Analysis of CAMP Report on the C-V2X Performance Assessment Project

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Abstract

The Crash Avoidance Metrics Partnership LLC (CAMP) published an overview presentation (referred to as the CAMP test report hereafter) on the C-V2X Performance Assessment Project on December 5, 2019. The goal of the C-V2X Project is to provide an evaluation of the C-V2X communication technology by developing V2X functional and performance test procedures, conducting testing and performance assessment, and documenting the results. The CAMP test report was published shortly before the Federal Communications Commission (FCC) issued a Notice of Proposed Rulemaking (NPRM) to change the 5.9 GHz band allocation that dedicated short range communications (DSRC) uses for vehicle-to-everything (V2X) safety applications and allocate the majority of the band (45 MHz) for commercial use such as general-purpose Wi-Fi® and cellular applications.

In our view, the CAMP tests were conducted with meaningful test conditions and sufficient test setups. The test results of different test scenarios with 20 MHz bandwidth and Hybrid Automatic Repeat Request (HARQ) enabled have provided valuable data points for comparing available V2X technologies. While the CAMP test report states that tests were conducted for both 10 MHz and 20 MHz cases combined with HARQ enabled and disabled, the results published in the publicly available report only cover the 20 MHz case with HARQ enabled. In addition, some real-life problem conditions which would have added more value to the tests (e.g., unavailable Global Navigation Satellite System (GNSS) signals or a near-far-problem setup) were not addressed.

The significant efforts in planning, preparing, conducting and reporting the CAMP tests deserve recognition and appreciation. However, the results themselves do not demonstrate clear advantages of C-V2X over DSRC. Rather, C-V2X performance limitations can be observed, for example, in overall communication range, message information age or the need for more bandwidth. In our opinion, the results are insufficient to justify the need and readiness of C-V2X for large-scale real-life deployment.

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[1] C-V2X Performance Assessment Project, https://pronto-core-cdn.prontomarketing.com/2/wp-content/uploads/sites/2896/2020/02/CAMP-CV2X_SAE_01152020_v2.pdf, December 5, 2019.

[2] FCC 19-129, ET Docket 19-138, NOTICE OF PROPOSED RULEMAKING, https://www.fcc.gov/ecfs/filing/1217200308588

The Analysis

Introduction

CAMP defines and develops pre-competitive elements of automotive crash avoidance countermeasures[3]. It has assessed performance of C-V2X PC5 sidelink mode 4 (referred to as C-V2X by CAMP). Results have been made public on the CAMP website in January 2020. The project outline below is posted on the report site:

Cellular V2X Device-to-Device Communication (C-V2X) Project	
Project Team	Cellular V2x Device-to-Device Communication (C-V2X) Consortium
Timeframe	October 2018 – December 2019
Sponsor(s)	CAMP
Synopsys	The goal of the C-V2X Project is to provide an objective evaluation of the C-V2X communication technology by developing V2X functional and performance test procedures, conduct testing, conduct performance assessment, and document the results.
Web site	https://www.campllc.org/project-cellular-v2x-device-to-device-communication-c-v2x/

The CAMP test focus was mainly on reliability and congestion control. It was not a comparison test with DSRC.

The Test Setup

The CAMP Cellular V2X Device-to-Device Communication (C-V2X) Project[4] reported a five-part test scenario. The C-V2X Performance Assessment Project[5] test summary appears to be the only available document report that is publicly available. From that summary, some insight into the testing and test results can be acquired. According to the report, the testing is divided into five parts:

1. Device Characterization
2. Bench Testing
3. Controlled Vehicle Testing – V2V and V2I Scenarios
4. Mixed Traffic Vehicle Testing
5. Congestion Control Testing

Summaries of the segment test setups are in Appendix I.

Strengths of the Test

The CAMP test report is well organized, and tests were conducted in a suitable manner, starting with bench characterization and leading to full congestion testing in the field. Tests are promised to have a good variety of parameters, like the use of a set of different realistic message sizes (slide 5). Congestion emulation appears to be reasonably well set up although the detailed specification of the emulation is not available to us at this time. For example, using "pods" to mimic a heavy amount of traffic in a small area, reflecting various congested highway scenarios (slide 54 and beyond).

