UE, and the synchronization reference is provided directly or indirectly. Depending on the UE presetting and network configuration, a certain priority exists between the time references. For example, the system information SIB type 12 contains a description of which synchronization method should be selected by the V2X UEs in its cell area [TS 38.331].

Fig. 59: NR-V2X synchronization aspects



SLSS: sidelink synchronization signal (PSSS and SSSS)

6 TESTING ASPECTS

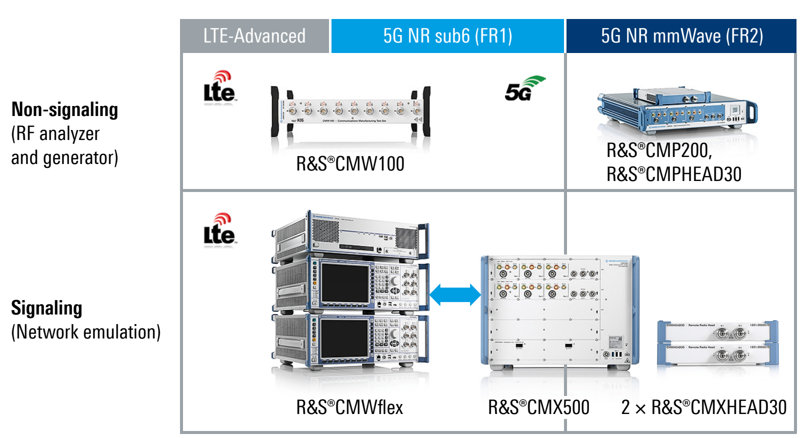
To ensure proper operation, interworking and interoperability between devices as well as correct deployment and implementation of the radio technologies, the previously described automotive connectivity technologies need to be tested. It is not only the technology that distinguishes between testing methodologies and solutions. There are additional aspects like the application field, e.g. whether a full vehicle or a single component should be tested, and the development timeline, e.g. whether the testing is more R&D-oriented or in final production. Chapter 6.1 discusses an approach for lab based testing solutions. In addition, mobile network testing is relevant in the automotive world since vehicles and automotive equipment are sold all over the world and must function properly in different networks. The landscape of automotive connectivity testing covers scenarios such as component testing, hardware in the loop testing of embedded devices, production testing, application testing and full vehicle testing. Some of these tests require a setup using shielded chambers and the connection between the test equipment and DUT is over the air (OTA). Since automotive is a broad field encompassing a huge range of technologies, additional tests are required that do not belong to automotive connectivity testing. At least a concise description of those test methods is given. The motivation behind this chapter is to provide a brief overview of the various aspects of automotive connectivity testing. Further details can be found in the referenced documents and at www.rohde-schwarz.com/automotive.

6.1 Lab based automotive connectivity testing aspects

6.1.1 Automotive connectivity testing

Since there are various radio technologies underlying automotive connectivity, the major requirements for test methodologies and solutions are flexibility, scalability, handling and operability, upgradeability and a future-proof modular hardware structure. A test setup should allow conformance and performance testing of radio technologies such as eCall, LTE, 2G, 3G, LTE-V2X, 5G, WLAN, Bluetooth® and UWB [Ref. 81]. To complete the testing requirements, such a setup should be scalable to allow additional testing of short-range wireless connectivity (UWB), broadcast (e.g. DAB, HD radio or FM), positioning (GNSS) and ECU (RKE, TPME, etc.) scenarios. The modular R&S®CMW and R&S®CMX platforms cover all test requirements in all phases of the product lifecycle. With just one basic investment, a wireless device can be tested over its entire lifecycle – from development to certification and device optimization to production and service. A specific field-to-lab application allows parameterization of the lab based mobile radio tester network configuration with data obtained from drive testing to emulate a real network in a lab environment [Ref. 28]. Scalability ensures that an existing configuration can easily be modified to handle other test and measurement tasks.

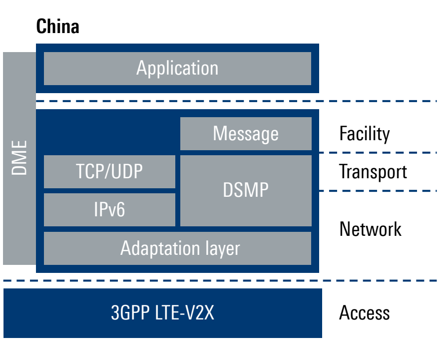
Fig. 60: Radio communications tester portfolio



The R&S®CMW500 combines RF and protocol tests in a single instrument. The R&S®CMW500 is all that is needed for RF tests, E2E measurements and OTT analysis in line with the OSI layer model [Ref. 25]. The R&S®CMW500 is the basis for testing user experience and applications such as battery life and OTA provisioning and OTT data transfer. The combination of complex IP analysis and simultaneous emulation of a variety of wireless technologies, including WLAN, Bluetooth®, 2G, 3G and LTE, makes the tests possible. These technologies are emulated to test wireless devices under both ideal and non-ideal conditions. Non-ideal operation is simulated using additional IP impairments emulating higher protocol layer impairments or using the internal fading option to simulate reproducible impairments on the physical layer. With the introduction of the R&S®CMX500, the modular concept of the platform is extended for 5G NR support [Ref. 57]. Since automotive devices like TCUs must also behave properly under mobility conditions, [Ref. 32] provides further details on handover testing of automotive infotainment devices. Some automotive test scenarios require a shielded environment and an over-the-air connection between the test equipment and the DUT. Rohde & Schwarz offers a wide range of shielding chambers covering aspects from shielded testing in a production environment through full type approval conformance testing [Ref. 78].

Compared to network based RAT testing (e.g. for LTE and 5G), direct communications C-V2X using LTE has, besides RF layer testing, certain region-specific characteristics. Fig. 11 shows the region-specific application layer in China, the USA and Europe. For radio layer testing, there is the common requirement across all three regions for RF layer specific testing of the RF characteristics according to TS 36.521, signaling and protocol-related testing according to TS 36.523, and radio resource management testing according to chapter 3 of TS 36.521. The application layer has certain region-specific adaptations as shown in the following figures:

Fig. 61: Connectivity testing – region China



Scope	Test specification	
Application	e.g. CATARC, CAICT	
Message	IMT-2020 conformance test specification application layer	
Transport and network	IMT-2020 conformance test specification network layer	
Radio access	RF	3GPP TS 36.521-1
	protocol	3GPP TS 36.523-1
	RRM	3GPP TS 36.521-3
Security	various requirements, use case specific	

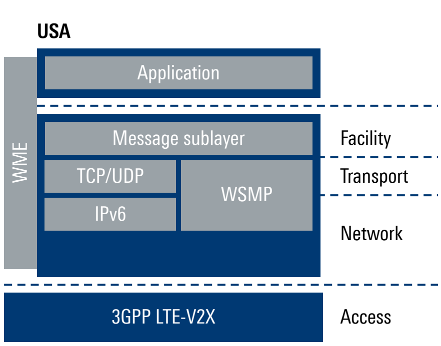
There is an ample set of test scenarios for V2X communications in China which are coordinated, specified and published by various Chinese standardization bodies.

Fig. 62: V2X test standards in China

	Standard/specification	Standard	Standard body
General	General technical requirements of LTE based vehicular communications	YD/T 3400-2018	CCSA/C-ITS
	Connected vehicular methodology	GB/T	NTCAS
Application layer	Technical requirement of application layer for LTE based vehicular communications	GB/T	NTCAS
	Cooperative intelligent transportation system; vehicular communications; application layer specification and data exchange standard	T/CSAE 53-2017	T/CSAE, CCSA, C-ITS
	Cooperative intelligent transportation system; vehicular communications; application layer specification and data exchange standard; phase 2	CSAE	T/CSAE, CCSA, C-ITS
	Technical requirement of message layer for LTE based vehicular communications	YD/T 3709-2020	CSSA, CSAE/CAICV, C-ITS
	Roadside unit message dictionary	T-ITS	C-ITS, CCSA
Security	Technical requirement of security for LTE based vehicular communications	YD/T	CSSA
	Technical requirement of CA management for LTE based vehicular communications	YD/T	CSSA
Network layer	Technical requirement of network layer for LTE based vehicular communications	YD/T 3707-2020	CSSA, C-ITS
	Cooperative intelligent transportation systems; dedicated short-range communications; part 3: technical requirement for network layer and application layer	GB/T 31024.3 2014	CSAE/CAICV, C-ITS
	Cooperative intelligent transportation systems; dedicated short-range communications; part 2: specification of media access control layer and physical layer	GB/T 31024.2 2014	CSAE/CAICV, C-ITS
Access layer	Technical requirement of air interface for LTE based vehicular communications	YD/T 3340-2018	CSSA, C-ITS
Equipment	Technical requirement of vehicle terminal for LTE based vehicular communications	YD/T	CSSA
	Technical requirement of roadside unit for LTE based vehicular communications	YD/T	CSSA
	Technical requirement of side link system for LTE based vehicular communications	YD/T	CSAE/CAICV, C-ITS
	Technical requirement of core network for LTE based vehicular communications	YD/T	CSSA
	Technical requirement of base station for LTE based vehicular communications	YD/T	CSSA
Vehicle and OBU	Technical requirement of vehicular communications system based on LTE-V2X direct communications	GB/T	NTCAS
Application layer	LTE-V2X terminal conformance test specification for network layer and application layer (in lab)		IMT-2020
Network layer	LTE-V2X terminal conformance test specification for network layer and application layer (in lab)		IMT-2020
	3GPP TS 36.521-3: user equipment conformance test specification – RF transmission and reception, part 3: RRM test	3GPP	
	Test methods of network layer of LTE based vehicular communications	YD/T 3708-2020	CSSA
RLC	LTE-V2X terminal function test specification (in lab)		IMT-2020
Physical	LTE-V2X terminal performance test specification (in lab)		IMT-2020
	3GPP TS 36.521-1: conformance test RF transmission and reception, part 1: conformance test	3GPP	
	Test method of vehicle terminal for LTE based vehicular communications	YD/T	CSSA
	Test method of roadside unit for LTE based vehicular communications	YD/T	CSSA
	Test method of base station for LTE based vehicular communications	YD/T 3629-2020	CSSA
	Test method of core network for LTE based vehicular communications	YD/T	CSSA
	Test method of message layer for LTE based vehicular communications	YD/T 3710-2020	CSSA
	Technical requirement of vehicular communications system based on LTE-V2X direct communications	GB/T	NTCAS

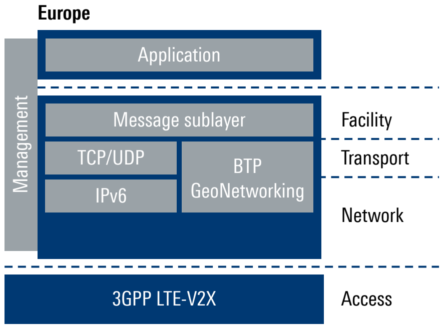
The following figure provides a coarse overview of the various test aspects test aspects in the EU and USA region.

