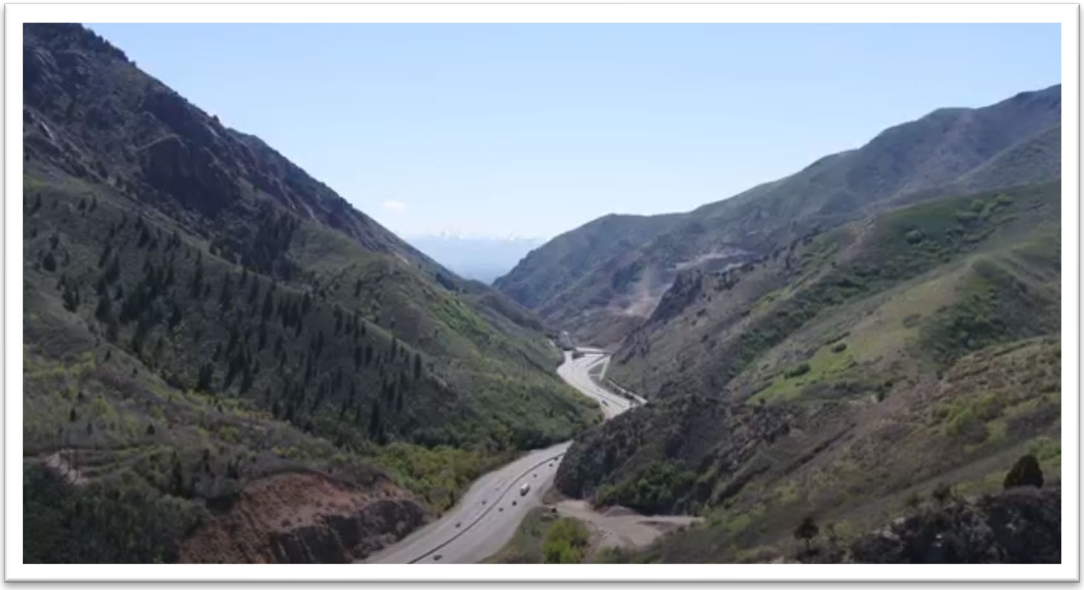
FIELD TESTS ON DSRC AND C-V2X RANGE OF RECEPTION ON UTAH ROADWAYS

April 23, 2021



Prepared for the Utah Department of Transportation by Panasonic Corporation of North America

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Executive Summary

The Utah Department of Transportation (UDOT) has been deploying connected vehicle communications systems for over six years. The goal of safer roads through transportation technology is constantly evolving, and UDOT seeks to be on the forefront of these deployments for safety and mobility. Dedicated Short Range Communications (DSRC), which is currently widely used in the industry, and Cellular Vehicle-to-Everything (C-V2X), which is emerging as a new technology in the industry, are two different methods for Connected Vehicle systems to operate and communicate within the 5.9 GHz spectrum (5.850 - 5.925 GHz). UDOT has deployed both technology platforms.

Recent actions by the FCC are reducing the available spectrum allocated for vehicle-to-vehicle and vehicle-to-infrastructure communications and have signaled a preference toward C-V2X technology. As the technologies mature and regulatory and market forces impact choices, UDOT sought to better understand the capabilities and relative strengths of both DSRC and C-V2X technologies. As part of a larger Connected Vehicle Ecosystem development and deployment project with UDOT, the Cirrus team at Panasonic Corporation of North America used connected vehicle devices to perform "range of reception" assessments in a real-world deployment environment. This testing took advantage of the unique situation in Utah where both technologies (DSRC and C-V2X) are actively deployed in "dual-mode" Roadside Units (RSUs). This document outlines the testing performed by Panasonic for UDOT on I-80 and on California Avenue to assess the range at which DSRC or C-V2X RSUs can receive a Basic Safety Message (BSM) from an On-Board Unit (OBU) in a vehicle. This study is one step toward a more complete understanding of these technologies and helps inform UDOTs plans for further deployments of connected vehicle technology.

In addition to the "range of reception" efforts, this report also presents Panasonic's findings on the status of DSRC and C-V2X in the marketplace, with an evaluation of vendor offerings, hardware maturity, certification, regulatory status, and agency use of each technology.

Findings: In over 99% of C-V2X tests and in over 97% of DSRC tests, the range of reception exceeded the nominally expected range of 300 meters in a single direction or 600 meters in both directions. Test results also show that C-V2X's range of reception was, on average, greater than the range of reception of DSRC by approximately 25% across all RSUs in all tests during this study. In addition, the range of reception is more consistent across each test in C-V2X compared to DSRC, indicated by the lower average standard deviation. Results also showed that operating DSRC and C-V2X in dual mode resulted in no significant decrease in range of reception when compared to single mode operations.

Although DSRC has a longer history of use in United States Department of Transportation (USDOT) and State-funded projects, today there are many vendors and deployments leveraging both DSRC and C-V2X technologies.

UDOT's Position on the Findings

In these tests, DSRC and C-V2X both substantially met the requirements for range. With potential changes to the 5.9 GHz spectrum and decisions signaling that C-V2X replace DSRC over a period of several years, this study adds to UDOT's valuable deployment experience with meaningful field performance data for these devices. Based on the range of receipt of BSM results, it is clear that both DSRC and C-V2X support UDOT's vehicle-to-infrastructure use cases for BSM data collection and event detection. Additional studies and evaluations are expected.

KEYWORDS: Connected Vehicles, C-V2X, DSRC, PER, UDOT, Panasonic

Introduction

Background

Dedicated Short Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X) are two different methods for Connected Vehicle systems to operate and wirelessly communicate within the 5.9 GHz spectrum (5.850 - 5.925 GHz). Although each technology is low-latency and utilizes the same frequency band, “a DSRC radio cannot [directly communicate with] a C-V2X radio, and vice versa” (Gettman, 2020).

Vehicle-to-Everything (V2X) systems include the ability for vehicles to share information with each other (vehicle-to-vehicle, or V2V), for vehicles to share information with the infrastructure (vehicle-to-infrastructure, or V2I) and for vehicles and the infrastructure to share information with other travelers, like pedestrians (V2P). These two-way V2X systems can be enabled with DSRC or C-V2X hardware, or the hardware may include both technologies. Recent advancements allow both technologies to operate simultaneously, or "dual mode". A V2X system typically consists of three major subsystems, as shown in Figure 1.

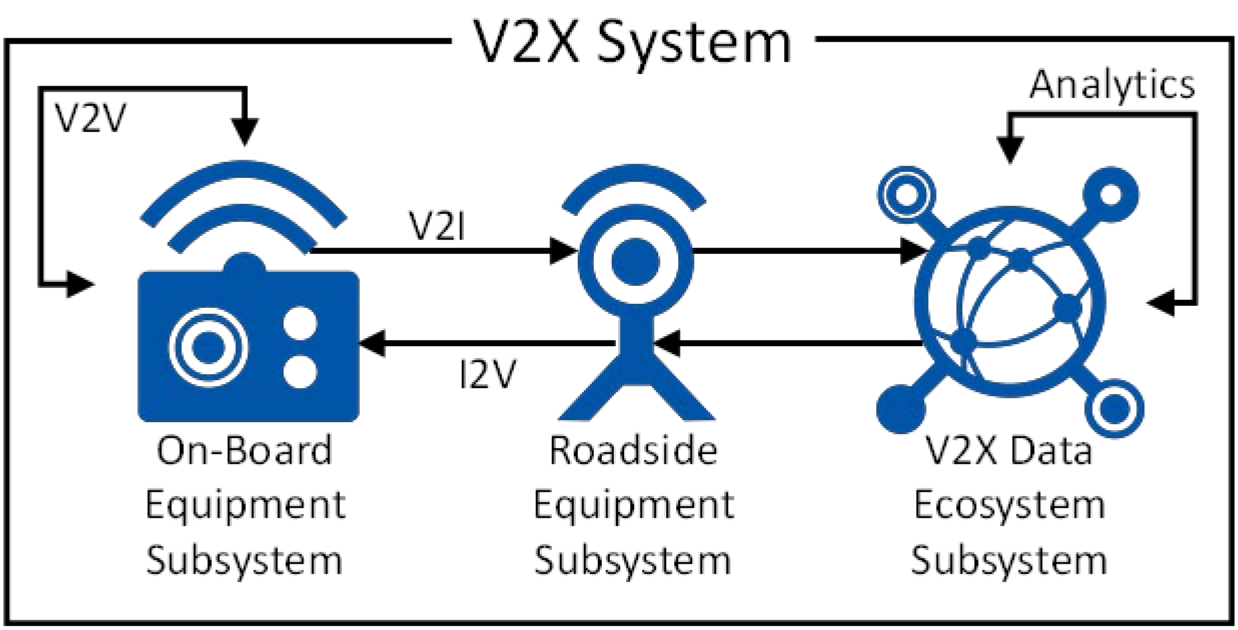


Figure 1 V2X System Components

Problem Statement

The primary objective of this assessment is to evaluate the viability of C-V2X compared to DSRC with a particular focus on performance in a production environment, the feasibility of near-term deployment, and compatibility. Performance and compatibility will be assessed by comparing the range of reception of messages sent by an OBU to the RSU in several operational environments. The RSUs will be tested while operating in DSRC-mode, C-V2X mode, and simultaneous dual mode (i.e. DSRC and C-V2X and operating on the same RSU at the same time). The performance tests seek to expand upon prior tests conducted by 5GAA (5GAA, 2019) and CAMP (CAMP – C-V2X Consortium, 2019) by evaluating different hardware (e.g. OBU and RSU manufacturers) and different metrics than the previous studies. In addition, other comparison metrics such as market adoption, device compliance with standards, and device availability will be summarized for RSU and OBU suppliers of DSRC, C-V2X, and dual mode units. Currently, UDOT has multiple RSUs deployed across the state, as shown in Figure 2, according to the FCC ULS Database (License Search, 2020), including dual mode RSUs deployed by Panasonic (other locations have been installed and had permits pending at the time of this study, which are not shown in Figure 2). This report may ultimately help inform the configuration of these dual mode RSUs (e.g. which RSUs will be set to C-V2X vs. DSRC) as well as provide insights to inform future RSU deployment locations.

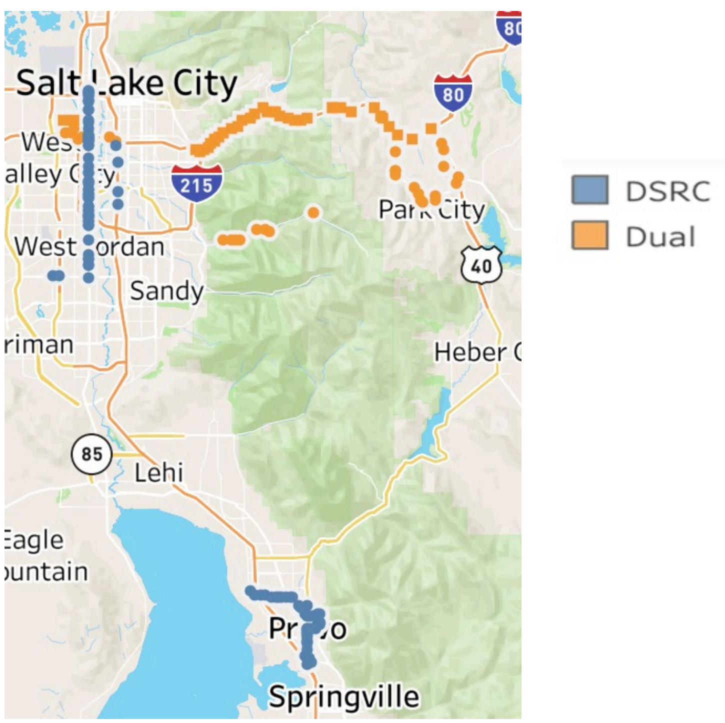


Figure 2 Current UDOT V2X RSU Deployment in Utah

Performance Testing

Devices & Configuration

For the performance tests, 4 Ficosa OBUs were prepared: 2 TCU-FITAX-3.5 DSRC OBUs configured to use channel 180 (10 MHz) and 2 PC5 CARCOM C-V2X OBUs configured to use channel 183 (20 MHz). All DSRC and C-V2X devices were set to an output power of 20 dBm maximum. One C-V2X OBU and one DSRC OBU were used for each test, and the two additional C-V2X and DSRC OBUs were available as back-up units if needed. This configuration was selected to align with the project team's expectation for future V2X regulations based on the December 2019 FCC Notice of Proposed Rulemaking (NPRM) (Rulemaking at the FCC, 2020). The DSRC OBUs were running firmware version 1.1.5, and C-V2X OBUs were running firmware version 2.4.0. Since this testing occurred within a live deployment, the temporary ID for each of the 4 OBUs was fixed in order to identify the Basic Safety Messages (BSMs) from these units during the test. In order to fix the temporary IDs, over-the-air message security also had to be disabled on the OBUs. Ficosa OBUs were selected for the test to be consistent with the 35 OBUs deployed within the UDOT fleet vehicles as part of the live environment.

Two 2020 KIA Optima vehicles were used during the test and identically outfitted with OBUs, as shown in Figure 3 and Figure 4, to reduce installation and vehicle geometry variability. The OBUs were not connected to the vehicle OBD-II port to reduce variability in BSM size due to data elements that might be populated from the vehicle. These additional data elements provide context about what is happening within the vehicle, such as brakes applied or headlights on, and therefore can change over time impacting BSM size. As a result, only core data elements derived from the GPS signal were included, such as speed, location, and heading. Finally, the installation utilized the same supporting hardware (e.g. antennas, cables, etc.) as the equipped UDOT fleet vehicles (Panasonic North America, 2020).

