Qualcomm

Cellular-V2X Technology Overview

80-PE732-63 Rev B

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U.S.A.

Objectives

- Introduce Cellular-V2X (C-V2X) direct mode
- Describe Link and System design details
- Review upper layers
- Discuss congestion control
- Lab, Range and Interference test results
- Outline C-V2X 5G evolution

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Assumed background of reader

Required

- Working knowledge of LTE and LTE Advanced

Suggested

- Knowledge of Wi-Fi

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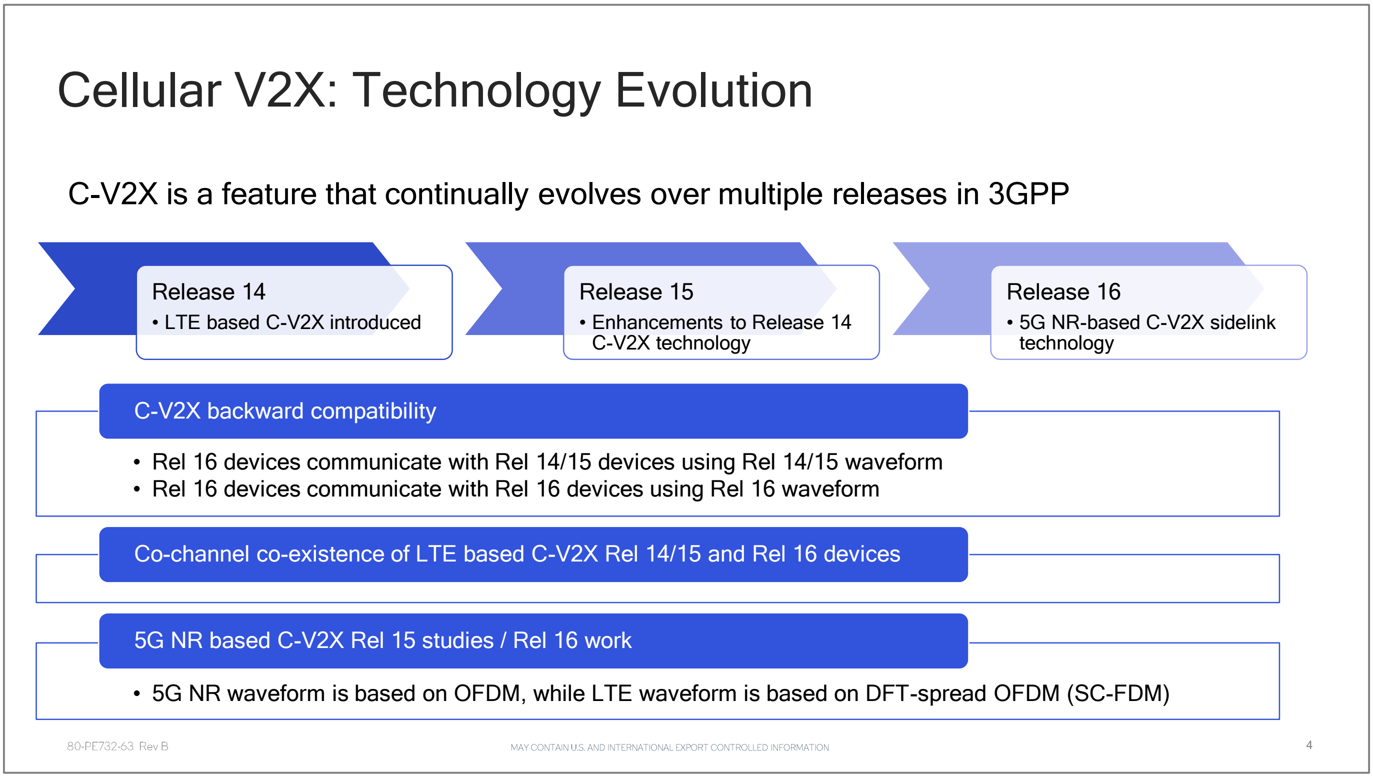
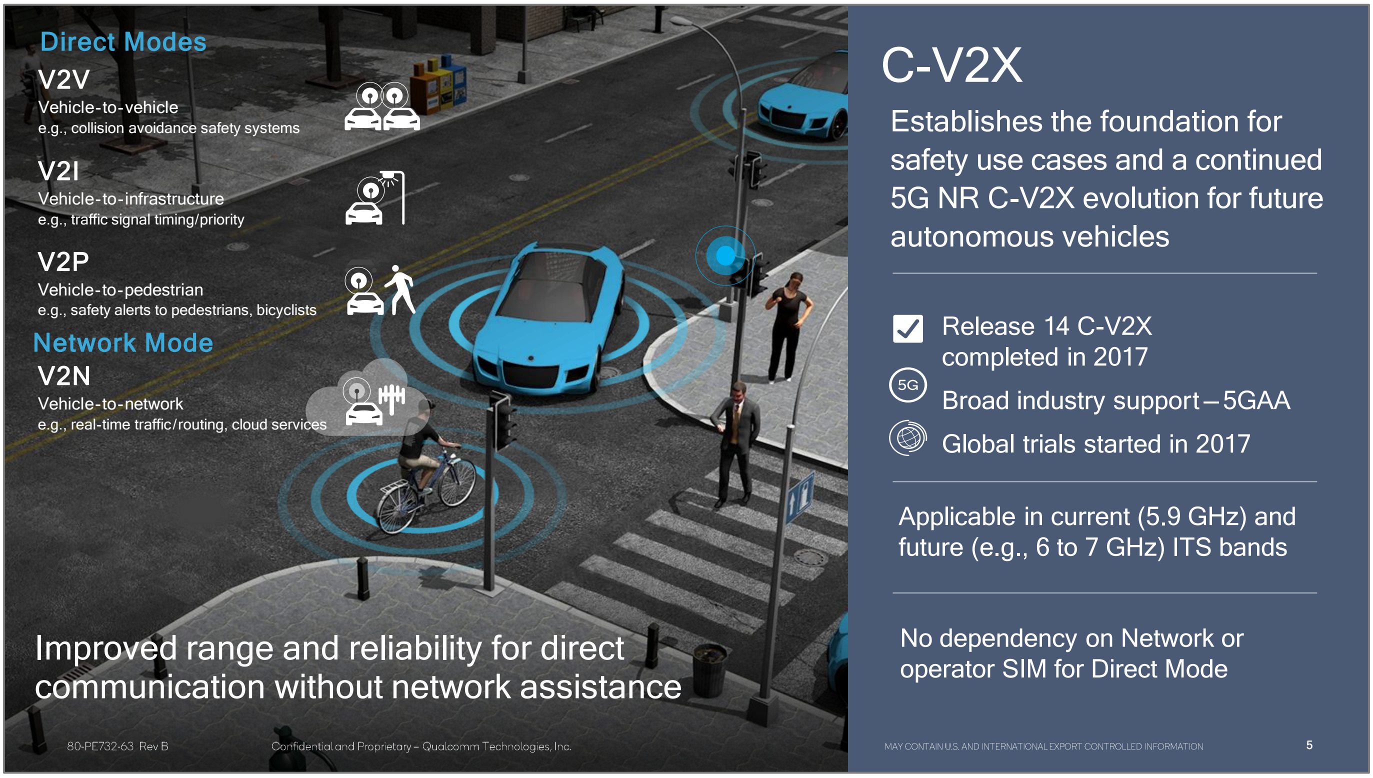


3GPP Standards:

- LTE based Rel-14 C-V2X – Completed in Q1 2017
- LTE based Rel-15 C-V2X – Completed June 2018
- Next set of specs – NR-based Rel-16 C-V2X sidelink – Slated for completion in Q4 2019


Direct Modes
V2V
Vehicle-to-vehicle
e.g., collision avoidance safety systems
V2I
Vehicle-to-infrastructure
e.g., traffic signal timing/priority
V2P
Vehicle-to-pedestrian
e.g., safety alerts to pedestrians, bicyclists
Network Mode
V2N
Vehicle-to-network
e.g., real-time traffic/routing, cloud services
Improved range and reliability for direct communication without network assistance
C-V2X
Establishes the foundation for safety use cases and a continued 5G NR C-V2X evolution for future autonomous vehicles
Release 14 C-V2X completed in 2017
5G
Broad industry support – 5GAA
Global trials started in 2017
Applicable in current (5.9 GHz) and future (e.g., 6 to 7 GHz) ITS bands
No dependency on Network or operator SIM for Direct Mode
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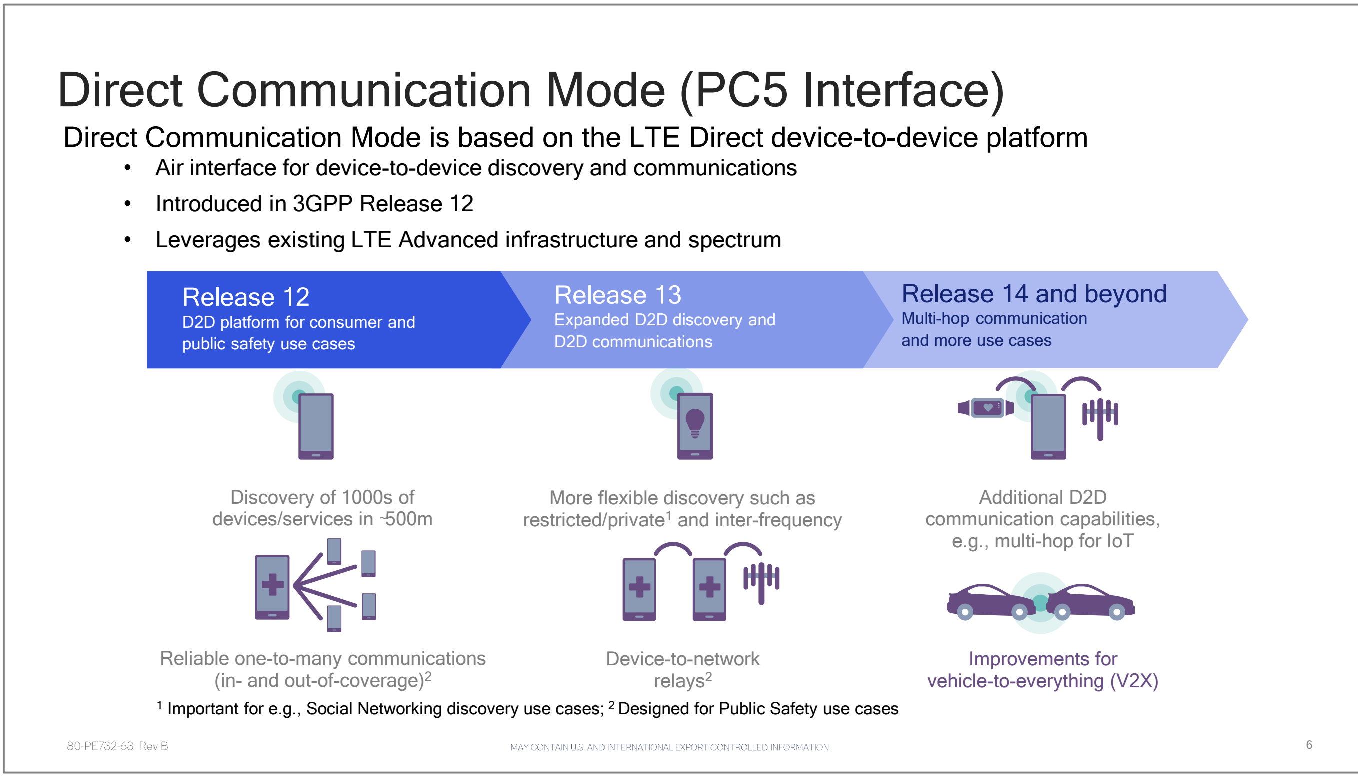


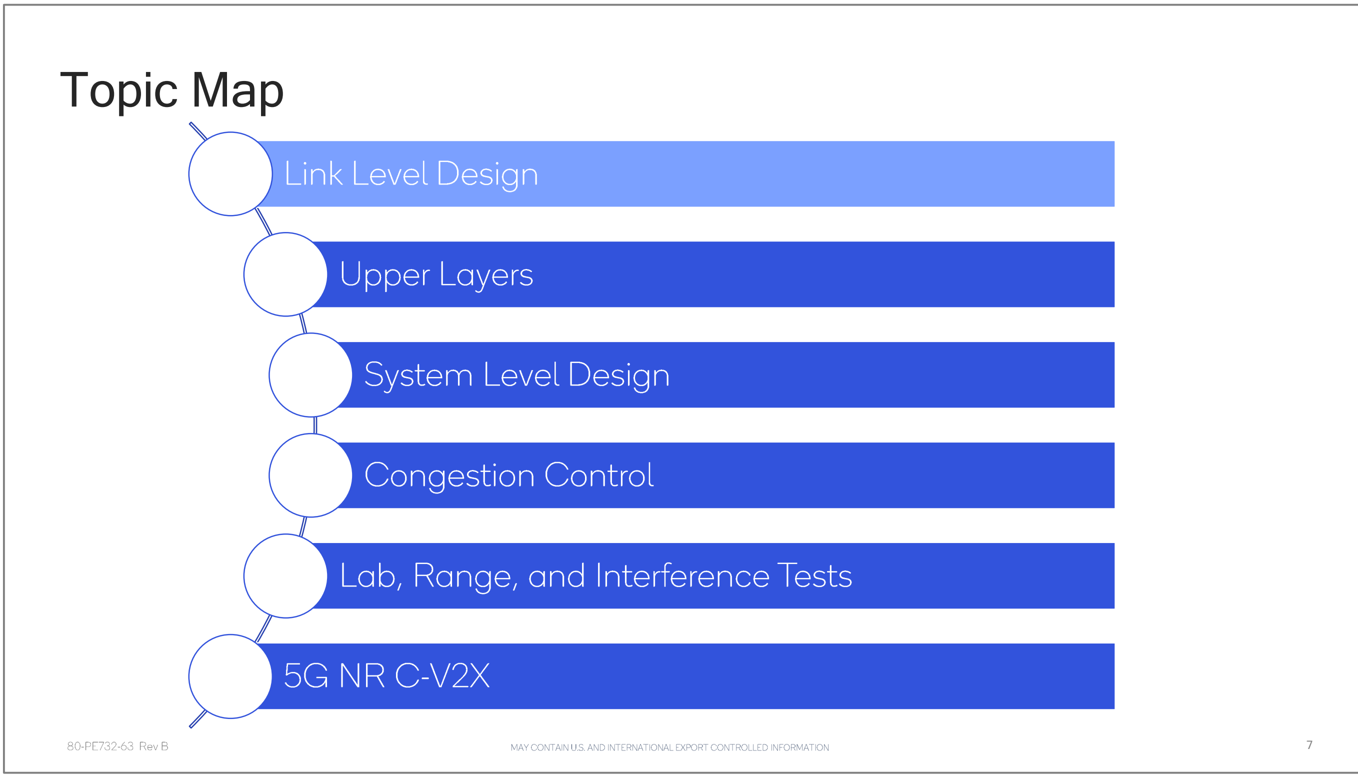
LTE Direct is a brand new air interface for device-to-device discovery and communications that was introduced in Release 12 of the 3GPP standard. LTE Direct enables operator-managed D2D services leveraging existing LTE Advanced infrastructure and spectrum.

Release 12 established the framework for this new technology enabling D2D discovery of 1000s of devices/services in approx. ½ a kilometer. This is empowering new proximity services. R12 also introduced one-to-many D2D communications designed for public safety use cases.

Release 13 and beyond are evolving and expanding the LTE Direct Platform, commonly known as ProSe.

- Enhancing the D2D discovery and communication capabilities, including multi-hop communication to extend the reach of the network.

