COURSE 8
COMMUNICATION SYSTEMS IN VEHICULAR NETWORKS
PART 2

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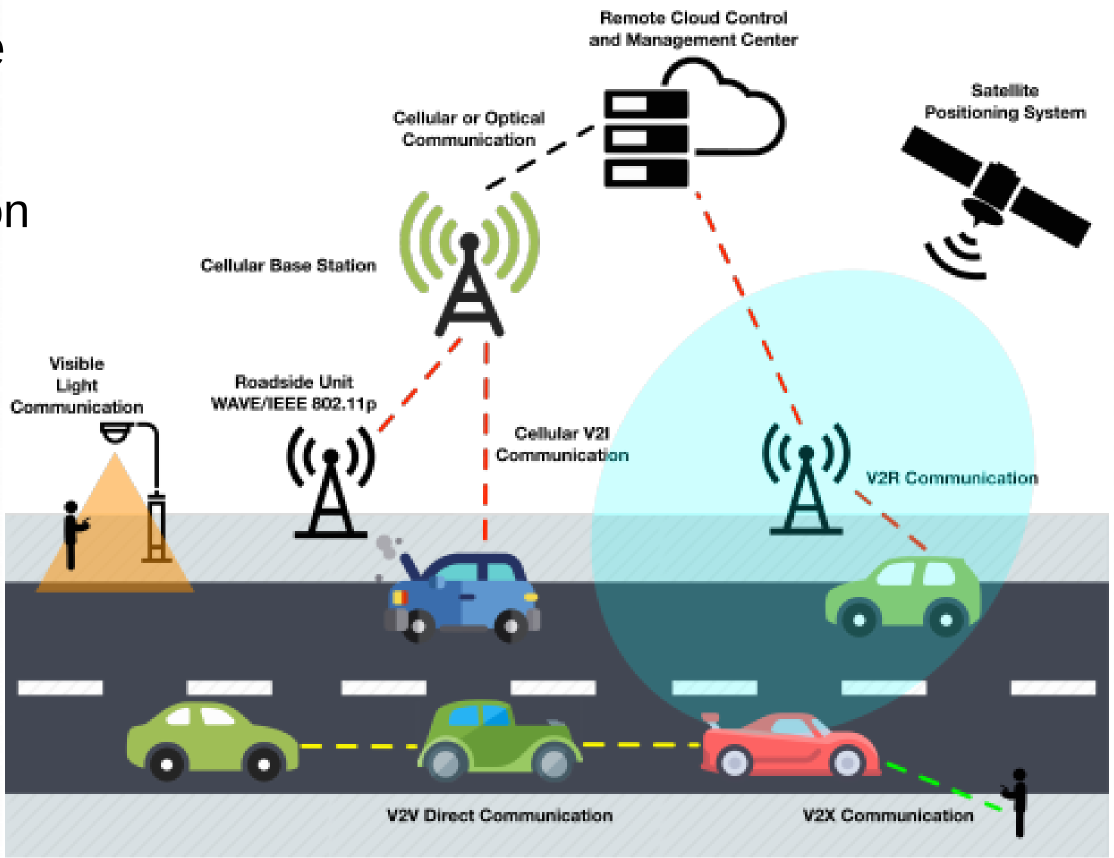
VEHICULAR NETWORKING

- The most important vehicular networking applications are:
  - Active road safety applications: based on a set of detailed data from local sensor measurements and from other participants, they provide drivers with an extensive field of view on the driving environment
    - System performance requirements: lower latency (=100 ms), short to long coverage distance (300 m to 20 km), minimum transmission frequency of 10 Hz, and low-to-medium data rates (1 to 10 kbps)
  - Cooperative traffic efficiency: provide additional information to improve the traffic flow, to enhance the traffic coordination and management, and to reduce the environmental impact
    - System performance requirements: medium latency (=200 ms), short to medium coverage (300 m to 5 km), minimum transmission frequency between 1 and 10 Hz, and data rates from one to tens of kbps.
  - Infotainment: provide the user with information to enhance the passenger comfort/convenience or enable global Internet services
    - System performance requirements: longer delay (=500 ms), short to long coverage distance from a few meters to full communication range, minimum transmission frequency of 1 Hz, and data rates of one to several hundreds of kbps

WIRELESS COMMUNICATIONS

- The field of transport is developing rapidly due to intelligent systems
  - Cooperation must be possible by communication between different systems, infrastructure and vehicles
- Two major categories of wireless communication systems exist:
  - Based on WLAN
    - WAVE and ITS-G5
  - Based on cellular technologies
    - LTE-V2X and 5G-V2X



IEEE 802.11P

- The 2010 IEEE 802.11p standard is the basis of wireless communication protocols used in vehicular systems (DSRC – Dedicated Short Range Communications):
  - WAVE (Wireless Access in Vehicular Environments) in USA
  - ITS-G5 (Intelligent Transportation System at 5.9GHz) in EU
- IEEE 802.11p allows two types of operations:
  - V2V – Vehicle-to-Vehicle
  - V2I – Vehicle-to-Infrastructure
- Each vehicle transmits once every 10s the position, direction and speed anonymously
  - Surrounding vehicles receive this message and asses if the transmitter represents a risk

IEEE 802.11P – PHY

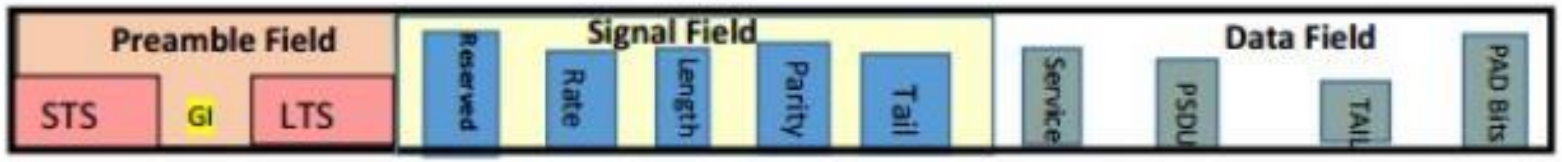
- The IEEE 802.11p physical layer is based on IEEE 802.11a:
  - 10 MHz bandwidth channels in the 5.9 GHz band are used
  - OFDM and extended subcarrier spacing are used to compensate for the Doppler effect
  - The size of the FFT is 64 and 52 subcarriers are used (48 data, 4 pilot)
    - Each subcarrier can have different modulation: BPSK, QPSK, 16QAM, 64QAM
  - The spectral masks used are stricter

