AB4Rail webinar:
"Advances in Communication Technologies for Transports"

Cellular – Vehicle-to-everything (C-V2X) for enabling Intelligent Transportation Systems (ITS)

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Università degli Studi
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Webinar: **“Advances in Communication Technologies for Transports”**

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Highlights

- Introduction on Intelligent Transportation Systems
- Vehicle/Road use cases for cellular networks
  - Connecting modes: V2X,…
  - Use cases in 3GPP and in 5GAA
- Application layer and architectures in C-V2X
- Radio interface in C-V2X and MEC/slicing
  - Improvements with 5G Release 16 and Release 17
- References

Intelligent Transportation Systems (ITS)

ITS = ICT + road transport

- ICT = Informatic, electronics and telecommunications
- Road transport (i.e., infrastructure, vehicles and users) for traffic and mobility management, as well as for interfaces with other modes of transport
- [cites: the directive of the European Union 2010/40/EU, July 7, 2010]

ITS goals

- To provide users with meaningful information
  - Facilitating a wide range of services, for transportation planners (e.g., pre-trip planning for logistics and en-route information)
- To improve road safety services
  - It is crucial that vehicles reliably communicate not only with each other, but also with the road infrastructure
  - The traffic management center (TMC) can be hosted in a central cloud (for coordinated information) or distributed in edge clouds (for responsiveness and local analytics)
- To support enhanced assisted driving.
  - Using the AI capabilities
- Strong connection between personal mobility and economic mobility
  - Environmental sustainability, Mobility as a Service (MaaS)

→ Future ITS: safe, efficient, inclusive, and serving the societal needs

Vehicular communications

- Importance of communications among vehicles
  - Intelligent Transport Systems (ITS)
  - Vehicular Networks
- Services
  - Safety
    - Minimize accidents and risks to passengers and road users
  - Non-safety
    - Improve traffic management
    - Maximize the efficiency of the existing road network,
    - Minimize the traffic congestion on economic productivity and environmental quality
  - Infotainment

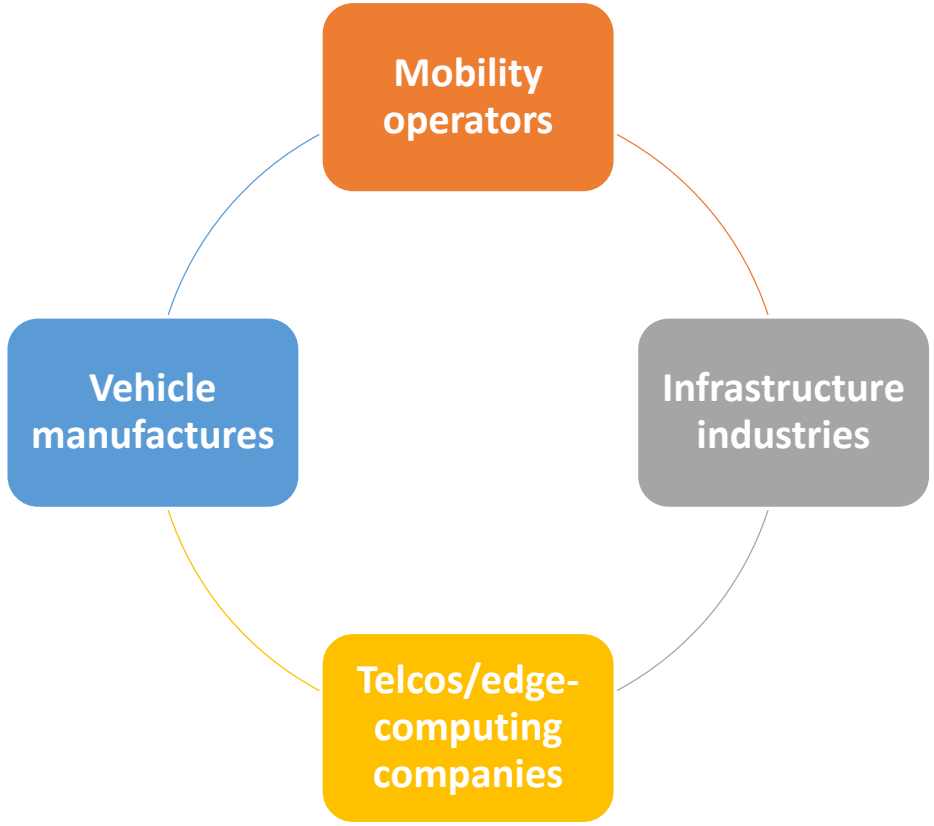
Two main communication technologies for access layer

- The European standard **ETSI ITS-G5**, based on Dedicated Short Range Communication (DSRC) and supporting IEEE 802.11p i.e., the vehicular ad-hoc connectivity Wireless Local Area Network(WLAN) technologies
  - Supported by Institute of Electrical and Electronics Engineers (IEEE)
- Cellular-based Vehicle to Everything (**C-V2X**), based on Long-Term Evolution (LTE) and 5G New Radio (NR)
  - Proposed by the Third Generation Partnership Project (3GPP)

- Both ETSI ITS (the standard in Europe) and IEEE 1609 family of standards, also known as Wireless Access in Vehicular Environments (WAVE) in U.S. adopted 802.11p/ITS-G5 or C-V2X in frequency at 5.9GHz
  - C-V2X can operate also in cellular licensed frequencies

Main issues for ITS diffusion

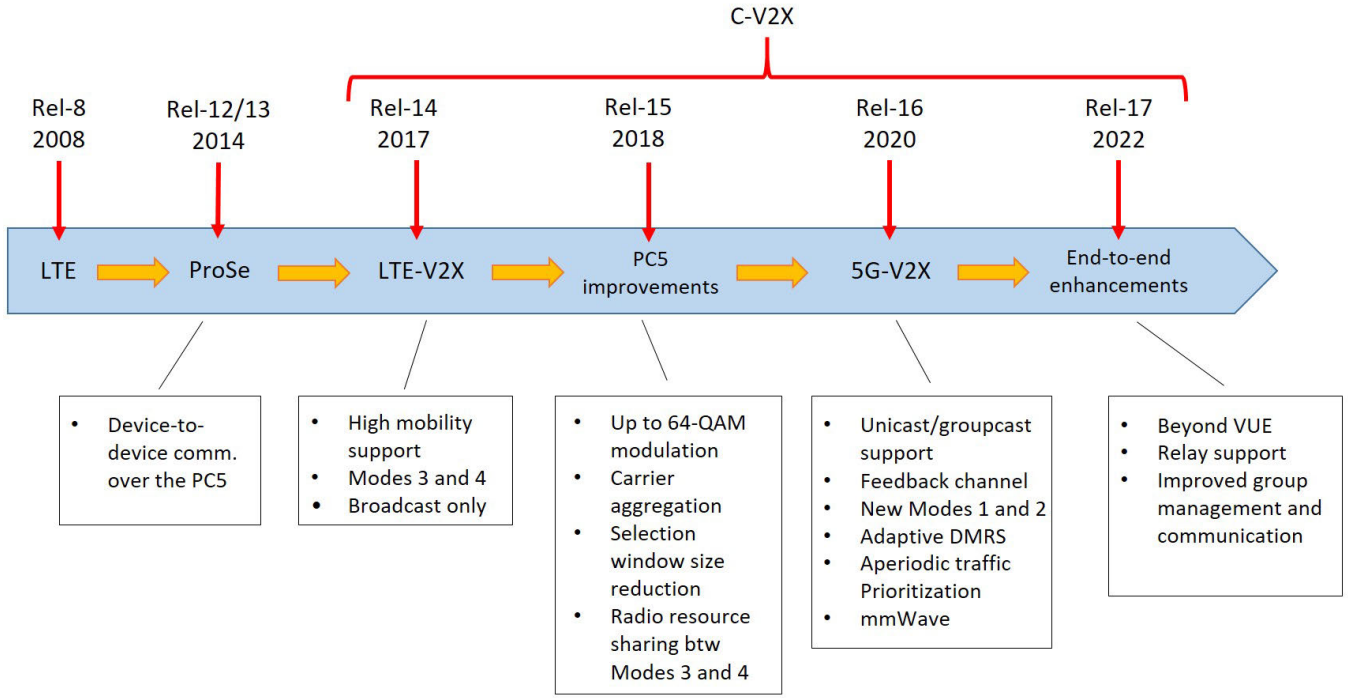
- Many actors and stakeholders
- Vehicle manufacturers followed their own technology development, usually proprietary solutions
- No cooperation with other service providers or road safety agencies
- No clear or working business models