Release 14 set the based for another important focus area for LTE Direct by expanding to new use cases with one key example being vehicle-to-vehicle and vehicle-to-infrastructure communications to increase safety and reduce congestion on the roads, which we will talk about more in the next few slides (slide 9 and 10).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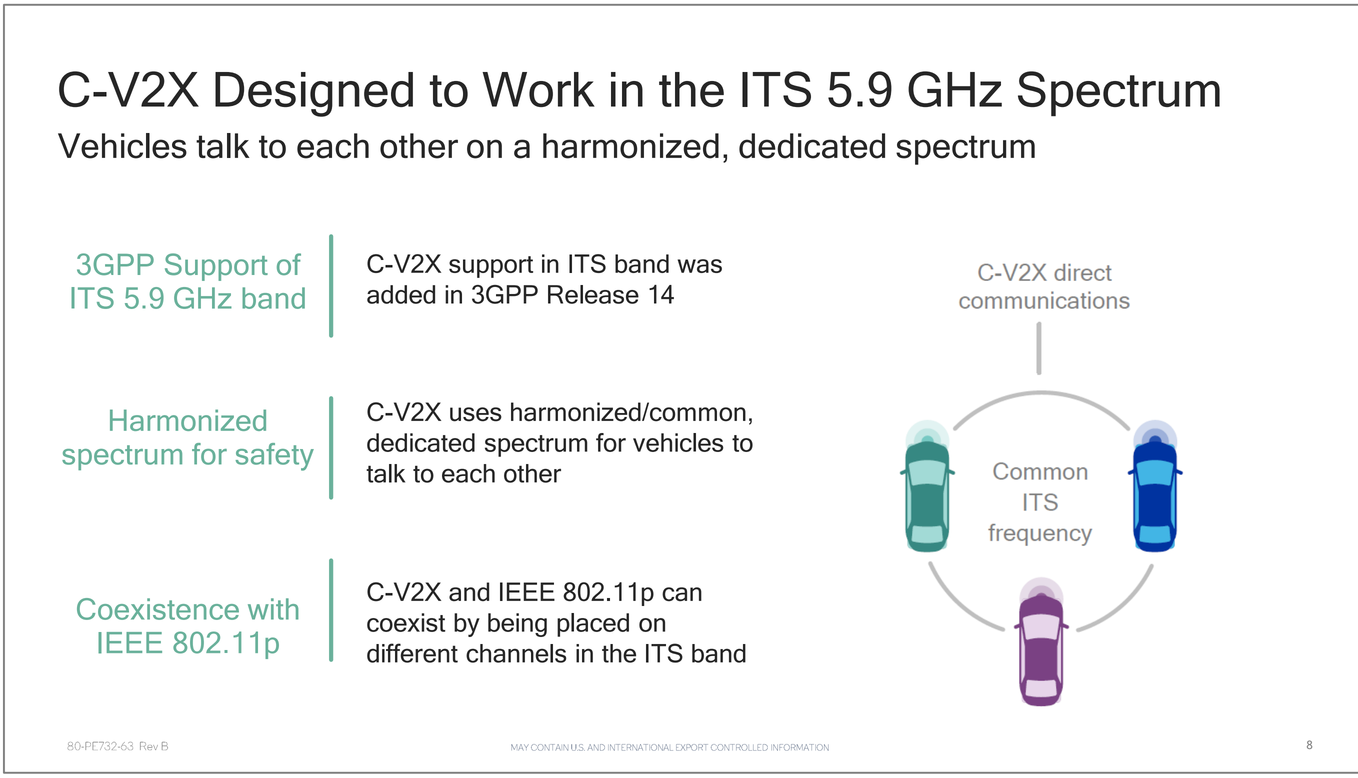
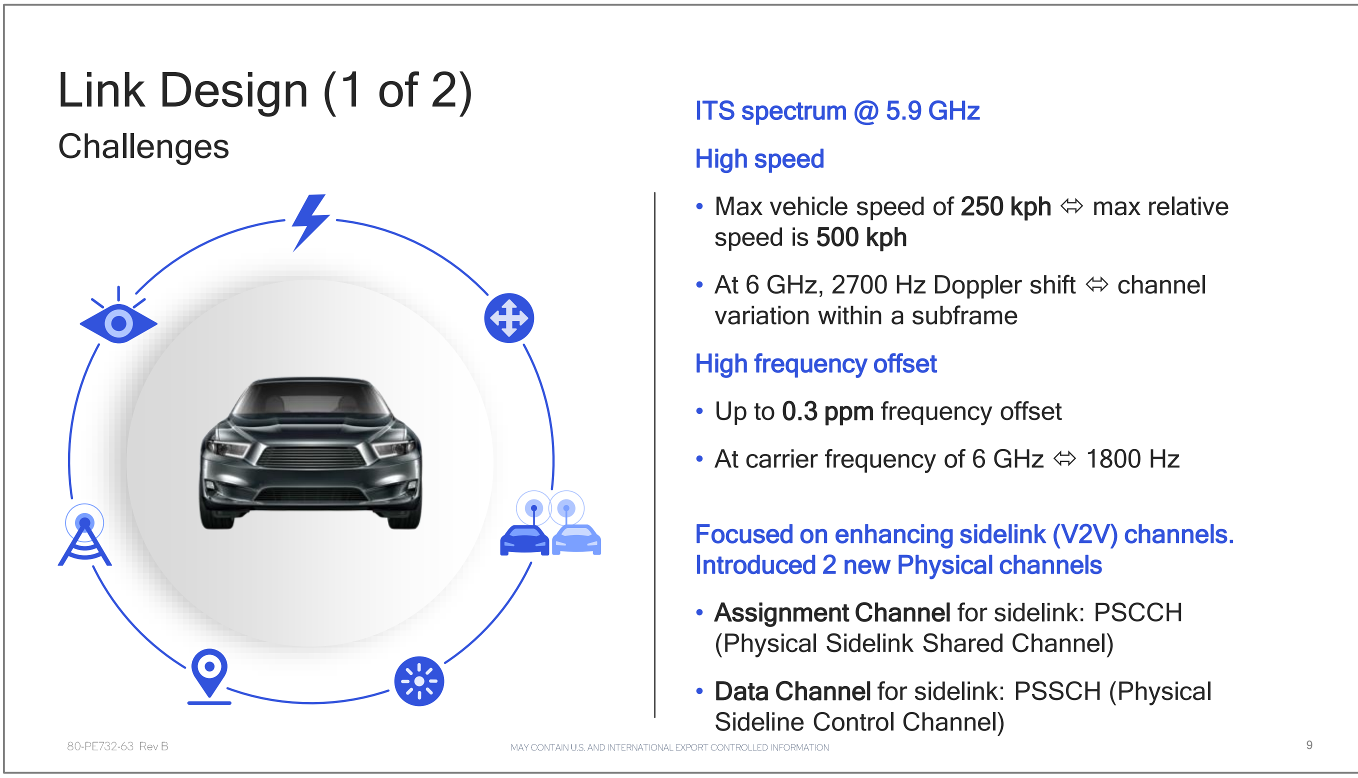


C-V2X in the direct mode operates in what is known as the ITS band in 5.9 GHz spectrum.

The support for 5.9 GHz band was introduced in 3GPP Release 14. It ensures that there is communication between all of the vehicles in this particular band. This band is also used by what is referred to as 802.11p or DSRC.

If C-V2X and 802.11p are on adjacent or near-adjacent channels, given strict out-of-band emission limits, coexistence is possible. This is the basis behind the Dual Mode RSU.

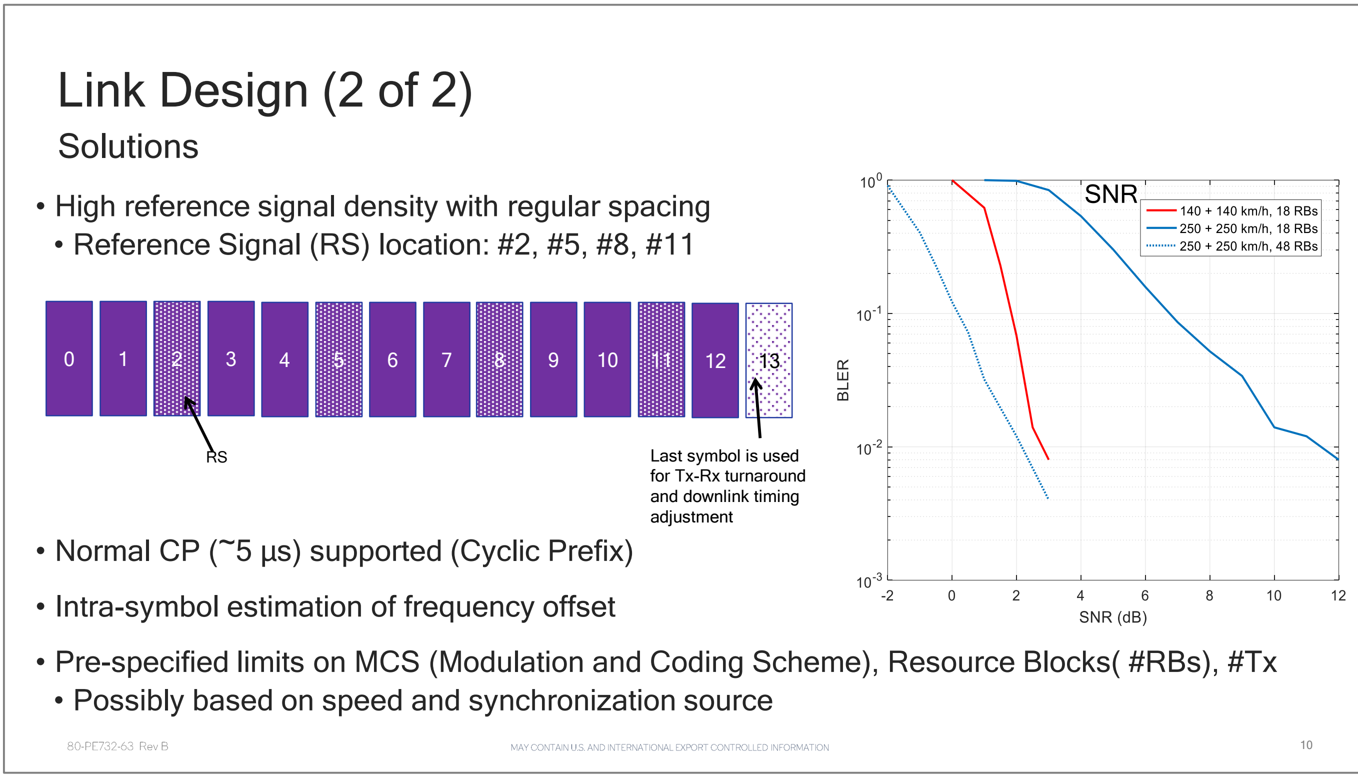


5.9 GHz spectrum is a high frequency spectrum and replete with challenges in high speed scenarios.

The LTE bands are deployed in various frequency bands and highest being around 2.5 GHz. There were some challenges that needed to be addressed when LTE technology is operated in 5.9 GHz band.

- With relative speeds of 500 Km/hr at 6 GHz, there is a very high Doppler shift of 2700 Hz leading to channel variation even within a subframe.
- There is also very high frequency offset of up to 0.3 ppm translating to 1800 Hz at 6 GHz.
- These changes in frequency at high speed situations impacts the way channel estimation can be done reliably.

3GPP Release 14 has introduced some advanced Link Layer enhancements to address these challenges in all scenarios.



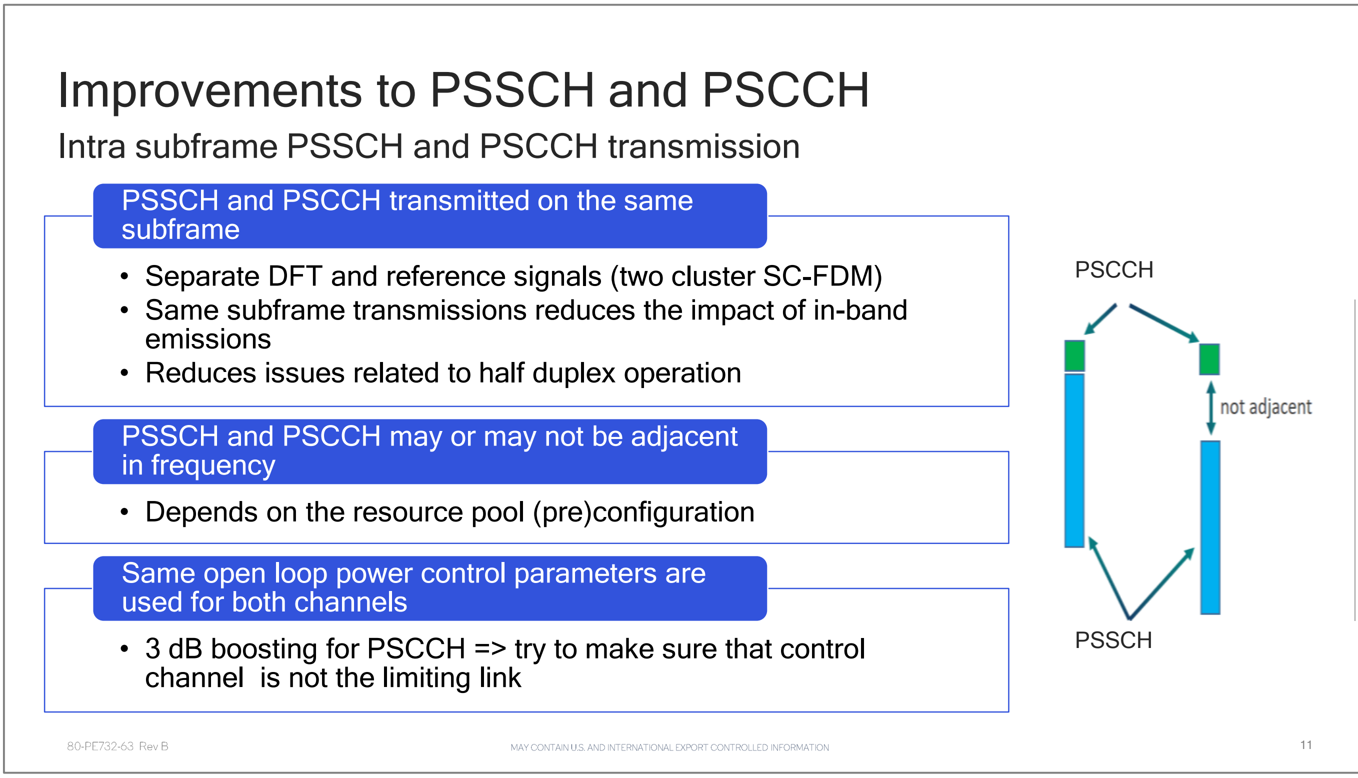
In LTE, a system frame of 10 ms is comprised of ten 1 ms subframes.
In each subframe, there are 14 symbols where data and control signals are transmitted.

In LTE, 2 of these symbols are used as reference signals for channel estimation. However, given the challenges that are more typical of high speed vehicular scenarios, it was determined that addition of 2 extra reference signals significantly increases the reliability of channel estimation. These reference signals at slot 2, 5, 8 and 11.

C-V2X operates with a normal cyclic prefix of about 5 µs.

Another way to address the challenges of high frequency and high speeds is providing a dynamic way of using Modulation and Coding scheme (MCS) and the number of Resource blocks. By increasing the number of resource blocks and using lower MCS, for much high speed situations, the signal-to-noise ratio (SNR) can be significantly reduced at which we have the standard 10% BLER, leading to much improved performance.

Another way to analyze is that for relatively lower speeds, lesser number of resource blocks are sufficient to give the same performance. Thus by adjusting the MCS and number of resource blocks in varying conditions, optimal performance is guaranteed.



3GPP Release 14 also introduced two new Physical channels for sidelink communication, namely the Physical sidelink shared channel (PSSCH) and Physical sideline control channel (PSCCH). As the name suggests, PSSCH carries data and PSCCH carries control information for decoding the data channel.

PSSCH and PSCCH are transmitted in the same subframe, unlike in LTE, where the shared channel is transmitted a few subframes after the control channel is transmitted. 3GPP spec also allows for adjacent and non-adjacent PSCCH and PSSCH transmission, in the frequency domain.

PSCCH

- One PSCCH transmitted for each PSSCH on the same subframe
- No combining of PSCCH retransmission
- Number of RBs = 2
- Blind detection of cyclic shift to improve PSCCH to PSCCH interference

PSSCH

- Max number of transmissions = 2
- RV ID sequence for HARQ transmissions are given by 0, 2
- Maximum distance between initial transmission and HARQ retransmission is 15
- Various phy parameters are a function of PSCCH CRC

C-V2X Rel-14 has Significantly Better Link Budget Than 802.11p*

Leading to longer range (~upto 2X range)—or more reliable performance at the same range

Transmission time
Longer transmit time leads to better energy per bit

Energy per bit is accumulated over a longer period of time for C-V2X

+

Channel coding
Gains from turbo coding and retransmission

Coding gain from turbo codes and HARQ (Hybrid Automatic Repeat Request) retransmission lead to longer range

~upto 2X
Longer range

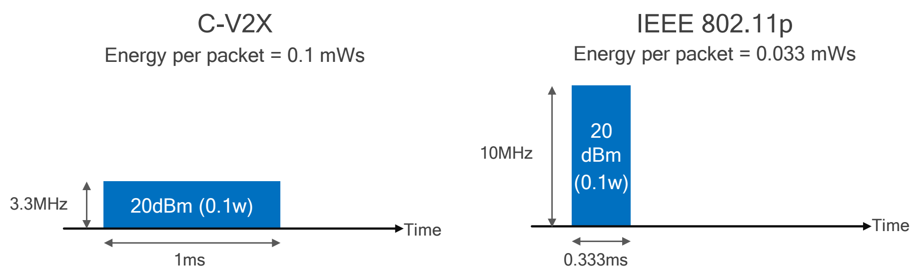
Longer Transmission Time: Leads to Link Budget Gain

Usage of FDM in C-V2X provides an advantage compared to TDM in 802.11p

Example*

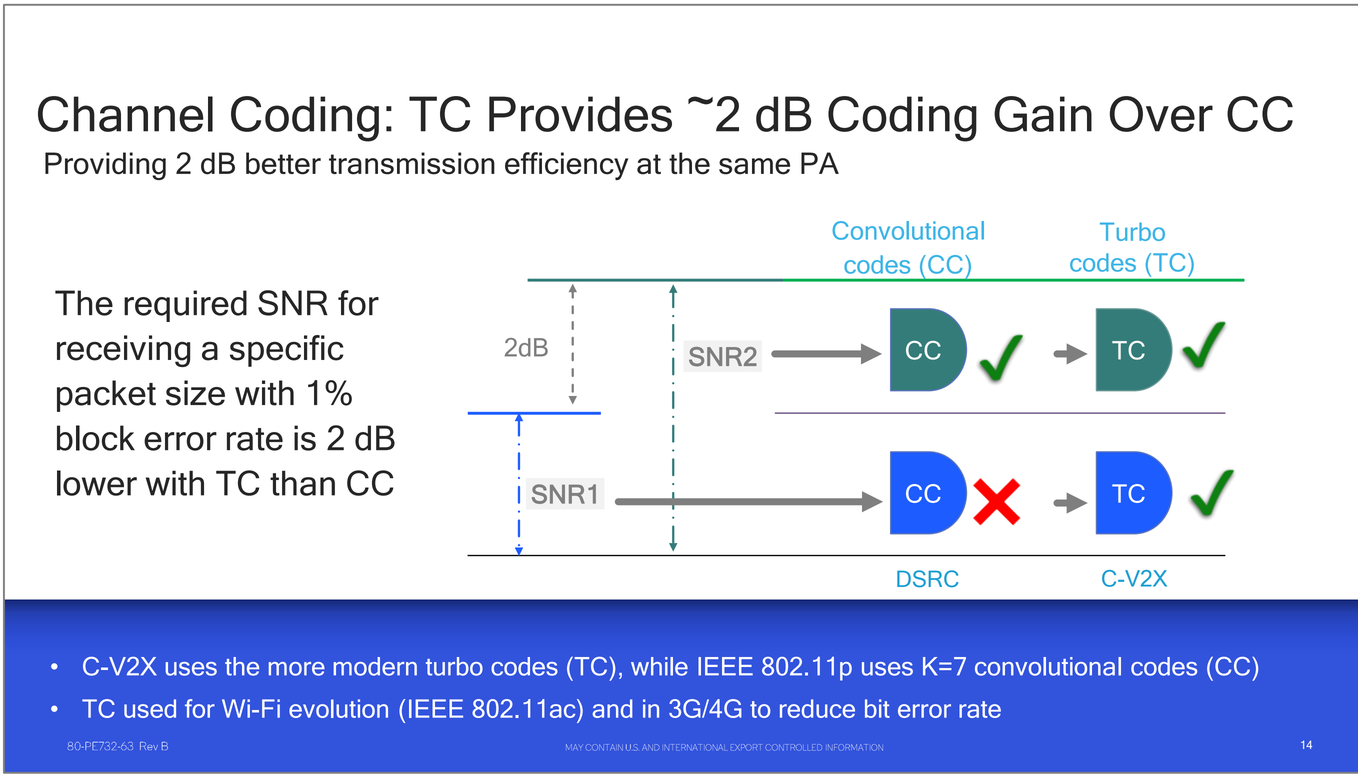
4.8dB (3X)