Figure 3 Field Test Vehicles

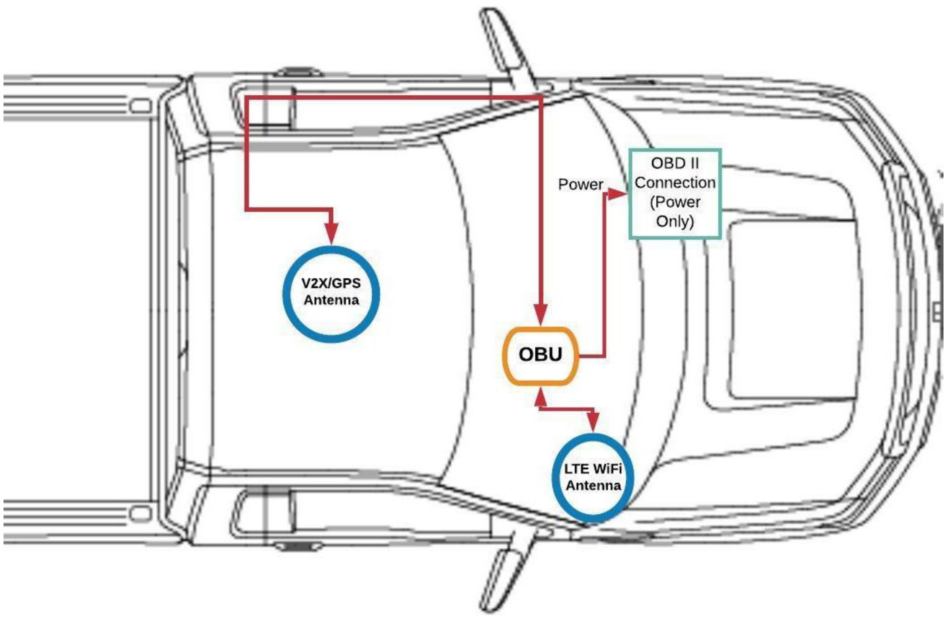
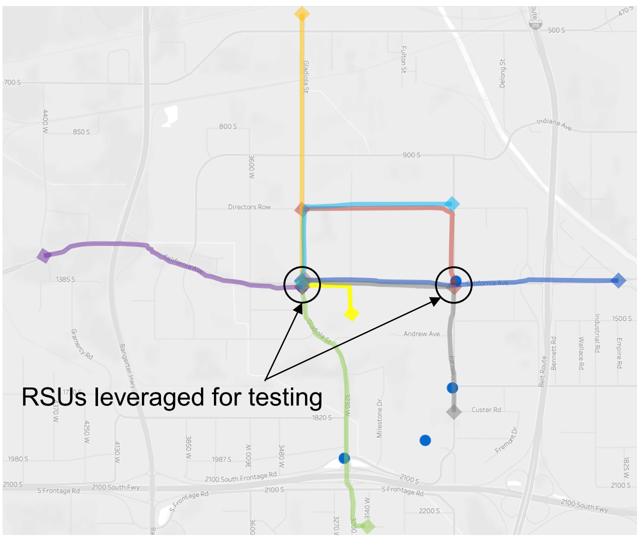


Figure 4 OBU Installation Diagram

RIS-9260 dual mode Kapsch RSUs utilized during the performance tests were already installed as part of the UDOT live environment (Panasonic North America, 2020) and configured with v1.16 firmware. In addition, these Kapsch RSUs supported single-mode as well as simultaneous dual mode with FCC-compliant, Omni-Air certified (DSRC only) units. During the test, security was disabled to ensure compatibility with the OBUs. In addition, the RSUs were configured as needed for the different stages of the test to DSRC only mode in channel 180, C-V2X only mode in channel 183, and simultaneous dual mode using channel 180 for DSRC and channel 183 for C-V2X.

Test Overview

The Panasonic team conducted field tests in Utah to analyze range of reception in the production deployment. The tests were broken into three primary groups for Line of Sight (LOS) and Non-Line of Sight (NLOS) urban tests with RSUs located at the intersections of 2700 West and Gladiola Street on California Avenue in Salt Lake City, in the vicinity of the UDOT Traffic Operations Center (TOC). A mountain corridor test was also conducted with RSUs deployed on Interstate 80 (I-80) from mile marker 127.96 to mile marker 146.83. Figure 5 and Figure 6 summarize the different locations in each test group.



Route	Start Location	End Location
Line of Site Range Test #1	Intersection of California Avenue and Gladiola Street End location	Intersection of California Avenue and Fortune Road
Line of Site Range Test #2	Intersection of California Avenue and Gladiola Street	End of Gladiola Street
Non Line of Site Range Test #1	Intersection of California Avenue and Gladiola Street	End of S3200W
Non Line of Site Range Test #2	Intersection of California Avenue and Gladiola Street	Intersection of W2210S and S3140W
Non Line of Site Range Test #3	Intersection of California Avenue and Gladiola Street	Intersection of California Avenue and S4400W
Non Line of Site Range Test #4	Intersection of California Avenue and Gladiola Street	Intersection of S2700W and Directors Row
Non Line of Site Range Test #5	Intersection of California Avenue and S2700W	Intersection of Gladiola Street and Directors Row
Non Line of Site Range Test #6	Intersection of California Avenue and Gladiola Street	Intersection of S2700W and Bridger Rd

Figure 5 TOC LOS and NLOS Test Locations

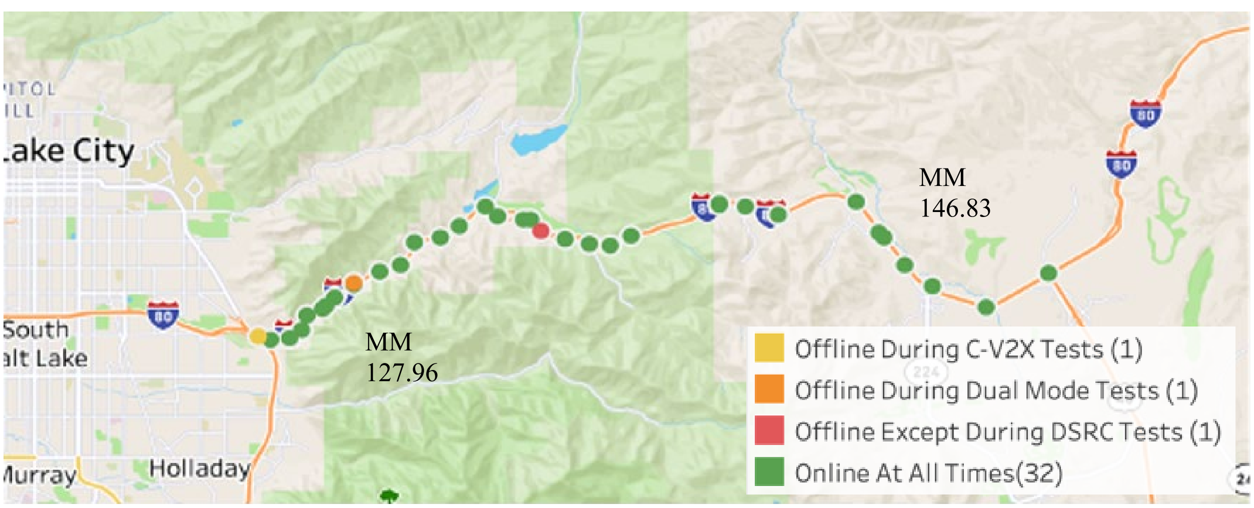


Figure 6 I-80 Test Location East of Salt Lake City (Note: Points show the 35 RSU locations on I-80)

Line of Sight (LOS) refers to “unimpeded view or access from one point to another point across a terrain or surface” (Dempsey, 2013). The LOS test locations were determined based on the availability of roadways with unobstructed line of sight to deployed RSUs in an urban setting, and each LOS route was at least 2.3 kilometers to ensure the full linear range would be observed. NLOS test locations were selected from roadways nearby the LOS tests in the same urban setting but with non-linear routes (e.g. routes with turns that caused obstruction of the RSU along the path). Each LOS and NLOS test utilized a single RSU for the assessment which was located at the start point of the test path. Finally, I-80 was leveraged as the mountain corridor test due to the 35 deployed RSUs, all of which were configured to collect BSMs for the analysis.

Performance testing took place from October 5-9, 2020. LOS and NLOS tests occurred the first two and a half days, followed by I-80 tests the second two and a half days. For each location, 5 round trips (loops) from the start point to the end point were made in each mode. This resulted in 5 loops with the RSU set to DSRC mode and the DSRC OBU mounted in the moving vehicle, 5 loops with RSU set to C-V2X mode and the C-V2X OBU mounted in the moving vehicle, and 5 loops with the RSU set to dual mode and both DSRC and C-V2X OBUs mounted in separate vehicles back to back to represent potential real-world deployment activity. Drivers were instructed to use constant speed in each test, and, when driving on the I-80 test loop, to stay within the middle lane whenever possible.

Once the testing was complete, all BSMs received by the deployed RSUs from the test OBUs were retrieved from the ecosystem database and analyzed to determine the range of reception for each mode, test, and loop. The primary method for calculating range leveraged Packet Error Rate (PER), as described in SAE J2945/1 and further detailed in Appendix B PER Calculation, to identify the first and last points where there were 5 consecutive seconds of BSMs received with PER less than 10%. The range was then computed as the linear distance between the first and last points for each test, loop, and mode by RSU, as illustrated in the shown in Figure 7. The range for messages transmitted in the opposite direction, sent by the RSU and received by the OBU was not evaluated since the initial UDOT deployment is focused on vehicle to infrastructure (V2I) communications and the use of BSM for collecting operational insights from the vehicle.

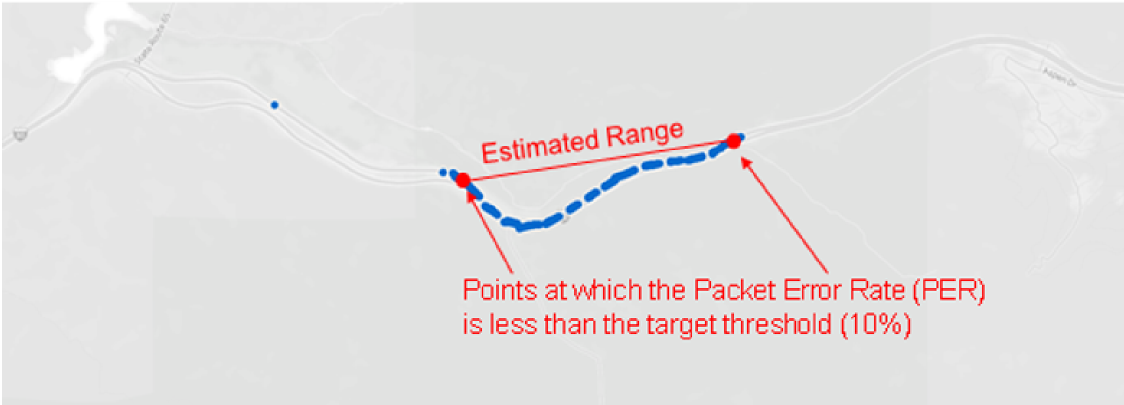


Figure 7 PER Range Calculation

Performance Test Results

The range of reception for each location in each mode for each loop was calculated using the PER method as explained above and then aggregated for this report. Figure 8 summarizes the average range of reception and Figure 9 summarizes the average standard deviation (SD) across locations for each test by mode. The LOS and NLOS tests were each conducted with a single RSU so the average range is calculated from the range observed on each loop, and the average standard deviation is simply the standard deviation across those loops. However, the I-80 test leveraged all operational RSUs on the corridor (Figure 5 shows which RSUs were included in each test), so the average range is the average of each RSU's range for each loop and the average standard deviation is the average of the standard deviation for each RSU. The standard deviation is calculated per RSU and then averaged rather than calculating standard deviation across all loops and all RSUs because it is expected that RSUs in different locations will have different ranges due to topography changes across the corridor. Figure 8 sugguests that C-V2X has greater average range of reception than DSRC for both single and dual mode by over 90% for LOS tests, over 33% for NLOS tests, and over 15% for I-80 tests. When comparing range across all RSUs regardless of test, C-V2X had approximately 25% greater range of reception compared to DSRC. Figure 8 suggests that C-V2X has lower variability (lower average SD) in 11 of 18 tests.