Vehicle/Road use cases for cellular networks

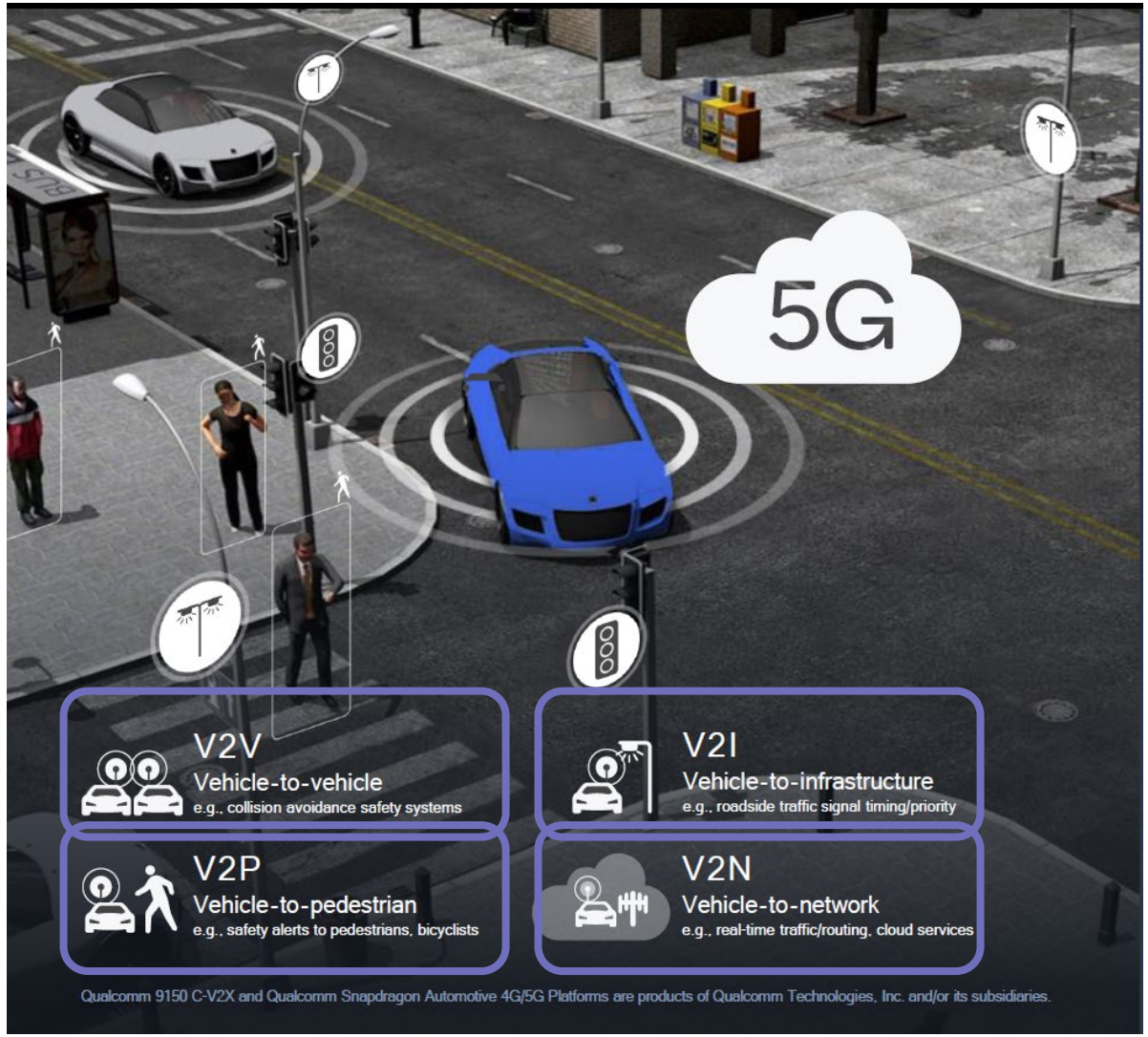
Evolution of C-V2X standards

- C-V2X is supported by a group of standards families:
  - Proximity-based services (ProSe), specified in 3GPP Release 12 (published in Mar. 2016) 3GPP TS 23.303 V12.8.0 (2016-03)
  - LTE based C-V2X, specified in 3GPP Release 14 (published in 2017), and Release 15 (published in 2018)
  - 5G and NR based C-V2X, specified in 3GPP Rel-16 (published in 2020) and with continuing evolution with further releases.

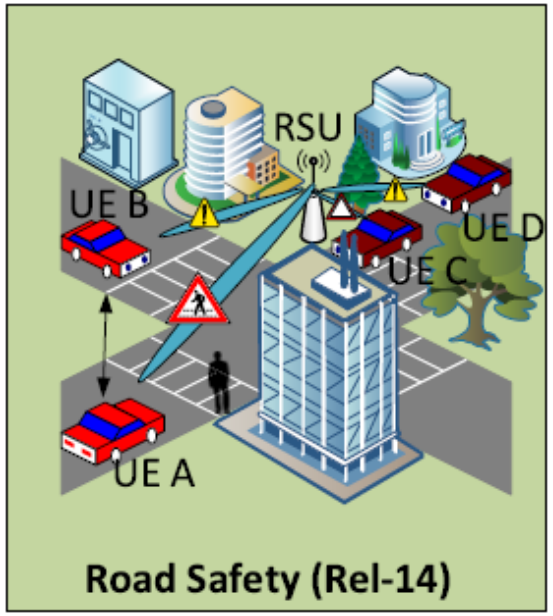


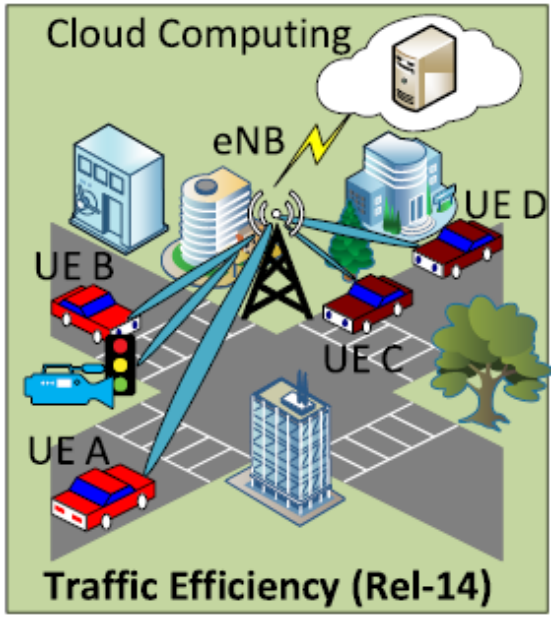
Types of Vehicle-to-Everything (V2X)

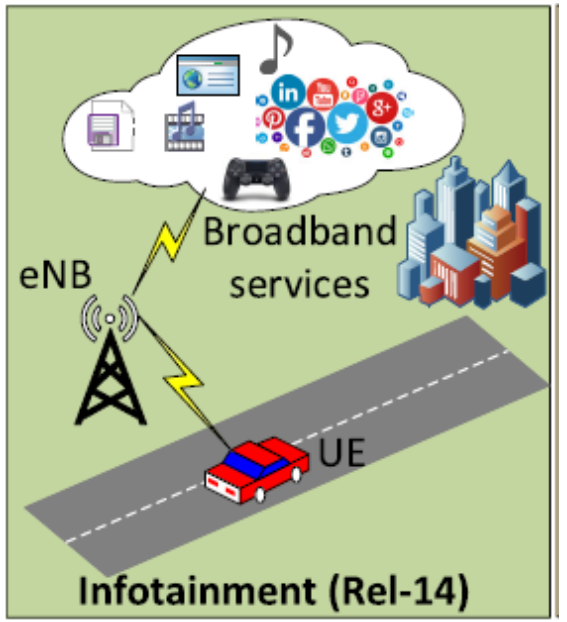
- **Vehicle-to-Vehicle** (**V2V**), directly between vehicular User Equipment (UEs);
- **Vehicle-to-Pedestrian** (**V2P**), between a vehicle and the UE of a pedestrian (**Vulnerable Road User**, VRU);
- **Vehicle-to-Infrastructure** (**V2I**), between a vehicle and fixed road infrastructure, for example, a **Roadside Unit** (RSU), providing V2X applications with connectivity support to other UEs
- **Vehicle-to-Network** (**V2N**), wide area communication over the cellular network between vehicles and a cellular network entities, for the support of V2X traffic operations.



Use cases in Release 14

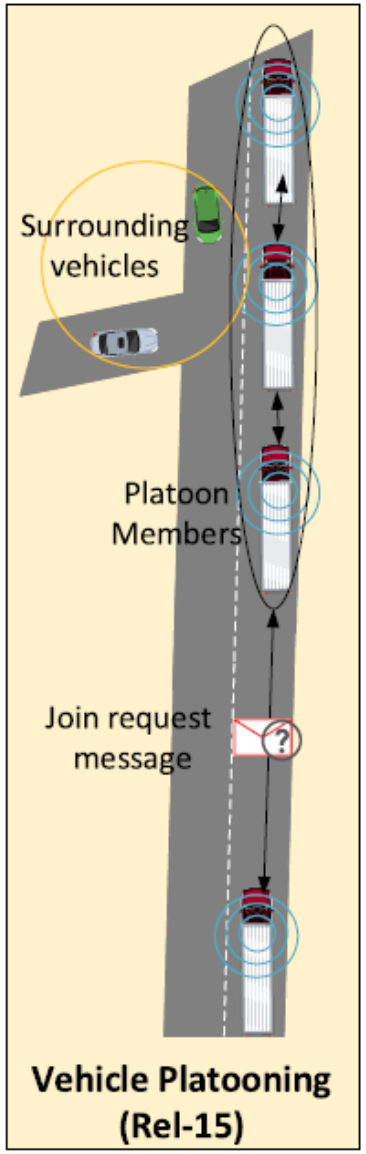






Use case in Release 15, NR V2X in TS 22.186

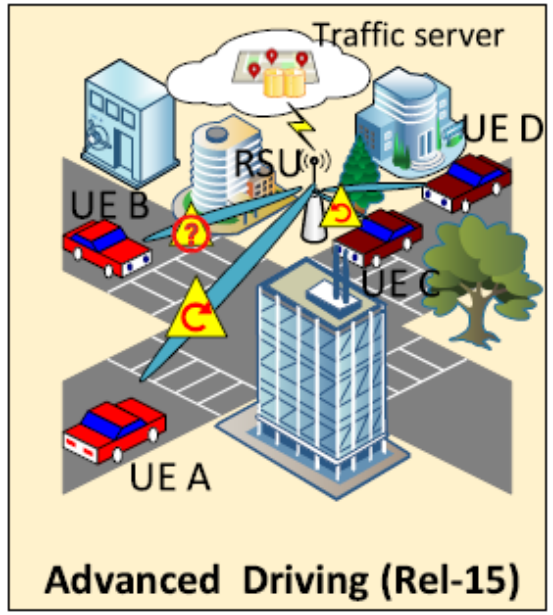
- **Vehicle Platooning + Platoon management**
- Aim:
  - Driving a group of vehicles together,
  - The proper management of such groups (addition, removal of vehicles) as and when required.
- Advantages in shortening the required reacting distance far below human standards → improving the capacity of roads and fuel economy
- High reliability and strict latency requirements.
- The lead vehicle periodically transmits data to other vehicles in the platoon, so as to control the operations of the ensemble of vehicles satisfactorily
  - Join/leave, group communications, announcement/warning
- Category: V2V, V2I



Vehicle Platooning (Rel-15)

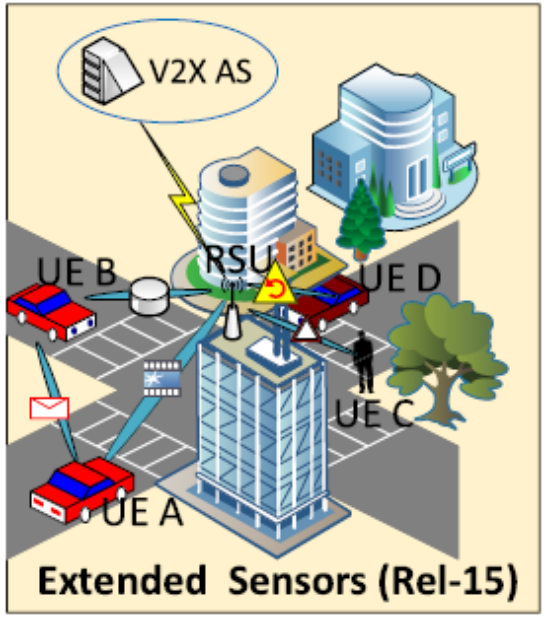
Use case in Release 15, NR V2X in TS 22.186