Gain per packet for C-V2X



*Assumptions: 190 bytes packet size, ½ rate coding for 802.11p, 0.444 rate coding for C-V2X, QPSK modulation used for both 802.11p and C-V2X,

- C-V2X has longer transmission time for the same number of transmitted bits, leading to better energy per bit (as energy is accumulated over a longer period of time)
- FDM transmission has been adopted as an efficient mode of packet transmission in 4G cellular systems

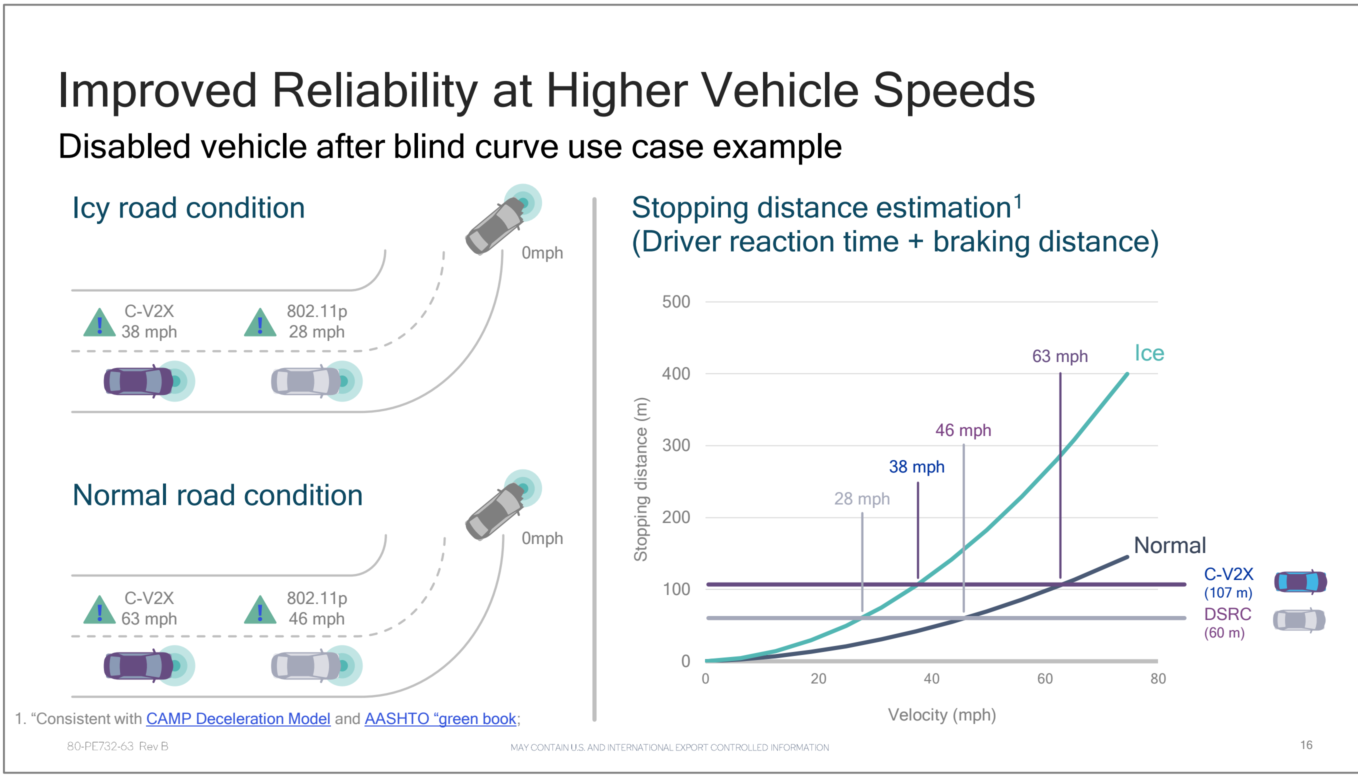


C-V2X with Turbo codes is designed to facilitate decoding capability even at lower SNR (SNR1) whereas for DSRC with convolutional codes requires higher SNR (SNR2) for successful decode.

Rel-14 C-V2X vs. (DSRC) (802.11p)

Technology Comparison – Phy Layer

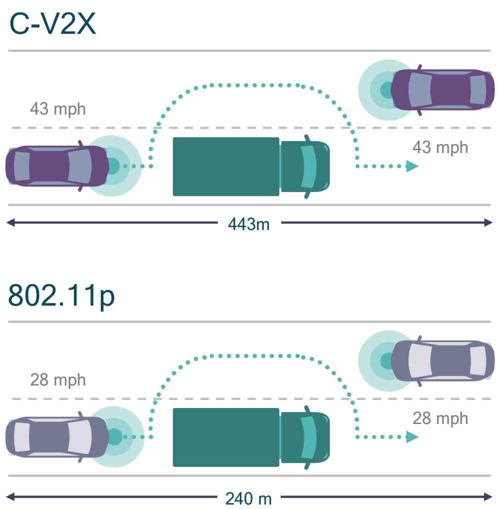
Parameters	DSRC (802.11p)	R14 C-V2X
Link Level		
Reference Signal Design	Advanced channel estimation needed at high speeds	Nominal channel estimation sufficient at high speeds
Multiplexing	TDM only	TDM/FDM
Rx Diversity	Not mandated	Yes
HARQ	No	Yes
Coding	Convolutional	Turbo
Modulation Scheme	OFDM	SC-FDM

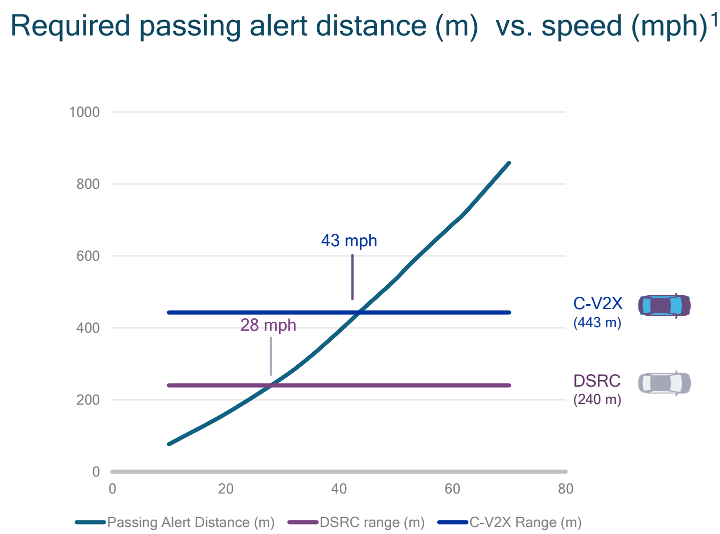


The intent of these simulation plots is to signify the advantage of vehicles operating with C-V2X compared with DSRC in real life conditions. The plots show that C-V2X can operate at higher speeds in icy road and normal road conditions to reliably bring moving vehicle to a complete stop and avoid collision with a stalled vehicle in their path.

Improved Reliability at Higher Speeds and Longer Ranges

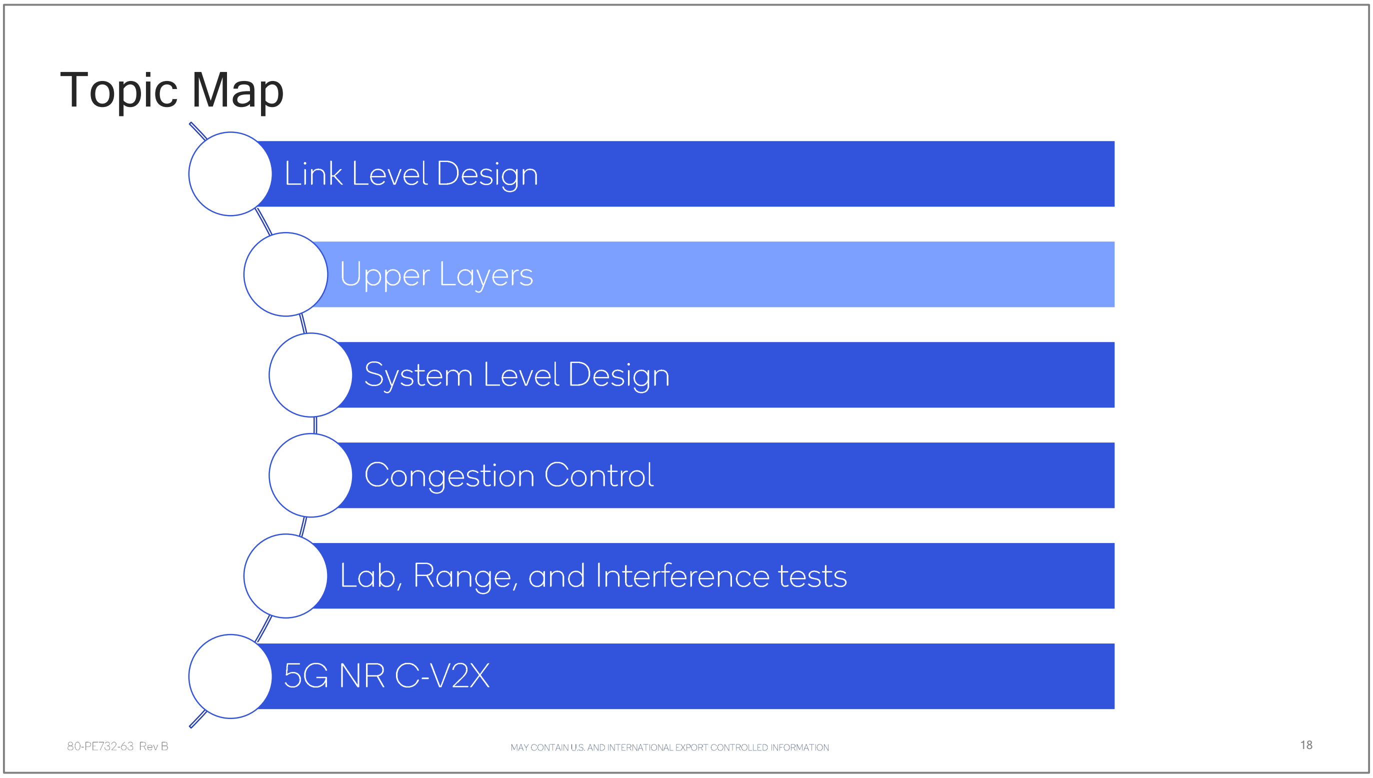
Do not pass warning (DNPW) use case example





1. Calculations based on AASHTO "green book"

The advantage of C-V2X in a "Do not pass warning" scenario is also evident from the fact that vehicles can operate at higher speeds and still get the messages reliably at larger inter vehicle distance, compared to DSRC, and thus safely make a vehicle pass maneuver.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PC5 Operational Details in Mode 4 (1 of 2)

UE Autonomous Mode

Mode applicability

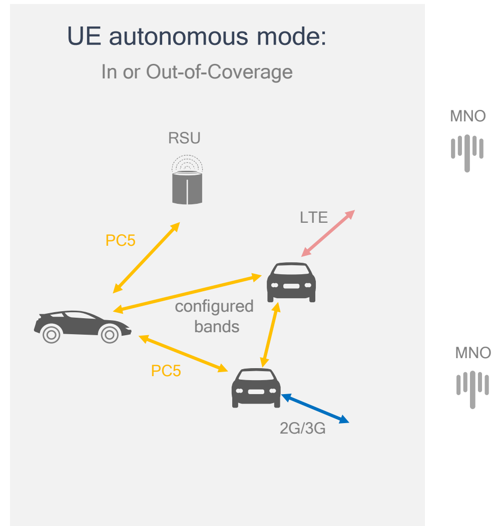
- Independent of network connectivity:
  - Out-of-Coverage - including when in 2/3G
  - Limited Service State
  - In-Coverage
- Work in both IDLE or CONNECTED state

Methods for UE configuration

- 3 possible ways for UE configuration:
  - Pre-configuration in ME (no need for UICC (Universal Integrated Circuit Card))
  - Configuration stored in UICC
  - Provisioning from Network (via OMA-DM (Open Mobile Alliance - Device Management))

Configuration parameters

- Allowed PLMNs; and whether OoC allowed
- Radio parameters with associated GeoArea
- Mapping of PSID/ITS-AID to L2 ID (Layer 2 ID)
- ProSe Per-Packet Priority (PPPP) to Packet Delay Budget (PDB) mapping
- PPPP and other parameters are being defined in SAE International J3161/1 (SAE International Standards for C-V2X)



PC5 Operational Details in Mode 4 (2 of 2)

UE Autonomous Mode

Band/Resources used

- C-V2X band defined in TS 36.101
- 5GAA Petition for waiver submitted for channel allocation

Timing/Synchronization

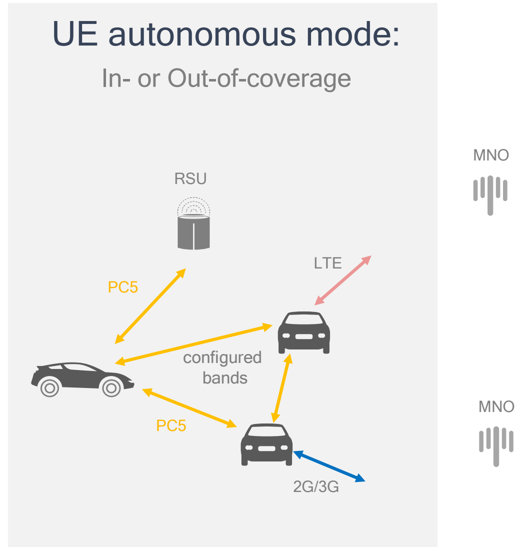
- GNSS (Global Navigation Satellite system) based

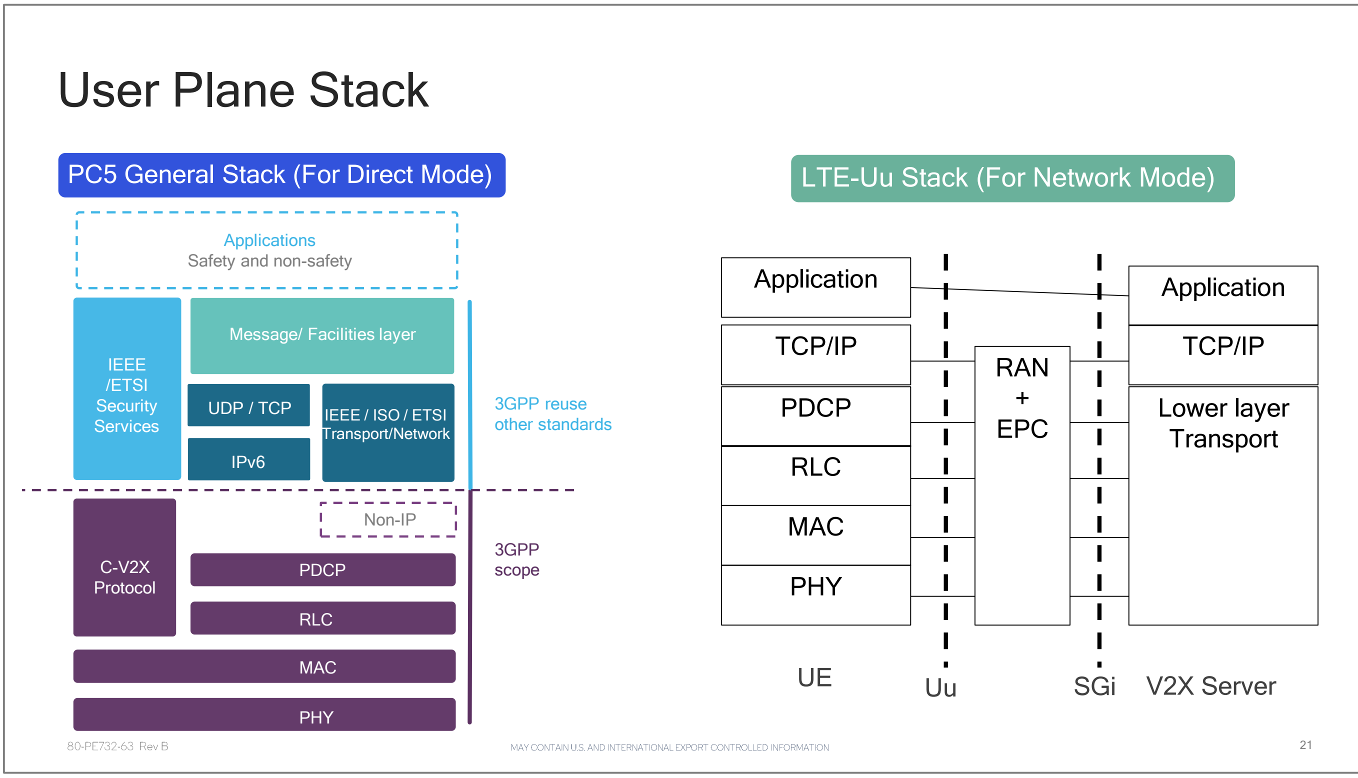
Resource selection/scheduling

- Distributed resources management
- UE autonomous selection based on sensing
- Distributed Congestion Control (DCC)