Gaps and Weaknesses of the Test

While the test was set up well, the resulting report appears incomplete to draw definite conclusions. Even though the "objective testing" (slide 5) mentions that 10 and 20 MHz channels are tested, it appears only 20 MHz tests are reported. Similarly, HARQ is mentioned as possibly enabled or disabled, but only results with HARQ enabled are reported. This lack of 10 MHz and HARQ-off results, while advertised, gives the impression that such results are available, but they are not included in the published report.

[3] Crash Avoidance Metrics Partnership LLC, https://www.campllc.org/about-camp/

[4] https://www.campllc.org/project-cellular-v2x-device-to-device-communication-c-v2x/

[5] C-V2X Performance Assessment Project, https://pronto-core-cdn.prontomarketing.com/2/wp-content/uploads/sites/2896/2020/02/CAMP-CV2X_SAE_01152020_v2.pdf, December 5, 2019.

In addition, the rigor of the initial test phases is relaxed in the final live tests. For example, in the test objective slide, different message sizes are indicated (slide 5), yet in the congestion section, the measurements fall back to a single size (slide 61): "all packets have the same size of 365 bytes". This is unfortunate because packet sizes are rather dynamic in real-life situations. It would have been beneficial to see how the semi-persistent scheduling of C-V2X would have dealt with this aspect, especially in congested situations.

It is also important to note the lack of certain real-life problem condition testing, e.g., a drop in of GNSS coverage. This is a known issue of the C-V2X technology because it is based on a synchronous time-slotted network that requires a GNSS clock to align all stations. This report gathers data on open field testing only—neither tunnels nor urban canyon with changing reflections and loss of GNSS are included.

Solutions with only one single silicon provider and one single stack provider were tested, so interoperability cannot be investigated or proven at this stage. This has happened in a previous C-V2X test[6] and the lack of interoperability testing is, in our view, a deficiency. With only one chipset vendor, the lower layers are automatically interoperable. Conversely, the DSRC ecosystem is very broad, with many manufacturers. Device interoperability is at the core of the DSRC technology and has been proven over the years, e.g., as it was in ETSI Plugtests in 2016.[7]

Finally, the tests from the CAMP test report are not intended for comparison to DSRC, and therefore it is not possible to draw a 1:1 conclusion based on the report. To provide greater benefit to the ITS community, we believe future V2X testing should include current state-of-the-art commercial DSRC solutions for direct comparison.

Analysis of the Test Results

This section captures observations on the reported performance of the C-V2X technology.

Going through the slides describing the test setup and measurements configurations, we highlight the following aspects:

- Transmit power is indicated to be 20 dBm. It is not clear if it is always set to 20 dBm or if 20 dBm is a maximum. When C-V2X messages occupy only a fraction of the band, the absolute transmit power should be reduced to ensure constant power spectral density (PSD), typically expressed in dBm/MHz.
- Packet sizes of 1000 and 1400 bytes, with advertised MCS configurations of MCS 5 and 7 respectively, occupy all subchannels in a 20 MHz channel. In a 10 MHz channel, such packets would require fragmentation over two subframes, which would have a major impact on range, and even more on latency.
- Overall, the communication ranges measured are not very large, typically a few hundred meters. This is evident during congestion testing where the packet error rate (PER) measurements are emphasized for the central ±300 m of the test track. The moving vehicle critical event testing with congestion is also a very short-range test—no more than 160 m. Overall, none of the critical event congestion testing exceeded 400 m in range. The reliability depends on the packet size, as can be seen on slide 32 (red curve vs. blue curve). This is the result of modulation and coding scheme (MCS) adaptation and is a strong limitation of the technology. It means that longer messages have less chance to arrive at a given distance, even though longer messages are likely more important. Longer messages typically reflect emergency situations, in which case certificates, signatures and optional fields are transmitted. If the certificate cannot be received, the trustworthiness of the information cannot be verified. The shorter basic safety message (BSM) messages, on the other hand, carry only the standard safety information, no critical events.