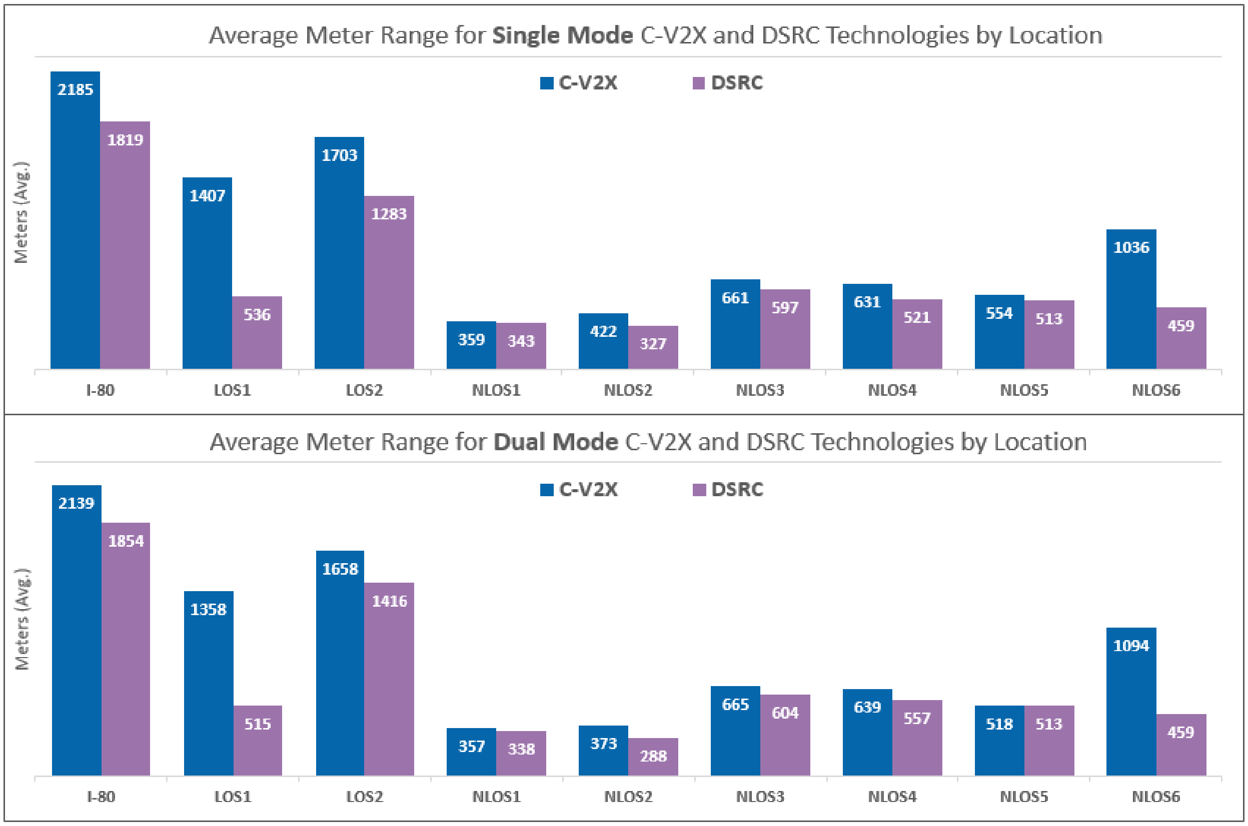


Figure 8 Performance Test Result Summary – Average Range of Reception

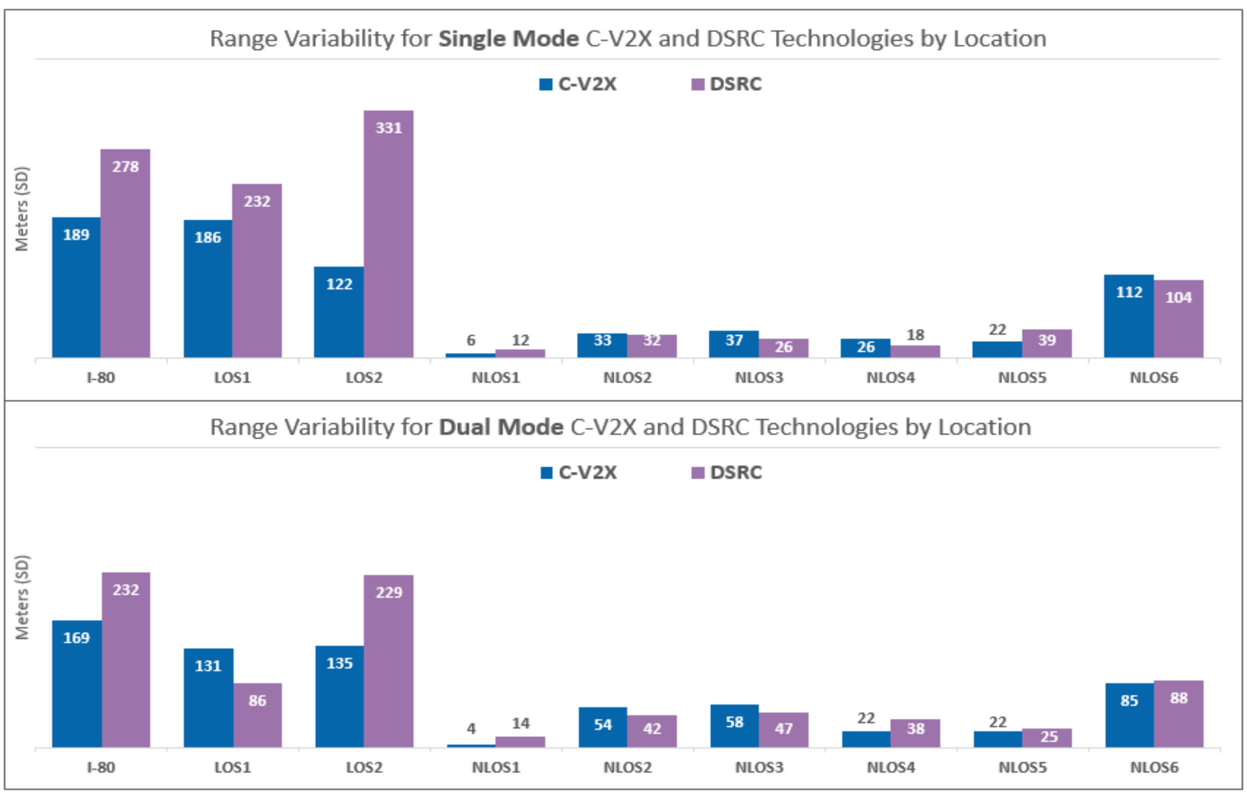


Figure 9 Performance Test Result Summary – Standard Deviation (SD) of Range of Reception

A series of independent-sample t-tests with p-value < 0.05 (Juliana Carvalho Ferreira, 2015) were conducted to compare range of reception between DSRC and C-V2X technologies across three groups (LOS, NLOS, and I-80) and two RSU modes (single and dual). Only RSUs that captured data in all modes are included in the analysis (i.e. if an RSU captured data for DSRC but was down for C-V2X and/or dual mode, then that RSU's data was excluded from the analysis). Results suggest that C-V2X has, with 95% confidence, a longer range of reception than DSRC for all conditions tested in this study. Table 1 presents the range difference between the two technologies for single mode and dual mode (C-V2X range minus DSRC range) as well as the percent difference (range difference divided by DSRC range). In the single mode tests, C-V2X communicated at a range that was 5 to 163 percent longer than DSRC, depending on the specific test configuration. Results were similar for dual mode tests. Only one test, NLOS5 in dual mode, produced a difference that was not statistically significant. Thus the null hypothesis that there is no difference in range of reception between DSRC and C-V2X is rejected because all other results indicate the greater C-V2X range was statistically significant with 95% confidence.

Table 1 PER Range Comparison (C-V2X to DSRC)

Test	Single Mode C-V2X Range Minus DSRC Range (Meters)	Single Mode Range Difference (Percentage)	Dual Mode C-V2X Range Minus DSRC Range (Meters)	Dual Mode Range Difference (Percentage)
LOS1	870.65	162.5%	843.29	163.7%
LOS2	420.04	32.7%	241.40	17.0%
NLOS1	16.09	4.7%	19.31	5.7%
NLOS2	94.95	29.1%	85.30	29.6%
NLOS3	64.37	10.8%	61.16	10.1%
NLOS4	109.44	21.0%	82.08	14.7%
NLOS5	40.23	7.8%	4.83*	0.9%
NLOS6	577.75	126.0%	635.69	138.6%
I-80	329.51	17.7%	289.48	15.3%

**Not statistically significant*

Additional Observations

Dual Mode Evaluation

In addition to comparing C-V2X and DSRC, a series of independent-sample t-tests were conducted using a p-value less than 0.05 (Juliana Carvalho Ferreira, 2015) to compare the range of reception difference between the RSUs in single mode and RSUs in dual mode for both DSRC and C-V2X across the three tests (LOS, NLOS, and I-80). As with the above analysis, only RSUs that captured data in all modes are included. As shown in Table 2, 14 out of 18 comparisons had no statistically significant difference in dual mode and single mode range of reception for DSRC and C-V2X tests with 95%

confidence. This leads us to conclude that operating the RSU in dual mode has no significant negative effect on the range at which either DSRC or C-V2X receive data.

Table 2 Range of Reception Comparison between Single and Dual Mode RSUs

Test	DSRC Range Difference in Meters (single mode minus dual mode)	C-V2X Range Difference in Meters (single mode minus dual mode)
LOS1	20.92*	48.28*
LOS2	-133.58*	45.06*
NLOS1	4.83*	1.61*
NLOS2	38.62	48.28
NLOS3	-6.44*	-3.22*
NLOS4	-35.41	-8.05*
NLOS5	0.00*	35.41
NLOS6	0.00*	-57.94*
I-80	-27.26*	12.77*

**Not statistically significant*

Alternate Range Calculations

While PER is the standard method for evaluating performance, calculation of PER relies on the BSM transmitted from the OBU to contain a consistent ID throughout the testing period in order to accurately order BSMs and identify missing packets. Although the Utah environment was altered to provide a consistent ID for this set of tests, having a consistent ID is not possible in most live environments with security enabled, as a rotating temporary ID is a key part of OBU security architecture. Therefore, additional calculations were performed using two alternate methods to compare results with the preferred PER method to determine if alternate calculations may be possible to measure RSU range of reception in such live environment settings rotating IDs.

First, a maximum receive range was calculated using the minimum and maximum latitude and longitude observed without removing any of the locations where PER exceeded allowable values,, as explained in Appendix C Other Calculations. Figure 10 below summarizes the results of the maximum observed range by test by mode, with the maximum range among all tests for both technologies occurring on the I-80 route.

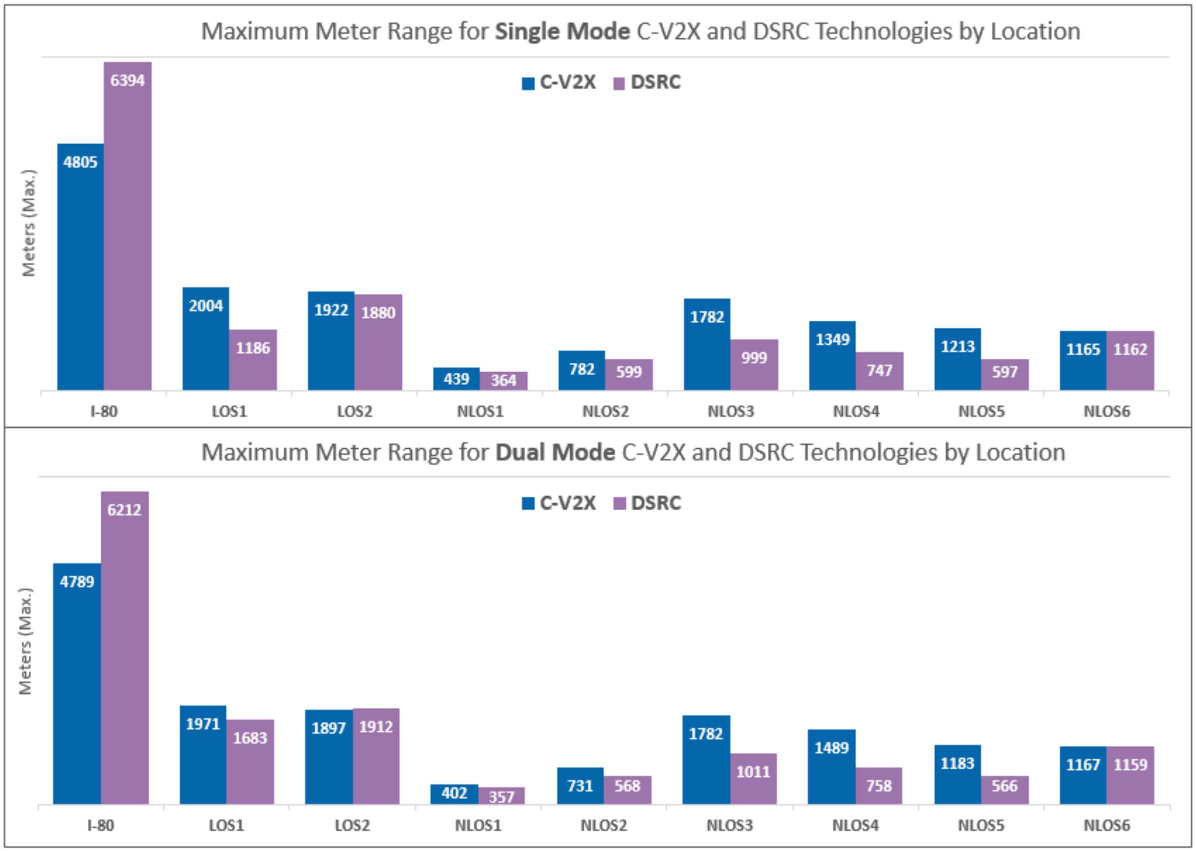


Figure 10 Maximum Observed Range Summary

Due to inclusion of points outside the reliable range (i.e. PER greater than 10%), results from this method are substantially different than the PER method and in some cases produce different conclusions. However, these “outliers” are not as useful for planning and operational purposes because of the higher rate of error, which could negatively impact system reliability and effectiveness. As an example, Figure 11 shows maps of the BSMs received at the maximum range calculated for DSRC (in orange dots) and C-V2X (in blue dots) from one RSU during the I-80 test and how the outliers (circled area) impact those results with inconsistent data collection on different loops.

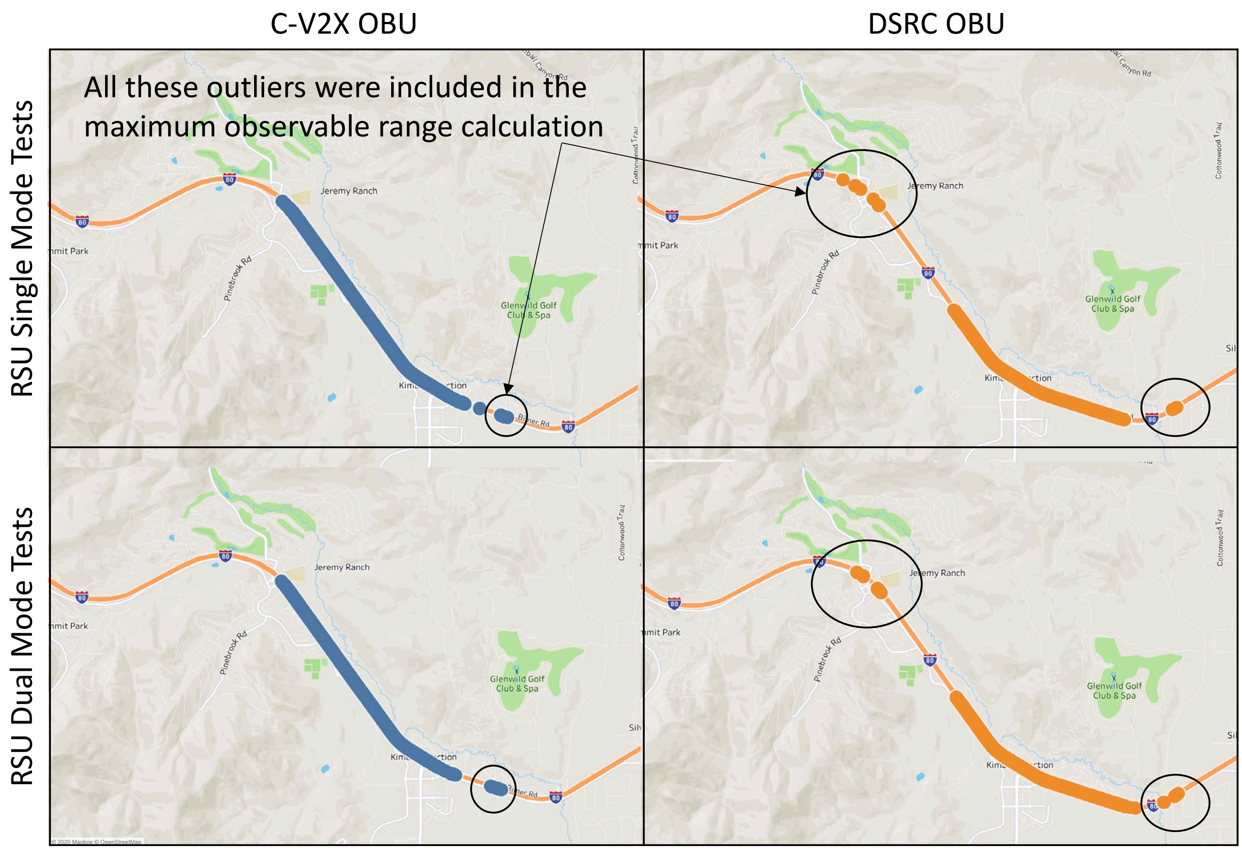


Figure 11 Maximum Observed Range Individual BSM Map

In an attempt to more accurately reflect the PER results, the points with the most extreme 5% of latitude and longitude values were removed and the remaining points were analyzed for range, as described in Appendix C Other Calculations. Figure 12 shows the average range of reception for each test location by mode calculated with this 95/05 percentile method.

