Qualcomm

Qualcomm Technologies, Inc.

C-V2X Technical Performance

Frequently Asked Questions

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Qualcomm Technologies, Inc.
5775 Morehouse Drive
San Diego, CA 92121
U.S.A.

Revision history

Revision	Date	Description
A	October 2019	Initial release

Contents

1 Introduction

To understand and characterize the performance of C-V2X technology, thorough and extensive testing has been undertaken. Results of these tests are detailed in the 5GAA P "*V2X Functional and Performance Test Report; Test Procedures and Results*" [1] and in a 5GAA Webinar presentation [2].

This frequently asked questions (FAQ) document provides technical responses to questions presented from those data collections.

The document is organized in the following categories:

- Compatibility with future C-V2X technology
- Commercial readiness of C-V2X deployment
- C-V2X performance gain over DSRC
- DSRC DUT equipment
- Test setup-related questions
- Congestion control
- Interference
- Security
- V2P capability

References to documents which provide detailed explanations and insights are included with the responses.

2 Compatibility with Future C-V2X Technology

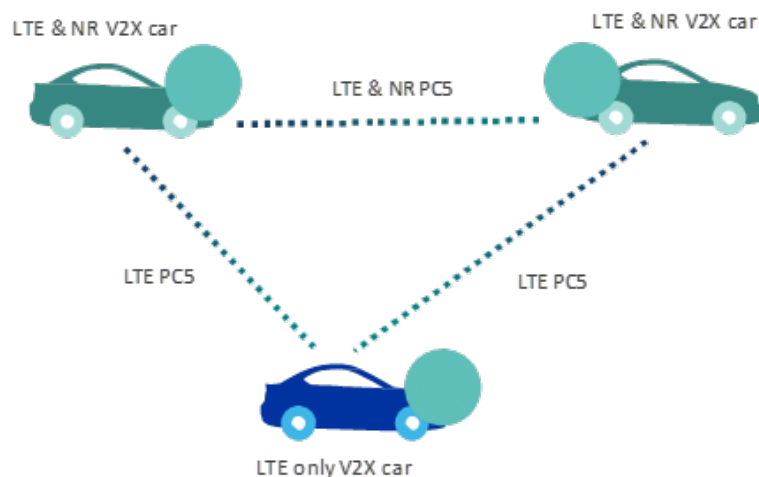1. **Will 5G NR-V2X coexist with LTE-V2X in 5.9 GHz ITS band?**

   Yes, 5G NR-V2X (3GPP R16 and beyond) capable devices offer additional ITS functionality to that of LTE-V2X (3GPP R14/15).

   5G NR C-V2X sidelink doesn't replace the need for LTE-V2X (R14/15) and implementations support both LTE-V2X and 5G NR C-V2X in the same solution, both operating in the 5.9 GHz ITS band. 5G NR C-V2X devices will coexist with LTE-V2X in 5.9 GHz band but are envisioned to use different channels. This is one reason why 5GAA has proposed 40 MHz for "Advanced C-V2X" in addition to 20 MHz for "Basic C-V2X" [3].

2. **Is 5G NR C-V2X backward compatible with LTE C-V2X?**

   - C-V2X has a clear and forward compatible evolution path to 5G NR C-V2X. LTE-V2X establishes the foundation for safety use cases in 3GPP R14/15, and a continued 5G NR C-V2X evolution for additional use cases.

   - 5G NR C-V2X capable devices will support LTE-V2X (R14/15) PC5 interface using 5.9 GHz band. 5G NR-V2X device will coexist with LTE-V2X in 5.9 GHz band as described in the answer to the previous question

   - 5G NR-V2X capable devices will interface with LTE-V2X devices using LTE-V2X (R14/15) PC5 for basic safety use cases.

   The following diagram illustrates that LTE C-V2X (R14/15) enabled devices will be able to communicate with 5G NR-V2X enabled vehicles. The 5G NR-V2X will support LTE-V2X PC5 interface in addition to 5G NR-V2X, PC5.