- **Advanced Driving**
- Aim:
  - Supporting the semi-automated or full self-driving
  - Sharing of collected data by sensors on vehicles and RSUs and driving plans
  - → coordinate maneuvers, adjust the course of vehicles for safety, Cooperative Collision Avoidance (CCA) and road efficiency
- Category: V2N

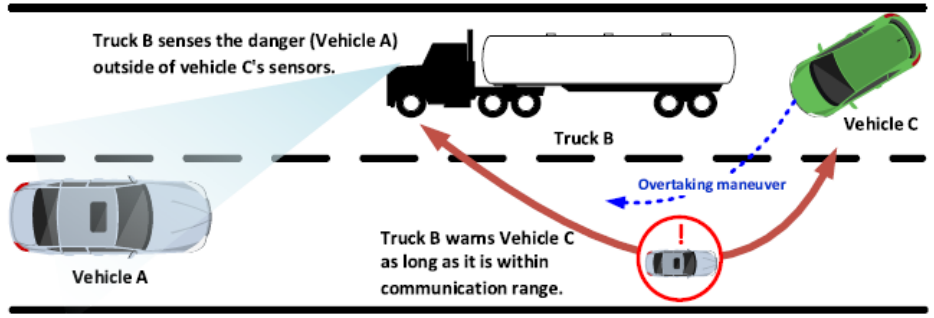


Use case in Release 15, NR V2X in TS 22.186

- **Extended Sensors**
- Aim:
  - Exchanging raw or processed data from local sensors
  - Sensor and State Map Sharing; Collective Perception of Environment; Video data sharing for automated Driving
- Variable requirements on latency, bandwidth and reliability depending on sensor data shared
- Range lower than 400m
- Extended raw environment (beyond own sensors)
- Category: V2V, V2P, V2I, V2N/V2X-AS

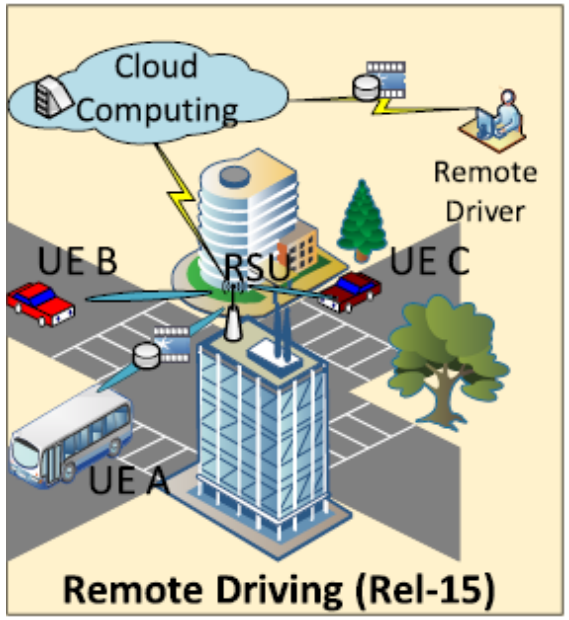


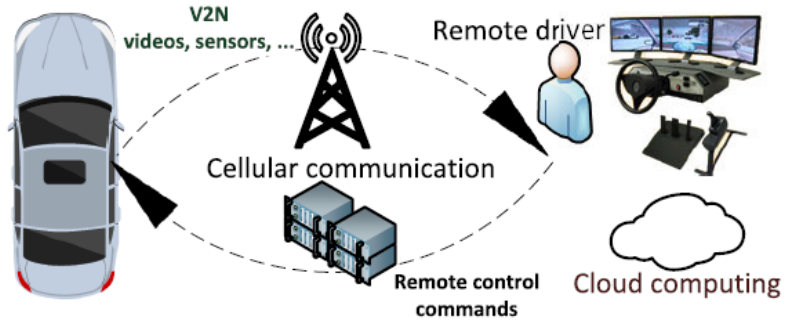
Collective Perception of Environment



Use case in Release 15, NR V2X in TS 22.186

- **Remote Driving**
- Aim:
  - Controlling a remote vehicle
  - Assisting a remote driver by V2X AS
- Useful for public transportation or hazardous environments
- Several services to support the remote driving by a cloud-based platform
- Very low latency and high reliability requirement; medium bandwidth (but symmetric UL/DL)
- Category: V2N





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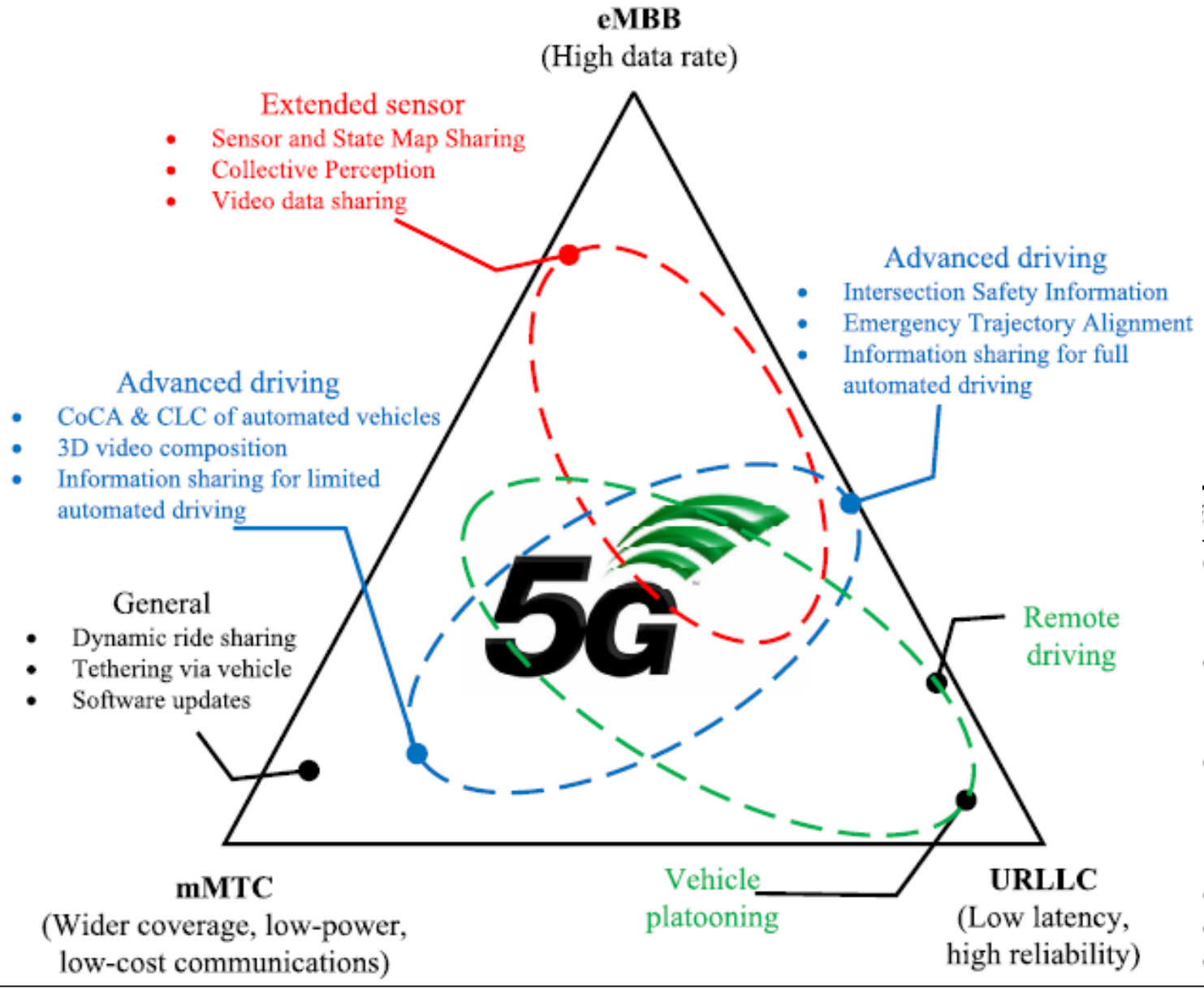


Scenario	*lity*	*Communication range*
Platooning, V2V, coopera	9%	>80–150 m
Platooning, V2V/V2I, rep	–	–
Platooning, V2I, info shar	–	>180–350 m
Advance driving, V2V, C	9%	–
Automated driving, V2V,	–	>700 m
Automated driving, V2I, i	–	>360–700 m
Emergency trajectory alig	9%	>500 m
Intersection safety inform	–	–
Cooperative lane change,	–	–
Video sharing, V2N	–	–
Video sharing, V2V	9%	100–400 m
Sensor info sharing, V2V	9%	50–1,000 m
Remote driving, V2N, inf	9%	–

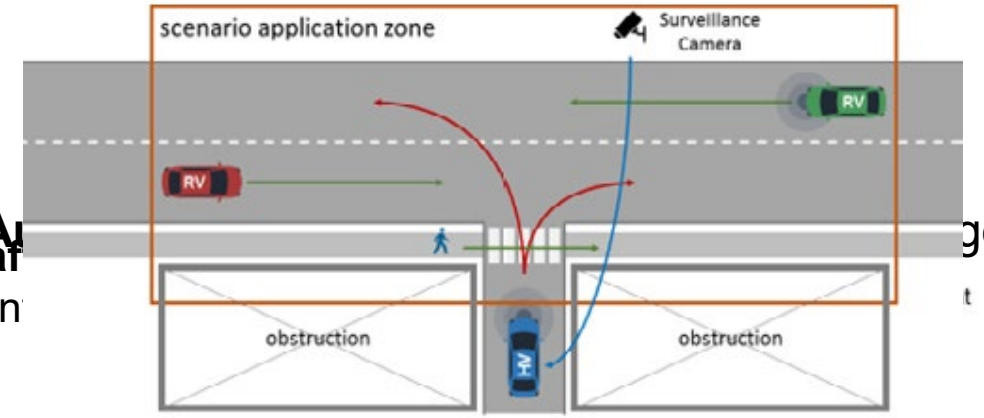
5GAA use case

- **Safety**: basic (e.g., emergency braking, collision warning, etc.), advanced (e.g., intersection management)
- **Vehicle operations management**: sensors monitoring, software updates, remote support for commercial vehicles
- **Convenience**: providing value and convenience to drivers and fleets (e.g., infotainment, assisted navigation, and smart parking)
- **Autonomous driving**: advanced driving, remote driving, and extended sensors groups defined by 3GPP.
- **Platooning**: similar as the 3GPP vehicles platooning use case group.
- **Traffic efficiency and environmental friendliness**: providing enhanced value to infrastructure or city providers (e.g. Green Light Optimal Speed Advisory, traffic jam information, routing advice, …
- **Society and community**: providing value and interest to the society and public (e.g., VRU protection, emergency vehicle approaching, emergency answering points, etc.)