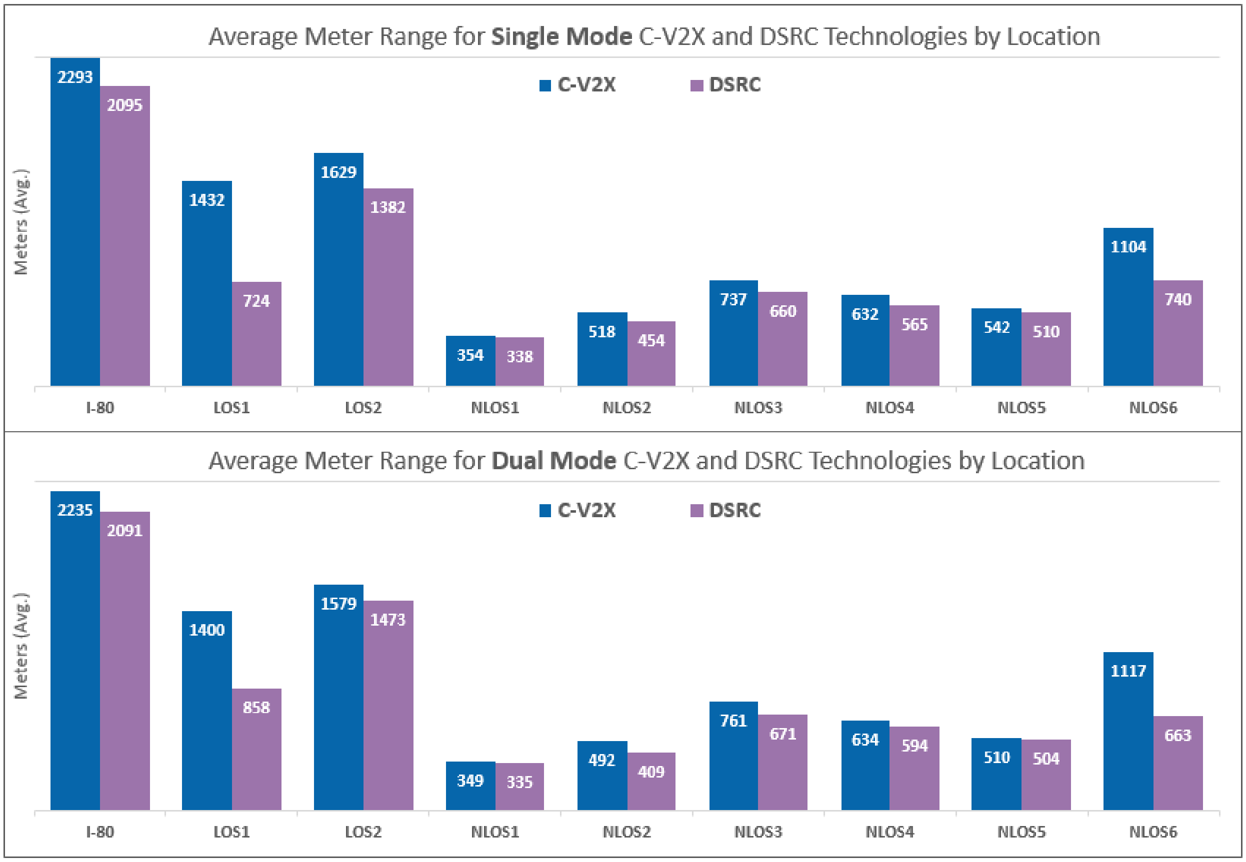


Figure 12 95/05 Percentile Method Range Summary – Average

Comparing the results from this method with the PER results, the range values are much closer than the maximum observable range method. A series of independent-sample t-tests with p-value < 0.05 (Juliana Carvalho Ferreira, 2015) were conducted to compare the range difference between the PER and the 95/05 percentile methods for both DSRC and C-V2X across the three tests (LOS, NLOS, and I-80) and two RSU modes (single and dual) by calculating 95/05 percentile results minus the PER results. As with the previous analyses, only RSUs that captured data in all modes are included. Based on the results in Table 3, the 95/05 percentile calculation produces a longer range than the PER method in 16 out of 22 statistically significant results. Because only 14 out of 36 results are not statistically significant, results from the 95/05 percentile method and the PER method cannot be considered equivalent (i.e: statistically insignificant in difference). Therefore, the percentile method is more accurate than the maximum range calculation but not equivalent to the PER calculation result.

Table 3 Range of Reception Comparison between PER method and 95/05 Percentile Method

Test	DSRC in Single Mode (Meters)	DSRC in Dual Mode (Meters)	C-V2X in Single Mode (Meters)	C-V2X in Single Mode (Meters)
LOS1	188.29	342.79	25.75*	41.84*
LOS2	48.28*	57.94*	-74.03	-78.86
NLOS1	-4.83*	-1.61*	-6.44	-8.05*
NLOS2	127.14	120.7	96.56	117.48
NLOS3	62.76	67.59*	75.64	96.56*
NLOS4	43.45	35.41	1.61*	-4.83*
NLOS5	-3.22*	-9.66	-11.27	-8.05
NLOS6	283.24	204.39	67.59*	20.92*
I-80	260.71	239.79	107.83	99.78

**Not statistically significant; Range difference calculated by (Percentile results - PER results)*

Market Research

Besides performance testing on real-world range of reception, other comparison metrics such as device market adoption, compliance, and availability were also researched for RSU and OBU suppliers of DSRC and C-V2X to support the assessment of deployment timing with each technology.

Adoption Research

The Federal Communication Commission (FCC) is an independent U.S. government agency overseen by Congress that "regulates interstate and international communications by radio, television, wire, satellite, and cable" in US jurisdictions, including "managing and licensing the electromagnetic spectrum for commercial users and for non-commercial users" (Licensing, 2020). C-V2X is currently designated as experimental by the FCC, and therefore licenses are required for every RSU and OBU deployed, whereas DSRC licenses are only required for RSUs. The DSRC licenses contains the information for buildout date, which allows us to understand whether the license is actively deployed. For C-V2X experimental license, there is no specific information regarding buildout, and the actively deployed licenses are filtered based on the whether the expiration date is passed or not when retrieving the data. Based on the FCC's Universal Licensing System (ULS) data, an analysis was conducted of registered C-V2X and DSRC licenses. As of Feburary 2021, according to the ULS data, 13% of actively deployed C-V2X (experimental) licenses were obtained by State entities (such as Utah Department of Transportation) and 87% of actively deployed C-V2X (experimental) licenses were obtained by Private Firm entities (such as Panasonic Corporation of North America). DSRC licenses, on the other hand, were 51% obtained by State entities, 37% by City/County entities (such as City of Salt Lake City), and 12% by Private Firm entities (see Figure 13 and Figure 14). Because of the different reporting requirements for C-V2X and

DSRC, the increase in private firms with C-V2X licenses may include OBU manufacturers which are not required to obtain DSRC licenses.

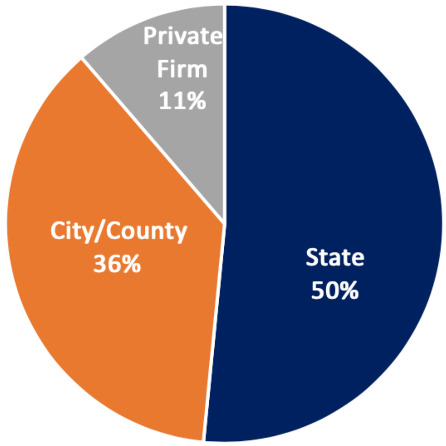


Figure 13 Distribution for FCC Licensed and Actively Deployed DSRC RSUs

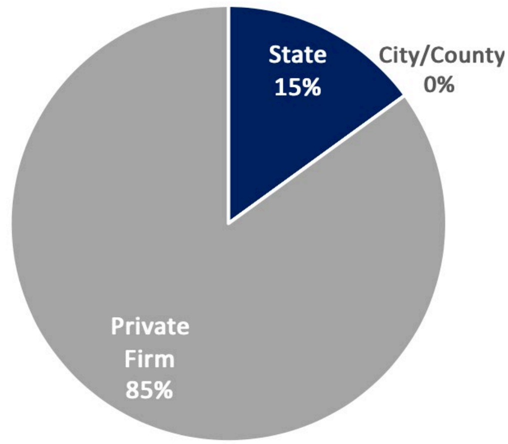


Figure 14 Distribution for FCC Licensed and Actively Deployed C-V2X RSUs

Due to the differences in license requirements for DSRC and C-V2X, it is not possible to make a direct comparison of quantities of licenses. However, an analysis was performed on location information registered on the FCC ULS database (Figure 15), and as of November 2020 15 states have C-V2X licenses registered within their boundaries compared to 27 states with DSRC licenses registered. Of the states with DSRC, 21 have active DSRC deployment (similar metrics are not available for C-V2X). There are 14 states with both C-V2X and DSRC licenses registered.

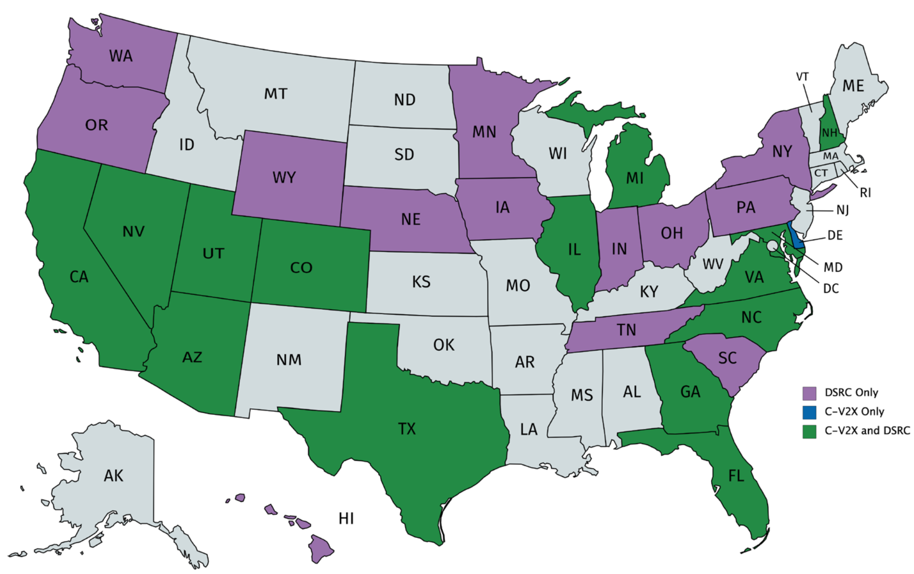


Figure 15 Adoption Distribution for C-V2X and DSRC in U.S.

Finally, an analysis of licenses over time was conducted also using FCC ULS data. Figure 16 summarizes the number of licenses year over year for DSRC and C-V2X. Again, the exact quantities of licenses cannot be compared due to differences in regulations for DSRC and C-V2X. Partial data for 2021 was excluded.

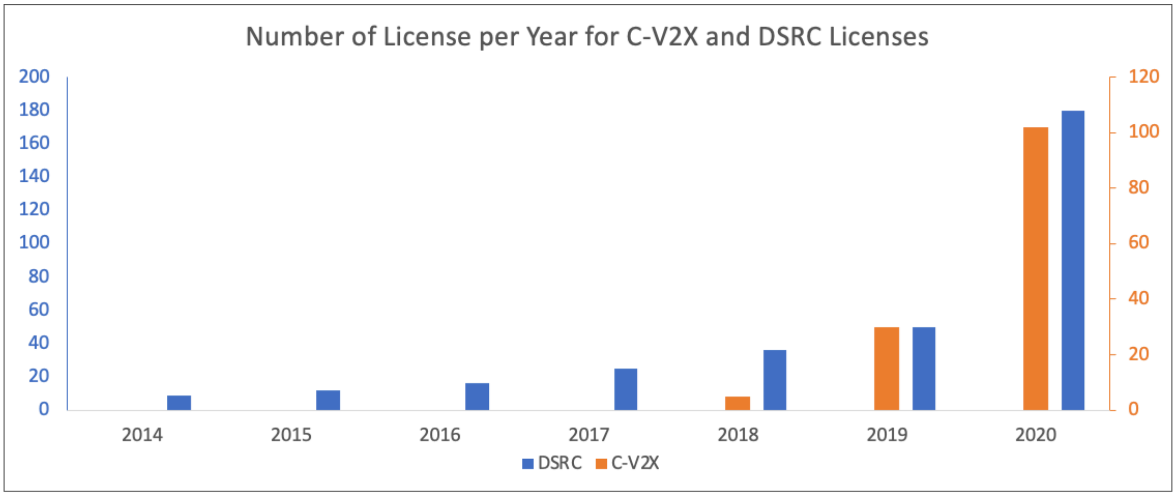


Figure 16 Number of License per Year for C-V2X and DSRC Licenses

Vendor Research

Vendor research was also conducted for RSUs and OBUs, with primary information coming from the official datasheets provided on the vendors' official websites. Of the vendors researched, 15 offer DSRC RSUs in the US, and 13 offer C-V2X RSUs in the US, with 12 of them providing both options. 16 vendors were identified offering DSRC OBUs in the US, and 15 vendors were identified offering C-V2X OBUs in the US, with 13 of them providing both options. It is important to note that multiple OBU vendors work as tier 1 suppliers directly for automotive manufacturers whose units are not commercially available and therefore not included in the OBU list.

