Qualcomm Technologies, Inc.

C-V2X Congestion Control Study

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Disclaimer

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Revision history

Revision	Date	Description
AA	June 2020	Initial release

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1 Executive Summary

This document describes methods and results from the laboratory and the field assessment of Rel-14 LTE cellular vehicle-to-everything (C-V2X) technology performance in congested environments.

The test cases detailed in this report were designed to examine the effectiveness of the rate control congestion control for C-V2X defined in:

- *On-Board System Requirements for V2V Safety Communications* (SAE J2945/1)
- Draft of *On-Board System Requirements for LTE V2X V2V Safety Communications* (SAE J3161/1)

Tests were conducted on a baseline lab environment and at-scale in the field. Field tests were subsequently validated by a host of automakers and Qualcomm Technologies, Inc. (QTI) in a Crash Avoidance Metrics Partners (CAMP) LLC battery of tests (see *C-V2X Performance Assessment Project*).

All tests show that channel congestion protocols can be triggered and are effective. These tests prove that C-V2X communication can effectively deliver safety messages in congested environments.

1.1 Overview

To demonstrate C-V2X congestion control, scalable test setup architectures (lab and field tests) were designed to allow flexibility in testing. The Vehicular Congestion Test Rack (VeCTR) is a lab setup that enables the focused study of one host and one remote vehicle that experience a concurrent channel load generated by up to 576 emulated background devices. The field setup deploys eight moving vehicles under test, and 50 stationary background devices emulating up to 250 background devices on a test track of variable length.

Key performance indicators (KPIs) such as the packet error rate (PER), inter-packet gap (IPG) and inter-transmission time (ITT) were measured to provide a comprehensive view of system performance. These KPIs describe the "goodness" of a sequence of packets for vehicular safety applications and constitute the accepted radio access technology performance parameters necessary to deliver these short range broadcast messages. They are based on extensive legacy research described in *Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application* (DOT HS 812 014).

Rate control algorithms defined in Section 6.3.8 of SAE J2945/1 and SAE J3161/1 were used where the system schedules transmissions according to the computed input for performance comparison with and without rate control usage.

The simulation results presented in this document describe C-V2X performance under different conditions and show the reliability of C-V2X for safety applications. Results collected from the lab and field closely align to simulations, and validate C-V2X as a technology for vehicular safety in congested environments.

1.2 Objective

The objectives of the tests performed in this document validate the following:

- C-V2X works reliably in congested environments in laboratory and field tests.
- C-V2X is ready for commercial deployments by testing Day 1 safety use cases in simulated real-world situations.
- SAE J2945/1 and SAE J3161/1 congestion control protocols work as intended with C-V2X.

1.3 Test scope

The following tests were performed:

- Baseline assessment of C-V2X congestion control in the lab (starting with a small scale four-device setup)
- 5G Automotive Association (5GAA) and CAMP LLC based testing (scaling the number of devices to 50 physical devices and up to 600 devices in emulation mode)

These tests validate that C-V2X technology works at scale, and under congested environments. To accomplish this, lab tests were matched to conducted simulations prior to executing tests at a larger scale.

Vehicles in a V2X environment are required to periodically transmit basic safety messages (BSMs). As vehicle density increases, any radio channel used for BSM transmission becomes congested and BSM packets are lost. This degrades safety technology performance. To overcome this problem, congestion control is required.

The congestion control technique used in these tests is based on SAE J2945/1 and SAE J3161/1, which reduces the BSM transmission rate when channel occupancy exceeds a predetermined threshold.

The emulated devices create channel occupancy ranging from 19.2-96%. This enables multiple tests under varying loads and does not change the Intelligent Transportation System (ITS) stack to function with C-V2X.

Tests that cover 300 m, 600 m, and 1200 m ranges with varying channel occupancy levels were implemented to characterize C-V2X performance over large distances and for different vehicle densities.

The ability of C-V2X to prioritize packets was tested by hard-braking tests to determine the reliability of higher priority messages under a high load and challenging channel conditions. These test results and their alignment with the simulations give confidence that the tests can be performed at scale in a real-world field environment.

Following this assessment, further field tests were performed. These tests are comprised of stationary congesting devices and moving cars where baseline message transmission-reception in the field line-of-sight (LOS) scenarios were evaluated in addition to performing non LOS testing.

1.4 Key takeaways

C-V2X performs well and exhibits no packet loss 95% of the time. KPI measurements (PER, IPG) confirm these results with SAE-specified congestion control enabled.

The background devices in emulation mode generate a total offered load between 19.2% and 96% in the 20 MHz carrier used in these tests. 1X (50 devices) and 2X (100 devices) emulation modes result in this setup showing good performance.

5X emulation mode (250 devices) shows the benefits of enabling congestion control. In 5X, the congestion control algorithm results in user equipment (UE) backing off to 600 ms from the nominal 100 ms BSM transmission periodicity. This results in the channel busy ratio (CBR) dropping from 87% with congestion control disabled to approximately 24% with congestion control enabled. PER improves significantly from about 4-5% to less than 1% between the host and remote vehicles under test.

The maximum PER experienced for the most distant devices under test (DUTs) is below 5%, with most links exhibiting PER less than 2% when congestion control is enabled. IPG with congestion control enabled suggests a loss of, at most, three consecutive packets. This low rate of packet loss is significant because it shows that the repeated BSM broadcasts were reliably received.

The corresponding low IPG measurements provide additional confidence of C-V2X performance under congested conditions. These tests were performed under varying congestion levels with 1X, 2X, and 5X loads.

Test results from both the lab and field deployments align with simulation results.

NOTE: Information age (IA) is not used. Many scenarios have shown that congestion control might push IA up to 600 ms while the tracking error remains acceptable for cars broadcasting safety messages. While IA is easier to measure, it should not be the main KPI for evaluating the performance of a safety messaging protocol for vehicle-to-vehicle (V2V). Tracking error is the better KPI.

2 Small Scale Four Device Setup

2.1 Summary

The small scale four-device setup provides a stable, scalable platform for testing.

This setup enables the following:

- Small scale device-to-device feature testing, namely Reference Signal Received Power (RSRP)-based resource exclusion
- Stability testing of congestion
- Incremental framework level development per test requirements

2.2 Setup

Figure 2-1 shows the setup connections for the device.

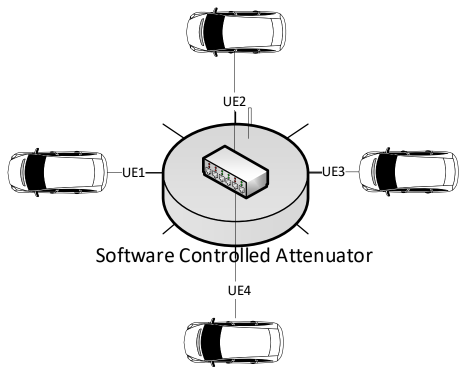


Figure 2-1 Small Scale Four-Device setup

Key features

- Devices are connected in a mesh network to enable communication between all devices.
- Devices are split into groups to be configured to perform different actions as desired by the end user.
- Users choose a path loss model to apply to the setup in order to control path loss between devices.
- Users enable/disable the Global Navigation Satellite System (GNSS) feed to a device.
- Users enable/disable modem level features on the desired device.
- Architecture has distributed asynchronous control which allows the user to control each device.

3 Vehicular Congestion Test Rack

3.1 Summary

The VeCTR Small Scale Lab setup simulates a field congestion scenario with multiple congesting nodes connected in a mesh network. The setup is scalable and uses 50 devices.

This framework can be utilized for:

- In-lab standalone congestion testing
- Stability testing of DUTs in a congested network

3.2 Setup

Figure 3-1 and Figure 3-2 show the VeCTR setup connections and the lab rack, respectively. The setup connections are comprised of 50 (scalable) congesting devices, 48 devices (in the lab rack), and two DUTs (HV and RV), connected in a mesh network where each device can talk to each other. These DUTs are interchangeable.

In Figure 3-1, the different colored lines track connections to their corresponding color coded devices:

- Black: HV – congesting vehicles
- Orange: RV – congesting vehicles
- Green: Congesting vehicle – congesting vehicle

The rectangles labeled "Combiner/divider" combine or divide the signals being fed. 16 Port M101 is the software controlled attenuator that sets path loss between the respective devices.

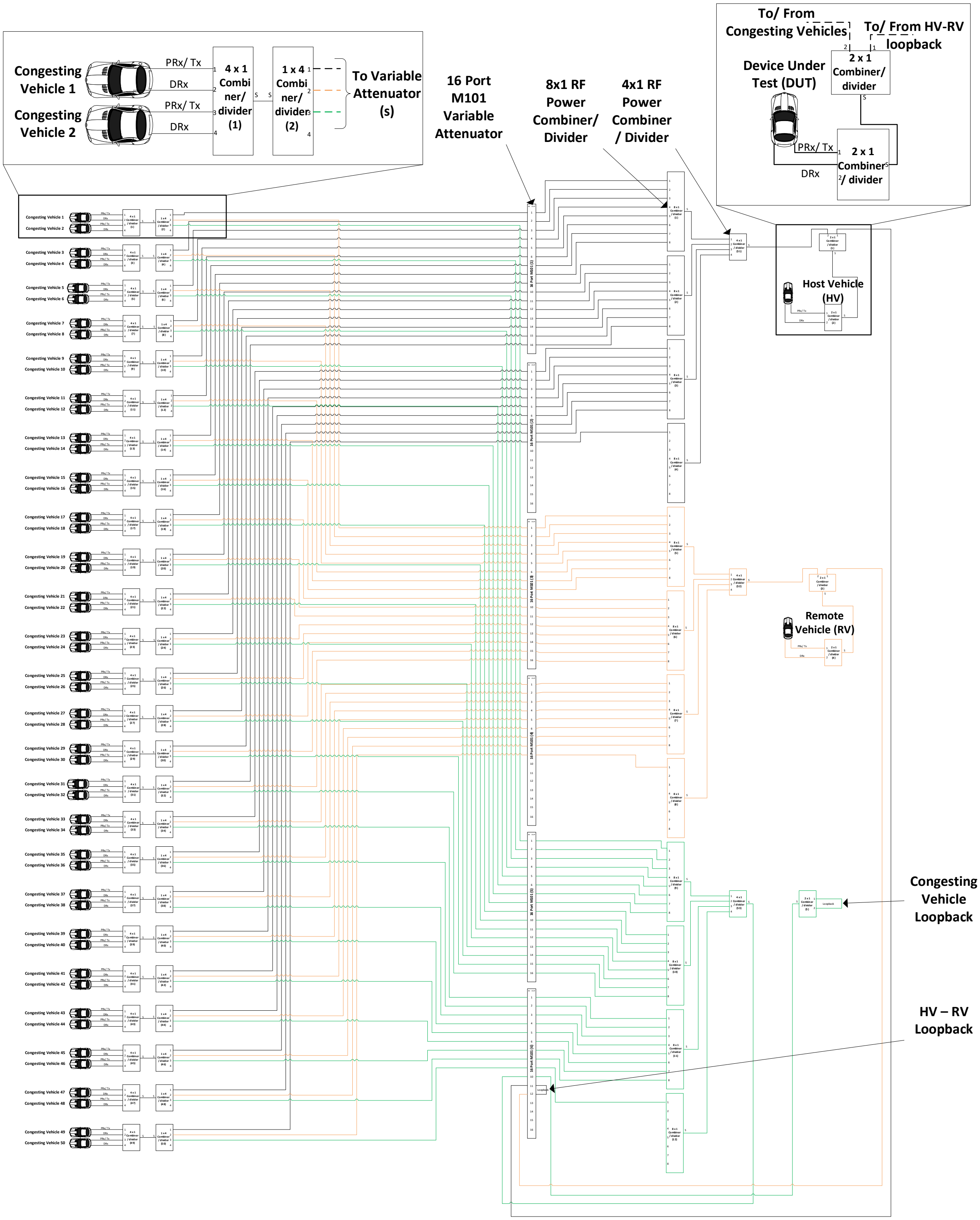


Figure 3-1 VeCTR – Small Scale Lab setup

Figure 3-2 VeCTR lab deployment

Key features

- Devices are connected in a mesh network to enable communication between all devices. These devices are split as one host vehicle (HV), one remote vehicle (RV), and 48 congesting devices.
- Architecture scalability allows for more congesting devices to be added in the future.
- Users choose a path loss model for the setup to control path loss between:
  - HV – congesting devices
  - RV – congesting devices
  - HV – RV
- Users enable/disable the GNSS feed to a device.
- Users enable/disable modem level features on the desired device.
- Architecture has distributed asynchronous control which allows the user to control each device.

4 Large Scale Field Test Setup

C-V2X large scale field congestion testing emulates an actual highway congestion scenario. The framework is designed to perform congestion testing with stationary congesting devices and moving DUTs (HVs and RVs) over different track lengths.

4.1 Setup

The modular architecture of the field test framework enables scalability and debugging. The key module is a pod containing the following:

- C-V2X device
- Mini PC
- A shark-fin antenna mounted on the pod assembly (approximately the height of a sedan's roof top) to emulate a stationary vehicle (for stationary congesting UE (pods) only)

Figure 4-1 and Figure 4-2 show the setup connections and an actual field deployment, respectively.

Key features

- Each pod is a standalone entity and controlled from the control and command center to perform the desired action.
- Figure 4-1 shows a configuration of 50 congesting (stationary pods) and eight DUTs.
- The distributed asynchronous control allows for testing different levels of congestion with this setup by configuring each node as desired.
- The architecture allows for enabling/disabling modem level features by changing file configurations on the DUTs.

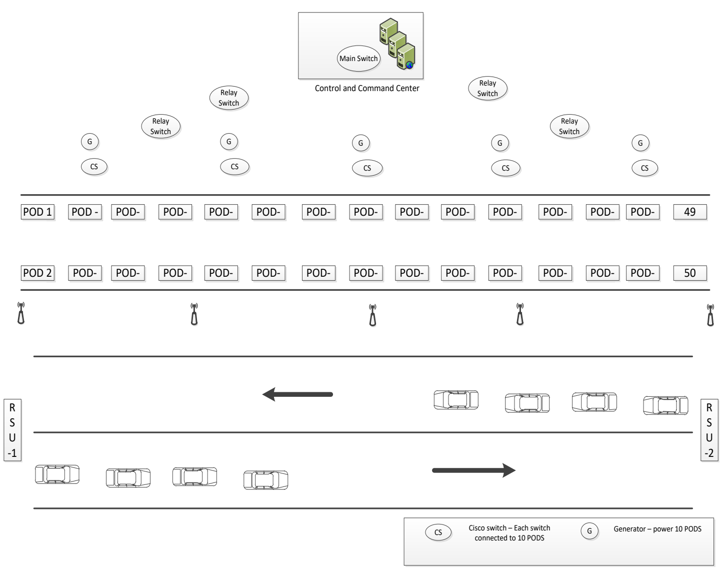


Figure 4-1 Large scale field setup for 300 m and 600 m tracks

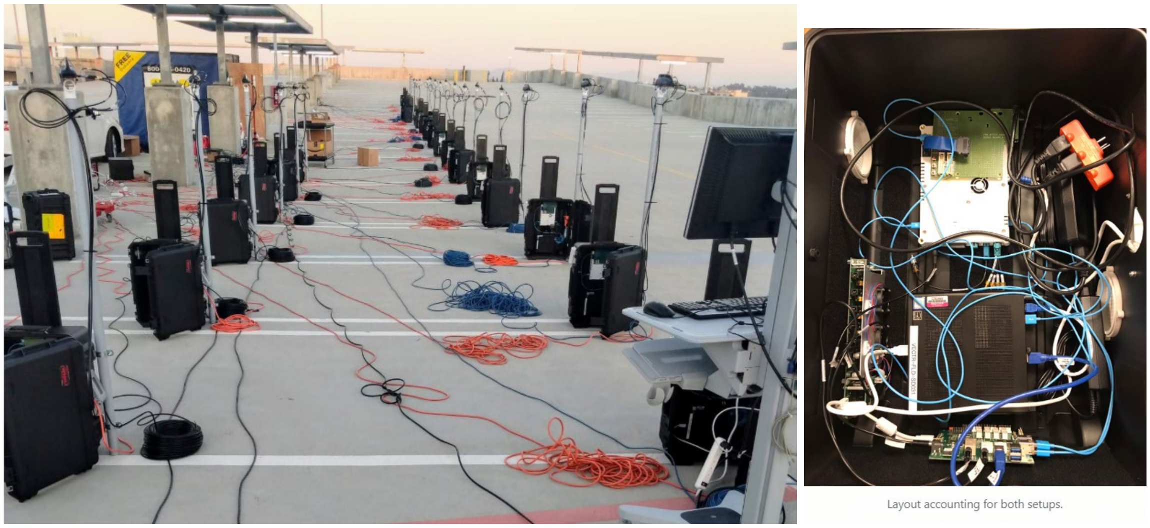


Figure 4-2 Field test setup – field deployment ready setup with pod details (inset)

5 Key Performance Indicators

This chapter provides an overview of KPIs that evaluate test performance.

Custom analyzer scripts help derive necessary KPIs, then check them for consistency between ITS stack and modem layers

5.1 Testing

Testing uses the following KPIs:

- PER
- IPG
- ITT
- Consecutive packet loss (CPL) or inter-packet count (IPC)
- CBR

This section defines these KPIs and clarifies the methods for postprocessing collected data.

Postprocessing of logs are a part of the VeCTR automation framework. The amount of data generated for every test run is large.

Application logs calculate PER, IPG, ITT, and CPL. The modem physical layer logs determine CBR.

5.1.1 Packet error rate

PER is the ratio (expressed as a percentage) of the number of missed packets at a receiver from a particular transmitter and the total number of packets queued at that transmitter.

A sliding window PER smooths the sudden fluctuations and obtains an average PER. PER is calculated using the sequence number contained in each message between a receiving HV and one or more transmitting RVs. PER is calculated and plotted versus time.

Figure 5-1 shows the PER sliding window, where δ equals the PER interval divided into sub-windows ω. The width of ω is normally set to 100 ms, which is one BSM sample time.