   For more information about 5G NR-V2X and LTE V2X interoperability, see:
   https://www.qualcomm.com/media/documents/files/5g-nr-based-c-v2x-presentation.pdf

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3. **When will R16 devices be widely available throughout road network?**

R16 is still in the standardization process. The 3GPP R16 specification is expected to be completed around March 2020. Currently, there is no published timeline for a commercially available R16 device, although commercial products typically sample 12 to18 months after features are specified in 3GPP.

3 Commercial Readiness of C-V2X Deployment

1. **Is C-V2X ready for commercial deployment? Can I purchase a device like the DSRC devices that are commercially available today?**

LTE-V2X[1] is now ready for commercial deployment. LTE-V2X chipsets are available from several manufacturers, including Qualcomm®. A variety of modules are now available from credible suppliers around the world.

These modules are being used in OBU and RSU commercial offerings which can enable production in vehicles starting as early as 2019, using the Qualcomm 9150 C-V2X chipset [4], and RSU deployments on the roads in 2019. In fact, 2018 saw some early deployments including in Colorado. In addition to Qualcomm, there are other LTE-V2X solutions available from a competitive ecosystem.

The following companies have commercial C-V2X modules available today:

- □ WNC
- □ Quectel
- □ ZTE
- □ LG Innotek
- □ SIMCom

The following RSU vendors have announced the availability of C-V2X capable RSUs for commercial deployment

- □ US: Savari, Kapsch Commsignia
- □ EU: SWARCO, Lacroix, Aximum
- □ China: Nebulalink, Genevict, Neusoft

16+ RSU products in the pipeline for commercial ready product in Q4 2019.

The following Tier-1/OBU vendors have announced availability of C-V2X capable OBUs for commercial deployment:

- □ Bosch
- □ Danlaw
- □ Ficosa/Panasonic
- □ Cohda
- □ Valeo

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[1] C-V2X is the umbrella term for both direct communications and network communications, with V2V/V2I/V2P using a direct connection in the 5.9 GHz band while V2N using the commercial cellular network. The 'C' represents the evolution of cellular technologies from 4G LTE to 5G NR. This question is asking when LTE-V2X direct communications is commercially available.

□ Savari

□ Continental

□ LG Electronics

□ Nebula

□ Commsignia

□ Genvict

10+ OBU suppliers are in the pipeline for commercial ready product in Q1 2019.

In addition to the OBU, RSU vendors, the following System Integrators are prepared to provide C-V2X system integration and support:

□ Sasken

2. Do standards exist such that multiple suppliers can independently implement, deploy, and be interoperable?

The 3GPP specifications related to LTE-V2X are published. Multiple chip vendors have developed LTE-V2X chipsets. Interoperability testing began in August 2018 and test equipment suppliers, global certification bodies, and OmniAir Consortium are engaged.

Multiple vendors have announced availability of the C-V2X based OBU and RSU. 3GPP Release 14 PC5 and Release 15 5G-NR are ready and supported by a broad ecosystem including automakers, Tier-1 suppliers, Tier-2 module manufacturers, automotive software developers, mobile operators, global semiconductor companies, test equipment vendors, telecom suppliers, traffic signal suppliers, RSU suppliers, and road operators.

Interoperability and performance test events have been conducted beyond chipset vendors, and also include ITS stack developers and automakers as shown in the following table.

Interoperability and performance test events

May-18	Detroit, MI	Omniair
Oct-18	College Station, TX	Omniair
Nov-18	Shanghai	C-SAE
Apr-19	Dekra, Klettwitz	5GAA
May-19	Montreal	Omniair

It should be noted that various standards bodies, such as US (SAE), EU (ETSI) and China (C-SAE) for the upper layer standards, continue to add to existing standards.