Several compliance and regulatory restrictions are implemented for vendors in the Connected Vehicle industry to follow. Organizations, such as OmniAir Consortium and Federal Communication Commission (FCC), provide RSU and OBU device certifications and compliance in DSRC and/or C-V2X. The FCC regulates interstate and international communications by radio, television,wire,satellite, and cable in all 50 states, the District of Columbia and U.S territories (Overview, n.d.). The FCC is responsible to "license DSRC Roadside Units (RSUs), communication units that are fixed along the roadside, under subpart M (Intelligent Transportation Radio Service) of Part 90 of the Commission's Rules" and "license On-Board Units (OBUs), in-vehicle communications units, by rule under new subpart L of Part 95 of our Rules" (Dedicated Short Range Communications (DSRC) Service, 2019, p. para.1). According to to FCC's

Dedicated Short Range Communications (DSRC) Service webpage – About section (2019), “On December 17,2003 the commission adopted a Report and Order establishing licensing and service rules for the Dedicated Short Range Communications (DSRC) Service in the Intelligence Transportation Systems (ITS) Radio Service in the 5.850-5.925 GHz band(5.9 GHz band)” (Dedicated Short Range Communications (DSRC) Service, 2019, p. para.3). More recently, the Federal Communications Commission voted in November 2020 “to split the 75 megahertz of formerly-DSRC spectrum at 5.850-5.925 GHz, allocating the lower 45 megahertz of the band for unlicensed use and the upper 30 megahertz for intelligent transportation systems that must use C-V2X technology” after an appropriate transition period. (Hill, 2020).

OmniAir is an association that promotes “interoperability and certification for connected vehicles, ITS, and transportation payment systems” (Organization - OmniAir, 2020) by certifying the connected vehicle device has “undergone bench and field testing to verify that test cases and protocol attributes follow standards and specifications developed and approved through OmniAir Certification Process and Working Groups for Conformance & Interoperability” (Connected Vehicle Certification, 2020). Some example standards tested by OmniAir include, but are not limited to:

1. IEEE 802.11:2012 (802.11p) Physical Layer (PHY) & MAC (Transmit & Receive, Power & Sensitivity);
2. SAE J2735:2015 Message Dictionary (BSMs for OBUs and BSMs (Rx), SPaT, MAP & TIMs for RSUs);
3. USDOT FHWA-JPO-17-589:2017 RSU 4.1 (Packaging Environment Attributes, Data Logging, SNMP Commands, Time Sources accuracy, SPaT/MAP/WSA Messaging, Immediate Forwarding/Store&Repeat) for RSU (Connected Vehicle Certification, 2020).
4. C-V2X Certification Program for test equipment qualification and laboratory authorization (target launch in December 2020) (OmniAir Working Groups Approve New Policies and Test Cases, 2020).

Table 4 below summarizes the RSU and OBU vendors identified for each mode, including the compliance and certification status of the associated units. No FCC certification information is listed for OBUs because it is not publicly available and requires direct inquiry to the vendor. In addition, the OmniAir Connected Vehicle certification process is currently only available for DSRC-V2X devices (Connected Vehicle Certification, 2020).

Table 4 V2X Vendors with Certification and Compliance (X=Available, O=OmniAir Certified, F=FCC Compliant)

Vendor	DSRC RSU	DSRC OBU	C-V2X RSU	C-V2X OBU
Applied Information (Applied Information Inc., 2020)	X		X	
Askey (Askey, 2020)	X	X	X	X
Bosch (Bosch, 2020)		X		X
Chemtronics (Chemtronics, 2019)	X O	X		X
Codha (Codha Wireless, 2020)	X F	X	X	X
Commsignia (Commsignia, 2020)	X O	X O	X	X
CTAG (CTAG, n.d.), (CTAG, n.d.)			X	X
Danlaw (Danlaw, 2019)	X O F	X O	X F	
Ficosa (Ficosa, 2020)		X		X
Genvict (Genvict, 2020)	X	X	X	X
INTERSECT / Orange Traffic (Intersect -IOT, 2018)	X O	X		X
iSmartWays (iSmartWays, 2020)	X	X	X	X
Kapsch (Kapsch, 2020)	X O F		X F	
LaCroix City (Lacroix City, 2019)		X		
Lear (OmniAir Consortium, 2020)	X O	X O		X
Neusoft (Neusoft, 2020)	X		X	X
Savari (Savari, 2020), (Savari, 2020)	X F	X O	X	X
Siemens (Siemens, 2020)	X O		X	
SiriusXM (OmniAir Consortium, 2020)		X O		
Unex (Unex, 2020), (Unex, 2020)	X	X	X	X
Valeo (Valeo, 2019)		X		X

Conclusions

Findings from this assessment of DSRC and C-V2X range of receipt in Utah are summarized below.

- In over 99% of C-V2X tests and in over 97% of DSRC tests, the range of reception exceeded the nominally expected range of 300 meters in a single direction or 600 meters in both directions.
- Based on the assessment of DSRC and C-V2X in a live environment in Utah, the C-V2X OBU to RSU range of reception was longer than the DSRC OBU to RSU range of reception in all line of sight, non-line of sight, and mountain corridor tests with statistically significant results in all but one test. In the single mode tests, C-V2X communicated at a range that was 5 to 163 percent longer than DSRC, depending on the specific test configuration.
- Dual mode tests showed similar results, and the OBU to RSU range of reception performance was not statistically different for single and dual mode RSU configurations for both C-V2X and DSRC, leading us to conclude that dual mode operation resulted in no significant decrease in range of reception .

- Two alternate RSU range of reception calculations were examined during this study in order to identify a suitable procedure that can be applied to live environments with rotating temporary IDs, but both methods produced statistically different results than the PER calculation, so neither can reliably replace the PER method.

Findings from the market research on DSRC and C-V2X vendors are summarized below.

- Out of the 28 states with V2X licenses registered with the FCC, 46% have DSRC only, 4% have C-V2X only, and 50% have both DSRC and C-V2X. Both technologies are showing an increase in the number of licenses every year.
- Of the 21 vendors identified as providing aftermarket V2X hardware to the US market, 15 offer DSRC RSUs (71%), 16 offer DSRC OBUs (76%), 13 offer C-V2X RSUs (62%), and 15 offer C-V2X OBUs (71%).

Based on these findings, it can be concluded that C-V2X and DSRC are both feasible deployment options from a market adoption and availability standpoint. Both DSRC and C-V2X meet minimum range of receipt requirements. Furthermore, since the FCC has recently determined that C-V2X will replace DSRC in V2X applications, it is useful to know that C-V2X offers a greater OBU to RSU range of reception and lower variability than DSRC with the units included in this test. Finally, a number of future considerations based on lessons learned from this project have been captured, and are presented in the next section.

Future Testing

Multiple ideas were presented while defining the scope of this project, and although not prioritized for execution in this report, they are captured below for consideration in future testing.

- Testing additional channels for C-V2X and/or DSRC
- Testing bi-directional communication (e.g. adding RSU to OBU transmissions)
- Increasing data elements populated in the test vehicle BSMs
- Increasing number of vehicles/OBUs in the test
- Implementing security during the test (possibility may exist with pilot certificates that does not preclude fixing temporary ID)
- Testing additional environments (e.g. geographies and weather conditions)
- Testing different output power levels on the OBUs

Future Analysis

After completing data analysis defined in this report, several lessons learned and suggestions for future analysis were identified and captured below.

- Adding analysis of PER across the entire range per RSU to check for gaps in coverage and consistency of OBU to RSU range of reception
- Analyzing range as distance from the RSU to the furthest point with acceptable PER instead of considering range as the distance between the extreme points with acceptable PER (this method may also enable anonymous range analytics without deviating from the preferred PER approach since the alternative calculations explored in this analysis were statistically different than the PER results).

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Appendix A Detailed Results by RSU

Table A1 Average Range of Reception for DSRC and C-V2X in Single and Dual Mode in I-80 Tests

Test	RSU Location	RSU Mode	OBU Mode	Avg. Distance (Meters)	Notes
I80	I-80 & I-215 MM127.96	cv2x	cv2x	N/A	RSU Offline
I80	I-80 & I-215 MM128.21	cv2x	cv2x	1541.75	
I80	I-80 & I-215 MM128.62	cv2x	cv2x	1337.36	
I80	I-80 East MM128.86	cv2x	cv2x	1202.18	
I80	I-80 West MM129.21	cv2x	cv2x	1429.09	
I80	I-80 East MM129.54	cv2x	cv2x	1413	
I80	I-80 West MM129.64	cv2x	cv2x	1636.7	
I80	I-80 East MM129.89	cv2x	cv2x	1488.64	
I80	I-80 & Pharaohs Glen MM130.36	cv2x	cv2x	1680.15	
I80	I-80 & Pharaohs Glen MM130.38	cv2x	cv2x	2088.92	Not Included in Analysis due to RSU offline during Dual Mode Tests
I80	I-80 East MM130.97	cv2x	cv2x	1398.52	
I80	I-80 West MM131.41	cv2x	cv2x	1598.07	
I80	I-80 & Mt. Aire Caynon MM131.99	cv2x	cv2x	1390.47	
I80	I-80 & Parleys Creek MM132.53	cv2x	cv2x	2399.53	
I80	I-80 MM133.00	cv2x	cv2x	1865.23	
I80	I-80 & SH-65 MM133.62	cv2x	cv2x	2690.82	
I80	I-80 & SH-65 MM133.90	cv2x	cv2x	1269.77	
I80	I-80 MM134.47	cv2x	cv2x	3278.23	
I80	I-80 MM134.55	cv2x	cv2x	1886.15	
I80	I-80 MM134.92	cv2x	cv2x	N/A	RSU Offline
I80	I-80 MM135.45	cv2x	cv2x	2460.68	
I80	I-80 & Lambs Canyon Rd MM135.96	cv2x	cv2x	2750.36	
I80	I-80 & Lambs Canyon Rd MM136.45	cv2x	cv2x	2496.09	
I80	I-80 MM136.94	cv2x	cv2x	3426.28	
I80	I-80 Parleys Ln Wildlife Overpass MM138.86	cv2x	cv2x	1948.91	
I80	I-80 Parleys Ln Wildlife Overpass MM138.89	cv2x	cv2x	2162.95	
I80	I-80 Parleys Ln MM139.40	cv2x	cv2x	1577.15	
I80	I-80 MM140.13	cv2x	cv2x	2864.63	
I80	I-80 & Homestead Rd MM141.80	cv2x	cv2x	3316.85	
I80	I-80 MM142.60	cv2x	cv2x	2991.76	

Test	RSU Location	RSU Mode	OBU Mode	Avg. Distance (Meters)	Notes
I80	I-80 Exit 144 Chain-Up Area MM142.75	cv2x	cv2x	3239.6	
I80	I-80 Exit 144/145 MM143.50	cv2x	cv2x	3395.71	
I80	I-80 MM144.20	cv2x	cv2x	3114.07	
I80	I-80 MM145.40	cv2x	cv2x	2927.39	
I80	I-80 & HWY-40/189 MM146.83	cv2x	cv2x	1860.4	
I80	I-80 & I-215 MM127.96	dsrc	dsrc	732.25	Not Included in Analysis due to RSU offline during C-V2X Mode Tests
I80	I-80 & I-215 MM128.21	dsrc	dsrc	1433.92	
I80	I-80 & I-215 MM128.62	dsrc	dsrc	1244.02	
I80	I-80 East MM128.86	dsrc	dsrc	984.92	
I80	I-80 West MM129.21	dsrc	dsrc	1213.44	
I80	I-80 East MM129.54	dsrc	dsrc	1314.83	
I80	I-80 West MM129.64	dsrc	dsrc	1235.97	
I80	I-80 East MM129.89	dsrc	dsrc	1207.01	
I80	I-80 & Pharaohs Glen MM130.36	dsrc	dsrc	1276.21	
I80	I-80 & Pharaohs Glen MM130.38	dsrc	dsrc	1361.5	Not Included in Analysis due to RSU offline during Dual Mode Tests
I80	I-80 East MM130.97	dsrc	dsrc	941.46	
I80	I-80 West MM131.41	dsrc	dsrc	1248.85	
I80	I-80 & Mt. Aire Caynon MM131.99	dsrc	dsrc	1231.15	
I80	I-80 & Parleys Creek MM132.53	dsrc	dsrc	2274	
I80	I-80 MM133.00	dsrc	dsrc	1646.35	
I80	I-80 & SH-65 MM133.62	dsrc	dsrc	1902.24	
I80	I-80 & SH-65 MM133.90	dsrc	dsrc	1081.48	
I80	I-80 MM134.47	dsrc	dsrc	3044.87	
I80	I-80 MM134.55	dsrc	dsrc	1615.78	
I80	I-80 MM134.92	dsrc	dsrc	2079.27	Not Included in Analysis due to RSU offline during Dual Mode Tests
I80	I-80 MM135.45	dsrc	dsrc	1771.88	
I80	I-80 & Lambs Canyon Rd MM135.96	dsrc	dsrc	2381.82	
I80	I-80 & Lambs Canyon Rd MM136.45	dsrc	dsrc	2972.45	
I80	I-80 MM136.94	dsrc	dsrc	2909.69	