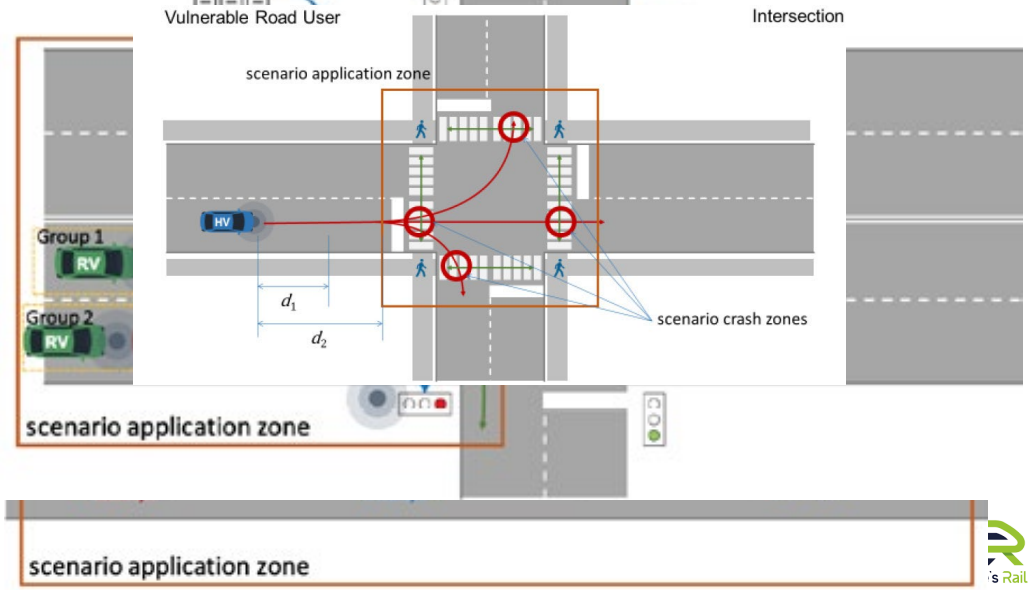
Autonomous Driving: Autonomous Vehicle Disengagement Report

Safety: cross-Traffic Left-Turn Assist

Convenince: Obstructed View Assist



Safety: VRU use case



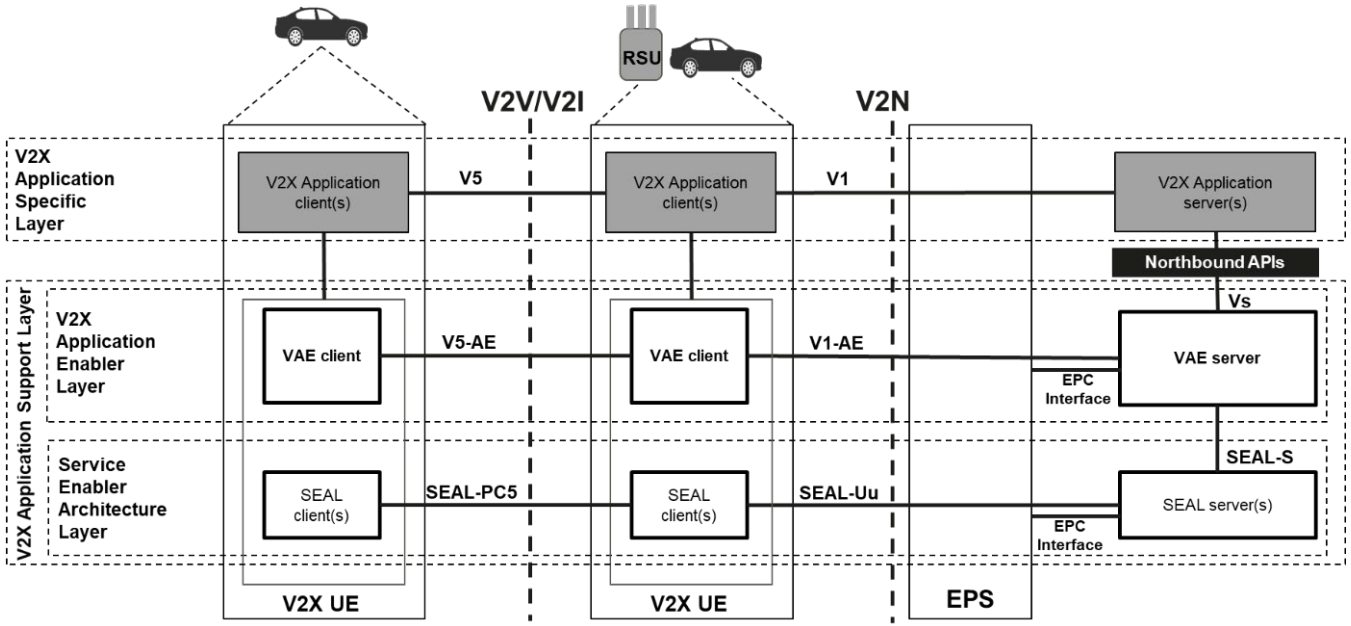
C-V2X service examples and recommended communication modes

Service Types	Example use cases	End-to-end latency (ms)	Reliability	Data rate	Recommended C-V2X mode
Safety	Cooperative Traffic Gap	50 ms	99.9%	2 Mbps	V2V
Safety	Interactive VRU crossing	100 ms	99.9%	64 Kbps	V2P
Vehicle Operation management	Software Update of Reconfigurable radio system	Delay tolerant (hours)	99%	200MB (delay tolerant)	V2N
Convenience	Automated Valet Parking (incl. authentication, proof of localization, wake up)	500 ms	99%	16 kbps	V2I
Convenience	Awareness confirmation	20 ms	99.9%	40 kbps	V2V, V2N
Convenience	Cooperative Curbside management	100 – 5000 ms	99.0%	Few kbps	V2P, V2I, V2N
Convenience	Cooperative Lateral Parking	10 – 100 ms	99.9%	27 Mbps	V2V
Convenience	In-vehicle entertainment	20 ms	99%	Up to 250 Mbps	V2N
Convenience	Obstructed view assist	50 ms	99%	5 Mbps	V2I, V2V
Autonomous Driving	Cooperative Lane merge	20 ms	99.9%	12 kbps	V2V
Autonomous Driving	Cooperative Maneuvers of AV for emergency situations	10 ms	95%	48 kbps	V2V
Autonomous Driving	Coordinated, cooperative driving maneuver	20 ms (each for 4 round trips)	99.9%	64 Mbps (system level)	V2V
Autonomous Driving	Vehicle Platoon in steady state	50 ms	99.0%	24 kbps	V2V
Autonomous Driving	Automated Intersection crossing	10 ms	99.9999%	~ 64 kbps	V2I
Autonomous Driving	HD Map Collecting and sharing	100 ms	99%	16 Mbps	V2N, V2I
Autonomous Driving	Infrastructure Assisted Environment perception	100 ms	99.99%	4 – 80 Mbps	V2I, V2N
Autonomous Driving	Infrastructure-based tele-operated driving	50 ms	99.999%	400 kbps	V2I, V2N
Autonomous Driving	Tele-operated Driving (ToD)	100 ms (UL); 20 ms (DL)	99.999%	36 Mbps (UL); 400 kbps (DL)	V2N
Autonomous Driving	Autonomous vehicle disengagement report	10 min	99.99%	26.7 Mbps	V2N
Traffic efficiency and society	Bus lane sharing request/revocation	200 ms	99%	40 kbps	V2I, V2N
Traffic efficiency and society	Continuous traffic flow via green light coordination	100 ms	95%	20 kbps	V2I, V2N
Traffic efficiency and society	Group start	10 ms	99.999%	20 kbps	V2I

Application layer and architectures in C-V2X

V2X application layer

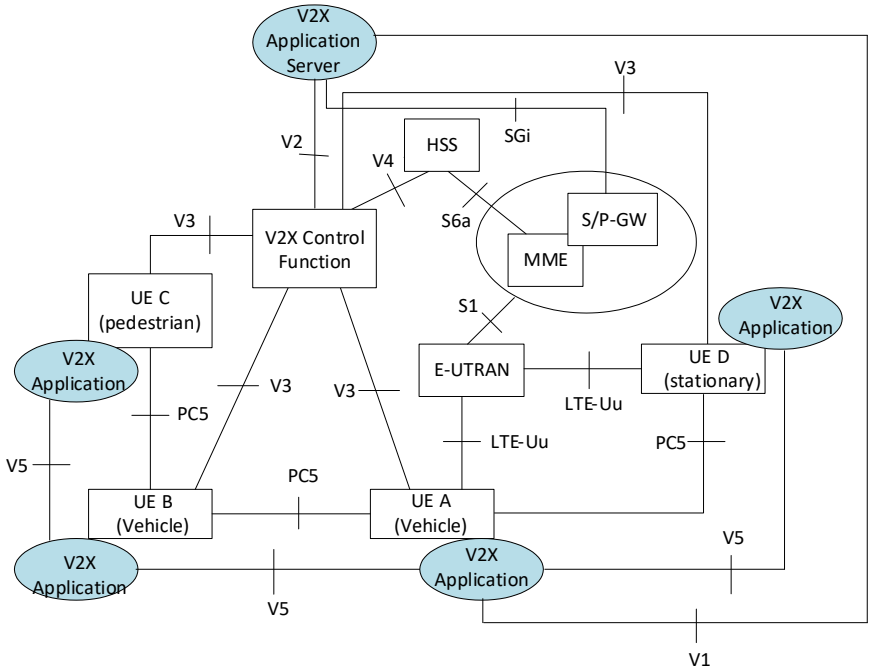
- **V2X application specific layer it** consists of V2X specific applications (e.g. Platooning, Vehicle safety)
- V2X application support layer consists of:
  - **V2X application enabler** (VAE) as specified in TS 23.286 (e.g. V2X service discovery, message delivery, service continuity)
  - **Service Enabler Architecture Layer** (SEAL) as specified in TS 23.434 (e.g. Group management, configuration management, location management)