Fig. 63: Connectivity testing – region USA



Scope	Test specification	
Application	FCC and SAE	
Message	OmniAir test suite structure and test purposes for SAE J2945/1	
Transport and network	OmniAir test suite structure and test purposes for network services (IEEE 1609.3)	
Radio access	RF	3GPP TS 36.521-1
	protocol	3GPP TS 36.523-1
	RRM	3GPP TS 36.521-3
Security	OmniAir test suite structure and test purposes for security services (IEEE 1609.3)	

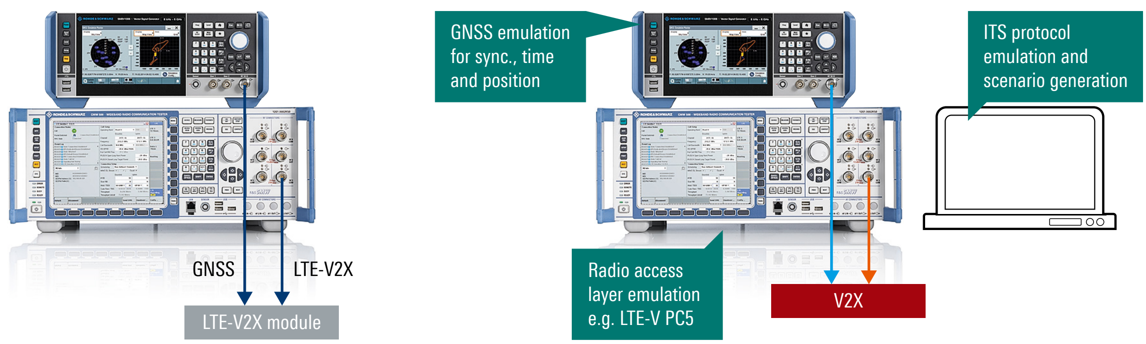
Fig. 64: Connectivity testing – region EU



Scope	Test specification	
Application	ETSI	
Message	ETSI TS 102868-2, ETSI TS 102869-2, ETSI TS 103191-2	
Transport and network	ETSI TS 102859-2, ETSI TS 102870-2	
Radio access	RF	3GPP TS 36.521-1
	protocol	3GPP TS 36.523-1
	RRM	3GPP TS 36.521-3
Security	ETSI TS 103096-2	

A flexible hardware setup supporting LTE-V2X PC5 connectivity is shown in the following figure.

Fig. 65: PC5 test setup for RF and application testing



This setup features e.g. LTE-PC5 communications test and transmission mode 4 supporting out-of-coverage operation with GNSS synchronization. With the option R&S®CMW-KK550, it offers GCF protocol conformance testing including LTE-V2V GCF work item 281 (V2V) and LTE-V2X GCF work item 282 (V2X). The R&S®CMW-KU514 software option offers a flexible and configurable LTE-V2X test solution for RX and performance tests including fading that can be adopted to regional behaviors. The test setup contains the R&S®CMW wireless radio communication tester platform (see [Ref. 24] and [Ref. 35]) emulating wireless communications technologies and the R&S®SMBV100B signal generator [Ref. 29], [Ref. 62] and [Ref. 73] for GNSS emulation.

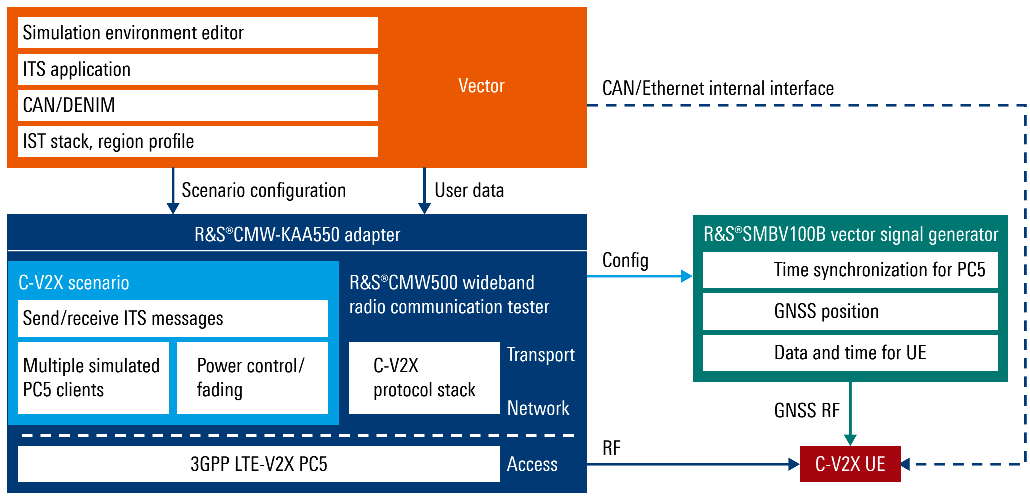
An example of full-range application and technology functionality testing is provided in [Ref. 34]. This setup verifies the functional operation of the cellular RATs GSM, UMTS and LTE, the non-cellular RATs Bluetooth®, UWB and WLAN, broadcast technologies like DVB-T and FM radio, and GNSS systems.

Cloud based service tests are possible as well. The flexibility of the platform allows integration of the test system with a user-specific cloud based service.

6.1.2 V2X application layer testing

V2X application testing combines emulation of the V2X scenario described by higher layers such as the ITS profiles with the radio protocol including RF layer emulation to test the RF link in combination with the ITS application. With the R&S®CMW-KAA550, Rohde & Schwarz developed an adapter for connecting industry-leading software simulation tools with the RF connectivity emulated by the R&S®CMW500 wideband radio communication tester. Vector's CANoe is a comprehensive software tool for development, testing and analysis of entire ECU networks and individual ECUs. It supports the entire development process – from planning to startup of entire distributed systems or individual ECUs. The versatile functions and configuration options of CANoe are used by network designers, developers and test engineers at OEMs and suppliers. Time-critical sequences are processed in real time. The incoming bus data is read via a bus interface, provided with a timestamp and processed. Data transmission to the bus also takes place in real time.

Fig. 66: C-V2X application and RF test solution



For analysis of wireless communications, the CANoe emulation software option CANoe .Car2x supports the C-V2X standard by communicating bidirectionally with the R&S®CMW500, used as an access point to the C-V2X radio interface known as PC5, and making use of the R&S®SMBV100B for simulating the satellite constellation needed to implement end-to-end test scenarios [Ref. 62]. Development takes place in a lab environment, making it possible to obtain reproducible test results with ECUs from various providers and under different, fully controllable radio conditions, including full control of the parameters used in all protocol layers from radio to ITS application.

The main features of this end-to-end solution are:

- Graphical user interface for easy and fast traffic scenario configuration and test result reporting
- GNSS route definition
- Communications between a real emulation of the C-V2X network layer and the application layer
- Flexible parameter configuration: vehicle speed, sidelink signal strength, radio interface scheduling parameter change, GNSS signal strength modification, etc.
- Multiple virtual cars for load simulation
- ITS event definition along the geographical route
- Full interpretation of ITS protocol stack messages for the existing standards: ETSI (EU), WAVE/SAE (USA), GB31024 (CN)
- Trace/graphic/data window for measurement and DUT-specific data
- Internal programming environment for advanced stimulation and analysis (CAPL)
- Bus connectivity CAN, LIN, FlexRay, Ethernet to analyze results or stimulate the ECU remotely

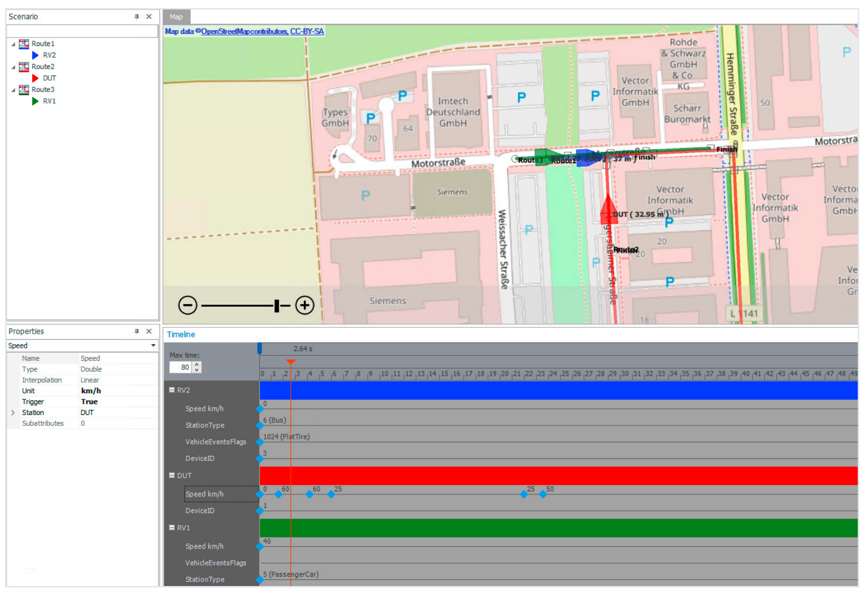
An example [Ref. 81] of an end-to-end scenario is the intersection collision warning test case (ICW) shown in Fig. 67. The purpose of this scenario is to test in a lab environment that, via the C-V2X channel, the device under test (DUT: ECU or OBU) receives a warning from the vehicle coming from the left or right, while the sight of the DUT is blocked by a building or another vehicle.

In the example scenario below, a stationary vehicle (blue color) is stopped near the intersection and blocks the visibility of the DUT (red color). While the remote vehicle (green color) approaches the intersection, the ICW application running on the DUT should warn the driver of the device under test about the risk of collision with the remote vehicle approaching the intersection. The timing of the warning should ensure that the driver has enough time to react and avoid the collision.

The speed of the remote vehicle and the DUT is fully controllable through the events defined on the timeline of the simulation. Additionally, various events as speed change, ITS events, sidelink power, etc., can be defined and configured. This makes it possible to simulate in great detail which event happens, where it happens and when it happens inside a scenario [Ref. 81]. Other scenarios can be emulated such as the scenarios presented in Chapter 2.1.

Fig. 67: Intersection collision warning test

Vector CANoe .Car2x software tool



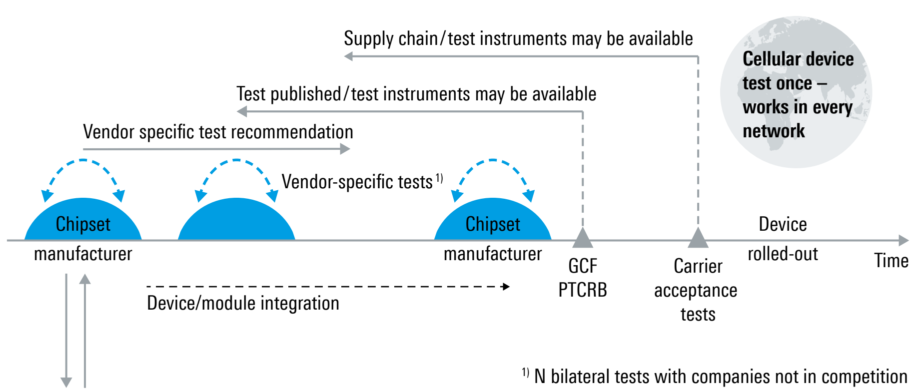
Another very important use case that is not easy to test in a real-world environment involves simulation of load in a traffic congestion case. The R&S®CMW-KAA550 end-to-end solution from Rohde & Schwarz and Vector allows simulation of more than 300 vehicles sending ITS messages. This allows testing the DUT under very difficult communications conditions.

The application note [GFM341] and the webinar [Ref. 58] describe further details of the application layer simulation connected to a mobile radio tester. [Ref. 65] gives a concise overview of trends in connected cars.