Test	RSU Location	RSU Mode	OBU Mode	Avg. Distance (Meters)	Notes
I80	I-80 Parleys Ln Wildlife Overpass MM138.86	dsrc	dsrc	1630.26	
I80	I-80 Parleys Ln Wildlife Overpass MM138.89	dsrc	dsrc	1210.22	
I80	I-80 Parleys Ln MM139.40	dsrc	dsrc	1287.47	
I80	I-80 MM140.13	dsrc	dsrc	2182.27	
I80	I-80 & Homestead Rd MM141.80	dsrc	dsrc	3225.12	
I80	I-80 MM142.60	dsrc	dsrc	2610.35	
I80	I-80 Exit 144 Chain-Up Area MM142.75	dsrc	dsrc	2581.38	
I80	I-80 Exit 144/145 MM143.50	dsrc	dsrc	3147.87	
I80	I-80 MM144.20	dsrc	dsrc	2655.41	
I80	I-80 MM145.40	dsrc	dsrc	2481.6	
I80	I-80 & HWY-40/189 MM146.83	dsrc	dsrc	1549.79	
I80	I-80 & I-215 MM127.96	dual	cv2x	885.14	Not Included in Analysis due to RSU offline during C-V2X Mode Tests
I80	I-80 & I-215 MM128.21	dual	cv2x	1514.39	
I80	I-80 & I-215 MM128.62	dual	cv2x	1330.92	
I80	I-80 East MM128.86	dual	cv2x	1240.8	
I80	I-80 West MM129.21	dual	cv2x	1392.08	
I80	I-80 East MM129.54	dual	cv2x	1429.09	
I80	I-80 West MM129.64	dual	cv2x	1477.37	
I80	I-80 East MM129.89	dual	cv2x	1504.73	
I80	I-80 & Pharaohs Glen MM130.36	dual	cv2x	1688.2	
I80	I-80 & Pharaohs Glen MM130.38	dual	cv2x	N/A	RSU Offline
I80	I-80 East MM130.97	dual	cv2x	1424.27	
I80	I-80 West MM131.41	dual	cv2x	1599.68	
I80	I-80 & Mt. Aire Caynon MM131.99	dual	cv2x	1404.95	
I80	I-80 & Parleys Creek MM132.53	dual	cv2x	2391.48	
I80	I-80 MM133.00	dual	cv2x	1876.49	
I80	I-80 & SH-65 MM133.62	dual	cv2x	2732.66	
I80	I-80 & SH-65 MM133.90	dual	cv2x	1319.66	
I80	I-80 MM134.47	dual	cv2x	3289.49	
I80	I-80 MM134.55	dual	cv2x	1839.48	
I80	I-80 MM134.92	dual	cv2x	N/A	RSU Offline
I80	I-80 MM135.45	dual	cv2x	2425.28	
I80	I-80 & Lambs Canyon Rd MM135.96	dual	cv2x	2666.68	

Test	RSU Location	RSU Mode	OBU Mode	Avg. Distance (Meters)	Notes
I80	I-80 & Lambs Canyon Rd MM136.45	dual	cv2x	2327.11	
I80	I-80 MM136.94	dual	cv2x	3411.8	
I80	I-80 Parleys Ln Wildlife Overpass MM138.86	dual	cv2x	1956.96	No BSM Captured During Loop 3-1
I80	I-80 Parleys Ln Wildlife Overpass MM138.89	dual	cv2x	2169.39	
I80	I-80 Parleys Ln MM139.40	dual	cv2x	1520.83	No BSM Captured During Loop 3-1
I80	I-80 MM140.13	dual	cv2x	2813.13	
I80	I-80 & Homestead Rd MM141.80	dual	cv2x	3376.4	
I80	I-80 MM142.60	dual	cv2x	2919.34	
I80	I-80 Exit 144 Chain-Up Area MM142.75	dual	cv2x	3093.15	
I80	I-80 Exit 144/145 MM143.50	dual	cv2x	3423.07	
I80	I-80 MM144.20	dual	cv2x	3122.12	
I80	I-80 MM145.40	dual	cv2x	3065.79	
I80	I-80 & HWY-40/189 MM146.83	dual	cv2x	1882.93	
I80	I-80 & I-215 MM127.96	dual	dsrc*	720.98	Not Included in Analysis due to RSU offline during C-V2X Tests
I80	I-80 & I-215 MM128.21	dual	dsrc*	1427.48	
I80	I-80 & I-215 MM128.62	dual	dsrc*	1252.07	
I80	I-80 East MM128.86	dual	dsrc*	994.57	
I80	I-80 West MM129.21	dual	dsrc*	1176.43	
I80	I-80 East MM129.54	dual	dsrc*	1310	
I80	I-80 West MM129.64	dual	dsrc*	1276.21	
I80	I-80 East MM129.89	dual	dsrc*	1184.47	
I80	I-80 & Pharaohs Glen MM130.36	dual	dsrc*	1271.38	
I80	I-80 & Pharaohs Glen MM130.38	dual	dsrc*	N/A	RSU Offline
I80	I-80 East MM130.97	dual	dsrc*	954.34	
I80	I-80 West MM131.41	dual	dsrc*	1260.11	
I80	I-80 & Mt. Aire Caynon MM131.99	dual	dsrc*	1231.15	
I80	I-80 & Parleys Creek MM132.53	dual	dsrc*	2204.8	
I80	I-80 MM133.00	dual	dsrc*	1617.39	
I80	I-80 & SH-65 MM133.62	dual	dsrc*	1836.26	
I80	I-80 & SH-65 MM133.90	dual	dsrc*	1105.62	

Test	RSU Location	RSU Mode	OBU Mode	Avg. Distance (Meters)	Notes
I80	I-80 MM134.47	dual	dsrc*	3130.17	
I80	I-80 MM134.55	dual	dsrc*	1459.67	
I80	I-80 MM134.92	dual	dsrc*	N/A	RSU Offline
I80	I-80 MM135.45	dual	dsrc*	1834.65	
I80	I-80 & Lambs Canyon Rd MM135.96	dual	dsrc*	2375.39	
I80	I-80 & Lambs Canyon Rd MM136.45	dual	dsrc*	3316.85	
I80	I-80 MM136.94	dual	dsrc*	2940.26	
I80	I-80 Parleys Ln Wildlife Overpass MM138.86	dual	dsrc*	1651.18	No BSM Captured During Loop 3-1
I80	I-80 Parleys Ln Wildlife Overpass MM138.89	dual	dsrc*	1227.93	
I80	I-80 Parleys Ln MM139.40	dual	dsrc*	1305.17	No BSM Captured During Loop 3-1
I80	I-80 MM140.13	dual	dsrc*	2336.76	
I80	I-80 & Homestead Rd MM141.80	dual	dsrc*	3099.59	
I80	I-80 MM142.60	dual	dsrc*	2748.75	
I80	I-80 Exit 144 Chain-Up Area MM142.75	dual	dsrc*	2724.61	
I80	I-80 Exit 144/145 MM143.50	dual	dsrc*	3524.45	
I80	I-80 MM144.20	dual	dsrc*	2639.32	
I80	I-80 MM145.40	dual	dsrc*	2386.65	
I80	I-80 & HWY-40/189 MM146.83	dual	dsrc*	1562.67	
LOS1	California Ave & Gladiola St	cv2x	cv2x	1406.56	Heavy freight traffic encountered during loop 1-1
LOS1	California Ave & Gladiola St	dsrc	dsrc	535.91	Heavy freight traffic encountered during entire test
LOS1	California Ave & Gladiola St	dual	cv2x	1358.28	
LOS1	California Ave & Gladiola St	dual	dsrc*	514.99	
LOS2	California Ave & Gladiola St	cv2x	cv2x	1702.68	
LOS2	California Ave & Gladiola St	dsrc	dsrc	1282.64	
LOS2	California Ave & Gladiola St	dual	cv2x	1657.62	
LOS2	California Ave & Gladiola St	dual	dsrc*	1416.22	
NLOS1	California Ave & Gladiola St	cv2x	cv2x	358.88	
NLOS1	California Ave & Gladiola St	dsrc	dsrc	342.79	
NLOS1	California Ave & Gladiola St	dual	cv2x*	357.27	
NLOS1	California Ave & Gladiola St	dual	dsrc	337.96	

Test	RSU Location	RSU Mode	OBU Mode	Avg. Distance (Meters)	Notes
NLOS2	California Ave & Gladiola St	cv2x	cv2x	421.65	Heavy freight traffic encountered during loops 1,2,3
NLOS2	California Ave & Gladiola St	dsrc	dsrc	326.7	Heavy freight traffic encountered during entire test
NLOS2	California Ave & Gladiola St	dual	cv2x*	373.37	
NLOS2	California Ave & Gladiola St	dual	dsrc	288.07	
NLOS3	California Ave & Gladiola St	cv2x	cv2x	661.44	
NLOS3	California Ave & Gladiola St	dsrc	dsrc	597.07	
NLOS3	California Ave & Gladiola St	dual	cv2x*	664.66	
NLOS3	California Ave & Gladiola St	dual	dsrc	603.5	
NLOS4	California Ave & Gladiola St	cv2x	cv2x*	630.86	
NLOS4	California Ave & Gladiola St	dsrc	dsrc	521.43	
NLOS4	California Ave & Gladiola St	dual	cv2x*	638.91	
NLOS4	California Ave & Gladiola St	dual	dsrc	556.83	
NLOS5	California Ave & 2700 W	cv2x	cv2x	553.61	
NLOS5	California Ave & 2700 W	dsrc	dsrc	513.38	Heavy freight traffic encountered during entire test
NLOS5	California Ave & 2700 W	dual	cv2x*	518.21	
NLOS5	California Ave & 2700 W	dual	dsrc	513.38	
NLOS6	California Ave & Gladiola St	cv2x	cv2x	1036.41	
NLOS6	California Ave & Gladiola St	dsrc	dsrc	458.66	
NLOS6	California Ave & Gladiola St	dual	cv2x	1094.35	
NLOS6	California Ave & Gladiola St	dual	dsrc*	458.66	

**Leading position during dual mode tests*

Appendix B PER Calculation

Introduction

The purpose of this appendix is to introduce how to order BSM messages and calculate the Packet Error Rate (PER) based on the ordered message, thus providing information on calculating the valid range of reception.

The PER calculation, which is an industry-accepted calculation, will be the primary method to generate the result. Based on SAE J2945/1, the PER is calculated between a pair of vehicles, the host vehicle (HV), and a given remote vehicle, RVi (in our case, a RSU). The system calculates the sliding-window PER over the interval, vPERInterval, at the end of the kth instance of vPERSubinterval (SAE Committee, 2016):

$$PER_i(k) = \frac{number\ of\ missed\ BSMs\ from\ RV_i\ during\ [w_{k-n+1}, w_k]}{total\ expected\ BSMs\ from\ RV_i\ during\ [w_{k-n+1}, w_k]}$$

Equation B1

In order to calculate the PER from BSMs received by each RSU, the messages need to be ordered in sequence as they were sent from the OBU by the time and position the message comes in (message count), then calculate how many messages were dropped in between based on the logic provided by SAE J2945/1. There are three data elements in the BSMs that can help with the sorting process:

1. sec_mark (SAE J2735):

   The DSRC second expressed in this data element consists of integer values from zero to 60999, representing the milliseconds within a minute (A leap second is represented by the value range 60000 to 60999).

2. msg_count (SAE J2735):

   The sequence number within a stream of messages with the same DSRCmsgID and from the same sender. A sender may initialize this element to any value in the range 0-127 when sending the first message with a given DSRCmsgID, or if the sender has changed identity (e.g. by changing its TemporaryID) since sending the most recent message with that DSRCmsgID. Depending on the application the sequence number may change with every message or may remain fixed during a stream of messages when the content within each message has not changed from the prior message sent. For this element, the value after 127 is zero.

The receipt of a non-sequential MsgCount value (from the same sending device and message type) implies that one or more messages from that sending device may have been lost, unless MsgCount has been re-initialized due to an identity change.

3. Timereceived:

   The Unix timestamp that records the time when the message was received by the cloud infrastructure, to the second level. This is not initially included in the SAE J2735 standard, and was created by AWS while receiving the message in the cloud infrastructure.

Problem Statement

When sorting the messages with **timereceived, sec_mark and msg_count**, it is important to note that sec_mark and msg_count will loop back to 0 when they reach the maximum value, which introduces the following challenges:

1. Msg_count encountered rollover, and the previous message's msg_count value (i.e: msg_count as 127) will be greater than the later message (msg_count as 0) when they are received in the same second, thus causing incorrect message order with msg_count;
2. Sec_mark encountered rollover, and the previous message's sec_mark value (i.e.: sec_mark as 59900) will be greater than the later message (sec_mark as 0) when they are received in the same second, thus cause incorrect message order with sec_mark.

To solve the issues above, the Panasonic team created a SQL query (see "PER Calculation SQL Query" of this appendix) to order the message sequence correctly and calculate the PER.

Logic Introduction

Figure B1 introduces the general processing steps for the PER calculation logic.

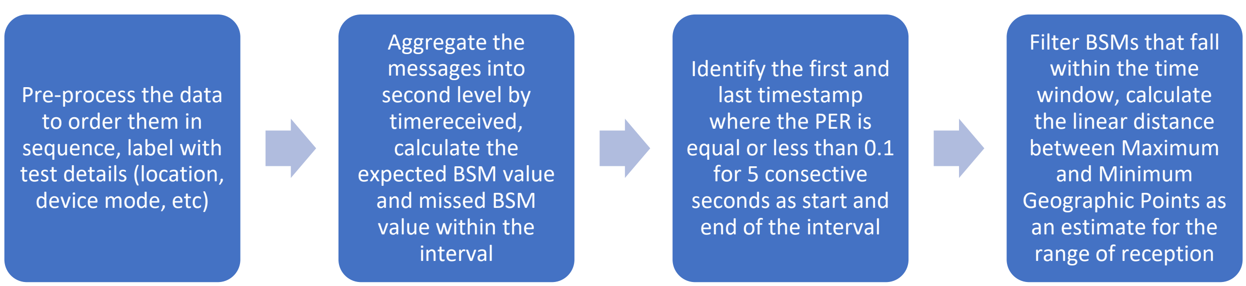

Figure B1 Analysis Process Steps for PER Calculation

And the detailed logic for Figure B1 is divided into 8 steps:

1. Identify the minimal sec_mark and msg_count within each second interval (timereceived) in order to identify if the rollover occurs, using the SQL code shown in
2. Figure B2.

```
SELECT
        timereceived,
        source,
        temp_id,
        MIN(sec_mark) AS min_sec_mark,
        MIN(msg_count) AS min_msg_count
FROM "gluedatabase-m7lipy10ft1z"."decoded-\
WHERE
        type = 'bsm' AND
        partition_1 = '2020' AND
        partition_2 = '08' AND
        partition_3 = '04' AND
        partition_4 = '01' AND
        source LIKE '%10.206.8.146%' AND
        temp_id = '5iXwSg=='
GROUP BY timereceived, source, temp_id
```