In Figure 5-1, $\delta = n * \omega$, where:

- n is normally set to a value such that a PER interval is 5 seconds, i.e., *n* is 50),
- *j* is the index of the PER interval occurring at the center of this interval, the number of missed packets, and the number of transmitted packets, and
- δ_j is the new PER interval,

PER is then calculated for index j at the center of each δ_j, using the surrounding n sub-windows:

$$PER_i(j) = \frac{\text{missed \# of BSMs from vehicle i during } \left[\omega_{\left(j-\frac{n}{2}\right)+1}, \omega_{\left(j+\frac{n}{2}\right)}\right]}{\text{total \# of BSMs from vehicle i during } \left[\omega_{\left(j-\frac{n}{2}\right)+1}, \omega_{\left(j+\frac{n}{2}\right)}\right]}$$

where $=j \geq n$.

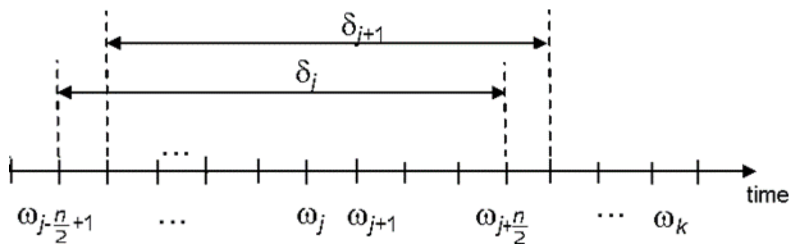


Figure 5-1 PER – sliding window (SAE J2945)

Sliding window PER values are plotted against the duration of the test. All sliding window PER values are averaged and plotted on the same figure. The PER metric in this case includes:

- Packet loss due to packets that were dropped from the transmit queue because a newer BSM arrived in the queue before the previous BSM could be transmitted due to a busy medium.
- Packets lost over-the-air (OTA) due to collisions or insufficient signal strength.

For additional information, see *On-Board System Requirements for LTE V2X V2V Safety Communications* (SAE J3161/1).

5.1.2 Inter-packet gap

IPG (in milliseconds) is the time between successive, successful packet receptions from a particular transmitter over an entire test run. IPG is calculated between a receiving HV and a transmitting RV, and expressed in milliseconds.

IPG_i between the $i-1^{th}$ message and the i^{th} message is:

$$IPG_i = r_i - r_{i-1}$$

where,

- r_i denotes Coordinated Universal Time (UTC) at which the i^{th} message from an RV is received by the HV, and
- r_{i-1} denotes the UTC time at which the $i-1^{th}$ message from the RV was received by the HV.

For additional information, see *V2X Functional and Performance Test Report* (5GAA TRP-170142).

5.1.3 Inter-transmit time

ITT is the time (in milliseconds) between two consecutive transmissions from the same transmitter for a particular flow.

5.1.4 Consecutive packet loss

CPL (or IPC) is the number of packets lost between two successive packet receptions for the same transmitter and receiver pair.

5.1.5 Channel busy ratio

CBR is the portion of subchannels in the resource pool with an S-RSSI measurement that exceeds a pre-configured threshold sensed over the last 100 ms (see Section 0).

CBR tracks channel utilization in C-V2X. For the complete definition of CBR, see *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements* (3GPP TS 36.214).

The measurement window is subframes [n-100, n-1] for CBR measured at subframe n.

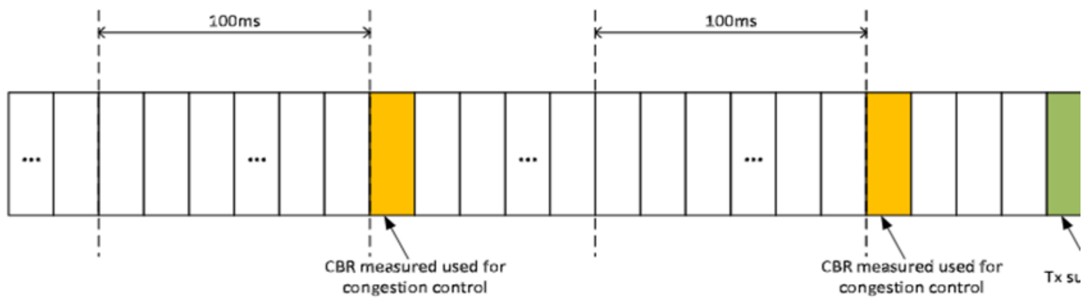


Figure 5-2 Sliding window CBR measurement

For additional information, see *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements* (3GPP TS 36.214).

5.1.6 Tracking error

The tracking error (ITS) is the error between the true location of the transmitter and the receiver's perception of the transmitter location. This is the transmitter estimate of the receiver error in tracking the transmitter.

For additional information, see *On-Board System Requirements for V2V Safety Communications* (SAE J2945/1).

5.2 Generation and evaluation

KPIs were collected from two DUTs (see Chapter 3) during lab testing, and calculated from eight DUTs in the field (see Chapter 4).

To evaluate system performance in real time and from postprocessing, VeCTR uses an automated process to measure KPIs from the logs collected during the test run. Analyzers provide real time statistics during test execution (such as CBR), the number of vehicles in range, and the number of transmit devices. CBR and the number of vehicles in range are derived from multiple nodes during field testing. The majority were captured from the edge and the center nodes on the test track, which enables validation of each test scenario.

During postprocessing, analyzers calculate KPIs for the modem and ITS stacks to generate KPIs and plots for every UE in the system.

5.3 Postprocessing efficiency

A congestion test generates roughly 50 GB of logs, containing both modem and ITS logs from all 50 devices (includes DUTs and congesting devices).

Figure 5-3 shows an overview of the efficient postprocessing framework that generates KPIs. The ITS and modem stack logs are converted into CSVs that are fed into the analyzers to generate desired KPIs.

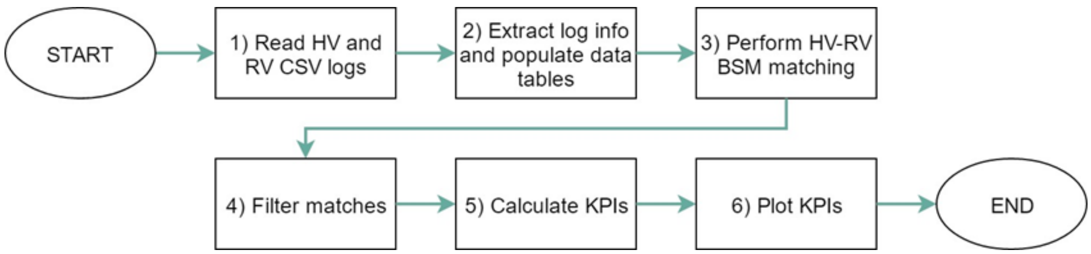


Figure 5-3 Postprocessing overview

The analyzers allow quick data processing. A distributed architecture schedules postprocessing for every UE in the system. The jobs are load-balanced over a farm of remote servers to postprocess large amounts of field data overnight.

6 Scenario Emulation

This chapter explains how a test case, or a scenario was constructed using automation software for VeCTR or the field test setup.

Figure 6-1 shows some of the elements that create a test case for C-V2X using VeCTR with multiple devices, i.e., configuring transmit and receive parameters to build the test case and environment. The use case configuration can be embedded in the ITS configuration.

NOTE: Software behavior does not change based on the number of devices in the test system. The number of devices used for a test case are scalable.

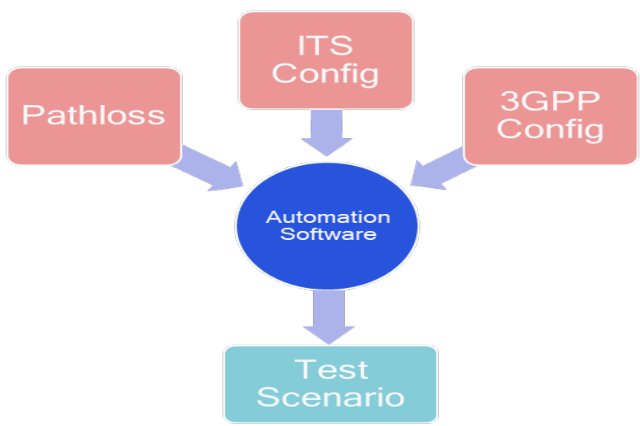


Figure 6-1 Scenario emulation using automation software

Table 6-1 lists assumptions while testing with VeCTR in the lab and the field.

Table 6-1 Assumptions

Environment	Purpose	Assumptions

Emulation mode (lab and field)	Emulates congestion scenarios	▪ Scenarios are run for 1X, 2X and 5X the load each for distributed congestion control enabled and disabled.
		  ▫ 1X load translates to 50 cars
		  ▫ 2X load (each car transmits at twice the periodicity in emulation mode) translates to 100 cars
		  ▫ 5X load (each car transmits at five times the periodicity in emulation mode) translates to 250 cars.
		▪ Congesting devices (C-V2X pods) simulate the load
		  ▫ At 1X load, pods transmit BSMs at 100 ms periodicity (50 pods = 50 cars)
		  ▫ At 2X load, pods transmit BSMs at 50 ms periodicity (50*2 pods = 100 cars)
		  ▫ At 5X load, pods transmit BSMs at 20 ms periodicity. [50*5 pods = 250 cars]
		▪ Lab testing uses 2 DUTs
		▪ Field testing uses 8 DUTs
		▪ DUTs send BSMs at 100 ms periodicity for all cases
		▪ If enabled, the SAE congestion control algorithm introduces rate control which affects transmission periodicity

Lab (during congestion control testing)	To get results similar to field congestion configuration	▪ While path loss is constant per DUT, it varies between DUTs and different congesting devices ▪ No fading or mobility is assumed for all devices in the lab system ▪ All devices operated under an open sky environment for good GPS signal strength ▪ DUTs are tested with inter-vehicle spacing of 75 m ▪ DUTs are placed in the center of the track to maximize the amount of congestion they would experience

Field		▪ Only DUTs are mobile
		  ▫ Traveled in a platoon at fixed speed (25 MPH) with constant spacing between DUTs when possible
		  ▫ During Hard Brake Test, DUTs traveled at 55 MPH
		▪ Congesting devices are stationary and maintain equal spacing between them along the track
		▪ All vehicles are the same height
		▪ Congestion control is performed using rate control

6.1 Path loss models

The path loss between a subset of devices or all devices is made possible by using software-controlled radio frequency (RF) attenuators in the lab setup.

Path loss testing in the lab was based on simulation results using different track lengths (see Figure 6-2). Accurate path losses were set for these links:

- Between congesting devices and two DUTs
- Between DUTs
- Combined attenuation between congesting devices

For a representative figure of this path loss model, see Figure 7-3.

Figure 6-2 shows that path loss is highest at the edges and reduces towards the center of the plot. This is in line with device placement along the 300 m and 600 m tracks in conjunction to the centered DUTs.

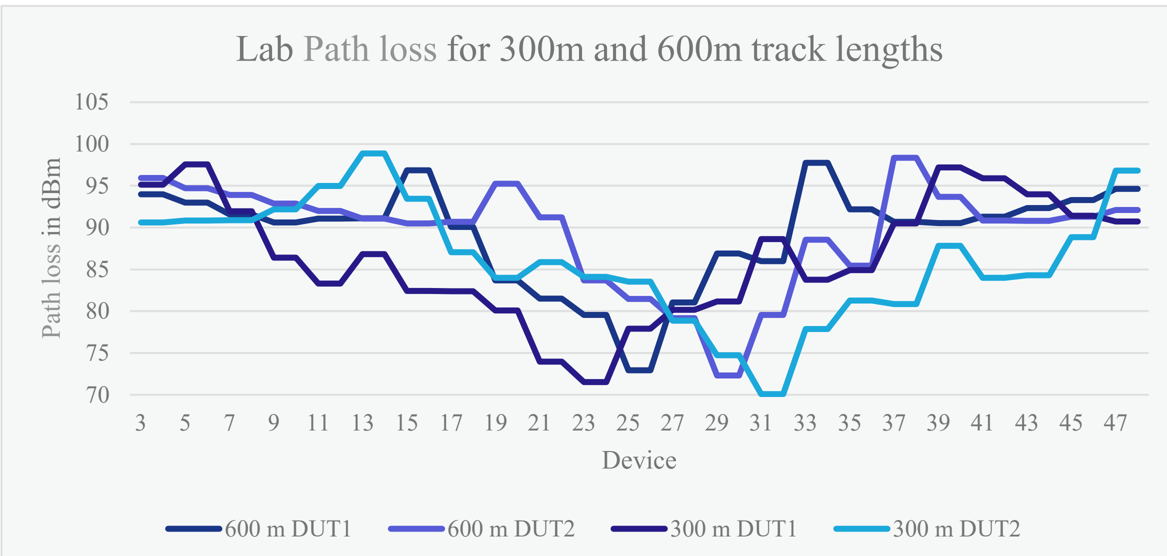


Figure 6-2 Lab path loss for 300 m and 600 m track lengths

6.2 Intelligent Transportation System software stack configuration

Table 6-2 details 12 scenarios executed in the lab and the field with configured ITS parameters necessary to emulate congestion. Each parameter was set on their respective devices.

Table 6-2 ITS software stack configuration per scenario

Scenario (Emulation)	Congesting UE packet periodicity	DUT packet periodicity	#Congesting devices	#DUT (lab)	#DUT (field)	Track length	Congestion control	Scaled vehicle density coefficient* (lab)	Scaled vehicle density coefficient* (field)
1X	100 ms	100 ms	48	2	8	600 m	OFF	75	25
2X	50 ms	100 ms	48	2	8	600 m	OFF	37.5	12.5
5X	20 ms	100 ms	48	2	8	600 m	OFF	15	5
1X	100 ms	100 ms	48	2	8	600 m	ON	75	25
2X	50 ms	100 ms	48	2	8	600 m	ON	37.5	12.5
5X	20 ms	100 ms	48	2	8	600 m	ON	15	5
1X	100 ms	100 ms	48	2	8	300 m	OFF	37.5	25
2X	50 ms	100 ms	48	2	8	300 m	OFF	19	12.5
5X	20 ms	100 ms	48	2	8	300 m	OFF	7.5	5
1X	100 ms	100 ms	48	2	8	300 m	ON	37.5	25
2X	50 ms	100 ms	48	2	8	300 m	ON	19	2.5
5X	20 ms	100 ms	48	2	8	300 m	ON	7.5	5
* For the vehicle density coefficient, see *On-Board System Requirements for V2V Safety Communications* (SAE J2945/1).									

Table 6-2 shows vehicle densities seen at the center and at the edge of the track.

Table 6-3 Vehicle densities

Track length	#Congesting devices	#DUT (lab)	#DUT (field)	Vehicles seen by DUT (in 100 m radius at center of track)	Vehicles seen by DUT (in 100 m radius at edge of track)
600 m	48	2	8	16	8
300 m	48	2	8	32	16
100 m chosen as the radius per *On-Board System Requirements for V2V Safety Communications* (SAE J2945/1) and *On-Board System Requirements for LTE V2X V2V Safety Communications* (SAE J3161/1).					

6.3 3GPP configuration

On-Board System Requirements for LTE V2X V2V Safety Communications (SAE J3161/1) provide configurations for congestion control testing, including:

- Channel 183-5915 MHz
- Bandwidth: 20 MHz (100 resource blocks (RBs))
- Tx power: 20 dBm
- Modulation coding scheme (MCS): 0-17
- Subchannel size: 10 RBs
- Number of subchannels: 10
- Sl-Reselectafter: n6
- allowedRetxNumberPSSCH-r14 : n1

For the complete Sl-V2X configuration, see Appendix B.

7 5G Automotive Association Congestion Control Lab Test

7.1 Background

The 5GAA congestion tests aimed to check performance of a V2X device in a congestion challenged channel. 5GAA congestion tests emulated 600 devices to show DUT performance under congestion load when the upper layer of congestion control was enabled (see *V2X Functional and Performance Test Procedures* (5GAA P-180092)).

The following lab tests were conducted to assess performance of the C-V2X systems in a congested environment. All cases listed here are V2V without network infrastructure coverage.

Carefully designed, cabled-up lab test beds produce repeatable and reproducible results. These tests provide a controlled and stable platform for comparing technologies and algorithms.

Unlike an OTA test bed that produces results that vary over time, performance comparisons obtained from cabled-up test beds are precise.

The congestion control lab setup evaluates the performance of speeding cars in the carpool lane of a traffic-jammed highway.

7.1.1 Assumptions

- There are two stationary DUTs.
- The operating system time of all devices is synchronized to a common GNSS clock with an error of no more than 1 ms.
  - This requirement ensures that end-to-end latency between the transmitter and receiver can be measured with an accuracy of 2 ms. This requirement is unrelated to the PHY layer synchronization requirement.
- For C-V2X, devices are preconfigured (see Section 0).

7.1.2 Test goals

This test was based on the CAMP scenario (with 5X emulation by the test devices) described in *Vehicle-To-Vehicle Communication Technology for Light Vehicles* (NHTSA-2015-0060). DUTs move on a 1200 m stretch of highway in carpool lanes, while the devices creating congestion are stationary on both sides of the carpool lanes.

The congesting test devices emulate columns of 10 cars on each side of the carpool lanes where the columns are separated by 12.5 m and lane width is 3.6 m. This scenario scales the congesting devices in emulation mode when more congestion is needed.

This test:

- Executes a BSM transmission and reception test between DUT1 and DUT2 in a congestion-challenged environment.
- Provides KPIs including PER, latency, and IPG for transmission and reception between DUT1 and DUT2.
- Compares the CDF of PER and CBR generated from the lab setup with the system-level simulation and verifies a match.

7.1.3 Setup

Configuration	C-V2X
Channel	5890 MHz (Channel 178)

In this setup, multiple congesting devices (also known as reference devices (REF)) generate traffic to simulate a congested environment. Two devices (DUT1 and DUT2) are used.

All devices are cabled and connected via splitters and combiners that satisfy requirements in the frequency range of C-V2X. Adequate insulation is also provided to prevent leakage.

Figure 7-1 shows a diagram of the BSM broadcast lab setup. Notes for reading the diagram:

- Devices labeled "UE" are congesting devices
- Variable attenuator (VA)
- DUT1 and DUT2 are shown as "HV" and "RV," respectively.
- N=2, so every two REF devices are grouped in terms of the path loss toward the DUT1 and DUT2.