Parameters	IEEE 802.11a	IEEE 802.11p	Changes
Bit rate (Mb/s)	6, 9, 12, 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18, 24, 27	Half
Modulation mode	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM	No change
Code rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	No change
Number of subcarriers	52	52	No change
Symbol duration	$4\,\mu s$	$8\,\mu s$	Double
Guard time	$0.8\,\mu s$	$1.6\,\mu s$	Double
FFT period	$3.2\,\mu s$	$6.4\,\mu s$	Double
Preamble duration	$16\,\mu s$	$32\,\mu s$	Double
Subcarrier spacing	0.3125 MHz	0.15625 MHz	Half

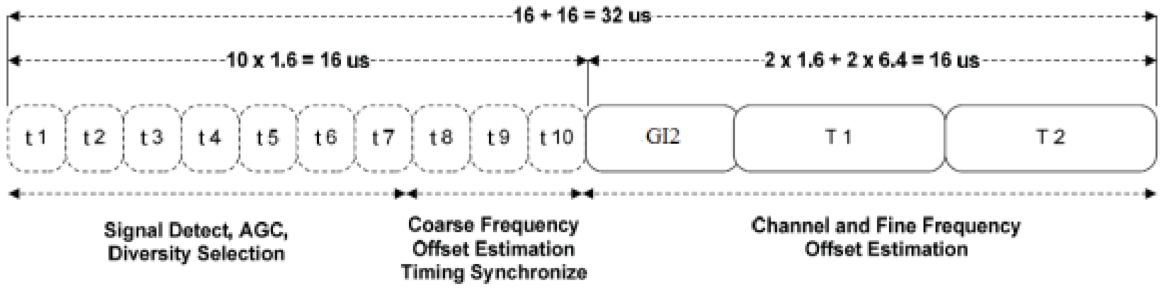
IEEE 802.11P – PHY

Parameter	IEEE 802.11a	IEEE 802.11p
Sample rate	20 MHz	10 MHz
Chip duration	50 ns	100 ns
Number of fft points	64	64
Number of subcarriers	52 + DC	52 + DC
Number of data subcarriers	52	52
Number of pilot subcarriers	4	4
OFDM symbol period	$T_{Symbols} = 80$ chips = 4 µs	8 µs
Cyclic prefix	16 chips = 0.8 µs	1.6 µs
FFT symbol period	64 chips = 3.2 µs	6.4 µs
Modulation scheme	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM
Coding scheme	1/2 industry convulutional	1/2
Puncturing	optional puncturing 3/4 or 2/3	3/4 or 2/3
Available data rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps	3, 4.5, 6, 9, 12, 18, 24, 27 Mbps

IEEE 802.11P – PHY

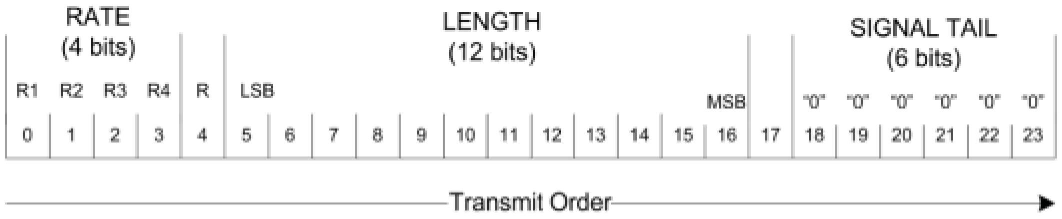


- PPDU (PLCP – Physical Layer Convergence Protocol – Protocol Data Unit) is formed of:
  - Preamble: used to mark the beginning of the physical frame, used for antenna selection and phase and time offset correction
    - STS – Short Training Sequence, GI – Guard Interval, LTS – Long Training Sequence



IEEE 802.11P – PHY

- Signal field: 24 bits, used to determine the transfer rate and data length
  - The first 4 bits are used to set the rates which should apply to the data field
  - The length field represents how long the PSDU is in bytes
  - Bit 17 is a parity bit for error detection
  - The bits in the tail field are reserved and set to 0



- Data field: used to transmit OFDM data symbols and is composed of 4 sub-fields:
  - Service field – 16 bits all set to 0
  - PSDU (PLCP Service Data Unit) – the size is on average 1024 bytes
  - The following 6 bits, all set to 0, represent the tail
  - Pad field is at least 6 bits long to make the size of the frame an integer multiple of the OFDM symbol size

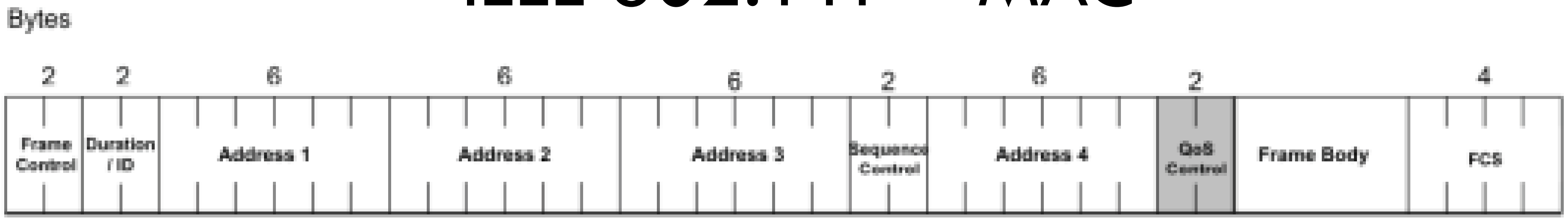
IEEE 802.11P – MAC

- IEEE 802.11p introduces changes also at the MAC level
  - Each 802.11p node must use the same channel and the same BSSID wildcard
- The MAC level is based on EDCA (Enhanced Distibuted Channel Access)
  - It is an access method similar to CSMA/CA
  - The frames are labeled as different user priorities and differentiated channel access is performed
  - The frame with the highest priority is sent on the channel first
  - The first 8 bits of the 16-bit traffic identifier field of the MAC service data unit (MSDU) indicates the frame priority