Architectural reference model

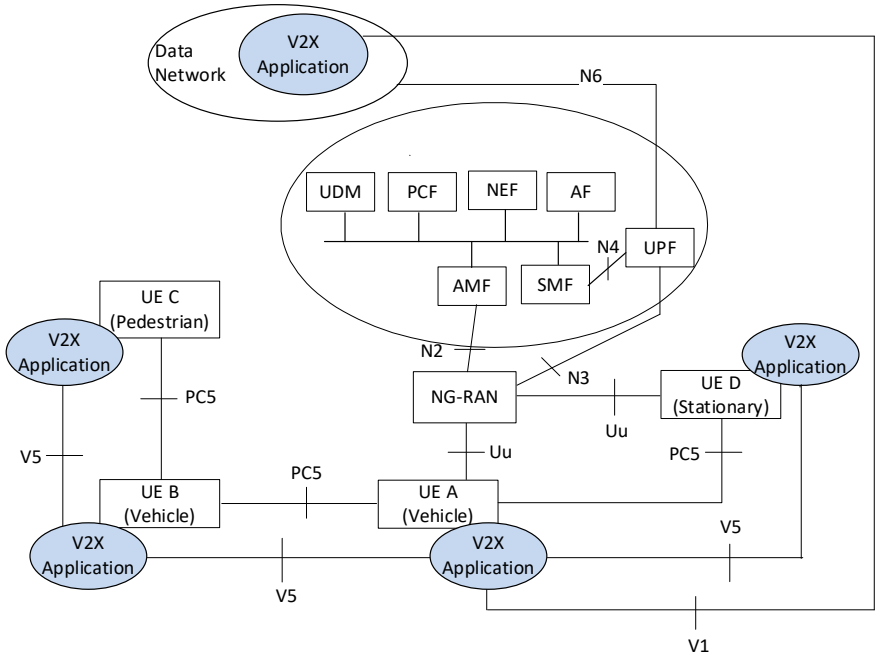
EPS Architecture

- V2X Control Function
- User Equipment (EU)
- V2X Application Server
- Mobility Management Entity (MME)
- BM-SC and MBMS-GW



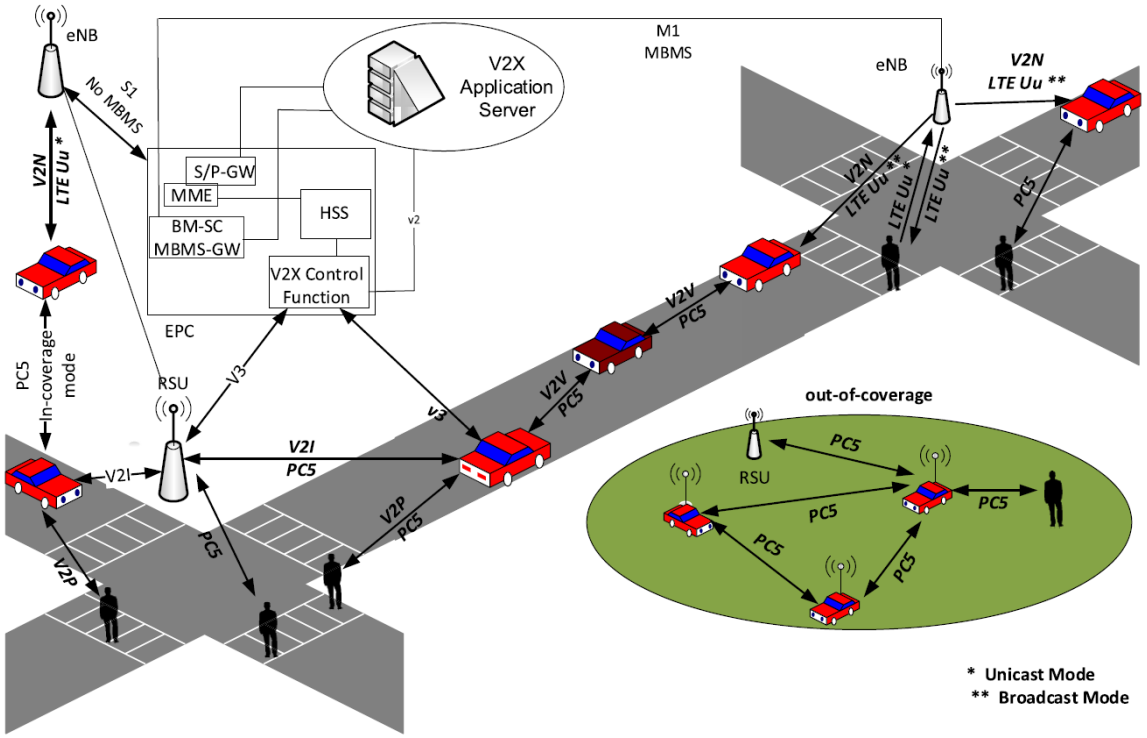
5GS Architecture

- Policy Control Function (PCF)
- User Equipment (EU)
- V2X Application Server
- Access and Mobility Management Entity (AMF)
- Unified Data Management/Repository (UDM/UDR)
- Network Exposure Function (NEF)