6.1.3 Aspects of V2X conformance testing

This topic is known in the wireless world since the introduction of GSM, the second generation of wireless communications, where aspects of international standardization and interoperability testing were discussed for the first time. Looking back now at this historical benchmarking decision, this was clearly a smart concept since it not only ensures proper interworking across various vendors and manufacturers, but can also be seen as a success story for market introduction. Since devices must go through a certification process to be certified for use in wireless communications networks like GSM, UMTS or LTE, end consumers can rely on this procedure and be confident of purchasing a working entity. With the introduction of direct communications technologies enabling communications between vehicles, it is obvious that vehicles from different vendors need to communicate properly with each other. Conformance testing ensures this interoperability. To understand the conformance process, first we consider standardization organizations like the 3GPP or IEEE which are relevant for automotive connectivity technologies. For example, the 3GPP specifies not only the technology itself but also some test parameters. The document [TS 36.521] contains the specification of RF parameters and performance aspects for LTE RF layer and RRM procedures. Signaling procedure requirements for LTE are standardized in [TS 36.523]. Besides the standardization organizations, we also need to understand the role of certification bodies like the GCF or CTIA/PTCRB. They define the certification criteria that are important for market introduction. Vendor-independent recognized test organizations (RTO) such as CTIA Authorized Testing Laboratories (CATL) represent the executive arm since they perform the actual conformance testing. Certification testing is not the last step in the product development cycle before market introduction. Preconformance testing, for example, allows a manufacturer of components or modems to perform in-house testing prior to final certification testing to increase the chances of successful final type approval. Not only devices have to undergo certification criteria, but also the test equipment has to pass test platform approval criteria to be designated as a validated test platform. Rohde & Schwarz has the longest history in type approval testing as it introduced the R&S®CRTP02 as the world's first GSM type approval system in 1991. Today, the company provides a wide range of preconformance and full type approval systems for various RATs. The latest solution released within this context is the R&S®TS8980FTA-3AM full type approval test system offering conformance testing from 2G to 5G, including both frequency ranges FR1 and FR2. The features required for automotive conformance testing are comprehensive technology support from 2G to 5G, a compact, modular and future-proof hardware setup, a user-friendly GUI, a concise reporting concept and, of course, outstanding specifications for the accuracy and test reliability. For further details on automotive conformance testing, see [Ref. 22] and [Ref. 25].

Fig. 68: Certification testing process



6.1.4 Data end-to-end testing including security analysis

The internet is becoming an integral part of our vehicles. An increasing number of vehicles are equipped with cellular and non-cellular wireless modules to exchange data, monitor measured values or even remotely control a system. The amount of IP traffic between the vehicle and the network is expected to drastically increase over the next few years, for example in automotive applications such as navigation, multimedia and firmware updates. A considerable number of vehicles will be connected to the internet using non-cellular technology such as WLAN or a cellular network such as LTE/LTE-A.

The R&S®CMW platform for LTE/WLAN and the R&S®CMX platform for 5G NR not only emulate a wireless connectivity network, but also provide a server extension with preinstalled application servers with the hardware option data application unit (DAU). This makes it possible to set up a reproducible data end-to-end connection in a lab based standalone environment for higher application testing. One example is the installed Iperf server (software.es.net/iperf) allowing UDP/TCP traffic scenario generation, which in combination with the RF layer fading option represents the perfect solution for emulating throughput testing scenarios under real-life conditions in a standalone environment. Furthermore, the R&S®CMW500 DAU allows bypassing of the internal server functions and connection to an external data server, e.g. enabling end-to-end application testing between a DUT and a user based cloud application server. This decouples the TCU software development or RF development from the application software development. The utilization range is extended through the entire development cycle of automotive applications, from hardware in the loop via software in the loop up to final integration and validation testing. A single platform supports all phases, from RF to protocol up to application and security layer testing [Ref.25], [Ref. 30], [Ref. 34]. As a specific test example and use case, [Ref. 33] provides further details of video quality application tests for automotive infotainment devices.

When designing connected vehicles, IP connection security becomes an important topic, particularly when the device will manage sensitive data or is connected to control systems. The term IP connection security originates from the IT world and describes the procedure used to secure the communications channels between two devices, typically by using authentication and encryption. Authentication and encryption are required for all communications channels to the internet in order to secure the information exchanged.

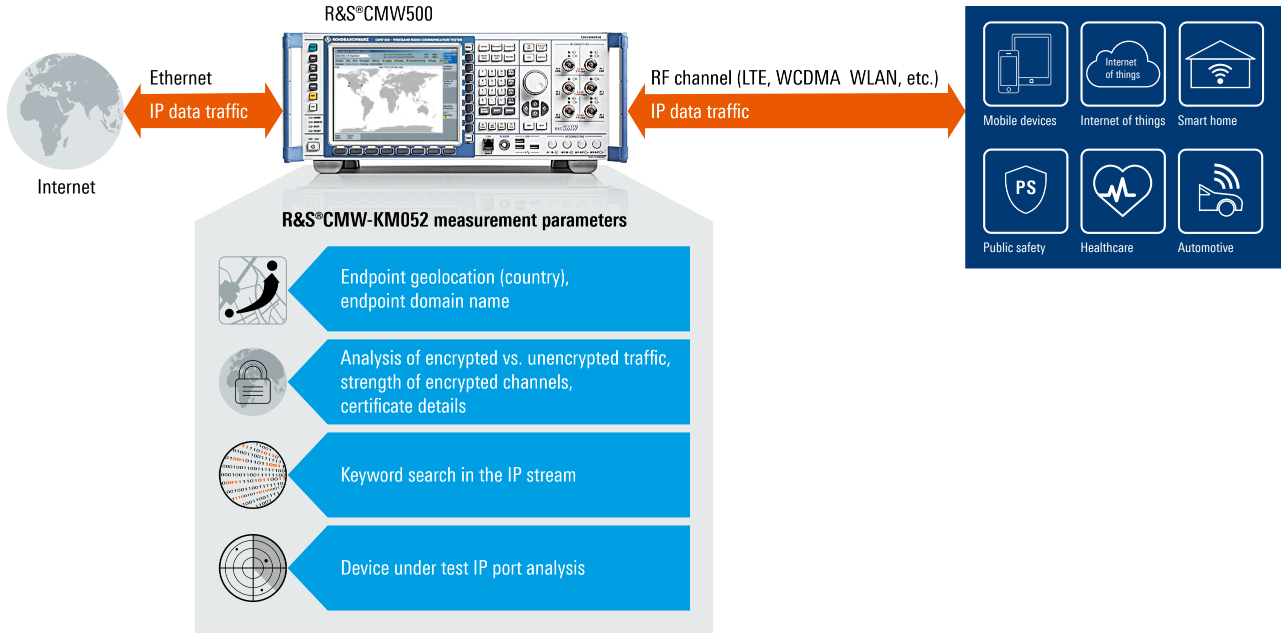
Developers need to focus on testing and identifying weak spots in their telematics applications at an early stage of development. This presents a challenge since measurement solutions for telematics units' IP connection security under fully controlled non-cellular and cellular network conditions are rather rare.

Rohde & Schwarz has integrated IP connection security analysis into its established R&S®CMW500 wideband radio communication tester. The R&S®CMW-KM052 option detects and analyzes IP data traffic in real time. It is a powerful add-on to the R&S®CMW500 real-time tester that supports all common cellular radio standards such as LTE, WCDMA and GSM as well as non-cellular standards such as WLAN in a single unit.

For the test, the R&S®CMW500 simulates the relevant network, including country and mobile network codes, and establishes a connection to the telematics device. The integrated data application unit (DAU) takes over IP configuration and establishes the IP connection. The DAU also provides internal services such as web servers, file transfer servers or an IMS server if required by the DUT. It is also a gateway to the internet and establishes the connections required for communications [Ref. 30] and [Ref. 31].

Fig. 69: Test setup for analyzing IP data traffic of mobile devices

[Ref. 30]



6.1.5 eCall and NGeCall setup and testing aspects

In-vehicle systems (IVS) are core elements in automobiles supporting eCall or NGeCall functionality. [Ref. 13], [Ref. 15] and [Ref. 63] provide details of eCall testing aspects. An eCall test setup should be able to emulate a GNSS signal to determine the current position and a cellular module (GSM, UMTS or LTE) to permit transmission of the minimum set of data (MSD) via a cellular network to a public safety answering point (PSAP). Modern eCall deployment is based on ETSI and CEN standards, whose development started more than a decade ago. The system uses an in-band modem to transfer the eCall minimum set of data (MSD) in a circuit-switched (CS) GSM voice channel over a 112 emergency call. 100% penetration of the system is estimated to be achieved by 2035, yet operators in Europe have already announced they will phase out support of CS GSM and UMTS networks over the next decade and want to replace it with 4G LTE and 5G infrastructures [Ref. 83]. This will also have an impact on the 112 emergency call, which will be replaced by an IMS emergency call for packet-switched (PS, i.e. IP based) networks like LTE and 5G. The new environment provides dramatic advantages in term of capabilities compared with the legacy eCall approach [Ref. 84]. Rohde & Schwarz offers a test solution for eCall and NGeCall where the R&S®CMW500 wideband radio communication tester is extended by the R&S®SMBV100B RF signal generator for GNSS emulation and the R&S®CMW-KA094 and R&S®CMW-KA095 software covers RF, signaling and conformance testing for eCall and NGeCall in line with CEN EN 16454.

Fig. 70: eCall and NGeCall test setup

Besides simple functional testing, eCall or NGeCall is tested in various lifecycle stages of the product: First, the design is verified at the module (or board) level in research and development. Production testing methods target mass throughput with automation functionality. Device level (IVS) testing includes coexistence and acceptance testing and device certification via conformance testing. In addition, at the system level (full vehicle testing) aspects such as radiated performance, desensitization and vehicle body specific tests are covered.

Testing of ERA/GLONASS is similar to eCall. The same hardware setup can be used and details of testing can be found in [Ref. 14]. The Rohde&Schwarz ERA/GLONASS solution is a test platform that has been accredited by the Russian Federation. There is no homologation of ERA/GLONASS devices in the applicable countries unless they are tested with the Rohde&Schwarz ERA/GLONASS test platform [Ref. 84].

6.1.6 Graphical test setup for automotive performance testing and field to lab

A telematic control unit (TCU) is an embedded system that enables vehicle tracking. It includes technology for positioning, mobile communications (including 2G, 3G, LTE or 5G), non-cellular technology (e.g. Bluetooth®, WLAN) and other processing capabilities.

A reliable mobile communications link is essential for good user experience even under very challenging radio channel propagation conditions and stressful application scenarios.

A scenario such as the TCU in a deep fade, for example, can result in a temporary failure of communications due to the severe drop in the channel's signal-to-noise ratio.

Using multiple radio technologies in a vehicle's TCU means a high probability of interference. LTE, Bluetooth® and WLAN can simultaneously operate in the 2.4 GHz band. It is an important topic of coexistence to ensure that these radio modules do not interfere with one another [Ref. 18].

To mitigate the fading effect, it is necessary to increase the radio coexistence capability and improve the TCU performance. Extensive tests must be conducted during the product design phase to ensure proper device performance. This can only be achieved with a good hardware design that includes the RF frontend, an error resilient receiver as well as modern and robust digital signal processing.