IEEE 802.11P – MAC

- EDCA defines 4 access categories for different types of traffic:
  - BK or AC0 – background traffic; in vehicular: information for establishing non-safety-related connections
  - BE or AC1 – best-effort traffic; in vehicular: information from other vehicles for help, not strictly related to safety issues
  - VI or AC2 – video traffic; in vehicular: presence and speed information broadcasted by vehicles
  - VO or AC3 – voice traffic; in vehicular: emergency information, especially for collision avoidance

IEEE 802.11P – MAC



- The MAC Protocol Data Unit (MPDU) consists of:
  - Frame Control: 2 bytes; includes information like protocol version (2 bits), frame type (2 bits), frame subtype (4 bits), and 1 bit for each of the following: to DS, from DS, more fragments, retry, power management, more data, protocol frame, order
  - Duration/ID: 16 bits; represents the duration for IEEE 802.11p application
  - The 4 MAC address fields are used selectively according to different types of frames
  - Frame Body (MAC Service Data Unit, MSDU): maximum 2304 bytes
  - QoS Control: 16 bits; first 3 bits indicate the TID, bit 4 is for end of service period purposes, bits 5-6 define the ACK policy, bit 7 is reserved, bits 8-15 carry out various functions

C-V2X

- C-V2X is a term for cellular technologies optimized for transportation and connected vehicles
  - The C refers to both 4G LTE and 5G NR (new radio), and X refers to multiple things' vehicles may connect with.
- C-V2X includes network-based communications, such as vehicle-to-network (V2N), and a complementary mode of operation first defined in the 3GPP Release 14 in 2017, which allows direct communications between vehicles (V2V), and between vehicle and road-side infrastructure (V2I and I2V)
  - It can further support vulnerable road users by integrating the direct communications technology into mobile and other devices.
  - The direct communications is used to specifically support safety critical services to reduce collisions, support automated driving, and improve traffic efficiency
  - LTE-V2X is the 3GPP nomenclature for direct communications as specified in releases 14 and 15, whereas 5G NR-V2X is from Release 16 onward

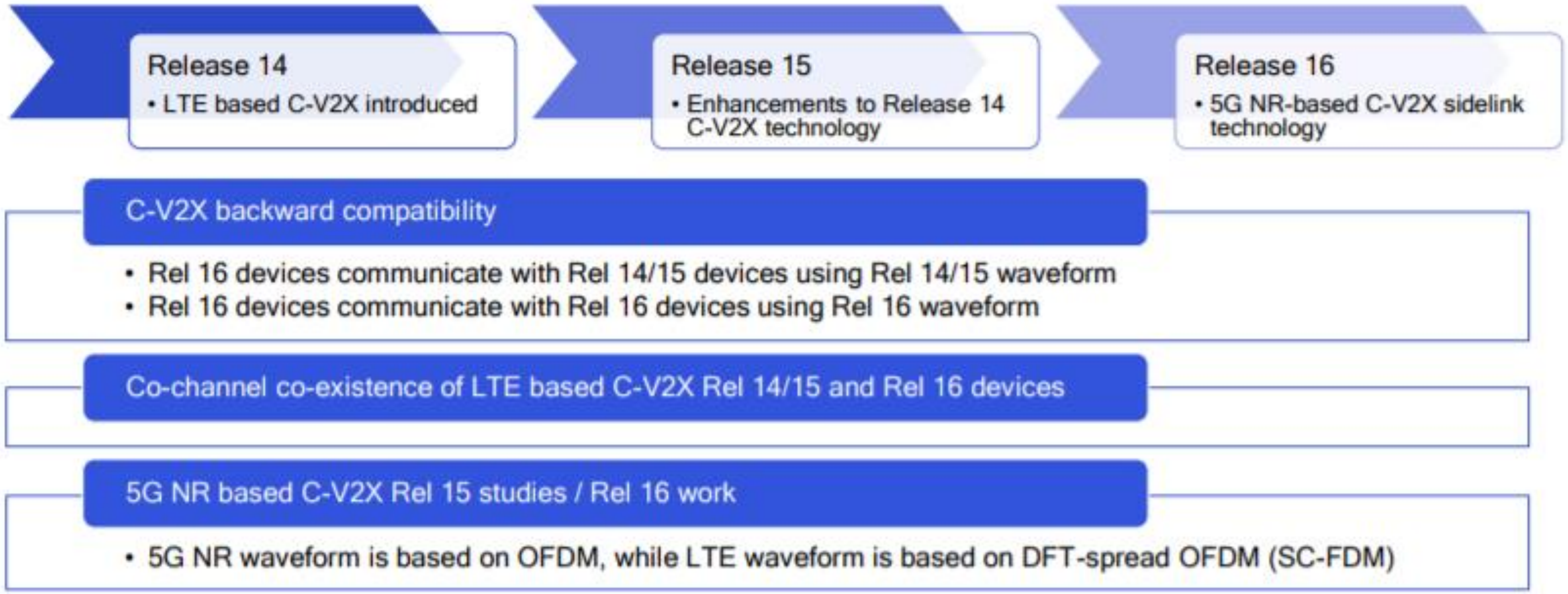
C-V2X

- Services offered by C-V2X according to 5GAA (5G Automotive Association)

Software updates	Provides mechanisms for vehicles to receive the latest software updates and security credentials required to ensure their safe operation.
Remote Vehicle Health Monitoring	Provides mechanisms to diagnose vehicle issues remotely. As driving becomes more autonomous this becomes the key mechanism for remote supervision of vehicle functions and its health.
Real-Time High Definition Maps	Provides situational awareness for Autonomous vehicles at critical road segments in cases of changing road conditions (e.g. new traffic cone detected by another vehicle some time ago)
High definition sensor sharing	Provides mechanism for vehicles to share high definition sensor data (Lidar, cameras, etc) to enable better driving coordination for platooning and intersection management
See-Through	Provides ability for vehicles such as trucks, minivans, cars in platoons to share camera images of road conditions ahead of them to vehicles behind them
Vulnerable Road User Discovery	Provides ability to identify potential safety conditions due to the presence of vulnerable road users such as pedestrians or cyclist