In this setup, there are 48 congesting devices (UE1-UE48 connected in a mesh network) to 2 DUTs (HV and RV). The HV-RV and congesting devices communicate with each other. The variable attenuator provides a means to modify the path loss between HV-RV.

For additional VeCTR setup details, see Section 3.2.

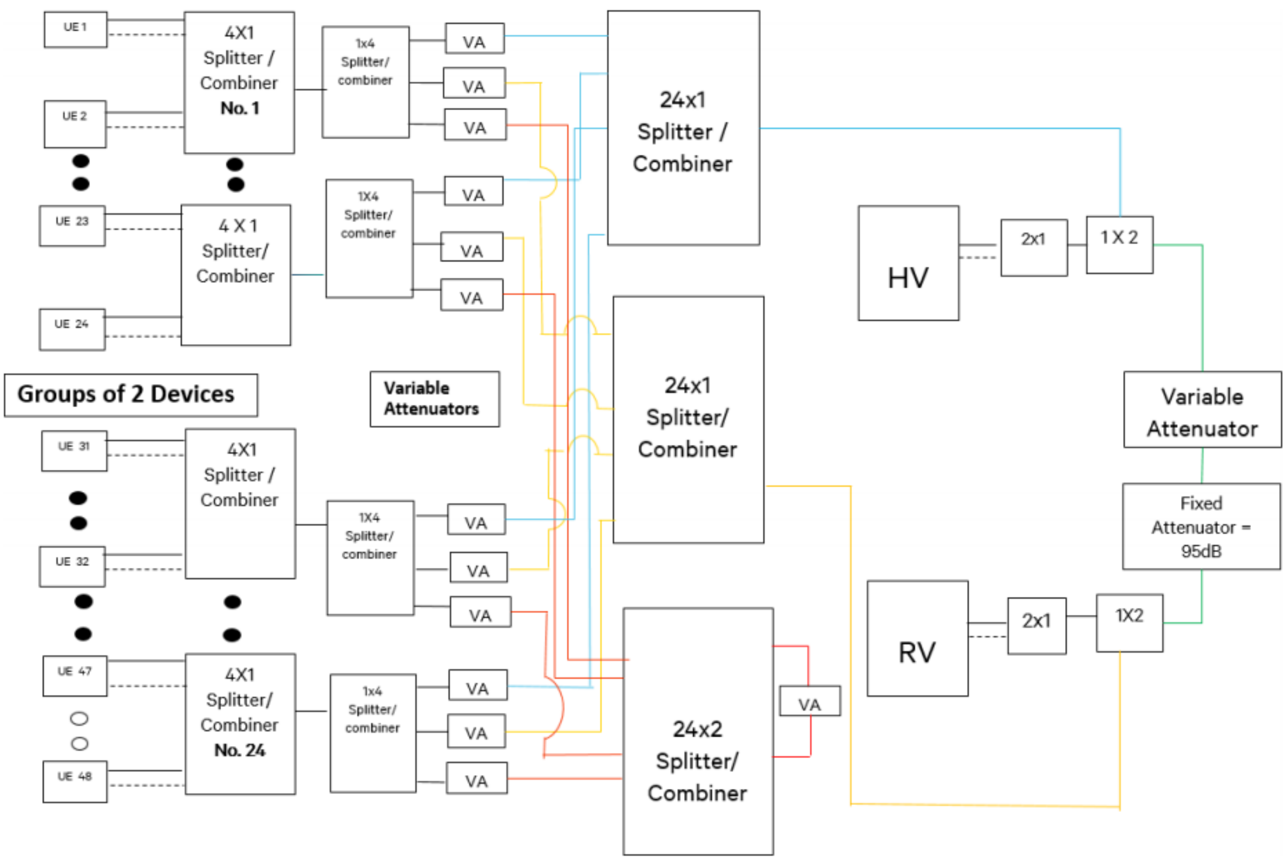


Figure 7-1 Regular BSM broadcast lab setup

7.1.4 Adaptations

The following changes were made to adapt the test to the lab environment:

- Two stationary DUTs are placed in the middle of a 1200-m stretch of highway, and they transmit every 100 ms.
- Modeling the Additive White Gaussian Noise (AWGN) channel is not necessary because the main source of error is interference from congesting devices.
- The main contributors to interference are the closest 576 cars that are in a traffic-jam on the highway. This number is determined by conducting simulations of a larger number of interfering devices spread over the full 1200 m stretch of highway (1940 cars), and then repeating the simulations with an increasingly smaller number of interfering cars to determine the smallest number of congesting devices for which the performance of the DUTs remains unchanged (see Figure 7-2 and *V2X Functional and Performance Test Procedures* (5GAA P-180092)).
- The 12-to-1 emulation ratio is produced for lab reference devices (see *V2X Functional and Performance Test Procedures* (5GAA P-180092)). The 576 interfering devices are emulated in the lab environment using 48 lab reference devices.
- The path loss model is the freeway scenario described in Section A.1.4 of *Study on LTE-based V2X services* (3GPP TR 36.885). It specifies the model of LOS in WINNER+B1. Path loss at 3 m is used if distance is less than 3 m.

Figure 7-2 shows the emulated congestion:

- DUT1 (in red) is the host vehicle. It is stationary in the test environment but transmits at the maximum frequency, once every 100 ms due to its higher speed in the emulated scenario.
- DUT2 (in grey) on the central lanes, is the remote vehicle. It transmits at the maximum frequency, once every 100 ms.
- The 576 interfering cars are also stationary in columns, spaced 12.5 m from each other. Within each column, 10 cars are spaced out within the lane (3.6 m) on each of the upper and the lower sides of the carpool lanes.

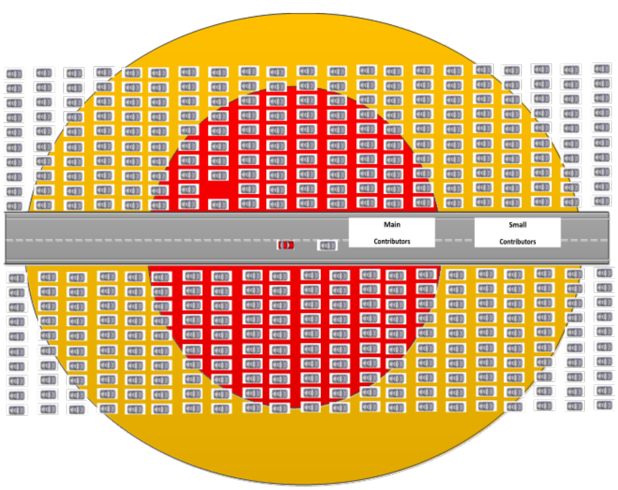


Figure 7-2 Emulated congestion

NOTE: This test exercises congestion control on devices in the lab setup. Without congestion control, all devices would transmit a BSM every 100 ms. Each of the 48 reference devices generates two semi-persistent scheduling (SPS) transmissions occupying four subframes every 100 ms (one transmission and one retransmission per SPS, each using 50 out of 50 RBs per subframe). Given that all devices are within communication range, this setup would produce a load of (48*4)/100 = 192%, almost twice what the channel bandwidth can support. Without congestion control, the system would fail to support every user in the system and result in large packet drops due to the high load.

7.1.5 Representative Lab setup

Figure 7-1 shows the Representative Lab setup, where HV and RV are DUT1 and DUT2, respectively.

This test setup uses VeCTR. It is constructed so that each device can hear other devices, while offering path loss control for specific device groups with other device groups.

Reference devices are shown to the left and grouped in pairs. HV-RV are on the right, communicating to each other through a separate path connected by fixed and variable attenuators. Separate paths are required because path loss between HV and RV reference devices are different:

- Blue and yellow line connectors – Connects all reference devices to HV and RV, respectively. Path losses between both are turned (via variable attenuator) per the simulation.
- Red connector – Connects reference devices. The variable attenuator for red connector paths is set to zero. Path loss between reference devices do not impact metrics collected at DUT1 and DUT2.
- Green connector – Connects HV-RV. This path has a fixed attenuator of 95 dB and a variable attenuator that applies values per test requirements.

This setup can be extended to accommodate a larger number of devices by using and cascading splitters/combiners and attenuators, and connecting to the overall grid.

Table 7-1 Representative Lab device settings

Device	Settings
DUT1 and DUT2	▪ Periodicity of 100 ms (in LTE C-V2X, an SPS flow shall be configured with a periodicity of 100 ms). ▪ Transmit on ITS band* with bandwidth of 10 MHz; transmits regular BSM messages. ▪ Configured to receive on ITS band* with 10 MHz bandwidth. ▪ Transmit power kept constant at 21 dBm. ▪ Both devices use MCS 8 and 14 RBs for transmission ▫ LTE C-V2X allows for a choice of different parameters in the presence of congestion. ▪ C-V2X Rx and Tx pool bitmap is set to an all 1 bitmap with a bitmap length of 20. Example: sl-Subframe bs20 : '11111111 11111111 1111'B ▪ Rx and Tx pools have a number of subchannels set to 10. The size of each sub-channel is 5. ▪ Frequency resources for both Tx and Rx pools have the start RB set to 0. ▪ CBR RSSI threshold is set to a value of 9, e.g., threshS-RSSI-CBR 9 ▪ Hybrid automatic repeat request (HARQ) is disabled. ▪ Vehicle density coefficient is set to 4. ▪ MAX_ITT for packets configured to 400 ms. ▪ Add a default attenuation of 95 dB between DUT1 and DUT2 as a reference starting point for this test ▪ All attenuations added through duration of the test are on top of the above default attenuation already present. ▪ Standard BSM packet length. ▪ Uses static GPS.
Adjustable attenuator or variable attenuator (see Figure 7-1)	Simulates different distances between DUT1 and DUT2.

Reference devices	▪ Transmit power kept constant at 21 dBm.
	▪ Periodic transmit packet flow with a periodicity and load specified to emulate multiple devices using the channel:
	  ▫ Increase number of RBs in use to 50 per transmission by using a packet size of 1736 bytes (versus 14 RBs for DUTs).
	  ▫ Enable HARQ retransmissions for emulation (versus none for DUTs).
	  ▫ Use two SPS flows on the device for emulation (versus one on DUTs).
	    – -With the above changes, a reference UE emulates about 12 interfering devices.
	▪ C-V2X Rx and Tx pool bitmap is set to an all 1 bitmap with a bitmap length of 20.
	  ▫ For example: sl-Subframe bs20 : '11111111 11111111 1111'B
	▪ Rx and Tx pools have a number of subchannels set to 10. The size of each sub-channel is 5.
	▪ Frequency resources for both Tx and Rx pools have the start RB set to 0.
	▪ CBR RSSI threshold is set to a value of 15, e.g., threshS-RSSI-CBR 15
	▪ Figure 7-3 shows position of REF devices (given the above 12-to-1 emulation):
	  ▫ Simulated devices are shown as light blue stars.
	  ▫ REF devices are shown as red stars. These devices are labeled from 1 to 24 and then 1' to 24'.
	  ▫ Devices x and x' have the same path loss toward DUT1 and DUT2 in the lab setup due to the grouping highlighted above (N=2).

* Center frequency is 5860 MHz.	

7.1.6 Reference device locations

This section provides additional information for Figure 7-3.

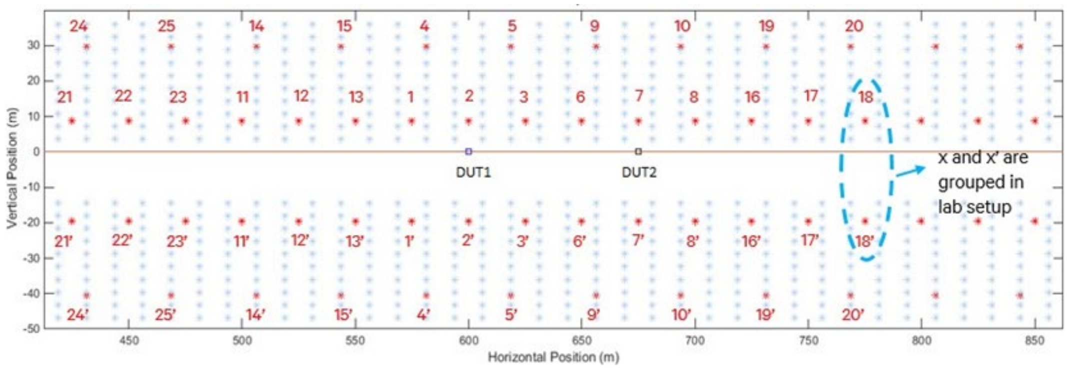


Figure 7-3 REF device locations

Table 7-2 details the dependencies of variable attenuator settings (in a cabled RF setup).

Table 7-2 Variable attenuator dependencies

Dependencies	Additional information
Number of "real" devices each reference device emulates	Since a reference device emulates three equivalent "real" devices within each transmission, the attenuation from this device to each DUT is divided by 3 to account for the reduced power per RB in the lab scenario.
Real world "distance" to be emulated	Distance is between a specific reference device and DUTs.
Attenuation between reference devices	▪ Attenuation is set to a fixed value corresponding to the average distance between the reference devices. ▪ In the default setup, path loss between any two reference devices is 103 dB (see Table 7-3). ▫ Transmit on ITS band with bandwidth of 10 MHz; transmits regular BSM messages. ▫ Configured to receive on ITS band with bandwidth of 10 MHz. ▫ Generation of BSM content is not synchronized, i.e., each reference device generates its content at a different (random) point in time to avoid synchronization of transmission behavior. ▫ Transmit power kept constant at 21 dBm ▫ Packet length of standard BSM (365 bytes) message (unless packet size is varied). ▫ Uses static GPS.

Dependencies	Additional information
SAE congestion control settings	▪ Max_ITT of 400 ms. ▫ Max_ITT was pushed lower (default was 600 ms) to ensure a higher load in the system. ▪ Density coefficient B is set to 25/6 ~= 4. ▫ Each device transmits two BSMs and emulates 12 devices. Thus, every received BSM emulates six BSMs in the original scenario. The congestion control density coefficient, which has a default value of 25 per specification, should be adjusted accordingly.
Data collection of DUT1 and DUT2	▪ Timestamp for each transmitted packet. ▪ Timestamp for each received packet. ▪ Receives signal power for each received packet. ▪ All KPIs listed in Chapter 5.
Data collection at each reference device	▪ Timestamp for each transmitted packet ▪ All KPIs listed in Chapter 5.
* Center frequency is 5860 MHz.	

NOTE: The set of attenuators discussed in the attenuations for the default test setup excludes the variable attenuator shown at the far-right side of Figure 7-1.

Figure 7-4 lists the positions and attenuations used in the default test setup:

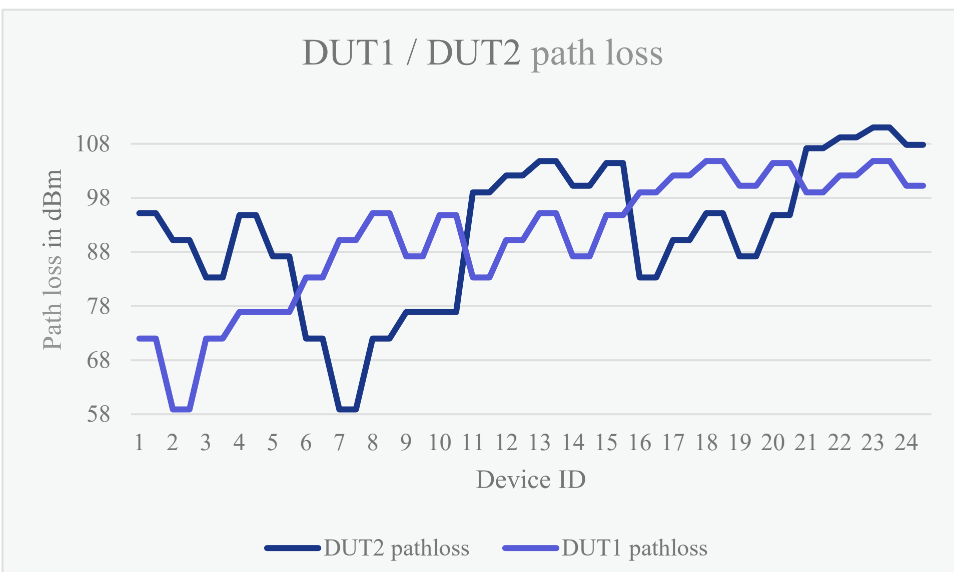


Figure 7-4 Positions and attenuations for default test

7.1.7 Test execution

In a congested environment created by reference devices, PER between DUT1 and DUT2 (observed as the distance between them) is gradually increased by adjusting the attenuation.

To set up a test bed where 48 reference devices simulates 576 devices:

1. Add a default attenuation of 95 dB between DUT1 and DUT2 as a reference starting point.

   The default attenuation of 95 dB was chosen to emulate approximately 75 m (per simulations in Section 0).
2. Set Variable Attenuator at the far-right of the diagram to 0 dB to simulate a short distance between DUTs.
3. Start transmission of regular BSMs at all reference devices.
4. Start transmission of regular BSMs at DUT1 and DUT2.
5. Record statistics and KPIs to a log file for DUT1, DUT2, and reference devices (see Figure 7-4).

NOTE: Logging/saving all KPIs is done for at least one reference device. Logging/saving is recommended for all reference devices.

6. Calculate PER between the two DUTs at both DUT1 and DUT2.
7. Increase attenuation at Variable Attenuator by 5 dB to simulate an increased distance between DUTs.
8. Repeat steps 5 through 7 until the overall attenuation reaches 115 dB (near sensitivity level).
9. Set Variable Attenuator at the far-right of the diagram to 0 dB to simulate a short distance between the DUTs.
10. Run this test using two C-V2X DUTs and up to 48 reference devices (see Section 7.1.3).

    All devices (DUT1, DUT2, reference devices) have congestion control switched on.

7.1.8 Required documentation

Table 7-3 summarizes the results based on data collected from log files.