4 C-V2X Performance Gain Over DSRC

1. **Bench tests showed that C-V2X has significant gain over DSRC. Explain this gain.**

    Several aspects of LTE-V2X (PC5) radio interface contribute to greater link budget as compared to DSRC/802.11p. These are as follows:

    □ **Greater Energy per bit**

    In PC5, a transmission can be narrowband over a longer time without loss in system capacity by sharing the channel with other transmissions, e.g., FDMA. The minimum allowed bandwidth of a transmission in PC5 is configurable and can be as low as four resource blocks, e.g., 720 kHz. This allows for much higher energy per information bit in PC5.

    For the test case described in [1], a basic safety message (BSM) of 193 bytes is transmitted using 643 us in PC5 for data symbols and 254 us in DSRC for data field.

    □ **Turbo coding**

    PC5 communication uses turbo codes as compared with convolutional coding used for DSRC communication.

    To compare, the turbo code used in PC5 provides larger coding gain and is more robust in varying radio conditions. The exact gain of the turbo code versus the convolutional code depends on coding rate and channel conditions.

    □ **Hybrid automatic repeat request (HARQ) technique**

    PC5 communication uses the blind hybrid automatic repeat request (HARQ) technique.

    HARQ communications use a combination of forward error correcting codes along with automatic repeat request (ARQ) error-control and soft-combining.

    PC5 communication is a broadcast communication. Hence, there is no feedback from the receiver to the transmitter indicating if the packet has been successfully received. With the PC5 communication technique, the same data packet is sent twice within the determined packet delay budget (PDB) time frame. The same data packets are sent with different coding. At the receiver, the two transmissions are then jointly used to determine the sent data. This communication technique is referred to as blind HARQ. DSRC communication does not use any form of HARQ communication. Use of this technique results in about 3 dB of link budget gain for PC5 communication. The lab test results for C-V2X, detailed in [1], illustrate HARQ improves C-V2X sensitivity by 3 dB in additive white Gaussian noise (AWGN) channels. See Tables 13 and 15 on pages 43 and 44 of [1].

□ **Channel Estimation**

In PC5, reference signals are inserted evenly in the transmission duration; in DSRC, this happens mainly at the beginning of the transmission. This leads to some performance gain in PC5 due to better channel estimation, particularly when the speed is high. The exact performance gain depends on the channel condition. For low-speed static AWGN channels, no loss due to channel estimation is expected for DSRC.

2. How do you relate bench test and field test results?

Field test results demonstrate better range for C-V2X as compared to DSRC under various LOS, NLOS, and interference scenarios.

Different radio conditions (characterized by different propagation models) could lead to different sustainable communication ranges for the same link budget.
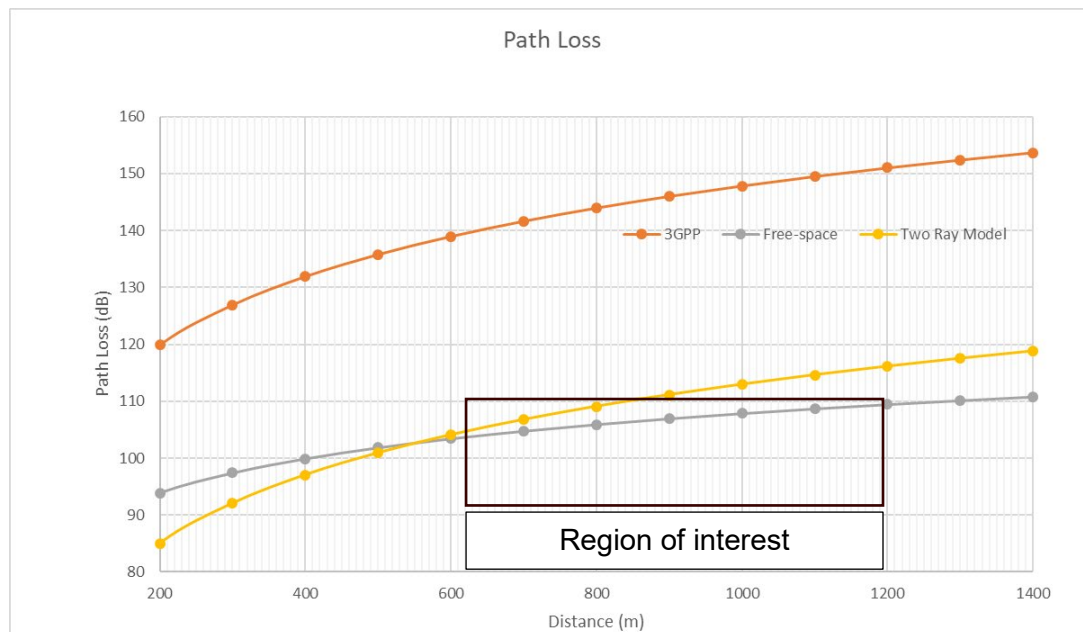
It should be noted that the path loss delta for difference in distance at the edge of coverage depends on the radio conditions and resulting propagation model as well as the path loss "region" under consideration.