R&S®CMWcards is a graphical test script creation tool that runs on the R&S®CMW500 wideband radio communication tester and requires no prior programming knowledge. It is possible to create various signaling test scripts by simply setting up a hand of cards.

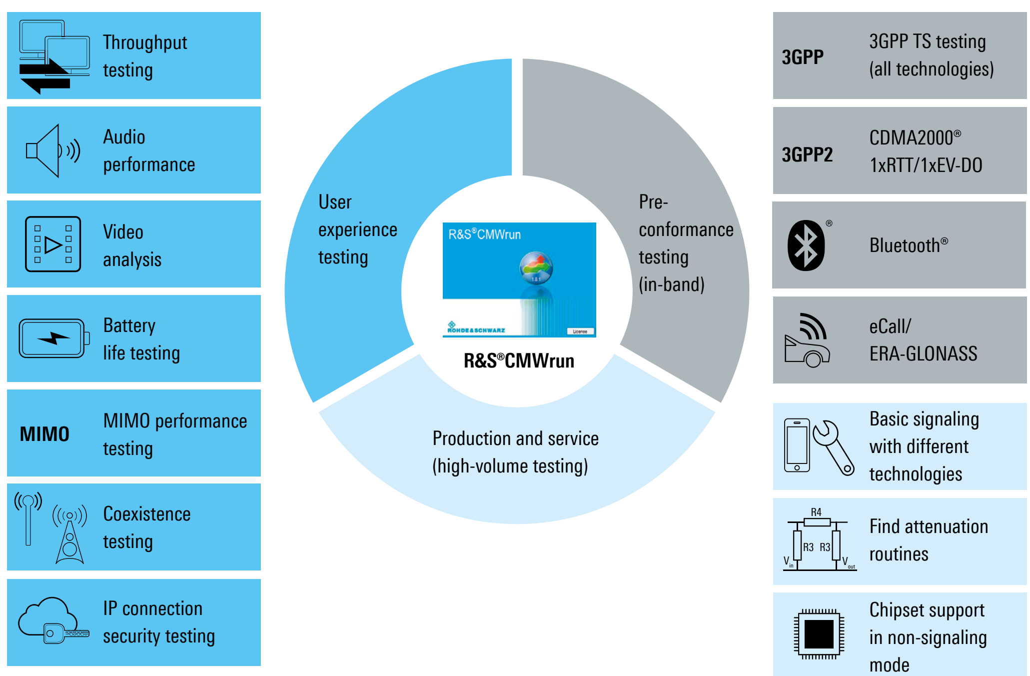
In combination with a configurable radio propagation channel with different fading profiles, the test scripts can be used to benchmark the performance of the device. R&S®CMWcards provides a repeatable and deterministic test environment in which test scenarios can easily be combined. See [Ref. 27] and [Ref. 28] for further details.

The field-to-lab (F2L) application works closely with R&S®CMWcards and allows users to reproduce real network scenarios in the lab. With the help of drive testing equipment like network scanners and/or smartphone based test tools like QualiPoc Android, users are able to measure network based key performance indicators (KPI) and collect network-specific parameters that can be used in lab based measurements. The majority of field issues can be investigated in a controllable, repeatable and deterministic environment.

R&S®CMWcards with F2L is a powerful tool for verifying field behavior. It extracts the network configurations from the field logs and imports them into R&S®CMWcards to simulate test scenarios with live network configurations, including cell information, RRC and NAS messages [Ref. 28].

R&S®CMWrun is an application platform consisting of the R&S®CMWrun sequence software tool and another basic set of applications allowing configuration of test sequences and parameters without detailed knowledge of the remote programming of the instrument. It is a versatile graphical tool to configure test sequences consisting of test steps, test parameters and of course a test report. With this tool, regression tests can be fully automated and benchmarking is possible in an easy way. A general overview of various applications that can be configured with R&S®CMWrun is given in [Ref. 26].

Fig. 71: R&S®CMWrun use cases



6.1.7 Infotainment testing

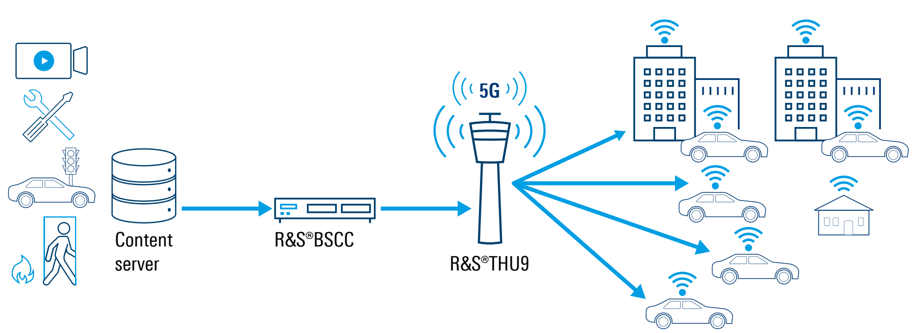
Testing of infotainment applications includes legacy audio and video services like analog FM radio reception or digital standards like DVB or DAB. A test setup should support compliance testing across various broadcast and connection standards. This includes testing of car radio modules and displays using all existing analog and digital TV and radio broadcast standards. Rohde & Schwarz has over 80 years of experience in broadcast and media including the relevant test and measurement aspects. The portfolio ranges from high-power amplifiers and media encoding solutions up to signal generators and analyzers supporting broadcast technology standards. The documents [Ref. 24] and [Ref. 43] provide several examples of automotive-related infotainment services, applications and testing aspects. Rohde & Schwarz is supporting the industry with a new and cost-effective end-to-end solution that is compliant with the 3GPP standard. This solution is intended to help network operators to deliver better quality of service in combination with higher quality of experience, all with reduced costs.

The 5G broadcast/multicast solution is composed of a multicast core network with high or medium power transmitters in the access network, supporting FeMBMS.

Running as a part of the core network, the software defined R&S®BSCC, including the broadcast multicast service center (BM SC), MBMS-GW and a centralized multicell/multicast coordination entity (MCE) is a new solution that enables the delivery of multimedia content over LTE/5G networks in broadcast mode. It encapsulates multimedia content into specific FeMBMS bearers to be delivered from the evolved packet core (EPC) down to the receiver. It allows network operators to roll out advanced FeMBMS services that mix potentially different types of media over networks with hybrid unicast/broadcast coverage.

The advantage of vehicle broadcasts compared to NR-V2X multicasts is a much larger coverage area, and large-area multicast operations complementing the services offered in the V2X domain [Ref. 26].

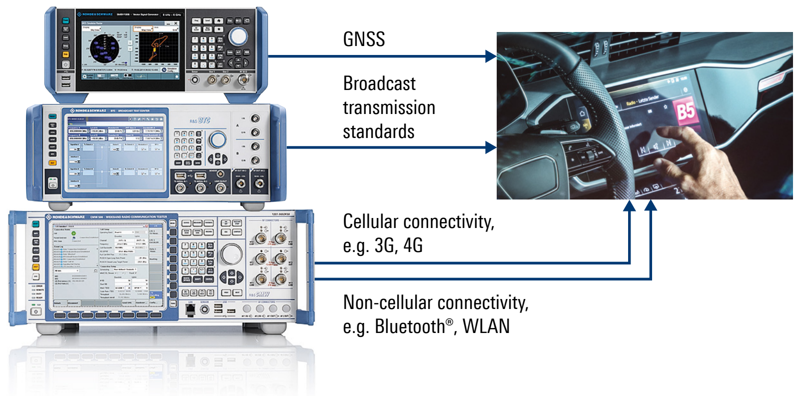
Fig. 72: 5G broadcast architecture and Rohde & Schwarz solution



Sophisticated infotainment modules will be extended with cellular connectivity (V2N) to support streaming services and non-linear traffic. The good old car radio has justifiably been rebranded as the car infotainment system, bringing a great deal of new functionality onboard. The main requirement for a test system is support for multiple technologies such as wireless connectivity (e.g. WLAN, Bluetooth® or UWB), cellular (e.g. 2G to 5G), video and audio (e.g. FM, DAB, DVB, etc.) and satellite navigation technologies. A test system should be flexible enough to support most of these technologies or be upgradable. Infotainment test requirements overlap partly with the end-to-end testing fields based on the R&S®CMW platform, but will further extend the services, e.g. by extending with broadcast technologies. One interesting example for automotive applications is transmission of a video stream over IP using the application server and either the R&S®VTE video tester or the R&S®AdVISE inspection software using an off-the-shelf

HD webcam and microphone to monitor audio and video quality KPIs. A setup described in [Ref. 41] enables simultaneous testing of vehicle infotainment devices. This infotainment test setup example consists of the R&S®CMW500 wideband radio communication tester, the R&S®SMBV100B RF signal generator and the R&S®BTC broadcast test center.

Fig. 73: Test setup example for automotive infotainment RF characterization



6.2 V2X performance testing in the field

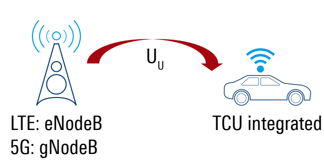
The previous chapter discussed the level of device testing in the lab, which is a clear precondition for good performance of connectivity modules integrated into vehicles.

However, for good performance of the complete vehicle with all of its integrated and embedded modules (TCU, antennas, etc.) during normal operation, it is recommended to verify the wireless connectivity also on test tracks in the field.

6.2.1 Responsibilities for in-field performance in the V2X ecosystem

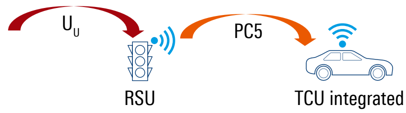
The automotive ecosystem of cellular V2X is just starting in the industry, but it is already clear that it will be complex in the sense that there are multiple players responsible for the performance of different parts of the overall solutions. This chapter will differentiate some of the in-field responsibilities. Since mission-critical and sometimes safety-critical use cases are involved, the expectation is that in the long run, we will also see service level agreements related to performance levels between different players' solutions that will need to be verified.

The following section lists the different responsibilities.



The car OEM is responsible for V2N performance in the field (including integrated TCU and car antennas). This can also be outsourced to a test service provider on behalf of the OEM.

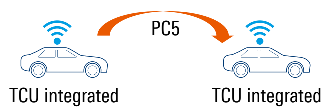
Typical questions are:
- ▶ What is the TX/RX performance/coverage using the integrated TCU (RF layer)?
- ▶ What application performance/QoE (data throughput, video performance, etc.) does the TCU provide (application layer)?



RSUs should support the Uu and the PC5 interface. The RSU supplier and RSU operator are responsible for the RSU coverage and performance in the field. The car OEM is responsible for the V2I performance in the field (including integrated TCU and car antennas). This can also be outsourced to a test service provider on behalf of the OEM.

Typical questions are:

- ▶ What is the coverage (RSRP) of the RSU PC5 related to the integrated TCU (RF layer)?
- ▶ What message performance/QoE does the RSU/TCU provide (application layer)?



The car OEM is responsible for the V2V performance in the field (including integrated TCU and car antennas). This can also be outsourced to a test service provider on behalf of the OEM.

Typical questions are:

- ▶ What is the coverage (RSRP) of TCU-TCU PC5 communications related to the integrated TCUs (RF layer)?
- ▶ What message performance/QoE does the TCU/TCU provide (application layer)?