[6] V2X Functional and Performance Test Report; Test Procedures and Results, page 16, https://5gaa.org/wp-content/uploads/2018/11/5GAA_P-190033_V2X-Functional-and-Performance-Test-Report_final-1.pdf

[7] Report on 5th ITS Cooperative Mobility Services Plugtest, https://portal.etsi.org/Portals/0/TBpages/CTI/Docs/5th_ITS_CMS_PLUGTEST_REPORT_FINAL.pdf

- Performance of C-V2X under congestion is not impressive:
  - Without congestion control, PER raised quickly (slide 106), bypassing the 10% mark on an already short range
  - With congestion control, performance seems to be rather stable, but information age (IA) increases. For example, on slide 70, the gap between transmissions (intertransmit time (ITT)), increases to above 200 ms. Nevertheless, the actual data does not come through at the speed expected from the latency numbers: the IA is significantly higher, on the order of 400 ms in the less congested test scenarios (slide 74), growing to above 0.5 second in highly congested situations (see "CC" curves, slide 93) and even up to 1 second (slide 109). From a message rate perspective, the congestion control is doing its job, as can be seen from the IA for measurements without congestion control (see "noCC" curves, slide 93).
- The way congestion is simulated is optimistic. Traffic generators use different subframes (slide 63), and they avoid the near-far problem, which is another known issue of C-V2X[8].
- The conclusion slide (126) shows that under congestion, performance just 'passes' and it seems to be at large latency, with IA as large as one second.

Benefits of DSRC: Field Test Results

Upon reviewing the CAMP test results, the question of technology comparison is still of importance. Early in 2019, after the 5GAA requested access to the safety band spectrum[9] for C-V2X, NXP conducted DSRC Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) field tests in Singapore. The results were published in an NXP whitepaper on the 5GAA comparison between C-V2X and DSRC/IEEE 802.11p[10]. Although not as extensive as the CAMP tests, we provide some remarks on the outcome in comparison to the CAMP C-V2X performance test report.

DSRC Test Conditions

The DSRC test conditions were set to be as comparable as possible to those described in the 2018 5GAA test report[11,12]. The NXP test used commercially available DSRC on-board units (OBUs) from Cohda Wireless[13]. The test highlights the need for publicly available comparative testing for the C-ITS community. Unfortunately, access to a (configurable) C-V2X system was not publicly available. As a result, the field test did not allow an exact 1:1 comparison with identical settings, but it is a qualitative test indicating the achieved performance using DSRC.

The main configuration parameters are captured in the following table:

Parameter	Value
Tx/Rx Channel	184 (SCH)
Channel Bandwidth	10 MHz
Carrier Frequency	5.920 GHz
OBU Tx Power (max)	23 dBm (equivalent to 11 dBm for C-V2X in 5GAA tests)
HARQ	not applicable
Tx/Rx Antenna Configuration	1-Tx/2-Rx
NLOS Obstruction Object Dimensions	50-seater bus (10.8 mx 2.5 mx 3.5 m)
Tx Antenna Height	~ 1455 mm
Rx Antenna Height	~ 1455 mm
Modulation Code (MCS)	QPSK ½ (MCS 2)

[8] IEEE802.11p ahead of LTE-V2V for safety applications, page 8, https://www.nxp.com/docs/en/white-paper/LTE-V2V-WP.pdf

[9] 5GAA PETITION FOR WAIVER, https://ecfsapi.fcc.gov/file/11212224101742/5GAA%20Petition%20for%20Waiver%20-%20Final%2011.21.2018.pdf

[10] On the 5GAA comparison between LTE-V2X and DSRC/IEEE 802.11p, page 5-6, https://www.nxp.com/docs/en/white-paper/LTEDSRC5GCOMWPA4.pdf

[11] 5GAA "V2X Functional and Performance Test Report; Test Procedure and Results", page 79, https://5gaa.org/wp-content/uploads/2018/11/5GAA_P-190033_V2X-Functional-and-Performance-Test-Report_final-1.pdf