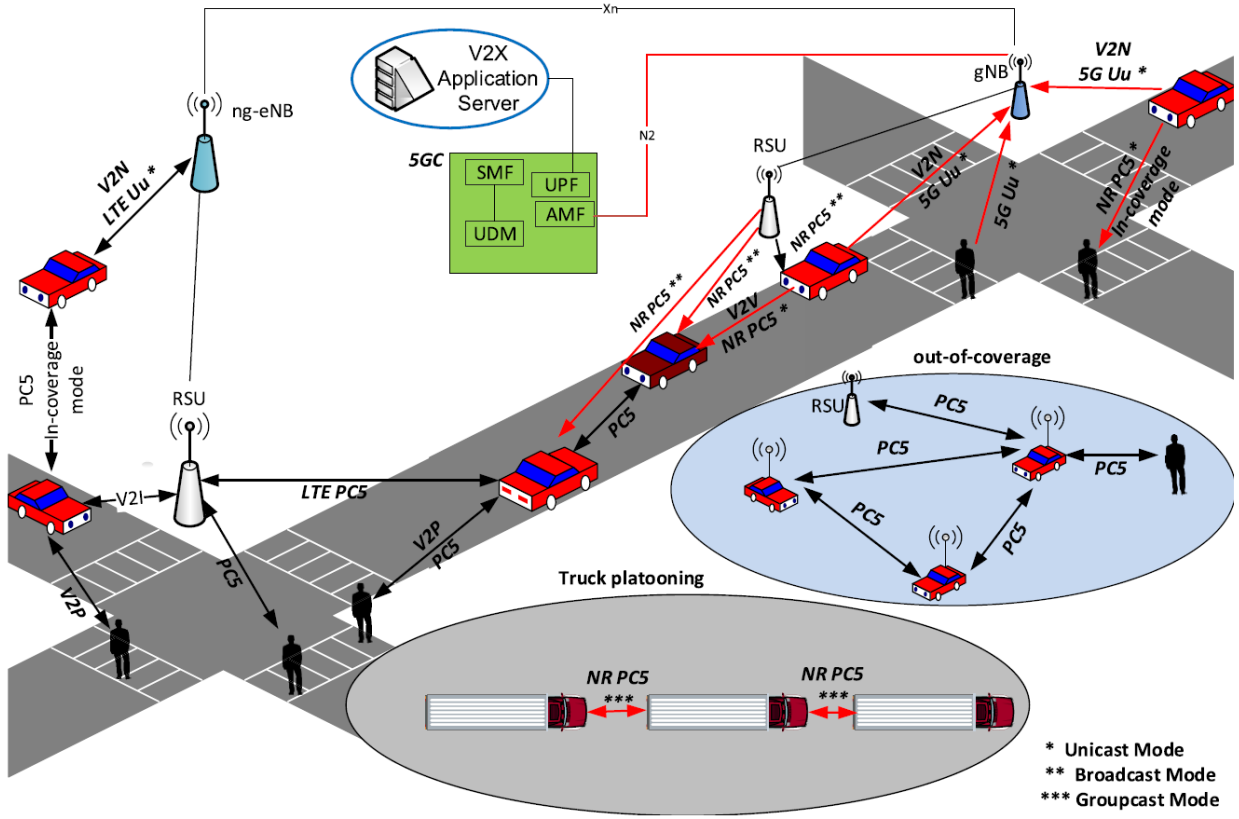


Architecture in Release 16

- Over EPS

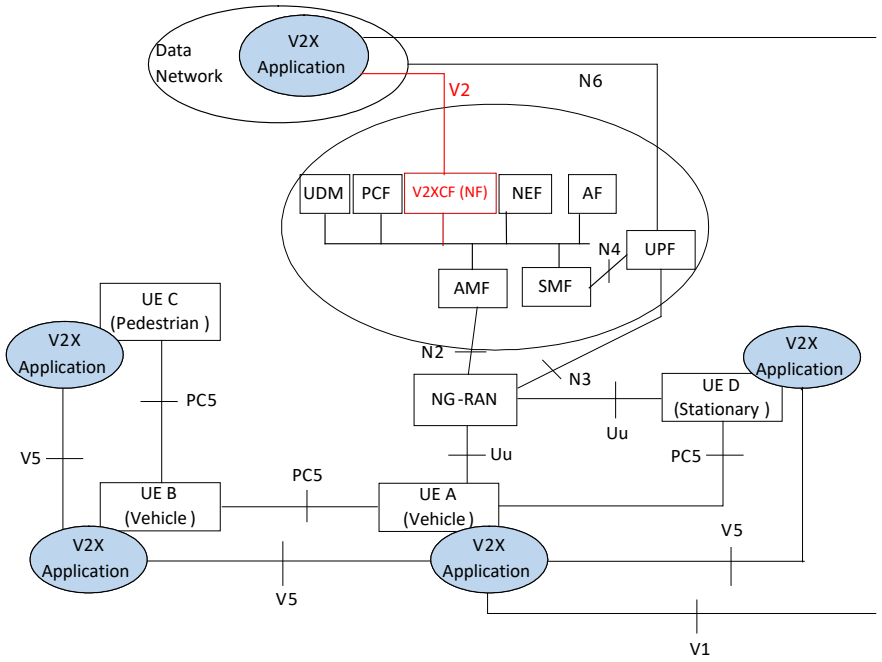


- Over 5GS

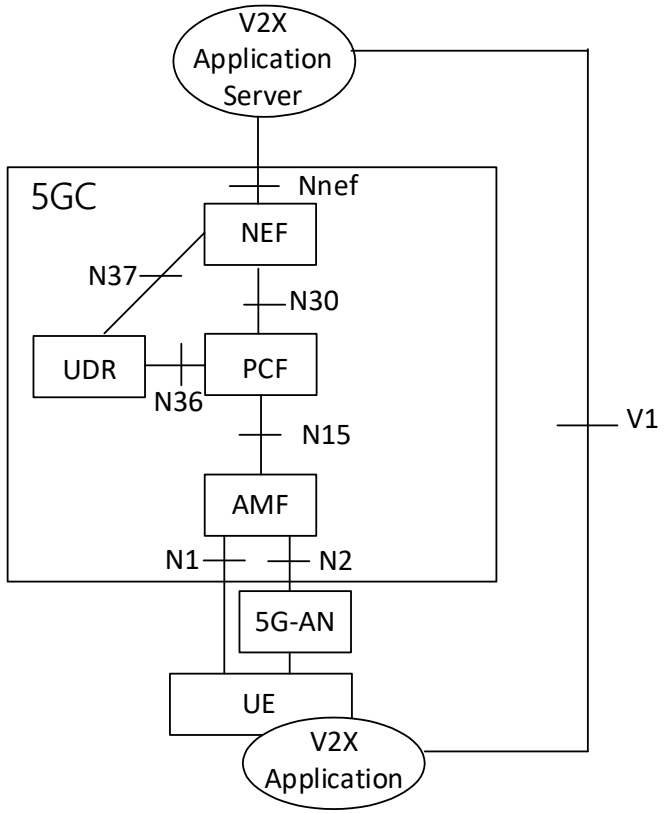


Architectural reference model

- Alternative architecture implementation

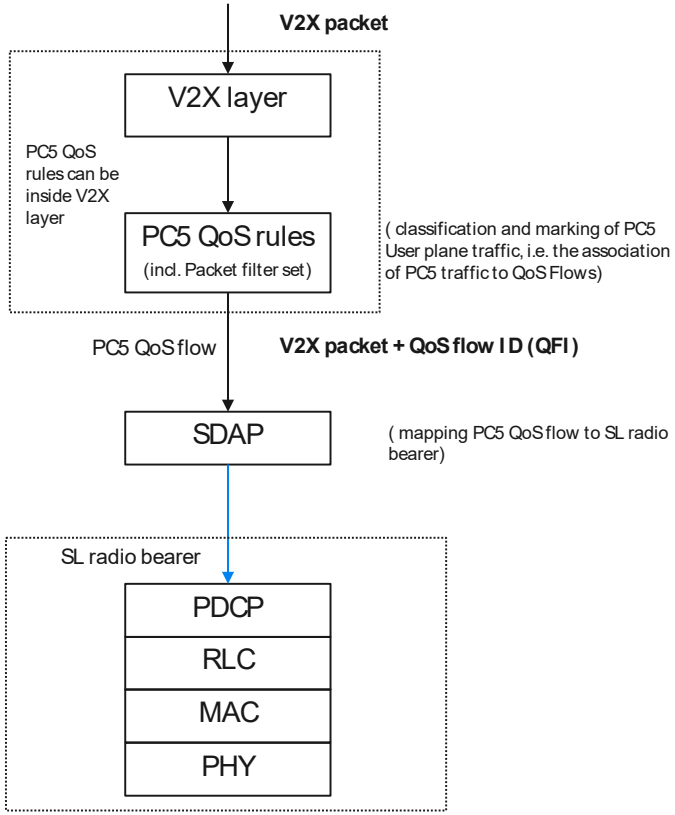


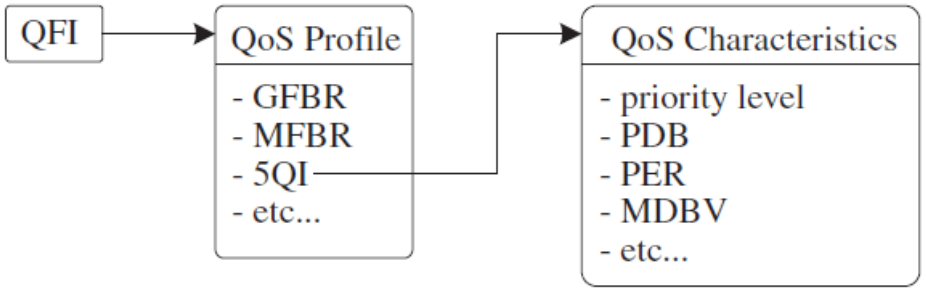
- AF-based service parameter provisioning for V2X communications



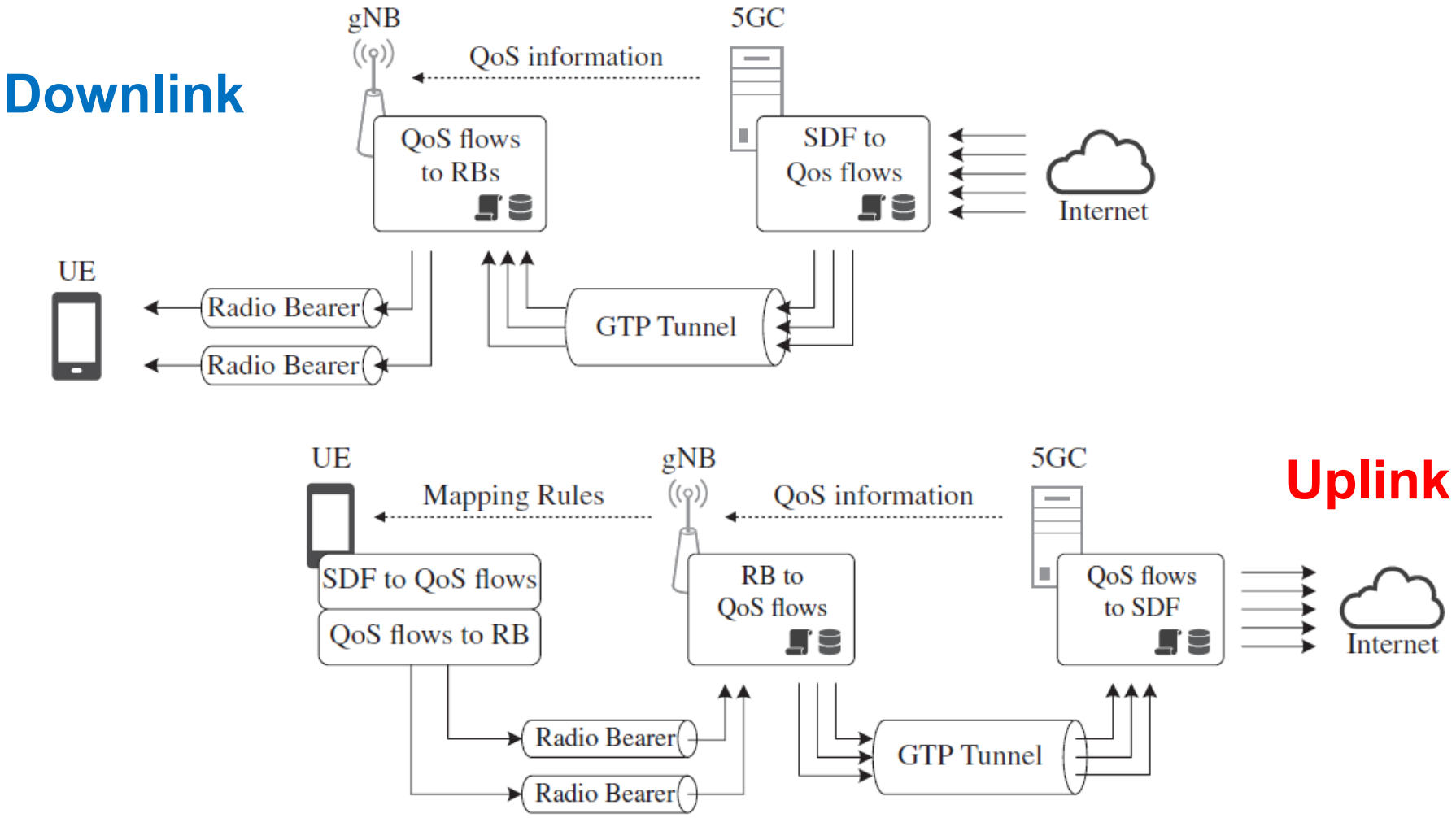
Per-flow QoS model for NR PC5

- Mapping of QoS flows into Data Radio Bearer (DRB) by Service Data Adaptation Protocol (**SDAP**)
- 5GC marks the flow with a **Quality of Service Flow ID** (**QFI**), used by the RAN to set the most suitable DRB
  - QFI: pointer to the profile described by some quality parameters for the flow (e.g. Guaranteed Flow Bit Rate (GFBR), Maximum Flow Bit Rate (MFBR) and Maximum Packet Loss Rate)
  - Other typical parameters of 5G services into **5G QoS Identifier** (**5QI**): priority level, Packet Delay Budget (PDB), Packet Error Rate (PER), and Maximum Data Burst Volume (MDBV)





SDAP: mapping of flows



Standardized 5QI to QoS mapping, Uu interface

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Default Maximum Data Burst Volume	Example Services
3	GBR	30	50 ms	10^{-3}	N/A	Real Time Gaming, V2X messages. Electricity distribution – medium voltage, Process automation monitoring
79	Non-GBR	65	50 ms	10^{-2}	N/A	V2X messages
83	Delay-critical GBR	22	10 ms	10^{-4}	1354 bytes	Discrete Automation; V2X messages (UE - RSU Platooning, Advanced Driving: Cooperative Lane Change with low LoA.
85	Delay-critical GBR	21	5 ms	10^{-5}	255 bytes	Electricity Distribution- high voltage. V2X messages (Remote Driving)
86	Delay-critical GBR	18	5 ms	10^{-4}	1354 bytes	V2X messages (Advanced Driving: Collision Avoidance, Platooning with high LoA)

Standardized 5QI (or PQI) to QoS mapping, PC5 interface

PQI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Example Services
21	GBR (NOTE 1)	3	20 ms	10^{-4}	Platooning between UEs – Higher degree of automation; Platooning between UE and RSU – Higher degree of automation
22	GBR (NOTE 1)	4	50 ms	10^{-2}	Sensor sharing – higher degree of automation
23	GBR (NOTE 1)	3	100 ms	10^{-4}	Information sharing for automated driving – between UEs or UE and RSU - higher degree of automation
55	Non-GBR	3	10 ms	10^{-4}	Cooperative lane change – higher degree of automation
56	Non-GBR	6	20 ms	10^{-1}	Platooning informative exchange – low degree of automation; Platooning – information sharing with RSU
57	Non-GBR	5	25 ms	10^{-1}	Cooperative lane change – lower degree of automation
58	Non-GBR	4	100 ms	10^{-2}	Sensor information sharing – lower degree of automation
59	Non-GBR	6	500 ms	10^{-1}	Platooning – reporting to an RSU
90	Delay Critical GBR (NOTE 1)	3	10 ms	10^{-4}	Cooperative collision avoidance (CCA); Sensor sharing – Higher degree of automation; Video sharing – higher degree of automation
91	Delay Critical GBR (NOTE 1)	2	3 ms	10^{-5}	Emergency trajectory alignment; Sensor sharing – Higher degree of automation

NOTE 1: GBR and Delay Critical GBR PQIs can only be used for unicast PC5 communications.