Field test results (shown in Figure 41 of [1]) show range of 625m for DSRC devices and 1050 m for C-V2X devices. The blue box in the graph (labelled "Region of interest") shows the related area on the path loss plot. Field measurement results indicate that radio conditions encountered during the tests can be described with a two-ray model. It can be seen that path loss delta for DSRC and C-V2X communication is likely to be of the order of ~9 dB. Note that different C-V2X and DSRC devices were used for lab and field tests.

3. When comparing packet loss based on attenuation, what is the line of sight distance between 116 dB in DSRC and 124 dB in C-V2X? What distance does the 8 dB attenuation amount to in packet loss?

As explained in the response to Q2 above, the difference in distance is a function of the propagation environment and the transmit power.

4. **Did you measure the attenuation as you did the line of sight field test results? Did they show 8 dB difference as in the lab?**

No, the attenuation was not measured during field tests. RSSI values measured by the device close to the noise floor are impacted by the noise figure of the device. To measure RSSI accurately would require setting up of additional measuring equipment in the vehicle being used for drive testing.

5. **In the cable radio test, does LTE-V2X have HARQ active? If so, is LTE-V2X transmitting the same information twice as many times as DSRC?**

Yes, HARQ is turned ON for both lab and field tests. Each packet is transmitted twice when HARQ is turned ON, per the 3GPP specification on how the technology works.

6. **Does HARQ adversely impact system capacity?**

First, it is worth noting that HARQ not only provides an increase in link budget, but also provides a diversifying mechanism against strong interference. For example, if one out of the two transmissions is lost due to a strong interference (for example, due to hidden node effect), the packet can still be successfully received by doing soft-combining with the remaining transmission. The performance gain in this case is much better than purely repeating the packet twice thanks to the coding gain.

C-V2X has adaptable HARQ that can be disabled when congestion is high. In other words, the system can benefit from larger range when congestion is not too high while not causing any additional interference in congested scenarios. It has been observed in our tests that due to back off by application layer congestion control mechanisms, the access layer is not really that congested and the system can still benefit from HARQ turned ON. In other words, due to application layer congestion control, the benefits of HARQ apply in almost all scenarios. If there is a case where the access layer does get significantly congested then HARQ can be adaptively turned off.

5 DSRC DUT Equipment

1. **What DSRC unit is used for the 5GAA test?**

   Savari MW1000 is used.

2. **What Chipset is used for MW1000**

   Qualcomm QCA6584 is used.

3. **What is the basis of selecting Savari MW1000 for the DSRC testing?**

   Savari MW1000 is one of the readily available DSRC OBU that is used for different trials and USDOT pilot projects. Also, based on results obtained from a reputed independent lab, we learned that Savari MW1000 performance is similar to other leading vendors DSRC OBU, e.g., NXP based Cohda.

4. **How does Savari MW1000 compare with other leading DSRC OBUs?**

   Independent tests show sensitivity of two different DSRC OBU manufacturer devices (Savari and Cohda) to vary between -90.5 dBm to -93.5 dBm.