Security/Certification/Privacy

- Privacy is protected - PC5 identifiers can change together with user IDs
- No bearer level security over PC5 - Rely on upper layer security
- Certification stored in the UE, or provisioned out-of-band
- Security/certification/privacy considerations are therefore the same as with DSRC

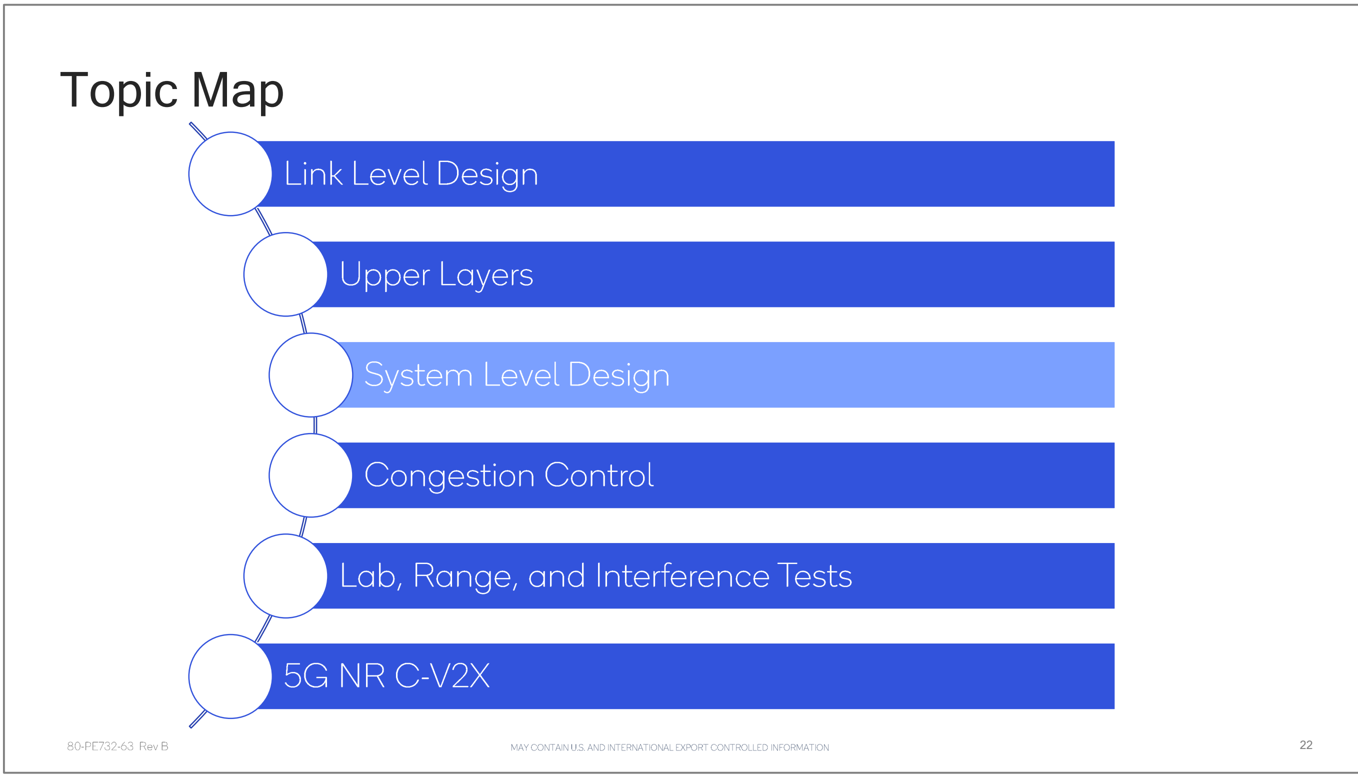




C-V2X device to device communication on PC5 interface, essentially relies on the 3GPP Release 14 defined lower layers commonly referred as PHY, MAC, RLC, PDCP for data transmission.

It also reuses the upper layer stacks from IEEE or ETSI (for US and EU regions respectively).

For comparison purposes, the similar protocol layers for the LTE Uu operation are also shown.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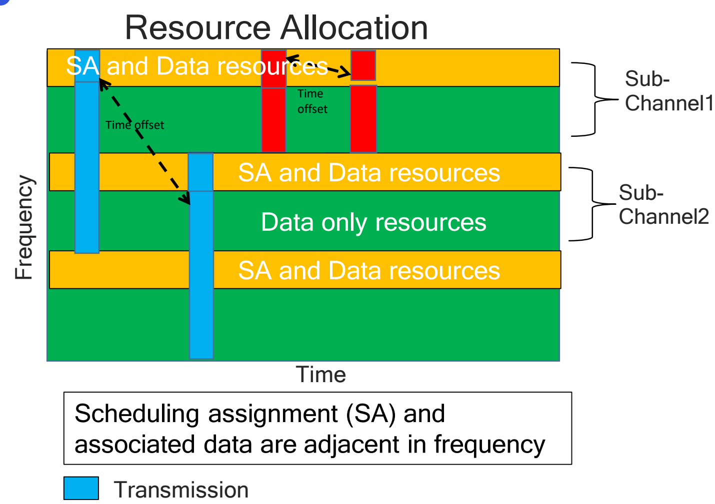
Resource Pool Design

Channel Configuration and Transmission

- Entire Bandwidth is divided into multiple subchannels
- Each subchannel consists of
  - SA and Data resources as well as
  - Data only resources
- PSCCH and PSSCH resource pools are FDM
- Allocations are made in terms of subchannels
- Transmissions may occupy one or more subchannels
- Configuration indicates whether scheduling assignment (SA) and associated data are adjacent in frequency or not

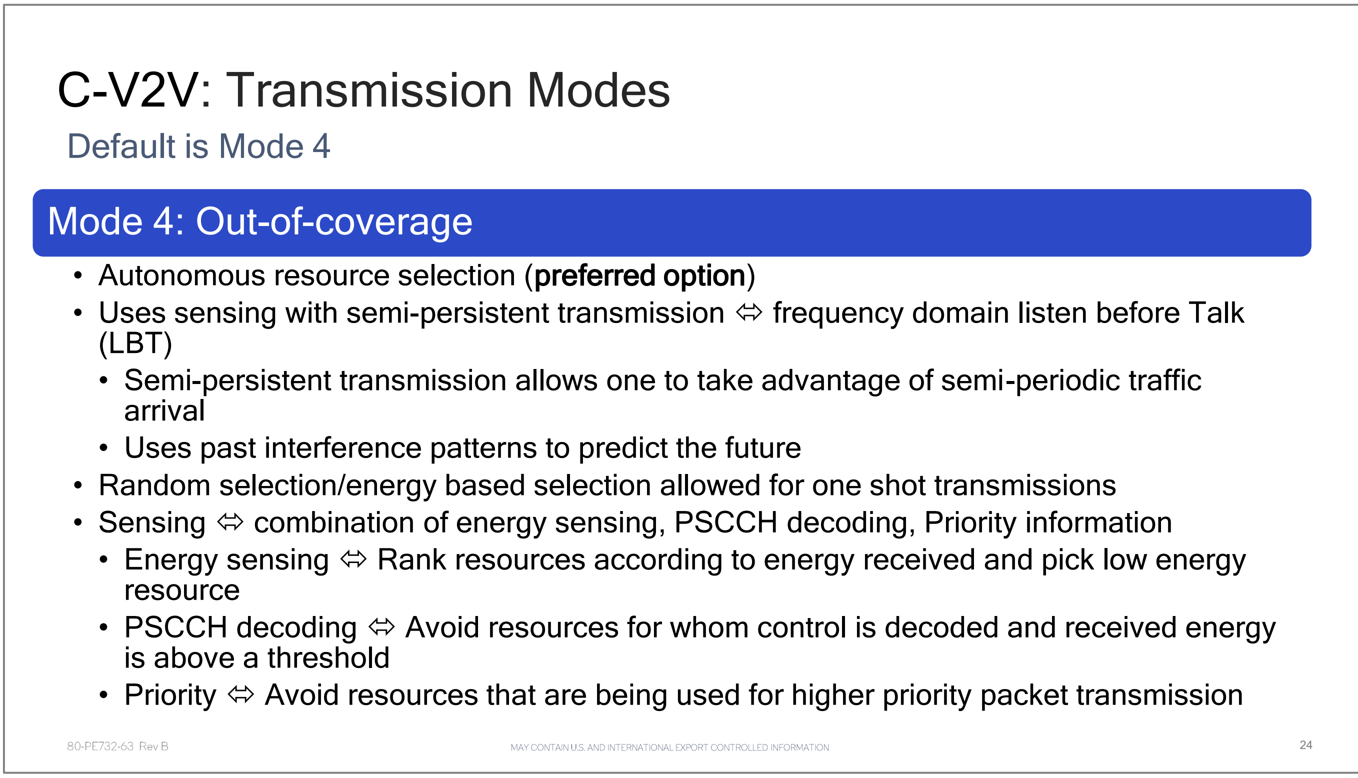


The entire C-V2X bandwidth is divided into multiple subchannels (subchannel is a group of multiple resource blocks) and each subchannel consists of schedule assignment (SA) and data resources.

SA convey the resources that can be used to provide the control information or PSCCH. There are also resources set aside for data transmission which is PSSCH. PSSCH and PSCCH can be sent on single or multiple subchannels per the pre-configuration. PSCCH occupies 2 RBs (resource blocks) and remaining RBs in that group of subchannels is used for PSSCH.

As explained earlier, the scheduling assignment and associated data may be adjacent in frequency or they may not be adjacent in frequency. The above diagram is an example of adjacent allocation.

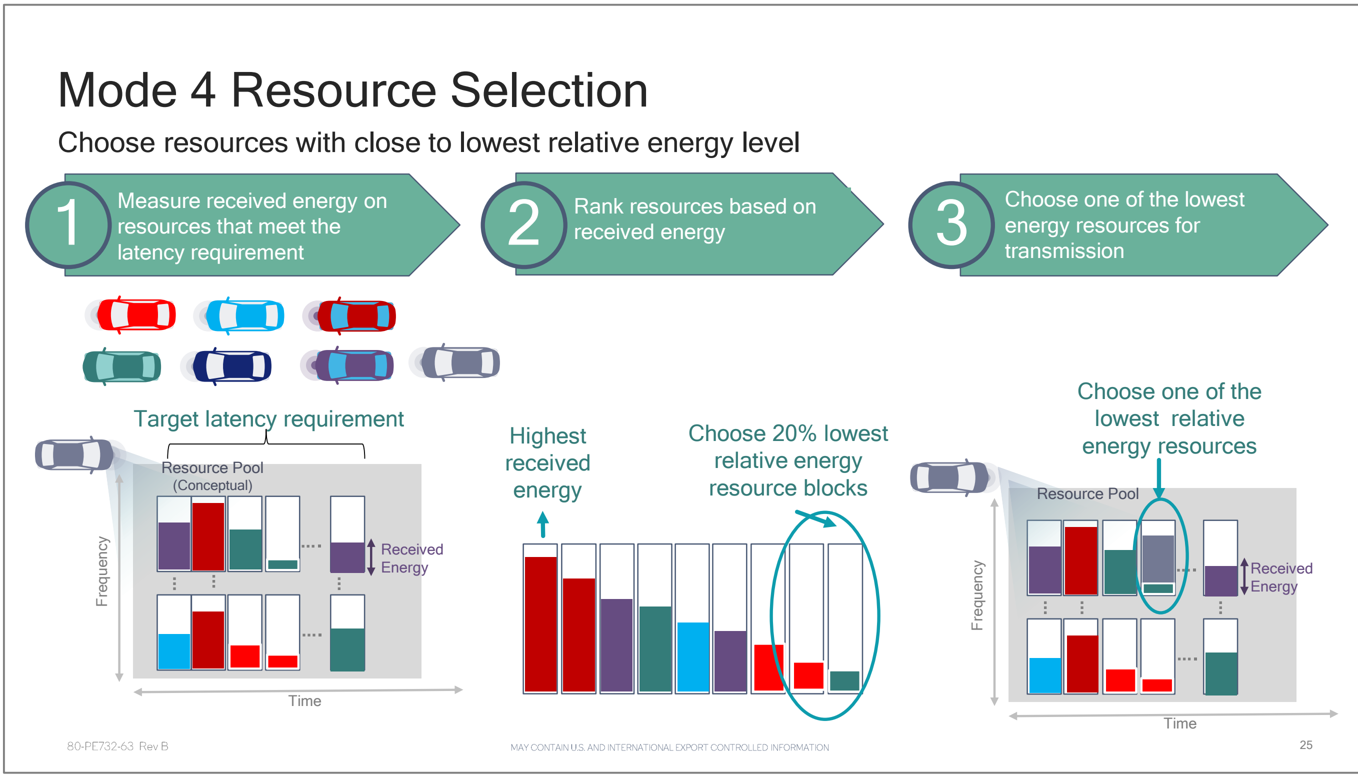
C-V2X also supports HARQ re-transmissions which allows the same transmission to be repeated at time offset either on same frequency resources or different resources to convey the same data as needed.



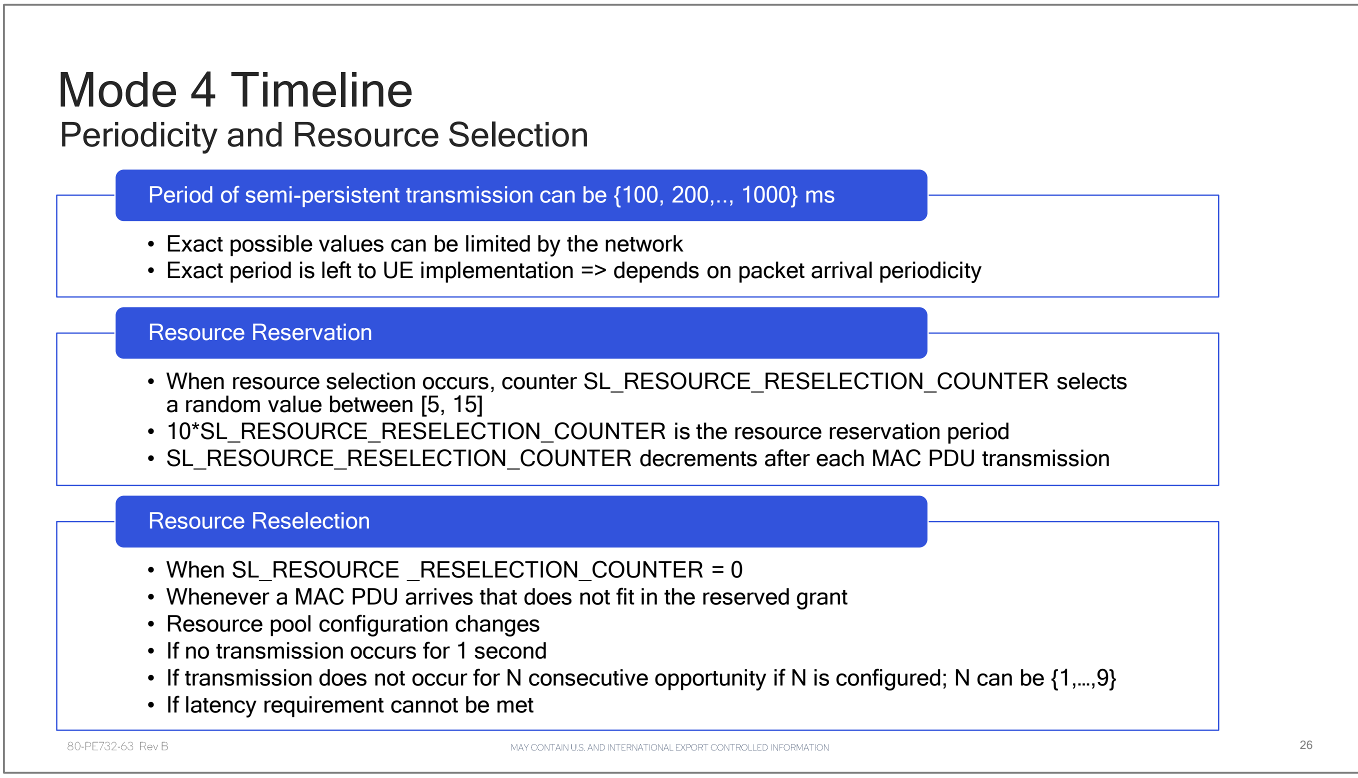
Autonomous resource selection is a method for channel sensing with semi-persistent transmission. It is essentially that the frequency domain listen before talk.

With semi-persistent transmission, vehicles can predict in the future what resources the adjoining UEs are going to be using and schedule transmissions based on that.

Sensing is a multistep process involving a combination of energy sensing, PSCCH decoding, and priority information. It can allow for resources to be allocated in a SPS manner or allow for single shot event driven messages to also be sent on best resources.



Resource selection measures the RSSI energy on resources available, sorts them in descending order per energy levels. It then chooses the lowest 20% energy resources and randomly picks resources from these for transmission.