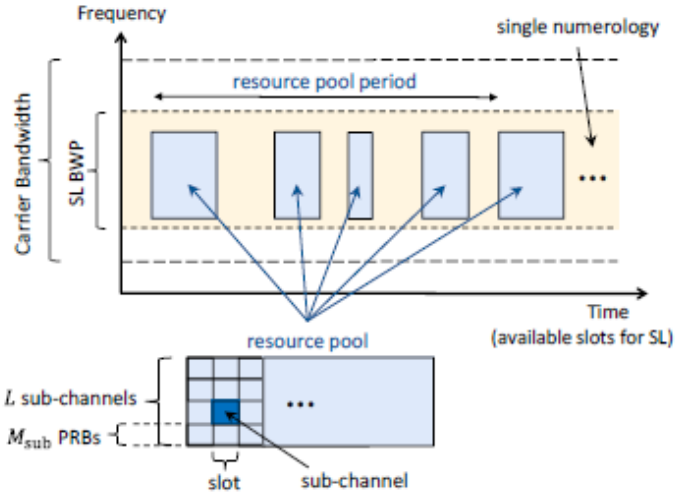
PC5 5QI = PQI

Radio interface in C-V2X

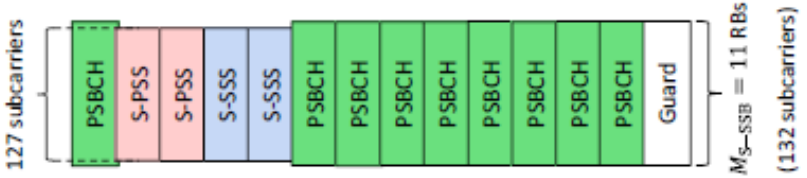
Sidelink signals

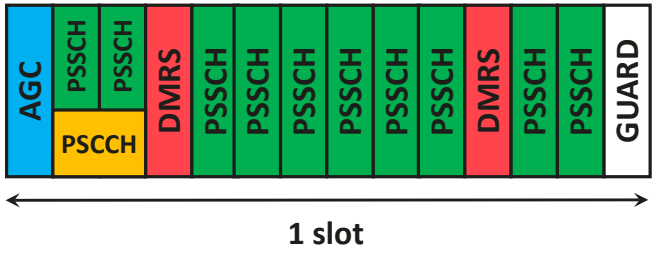
- Sidelink signal (SL) for direct communications between UEs
- Introduced in Rel. 14 (LTE-PC5), and in Rel. 16 (NR-PC5)
- Follows the same numerology of NR:
  - SCS =15kHz – 120kHz; slot per subframe = 1 – 8; slot duration=1 ms – 0.125 ms.
- Resources of SL defined within Band Width Part (BWP): M_{sub} = 10 - 100 PRBs.
- Resource Pool (RP) for Tx and Rx

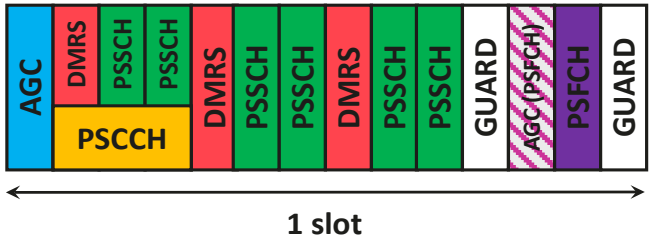
- Physical channels and signals in NR V2X sidelink:
  - Physical sidelink broadcast channel (PSBCH) and its de-modulation reference signal (**DMRS**)
  - Physical sidelink control channel (**PSCCH**) and its DMRS
  - Physical sidelink shared channel (**PSSCH**) and its DMRS
  - Physical sidelink feedback channel (**PSFCH**)
  - Sidelink primary and secondary synchronization signals (**S-PSS** and **S-SSS**)
  - Phase-tracking reference signal (PT-RS) in FR2
  - Channel state information reference signal (CSI-RS)



SCI 1st–stage
SCI 2nd–stage
Transport Block

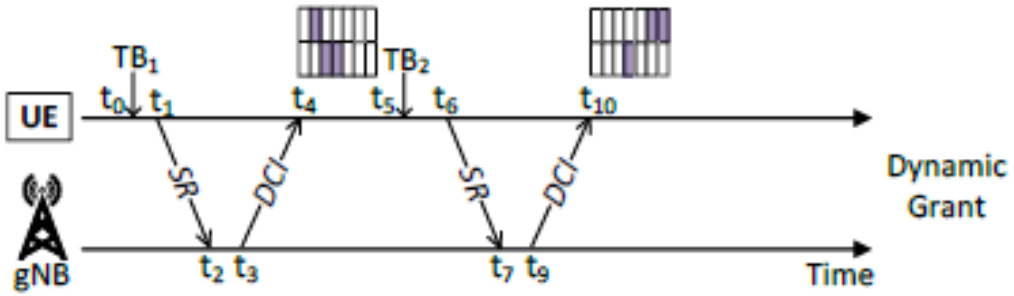


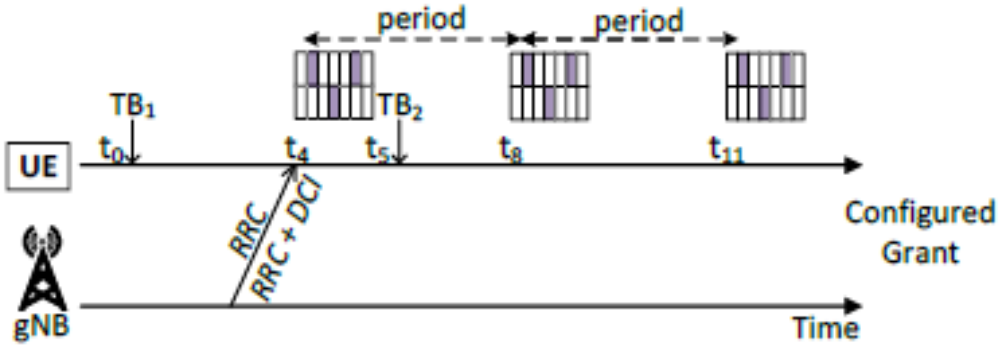




Resource allocation in LTE-PC5 and NR-PC5

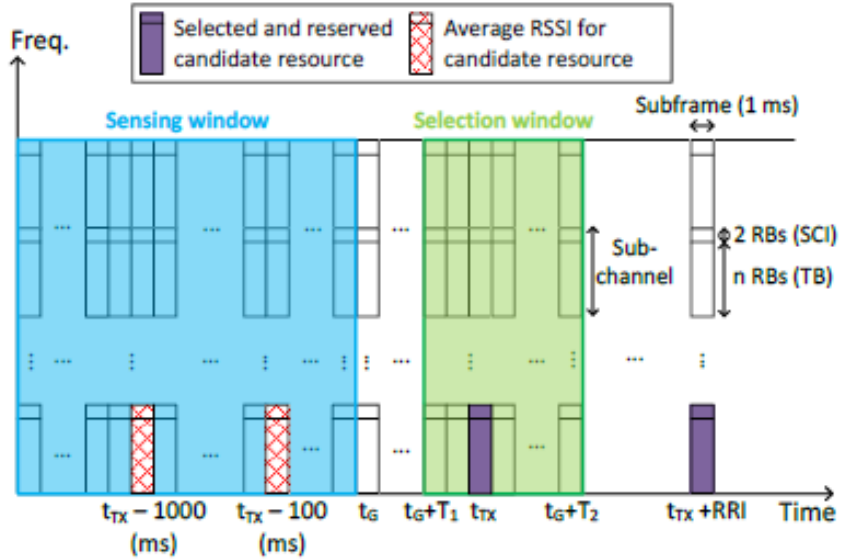
- Mode 3 for LTE-PC5 and Mode 1 for NR-PC5
  - Dynamic Grant (DG)
  - Semi-Persistent Scheduling (SPS)

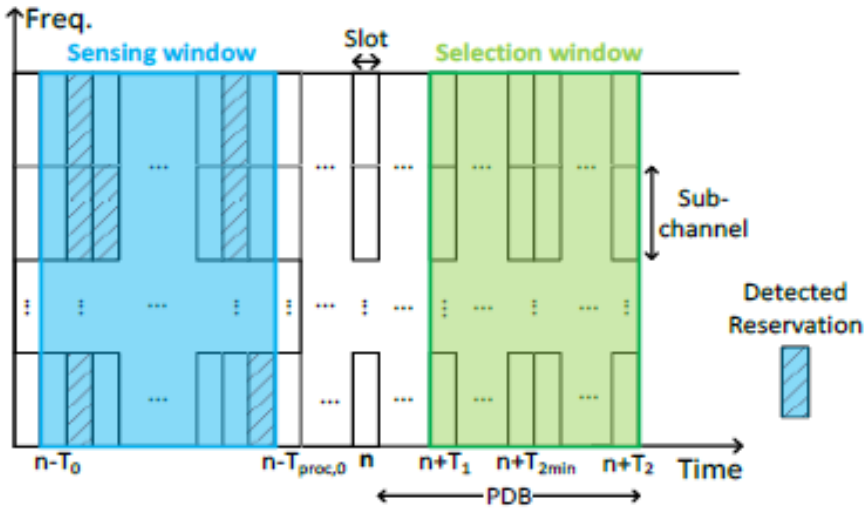




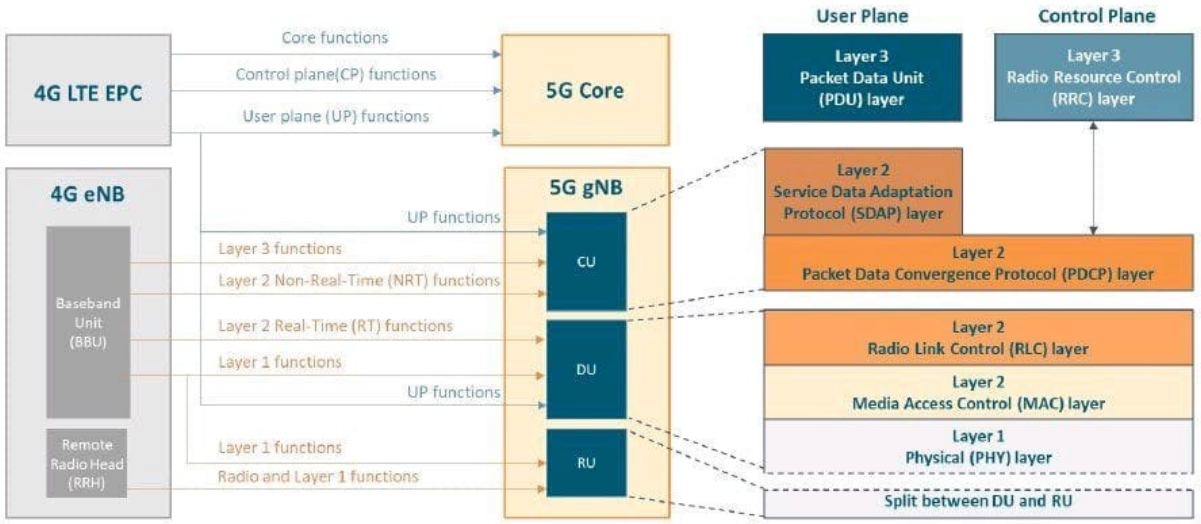
Resource allocation in LTE-PC5 and NR-PC5