C-V2X

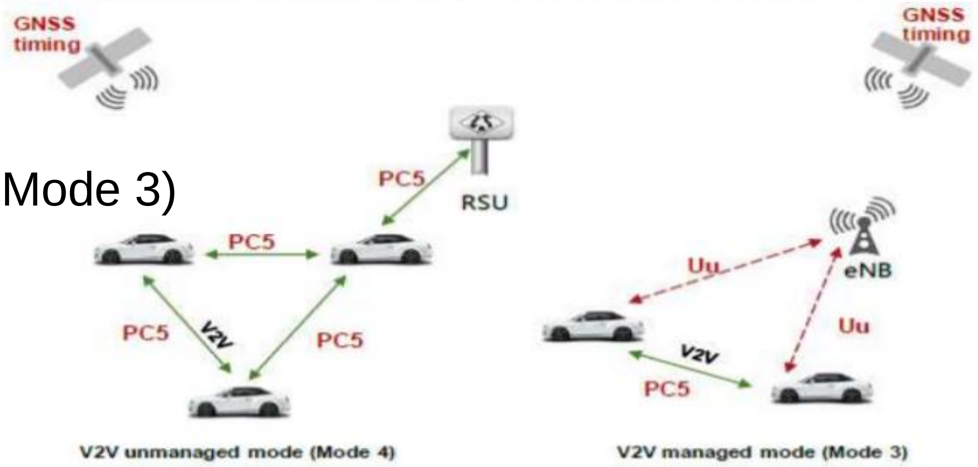
- C-V2X timeline



LTE-V2X

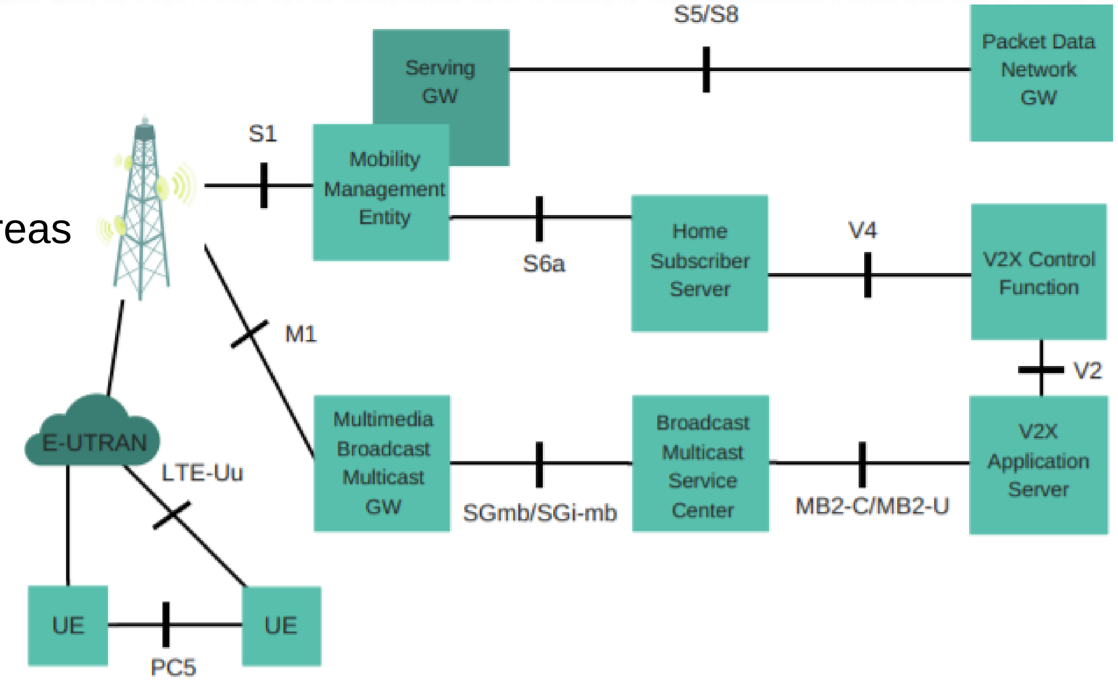
- The standard was published in 3GPP Rel. 14 in 2017
- Two technologies are supported:
  - Direct communications (Mode 4)
    - Direct connections with low latencies over short distances without the involvement of the cellular network
    - 5.9GHz frequency
    - No SIM required
  - Cellular communications – V2N (Vehicle-to-Network; Mode 3)
    - Network support for security features
    - Commercial services
    - Access to data stored in the cloud
    - Collaboration with network operators is required

Term	Description	Range	Advantage	Application
V 2V / 2I / 2P	Direct communication (LTE PC5)	Limited to close proximity	Low latency, ubiquitous connectivity	Immediate warning, machine control
V2N 2V / 2I / 2P	Indirect communication (LTE Uu or PC5 to Uu)	Unlimited, dependent on geographic relevance	Wide range, incorporates legacy devices	Long term warning, advisory



LTE-V2X – ARCHITECTURE

- The LTE-V2X network consists of::
  - UE (User Equipment or OBU – On-Board Unit)
  - eNB wireless interface of the LTE network
  - V2X Application Server
    - Responsible of message distribution in different areas
  - V2X Function Control
    - Responsible for authorizing and revoking services
  - Multimedia Brodcast Multicast Service (MBMS)
- Two interfaces are defined for the UE:
  - PC5 used in Mode 4
  - LTE Uu used in Mode 3



LTE-V2X – PHY

- RSU (Road Side Unit) can be implemented in 2 ways:
  - Static UE static or part of eNB