6.2.2 V2X testing use cases in the field

From the different responsibilities within the automotive ecosystem, we can derive V2X testing use cases in the field.

6.2.2.1 Car connectivity test in the field

This test should verify the performance of the car connectivity with the integrated TCU connected to integrated antennas concerning the mobile network connectivity (Uu interface) and TCU connectivity to RSU and other cars (PC5 interface).

a) Using a reference RF measurement (e.g. with an R&S®TSMA scanner connected to R&S®ROMES4 software for real-time in-field analysis) in parallel to the in-field TCU test, the tester can compare the behavior and the results of the car coverage measurements with the reference RF situation (in terms of signal strength, RSRP, and signal quality, SINR) indicated by the scanner measurement.

R&S®TSMA6 autonomous mobile network scanner

b) If application layer tests (e.g. data throughput, video streaming performance, etc.) are also required, QualiPoc Android (smartphone based optimization software for quality of experience (QoE) evaluation) is recommended for use in parallel to application testing of the TCU in the field. Here, it must be kept in mind that the smartphone is using its internal antennas (probably inside the car). The QualiPoc Android smartphone will provide lower application performance due to reception disadvantages compared to the car antennas. However, getting lower application performance of the car compared to the smartphone gives a clear indication of the problem.

Qualipoc Android

6.2.2.2 RSU performance verification

Roadside units (RSU) are a sort of base station and like any other base station, the deployment must be accepted. RSUs are often situated at traffic lights and help to make the traffic flow safer and smarter. Since non-optimized deployment of an RSU can be dangerous (safety-critical), a site acceptance test analyzing the coverage area and message performance of an RSU is highly recommended to ensure that vehicles obtain RSU information with sufficient performance and early enough. The RSU coverage test ideally uses an R&S®TSMA scanner connected to R&S®ROMES4 software for real-time in-field analysis. The message performance from the RSU can be tested using QualiPoc Android (smartphone based optimization software for quality of experience (QoE) evaluation), once smartphones are able to understand the PC5 interface (announced by major smartphone chipset suppliers towards the end of 2020) [Ref. 87].

6.3 Chamber and OTA based automotive connectivity test aspects

6.3.1 Over-the-air (OTA) testing

OTA is a common buzzword in test and measurement, especially since the introduction of 5G NR, describing a test setup in a shielded environment using an over-the-air (OTA) connection between the test equipment and DUT. A simple example demonstrating the obvious need for an OTA connection is the introduction of smart antennas leveraging beamforming. This has created a new T&M domain due to the need to analyze the signal quality versus the spatial domain. The 3D antenna radiation pattern represents the only way to verify whether the smart antenna directs the beam in the desired direction. Therefore, testing is necessary in an OTA environment. [Ref. 36] provides a general overview of the most relevant antenna test parameters such as EIRP, TRP, TIS, gain and directivity. Requirements for OTA test setups range from small form factor shielding chambers designed for production environment testing, through high accuracy and high shielding chambers optimized for type approval testing, up to large chamber sizes for large devices, even up to full vehicle testing. The target set of antennas under test (AUT) ranges from passive antennas via active antennas with integrated amplifiers up to high integration circuit antennas. Major aspects that should be considered in an OTA test setup are the aperture size D affecting the near-field and far-field distance given by the Fraunhofer formula $(2 \cdot D^2 / \lambda)$, the frequency range, the shielding effectiveness and the quality of the quiet zone. An additional requirement for the OTA setup in many cases is compliance with standards according to regulatory bodies such as CTIA. The white paper

[Ref. 59] and application note [Ref. 85] describe general aspects and considerations of OTA testing in a detailed way.

In the automotive environment, OTA testing is required in several situations, e.g. directive antenna testing, situations where shielding is required, situations where access to the DUT via cable is not possible, EMC testing, radar testing and full vehicle testing.

Rohde & Schwarz has a long history as well as extensive experience in OTA testing. Together with a broad portfolio of test and measurement equipment, we provide a one-stop shop for OTA testing. The Rohde & Schwarz portfolio of OTA chambers covers the full range from multipurpose, full anechoic chambers up to chambers designed for specific applications, such as EMC chambers. Fig. 74 provides an overview of the Rohde & Schwarz chamber portfolio for OTA test scenarios. Some details about these chambers from left to right:

With the wireless performance test chamber (WPTC), Rohde & Schwarz offers a chamber portfolio with five standard sizes from approx. 2 m^3 up to 5 m^3 and even user-specific sizes. It is designed for wide frequency range OTA testing of larger DUT sizes allowing near-field or far-field OTA measurements. The application range covers research and development as well as validation and conformance testing (e.g. CTIA) of passive and active antennas.

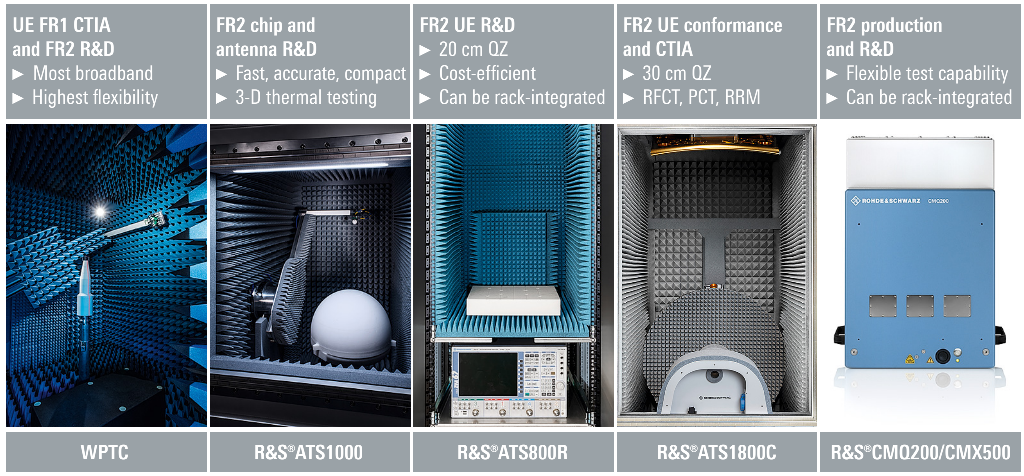
To fulfil the requirement for high shielding effectiveness and provide compact and portable OTA systems targeting direct far-field (DFF) measurements of chipsets, antennas and components, Rohde & Schwarz introduced the R&S®ATS1000 antenna test system [Ref. 75]. As an innovative extension representing very interesting use cases, R&S®ATS-TEMP allows thermal diagnosis for antenna characterization in a temperature range from –40 °C up to +85 °C.

To perform indirect far-field (IFF) testing based on the principle of CATR using a reflector allowing larger DUT sizes in a compact chamber, Rohde & Schwarz introduced two chambers with the R&S®ATS800 and R&S®ATS1800C. The R&S®ATS800 either as a benchtop setup (R&S®ATS800B) or rack based solution (R&S®ATS800R) allows quick antenna characterization for DUT sizes up to 40 cm in a compact form factor. The R&S®ATS1800C offers very high quiet zone accuracy combined with very high shielding effectiveness in a compact range [Ref. 76]. The target application group is research and development and 3GPP-compliant conformance and preconformance testing. With the azimuth over elevation positioner, the DUT can be tested in full 3D radiation.

The R&S®CMQ200/R&S®CMQ500 shielding cube offers an OTA solution with a very small form factor and high shielding effectiveness. It is designed for production environments or research and development. With features such as an automatic door and up to six cubically arranged antenna probe positions, OTA tests with high throughput can be performed easily and reliably.

To tackle the challenge of OTA testing of large-aperture antenna arrays in the FR1 frequency range within a relatively small space, Rohde & Schwarz developed the R&S®PWC200 plane wave converter. It can be understood as a phased antenna array that forms planar waves inside a specified quiet zone within the radiating near field of the 5G FR1 DUT for real-time radiated power and transceiver measurements (EVM, ACLR, SEM, etc.) [Ref. 77].

Fig. 74: OTA chamber portfolio overview



6.3.2 Interference testing/EMC

The aspect of electromagnetic compatibility is not only related to automotive, but due to the high integration level of various technologies in a small form factor, EMC is an important aspect to be considered in test and measurement for automotive. Due to space constraints, this technology paper cannot focus on EMC details. As a key player in EMC testing, Rohde & Schwarz provides various turnkey solutions, including RF chambers, test receivers, broadband amplifiers, signal generators, turntables and vehicle lifts. As a trusted partner for test and measurement solutions, Rohde & Schwarz provides solutions for EMC component or subsystem testing, i.e. hardware in the loop as well as full vehicle validation testing. EMC precompliance and compliance test systems provide an off-the-shelf solution from a single supplier. As technology leader in EMC testing, we must comply with various norms and regulation processes. For example, IATF 16949:2016 specifies that external calibration laboratories need to fulfill the requirements for accredited calibrations and test equipment management in addition to the ISO 9001 requirements. Rohde & Schwarz fulfills this requirement with its R&S®Accredited Calibration. Companies need to consider the accredited calibration scope of the calibration laboratory when selecting an external calibration partner in the future. Other important standards for EMC testing are e.g. CISPR 12 – automotive, protection of off-board receivers, CISPR 25 – automotive, protection of on-board receivers, CISPR 36 – automotive, radiated emissions below 30 MHz and the radio equipment directive (RED) 2014/53/EU adopted April 16, 2014, effective June 13, 2016.

Further details on EMC test aspects can be found in [Ref. 66] and [Ref. 67].

6.3.3 Full vehicle testing (FVT)

Today's vehicles support not only simple broadcast radio systems but also include complex connectivity domain controllers. To support these connectivity based functions and services, vehicles require a large number of high-performance antennas, integrated at various locations inside and outside the vehicle. The body and shape of the vehicle affect the antenna performance and the antennas must function as an integral part of the vehicle. There is no clear trend visible in the industry; budget cars are equipped with individual antenna solutions for mobile communications and navigation while premium cars apply highly integrated antenna modules. Several control units are integrated into the antenna module to reduce system complexity. Connection to other control units in the vehicle may be via RF coaxial cabling, twisted pair Ethernet or even wireless connections within the vehicle itself. Colocating of control units and antennas simplifies and reduces wiring throughout the vehicle and takes up less space to save costs. Through testing, one may verify the proper interworking and improve the signal quality. There are known effects such as mutual coupling, interference or coexistence between different radios and antennas, and the influence of radiation characteristics by cable length and antenna design.

To understand the difference between passive antenna testing and active antenna testing, in a simple OTA setup for a passive antenna, a vector network analyzer is applied to provide the input signal into the antenna under test and to measure the output. The measurement results are the well-known S-parameters, e.g. transmission coefficient or reflection coefficient [Ref. 80]. Passive antenna testing happens mainly in module or component development to verify the behavior of one single entity. Full vehicle antenna testing (FVT) considers the entire car as the device under test and uses an indoor test facility including high-performance full anechoic chambers for precise measurement and reproducible testing methodologies. An important aspect is the requirement within FVT setups to emulate and test multiple radio technologies in parallel, especially when considering coexistence aspects among them.

Analysis of car antenna transmit levels is possible in real-world operation. Test setups may include customized 3D solutions with a turntable, vehicle lift and single-probe moving antenna arm, and complete 3D antenna characterization of the DUT with two-axis positioner and spherical gantry system. Different spherical antenna scan modes can be implemented [Ref. 82].