Table 7-3 Reference device location test results

Attenuation value between DUTs (dB)	Number of reference devices	Number of transmitted packets		Number of received packets		Calculated at receiver					
		DUT1	DUT2	DUT1	DUT2	PER % (DUT1)	PER % (DUT2)	95th percentile IPG value (DUT1)	95th percentile value (DUT2)	95th percentile latency value (DUT1)	95th percentile latency value (DUT2)
95	48	2071	2076	2043	2029	1.6	2.0	105	104	97	102
100		2068	2055	1952	1964	5.0	5.0	108	105	104	101
105		2068	2072	1850	1967	10.7e	4.8	105	105	99	97
110		2065	2067	1847	1846	10.6	10.6	212	104	100	90
115		2067	2066	1720	1681	16.7	18.6	214	215	92	102

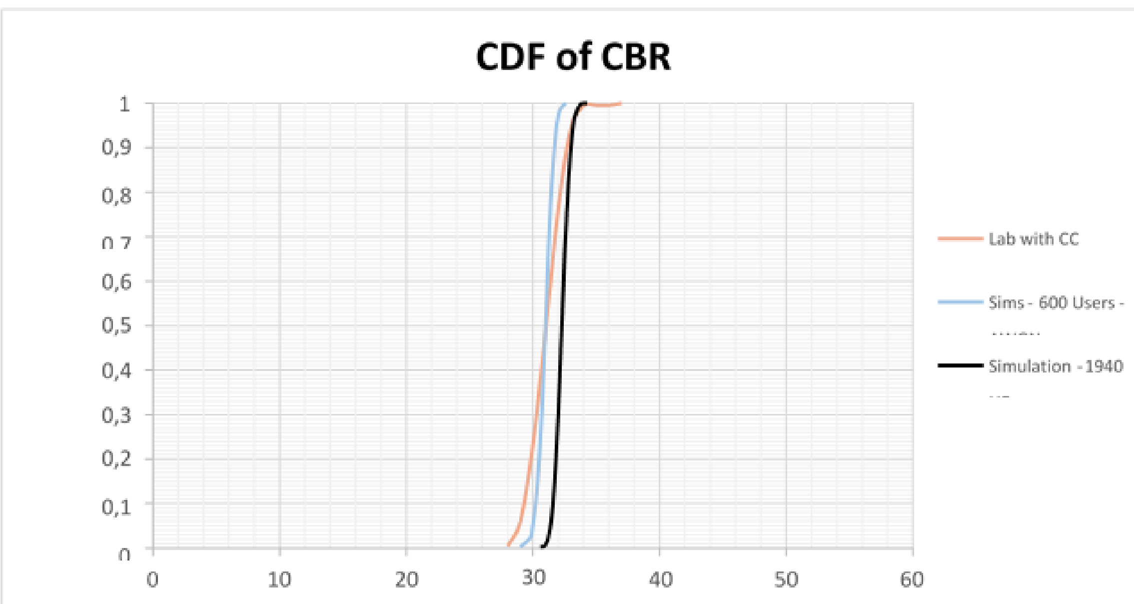


Figure 7-5 Cumulative distribution function (CDF) of CBR

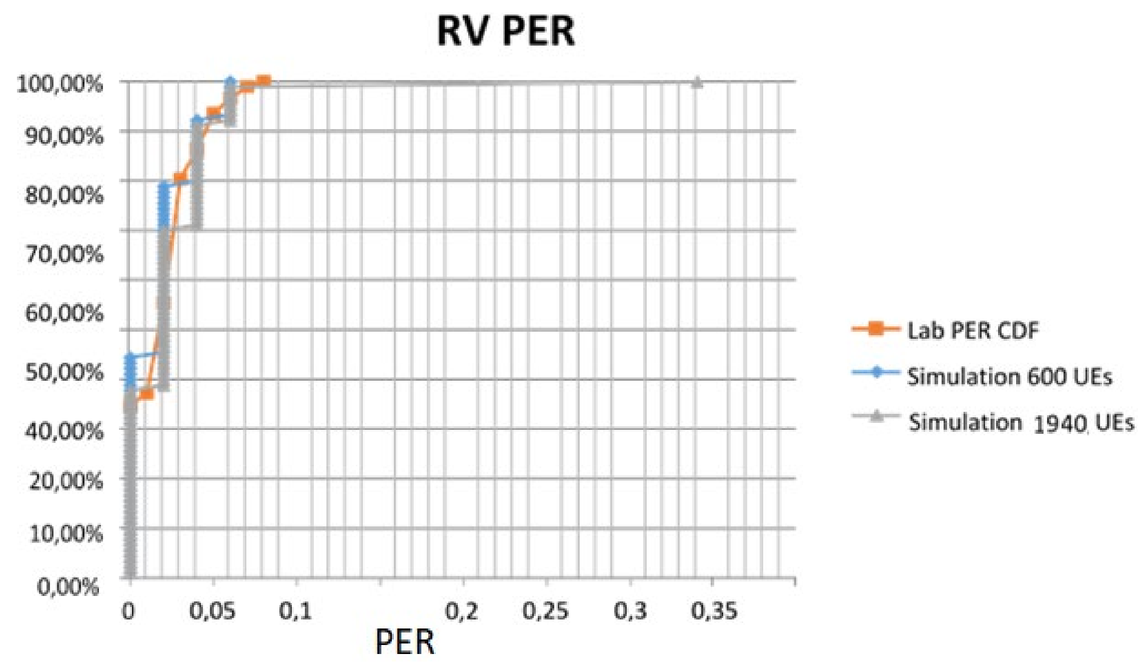


Figure 7-6 CDF of PER

7.1.9 Evaluation criteria

Evaluation criteria assess the V2X performance in highly congested environments. Criteria include the performance of the congestion control mechanism implemented on the DUT under different CBR values.

Evaluation criteria also verifies that lab data at the 75 m distance point (95 dB attenuation) matches the simulation data for the CDF ofCBR and the CDF of PER. A match for both these metrics implies that channel utilization is commensurate to the load on the system and that packet loss under the observed congestion environment is as expected.

7.1.10 Key takeaways

- For both CBR and PER, metrics observed in the lab and the simulation are comparable. SAE congestion control works as expected for C-V2X.
- All devices in the system back off to an ITT of 400 ms as soon as congestion is detected per test parameters. Devices in the setup choose their transmission resources while avoiding transmissions chosen by other devices, which helps improve overall PER as measured on DUT1 and DUT2.
- This set of tests confirms that a low PER was maintained in a congested environment.

7.2 V2V congestion control in lab environment (critical BSM broadcast)

This test verifies that C-V2X devices can transmit and receive BSM messages with critical priority over the PC5 interface in a congestion-challenged channel. This corresponds to a critical event condition, and corresponding messages are transmitted with a higher priority.

In the following lab tests, there is an equivalent load of 578 devices like the earlier test with 48 special configured devices and two DUTs (see Section 7.1.3).

7.2.1 Assumptions

See Section 7.1.1.

7.2.2 Setup

For setup, see Section 7.1.3.

Table 7-4 notes changes and differences for this test.

Table 7-4 V2V congestion control in lab settings

Device/dependencies	Settings
DUT1 and DUT2	▪ Same as specified in Section 7.1.3 ▪ Includes that reference devices only sends regular BSM messages (no critical ones)
Data collection at DUT1	Same as specified in Section 7.1.3, including: ▪ Priority (critical or regular) for each transmitted packet ▪ Priority (critical or regular) for each received packet ▫ Data collection takes place at each reference device (see Section 7.1.3)

7.2.3 Test execution

In a congested environment created by reference devices creating a congested environment, PER between DUT1 and DUT2 (observed as the distance between them) is gradually increased by adjusting the attenuation.

To execute the test:

1. Set up the test bed where the total quantity of reference devices is 48 (see Section 7.1.3).

   The default attenuation of 95 dB was chosen to emulate about 75 m (according to simulations).

2. Set Variable Attenuator (at the far-right side of Figure 7-1) to 0 dB to simulate a short distance between the DUTs.
3. Start transmission at all reference devices (regular BSM broadcast).
4. Start transmission at DUT1 and DUT2 (BSM broadcast).

   Normally, BSM messages of a given DUT are sent with regular priority, but can be sent with critical priority, according to the following:

   - Critical BSMs are transmitted with highest priority at the occurrence of an event. After the first transmission of a critical BSM, a periodicity of 10 Hz is maintained until the event is over. Event duration was set to 5 sec for the test.
   - At the end of the event, the device reverts to sending BSM messages with regular priority. The event repeats 5-10 times in the overall test duration.

5. Record data and KPIs to a log file for DUT1, DUT2, and the reference devices.

   Logging/saving all KPIs is done for at least one reference device. Logging/saving is recommended for all reference devices.

6. Calculate PER between the two DUTs at both DUT1 and DUT2.

   Perform these calculations separately for critical and regular BSM messages.

NOTE: Perform these calculations separately for critical and regular BSM messages.

7. Increase the attenuation at Variable Attenuator (see far-right side of Figure 7-1) by 10 dB to simulate an increased distance between DUTs.
8. Repeat steps 5 through 7 until the overall attenuation reaches 115 dB. PER will be considered separately for critical and regular BSM messages.
9. Run this test using two C-V2X DUTs and up to 48 reference devices with special configuration (see Section 0).

   All devices (DUT1, DUT2, reference devices) have congestion control switched on.

7.2.4 Required documentation

Table 7-5 uses data collected from log files or observed from any on board unit (OBU) user interface.

Attenuation value between DUTs (dB)	Number of transmitted packets				Number of received packets				Calculated at receiver							
	DUT1		DUT2		DUT1		DUT2		PER % (DUT1)		PER % (DUT2)		95th percentile IPG (ms)		95th percentile latency (ms)	
	Critical BSM	Regular BSM	Critical BSM	Regular BSM	Critical BSM	Regular BSM	Critical BSM	Regular BSM	Critical BSM	Regular BSM	Critical BSM	Regular BSM	DUT1	DUT2	DUT1	DUT2
95	350	1448	399	1669	394	1667	347	1426	1.2	1.9	0.8	1.5	105	105	98	101
100	350	1449	400	1660	388	1542	340	1320	2.9	7.1	2.8	8.8	105	105	101	103
105	350	1451	395	1658	383	1511	330	1291	3.1	8.8	5.6	11.0	105	105	103	102
110	350	1449	400	1662	367	1408	323	1279	8.2	15.3	7.5	11.4	215	105	102	101
115	350	1450	400	1665	351	1281	322	1201	12.3	23.1	8	17.2	219	105	100	100

Table 7-5 V2V congestion control test results

7.2.5 Pass-fail criterion

Pass-fail criterion is met if satisfactory performance of lab tests with congestion control where PER performance of high-priority BSM messages is better than, or at least, equal to the low-priority messages.

7.2.6 Key takeaways

- Test results with high and low priority messages and their respective KPIs showed C-V2X to be reliable in both cases.
- Results show that PER performance of high-priority BSM messages is better than lower priority messages when high attenuations are used or when reception signals are weak.
- Under poor communication environments, high-priority BSM messages show more reliable performance compared to lower priority messages. High priority safety messages are protected more efficiently for congested and collision scenarios by the C-V2X resource selection algorithm.
- Under low attenuation or strong reception signal environments, PER improvement of high-priority BSM messages is marginal. This is expected due to PER performance of satisfactory low priority BSM messages.
- For C-V2X deployment, PER improvement of high priority BSM messages is expected to translate into noticeable and meaningful reliability improvement of critical safety messages under highly congested scenarios.

8 Crash Avoidance Metrics Partners Based Lab Congestion Scenarios

8.1 Background

CAMP LLC based lab congestion scenarios use VeCTR to emulate up to 250 devices, and show DUT performance under varying load levels with and without the congestion control algorithm enabled.

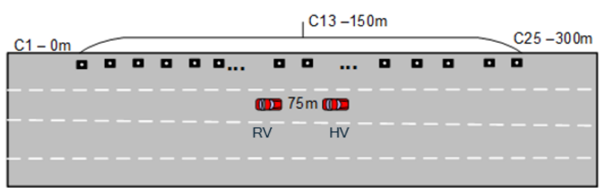
Simplifications to this test include:

- Reducing to two DUTs and 48 congesting nodes
- Using the simple path loss model
- Eliminating mobility and fading

This test is designed to mimic a real test track in the lab environment with the DUTs experiencing the maximum congestion to show the worst case performance. The DUTs subsequently experience a path loss similar to operating in the most congested area of the track (i.e., center of the test track) to capture the worst case performance (see Figure 9-1).

Each pod represents two C-V2X devices. There are 25 pods overall, evenly distributed over a 300 m track.

Path loss between HV-RV, HV-CV2X_PODS, and RV-CV2X_PODS were configured for their respective spatial positions. Scenarios were run for 1X, 2X, and 5X loads.



# Tests	6
Emulation (1x,2x,5x)	3
CC on/off	2

Figure 8-1 CAMP-based lab congestion overview

8.2 Configuration and parameters

- All devices transmit (with HARQ) a BSM payload of 383 bytes with a priority of 5, as an SPS-based flow. This translates to an MCS of 11 and 20 RB grant selection.
- Uses path loss model (see Section 6.1).
- DUTs always transmit BSMs at 100 ms.
- Congesting nodes change periodicity and transmit BSMs at the following:
  - 1X emulation – 100 ms periodicity
  - 2X emulation – 50 ms periodicity
  - 5X emulation – 20 ms periodicity
- For more information on parameters and path loss models, see Section 0.

8.3 Test results

In the following tables, rows represent transmission from devices versus column headers, i.e., reception on devices. IPG and ITT tables represent values in milliseconds.

8.3.1 1X emulation mode

Figure 8-2 provides an overview of test results for congestion control disabled and enabled cases for 1X emulation mode.

CC Disabled, 1x load (100ms) - CBR: 27%

Percentage PER matrix

	HV	RV
HV	nan	1.32812
RV	0.078064	nan

95th Percentile IPG matrix

	HV	RV
HV	nan	126
RV	118.1	nan

Mean ITT matrix

	HV	RV
HV	nan	100.001
RV	100	nan

CC Enabled, 1x load (100ms) - CBR: 24%

Percentage PER matrix

	HV	RV
HV	nan	0.320171
RV	0.108578	nan

95th Percentile IPG matrix

	HV	RV
HV	nan	204.35
RV	205	nan

Mean ITT matrix

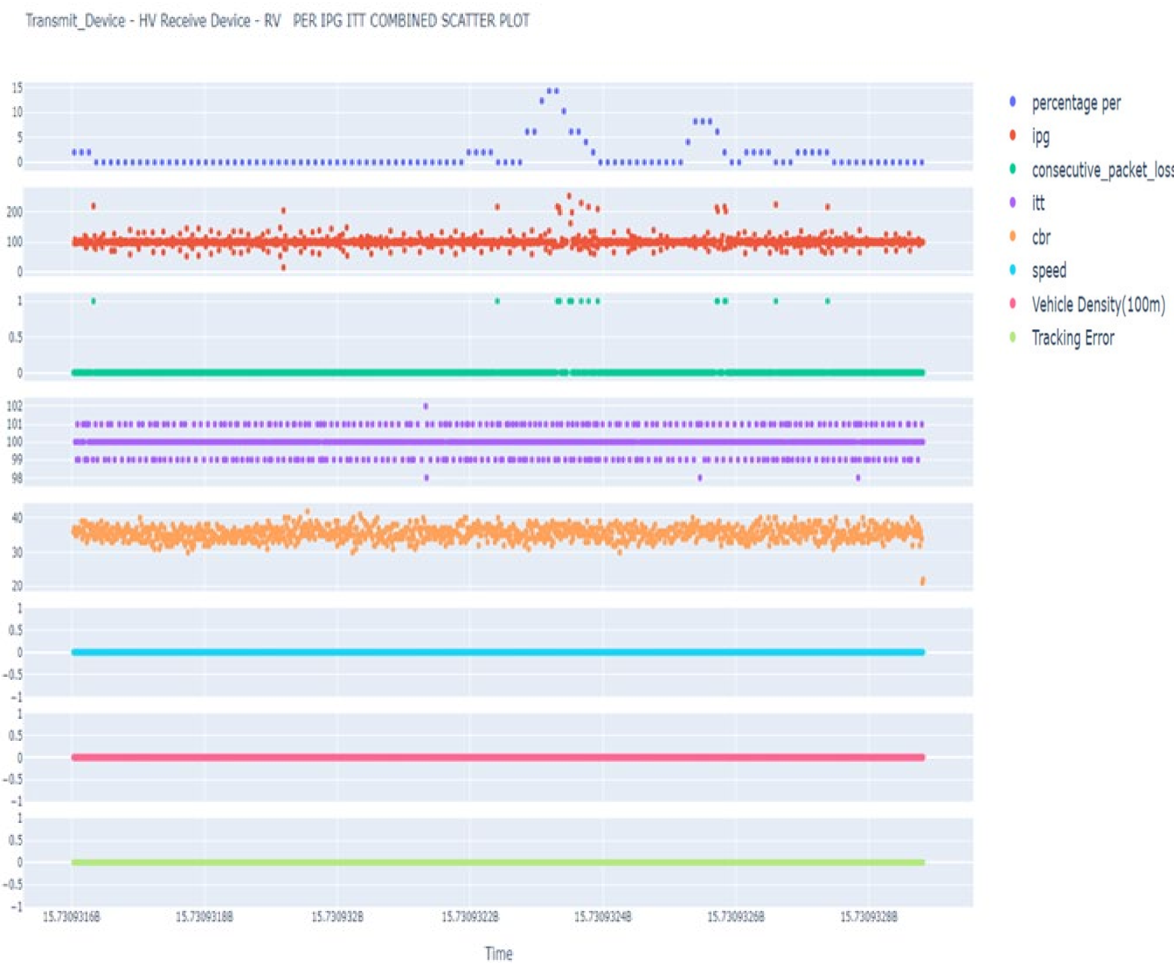
	HV	RV
HV	nan	136.12
RV	138.615	nan

Figure 8-2 CAMP test – 1X congestion control disabled/enabled

Figure 8-3 shows plots of various KPI metrics (y-axis) against duration of the entire test run (x-axis). Each KPI has a different scale on the y-axis.

Starting from the top of each congestion control disabled and enabled case with 100 ms packet periodicity, the following subplots show PER, IPG, loss of consecutive packets, ITT, CBR, speed, vehicle density and tracking error (see *On-Board System Requirements for V2V Safety Communications* (SAE J2945/1)).