Figure B2 Step 1 – PER Calculation

3. Create **sec_mark_adjusted** by increasing the sec_mark values immediately after a rollover so that the messages are ordered correctly. This is accomplished by joining the minimal sec_mark and msg_count for each timereceived with the original message, when the message's sec_mark is less than 2000, and the minimal sec_mark for the timereceived window is less than 1000, then add 61000 (60000 + 1000 leap second reserved frame) to the sec_mark, as shown in . Two specific cases dealt with in this process are as follows:
    a. Choose 1000 as the boundary for minimal sec_mark within each timereceived because if the minimal sec_mark within the timereceived window is less than 1000, that means there may be a rollover for sec_mark within the second (based on 1000 ms = 1 second). In this case, those messages need to be marked out as the first step.
    b. Choose 2000 as the sec_mark boundary because the maximal delayed time for a message that comes in is less than 1 second plus 1 leap second range (which comes to the total of 2000 milliseconds).

```
WITH msg AS (
        SELECT
                m.timereceived,
                m.source,
                m.temp_id,
                CASE WHEN m.sec_mark >= 61000 THEN NULL ELSE m.sec_mark END AS sec_mark,
                CASE WHEN m.sec_mark < 2000 AND a.min_sec_mark < 1000 THEN m.sec_mark + 61000 WHEN
m.sec_mark >= 61000 THEN NULL ELSE m.sec_mark END AS sec_mark_adjusted,
```

Figure B3 Step 2 - PER Calculation

4. Create **msg_count_adjusted** by increasing the msg_count values immediately after a rollover so that the messages are ordered correctly. This is accomplished similar to the sec_mark_adjusted logic by joining the minimal msg_count and msg_count for each timereceived with the original message, when the message's msg_count is less than 20, and the minimal msg_count for the timereceived is less than 10, then add 128 to the msg_count, as shown in .
    a. Choose 10 as the boundary for minimal msg_count within each timereceived is because if the minimal msg_count within the timereceived window is less than 10, that means there may be a rollover for msg_count within the second (with the assumption of 10 messages/second). In this case, it is necessary to mark out those messages as the first step.
    b. Choose 20 as the msg_count boundary because the maximal delayed time for a message that comes in is less than 1 second plus 1 leap second range (which comes to the total of 20 messages).

```
                m.msg_count,
                CASE WHEN m.msg_count < 20 AND a.min_msg_count < 10 THEN m.msg_count + 128 ELSE
m.msg_count END AS msg_count_adjusted,
```

Figure B4 Step 3 – PER Calculation

5. Mark the row number for each BSM entry with **timereceived, sec_mark_adjusted and msg_count_adjusted**, as shown in **.**

```
                ROW_NUMBER() OVER(ORDER BY
                        m.timereceived,
                        CASE WHEN m.sec_mark < 2000 AND a.min_sec_mark < 1000 THEN m.sec_mark + 61000
WHEN m.sec_mark >= 61000 THEN NULL ELSE m.sec_mark END,
                        CASE WHEN m.msg_count < 20 AND a.min_msg_count < 10 THEN m.msg_count + 128 ELSE
m.msg_count END
                        ) AS rank,
                CASE WHEN m.sec_mark >= 61000 THEN 'check' ELSE NULL END AS sec_mark_issue
        FROM
```

Figure B5 Step 4 – PER Calculation

6. Calculate message difference as **msg_diff** by finding the message gaps between each message and its next message, as shown in Figure B6:
    a. When the msg_count_adjusted in the prior message is greater than the msg_count_adjusted in the following message, need to add 128 in the following message's msg_count_adjusted to avoid incorrect value, and then get the difference between the two msg_count_adjusted in order to get the msg_diff as message difference.
    b. When the msg_count_adjusted in the prior message is less than the msg_count_adjusted in the following message, simply subtract the latter with the prior msg_count_adjusted to get the msg_diff as the message difference.

```
SELECT
        m1.source,
        m1.temp_id,
        m1.timereceived,
        m1.sec_mark,
        m1.sec_mark_adjusted,
        m1.msg_count,
        m1.msg_count_adjusted,
        m1.rank,
        m1.sec_mark_issue,
        m2.timereceived AS timereceived_next,
        m2.sec_mark AS sec_mark_next,
        m2.sec_mark_adjusted AS sec_mark_adjusted_next,
        m2.msg_count AS msg_count_next,
        m2.msg_count as msg_count_adjusted_next,
        m2.rank AS rank_next,
        CASE WHEN m2.msg_count < m1.msg_count THEN m2.msg_count + 128 - m1.msg_count - 1 ELSE m2.msg_count
- m1.msg_count - 1 END AS msg_diff
```

Figure B6 Step 5 - PER Calculation

7. Calculate sum of messages received per timereceived (msg_received) and sum of msg_diff by each timereceived (msg_diff_sum), then calculate the PER rate (per) using: msg_diff_sum/ msg_total, as shown in .

```
SELECT timereceived, source,temp_id,
count(*) AS msg_received,
sum(msg_diff) AS msg_diff_sum,
(count(*)+sum(msg_diff)) AS msg_total,
round(sum(msg_diff)/(count(*)+sum(msg_diff)),2) as per
FROM (
```

Figure B 7 Step 6 - PER Calculation

8. Our current definition for outside the effective range of reception is when the PER is below or equal to 10% within the rolling 5-second windows for every 1 second. After the PERs are

calculated for each second (timereceived) per Step 6, we create a query to identify the timestamps that match the requirement above.

Then, we are using the query (as shown in Figure B8) to identify:

a. The first timestamp that all PER rates are below 0.1 (10%) for 5 consecutive seconds

b. The last timestamp that all PER rates are below 0.1 (10%) for 5 consecutive seconds

And return the timestamps, temp ID, and RSU to trace back in BSM for location information.

```
select temp_id, source, in(tr_1) as start_ts, max(tr_5) as end_ts from
(select a1.temp_id as temp_id,a1.source as source, a1.timereceived as tr_1,a5.timereceived as tr_5 from
per_calc a1
left join per_calc a2 on a1.timereceived+1=a2.timereceived
left join per_calc a3 on a3.timereceived=a2.timereceived+1 and a3.timereceived=a1.timereceived+2
left join per_calc a4 on a4.timereceived = a3.timereceived+1 and a4.timereceived=a2.timereceived+2 and
a4.timereceived=a1.timereceived+3
left join per_calc a5 on a5.timereceived=a4.timereceived+1 and a5.timereceived=a3.timereceived+2 and
a5.timereceived=a2.timereceived+3 and a5.timereceived=a1.timereceived+4
where a1.per<=0.1 and a2.per<=0.1 and a3.per<=0.1 and a4.per<=0.1 and a5.per<=0.1)a
group by a1.temp_id,a1.source
```

Figure B8 Step 7 - PER Calculation

9. Once the data has been processed, conduct the following steps to calculate the range of reception by:

    1. Filter the BSMs for those that fall within the first and last timestamp and get the minimum and maximum latitude and longitude of the filtered BSMs.
    2. Calculate the distance between the two points (minimum latitude, minimum longitude, and maximum latitude, maximum longitude) as an estimate for the range of reception for a certain RSU location.

Example Calculation

Here's an example of the whole calculation process. The BSMs that were received by RSU with ip 10.206.8.146 and sent by the OBU 5iXwSg== from 2020-08-04 01:00:00 UTC to 2020-08-04 01:59:59 UTC were included as the calculation example here.

The raw data before any calculation is listed as (ordered by timereceived, sec_mark, and msg_count):

timereceived	source	temp_id	msg_count	sec_mark
1596502800	{"ip":"10.206.8.146"}	5iXwSg==	4	0
1596502800	{"ip":"10.206.8.146"}	5iXwSg==	6	203
1596502800	{"ip":"10.206.8.146"}	5iXwSg==	3	59900
1596502801	{"ip":"10.206.8.146"}	5iXwSg==	16	1500
1596502802	{"ip":"10.206.8.146"}	5iXwSg==	20	1900
1596502803	{"ip":"10.206.8.146"}	5iXwSg==	29	2900
1596502803	{"ip":"10.206.8.146"}	5iXwSg==	35	3500
1596502803	{"ip":"10.206.8.146"}	5iXwSg==	36	3600
1596502804	{"ip":"10.206.8.146"}	5iXwSg==	41	4000
1596502805	{"ip":"10.206.8.146"}	5iXwSg==	50	4999
1596502805	{"ip":"10.206.8.146"}	5iXwSg==	51	5100
1596502805	{"ip":"10.206.8.146"}	5iXwSg==	56	5700
1596502806	{"ip":"10.206.8.146"}	5iXwSg==	59	5900
1596502807	{"ip":"10.206.8.146"}	5iXwSg==	67	6900
1596502807	{"ip":"10.206.8.146"}	5iXwSg==	69	7100
1596502808	{"ip":"10.206.8.146"}	5iXwSg==	83	8700
1596502809	{"ip":"10.206.8.146"}	5iXwSg==	86	8900

Figure B9 Sample Data Preview

The third row should be in the first row to reflect the correct order, and the incorrect order is due to the third message having a larger sec_mark than the first message, which matches the number 2 case in our problem statement.

In this case, the logic mentioned above needs to be implemented to process the data and place them into the correct order. The data after processing will be:

source	temp_id	timereceived	sec_mark	sec_mark_...	msg_count	msg_count...	rank
{"ip":"10.20...	5iXwSg==	1596502800	59900	59900	3	131	1
{"ip":"10.20...	5iXwSg==	1596502800	0	61000	4	132	2
{"ip":"10.20...	5iXwSg==	1596502800	203	61203	6	134	3
{"ip":"10.20...	5iXwSg==	1596502801	1500	1500	16	16	4
{"ip":"10.20...	5iXwSg==	1596502802	1900	1900	20	20	5
{"ip":"10.20...	5iXwSg==	1596502803	2900	2900	29	29	6
{"ip":"10.20...	5iXwSg==	1596502803	3500	3500	35	35	7
{"ip":"10.20...	5iXwSg==	1596502803	3600	3600	36	36	8
{"ip":"10.20...	5iXwSg==	1596502804	4000	4000	41	41	9
{"ip":"10.20...	5iXwSg==	1596502805	4999	4999	50	50	10
{"ip":"10.20...	5iXwSg==	1596502805	5100	5100	51	51	11
{"ip":"10.20...	5iXwSg==	1596502805	5700	5700	56	56	12
{"ip":"10.20...	5iXwSg==	1596502806	5900	5900	59	59	13
{"ip":"10.20...	5iXwSg==	1596502807	6900	6900	67	67	14
{"ip":"10.20...	5iXwSg==	1596502807	7100	7100	69	69	15
{"ip":"10.20...	5iXwSg==	1596502808	8700	8700	83	83	16

Figure B10 Processed Sample Data Preview

Then the message difference between each message can be calculated as below:

c_mark_...	msg_count	msg_count...	rank	sec_mark_...	timereceiv...	sec_mark_...	sec_mark_...	msg_count...	msg_count...	rank_next	msg_diff
900	3	131	1	<null>	1596502800	0	61000	4	4	2	0
000	4	132	2	<null>	1596502800	203	61203	6	6	3	1
203	6	134	3	<null>	1596502801	1500	1500	16	16	4	9
00	16	16	4	<null>	1596502802	1900	1900	20	20	5	3
00	20	20	5	<null>	1596502803	2900	2900	29	29	6	8
00	29	29	6	<null>	1596502803	3500	3500	35	35	7	5
00	35	35	7	<null>	1596502803	3600	3600	36	36	8	0
00	36	36	8	<null>	1596502804	4000	4000	41	41	9	4
00	41	41	9	<null>	1596502805	4999	4999	50	50	10	8
99	50	50	10	<null>	1596502805	5100	5100	51	51	11	0
00	51	51	11	<null>	1596502805	5700	5700	56	56	12	4
00	56	56	12	<null>	1596502806	5900	5900	59	59	13	2
00	59	59	13	<null>	1596502807	6900	6900	67	67	14	7
00	67	67	14	<null>	1596502807	7100	7100	69	69	15	1
00	69	69	15	<null>	1596502808	8700	8700	83	83	16	13
00	83	83	16	<null>	1596502809	8900	8900	86	86	17	2

Figure B11 Message Difference From Sample Data - Preview

The visualization for the distributions for each BSMs by order rank is as below:

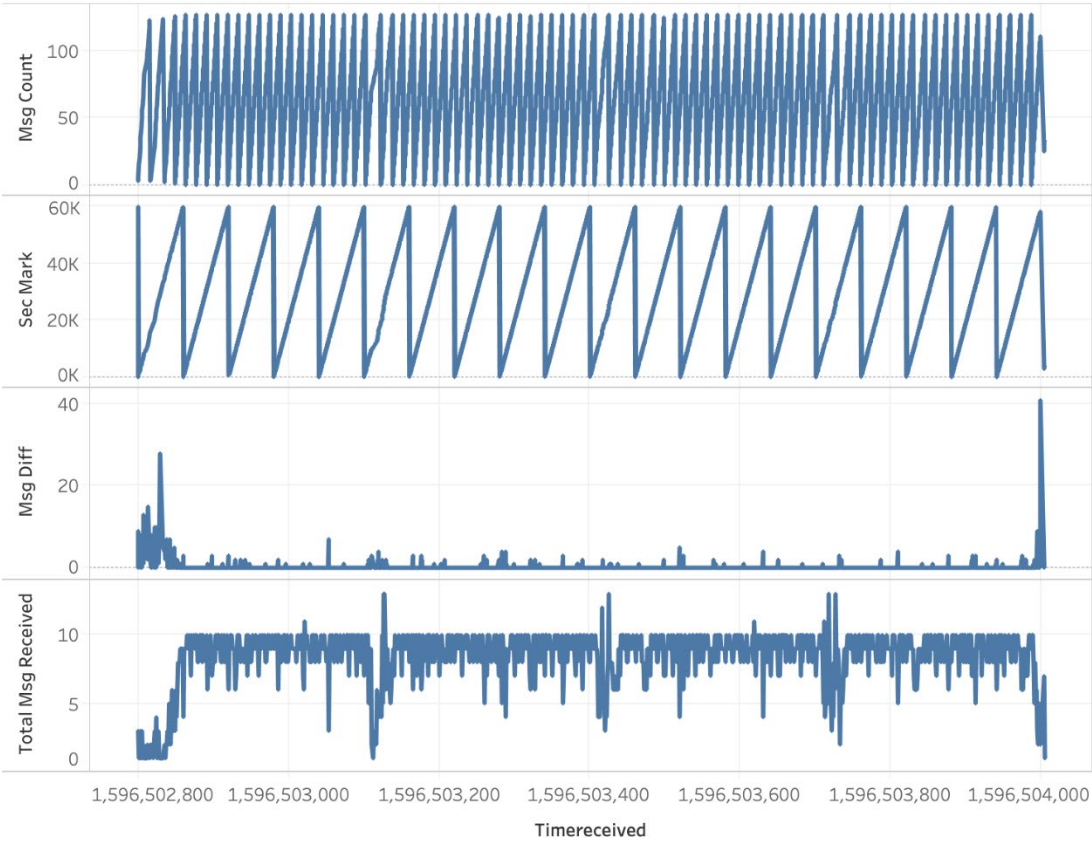

Figure B12 Visualization for Sample Data

In this visualization, it shows as timereceived increases, the rank for each message is increasing steadily, the message count (msg_count) and sec mark (sec_mark) are in wave shapes, which indicate the rollover mentioned above. The message difference (msg_diff) and total message received have a reversed relationship – with higher value of total message received in each second, there's lower msg_diff for each second interval.