For size reasons, such systems are specifically designed for near field antenna measurements.

Test aspects of full vehicle systems include:
- Frequency ranges from 400 MHz to 6 GHz with possible extension to mmWaves
- Passive antenna measurements such as directivity, gain, efficiency, radiation pattern, phase center determination
- Near field – far field (NF-FF) transformation: magnitude and phase information measured in near field and then converted to far field
- Measurements based on CTIA-certified test methods
- Active antenna measurements such as equivalent isotropic radiated power (EIRP), total radiated power (TRP), total isotropic sensitivity (TIS), sensitivity, half power beam width, error vector magnitude (EVM) and adjacent channel leakage ratio [Ref. 36]

Active antenna measurements would involve connecting the vehicle to the radio communication tester, performing an antenna radiation pattern measurement and plotting the radiation pattern in 3D. An anechoic 3D measurement chamber is required and the DUT is lifted a bit higher and rotated 360° in 2D. The gantry arm with single pole antenna implements one of the predefined antenna spherical scan modes. The measurement also includes approx. 30° under the vehicle, i.e. approx. 210° in 3D antenna radiation pattern.

The car radio system supports bidirectional communications. It is important to ensure that the transmitter has very good spurious-free emissions. For performing the spurious emissions test, the car is placed on a turntable in a 2D semi-anechoic chamber. The wireless modules of interest are connected over the air (OTA) with a radio communication tester using a signaling connection and the DUT is rotated over 360°. A spectrum analyzer monitors the transmitted signal in different subbands. For measuring the lower subband from 400 MHz to 1 GHz, a lowpass filter is used before the spectrum analyzer to just measure the lower band. For the middle section, a bandpass filter is used before the spectrum analyzer to measure from 1 GHz to 3 GHz. Finally, a highpass filter is used to measure the upper band from 3 GHz to 18 GHz.

The reason why the spurious performance is checked up to 18 GHz is that there are some automotive standards operating at 5.9 GHz and the third harmonic is around 18 GHz. This is in compliance with e.g. the European radio emission directivity (RED) regulation [Ref. 79].

In addition to an RX antenna connected to a spectrum analyzer outside the vehicle, it is possible to place a power measurement device such as the R&S®NRQ6 inside the cabin to monitor faint signals that may be absorbed by the body or seat material inside. If these signals emitted by the radio modules inside the vehicle are absorbed, the outside chamber antennas will not be able to pick them up. Any passengers inside the vehicle with implanted medical devices would be at risk. The advantage of the R&S®NRQ6 frequency selective power sensor is that it is connected via LAN and does not emit any radio signals that would obstruct the measurements.

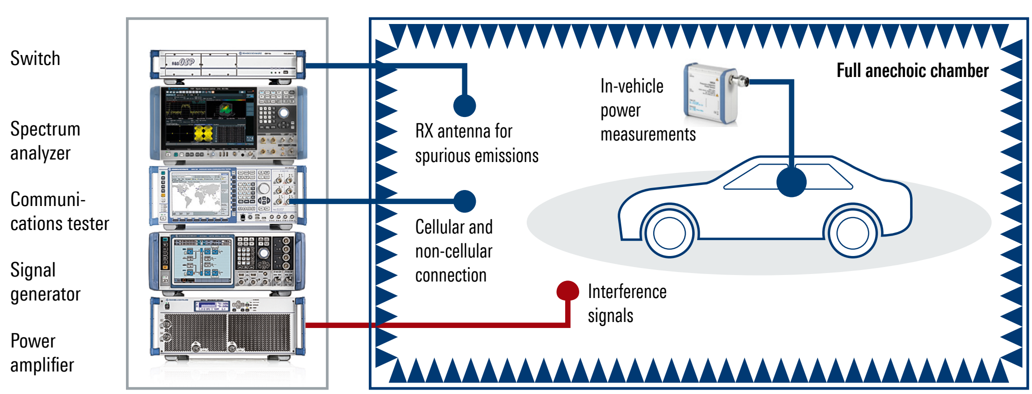
FVT also includes receiver coexistence testing. After the car is connected to the radio communication tester in combination with a vector signal generator, interference signals are introduced. However, receiver coexistence testing is performed depending on the test plan. The test plan consists of multiple modules such as risk assessment, intended use determination, functional wireless performance and worst case determination, RF EM environment re-creation and testing and reporting [Ref. 80].

One very important aspect to keep in mind for the test is the absorber material of the test chamber. It is critical to have radio silence inside the test chamber. The shielding effectiveness of the absorber is very important up to at least 18 GHz, and if radar is tested in the same chamber, than up to at least 90 GHz.

The test setup challenges are operability and flexibility in addition to size and equipment variety. Rohde & Schwarz works as a single-source supplier to provide turnkey solutions for full vehicle testing.

Further aspects of over-the-air testing of automotive connectivity systems at the full vehicle level are covered in [Ref. 78].

Fig. 75: Full vehicle OTA testing setup example



6.4 Additional automotive test and measurement aspects

The objective of this document is to present the various technology aspects of automotive connectivity. It is clear that there are many other electronic, electrical and wireless applications and technologies inside a vehicle. For the sake of completeness, the following chapter provides a concise overview of the test and measurement aspects of these additional automotive applications along with literature sources where readers can find more detailed information.

6.4.1 Production testing for vehicle applications, ECU

An electronic control unit (ECU) is a small device in a vehicle body that is responsible for controlling specific functions from engine control to window openers, door locks and emergency braking.

Each ECU typically contains a dedicated chip that runs its own software or firmware and requires power and data connections to operate.

ECUs receive input from different parts of the vehicle depending on their function. they communicate with actuators to perform an action based on the inputs. For example, an airbag ECU would receive inputs from crash sensors and sensors to detect when someone is sitting in a particular seat and start the airbag ignition function.

Electronic control units (ECU), telematics control units (TCU) and other automotive modules are produced at high volume. Production requires short test times and high precision. Today's production lines for wireless devices require an optimal combination of flexibility, performance and capacity utilization. The R&S®CMW platform with its R&S®CMW100 communications manufacturing test set and R&S®CMP200 for 5G FR2 testing represents an ideal solution for production, supporting high efficiency through parallel testing, high measurement accuracy and optimized test times [Ref. 25]. Providing a comprehensive and flexible wireless communications tester, the R&S®CMW100 not only supports cellular standards but also wireless connectivity such as WLAN, Bluetooth® or UWB. Up to eight RF ports support parallel testing. A wide range of shielded boxes offer compact turnkey off-the-shelf solutions from a single supplier. Some of them are specially designed for manufacturing purposes featuring automatic doors, self-calibration routines and wide frequency ranges.

Since production testing of automotive units such as ECUs, TCUs, etc. entails broader test aspects such as multiple bus systems to interconnect the entities, positioning systems, various radio technologies and even environmental simulations such as climate chambers, Rohde & Schwarz offers a wide range of solutions that can be combined and remote controlled. With the R&S®CompactTSVP, a modular platform supports parallel testing of several bus connections such as BroadR-Reach, CAN, LIN, USB and audio testing, or just simple functional testing such as the airbag control ECU. The R&S®RTP oscilloscope family offers a modular, scalable platform for automated in-circuit, boundary scanning and functional tests for ECUs in mass production. It ensures test system reliability based on its built-in self-testing capability and in-system calibration especially for RF connectivity and radar boards. Since the different aspects of vehicle based ECUs are not part of this technology paper, further information is available via [Ref. 60].

6.4.2 TCU/smart antenna testing

With the introduction of automotive connectivity into telematic control units (TCU), the digital cockpit is becoming a reality. Over the air software provisioning, artificial intelligence and augmented reality routines adopting driver behavior and real-time mobility service provisioning are only a few new applications that require testing. One major aspect in terms of TCU testing is the over-the-air connection between a system simulator and the DUT. Vehicular modems apply more and more smart antenna designs entailing directive radiation behavior (beamforming) and the integration level of TCUs is getting higher and higher. As a result, conducted access for testing is not always possible. OTA test setups must contain a shielded chamber to avoid interference from outside. They must also suppress reflections since they are full anechoic chambers (FAC). Rohde & Schwarz offers a broad portfolio of such chambers, from small shielding chambers for module and component testing and various full anechoic chambers (Fig. 74) up to user-specific chamber sizes enabling full vehicle testing.

A major challenge in TCU testing is the high integration level with multiple modems and RATs in a vehicle and the parallel testing approach. The focus is on standardized turnkey solutions in production line testing with support for RAT and connectivity aspects such as:

- Over-the-air software updates and diagnostics (5G FR1 and later, FR2 mmWave)
- eCall, C-V2X connection
- Multiple bus systems, including CAN, FlexRay, LIN, Ethernet
- Support for 4G LTE/5G with backward compatibility
- Location positioning via GPS, Galileo, GLONASS, BeiDou
- IEEE 802.11p (DSRC)
- Integrated antennas for wireless connectivity and broadcast technologies such as FM, DVB-T2, DAB, etc.

With the R&S®CompactTSVP family of products, Rohde & Schwarz offers an open test platform based on CompactPCI and PXI (PCI eXtensions for Instrumentation) that has been developed for high-performance automated test equipment (ATE) applications. To allow flexibility, the R&S®CompactTSVP can be used as a test and measurement platform controlling test instruments such as mobile radio testers, or as a switching application platform to perform time consecutive measurements in an automated test setup. In addition to the R&S®CMW100 and R&S®CMP200 mobile radio testers, various measurement modules are available for industrial use in research, development and production.

Further details on TCU test aspects are provided in [Ref. 61] and [Ref. 44].

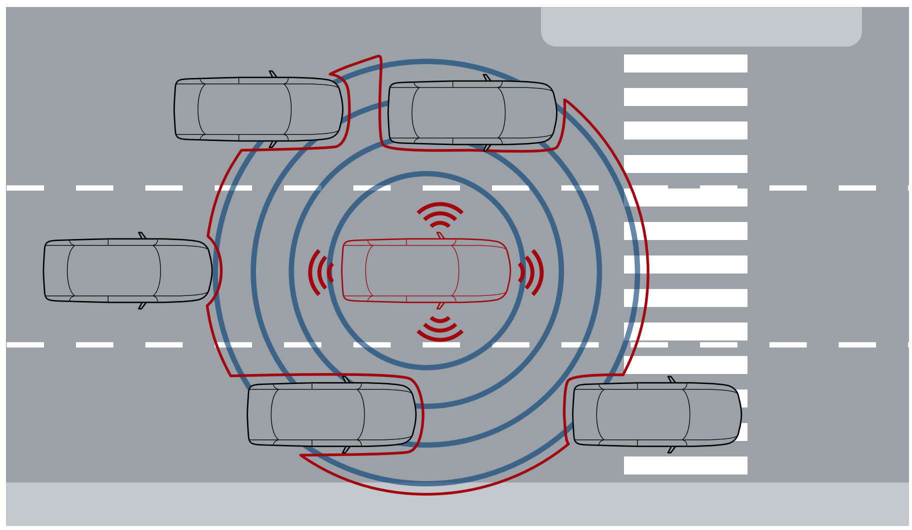
Fig. 76: TCU feature test coverage with a production focus

Feature	R&S®CMW100	R&S®CompactTSVP	R&S®CMP200
Cellular			
2G	•		
3G	•		
4G	•		
5G (sub6 GHz FR1)	•		
5G (FR2/mmWave)			•
GNSS			
GPS	•		
Galileo	•		
GLONASS	•		
BeiDou	•		
V2X			
DSRC	•		
C-V2X	•		
eCall			
Micro		•	
A2B		•	
AMP		•	
Vehicle access			
Bluetooth® low energy	•		
UWB			•
K-LIN		•	
Tuner			
AM		•	
FM	•		
DAB	•		
Wi-Fi	•		
Bluetooth® low energy	•		
TPMS (tire pressure monitoring system)	•	•	
CAN		•	
LIN		•	
Backup battery		•	
USB		•	
Ethernet (1000BASE-T)		•	

6.4.3 Automotive radar

The different aspects of automotive radar are not a topic of this white paper, but they play an essential role in the evolution of ADAS and self-driving cars. There are various test aspects in the background of radar such as ensuring radar fitness, providing target simulation and testing signal quality including interference influences. Rohde & Schwarz has a huge portfolio of groundbreaking radar test solutions such as radar signal generation, radar signal analysis, radar interference testing, high-resolution radar material analysis, compliance testing, target simulations, sensor calibration and OTA testing setups. Rohde & Schwarz offers the R&S®ATS1500C, a full anechoic chamber specifically designed for automotive radar sensors [Ref. 74]. A comprehensive overview of automotive radar testing is provided in [Ref. 47] and [Ref. 68].