- Mode 4, PC5 interface
  - It is based on the LP D2D (Low Power Device-to-Device) platform in 3GPP Release 12
    - Release 12 allows the discovery of 1000 devices within a radius of 500m
    - Release 13 extends the platform under the name of ProSe
  - C-V2X and DSRC can coexist
  - To compensate for the Doppler effect (relative speeds up to 500km/h) and the frequency offset, changes have been introduced compared to LTE
    - 4 reference symbols/frames are used, instead of 2, on slots 2, 5, 8 and 11
    - The cyclic prefix is 5us

LTE-V2X – PHY

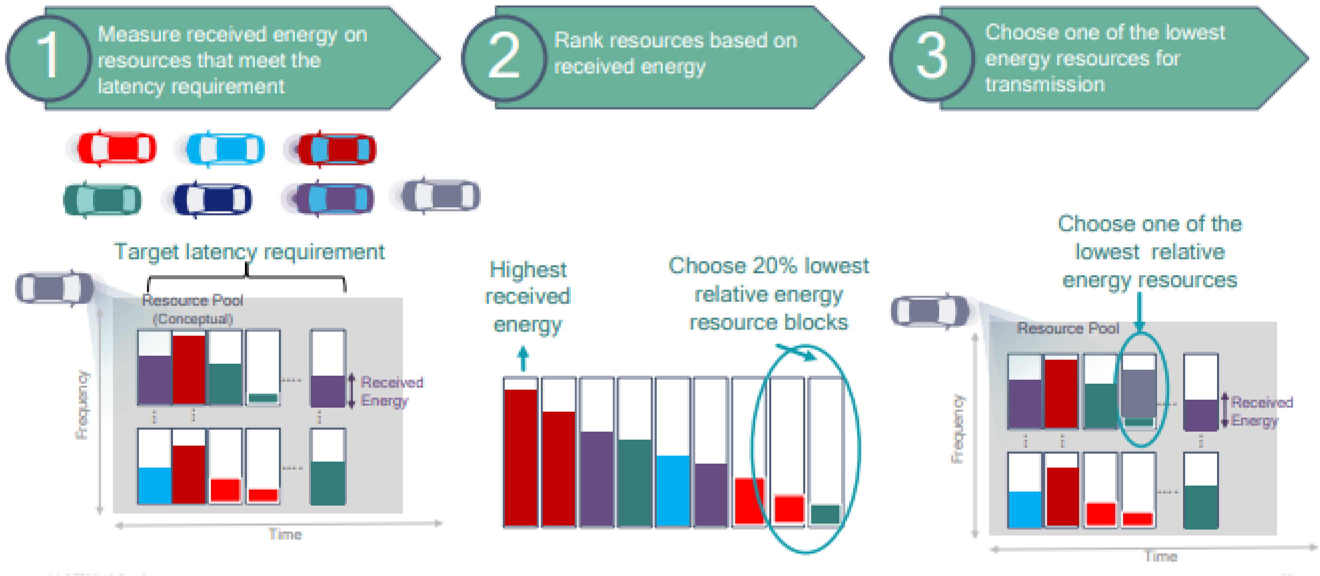
- LTE-V2X uses SC-FDMA (Single-Carrier Frequency-Division Multiple Access)
- It supports 10 and 20MHz channels
  - The channel is divided into 180kHz resource blocks that correspond to 12 subcarriers of 15 kHz each
  - In the time domain the channel is organized in 1ms subframes
  - Each subframe has 14 OFDM symbols with normal cyclic prefix
    - 9 symbols are used for data transmission
    - 4 symbols (3, 6, 9, 12) are used for DMRS transmission for channel estimation and combating the Doppler effect at high speeds

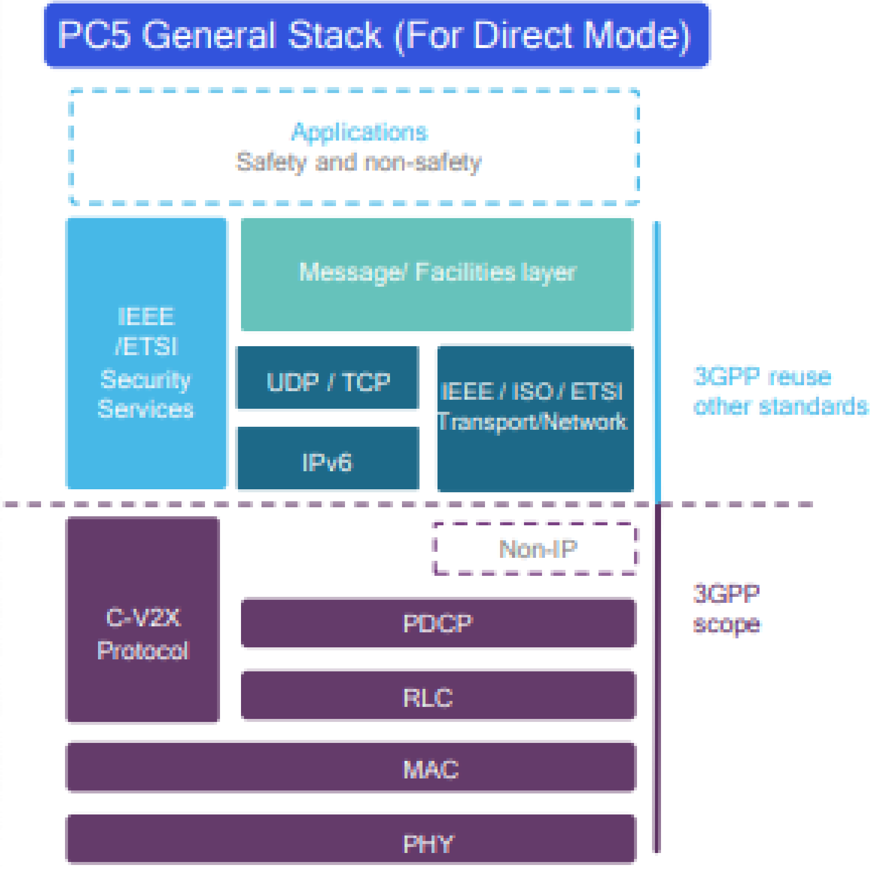
LTE-V2X – PHY

- LTE-V2X introduces 2 additional physical channels:
  - PSSCH –Physical Sidelink Shared Channel for data transmission
  - PSCCH –Physical Sidelink Control Channel for transmission of control information
  - PSSCH and PSCCH are transmitted in the same subframe
  - HARQ is used
- Turbo codes that offer better performance than convolutional codes (DSRC) are used
- Multiplexing in both time and frequency is possible
- GNSS is used for synchronization and time