[12] Re: 5GAA Petition for Waiver to Allow Deployment of Cellular Vehicle-to-Everything (C-V2X) Technology in the 5.9 GHz Band; GN Docket No. 18-357, page 23, https://ecfsapi.fcc.gov/file/104030451515194/5GAA%20Band%20Plan%20Ex%20Parte%20-%20FINAL.pdf

[13] MK5 On–Board Unit (OBU) description, https://cohdawireless.com/solutions/hardware/mk5-obu/

Based on our understanding of the 5GAA C-V2X test configuration (users occupying only a fraction of the bandwidth, HARQ retransmission, different data rate, etc.), a setting of 23 dBm transmit power for DSRC should be used to be comparable with 5GAA C-V2X configuration (with 11 dBm). A detailed explanation is given in Appendix II.

Singapore Test Site and Equipment

The test site in Singapore selected for performing the measurements was a road (Lim Chu Kang Road, see Figure 1), which has a stretch of over 2 km of undisturbed line of sight. In this sense, the location is somewhat comparable to the location used in the CAMP tests.

Figure 1: Testing site: Lim Chu Kang Rd., Singapore, 2 km LOS

Line-of-sight (LOS) Field Test Result

For the LOS measurements, two passenger vehicles were used, as shown in Figure 2.

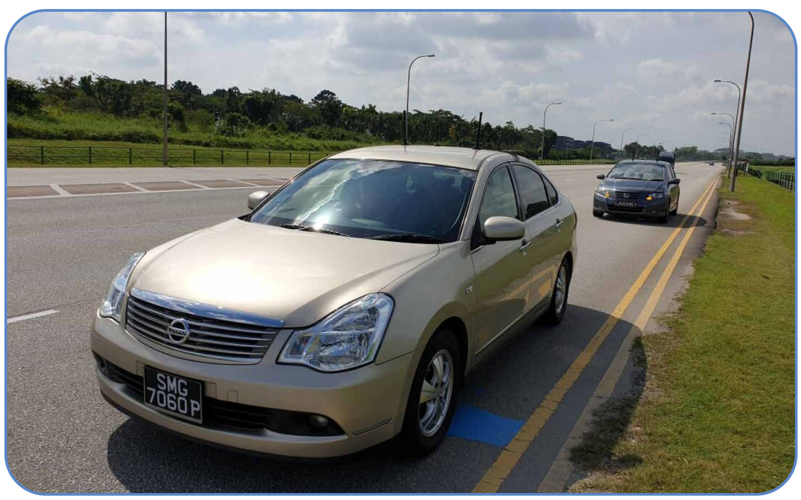

Figure 2: Vehicles used in LOS tests

From the measurements performed, the LOS results are in line with the expectation, achieving a range of up to 1.4 km before any drop of packet reception rate (PRR) below 90%, as shown in Figure 3. After this, reception varies, due to well-known multi-path reflection effects, giving occasional reception up to 2 km. Compared to the 5GAA report[14,15], this is significantly better than the results 5GAA presented for DSRC[13,14].

[13] MK5 On–Board Unit (OBU) description, https://cohdawireless.com/solutions/hardware/mk5-obu/

[14] 5GAA "V2X Functional and Performance Test Report; Test Procedure and Results", page 84, https://5gaa.org/wp-content/uploads/2018/11/5GAA_P-190033_V2X-Functional-and-Performance-Test-Report_final-1.pdf

[15] Re: 5GAA Petition for Waiver to Allow Deployment of Cellular Vehicle-to-Everything (C-V2X) Technology in the 5.9 GHz Band; GN Docket No. 18-357, page 25, https://ecfsapi.fcc.gov/file/104030451515194/5GAA%20Band%20Plan%20Ex%20Parte%20-%20FINAL.pdf

As indicated in an earlier white paper by NXP[16], 5GAA results for DSRC do not appear representative for the technology, but for the equipment and modem chipset used in their setup. The 5GAA results should therefore not be taken as representative for the current state-of-the-art commercial DSRC equipment. The NXP DSRC measurements even marginally outperform the 5GAA C-V2X LOS results.