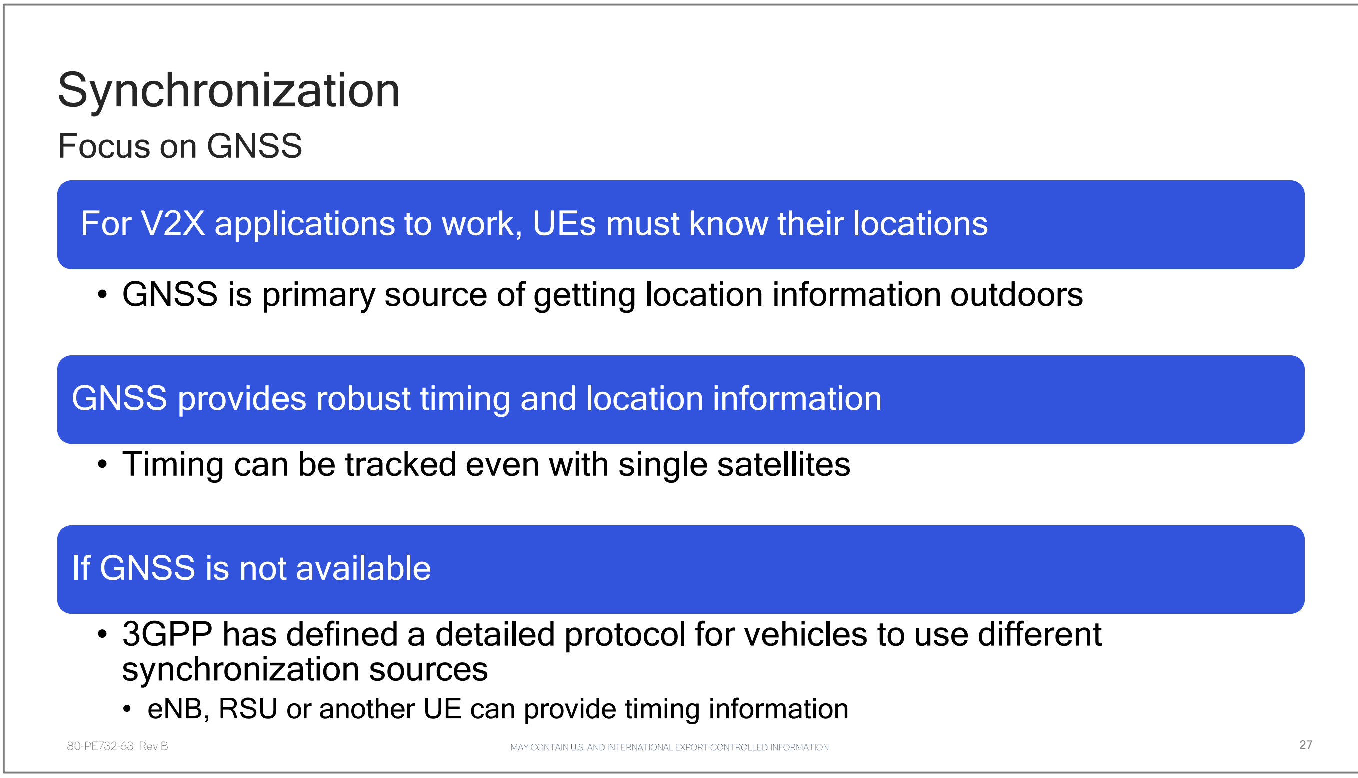
SL_RESOURCE_RESELECTION_COUNTER is decremented after every MAC PDU transmission

If *SL_RESOURCE_RESELECTION_COUNTER* goes to zero then with probResourceKeep the resource is not reselected

- *SL_RESOURCE_RESELECTION_COUNTER* is again randomly selected between [5, 15]
- *probResourceKeep* can be one of the following values {0, 0.2, 0.4, 0.6, 0.8} and is calculated when the counter value is 1

Else after 10**SL_RESOURCE_RESELECTION_COUNTER* opportunities resource is given up

- Reselection occurs only when a MAC PDU arrives



C-V2X is a synchronous system requiring the precise timing information for its operation. The most precise and reliable timing source is GNSS, although specs allow for other sources as timing information as well, similar to eNB, road side units, etc.

DFN (Direct Frame Number) = Floor (0.1*(Tcurrent -Tref)) mod 1024

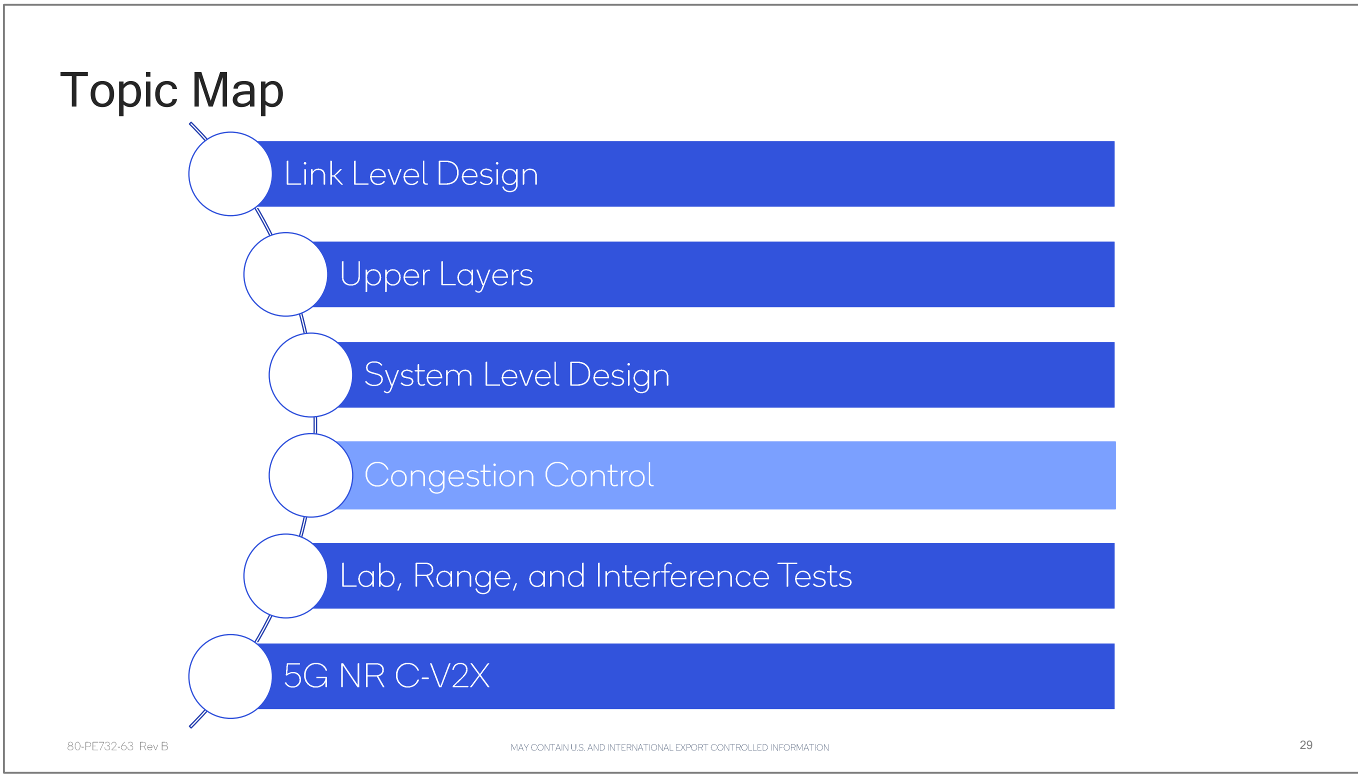
SubframeNumber = Floor (Tcurrent -Tref) mod 10

- **Tcurrent** is the current UTC time that obtained from GNSS. This value is expressed in milliseconds;
- **Tref** is the reference UTC time 00:00:00 on Gregorian calendar date 1 January, 1900 (midnight between Thursday, December 31, 1899 and Friday, January 1, 1900). This value is expressed in milliseconds

Rel-14 C-V2V vs. (DSRC) 802.11p

Technology Comparison – MAC Layer

Parameters	DSRC (802.11p)	R14 C-V2V
	System Level	
Synchronization	Asynchronous	Synchronous
Access mechanism	Time domain LBT Chooses ‘good’ enough resource; overhead	Time/Frequency domain LBT Semi-persistent transmission with choosing close to ‘best’ resources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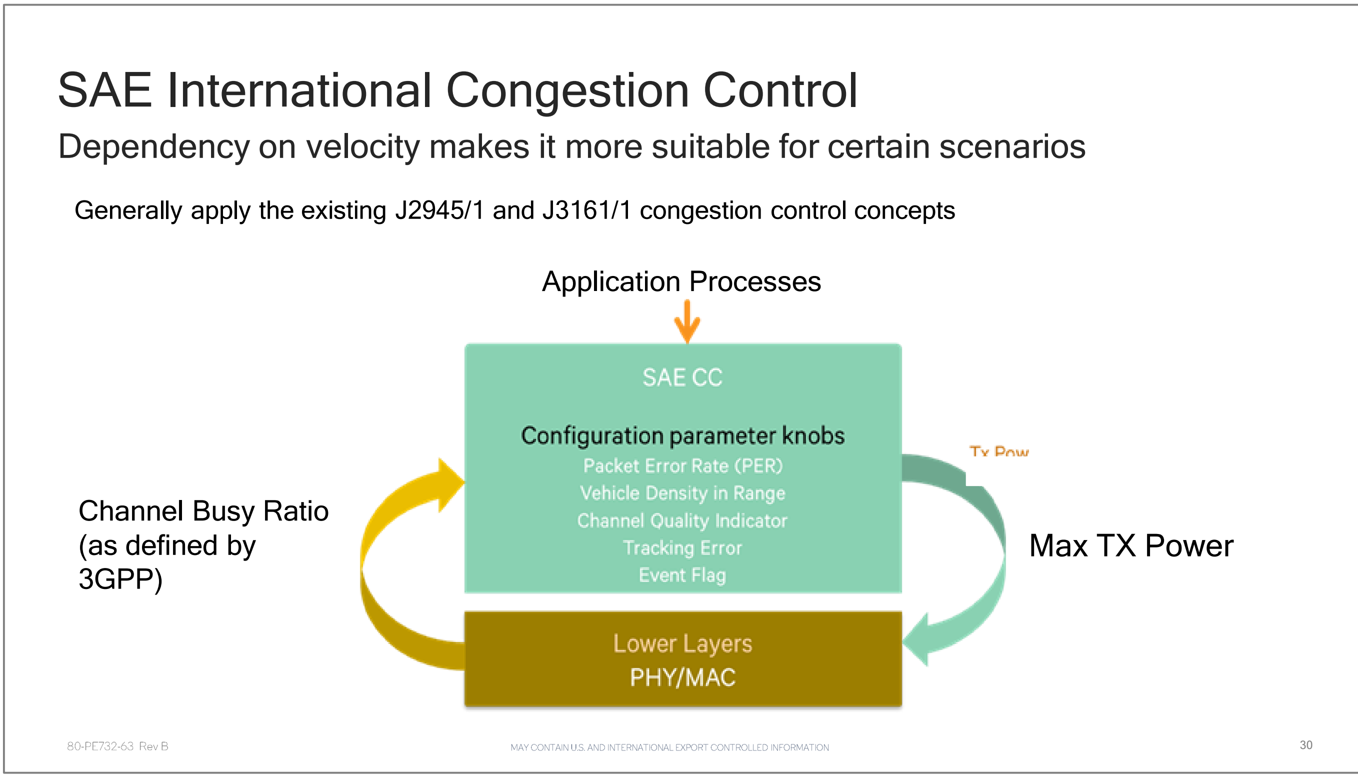

Channel Busy Ratio (CBR) is the fraction of subframes for which RSSI exceeds a predetermined threshold. The measurement is taken over a sliding window that is 100 subframes wide.

SAE International (Society of Automotive engineers) congestion control also utilizes the same CBR parameter for the evaluation of congestion. However it has its own mechanisms in upper layers by which it restricts the vehicles transmission.

Topic Map

- Link Level Design
- Upper Layers
- System Level Design
- System Simulations
- Congestion Control
- Lab, Range and Interference Tests
- 5G NR C-V2X

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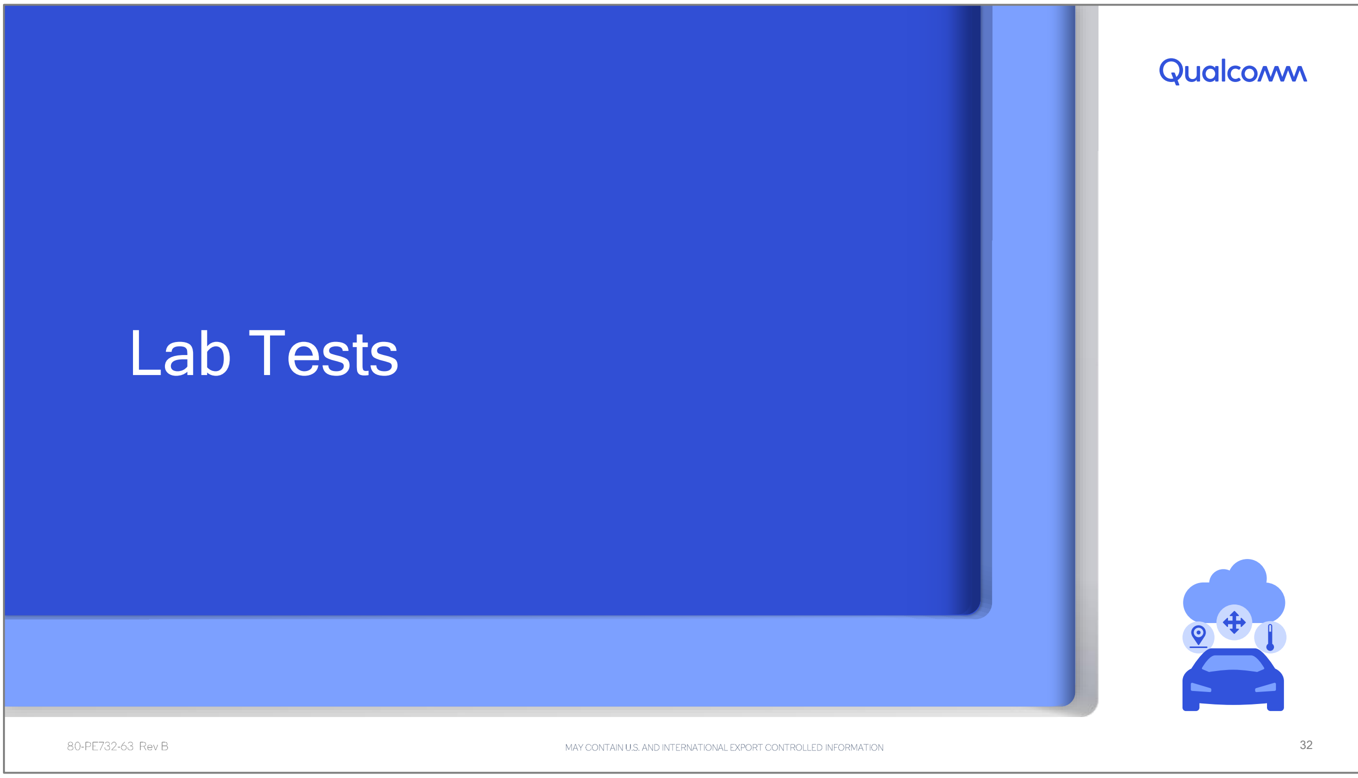
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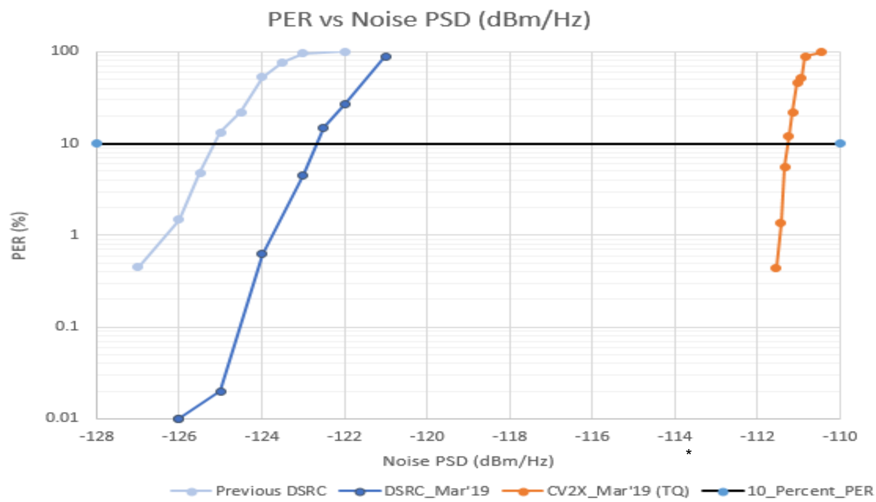
Cabled Radio Lab Test Results

Purpose: Measure radio performance with added channel impairment



**Previous C-V2X results overlap C-V2X Mar'19 results*

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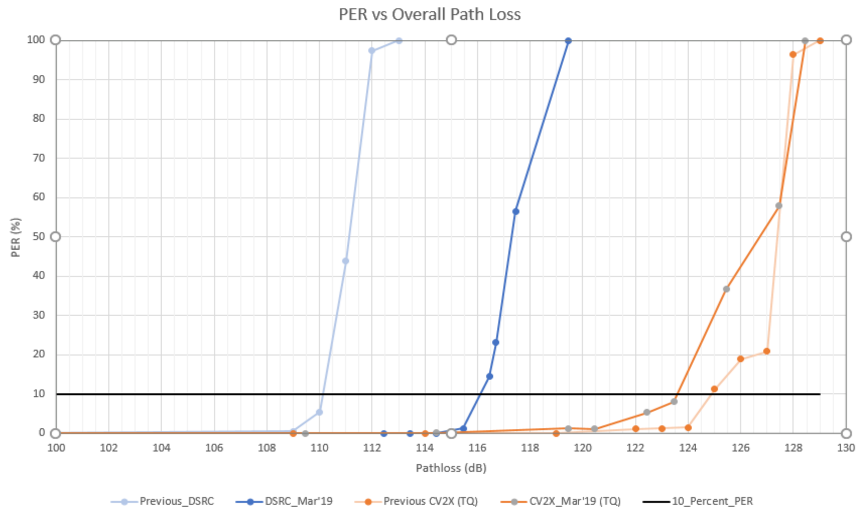
Cabled Radio Lab Test Results