LTE-V2X – RESOURCE ALLOCATION

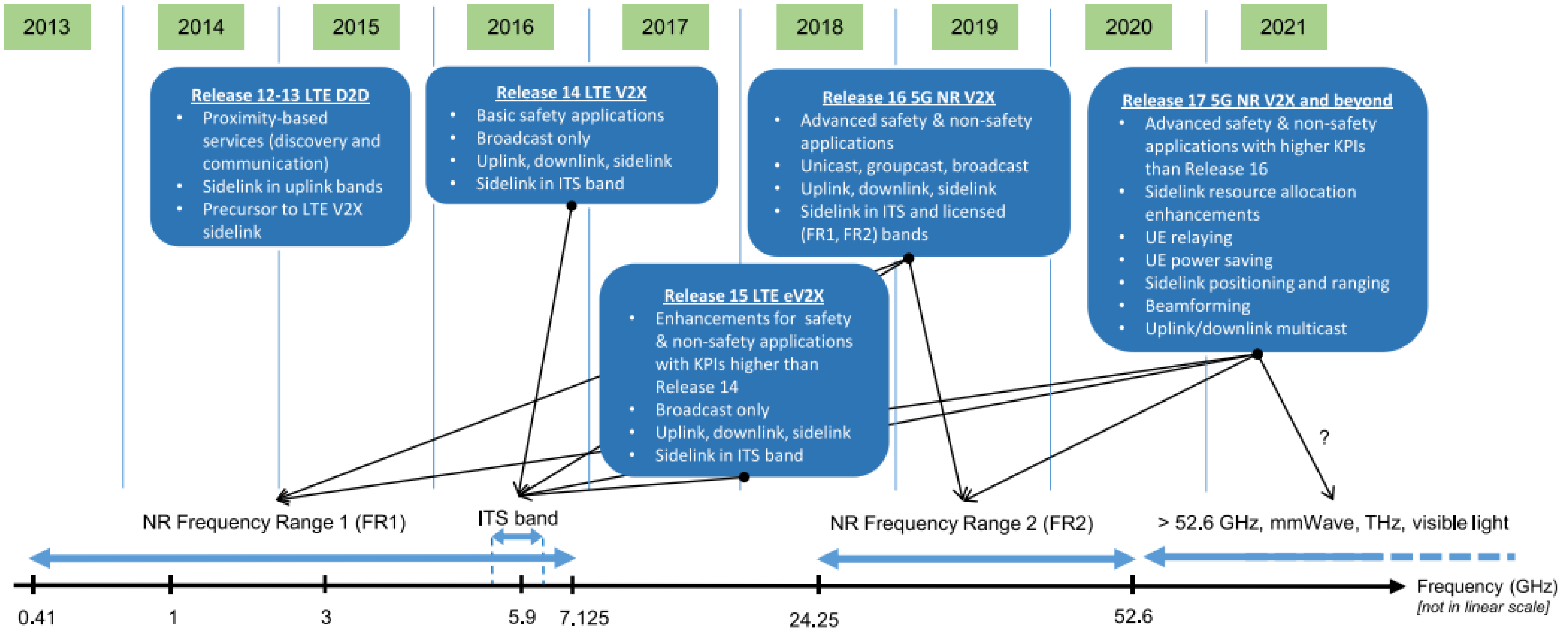
- Resource allocation
  - Resource management is distributed
  - Resources are selected by the UE autonomously
  - There is a distributed congestion control mechanism





5G NR-V2X

- Complete in 3GPP Release 16 in March 2020 (complet)



5G NR-V2X

- 3GPP Rel 16 introduces additional capability to 5G NR, in terms of short range direct communication, increasing bandwidth and reducing latency, referred to as URLLC
- Key features of 5G for C-V2X:
  - Scalable OFDM, dynamic frame structure allowing lower delays, usage of LPDC/polar codes, high bandwidth carriers that ensure high speeds, high number of antennas that extend the range
- 5G NR-V2X offers the features necessary for highly and fully automated and cooperative driving, such as the exchange of:
  - Sensor data sharing for collective perception (e.g., video data)
  - Control information for platoons from very close driving vehicles (only a few meters gap)
  - Vehicle trajectories to prevent collisions (cooperative decision making).

5G NR-V2X – USE CASE GROUPS

- Safety: safety for vehicles and other traffic participants
  - E.g. emergency braking, collision warning, intersection management, etc.
- Vehicle operations management: improved operation of vehicles for various users
  - E.g. sensors monitoring, software updates, remote support, etc.
- Convenience: value and convenience to either the driver or the fleet management company
  - E.g. infotainment, assisted navigation, and smart parking
- Society and community: are of value and interest to the society and public
  - E.g. Vulnerable Road User (VRU) protection, emergency vehicle approaching, emergency answering points, etc.
- Traffic efficiency, environmental friendliness: enhanced value to infrastructure or city providers
  - E.g. Green Light Optimal Speed Advisory (GLOSA), traffic jam information, routing advice, etc.