100 ms CC disabled



100 ms CC enabled

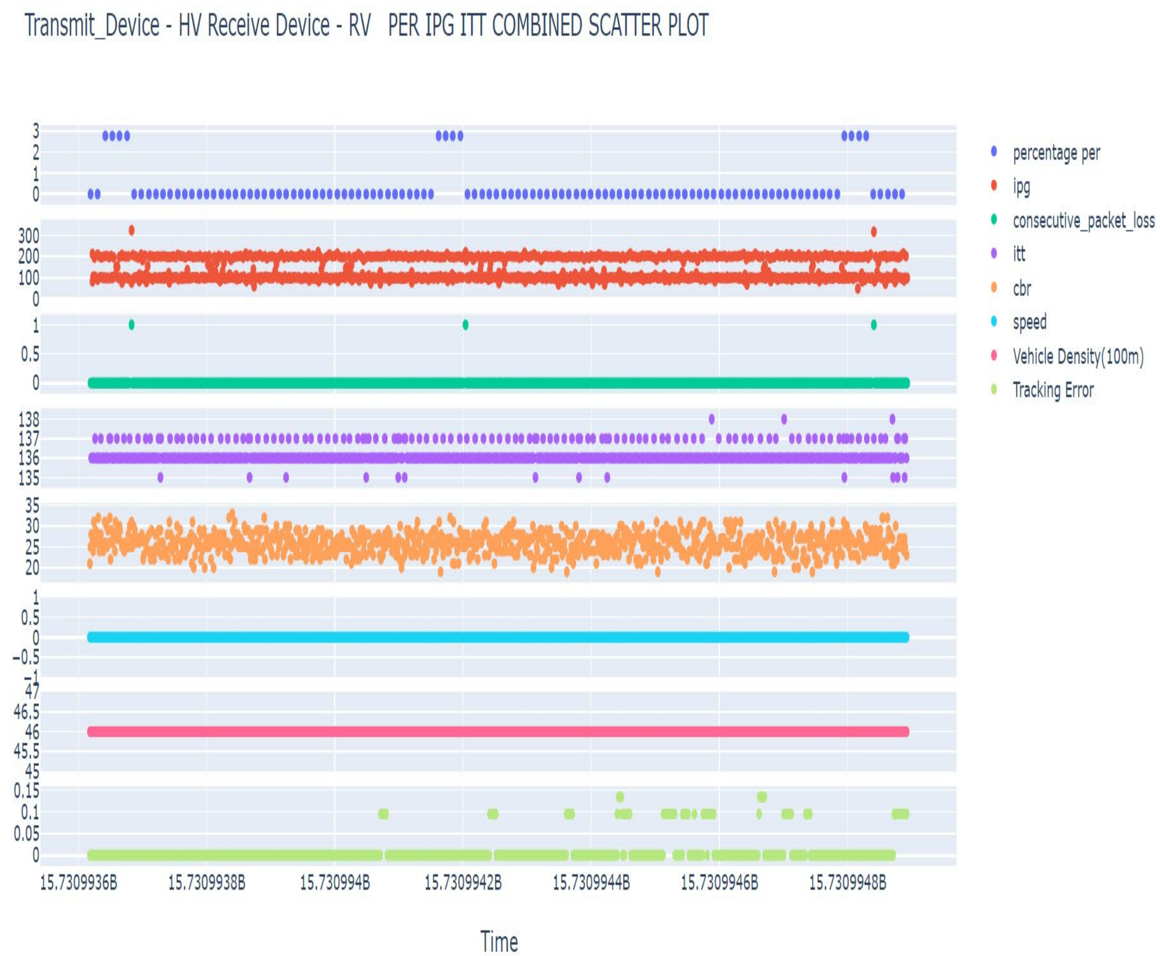


Figure 8-3 CAMP test – 1X KPI metrics

8.3.2 2X emulation mode

Figure 8-4 provides an overview of test results for congestion control disabled and enabled cases for 2X emulation mode.

CC Disabled, 2x load (50ms) - CBR: 48%

Percentage PER matrix		
	HV	**RV**
HV	nan	0.042626
RV	0.056834	nan

95th Percentile IPG matrix		
	HV	**RV**
HV	nan	109
RV	109	nan

Mean ITT matrix		
	HV	**RV**
HV	nan	100
RV	99.999	nan

CC Enabled, 2x load (50ms) - CBR: 24%

Percentage PER matrix		
	HV	**RV**
HV	nan	0.207125
RV	0.041415	nan

95th Percentile IPG matrix		
	HV	**RV**
HV	nan	311
RV	312	nan

Mean ITT matrix		
	HV	**RV**
HV	nan	293.12
RV	293.112	nan

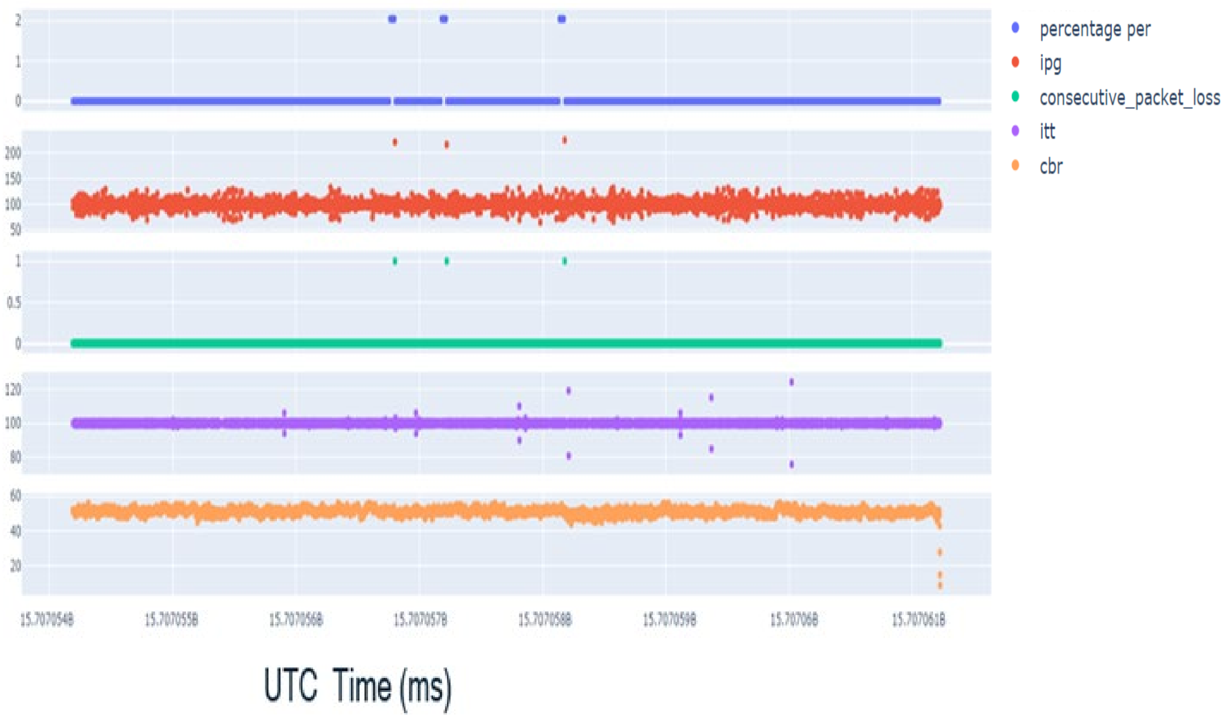
Figure 8-4 CAMP test – 2X congestion control disabled/enabled

Figure 8-5 shows plots of various KPI metrics (y-axis) against duration of the entire test run (x-axis). Each KPI has a different scale on the y-axis.

Starting from the top of each congestion control disabled and enabled case with 50 ms packet periodicity, the following subplots show PER, IPG, loss of consecutive packets, ITT, and CBR (see *On-Board System Requirements for V2V Safety Communications* (SAE J2945/1)).

50 ms CC disabled

HV transmit device – RV receive device



50 ms CC enabled

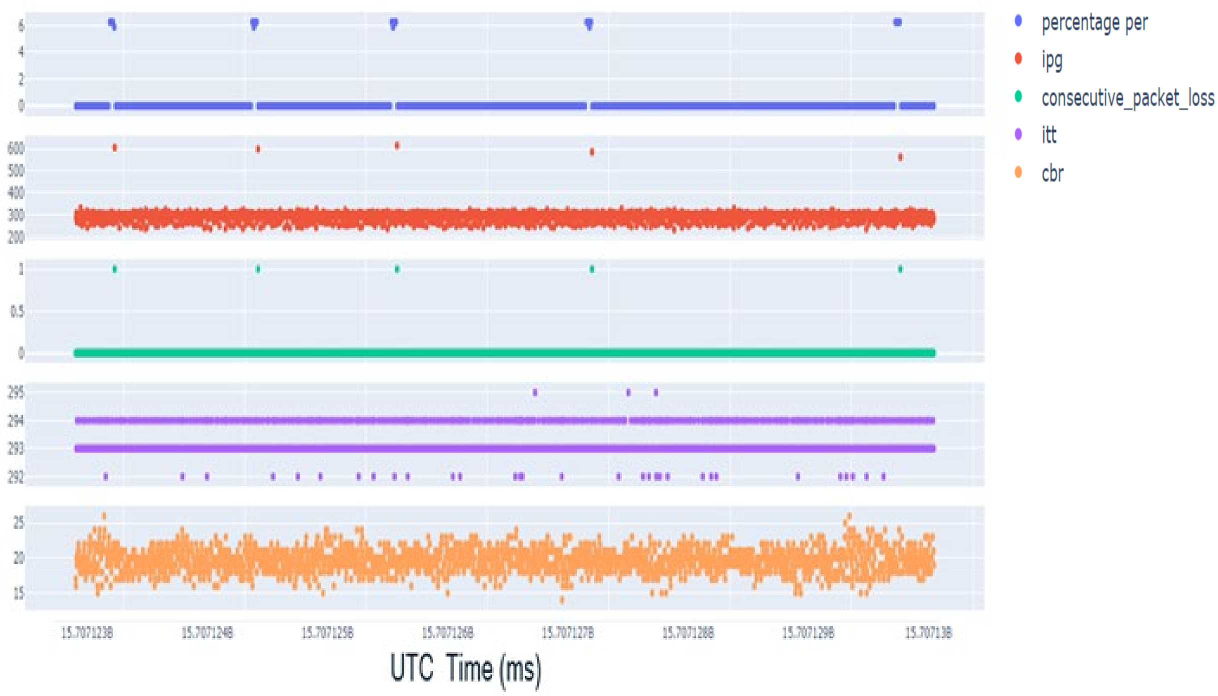


Figure 8-5 CAMP test – 2X KPI metrics

8.3.3 5X emulation mode

Figure 8-6 provides an overview of test results for congestion control disabled and enabled cases for 5X emulation mode.

CC Disabled, 5x load (20ms) - CBR: 88%

Percentage PER matrix

	HV	RV
HV	nan	4.18737
RV	3.392	nan

95th Percentile IPG matrix

	HV	RV
HV	nan	112
RV	112	nan

Mean ITT matrix

	HV	RV
HV	nan	100
RV	100	nan

CC Enabled, 5x load (20ms) - CBR: 24%

Percentage PER matrix

	HV	RV
HV	nan	0.509338
RV	0.933786	nan

95th Percentile IPG matrix

	HV	RV
HV	nan	612.5
RV	612	nan

Mean ITT matrix

	HV	RV
HV	nan	600.119
RV	600.117	nan

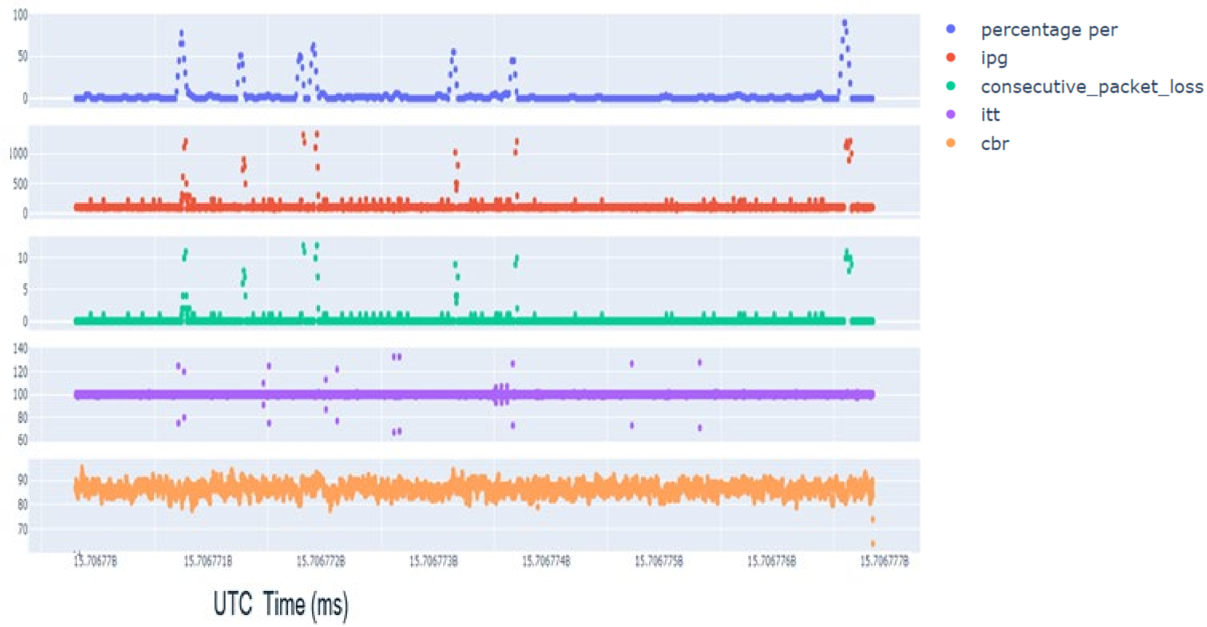
Figure 8-6 CAMP test – 5X congestion control disabled/enabled

Figure 8-7 shows plots of various KPI metrics (y-axis) against duration of the entire test run (x-axis). Each KPI has a different scale on the y-axis.

Starting from the top of each congestion control disabled and enabled case with 20 ms packet periodicity, the following subplots show PER, IPG, loss of consecutive packets, ITT, and CBR (see *On-Board System Requirements for V2V Safety Communications* (SAE J2945/1)).

20 ms CC disabled

HV transmit device – RV receive device



50 ms CC enabled

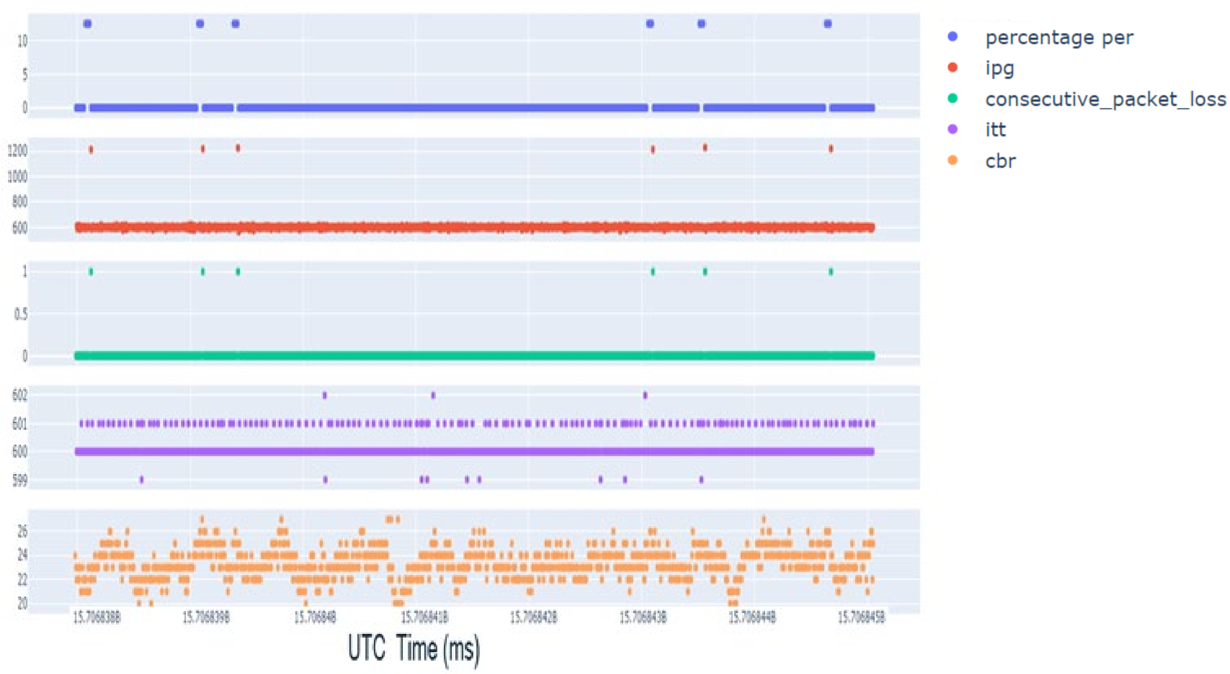


Figure 8-7 CAMP test – 5X KPI metrics

8.4 Key takeaways

- In 1X emulation mode, there is very little backoff applied by the congestion control algorithm, which results in a similar performance for both congestion control disabled and enabled cases. PER stays less than 1% and the 95th percentile IPG shows no packet loss. The CBR between both is also very comparable (approximately 25%).
- In 2X emulation mode with congestion control enabled, the congestion control algorithm results in the UE backoff for as much as 300 ms from the nominal 100 ms BSM transmission periodicity. This results in CBR dropping from 48% with no congestion control to 24% with congestion control enabled. PER (less than 1%) and IPG metrics remain fairly consistent, indicating no loss for the 95thpercentile.
- In 5X emulation mode, the congestion control algorithm shows the maximum benefit, with UE backoffs to 600 ms from the nominal 100 ms BSM transmission periodicity. This results in CBR dropping from 87% in congestion control disabled to approximately 24% with congestion control enabled. PER improves significantly from about 4-5% to less than 1% with congestion control enabled.
- The results derived from this experiment match results seen in the field for equivalent devices (HV1-HV2).

9 Four-Car Moving Platoon Simulation Results

This simulation checks performance in field tests. It is expected that performance trends will align, but due to difficulty in simulating exact path losses and field conditions, PERs might be better in simulations.

The 25 MPH four-car moving platoon scenario that was tested in the field was simulated for comparison. The setup was simulated on a 600 m track.