In terms of LOS range, C-V2X is at its best on par with DSRC, based on the available results of the 2019 Singapore test, the 2018 5GAA test and the 2019 CAMP tests.

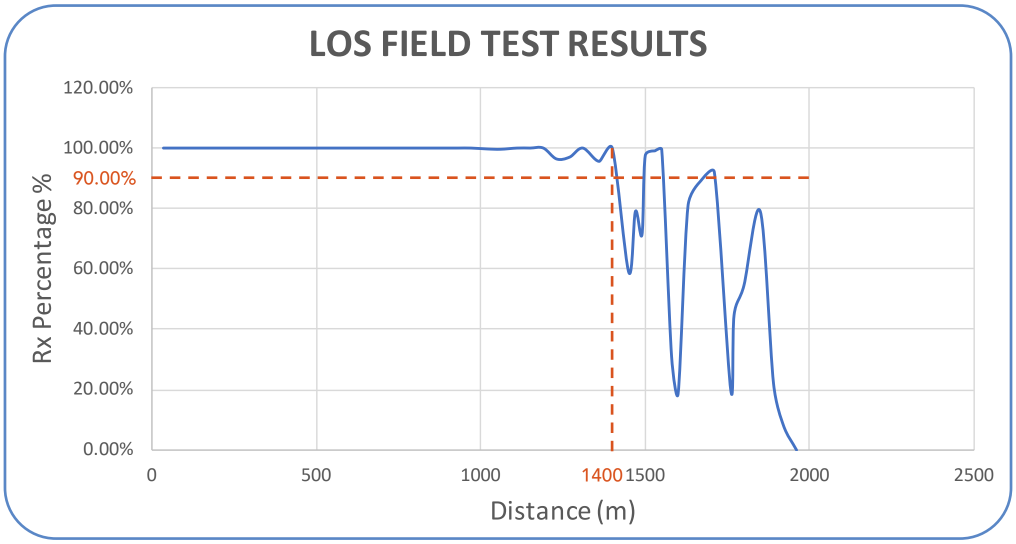

Figure 3: Test result of LOS range field test

NLOS Field Test Result

For the NLOS measurements, a passenger bus was utilized as an obstruction (Figure 4).

Figure 4: Vehicles and obstacle used in NLOS tests

[16] https://www.nxp.com/docs/en/white-paper/LTEDSRC5GCOMWPA4.pdf

The NLOS measurements give excellent results that are in line with the expectation—the range of over 1 km was achieved before any drop of PRR below 90%, as shown in Figure 5. DSRC significantly outperforms C-V2X under NLOS conditions according to the 5GAA report[17,18]. The unique benefit of the V2X technology is its capability of "seeing-around-corners," thus the NLOS performance is of particular interest.