   It should be noted that different receivers of the same type from the same manufacturer may have up to a few dB variation in their noise figure and resulting sensitivity which would impact resulting link budget.

5. **What scheme is used for the Rx diversity?**

   Savari MW1000 (QCA6584) and Qualcomm® C-V2X Technology solution both are using maximum ratio combining (MRC) scheme for the Rx diversity.

6. **Was Tx diversity active on the DSRC modem for the 5GAA testing?**

   No, Tx diversity was not active for the DSRC OBU and C-V2X OBU.

7. **With the clean channel and no-load scenario, it is expected that end-to-end latency should be in order 2-3 ms. How do you explain ~17 ms latency observed in the 5GAA DSRC test?**

   Based on further investigation, we found that end-to-end latency for the DSRC OBU (unloaded – clean channel scenario) is 2-3 ms without security. Due to a driver misconfiguration, the 5GAA test results of 17 ms end-to-end latency are not typical for the DSRC OBU on an unloaded channel.

6 Test Setup

1. **Most OEM may not use high performance 6 dBi ECOM6 antennas. Why are they used?**

   The goal of this test activity is to compare the relative performance of the C-V2X and DSRC. Hence, the same antennas are used for the DSRC and C-V2X tests. This ensures that antenna performance does not impact the relative performance of the C-V2X or DSRC.

2. **It was stated earlier that two Rx signals were supported by both radios. Did the radio software support receive diversity processing? If not, then the antenna patterns become critical to ensure the null was not directed toward the receiving signal.**

   As mentioned in 5 *DSRC DUT Equipment*, MW1000 used in the tests supported Rx diversity, specifically MRC is supported by MW1000.

3. **What were the MCS, transmit power, packet size, and HARQ parameters used for the cabled radio lab tests?**

Configuration	DSRC	C-V2X (PC5 Mode 4)
Channel	Channel 172	5860 MHz (Channel 172)
Bandwidth	10 MHz	10 MHz
Modulation	QPSK ½ (6 Mbps burst rate)	QPSK 0.46 (MCS 5)
Application used	Savari	Savari
Tx/Rx configuration	1 Tx 2 Rx	1 Tx 2 Rx
Device details	Savari MW1000	Roadrunner platform
HARQ	NA	Enabled
Tx power	21 dBm	21 dBm
Packet size	193 Bytes	193 Bytes

   See [1].

7 Congestion Control

1. **How many vehicles are used for the congestion tests conducted in [1]?**

   Congestion tests were conducted in the lab using 48 OBU as super UE to create similar congestion load as described in the CAMP. The congestion test was based on the CAMP scenario described in [NHTSA-2015-0060] where the devices under test move on a 1200-meter stretch of highway in the carpool lanes, while the devices creating the congestion are stationary on both sides of the carpool lanes.

2. **Why is CBR only 30% in the congestion lab test? This is not really a congested scenario as the Distributed Congestion Control algorithms usually activates at CBR=60%.**

   The congestion test used the CAMP congestion scenario where transmission rate changed when vehicle identifies there are more vehicles within the range than vDensityCoefficient (defined in SAE J2945/1). Congestion lab test results showed that with SAE congestion control ON – PER and CBR remains low (less than 10% and 30% respectively) even in dense congestion scenario.

   This congestion test did not use "CBR" or channel utilization to control the OBU transmit power. It used the vehicle density to control the BSM transmission rate as defined in J2945/1.

   As shown in Figure 32 of [1], lab test results closely match those obtained through simulation.

3. **Do you have a performance comparison of C-V2X and DSRC under congestion?**

   Congestion tests were done only using C-V2X DUT. No congestion tests were done for the DSRC

4. **In the field tests, you showed that LTE-V2X has a broader range than DSRC. However, in the congested test, you claim you can only focus on the cars nearby (in the red area). So, is the extra range really needed?**

   As mentioned in [1], "the main contributors to interference are the closest 576 cars that are traffic-jammed on the highway. This number was determined by conducting simulations of a larger number of interfering devices spread over the full 1200-meter stretch of highway (1940 cars) and then repeating the simulations with an increasingly smaller number of interfering cars to determine the smallest number of congesting devices for which the performance of the DUTs remains unchanged". For this reason, cars in the red area are considered for lab study.