5G NR-V2X – USE CASE GROUPS

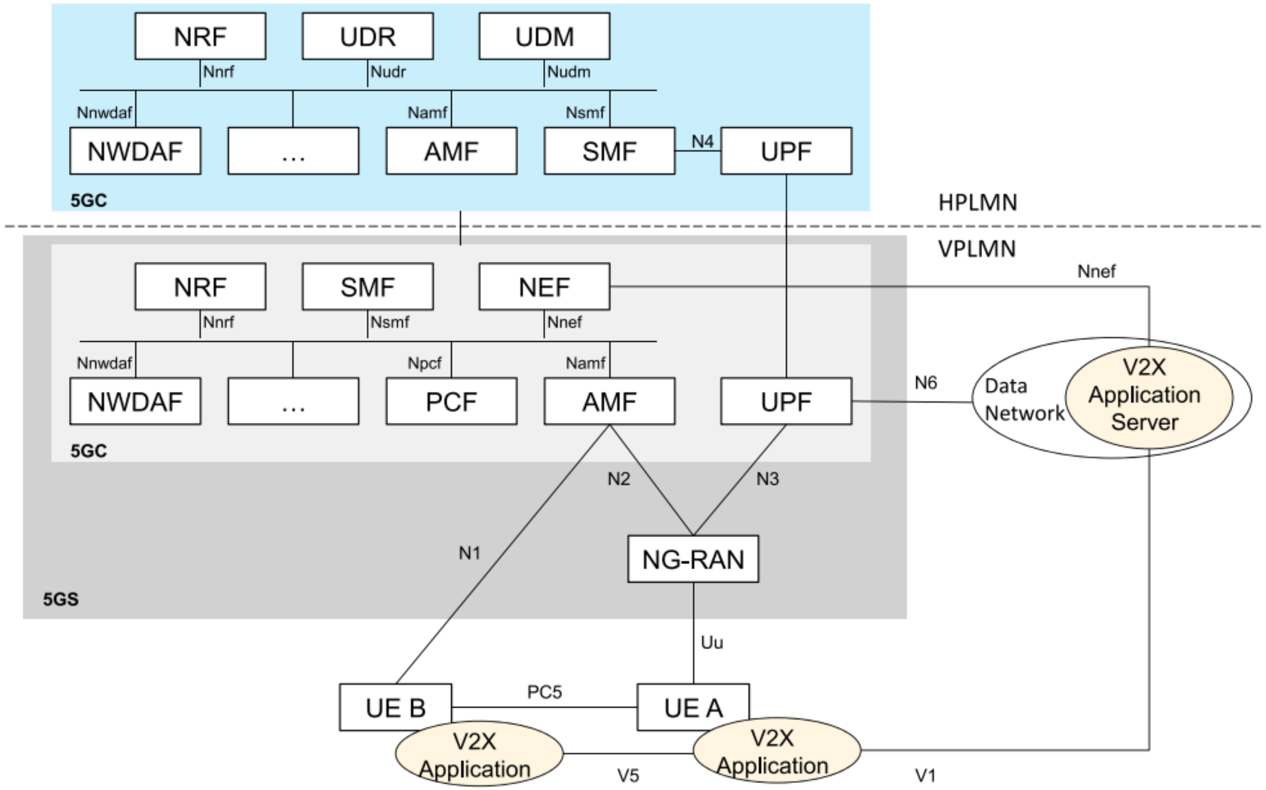
- Autonomous driving: enable semi-automated or fully-automated driving
  - Vehicles share data obtained from their local sensors with surrounding vehicles in proximity; vehicles also share their driving intention to coordinate their trajectories increasing safety and improving traffic efficiency
  - Enables the exchange of sensor data collected through local sensors between vehicles, RSUs, devices of pedestrians, and V2X application servers.
    - The objective is to improve the perception of the environment beyond the perception capabilities of the vehicles' own sensors
  - Enables a remote (teleoperated) driver or a V2X application to operate a vehicle
    - For passengers that cannot drive themselves, for vehicles located in hazardous environment and for complex situation which automated vehicles are unable to drive safely
- Platooning: for the dynamic formation and management of groups of vehicles in platoons
  - Vehicles in a platoon exchange data periodically to ensure the correct functioning of the platoon
  - The inter-vehicle distance between vehicles in a platoon may depend on the available QoS

5G NR-V2X – ARCHITECTURE

- 5G architecture support 2 operation modes for V2X communications:
  - Over the PC5 reference point/interface
    - Supports Sidelink (SL) V2X for NR and LTE
  - Over the Uu reference point/interface
    - Transmission possible under NR standalone and Non-Standalone deployments
    - Supported only for unicast in Rel 16, broadcast and multicast are foreseen in Rel 17
- HPLMN (Home PLMN) is the network the user is subscribed to; VPLMN (Visitor PLMN) is the network to which the user roams
- 5GS (5G System) consists of NG-RAN (Next Generation RAN) and 5GC (5G Core Network) domains

5G NR-V2X – ARCHITECTURE

- 5GC includes several Network Functions (NF):
  - Access and Mobility Management Function (AMF)
  - Policy Control Function (PCF)
  - Network Data Analytics Function (NWDAF)
  - Network Repository Function (NRF)
  - Network Exposure Function (NEF)
  - Unified Data Repository (UDR)
  - Unified Data Management (UDM)
  - User Plane Function (UPF)
  - Session Management Function (SMF)