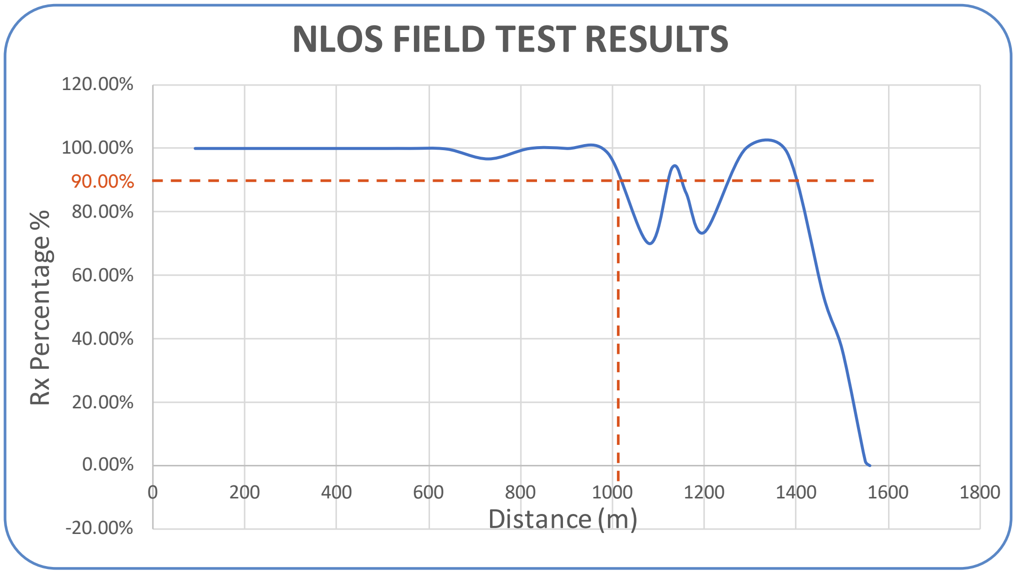

Figure 5: Test result of NLOS range field test

Conclusion

The CAMP C-V2X Performance Assessment test seems generally well performed. However, the published report lacks some key details.

Performance and Bandwidth Used By C-V2X

Looking at the CAMP test results, we see certain expectations confirmed. First, C-V2X performance seems on-par with DSRC in the best case (LOS); for example, compared with the DSRC measurements from the NXP Singapore DSRC test, and worse in the case of NLOS, despite the increase in channel bandwidth to 20 MHz. Although stated in the test setup description, the non-HARQ and 10 MHz bandwidth results were unfortunately not included in the published CAMP C-V2X project presentation[19].

The need of 20 MHz leaves little room for other V2X use cases and applications next to the use for basic safety messages, making C-V2X, more or less, a dead end if the FCC NPRM is accepted in its current form. As 5GAA is promoting 5G-V2X for enhanced use cases, this again will demand significantly more bandwidth in addition to the basic safety message functionality spectrum, something the current FCC proposal will not provide.

[17] 5GAA "V2X Functional and Performance Test Report; Test Procedure and Results", page 89, https://5gaa.org/wp-content/uploads/2018/11/5GAA_P-190033_V2X-Functional-and-Performance-Test-Report_final-1.pdf

[18] Re: 5GAA Petition for Waiver to Allow Deployment of Cellular Vehicle-to-Everything (C-V2X) Technology in the 5.9 GHz Band; GN Docket No. 18-357, page 27, https://ecfsapi.fcc.gov/file/104030451515194/5GAA%20Band%20Plan%20Ex%20Parte%20-%20FINAL.pdf

[19] https://pronto-core-cdn.prontomarketing.com/2/wp-content/uploads/sites/2896/2020/02/CAMP-CV2X_SAE_01152020_v2.pdf

Congestion Control and Information Age

On the aspect of congestion control, the test set up using the pods generating virtual car signals was well done.

The results, however, were unsatisfactory, as the "information age" increases to significant values. Communication latency and IA go hand-in-hand and both need to be kept sufficiently low. High information age, e.g., IA that approaches 1 s as shown in the report, compromises the usefulness of the messages, regardless of latency.

There are certain test items which are not mentioned in the report and which would have been useful. One example, details on behavior after GNSSS signal loss, may be one of the weak points of the current solution. Also, some inherent weaknesses of the cellular setup, such as the near-far problem[20], are not reported and may not have been measured. This may have been a deliberate choice to keep the test scope limited, or might have been omitted from the report, as is the case for other topics on the original CAMP scope (no HARQ, 10 MHz bandwidth mode).

Congestion control schemes for IEEE® 802.11p communication systems have been tested and studied extensively by the ITS community and several technical papers are available on IEEE. For example, an NXP paper[21] shows that a large number of vehicles can be accommodated without noticeable impact on performance. In contrast, there are fewer published technical papers covering congestion control schemes and resulting performance for C-V2X.

In summary, it is our opinion that the CAMP test results are insufficient to be used as justification that C-V2X is ready for deployment. C-V2X is not projected to achieve the current DSRC production maturity anytime soon. With more than 36,000 casualties and 2.7 million injuries every year according to the U.S. Department of Transportation,[22], the National Highway Traffic Safety Administration (NHTSA) indicated V2X technology has the potential to significantly decrease these numbers[23].