Fig. 77: Automotive radar



6.4.4 Automotive Ethernet

Developments in advanced driver assistance systems (ADAS) are creating a new approach to in-vehicle network (IVN) architecture design. With today's vehicles leveraging at least one hundred ECUs, the current network architecture has reached its limits. The automotive industry is now focusing on a domain or zonal controller architecture to simplify network design and maximize performance. A domain controller can replace the functions of many ECUs providing capabilities for high speed communications, sensor fusion and decision-making, as well as supporting high speed camera, radar and lidar interfaces. All these interfaces will require a much larger bandwidth than what is offered by today's most common automotive interfaces (CAN, LIN, etc.). Data traffic from sensors traveling through ECUs and gateways to the actuators needs to have additional levels of security and include time-sensitive information for sensor fusion. Automotive Ethernet was introduced in 2012 to solve these problems by making use of existing TCP/IP technologies that are familiar from the computer world. It is based on a single twisted pair and can scale up from 10 Mbps to 10 Gbps speeds depending on the application.

The R&S®RTP oscilloscope and the Rohde & Schwarz vector network analyzer (VNA) families can help users verify correct protocol and data transmission, validate sleep and wake-up cycles as well as perform precise measurements on boot times. The solutions can check whether Ethernet communications is resistant to EMI and ensure interface compliance on the physical layer. The R&S®RTP and the Rohde & Schwarz VNAs can also test additional technologies used for ECUs and in-vehicle networks, e.g. signal integrity, debugging DDR, PCIe, EMI and bus systems such as Ethernet, CAN, LIN. Further information is available in [Ref. 37] and [Ref. 69].

6.4.5 Power supply testing

48 V mild hybrid electrical vehicles (MHEV) help to reach the required CO_2 fleet average and are expected to dominate the market for the next years. The moderate safety regulations (< 60 V) and low additional costs make MHEV an attractive alternative to other EV technologies. One of the key success factors for MHEV is optimizing the performance of the 48 V battery pack formed by multiple low voltage battery cells (e.g. 3.7 V). Intelligent battery management systems (BMS) allow active monitoring, control and management of various battery cell parameters such as voltage, current, thermal and energy management, cell balancing state of charge (SOC) and state of health (SOH). A typical BMS consists of one or more cell monitoring controllers (CMC) and a battery management controller (BMC) depending on the voltage level of the battery pack; BMC and CMC are set up in a primary/replica architecture. The voltage limitation of the CMC or the number of cells determines the number of required CMC (e.g. 14 cells per controller).

The R&S®RTP oscilloscope family provides a customizable test system that is scalable to the required number of cells. It supports four channels up to 64 V/20 A or one channel up to 256 V or 80 A. Battery models with voltage and impedance can be loaded.

This white paper does not provide details on electric vehicle battery testing, but such details can be found in [Ref. 86].

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Note: All links have been checked and were functional when this document was created. However, we cannot rule out subsequent changes to the links in the reference list.

8 SPECIFICATIONS

ETSI TS 102637-3	Intelligent transport systems (ITS); vehicular communications; basic set of applications; part 3: specifications of decentralized environmental notification basic service (2010-09)
ETSI EN 302637-2	Intelligent transport systems (ITS); vehicular communications; basic set of applications; part 2: specification of cooperative awareness basic service (2014-09)
ETSI EN 302637-3	Specifications of decentralized environmental notification basic service (2014-09)
ETSI EN 303613	Intelligent transport systems (ITS); LTE-V2X access layer specification for intelligent transport, systems operating in the 5 GHz frequency band
IEEE 802.11, Part 11	Wireless LAN medium access control (MAC) and physical layer (PHY) specifications (2012)
IEEE 802.11bd/D.2	Draft standard for information technology – telecommunications and information exchange between systems local and metropolitan area networks – specific requirements/D.2 part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications
IEEE 802.15, IEEE 802.15.4z	HRP/LRP UWB enhancements
TR 38.885, 3GPP TR 38.885	Study on NR vehicle-to-everything (V2X) (Release 16)
TS 23.002, 3GPP TS 23.002	Network architecture
TS 23.287, 3GPP TS 23.287	Architecture enhancements for 5G System (5GS) to support vehicle-to-everything (V2X) services (Release 16)
TS 24.008, 3GPP TS 24.008	Technical specification group core network and terminals; mobile radio interface layer 3 specification; core network protocols; stage 3
TS 24.301, 3GPP TS 24.301	Non-access stratum (NAS) protocol for evolved packet system (EPS)
TS 24.501, 3GPP TS 24.501	Non-access-stratum (NAS) protocol for 5G system (5GS); stage 3
TS 25.101, 3GPP TS 25.101	UMTS UE radio transmission and reception (FDD)
TS 36.300, 3GPP TS 36.300	Technical specification group radio access network; evolved universal terrestrial radio access (EUTRA) and evolved universal terrestrial radio access network (EUTRAN); overall description; stage 2
TS 36.302, 3GPP TS 36.302	Evolved universal terrestrial radio access (EUTRA); services provided by the physical layer
TS 36.321, 3GPP TS 36.321	Evolved universal terrestrial radio access (EUTRA); medium access control (MAC) protocol specification
TS 36.322, 3GPP TS 36.322	Evolved universal terrestrial radio access (EUTRA); radio link control (RLC) protocol specification
TS 36.323, 3GPP TS 36.323	Evolved universal terrestrial radio access (EUTRA); packet data convergence protocol (PDCP) specification

TS 36.300, 3GPP TS 36.300	evolved universal terrestrial radio access (EUTRA) and evolved universal terrestrial radio access (EUTRAN); overall description; stage 2
TS 36.211, 3GPP TS 36.211	Evolved universal terrestrial radio access (EUTRA); physical channels and modulation
TS 36.331, 3GPP TS 36.331	Evolved universal terrestrial radio access (EUTRA); Radio resource control (RRC); protocol specification
TS 38.304, 3GPP TS 38.304	NR; user equipment (UE) procedures in idle mode and in RRC inactive state (Release 16)
TS 33.501, 3GPP TS 33.501	Security architecture and procedures for 5G system
TS 33.401, 3GPP TS 33.401	Security architecture and procedures for EUTRAN
TS 37.355, 3GPP TS 37.355	LTE positioning protocol (LPP)
TS 37.324, 3GPP TS 37.324	Service data adaptation protocol (SDAP) specification (Release 16)
TS 38.201, 3GPP TS 38.201	NR; physical layer; general description
TS 38.202, 3GPP TS 38.202	NR; services provided by the physical layer
TS 38.211, 3GPP TS 38.211	NR; physical channels and modulation (Release 16)
TS 38.213, 3GPP TS 38.213	NR; physical layer procedures for control (Release 16)
TS 38.214, 3GPP TS 38.214	NR; physical layer procedures for data (Release 16)
TS 38.455, 3GPP TS 38.455	NG-RAN; NR positioning protocol A (NRPPa) (Release 16)
TS 38.321, 3GPP TS 38.321	NR; medium access control (MAC) protocol specification (Release 16)
TS 38.322, 3GPP TS 38.322	NR; radio link control (RLC) protocol specification (Release 16)
TS 38.323, 3GPP TS 38.323	NR; packet data convergence protocol (PDCP) specification (Release 16)
TS 38.331, 3GPP TS 38.331	NR; radio resource control (RRC); Protocol specification (Release 16)
TS 38.521, 3GPP TS 38.521	NR; user equipment (UE) conformance specification; radio transmission and reception; parts 1 to 4
TS 38.523, 3GPP TS 38.523	5GS; UE conformance specification; Parts 1 to 3

9 LIST OF ABBREVIATIONS

Term	Explanation
3GPP	3rd Generation Partnership Project
5G-GUTI	5G globally unique temporary identity
5G-AN	5G access network
5GC	5G core network
5GMM	5G mobility management
5GSM	5G session management
5GTF	5G Technical Forum
5QI	5G QoS identifier
5GAA	5G Automotive Association
5G NR	5G New Radio
A	
ACK	Acknowledge
ADAS	Advanced driver assisted system
AAA	Authentication, authorization and accounting
AAS	Advanced antenna systems
ACK	Acknowledgment
AKA	Authentication and key agreement
AM	Acknowledged mode
AMC	Adaptive modulation and coding
AMD	Acknowledge mode data
AMF	Access and mobility management function
AN	Access network
APN	Access point name
ARFCN	Absolute radio frequency channel number
ARP	Address resolution protocol,
ARQ	Automatic repeat request
AS	Access stratum
ASN.1	Abstract syntax notation one
AUSF	Authenticaton server function
AUTN	Authentication token
AWGN	Additive white Gaussian noise
B	
BA	Bandwidth adaptation
BBU	Baseband unit
BCCH	Broadcast control channel (logical channel)
BCH	Broadcast channel (transport channel)
BER	Basic encoding rules
BER	Bit error rate
BLER	Block error rate
BMC	Battery management controller
BPSK	Binary phase shift keying
BS	Base station
BSA	Basic set of applications
BSM	Basic safety messages
BSR	Buffer status report
BSS	Basic service set
BTP	Basic transport protocol
BWP	Bandwidth part

Term	Explanation
C	
C2C	Car to car
C-ITS	Cooperative intelligent transportation system
C-RNTI	Cell RNTI
CA	Carrier aggregation
CAM	Cooperative awareness message
CATR	Compact antenna test range
CBG	Code block group
CCCH	Common control channel
CCE	Control channel element
CDM	Code division multiplex
CDMA	Code division multiple access
CE	Control element
CFRA	Contention free random access
CISPR	Comité international spécial des perturbations radioélectriques
CK	Ciphering key
CP	Cyclic prefix or control plane
CP-OFDM	Cyclic prefix OFDM
CP-OFDMA	Cyclic prefix OFDMA
CQI	Channel quality indicator
CRC	Cyclic redundancy check
CRS	Cell specific reference signals (LTE)
CS	Configured scheduling
CSI	Channel-state information
CSI-RS	Channel-state information reference signal
CTIA	Cellular Telecommunications and Internet Association
CW	Continuous wave
D	
D2D	Device to device
DAB	Digital audio broadcast
DC	Dual connectivity or direct current
DCCH	Dedicated control channel
DCI	Downlink control information
DDR	Double data rate
DE	Data element
DEN	Decentralized environmental notification
DENM	DEN message
DF	Data frame
DFF	Direct far field
DFT	Discrete Fourier transformation
DFT-s-OFDM	Discrete Fourier transform-spread-orthogonal frequency division multiplexing
DL	Downlink
DL-SCH	Downlink shared channel
DME	DSRC management entitiy
DMRS	Demodulation reference symbols
DN-AAA	Data network authentication, authorization and accounting
DNN	Data network name
DRB	Data radio bearer
DRX	Discontinuous reception
DSMP	DSRC short message protocol
DSRC	Dedicated short-range communications (USA initiative)
DTCH	Dedicated traffic channel
DTX	Discontinuous transmission
DUT	Device under test
DVB	Digital video broadcast