As detailed in [5] longer communication range is important in several scenarios including high speed, freeway scenarios as well as low speed, urban scenarios. For freeways, the longer range translates to more time for drivers to react to sudden changes in traffic condition. In urban scenarios, higher tolerable path loss is important in non-line of sight (NLOS) scenarios typically encountered at intersections, since the link margin advantage of C-V2X equates to high packet reception rate, or system reliability, at a given range.

The following graph shows the variation in stopping distance with speed on normal and icy roads. Overlaid are likely communication distance for C-V2X and DSRC under the considered non-line of sight conditions. The communication range for C-V2X is determined to be 107 m whereas for DSRC the communication range is 60 m.
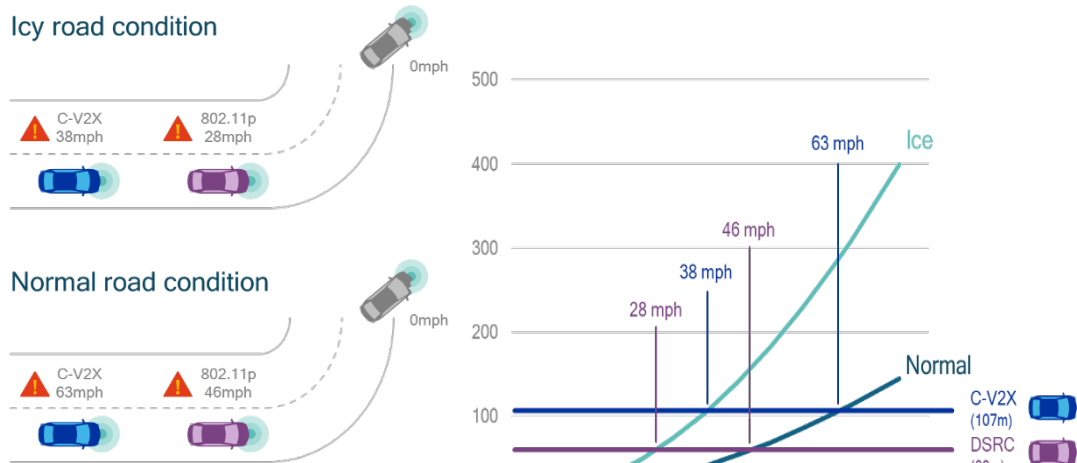
As can be seen from the graph, for vehicles utilizing DSRC communication, the maximum speed is limited to 46 mph as compared to 63 mph for vehicles using C-V2X communication under normal road conditions. For icy road conditions, maximum speed for vehicles with DSRC communication is limited to 28 mph whereas that for vehicles with C-V2X communication is 38 mph.