Appendix I: Detailed Description of the Test Set Up

Appendix I contains a descriptive summary of each of the test segments as they were published in the CAMP Report on the C-V2X Performance Assessment Project.

The Device Characterization testing that was reported, appeared to consist of single OBU testing under specific test conditions. Measurements of transmit power accuracy, receiver sensitivity, 10 and 20 MHz transmit mask (channels 184 and 183), adjacent channel selectivity and in-band blocking, transmission timing synchronization, system clock accuracy and channel busy ratio estimate were made at minimum. Other device characterization measurements may have been made but are not listed in the summary.

The Bench Testing section presented data on cabled (2Rx), "Last Link Wireless" (2Rx), average inter-packet gap (IPG), and 95th percentile application layer latency. No maximum or minimum latency was reported out. Only 200-byte packets were tested.

Controlled Vehicle Testing (V2V and V2I Scenarios) involved up to eight vehicles, two vehicles donated from each motor company, each outfitted with an OBU, and two roadside units (RSUs). LOS V2V and V2I, NLOS V2V and V2I, high-speed opposite direction (HSOD) V2V, and Intersection NLOS test scenarios were evaluated.

HSOD testing was only reported with one vehicle speed of 80 mph and the other at 70 mph. It would be anticipated that a closing speed on more than 150 mph would be necessary in the real world, especially in the case of a high-speed pursuit. Transmitted packets for this section of the testing were limited to 365 or 1400 bytes with inter-transmit times reported to be approximately 100 ms, without specifying a timing tolerance. There are no controlled vehicle test results reported indicating performance with single antenna/receiver receive, with HARQ off, or in 10 MHz channels. All reported testing in this section of the test summary utilized a 20 MHz waveform, HARQ and dual-antenna receive.

[20] IEEE802.11p ahead of LTE-V2V for safety applications, page8, https://www.nxp.com/docs/en/white-paper/LTE-V2V-WP.pdf

[21] V2X Application-Reliability Analysis of Data-Rate and Message-Rate Congestion Control Algorithms, https://ieeexplore.ieee.org/abstract/document/7867057

[22] U.S. DOT's March 13, 2020 Response to the FCC Notice of Proposed Rulemaking, page 3, https://ecfsapi.fcc.gov/file/10313251510165/5.850-5.925%20GHz%20Band%2C%20ET%20Dkt%20No.%2019-138.pdf

[23] NHTSA V2V NPRM of 2017, section "Overall Crash Population That V2V Could Help Address", page 3,860, https://www.regulations.gov/document?D=NHTSA-2016-0126-0009

For the vehicle testing, two V2X antennas were each located on the apex of the vehicle roof, equally offset, left and right from the longitudinal center of the vehicle for vehicles without a sunroof. In cases where a sunroof was present, the V2X antennas were set outboard of the sunroof. GPS antennas were located along the longitudinal center of the roof either at the apex of it or aft of the sunroof. The summary report did not indicate which vehicles had sunroofs and which ones did not, and it was not possible to discern from the vehicle photos if sunroofs were present. Specific measurements of the antenna locations by vehicles were not detailed in the summary. The V2X antennas were pattern tested while mounted in the center of a 1-meter diameter circular ground plane. The directive gain varied from -4 dBi to 0 dBi according to the test summary document.[24] The Cellular V2X Device-to-Device Communication Consortium of CAMP assumed this also held true on the vehicle. However, no in situ vehicle antenna testing was reported for any of the test vehicles. Power output of each OBU was listed as 20 dBm. The test summary cited approximately 3 dB loss in the cabling.

The Mixed Traffic Vehicle Testing data was presented as a summation over two caravans for two routes in the Detroit area. The summary data only delineated results between the lead car in a group and the second or third vehicle in the caravan(s). Even though the summary indicated that packets with payloads of 365, 1,000 and 1,400 bytes would be transmitted, data was only presented for 365- and 1400-byte payloads. Again, although the summary also indicated that single and dual receive chain modes would be tested, only data with dual receive chains was presented. All reported mixed-traffic vehicle testing was performed with HARQ enabled.