9.1 Test parameters

Figure 9-1 shows the test layout. Congesting devices are evenly distributed over a distance of 600 m. The four RVs are stationary and placed at 75 m intervals, such that the mid-distance between RV2 and RV3 is at the center of the track.

The four HVs maintain a 75 m distance between consecutive vehicles. All four HVs travel at 25 MPH starting at one edge of the track, making a U-turn at the other edge of the track, and then driving back. This is repeated for the duration of the simulation.

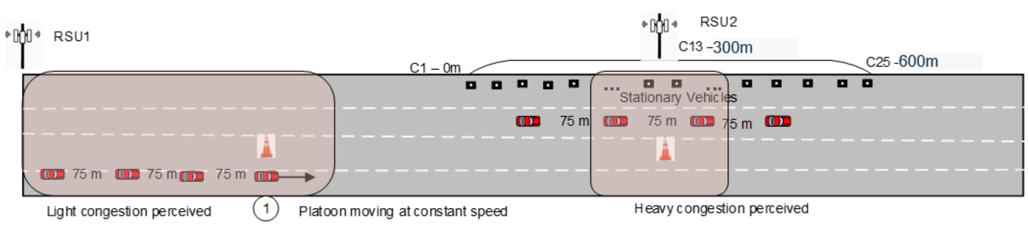


Figure 9-1 Simulated four-car moving platoon – Device layout

Ranging tests conducted with two vehicles on a similar track determine the path loss between devices (see Figure 9-2). The spike at 100 m is due to ground reflection.

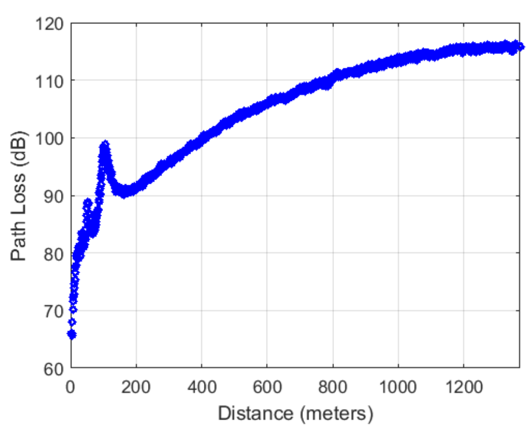


Figure 9-2 Path loss (dB) vs. distance (m)

9.2 Simulation configuration

- All devices transmit a BSM payload of 383 bytes with a priority of 2 and as an SPS-based flow. This translates to an MCS of 11 and 20 RB grant selection.
- DUTs transmit BSMs at 100 ms in the congestion control disabled scenarios.
- Congesting nodes change the periodicity of BSM transmission per emulation mode of the scenario. With congestion control disabled, congesting nodes transmit BSMs at the following:
  - 1X emulation – 100 ms periodicity
  - 2X emulation – 50 ms periodicity
  - 5X emulation – 20 ms periodicity
- DUTs and congesting nodes back off per the SAE congestion control algorithm in the congestion control enabled scenarios.

9.3 Test results

These simulation results are from a run on a 600 m track with the congestion control algorithm enabled and disabled. This section presents simulation results for the 600 m track length scenario.

9.3.1 1X load

Figure 9-3 shows performance between all transmitter-receiver DUT pairs in the 1X congestion control disabled/enabled scenarios.

Row headings are the transmit devices and the column headings denote receiving devices. From top to bottom, these tables provide the average PER, 95th percentile IPG, and maximum IPG between the DUTs.

CC Disabled, 1x load (100ms) - CBR: 25.82%

Percentage PER Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.025%	0.087%	0.062%	0.300%	0.054%	0.071%	0.140%
HV2	0.000%	nan	0.017%	0.058%	0.032%	0.359%	0.050%	0.072%
HV3	0.032%	0.017%	nan	0.199%	0.015%	0.097%	0.058%	0.080%
HV4	0.079%	0.090%	0.080%	nan	0.057%	0.089%	0.056%	0.075%
RV1	0.044%	0.057%	0.040%	0.024%	nan	0.023%	0.033%	0.071%
RV2	0.205%	0.057%	0.337%	0.162%	0.014%	nan	0.000%	0.019%
RV3	0.025%	0.022%	0.032%	0.040%	0.033%	0.017%	nan	0.024%
RV4	0.049%	0.064%	0.057%	0.049%	0.015%	0.033%	0.000%	nan

95th Percentile IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	121	122	122	122	122	122	122
HV2	122	nan	122	122	122	123	122	123
HV3	124	124	nan	124	124	124	124	124
HV4	124	124	124	nan	124	124	124	124
RV1	126	126	126	126	nan	126	126	127
RV2	126	126	126	126	125	nan	125	125
RV3	123	123	123	123	123	123	nan	123
RV4	126	126	126	126	126	126	126	nan

Max IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	200	200	200	1530	200	200	223
HV2	183	nan	200	200	200	830	200	200
HV3	200	200	nan	1419	200	200	200	200
HV4	700	600	700	nan	200	227	227	227
RV1	200	200	200	200	nan	200	219	200
RV2	796	219	838	838	200	nan	182	200
RV3	200	200	200	200	200	200	nan	200
RV4	200	232	232	200	200	200	183	nan

CC Enabled, 1x load (100ms) - CBR: 25.18%

Percentage PER Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.000%	0.033%	0.047%	0.119%	0.190%	0.038%	0.058%
HV2	0.000%	nan	0.075%	0.073%	0.082%	0.090%	0.080%	0.128%
HV3	0.042%	0.082%	nan	0.087%	0.078%	0.092%	0.223%	0.077%
HV4	0.070%	0.007%	0.028%	nan	0.063%	0.087%	0.115%	0.213%
RV1	0.017%	0.000%	0.025%	0.033%	nan	0.008%	0.072%	0.075%
RV2	0.025%	0.023%	0.030%	0.040%	0.008%	nan	0.017%	0.053%
RV3	0.134%	0.127%	0.098%	0.098%	0.080%	0.008%	nan	0.015%
RV4	0.166%	0.183%	0.157%	0.055%	0.033%	0.032%	0.000%	nan

95th Percentile IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	122	122	122	122	122	122	122
HV2	125	nan	125	125	126	126	126	126
HV3	123	123	nan	124	123	123	124	123
HV4	125	125	125	nan	125	125	125	125
RV1	128	127	128	128	nan	128	128	128
RV2	127	127	127	127	127	nan	127	127
RV3	124	124	124	124	124	123	nan	123
RV4	131	131	131	131	131	130	130	nan

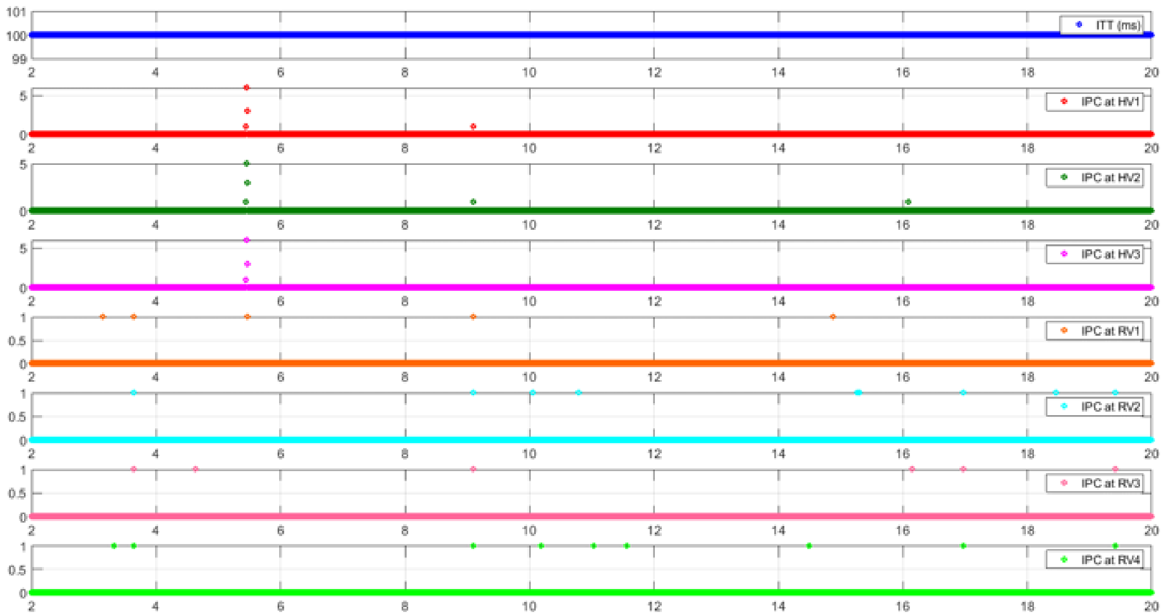
Max IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	181	200	200	701	706	200	206
HV2	182	nan	200	200	200	200	200	858
HV3	200	204	nan	215	215	218	906	201
HV4	700	200	200	nan	200	234	700	700
RV1	200	183	200	200	nan	200	200	200
RV2	200	200	200	200	200	nan	200	200
RV3	806	806	806	806	806	200	nan	200
RV4	673	673	673	200	200	200	182	nan

Figure 9-3 Lab – 1X congestion control disabled/enabled performance

Figure 9-4 shows CPL/IPC analysis for transmissions from HV4 toward all other DUTs. The top plot shows ITT at HV4. Each colored line in the following plots show CPLs between HV4 and other DUTs.

100 ms DCC disabled



100 ms DCC enabled

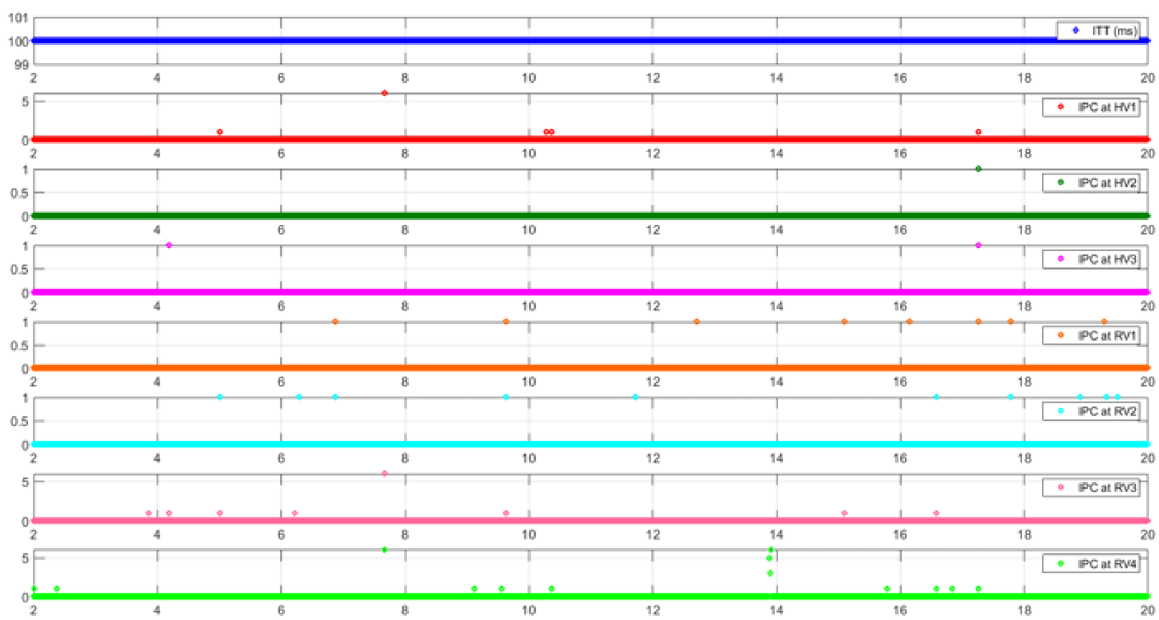


Figure 9-4 Lab – 1X CPL/IPC analysis

Figure 9-5 provides further analysis of transmission performance from HV4 to HV1 in the 1X congestion control enabled scenario. The plots cover these metrics:

- PER at HV1
- IPG at HV1
- CPL/IPC at HV1
- ITT at HV4
- CBR at HV4

100 ms CC enabled detailed simulation metric analysis

Transmit device HV4 vs. Receive device HV1

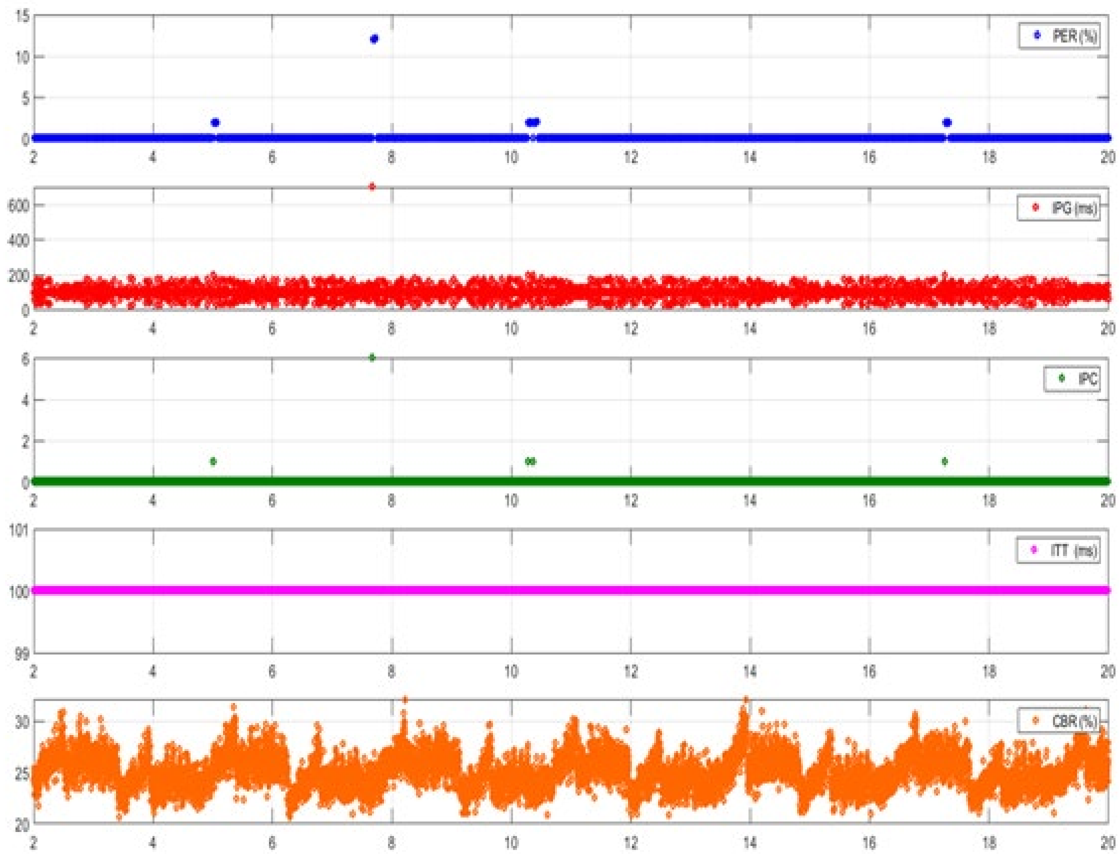


Figure 9-5 Simulation – 1X transmission performance from HV4 to HV1

9.3.1.1 Key takeaways

- CBR for this test is 25% (congestion control enabled) and 25% (congestion control disabled). A congestion control enabled case does not cause any backoff. Congestion control enabled and congestion control disabled scenarios are identical in this case.
- PER and IPG performance are the same for both the congestion control enabled and congestion control disabled scenarios.
- Overall PER is low with a maximum below 0.5%.
- The 95th percentile IPG peaks at about 130 ms.
- Maximum IPG is less than 0.9 s for most links outside a couple of outliers.

9.3.2 2X load

Figure 9-6 shows performance between all transmitter-receiver DUT pairs in the 2X scenario.