Purpose: Measure radio performance under varying receive power conditions



Transmit Power = 20 dBm

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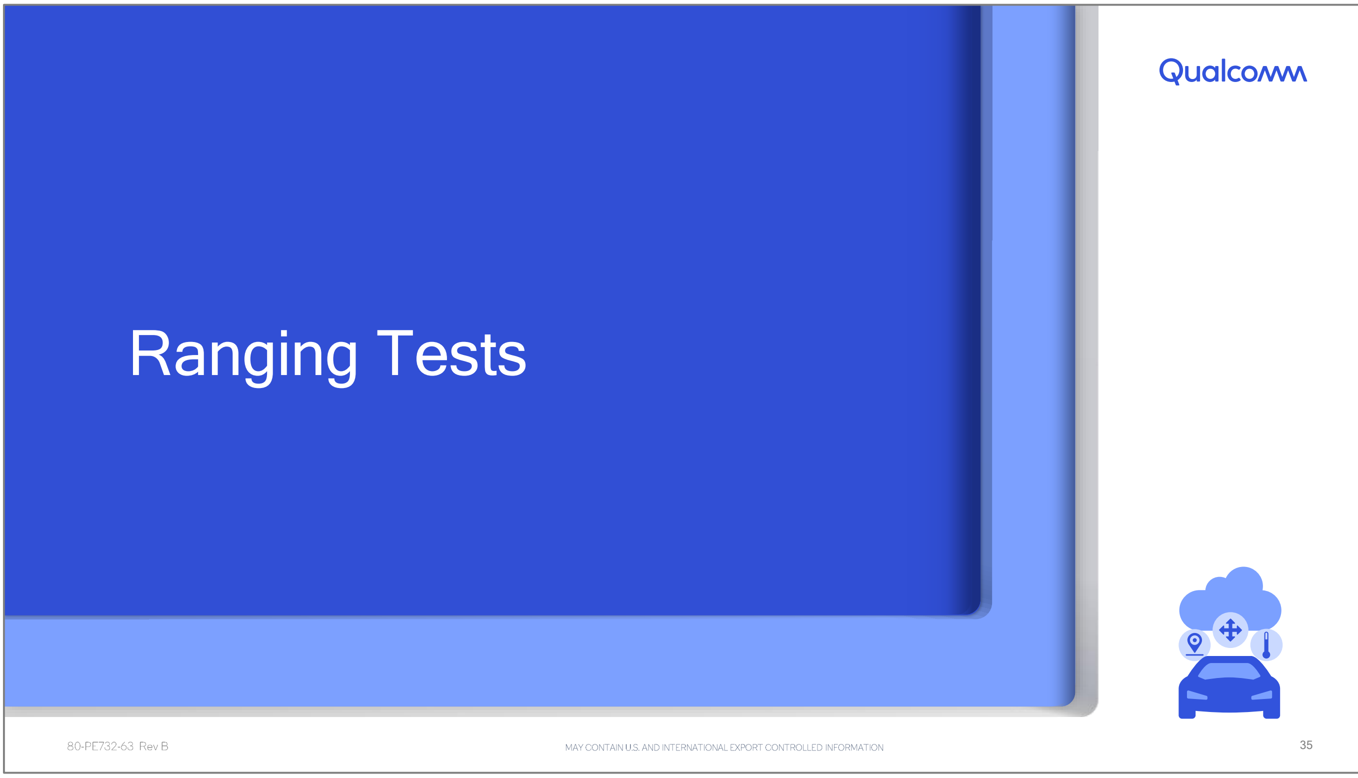
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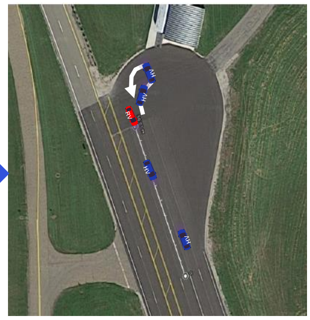
Test track and configurations

Track: Fowlerville Proving Ground, Road A (straight-away 1350m long)



Parameter[1]	DSRC	C-V2X
Vehicle	Fusion (w/o moon roof)	Fusion (w/o moon roof)
Modulation and coding	QPSK, ½	MCS5 (QPSK)
HARQ	Not available	Yes
Channel	CH184 (5,920 MHz)[2]	CH184 (5,920 MHz)
Bandwidth (message)	10 MHz	10 MHz
Packet size	193B	193B
Message frequency	10 Hz	10 Hz
Antenna[3]	ECOM6-5500 (6dBi)	ECOM6-5500 (6dBi)
Diversity	1Tx, 2Rx	1Tx, 2Rx
Equivalent Tx Power (with attenuation)[4]	5 & 11 dBm	5 & 11 dBm

[1] Selected parameters include **standard options**. Proprietary options were not considered.

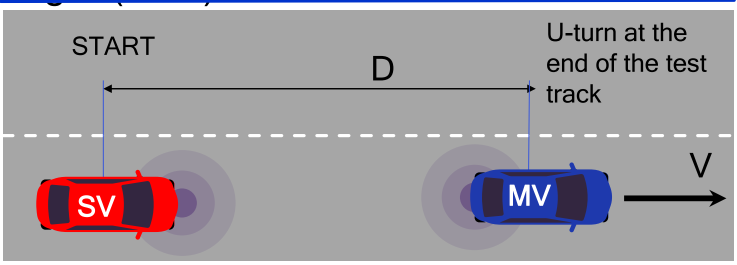
[2] We used CH184 to avoid any impact of the existing UNII-3 devices operating near the test track that we don't necessarily have control over.

[3] Antennas were mounted 24-in apart in the middle of the roof: driver side Primary (Tx), passenger side Secondary.

[4] Equivalent Tx power is the OBU total Tx power out minus attenuation on each RF antenna cable. Tx power was 21 dBm and the total attenuation was 10dB (on both Rx ends combined) resulting in 11dBm equivalent Tx power. *Equivalent transmit power was set at 11dBm for both DSRC and C-V2X to fit measured range into the test track and to match the setting in previous tests by the industry.*

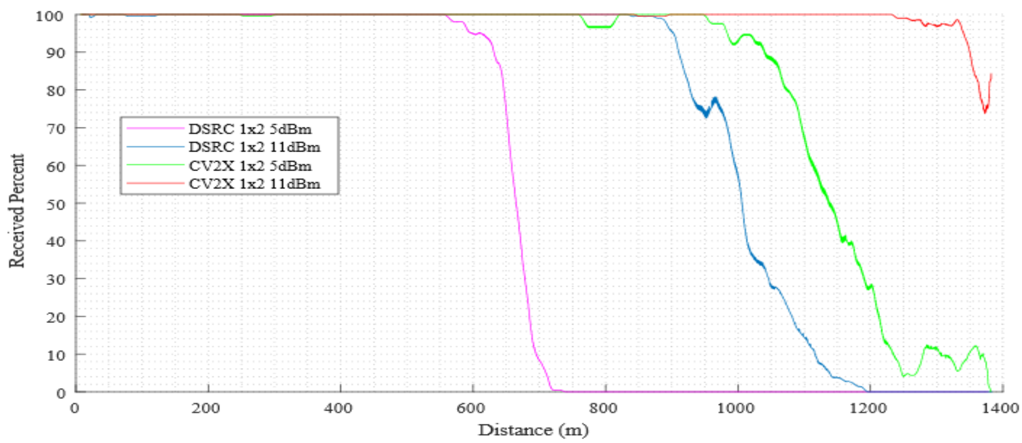
Line-of-Sight Field Test

Purpose:
Assess baseline capability for V2V message exchange in line of sight (LOS).



Note: Equivalent transmit power levels were set at 5dBm and 11dBm for both DSRC and C-V2X to fit measured range into the test track (1350m long) and to match the setting in previous tests by the industry.

Line-of-Sight Field Test Results



Stationary vehicle reception plots

HI	LO	Weather Conditions	Track Conditions
22ºF	8ºF	Snowy, Very windy	Track wet

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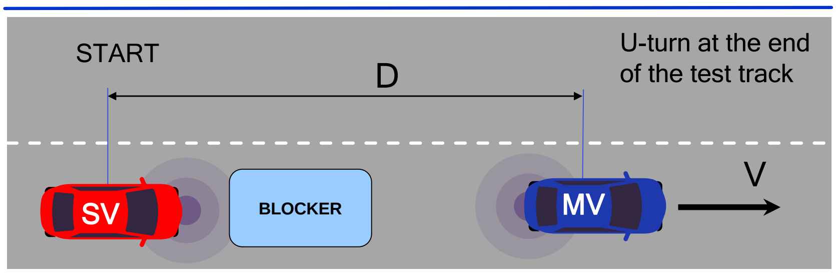
5GAA Shadowing Test

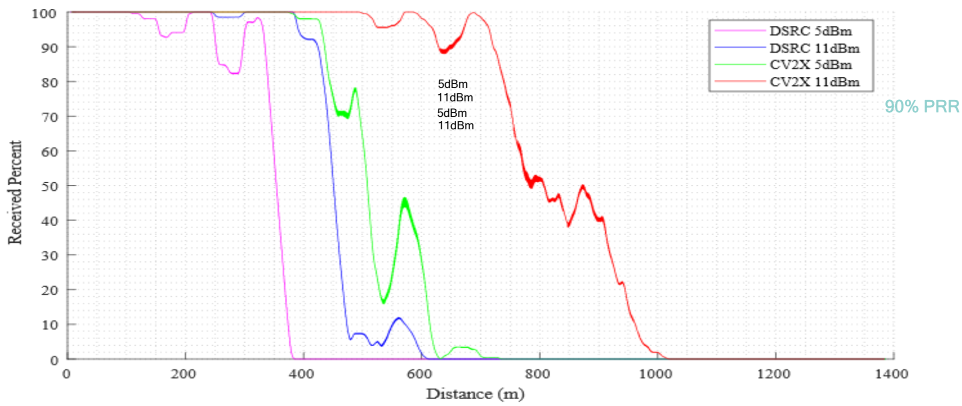
Purpose:

Assess capability for V2V message exchange in non-line of sight (NLOS) scenario with significant obstruction.



Note: The blocker is positioned in front of the stationary vehicle in order to create a significant (and constant) line of sight obstruction. **The Stationary Vehicle and Blocker remain motionless during the entire test**.

5GAA Shadowing Test Results



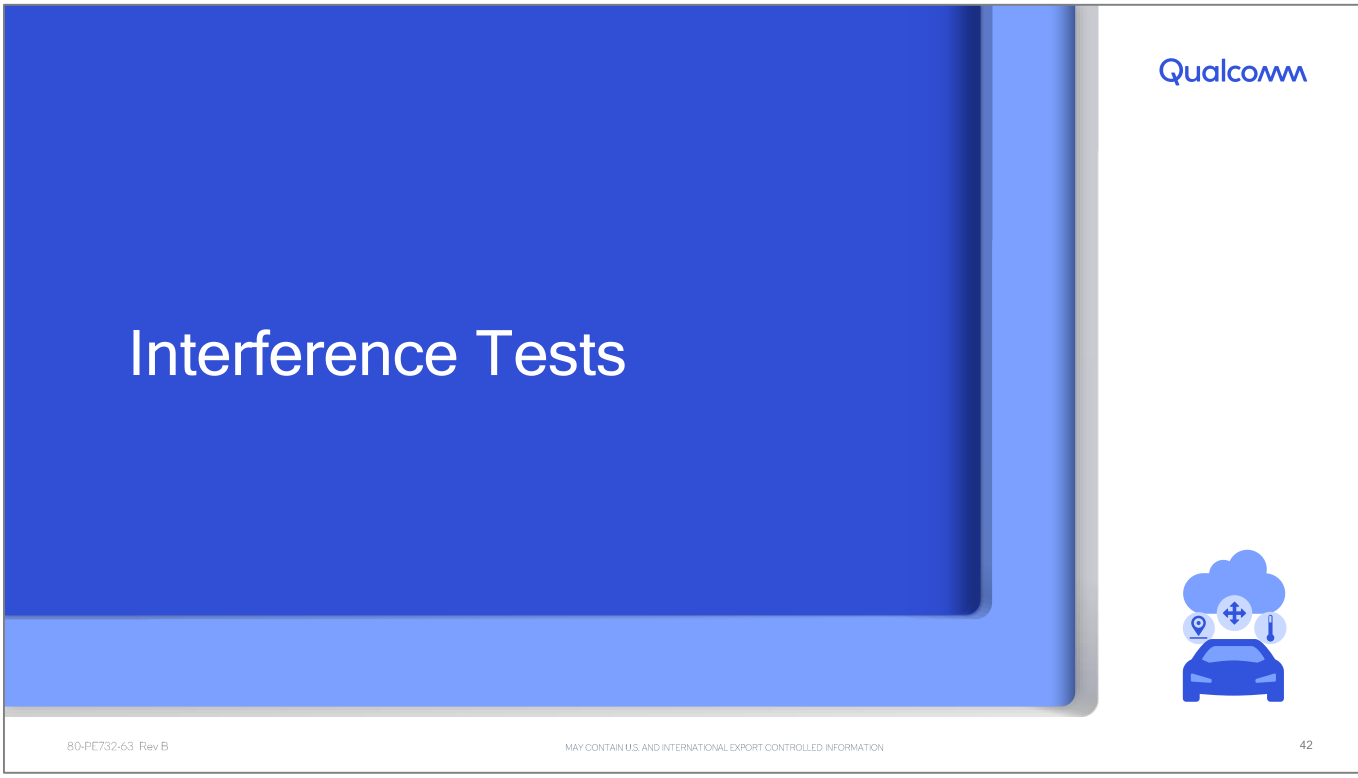
Stationary vehicle reception plots

HI	LO	Weather Conditions	Track Conditions
22ºF	8ºF	Snowy, Windy	Snow on Track

Technology Benchmark Summary

Congestion	**Lab** Cabled Congestion Control	Pass
Reliability	**Lab** Cabled Tx and Rx Tests	C-V2X better
	Field Line-of-Sight (LOS) Range Tests	C-V2X better
	Field Non-Line-of-Sight (NLOS) Range Tests	C-V2X better
Interference	**Lab** Cabled Test with Simulated Co-channel Interference	C-V2X better
	Lab Cabled Near-Far Test	Pass
	Field Co-existence with Wi-Fi 80 MHz Bandwidth in UNII-3	C-V2X better
	Field Co-existing of C-V2X with Adjacent DSRC Carrier	Pass

C-V2X radio technology consistently outperforms DSRC.


Interference Tests
Qualcomm
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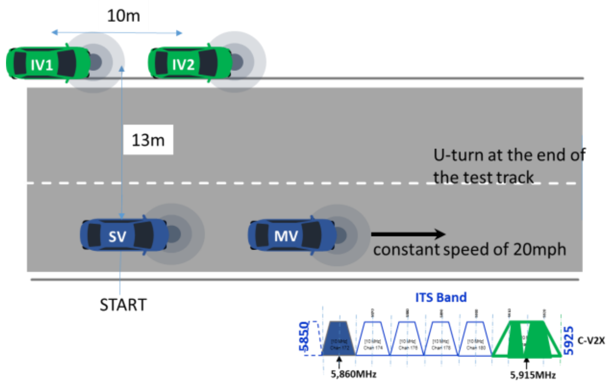
High Load Interference Test – Channel 172

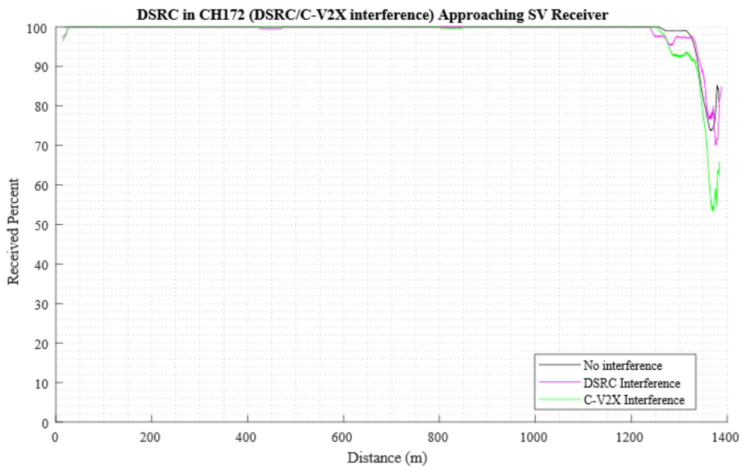
Purpose:
Assess impact on DSRC safety message traffic in CH172 from C-V2X/DSRC traffic in CH183/CH 182+184



Parameters	C-V2X/DSRC interference	DSRC OBU1	DSRC OBU2
Channel	183/(182 and 184)	172	172
Frequency (Hz)	NA	10	10
Payload (Bytes)	Variable	193	193
Power at Antenna Input (dBm)	18	18	18
Channel Load (%)	~85		

Note: The high loads used for the test are exaggerated and will rarely be experienced by a vehicle or RSU in realistic scenarios

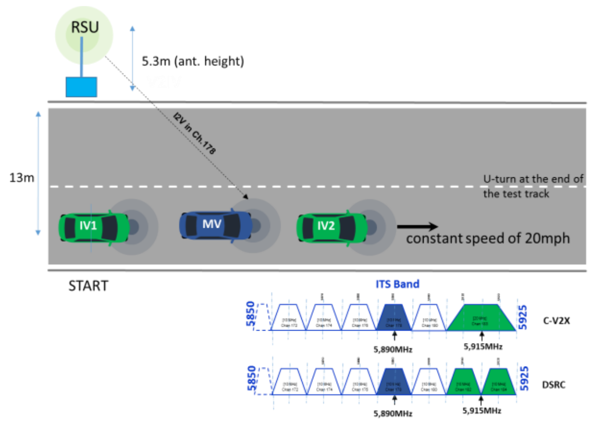
High Load Interference Test Results – Channel 172