Congestion Control Testing results were the last set of data that was presented in the summary. Testing was broken up into 20 mph platoon tests, 80 mph high-speed tests, critical event tests at 55 mph and stationary tests. According to the summary, all packet payloads were 365 bytes. All communications were performed on channel 183 (20 MHz wide). HARQ was also implemented. Additionally, the congestion control was implemented according to SAE J3161/1. As of this writing, the standard is still a work in progress and not available for purchase.[25] Similarly, SAE J3161, the C-V2X deployment profile, is also still a work in progress and not available for purchase.[26] Receive-only data summaries were presented only among the group of vehicles that were outfitted with OBUs. No data is presented on packets received by the virtual vehicles in the congestion group. The congestion group was simulated with virtual vehicles transmitting radio signals. The virtual congestion range was varied from 300 to 1200 m long in increments of 300 m. Congestion density was 50, 100 or 250 virtual vehicles over the ranges identified. Not all tests utilized or reported all congestion ranges. Throughout the congestion testing, it is not possible to determine if the congestion testing was performed with virtual moving congestion or virtual stationary congestion. This may be indicated in SAE J3161/1, however is yet to be completed and made available for sale. In general, data was highlighted for the driving range that corresponded and aligned with the congestion region and not beyond.

[24] C-V2X Performance Assessment Project, https://pronto-core-cdn.prontomarketing.com/2/wp-content/uploads/sites/2896/2020/02/CAMP-CV2X_SAE_01152020_v2.pdf, December 5, 2019.

[25] On-Board System Requirements for LTE V2X V2V Safety Communications J3161/1, https://www.sae.org/standards/content/j3161/1/, April 1, 2020.

[26] C-V2X Deployment Profile, https://www.sae.org/standards/content/j3161/, April 1, 2020.

Appendix II: Transmit Power Comparison

Appendix II: Based on our understanding of the 5GAA C-V2X test configuration, a setting of 23 dBm transmit power for DSRC should be used to be comparable with 5GAA C-V2X 11 dBm configuration. The motivation for such power configurations is expressed below:

- HARQ retransmission was enabled on C-V2X transmissions
  - This drives approximately +3 dB improvement for C-V2X (at the expense of using twice the amount of resources)
- C-V2X and DSRC have different way to allocate resources to the users.
  - In particular, C-V2X has a multiple users access scheme, where several users can be allocated in the same subframes in different sets of subcarriers (called subchannels). With the selected parameters C-V2X users use approximately half of the bandwidth compared to DSRC users (which occupy the full 10 MHz channel). However, in our understanding, regulators usually set a maximum transmit power in terms of PSD, expressed typically in dBm/MHz.
  - Thus, we believe that usage of half of the bandwidth should translate into a 3 dB transmit power reduction on C-V2X transmission
- C-V2X and DSRC have different modulation and coding schemes, which drive a different effective data rate.
  - In 5GAA tests, C-V2X uses MCS 5, which is very robust yet allows a lower data rate than the IEEE 802.11p MCS2 (QPSK ½). A fair comparison would require the two technologies to have the same effective data rate.
  - With IEEE 802.11p MCS2 (QPSK ½), DSRC has an effective data rate of 4.5 Mbit/s. Based on 3GPP Rel 14 specifications, 4.5 Mbit/s are obtained with MCS7 which has 4 dB less performance than MCS5.
  - Thus, we believe usage of LTE MCS 5 brings a 4 dB advantage compared to LTE MCS 7 or equivalent DSRC MCS 2.
- 5GAA mentions in their note (4) that "Tx power was 21 dBm and the total attenuation was 10 dB (on both Rx ends combined) resulting in 11 dBm equivalent Tx power. For DSRC OBU the matching Tx power was 23 dBm."[27]

[27] 5GAA "V2X Functional and Performance Test Report; Test Procedure and Results", page 79, https://5gaa.org/wp-content/uploads/2018/11/5GAA_P-190033_V2X-Functional-and-Performance-Test-Report_final-1.pdf

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