Term	Explanation
E	
E-RAB	EUTRAN radio access bearer
E2E	End to end
EAP	Extensible authentication protocol
EARFCN	EUTRA ARFCN
ECGI	EUTRAN cell global identity
ECU	Electric control unit
EMM	EPS mobility management
eMTC	Enhanced machine type communication
EN-DC	EUTRA NR dual connectivity
eNB	EUTRAN NodeB
EPC	Evolved packet core
EPS	Evolved packet system
ESM	EPS session management
ETSI	European Telecommunications Standard Institute
EUTRA	Evolved universal terrestrial radio access
EUTRAN	Evolved universal terrestrial radio access network
EVM	Error vector magnitude
F	
F2L	Field to lab
FDMA	Frequency division multiple access
FEC	Forward error correction
FeMBMS	Further enhanced multimedia broadcast and messaging services
FFS	For further study
FR1	Frequency range 1
FR2	Frequency range 2
FWA	Fixed wireless access
G	
GBR	Guaranteed bit rate
GCF	Global certification forum
GERAN	GSM/EDGE radio access network
GF	Grant-free
GMSK	Gaussian minimum shift keying
gNB	NR NodeB
GNSS	Global navigation satellite system
GPRS	General packet radio services
GPS	Global positioning system
GSM	Global system for mobile communications
GW	Gateway
H	
HARQ	Hybrid automatic repeat request
HSDPA	High speed downlink packet access – 3GPP Release 5
HEV	Hybrid electric vehicle
HMI	Human machine interface
HSS	Home subscriber server
HSUPA	High speed uplink packet access – 3GPP Release 6

Term	Explanation
I	
ICI	Inter-carrier interference
IE	Information element
IEEE	Institute of Electrical and Electronics Engineers
IEI	Information element identifier
IETF	Internet Engineering Task Force
IFF	Indirect far field
IFFT	Inverse fast Fourier transformation
IK	Integrity key
IMEI	International mobile equipment identity
IMS	IP multimedia subsystem
IMSI	International mobile subscriber identity
IMT	International mobile telecommunication
IoT	Internet of things
IP	Internet protocol
ISM	Industry scientific and medicine (unlicensed bands)
ISI	Inter-symbol interference
ISO	International standard organization
ITS	Intelligent transportation system
ITS-G5	Intelligent transportation system standard (EU initiative)
ITU	International Telecommunications Union
IVS	In-vehicle system (eCall UE)
K	
kB	Kilobyte (1000 bytes)
KDF	Key derivation function
KPI	Key performance indicator
L	
L2	Layer 2 (data link layer)
L3	Layer 3 (network layer)
LAN	Local area network
LDM	Local dynamic map
LDPC	Low density parity check
LI	Layer indicator
LIN	Local interconnect network
LOS	Line of sight
LSB	Least significant bits
LTE	Long Term Evolution

Term	Explanation
M	
MAC	Medium access control
MBMS	Multimedia broadcast and messaging services
MCC	Mobile country code
MCG	Master cell group
MCS	Modulation and coding scheme
ME	Mobile equipment
MEC	Mobile edge computing
MIB	Master information block
MIMO	Multiple input multiple output
mIoT	Massive internet of things
MME	Mobility management entity
mMTC	Massive machine type communications
MN	Master node
MNC	Mobile network code
MPP	Multipath propagation
MR-DC	Multiradio dual connectivity
MSI	Minimum system information
MSD	Minimum set of data (eCall message)
MU-MIMO	Multi-user MIMO
N	
N3IWF	Non-3GPP interworking functions
NACK	Non-acknowledge
NAI	Network access identifier
NAS	Non-access stratum
NB-IoT	Narrowband IoT
NCC	Next hop chaining counter or network color code
NCGI	NR cell global identifier
NCR	Neighboring cell relation
NDI	New data indicator
NF	Network function
NG-RAN	NG radio access network
NGAP	NG application protocol
ng-eNB	Next generation evolved NodeB
NLOS	Non line of sight
NR	New radio
NSA	Non-standalone
NSSAI	Network slice selection assistance information
NW	Network
O	
OBU	On-board unit
OEM	Original equipment manufacturer
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
OSI	Open system interconnection, Other system information
OTA	Over the air
OTT	Over the top

Term	Explanation
P	
P-GW	Packet gateway
PAPR	Peak-to-average power ratio
PBCH	Physical broadcast channel
PCCH	Paging control channel
PCell	Primary cell
PC5	interface for direct communication
PCF	Policy control function
PCH	Paging channel
PCI	Physical cell identity
PCRF	Policy control and routing function
PDB	Packet delay budget
PDCCH	Physical downlink control channel
PDCP	Packet data convergence protocol
PDSCH	Physical downlink shared channel
PDU	Protocol data unit
PER	Packet error rate
PH	Power headroom
PHICH	Physical hybrid indicator channel
PHR	Power headroom report
PL	Path loss
PLL	Phase locked loop
PLMN	Public land mobile network
PMI	Precoding matrix indication
PRACH	Physical random access channel
PRB	Physical resource block
PRG	Precoding resource block group
PSAP	Public safety answering point
PSBCH	Physical sidelink broadcast channel
PSFCH	Physical sidelink feedback channel
PSCCH	Physical sidelink control channel
PSSCH	Physical sidelink shared channel
PSS	Primary synchronisation signal
PSSS	Primary sidelink synchronization signal
PTCRB	USA certification forum (originally PCS type certification review board)
PTRS	Phase tracking reference signal
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
PWC	Plane wave converter
PWS	Public warning system

Term	Explanation
Q	
QAM	Quadrature amplitude modulation
QCI	QoS class identifier
QCL	Quasi colocation
QFI	QoS flow ID
QoS	Quality of service
QPSK	Quadrature phase shift keying
QZ	Quiet zone
R	
RA-RNTI	Random access radio network temporary identifier
RACH	Random access channel
RAN	Radio access network
RAT	Radio access technology
RB	Radio bearer or resource block
RBG	Resource block group
RBP	Resource block pool
RED	Radio emission directivity
RF	Radio frequency
RFC	Request for comments
RHW	Road hazard warning
RI	Rank indicator
RKE	Remote keyless entry
RLC	Radio link control
RMSI	Remaining minimum system information
RNTI	Radio network temporary identifier
ROHC	Robust header compression
RSU	Roadside unit
RRC	Radio resource control
RRH	Remote radio head
RRU	Remote radio unit
RSRP	Reference signal received power
RSSI	Received signal strength indicator
RTK	Real-time kinematics
RTP	Real-time protocol
RTT	Round trip time
RU	Radio unit
RV	Redundancy version
RX	Reception

Term	Explanation
S	
S-GW	Serving gateway
SA	Standalone
SAE	Service architecture evolution
SAE	Society of automotive engineers
SAP	Service access point
SBCCH	Sidelink broadcast control channel
SC-FDMA	Single carrier FDMA
SCell	Secondary cell
SCG	Secondary cell group
SCH	Shared channel
SCI	Sidelink control information
SCS	Subcarrier spacing
SD	Slice differentiator
SDAP	Service data adaptation protocol
SDF	Service data flow
SDL	Supplementary downlink
SDU	Service data unit
SEAF	Security anchor function
SF	Subframe
SFN	System frame number
SFN	Single-frequency network
SI	System information
SIB	System information block
SIM	Subscriber identity module
SINR	Signal to interference plus noise ratio
SIP	Session initiation protocol
SISO	Single input single output
SLA	Service level agreement
SLIV	Start and length value
SLSS	Sidelink synchronization signal
SL	Sidelink
SL-BCH	Sidelink broadcast channel
SL-SCH	Sidelink shared channel
SMF	Session management function
SN	Sequence number, Secondary node
SNR	Signal-to-noise ratio
SpCell	Special cell
SP	Subframe pool
SPS	Semi-persistent scheduling
SQN	Sequence number (ciphering)
SR	Scheduling request
SRB	Signalling radio bearer
SRS	Sounding reference signal
SS	Synchronization signal
SSB	Synchronization signal block
S-SSB	Sidelink synchronization signal block
SSID	Sidelink synchronization ID
SSS	Secondary synchronisation signal
SSSS	Secondary sidelink synchronization signal
SU-MIMO	Single user MIMO, also referred to as spatial multiplexing
SUL	Supplementary uplink
SUPI	Subscription permanent identifier

Term	Explanation
T	
T&M	Test and measurement
TA	Timing advance or tracking area
TAG	Timing advance group
TB	Transport block
TBS	Transport block size
TCI	Transmission configuration indicator
TCP	Transmission control protocol
TCU	Telematic control unit
TDD	Time division duplex
TDMA	Time division multiplex access
TEC	Traffic event compact
TM	Transmission mode
TPC	Transmit power control
TPEG	Transport Protocol Experts Group
TPMS	Tyre pressure monitoring system
TRP	Transmission and reception point
TRP	Total radiated power
TIS	Total isotropic sensitivity
TRS	Tracking reference signal
TTCN-3	Testing and test control notation version 3
TTI	Transmission time interval
TX	Transmission
U	
UCI	Uplink control information
UDM	Unified data management
UDP	User datagram protocol
UE	User equipment
UICC	Universal integrated circuit card
UL	Uplink
UL-SCH	Uplink shared channel
UM	Unacknowledged mode
UMTS	Universal mobile telecommunications system
UP	User plane
UPF	User plane function
URLLC	Ultra-reliable, low latency communications
USB	Universal serial bus
USIM	UMTS subscriber identity module
UWB	Ultrawideband (IEEE 802.15.4)
UTC	Coordinated universal time
V	
VANET	Vehicular ad-hoc network
VCO	Voltage-controlled oscillator
V2V	Vehicle-to-vehicle communications
V2X	Vehicle-to-everything communications
V2P	Vehicle to pedestrians
V2N	Vehicle to network
V2I	Vehicle to infrastructure

Term	Explanation
W	
WLAN	Wireless LAN
WAVE	Wireless access in vehicular environment
WBSS	WAVE BSS
WCDMA	Wideband code division multiple access
WME	WAVE management entity
WSMP	WAVE short message protocol
X	
X2	Interface between eNBs
X-MAC	Computed MAC-I
xNB	NR NodeB or EUTRA NodeB
Xn	Interface between gNBs
Xn-C	Xn-Control plane
Xn-U	Xn-User plane
XnAP	Xn application protocol
XRES	Expected response
Z	
ZF	Zero forcing equalization
ZP CSI-RS	Zero power CSI-RS

Rohde & Schwarz

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