No impact from C-V2X in CH183 on DSRC basic safety communications in CH172

High Load Interference Test – Channel 178

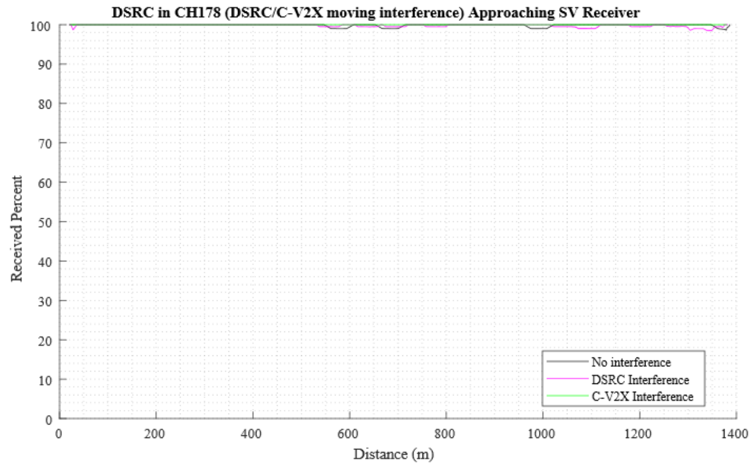
Purpose:
Assess impact on DSRC I2V communication in CH178 from C-V2X/DSRC traffic in CH183/CH 182+184



Parameters	C-V2X/DSRC interference	DSRC OBU	DSRC RSU
Channel	183/(182 and 184)	178	178
Frequency (Hz)	NA	10	10
Payload (Bytes)	Variable	193	193
Power at Antenna Input (dBm)	18	18	18
Channel Load (%)	~85		

Note: The high loads used for the test are exaggerated and will rarely be experienced by a vehicle or RSU in realistic scenarios

High Load Interference Test – Channel 178



No impact from C-V2X/DSRC in CH183/CH182 + 184 on DSRC V2I/I2V communications in CH178

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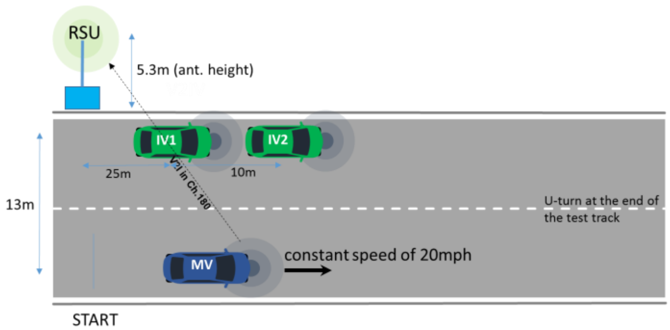
High Load Interference Test – Channel 180 Stationary Interferers

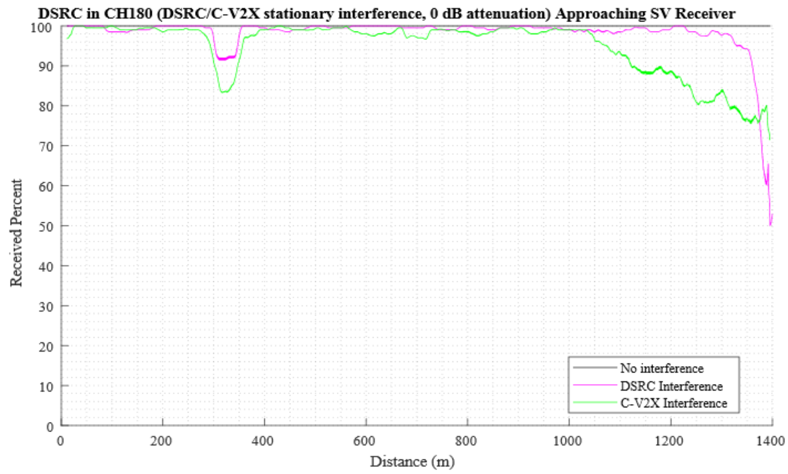
Purpose:
Assess impact on DSRC V2I/I2V communication in CH180 from C-V2X/DSRC traffic in CH183/CH 182+184



Parameters	C-V2X/DSRC interference	DSRC OBU	DSRC RSU
Channel	183/(182 and 184)	180	180
Frequency (Hz)	NA	10	10
Payload (Bytes)	Variable	193	193
Power at Antenna Input (dBm)	18	18	18
Channel Load (%)	~85		

Note: The high loads used for the test are exaggerated and will rarely be experienced by a vehicle or RSU in realistic scenarios

High Load Interference Test – Channel 180 Stationary Interferers



Minimal impact from C-V2X/DSRC in CH183/CH182 + 184 on DSRC V2I/I2V communications in CH180

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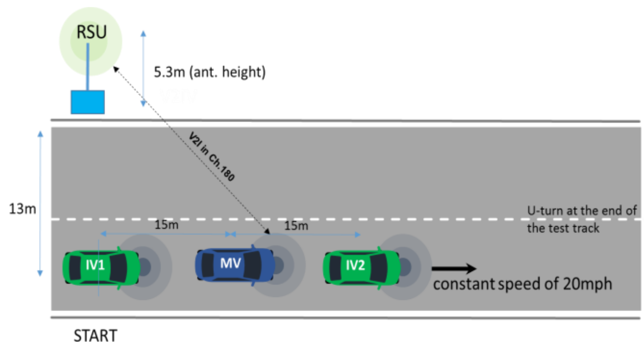
High Load Interference Test – Channel 180 Moving Interferers

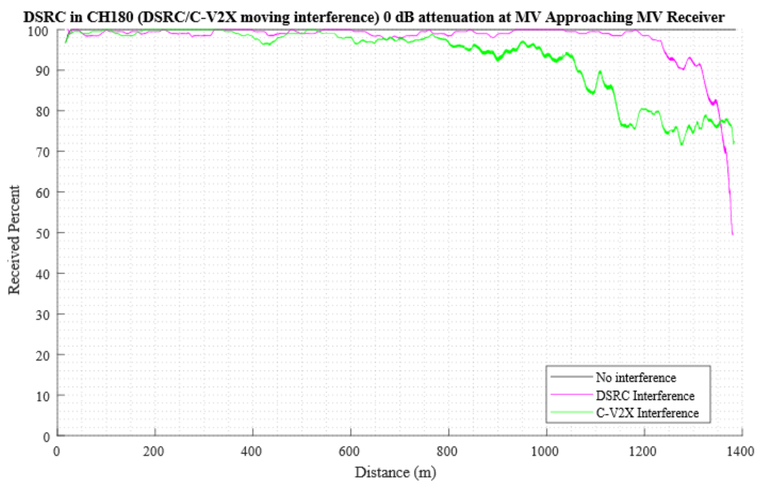
Purpose:
Assess impact on DSRC V2I/I2V communication in CH180 from C-V2X/DSRC traffic in CH183/CH 182+184



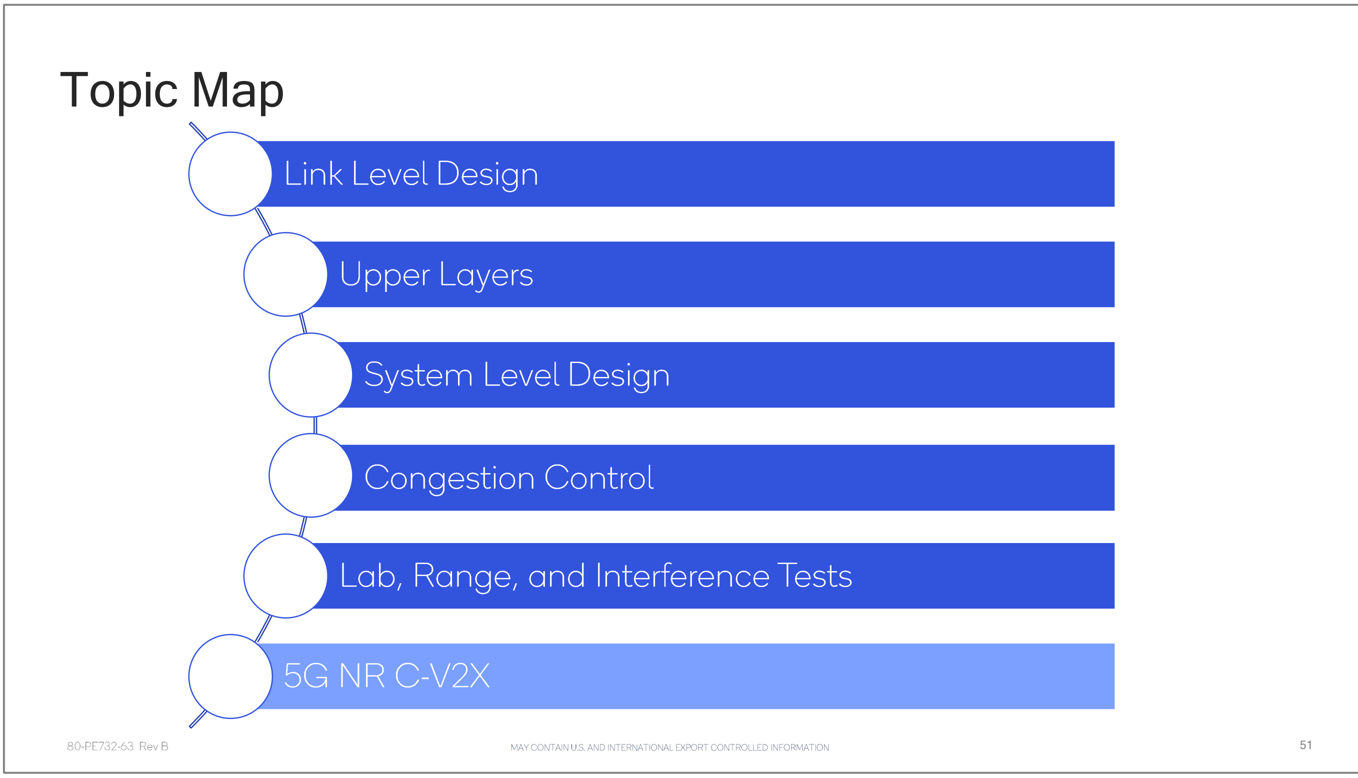
Parameters	C-V2X/DSRC interference	DSRC OBU	DSRC RSU
Channel	183/(182 and 184)	180	180
Frequency (Hz)	NA	10	10
Payload (Bytes)	Variable	193	193
Power at Antenna Input (dBm)	18	18	18
Channel Load (%)	~85		

Note: The high loads used for the test are exaggerated and will rarely be experienced by a vehicle or RSU in realistic scenarios

High Load Interference Test – Channel 180 Moving Interferers



Minimal impact from C-V2X/DSRC in CH183/CH182 + 184 on DSRC V2I/I2V communications in CH180


Topic Map
Link Level Design
Upper Layers
System Level Design
Congestion Control
Lab, Range, and Interference Tests
5G NR C-V2X
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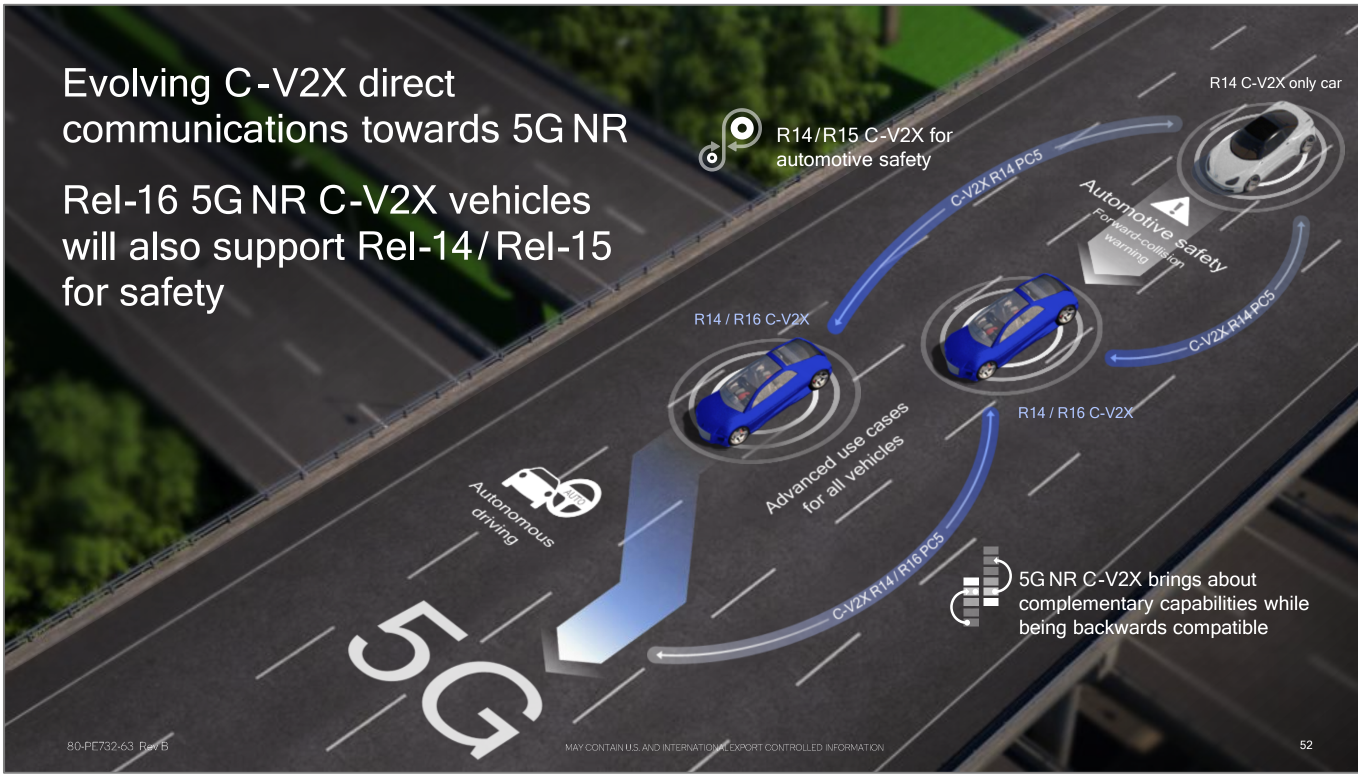
Evolving C-V2X direct communications towards 5G NR
Rel-16 5G NR C-V2X vehicles will also support Rel-14/Rel-15 for safety
R14/R15 C-V2X for automotive safety
R14 C-V2X only car
C-V2X R14 PC5
Automotive safety
Forward-collision warning
R14 / R16 C-V2X
C-V2X R14 PC5
R14 / R16 C-V2X
Advanced use cases for all vehicles
Autonomous driving
AUTO
C-V2X R14/R16 PC5
5G NR C-V2X brings about complementary capabilities while being backwards compatible
5G
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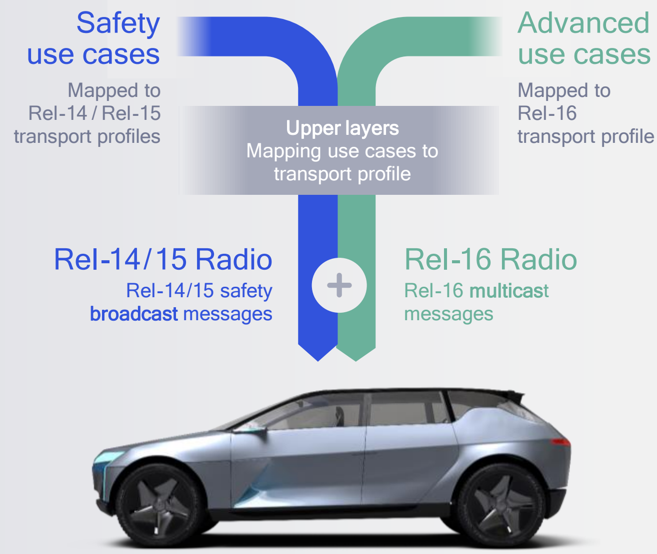
5G NR C-V2X is backward compatible at upper layers