Packet Error Rate (PER) can be then calculated for each second (timereceived) as the next step from the data above:

timereceived	source	temp_id	msg_received	msg_diff_sum	msg_total	per
1596502800	{"ip":"10.206.8.146"}	5iXwSg==	3	10	13	0.77
1596502801	{"ip":"10.206.8.146"}	5iXwSg==	1	3	4	0.75
1596502802	{"ip":"10.206.8.146"}	5iXwSg==	1	8	9	0.89
1596502803	{"ip":"10.206.8.146"}	5iXwSg==	3	9	12	0.75
1596502804	{"ip":"10.206.8.146"}	5iXwSg==	1	8	9	0.89
1596502805	{"ip":"10.206.8.146"}	5iXwSg==	3	6	9	0.67
1596502806	{"ip":"10.206.8.146"}	5iXwSg==	1	7	8	0.88
1596502807	{"ip":"10.206.8.146"}	5iXwSg==	2	14	16	0.88
1596502808	{"ip":"10.206.8.146"}	5iXwSg==	1	2	3	0.67
1596502809	{"ip":"10.206.8.146"}	5iXwSg==	1	4	5	0.8
1596502811	{"ip":"10.206.8.146"}	5iXwSg==	1	3	4	0.75
1596502812	{"ip":"10.206.8.146"}	5iXwSg==	2	5	7	0.71
1596502813	{"ip":"10.206.8.146"}	5iXwSg==	1	15	16	0.94
1596502815	{"ip":"10.206.8.146"}	5iXwSg==	2	11	13	0.85
1596502816	{"ip":"10.206.8.146"}	5iXwSg==	1	2	3	0.67
1596502817	{"ip":"10.206.8.146"}	5iXwSg==	2	3	5	0.6
1596502818	{"ip":"10.206.8.146"}	5iXwSg==	2	8	10	0.8
1596502820	{"ip":"10.206.8.146"}	5iXwSg==	1	3	4	0.75
1596502821	{"ip":"10.206.8.146"}	5iXwSg==	2	1	3	0.33
1596502822	{"ip":"10.206.8.146"}	5iXwSg==	3	10	13	0.77
1596502823	{"ip":"10.206.8.146"}	5iXwSg==	2	7	9	0.78
1596502824	{"ip":"10.206.8.146"}	5iXwSg==	4	6	10	0.6
1596502825	{"ip":"10.206.8.146"}	5iXwSg==	1	10	11	0.91
1596502826	{"ip":"10.206.8.146"}	5iXwSg==	2	4	6	0.67
1596502827	{"ip":"10.206.8.146"}	5iXwSg==	3	6	9	0.67
1596502828	{"ip":"10.206.8.146"}	5iXwSg==	1	8	9	0.89

Figure B13 Sample Data PER Results - Preview

And this is the PER across time:

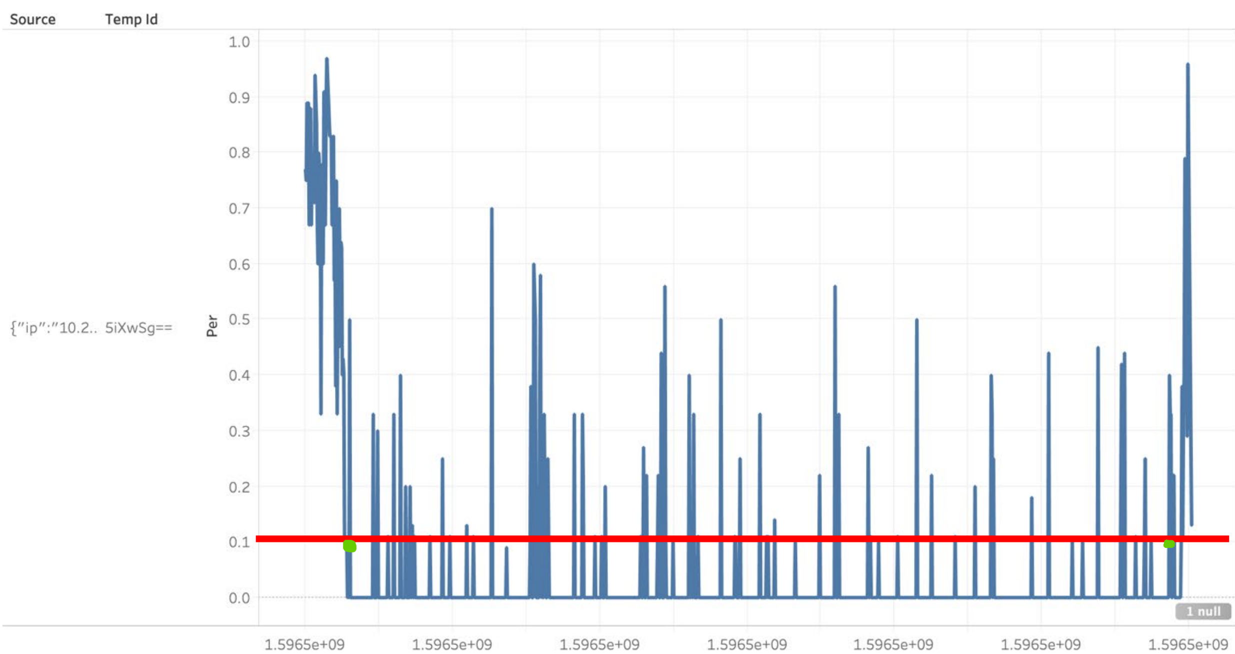

Figure B14 PER Distribution - Sample Data

With the pre-defined acceptable value of 10% (red line above), the PER valid interval (between the green dots above) can be identified. By filtering for only BSMs received between the green dots, receive range for this RSU can be calculated from the minimum and maximum latitude and longitude received within this window of time.

PER Calculation SQL Query

The following SQL queries were used to sort BSMs and calculate PER. The variables used in the query may vary based on different data in database (i.e: table name, filter conditions on time and IP).

```
WITH msg AS (
        SELECT
                m.timereceived,
                m.source,
                m.temp_id,
                CASE WHEN m.sec_mark >= 61000 THEN NULL ELSE m.sec_mark END AS sec_mark,
                CASE WHEN m.sec_mark < 2000 AND a.min_sec_mark < 1000 THEN m.sec_mark + 61000 WHEN
m.sec_mark >= 61000 THEN NULL ELSE m.sec_mark END AS sec_mark_adjusted,
                m.msg_count,
                CASE WHEN m.msg_count < 20 AND a.min_msg_count < 10 THEN m.msg_count + 128 ELSE
m.msg_count END AS msg_count_adjusted,
                ROW_NUMBER() OVER(ORDER BY
                        m.timereceived,
                        CASE WHEN m.sec_mark < 2000 AND a.min_sec_mark < 1000 THEN m.sec_mark + 61000
WHEN m.sec_mark >= 61000 THEN NULL ELSE m.sec_mark END,
                        CASE WHEN m.msg_count < 20 AND a.min_msg_count < 10 THEN m.msg_count + 128 ELSE
m.msg_count END
                        ) AS rank,
                CASE WHEN m.sec_mark >= 61000 THEN 'check' ELSE NULL END AS sec_mark_issue
        FROM
                "gluedatabase-m7lipy10ft1z"."decoded-v1" m LEFT JOIN (
                        SELECT
                                timereceived,
                                source,
                                temp_id,
                                MIN(sec_mark) AS min_sec_mark,
                                MIN(msg_count) AS min_msg_count
                        FROM "gluedatabase-m7lipy10ft1z"."decoded-v1"
                        WHERE
                                type = 'bsm' AND
                                partition_1 = '2020' AND
                                partition_2 = '08' AND
                                partition_3 = '04' AND
                                partition_4 = '01' AND
                                source LIKE '%10.206.8.146%' AND
                                temp_id = '5iXwSg=='
                        GROUP BY timereceived, source, temp_id
                ) a ON (m.timereceived = a.timereceived AND m.source = a.source AND m.temp_id = a.temp_id)
        WHERE
                m.type = 'bsm' AND
                m.partition_1 = '2020' AND
                m.partition_2 = '08' AND
                m.partition_3 = '04' AND
                m.partition_4 = '01' AND
                m.source LIKE '%10.206.8.146%' AND
                m.temp_id = '5iXwSg=='
        ORDER BY m.timereceived, m.sec_mark, m.msg_count
)
SELECT timereceived, source,temp_id,
count(*) AS msg_received,
sum(msg_diff) AS msg_diff_sum,
(count(*)+sum(msg_diff)) AS msg_total,
round(sum(msg_diff)/(count(*)+sum(msg_diff)),2) as per
FROM (
SELECT
        m1.source,
        m1.temp_id,
        m1.timereceived,
        m1.sec_mark,
        m1.sec_mark_adjusted,
        m1.msg_count,
```

```
        m1.msg_count_adjusted,
        m1.rank,
        m1.sec_mark_issue,
        m2.timereceived AS timereceived_next,
        m2.sec_mark AS sec_mark_next,
        m2.sec_mark_adjusted AS sec_mark_adjusted_next,
        m2.msg_count AS msg_count_next,
        m2.msg_count as msg_count_adjusted_next,
        m2.rank AS rank_next,
        CASE WHEN m2.msg_count < m1.msg_count THEN m2.msg_count + 128 - m1.msg_count - 1 ELSE m2.msg_count
- m1.msg_count - 1 END AS msg_diff
FROM
        msg m1 LEFT JOIN
        msg m2 ON (m1.rank = m2.rank - 1 AND m1.source = m2.source AND m1.temp_id = m2.temp_id)
ORDER BY m1.rank )aa
GROUP BY timereceived,source,temp_id ORDER BY timereceived
```

Valid Range:

```
select temp_id, source, in(tr_1) as start_ts, max(tr_5) as end_ts from
(select a1.temp_id as temp_id,a1.source as source, a1.timereceived as tr_1,a5.timereceived as tr_5 from
per_calc a1
left join per_calc a2 on a1.timereceived+1=a2.timereceived
left join per_calc a3 on a3.timereceived=a2.timereceived+1 and a3.timereceived=a1.timereceived+2
left join per_calc a4 on a4.timereceived = a3.timereceived+1 and a4.timereceived=a2.timereceived+2 and
a4.timereceived=a1.timereceived+3
left join per_calc a5 on a5.timereceived=a4.timereceived+1 and a5.timereceived=a3.timereceived+2 and
a5.timereceived=a2.timereceived+3 and a5.timereceived=a1.timereceived+4
where a1.per<=0.1 and a2.per<=0.1 and a3.per<=0.1 and a4.per<=0.1 and a5.per<=0.1)a
group by a1.temp_id,a1.source
```

Appendix C Other Calculations

Maximum range of reception was used to understand the technology extremes (e.g. maximum distance between all points received) and compare with the PER range calculation. The calculation uses the maximum and minimum geographic points received by each RSU in each mode for each test without removing any extreme values. The range is then calculated as the linear distance between the two points by the equation below (Meier, 2016), which returns a range estimate in miles.

$$\begin{aligned}
&\textit{Maximum Receivable Range} = 2 * 3960 * \textit{asin}(\textit{sqrt}(\\
&\quad (\sin(\text{radians}(([\text{Min Latitude}] - [\text{Max Latitude}]) / 2)))\text{^}2 + \\
&\quad \cos(\text{radians}([\text{Max Latitude}])) * \\
&\quad \cos(\text{radians}([\text{Min Latitude}])) * \\
&\quad (\sin(\text{radians}(([\text{Min Longitude}] - [\text{Max Longitude}]) / 2)))\text{^}2\ ))
\end{aligned}$$

Equation C1

In addition to the maximum range of reception and the PER calculation, a third method was leveraged to compute the 95/05 percentile range of reception, which is defined as finding the 5 percentile and 95 percentile values for the geographic points (latitude and longitude) to exclude extreme outliers then calculate the linear distance between the two points. Figure C1 illustrates the detailed concept and calculation. This method was assessed as a potential way to estimate range when PER is not possible, such as in a live environment with anonymous BSMs (e.g. non-fixed temporary IDs).

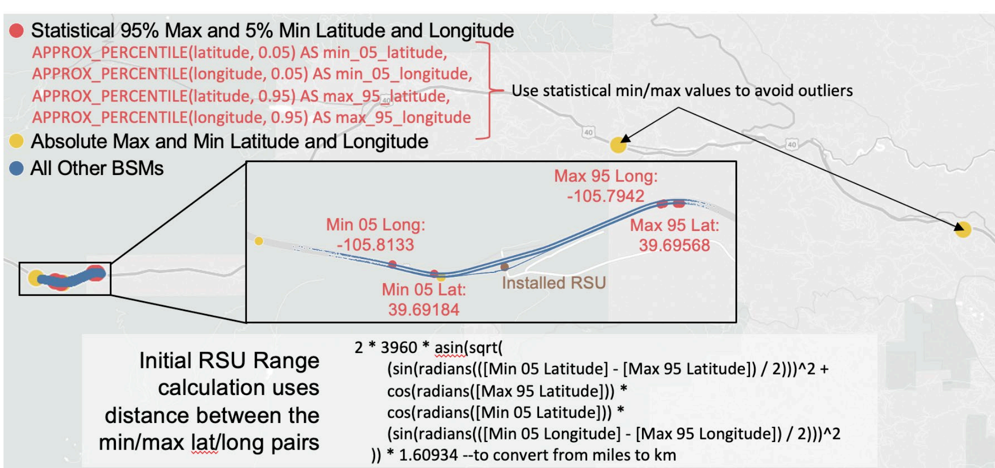

Figure C1 95/05 Percentile Range of Reception Calculation Concept and Calculation