CC Disabled, 2x load (50ms) - CBR: 46.58%

Percentage PER Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.017%	0.065%	0.015%	0.140%	0.167%	0.142%	0.133%
HV2	0.000%	nan	0.000%	0.015%	0.275%	0.273%	0.154%	0.211%
HV3	0.015%	0.000%	nan	0.017%	0.082%	0.213%	0.071%	0.089%
HV4	0.032%	0.000%	0.008%	nan	0.064%	0.042%	0.047%	0.082%
RV1	0.119%	0.136%	0.078%	0.083%	nan	0.000%	0.049%	0.106%
RV2	0.204%	0.040%	0.233%	0.064%	0.007%	nan	0.008%	0.033%
RV3	0.024%	0.040%	0.015%	0.025%	0.015%	0.000%	nan	0.017%
RV4	0.008%	0.022%	0.024%	0.040%	0.015%	0.008%	0.000%	nan

95th Percentile IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	119	119	119	119	119	119	119
HV2	123	nan	123	123	125	124	124	124
HV3	119	118	nan	119	119	119	119	119
HV4	121	121	121	nan	121	121	121	121
RV1	121	122	121	121	nan	121	121	122
RV2	122	122	122	122	122	nan	122	122
RV3	119	119	119	119	119	119	nan	119
RV4	122	122	122	122	122	122	122	nan

Max IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	200	222	200	687	687	687	687
HV2	181	nan	181	200	400	839	632	900
HV3	200	183	nan	202	202	600	200	200
HV4	200	177	200	nan	200	200	213	200
RV1	800	800	535	535	nan	179	200	409
RV2	882	213	882	268	200	nan	200	213
RV3	224	224	224	200	200	179	nan	200
RV4	200	200	200	200	200	200	178	nan

CC Enabled, 2x load (50ms) - CBR: 32.47%

Percentage PER Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.072%	0.056%	0.091%	0.348%	0.312%	0.547%	0.232%
HV2	0.030%	nan	0.035%	0.142%	0.532%	0.703%	0.437%	0.367%
HV3	0.065%	0.031%	nan	0.042%	0.390%	0.316%	0.273%	0.432%
HV4	0.043%	0.056%	0.009%	nan	0.331%	0.421%	0.378%	0.253%
RV1	0.079%	0.074%	0.095%	0.104%	nan	0.024%	0.101%	0.121%
RV2	0.104%	0.164%	0.118%	0.142%	0.028%	nan	0.015%	0.364%
RV3	0.198%	0.179%	0.086%	0.142%	0.131%	0.014%	nan	0.039%
RV4	0.151%	0.126%	0.165%	0.171%	0.158%	0.145%	0.021%	nan

95th Percentile IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	200	200	200	200	200	200	200
HV2	200	nan	200	200	200	200	200	200
HV3	200	200	nan	200	200	200	200	200
HV4	200	200	200	nan	200	200	200	200
RV1	200	200	200	200	nan	200	200	200
RV2	200	200	200	200	200	nan	200	200
RV3	200	200	200	200	200	200	nan	200
RV4	200	200	200	200	200	200	200	nan

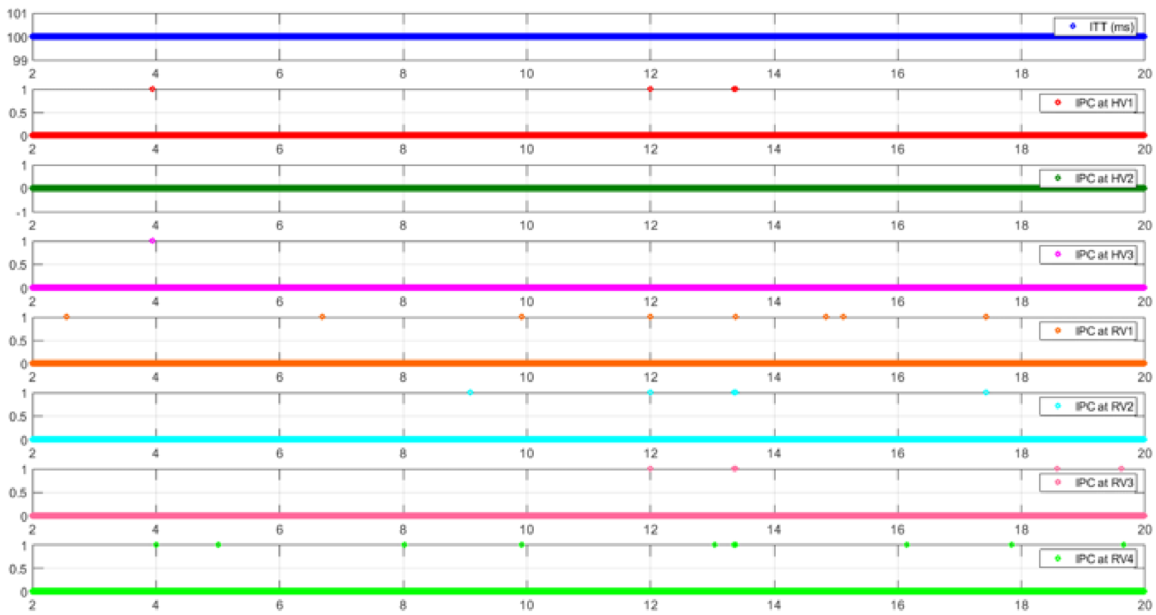
Max IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	337	337	337	357	400	400	400
HV2	361	nan	300	377	361	400	400	400
HV3	400	300	nan	400	400	348	400	395
HV4	300	300	270	nan	300	338	300	300
RV1	300	300	300	347	nan	312	300	300
RV2	400	400	400	400	300	nan	356	591
RV3	775	400	400	400	400	300	nan	387
RV4	400	300	400	400	400	400	300	nan

Figure 9-6 2X congestion control disabled/enabled performance

Figure 9-7 shows 2X CPL/IPC analysis for transmissions from HV4 toward all other RX devices.

50 ms DCC disabled



50 ms DCC enabled

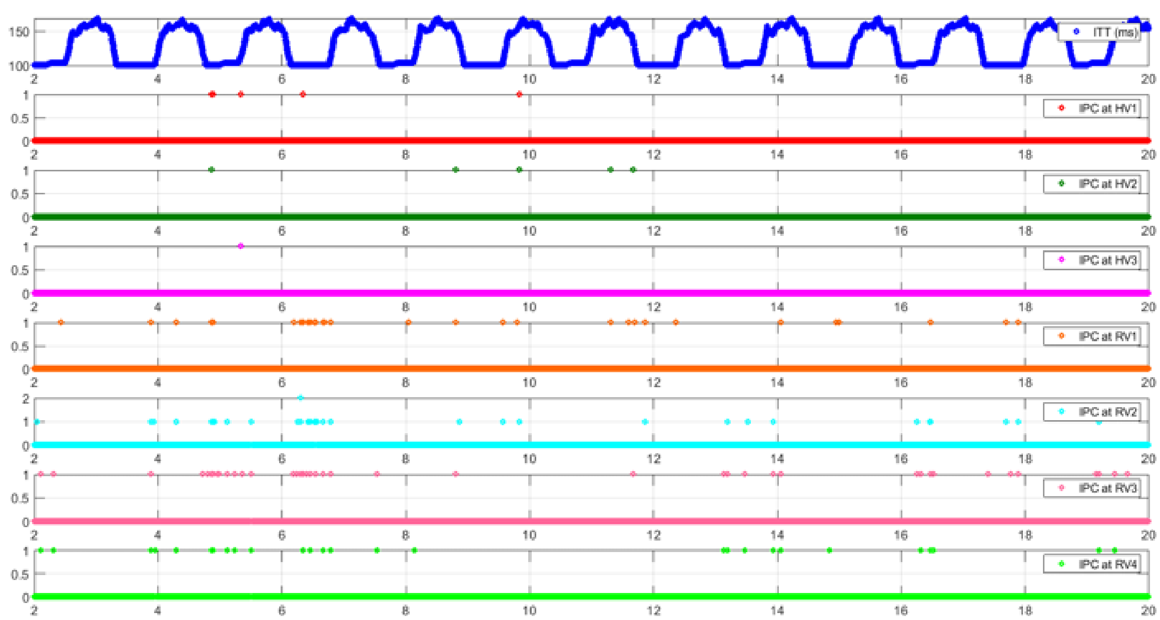


Figure 9-7 2X CPL/IPC analysis

Figure 9-8 provides further analysis of transmission performance from HV4 to HV1 in the 2X congestion control enabled scenario.

50 ms CC enabled detailed simulation metric analysis

Transmit device HV4 vs. Receive device HV1

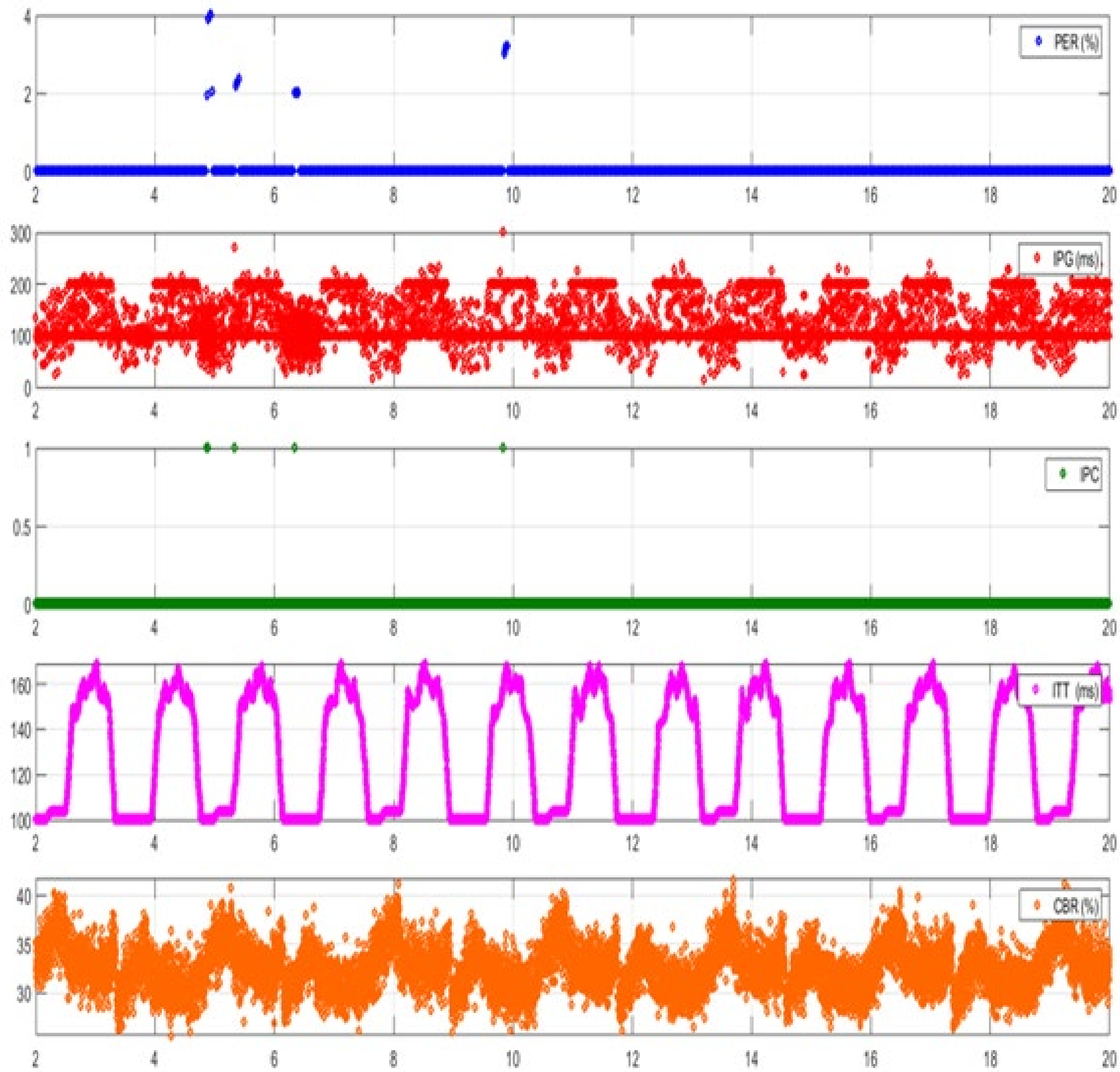


Figure 9-8 2X transmission performance from HV4 to HV1

9.3.2.1 Key takeaways

- CBR for this test is 33% (congestion control enabled) and 47% (congestion control disabled). A congestion control enabled case causes the CBR to drop as all the devices back off to a higher ITT.
- Overall PER is low with a maximum of approximately 0.7%.
- The 95th percentile IPG peaks at about 125 ms for congestion control disabled, and 200 ms for congestion control enabled cases.
- The maximum IPG is less than 0.9 s for both the congestion control disabled and enabled cases. There are more links that exceed 0.5 s in the congestion control disabled case.
- ITT indicates that applied backoffs in this case are as expected, i.e., DUT backoff to ITT of 170 ms from a nominal 100 ms in the most congested areas of the track.

9.3.3 5X load

Figure 9-9 shows performance between all transmitter-receiver DUT pairs in the 5X scenario.

CC Disabled, 5x load (20ms) - CBR: 82.31%

Percentage PER Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.233%	0.985%	1.604%	12.565%	12.218%	12.132%	7.094%
HV2	0.035%	nan	0.053%	1.662%	13.247%	11.582%	12.380%	7.066%
HV3	3.601%	0.139%	nan	0.240%	11.657%	13.160%	12.668%	7.797%
HV4	1.710%	1.690%	0.000%	nan	10.524%	12.309%	9.370%	4.883%
RV1	4.916%	4.570%	4.862%	4.775%	nan	0.258%	1.593%	4.276%
RV2	1.589%	1.853%	1.712%	2.188%	0.225%	nan	0.235%	2.501%
RV3	2.327%	1.486%	1.560%	2.043%	5.190%	1.967%	nan	0.420%
RV4	4.368%	4.228%	4.502%	3.935%	4.666%	4.637%	0.000%	nan

95th Percentile IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	121	123	124	147	147	145	133
HV2	119	nan	119	123	149	144	157	134
HV3	127	122	nan	122	153	155	153	135
HV4	124	122	120	nan	136	141	139	129
RV1	134	133	133	133	nan	122	128	132
RV2	125	125	127	126	122	nan	123	128
RV3	125	124	124	124	129	123	nan	122
RV4	128	128	128	128	133	129	122	nan

Max IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	1561	1561	1283	2548	2548	2557	2557
HV2	200	nan	200	1246	2266	2266	2094	2094
HV3	1566	827	nan	1430	1566	1566	1763	2428
HV4	1607	1630	179	nan	1776	1776	1567	1630
RV1	1579	1579	1579	1516	nan	845	1494	2962
RV2	899	945	899	1027	780	nan	317	1083
RV3	1640	1003	1003	1388	1593	1555	nan	1003
RV4	1602	1602	1602	1602	1284	1602	179	nan

CC Enabled, 5x load (20ms) - CBR: 29.12%

Percentage PER Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.083%	0.560%	0.489%	2.092%	2.013%	2.025%	1.623%
HV2	0.000%	nan	0.089%	0.664%	2.295%	2.250%	2.190%	1.923%
HV3	0.508%	0.081%	nan	0.177%	2.274%	2.811%	2.216%	1.932%
HV4	0.554%	0.799%	0.055%	nan	1.821%	1.789%	1.447%	1.668%
RV1	1.057%	1.025%	1.178%	1.509%	nan	0.000%	1.057%	1.349%
RV2	0.858%	0.913%	0.828%	0.685%	0.056%	nan	0.000%	0.832%
RV3	1.325%	0.773%	1.529%	1.433%	1.103%	0.000%	nan	0.126%
RV4	1.080%	1.063%	0.916%	0.783%	1.402%	1.219%	0.047%	nan

95th Percentile IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	400	400	400	406	406	407	405
HV2	433	nan	435	442	455	459	461	459
HV3	437	434	nan	435	463	467	463	463
HV4	400	400	400	nan	400	400	400	400
RV1	400	400	400	400	nan	400	400	400
RV2	500	500	500	500	500	nan	500	500
RV3	500	500	500	500	500	500	nan	500
RV4	400	400	400	400	400	400	400	nan

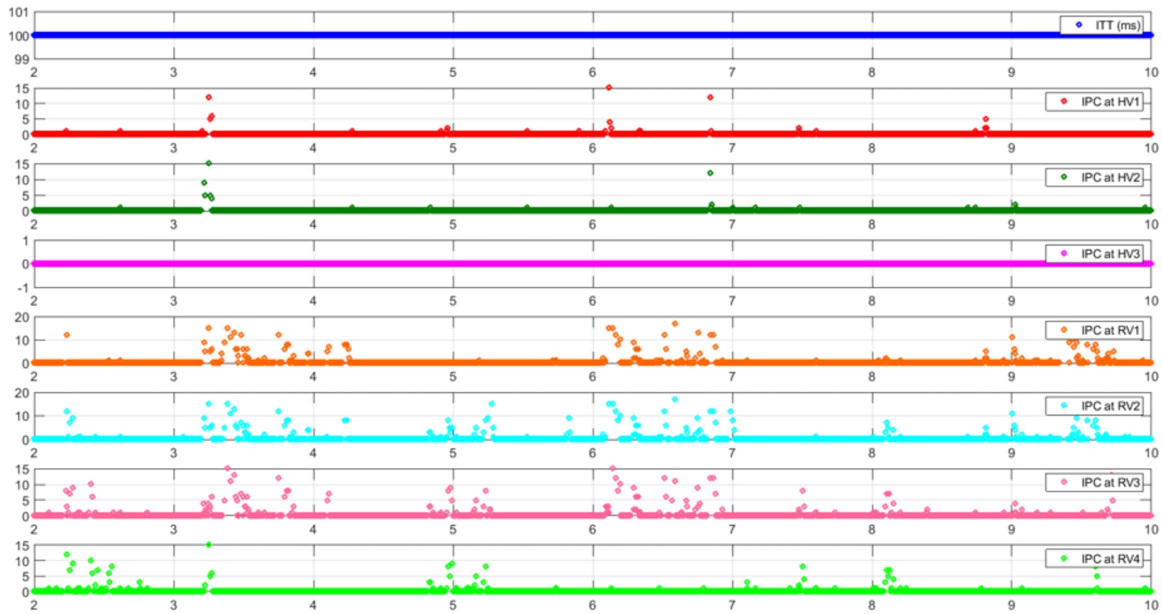
Max IPG Matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	700	800	800	834	801	1200	1200
HV2	510	nan	800	1100	1625	1100	900	1092
HV3	860	700	nan	800	900	1300	900	900
HV4	800	812	800	nan	1600	820	800	1236
RV1	1000	800	800	800	nan	443	800	1000
RV2	900	900	900	957	799	nan	518	900
RV3	900	900	975	964	1200	506	nan	793
RV4	782	800	800	800	1100	1100	655	nan

Figure 9-9 5X congestion control disabled/enabled performance

Figure 9-10 shows 5X CPL/IPC analysis for transmissions from HV4 toward the other DUTs.

20 ms DCC disabled



20 ms DCC enabled

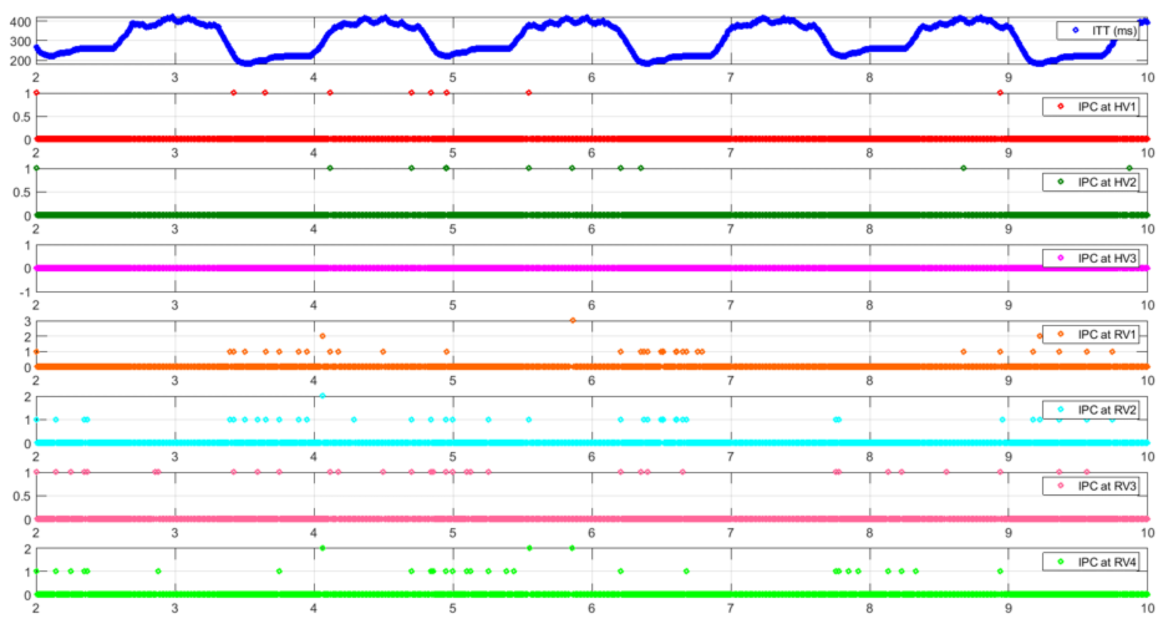


Figure 9-10 5X CPL/IPC analysis

Figure 9-11 provides further analysis of transmission performance from HV4 to HV1 in the 5X congestion control enabled scenario.