By facilitating coexistence of Rel16 with previous releases



Rel-16 C-V2X vehicles will be designed to support Rel-14/Rel-15 for safety

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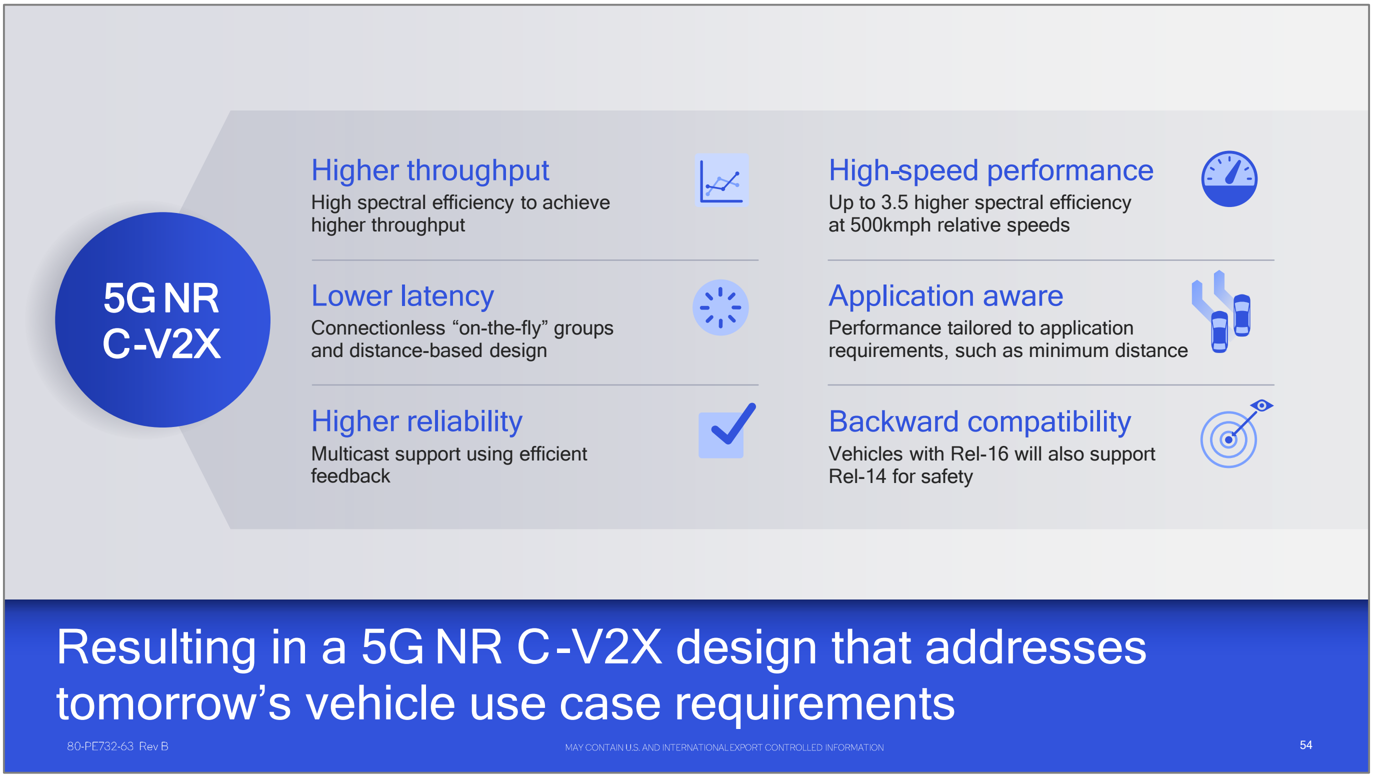
5G NR C-V2X
Higher throughput
High spectral efficiency to achieve higher throughput
Lower latency
Connectionless “on-the-fly” groups and distance-based design
Higher reliability
Multicast support using efficient feedback
High-speed performance
Up to 3.5 higher spectral efficiency at 500kmph relative speeds
Application aware
Performance tailored to application requirements, such as minimum distance
Backward compatibility
Vehicles with Rel-16 will also support Rel-14 for safety
Resulting in a 5G NR C-V2X design that addresses tomorrow’s vehicle use case requirements
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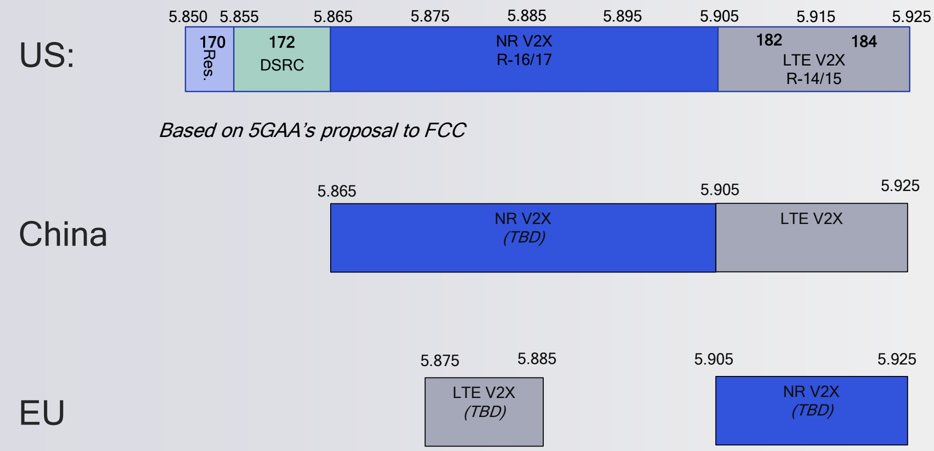
ITS Spectrum for LTE V2X & NR V2X

New allocation and/or reallocation of ITS spectrum is needed



V2X can also be deployed over licensed spectrum but business case needs to be understood

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5G NR C-V2X supports advanced use cases

Increased situational awareness

Sharing of vehicle-specific info with other vehicles and road infra-structure (e.g. door open warning)

Sensor sharing

Sharing of sensor data, e.g., vehicle's perception, including road world model

Coordinated driving/ intention sharing

Exchanging intention and sensor data for more predictable, coordinated autonomous driving

Real-time infrastructure updates

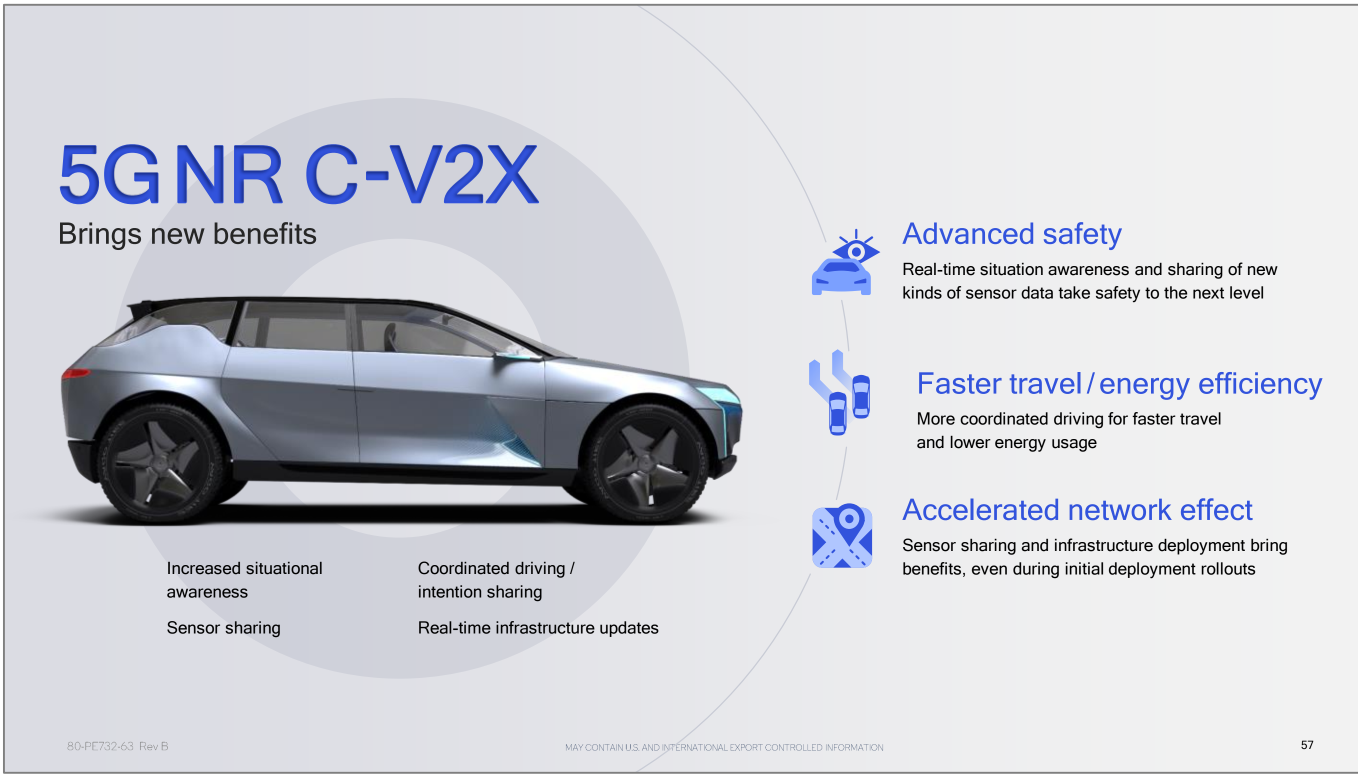
Real-time sharing of 3D HD map and other information between vehicles and infrastructure

Higher throughput

Lower latency

Higher reliability

Application aware


5G NR C-V2X
Brings new benefits
Increased situational awareness
Sensor sharing
Coordinated driving / intention sharing
Real-time infrastructure updates
Advanced safety
Real-time situation awareness and sharing of new kinds of sensor data take safety to the next level
Faster travel / energy efficiency
More coordinated driving for faster travel and lower energy usage
Accelerated network effect
Sensor sharing and infrastructure deployment bring benefits, even during initial deployment rollouts
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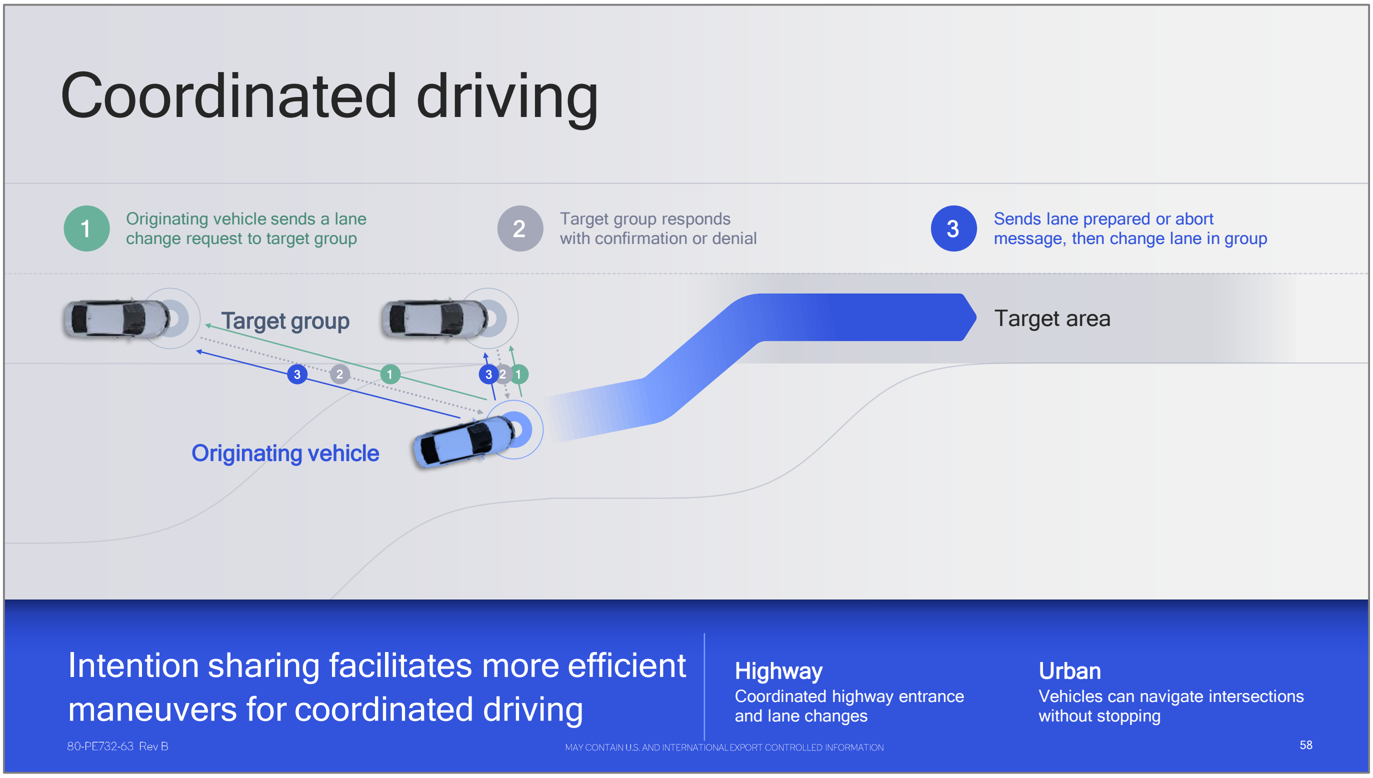
Coordinated driving
1 Originating vehicle sends a lane change request to target group
2 Target group responds with confirmation or denial
3 Sends lane prepared or abort message, then change lane in group
Target group
Target area
Originating vehicle
Intention sharing facilitates more efficient maneuvers for coordinated driving
Highway
Coordinated highway entrance and lane changes
Urban
Vehicles can navigate intersections without stopping
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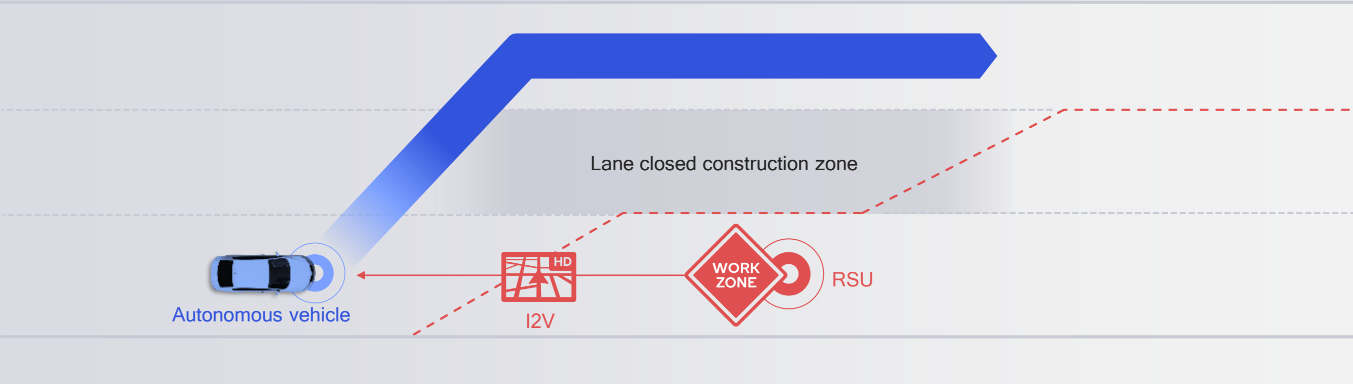
Autonomous driving

Benefits from real-time update from infrastructure



RSU sends a 3D HD map update to oncoming vehicles with the lane reconfiguration due to construction

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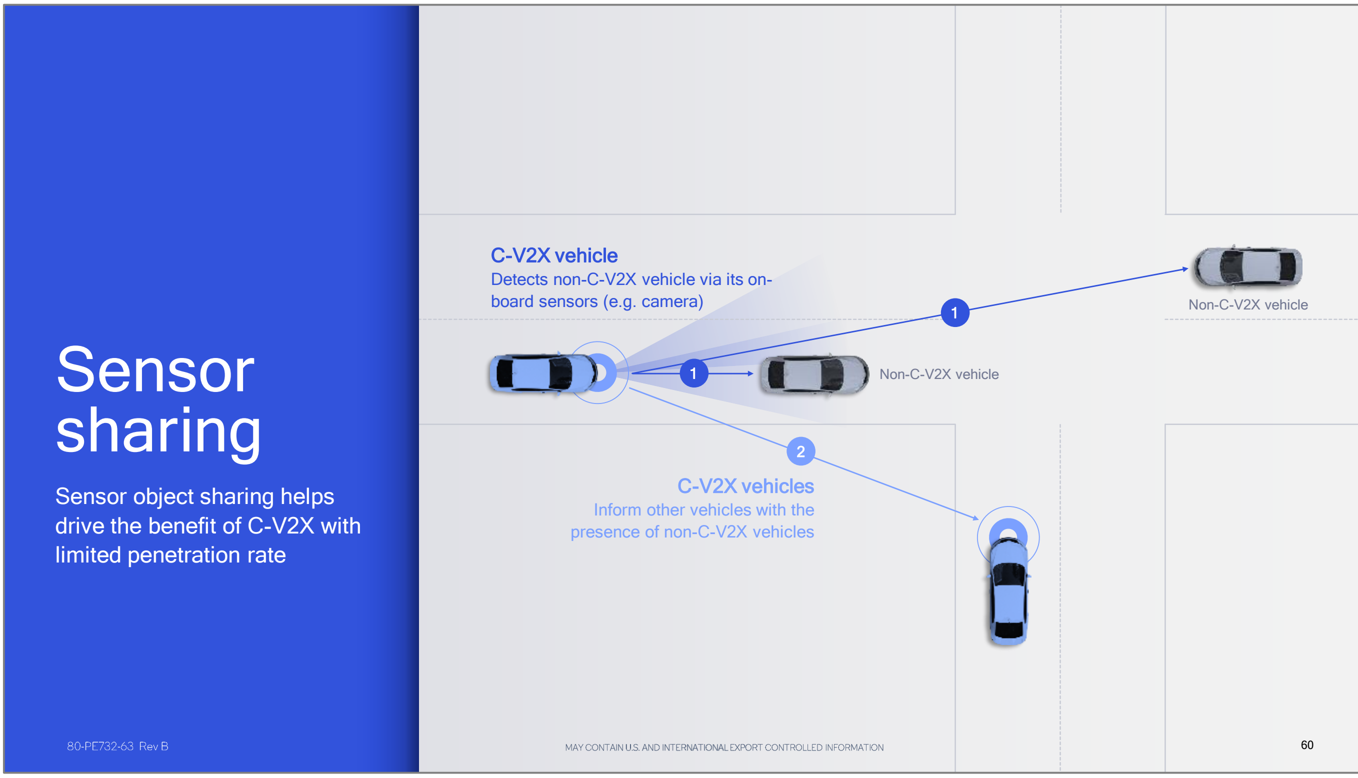
Sensor sharing
Sensor object sharing helps drive the benefit of C-V2X with limited penetration rate
C-V2X vehicle
Detects non-C-V2X vehicle via its on-board sensors (e.g. camera)
1
1
Non-C-V2X vehicle
Non-C-V2X vehicle
2
C-V2X vehicles
Inform other vehicles with the presence of non-C-V2X vehicles
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Key Takeaways

- Direct communication mode (PC5) used for V2V, V2I, and V2P communication
- High reference signal density and intra-subframe control and data information characterize C-V2X (PC5) link design
- Transmission mode 4 (preferred mode) based PC5 communication relies on autonomous resource selection by each vehicle for transmission
- Congestion control algorithm seeks to control channel access based on channel loading
- C-V2X technology outperforms DSRC on link level as well as system level in all scenarios
- New 5G platform, which is backward compatible with existing Release 14 C-V2X technology, will augment/complement C-V2X with applications like sensor sharing, trajectory sharing, and ranging/positioning
  - No need to ‘rip and replace’ existing Release 14 C-V2X devices