Next, we consider a passing scenario on a single lane road. The communication range for such a scenario is estimated to be 240 m for vehicles using DSRC compared with 443 m for vehicles using C-V2X. The maximum speed for vehicles with DSRC communication would be 28 mph whereas that for vehicles equipped with C-V2X communication would be 43 mph.
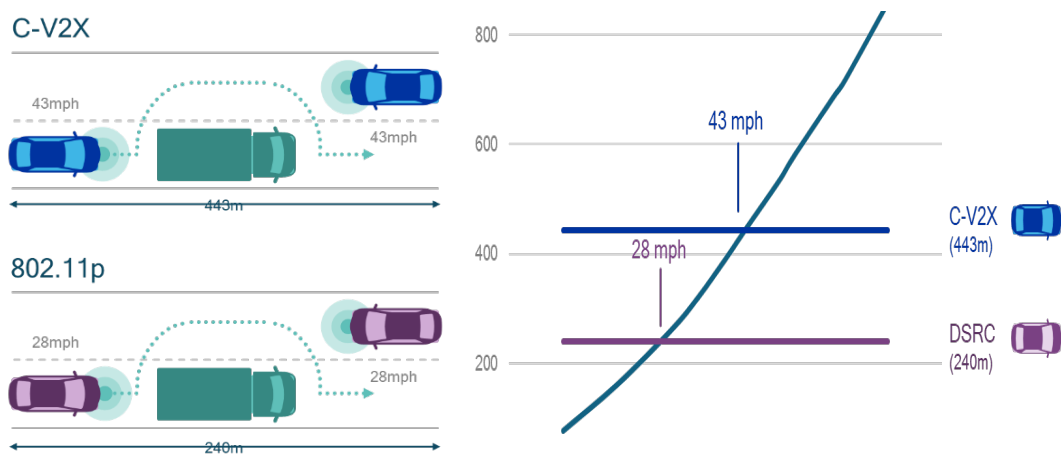
System performance evaluations conducted in [5] show the benefits of C-V2X communication (as compared to DSRC) for freeway and urban scenarios. As noted, even a small improvement in an urban scenario can have significant impact on urban transport safety.

5. **Without the support of the base station, C-V2X will broadcast on pre-defined resources and congestion similar to DSRC may occur. Is there any mechanism to deal with this?**

In transmission mode 4, C-V2X vehicles decide on the resources to be used by measuring the energy in different resources in the preceding time interval. They then randomly select needed resources from 20% of the cleanest resources as shown in the following figure:
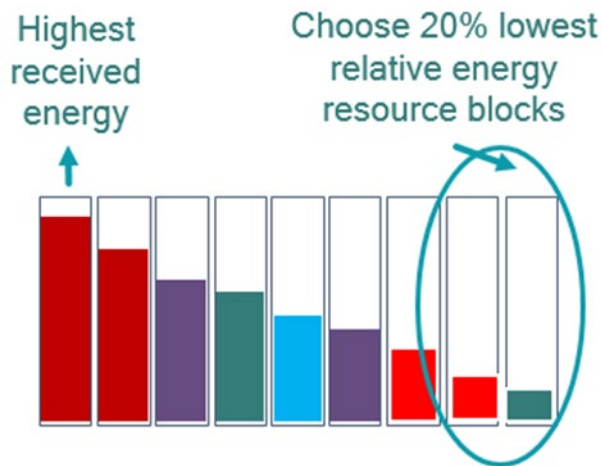
For V2V applications, transmission mode 4 offers several features. These include independence from cellular operators, autonomous resource selection as well as access layer congestion control. Further, application layer congestion control algorithms offer various techniques to detect and alleviate congestion autonomously.

6. **What range do you feel is required for V2V Safety? At only 11 dBm DSRC is getting over 600 m. SAE J2945/1 allows it to go up to 20 dBm. This seems sufficient. Increased range will lead to increased interference which may complicate things when it comes to congestion control**.

Refer to the discussion in Q4 on the benefits of extended range, which is important for some use cases. Remember, increased packet reception reliability at set ranges will enable shorter range safety services.

Now, the congestion control algorithm offers various techniques to combat longer range. These include reduction in transmit power and reduction in message transmission rate when congestion is detected. As shown by lab congestion tests, reduction in rate can be effectively used to alleviate congestion.

Also the 600 m range does not apply for all the channel models. Again, for various scenarios practical range could be less than 600 m.

8 Interference

1. **Are there any adjacent and non-adjacent channel interference tests conducted on C-V2X?**

   Yes, the following adjacent and non-adjacent channel interference field and lab tests have been performed:

   Lab test – Hidden Node Scenario (Section 7.3.1 of [1])

   Lab test – Interference caused by Near-Far Effect (Section 7.3.2 of [1])

   Field test – Interference originating in the channel adjacent to the operating (safety) channel (CH172) (Section 8.6 of [1])

   The studies in [1] focus on impact on 10 MHz C-V2X operation in channel 184. Impact of 20 MHz C-V2X operation in channel 183 are characterized in [6]. It is shown (in [6]) that:

   a. Reliability of the C-V2X message transmissions in the 20 MHz channel is close to that measured in 10 MHz.

   a. C-V2X communications in the 20 MHz channel 183 impacts existing V2X transmission in the neighboring adjacent and non-adjacent ITS channels similar to DSRC transmissions in the same 20 MHz with the same load and RF characteristics.