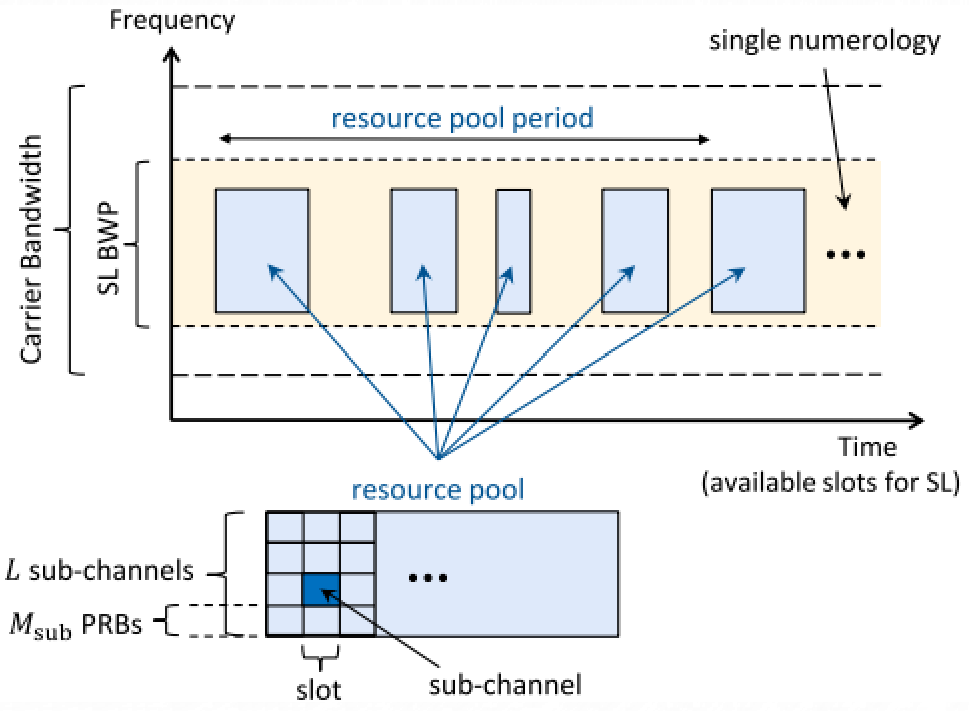


5G NR-V2X – PHY

- Numerology: Rel 16 V2X SL can operate at the same frequencies as Rel 15 NR Uu
  - Frequency range 1: 410MHz – 7.125GHz
    - The design of V2X SL was mainly for this range
  - Frequency range 2: 24.25GHz – 52.6GHz
  - Transmissions use OFDM waveform with cyclic prefix
  - A radio frame has 10ms duration and is composed of 10 subframes
    - The number of slots per subframe and the subcarrier spacing (SCS) can be flexible for 5G NR
    - The maximum bandwidth depends on the SCS for NR V2X SL too
  - The selection of the numerology depends on the carrier frequency, radio channel conditions (e.g., due to mobility), requirements (e.g., latency) and hardware features (e.g., complexity)
  - The smallest unit of time for scheduling SL transmissions in NR V2X is a slot in contrast to Rel. 15 NR Uu which supports mini-slot scheduling

5G NR-V2X – PHY

- SL BWP (Sidelink Bandwidth Parts)
  - SL BWP occupies a contiguous portion of bandwidth within a carrier
  - In a carrier, only one SL BWP is (pre-)configured for all UEs
  - SL UE transmissions and receptions are contained within the SL BWP and use the same numerology
    - All physical channels, reference signals and synchronization signals in NR V2X SL are transmitted within the SL BWP
  - The SL BWP is divided in RBs, a RB consists of 12 consecutive subcarriers with the same SCS



5G NR-V2X – PHY

- Resource pools: a subset of the available SL resources is (pre-)configured to be used by several UEs for their SL transmissions
  - The common RBs in a resource pool are the physical resource blocks (PRBs)
  - A resource pool consists of contiguous PRBs and contiguous or non-contiguous slots that have been (pre-)configured for SL transmissions
    - A resource pool must be defined within the SL BWP
    - The slots from a resource pool are (pre-)configured and have a periodicity of 10240ms
  - In the frequency domain, a resource pool is divided into a (pre-)configured number of contiguous sub-channels, where a sub-channel consists of a group of consecutive PRBs in a slot
    - In NR V2X SL, the sub-channel size can be equal to 10, 12, 15, 20, 25, 50, 75, or 100 PRBs
    - A sub-channel represents the smallest unit for a SL data transmission or reception
      - A SL transmission can use one or multiple sub-channels.

5G NR-V2X – PHY

- The physical channels specified in NR V2X SL:
  - Physical Sidelink Control Channel (PSCCH): carries control information in the sidelink
  - Physical Sidelink Shared Channel (PSSCH): carries data payload in the sidelink and additional control information
  - Physical Sidelink Broadcast Channel (PSBCH): carries information for supporting synchronization in the sidelink. PSBCH is sent within a sidelink synchronization signal block (S-SSB).
  - Physical Sidelink Feedback Channel (PSFCH): carries feedback related to the successful or failed reception of a sidelink transmission

5G NR-V2X – PHY

- The following signals are defined for NR V2X SL:
  - Demodulation reference signal (DMRS): used by a receiver for decoding the associated sidelink physical channel; the DMRS is sent within the associated sidelink physical channel
  - SL primary synchronization signal (S-PSS) and SL secondary synchronization signal (S-SSS): used by a receiver to synchronize to the transmitter; S-PSS and S-SSS are sent within an S-SSB; these signals are generated from Gold sequences
  - SL Channel state information reference signal (SL CSI-RS): used for measuring channel state information at the receiver that is fed back to the transmitter; the transmitter can adjust its transmission based on the fed back CSI; SL CSI-RS is sent within the PSSCH region of the slot
  - SL Phase-tracking reference signal (SL PT-RS): used for mitigating the effect of phase noise resulting from imperfections of the oscillator; SL PT-RS is sent in the PSSCH region of the slot

5G NR-V2X – RESOURCE ALLOCATION

- Rel. 16 defines modes 1 and 2 for the selection of sub-channels in NR V2X SL
- Mode 1: similar to mode 3 in LTE-V2X, the gNB or eNB assigns and manages the SL radio resources for V2V communications
  - Mode 1 can use dynamic grant scheduling when UEs must request resources to the base station for each transmission block (TB)
    - UEs send a SR (Scheduling Request) to the gNB using PUCCH and the gNB responds with DCI (Downlink Control Information) over the PDCCH
  - To reduce delays gNB can pre-allocate a set of SL resources to a UE transmitting several TBs, this is referred to as configured grant (CG) and is configured by RRC signaling
    - CG type 1: can be used immediately until it is released by the base station
    - CG type 2: can be used only after it is activated by the gNB until it is deactivated

5G NR-V2X – RESOURCE ALLOCATION

- Mode 2: like with mode 4 in LTE-V2X, UEs can autonomously select their SL resources from a resource pool
  - Mode 2 can operate using a dynamic or a semi-persistent scheduling scheme
  - The dynamic scheme selects new resources for each TB and can only reserve resources for the retransmissions of that TB
    - A reserved resource is a selected resource that a UE reserves for a future transmission
  - A UE can select and reserve resources for the transmission of several TBs (and their retransmissions) when utilizing the semi-persistent
  - The UE randomly selects the SL resource from the list of available candidate resources, RSSI is not taken into consideration anymore
  - Rel 16 also supports congestion control for NR V2X SL Communications in mode 2