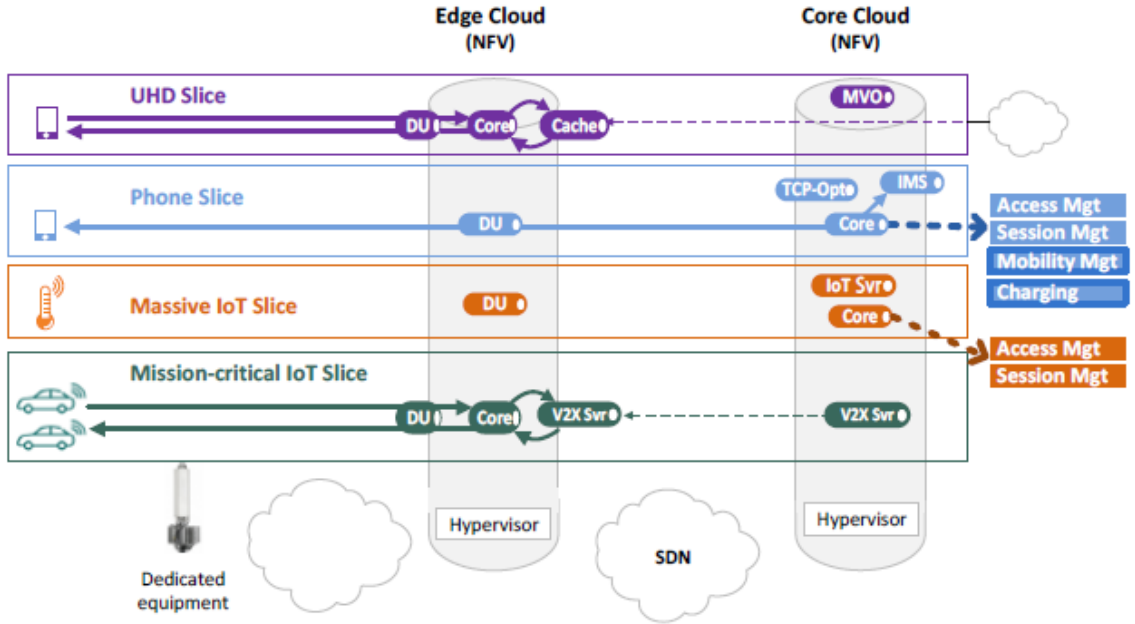
- Mode 4 for LTE-PC5 (sensing-based SPS scheduling)
  - Selection window, Selection window, transmission of V2X packet (SCI+TB)
- Mode 2 for NR-PC5
  - Already-Reserved resources (signaled by another UE by 1st-stage SCI)
  - Dynamic (i.e., resource for a single TB)
  - Semi-Persistent Scheduling (i.e., reserving resources for Reselection Counter (RC) consecutive TBs with a time interval of Resource Reservation Interval (RRI) slots)
- Sensing window (to identify available candidate resources, decoding the 1st-stage SCI of PRBs and measuring the RSRP),
- Selection window (based on the Packet Delay Budget, PDB), 2-step process:
  - Exclusions of PRBs (already used for transmissions, already used by other UEs with a power higher than a RSRP threshold,…)
  - Randomly selecting the SL resource from the candidates





5G network and slicing





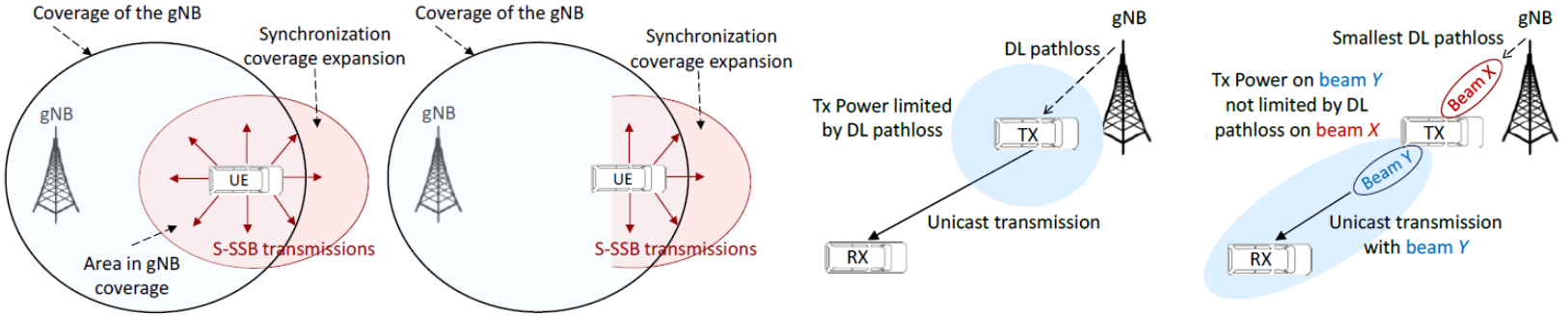
Source: netmanias

Improvements with 5G Release 16: new features

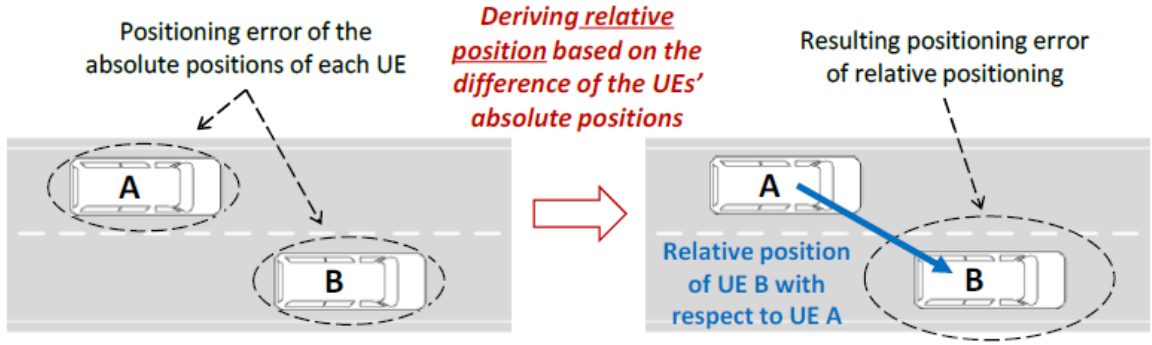
- QoS Sustainability analytics for C-V2X application servers (in 3GPP TS 23.287), also known as “Predictive QoS”,
- Support of Alternative QoS Requirements from C-V2X application servers (in 3GPP TS 23. 287 and TS 23.501)
- Standardized V2X Slice/Service Type (SST) (in 3GPP TS 23.501)
- Mobility enhancements for managing the handovers

Improvements with 5G Release 17

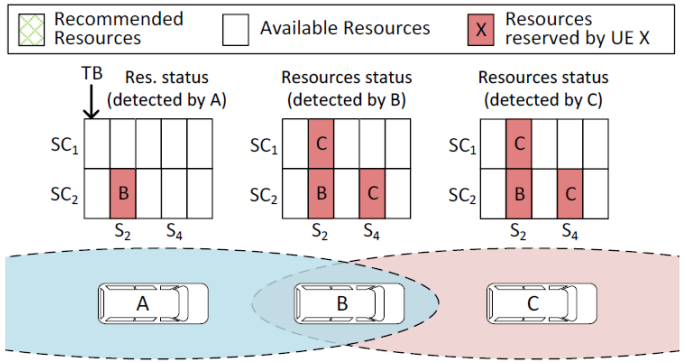
- Beam forming in SL



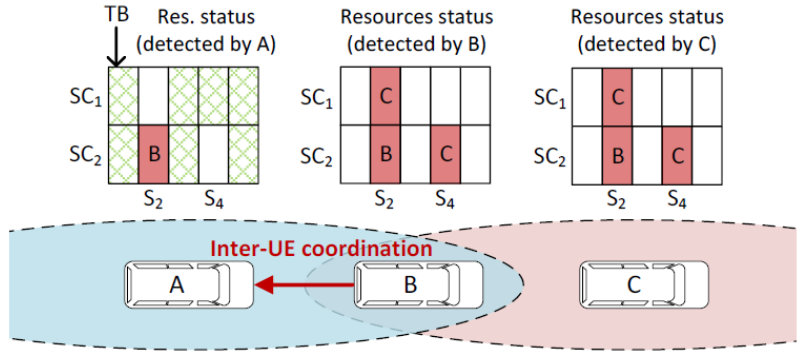
- Derive relative position for increasing maneuver accuracy



- Enhancements to resource allocation



- UE multiple relaying
  - In-coverage, partial, out-of-coverage



References

- 5GAA, “C-V2X Use Cases Volume II: Examples and Service Level Requirements”, 20 October 2020, Available: https://5gaa.org/wp-content/uploads/2020/10/5GAA_White-Paper_C-V2X-Use-Cases-Volume-II.pdf
- M. H. C. Garcia et al., "A Tutorial on 5G NR V2X Communications," in IEEE Communications Surveys & Tutorials, vol. 23, no. 3, pp. 1972-2026, thirdquarter 2021, doi: 10.1109/COMST.2021.3057017.
- A. Alalewi, I. Dayoub and S. Cherkaoui, "On 5G-V2X Use Cases and Enabling Technologies: A Comprehensive Survey," in IEEE Access, vol. 9, pp. 107710-107737, 2021, doi: 10.1109/ACCESS.2021.3100472.
- A. Bazzi, A. O. Berthet, C. Campolo, B. M. Masini, A. Molinaro and A. Zanella, "On the Design of Sidelink for Cellular V2X: A Literature Review and Outlook for Future," in IEEE Access, vol. 9, pp. 97953-97980, 2021, doi: 10.1109/ACCESS.2021.3094161.
- M. Harounabadi, et al., “V2X in 3GPP Standardization: NR Sidelink in Rel-16 and Beyond”, accepted in IEEE Communication Standards Magazine, 2022
- D. Garcia-Roger, et al., "V2X Support in 3GPP Specifications: From 4G to 5G and Beyond," in IEEE Access, vol. 8, pp. 190946-190963, 2020, doi: 10.1109/ACCESS.2020.3028621.
- 5G Americas, “Vehicular Connectivity: C-V2X & 5G”, Sept. 2021

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Cellular-Vehicle-to-everything (C-V2X) for enabling Intelligent Transportation System (ITS)

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Department of Engineering Science

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