   For more information on details of the test and related results, see [6].

2. **How do you avoid interference from Wi-Fi security cameras in future?**

   To assess resilience of V2X technologies from out-of-band interference like Wi-Fi security camera, U-NII-3 802.11ac Interference Test (8.6.1) is done. V2X technology is proven more resilient with the presence of interference. See the results of U-NII-3 802.11ac Interference Test (8.6.1). Both DSRC and C-V2X range is decreased in the presence of UNII-3 transmission. However, C-V2X performed better than DSRC in the presence of the interference.

   See the following table (*Range comparison between DSRC and C-V2X for at 11 dBm effective transmit power* from Section 8.6 of [1]).

Test procedure	Range in (m) at 90% reliability	
	DSRC	**C-V2X**
Line-of-sight (LOS) range	925	>1350**
Non-line-of sight (NLOS) blocker (5GAA)	425	625*/725
Non-line-of-sight (NLOS) intersection	90*/400	600*/800
Co-existence with Wi-Fi 80 MHz bandwidth in UNII-3	550	950
Co-existence of V2X with adjacent DSRC carrier	100*/325	950

   * First drop below 90% packet reception rate (PRR)
   ** C-V2X range >1350 m since we reached the end of the track

9 Security

1. **How does security differ from the DSRC to the C-V2X?**

   There will be no difference in the privacy and security for the C-V2X compared to 802.11p based DSRC solution.

   Application-level security defined in IEEE 1609.2 "SCMS" and its ETSI-ITS similar counterpart will be used transparently for the C-V2X.

10 V2P Capability

1. **V2P is a good use case for C-V2X. Is there a QTI chip in the works for this?**

   Qualcomm® C-V2X chipsets have been used for the trials that include V2P use cases along with other Day 1 V2V and V2I use case.

2. **Any plans for smartphones to enter the 5.9 GHz band for the V2P use cases?**

   QTI has not announced any C-V2X-enabled chipset for smartphones UE as yet. Optimizations to PC5 solution for use in smartphones is under consideration.

A References

1. 5GAA P-190033, "V2X Functional and Performance Test Report; Test Procedures and Results", 5GAA April 2019

2. "Talking Cars: Field Test Results Talking Cars: Field Test Results Talking Cars: Field Test Results Comparing DSRC & C-V2X Technology", Webinar presentation by 5GAA, 17 October 2018

3. *5GAA Ex Parte Notice to FCC*, 1 July, 2019 https://ecfsapi.fcc.gov/file/106281501223885/5GAA%20Ex%20Parte%20Notice%206.28.19.pdf

4. C-V2X commercial devices: https://www.qualcomm.com/solutions/automotive/c-v2x (scroll down the page to see the current list)

5. Tien Viet Nguyen, Shailesh Patil, Baghel Sudhir, Gulati Kapil, Libin Jiang, Zhibin Wu, Durga Malladi and Junyi Li, "A comparison of Cellular Vehicle-to-Everything and Dedicated Short Range Communication", 2017 IEE Vehicular Networking Conference (VNC)

6. 5GAA P-180106, "Addendum to V2X Functional and Performance Test Report; Test Procedures and Results for 20-MHz Deployment in CH183" 5GAA May 2019

7. SAE J2945/1, "On-board Minimum Performance Requirements for V2V Safety Communications", Version 1, March 2016

8. 3GPP TS 36.213 Rel. 14

9. 3GPP TS 36.331 Rel. 14

10. Durga Malladi, *"5G NR based C-V2X"*: https://www.qualcomm.com/media/documents/files/5g-nr-based-c-v2x-presentation.pdf