20 ms CC enabled detailed simulation metric analysis

Transmit device HV4 vs. Receive device HV1

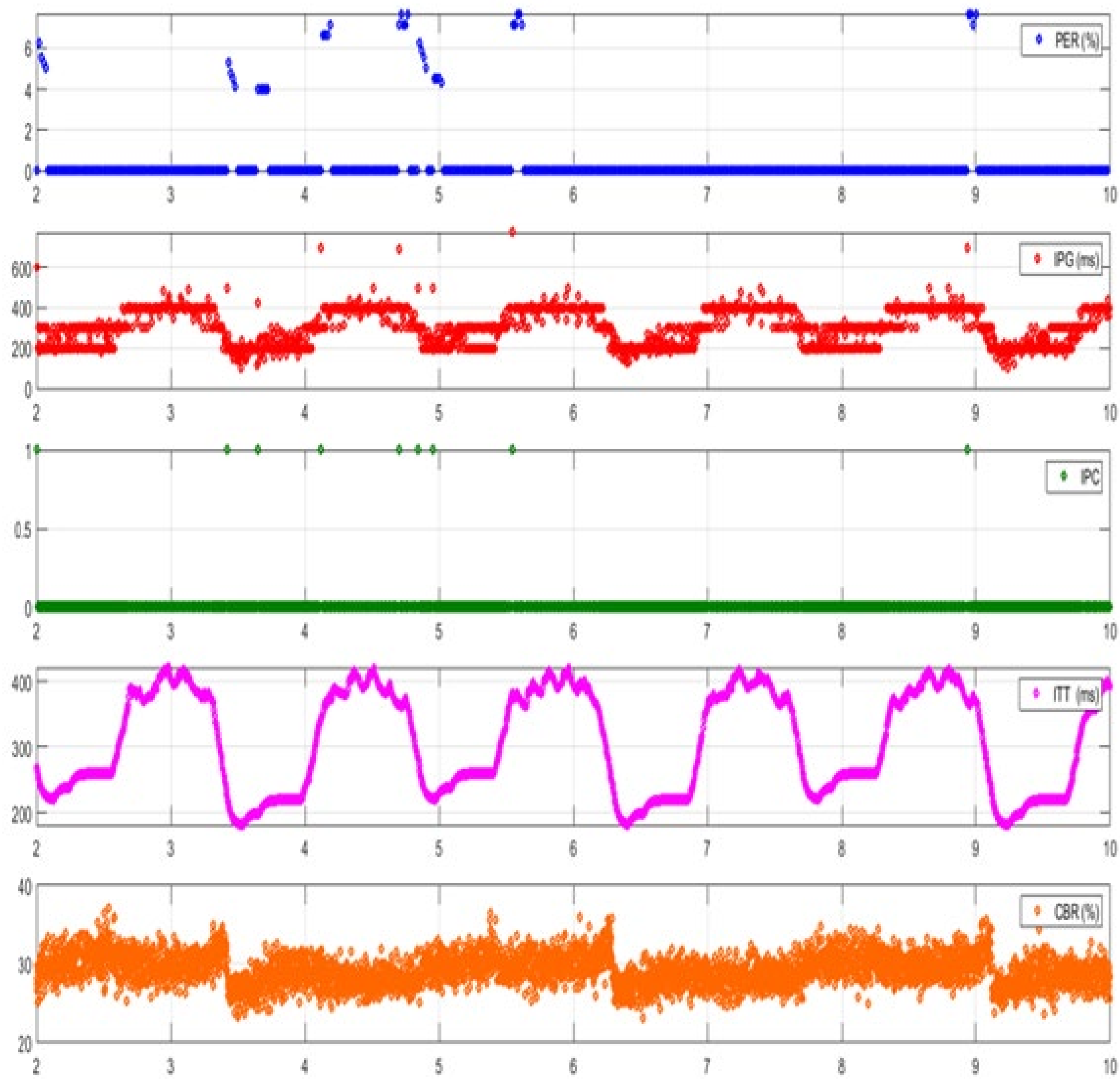


Figure 9-11 5X transmission performance from HV4 to HV1

9.3.3.1 Key takeaways

- CBR for this test is 29.12% (congestion control enabled) and 82.31% (congestion control disabled). The congestion control enabled case causes CBR to drop as all devices back off to a higher ITT.
- PER is high in the congestion control disabled case, reaching up to 13%. However, PER is low at less than 3% in the congestion control enabled case.
- The 95th percentile IPG peaks at about 160 ms for the congestion control disabled case and 500 ms for the congestion control enabled case.
- The maximum IPG is around 3 s for the congestion control disabled case, and 1.6 s for the congestion control enabled case.
- The maximum IPG is generally high in the congestion control disabled case with several links experiencing an IPG of more than 2 s. Maximum IPG is lower in the congestion control enabled case with most links at less than 1.2 s.

9.3.4 Key takeaways for the 600 m tests

- In 1X emulation mode, enabling congestion control does not result in any backoff due to low load. PER and IPG performance are excellent for both the congestion control enabled and congestion control disabled cases. PER remains less than 0.5% and 95th percentile IPG shows no packet loss 95% of the time. CBR is about 25%.
- In 2X emulation mode, PER and IPG performance are excellent for both congestion control enabled and congestion control disabled cases. PER remains less than 0.7% and 95th percentile IPG shows no packet loss 95% of the time. With congestion control enabled, CBR drops to about 33%, while the congestion control disabled case has a CBR of approximately 47%.
- In 5X emulation mode, CBR drops from about 82% with congestion control disabled, to approximately 29% with congestion control enabled as devices backoff to about 450 ms from the nominal 100 ms periodicity. PER in this mode significantly improves with congestion control disabled (showcasing PER of up to 13%) while congestion control enabled reduces PER to less than 3% for all links. The maximum IPG is about 3 s for the congestion control disabled case, while it is reduced to 1.6 s for the congestion control enabled case.
- Congestion based rate control helps improves the PER and maximum IPG metrics.

10 Field Testing

Field testing was performed at the San Diego County Credit Union Stadium in September 2019 with the MDM-9150-CS3 build. For a diagram showing actual deployment of the field test setup, see Figure 4-1.

Tests conducted as part of this effort use the large scale field test setup described in Chapter 4 to perform the following tests:

- Four car moving platoon (for a track length of 600 m and 300 m)
- Hard-brake tests in a congested environment (for a track length of 600 m and 300 m)
- Non-line of sight (NLOS) test for C-V2X transmission and reception in a congested environment (for a track length of 300 m)

10.1 Configuration

- All devices transmit a BSM payload of 383 bytes with a priority of 2, and as an SPS-based flow. This translates to an MCS of 11 and 20 RB grant selection.
- Only the critical BSM message that conveys hard-braking is transmitted as event-based flows with a priority of 0 for the duration of the event.
- Congesting nodes change the periodicity of BSM transmission per emulation mode of the scenario. With congestion control disabled, congesting nodes transmit BSMs at the following:
  - 1X emulation – 100 ms periodicity
  - 2X emulation – 50 ms periodicity
  - 5X emulation – 20 ms periodicity

10.2 600 m test results

This section presents field test results for the 600 m track length scenario. These field tests were run with the congestion control algorithm enabled and disabled.

10.2.1 Four-car moving platoon test (20 MPH)

In this test, there are four moving vehicles in a platoon. The moving vehicles provide transient PER samples against stationary vehicles.

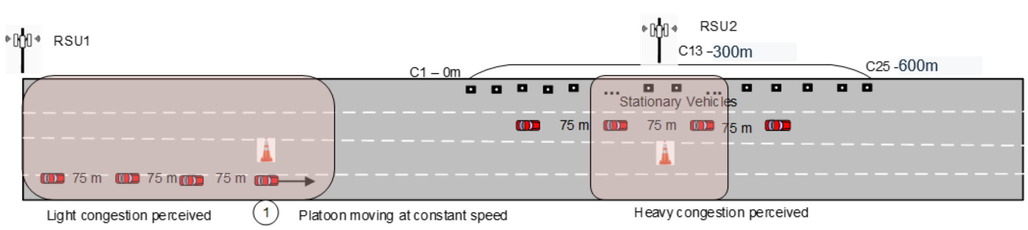


Figure 10-1 Field – Four-car moving platoon test (20 MPH)

10.2.1.1 1X load

Figure 10-2 shows performance between all transmitter-receiver DUT pairs in the 1X congestion control disabled and enabled scenarios. Row headings are the transmit devices and the column headings denote receiving devices. From top to bottom, these tables provide the average PER, 95th percentile IPG, and maximum IPG between the DUTs.

CC Disabled, 1x load (100ms) - CBR: 24%

Percentage PER matrix							
	HV1	HV2	HV3	HV4	RV1	RV2	RV4
HV1	nan	0.01	0.01	0.08	0.07	0.08	0.03
HV2	0.03	nan	0.12	0.15	0.23	0.45	0.14
HV3	0.01	0.04	nan	0.05	0.05	0.05	0.08
HV4	0.14	0.12	0.08	nan	0.08	0.07	0.05
RV1	0.05	0.15	0.07	0.08	nan	0.09	0.11
RV2	0.03	0.41	0.03	0	0.04	nan	0.04
RV4	0.27	0.04	0.05	0.07	0.28	0.05	nan

95th Percentile IPG matrix							
	HV1	HV2	HV3	HV4	RV1	RV2	RV4
HV1	nan	120	121	120	120	120	120
HV2	119	nan	118	119	120	120	120
HV3	121	121	nan	121	122	121	121
HV4	120	120	120	nan	121	120	120
RV1	122	122	123	122	nan	122	122
RV2	118	119	118	118	118	nan	118
RV4	123	122	122	122	122	122	nan

Max IPG matrix							
	HV1	HV2	HV3	HV4	RV1	RV2	RV4
HV1	nan	149	217	219	222	223	222
HV2	217	nan	223	235	240	643	223
HV3	220	218	nan	219	220	222	224
HV4	223	225	222	nan	221	222	219
RV1	220	313	234	229	nan	232	230
RV2	219	622	232	180	222	nan	267
RV4	480	222	219	223	500	217	nan

CC Enabled, 1x load (100ms) - CBR: 24%

Percentage PER matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.07	0.1	0.09	0.27	0.16	0.11	0.1
HV2	0.04	nan	0.01	0.06	0.04	0.03	0.1	0.1
HV3	0.1	0.09	nan	0.07	0.09	0.1	0.09	0.2
HV4	0.03	0.04	0.04	nan	0.06	0.11	0.43	0.1
RV1	0.2	0.1	0.11	0.14	nan	0.13	0.14	0.11
RV2	0.06	0.07	0.09	0.1	0.03	nan	0.1	0.07
RV3	0.14	0.39	0.14	0.14	0.43	0.45	nan	0.13
RV4	0.1	0.06	0.09	0.07	0.09	0.06	0.04	nan

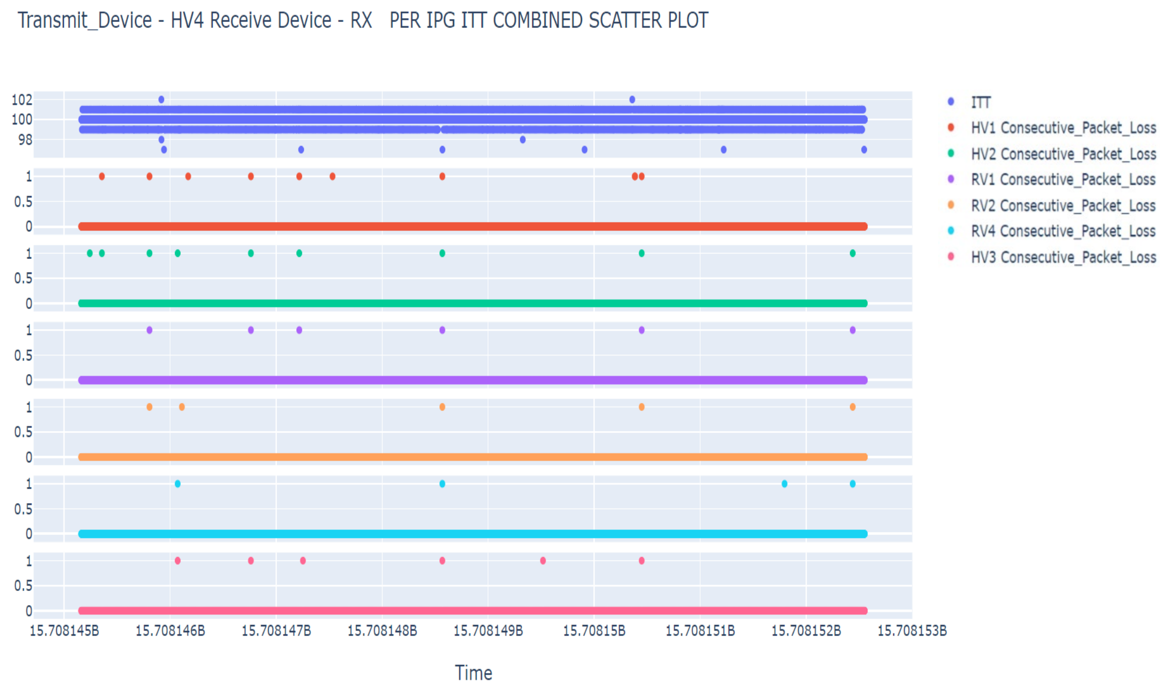
95th Percentile IPG matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	125	125	125	126	126	126	126
HV2	118	nan	118	117	118	117	118	117
HV3	116	117	nan	116	116	116	116	116
HV4	122	122	122	nan	123	123	125	123
RV1	126	126	125	126	nan	125	126	125
RV2	120	120	120	120	120	nan	119	120
RV3	121	121	122	121	122	121	nan	121
RV4	121	120	121	120	121	120	120	nan

Max IPG matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	228	239	237	239	239	222	225
HV2	221	nan	216	222	223	220	219	248
HV3	236	225	nan	227	222	245	242	241
HV4	218	219	227	nan	234	229	857	228
RV1	690	604	696	521	nan	605	698	693
RV2	240	226	239	227	246	nan	442	227
RV3	228	821	317	512	814	820	nan	221
RV4	220	221	234	219	220	220	221	nan

Figure 10-2 Field, four-car (600 m) – 1X congestion control disabled/enabled performance

Figure 10-3 shows 1X CPL analysis for transmissions from HV4 toward all other DUTs. The top plot shows ITT at HV4. The subsequent seven plots show the CPLs between HV4 and other DUTs.

100 ms CC disabled



100 ms CC enabled

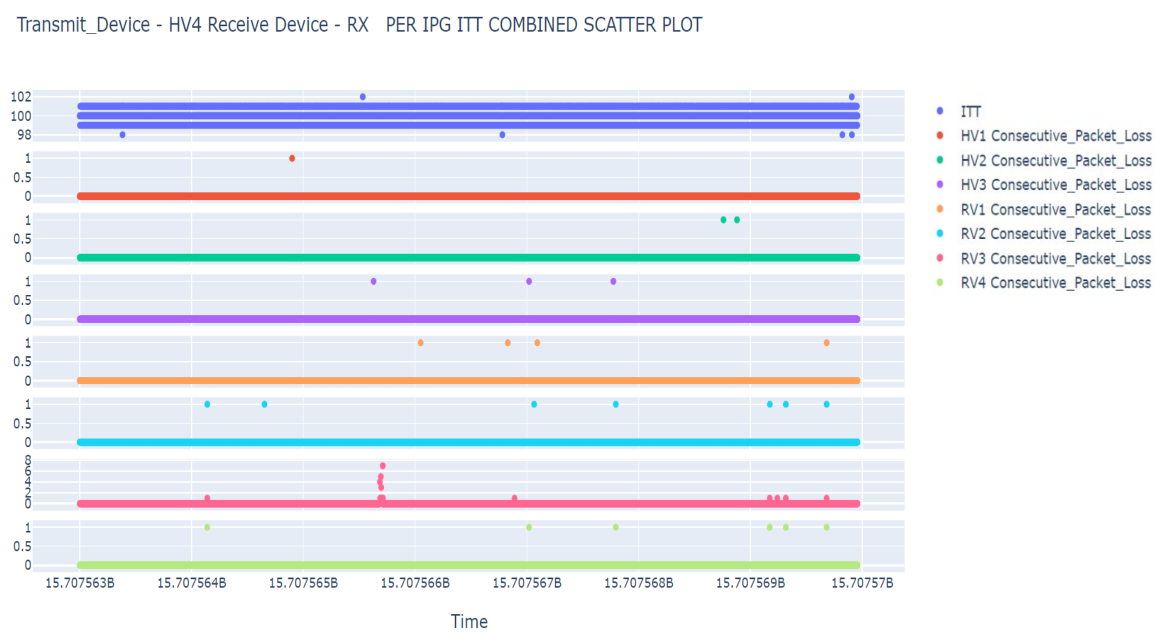


Figure 10-3 Field, four-car (600 m) – 1X CPL analysis

Figure 10-4 provides further analysis of transmission performance from HV4 to HV1 in the 1X congestion control enabled scenario. The plots cover these metrics:

- Modem: CBR, CPL
- ITS: PER, IPG, ITT, vehicle density, and tracking error

100 ms CC enabled detailed test metric analysis

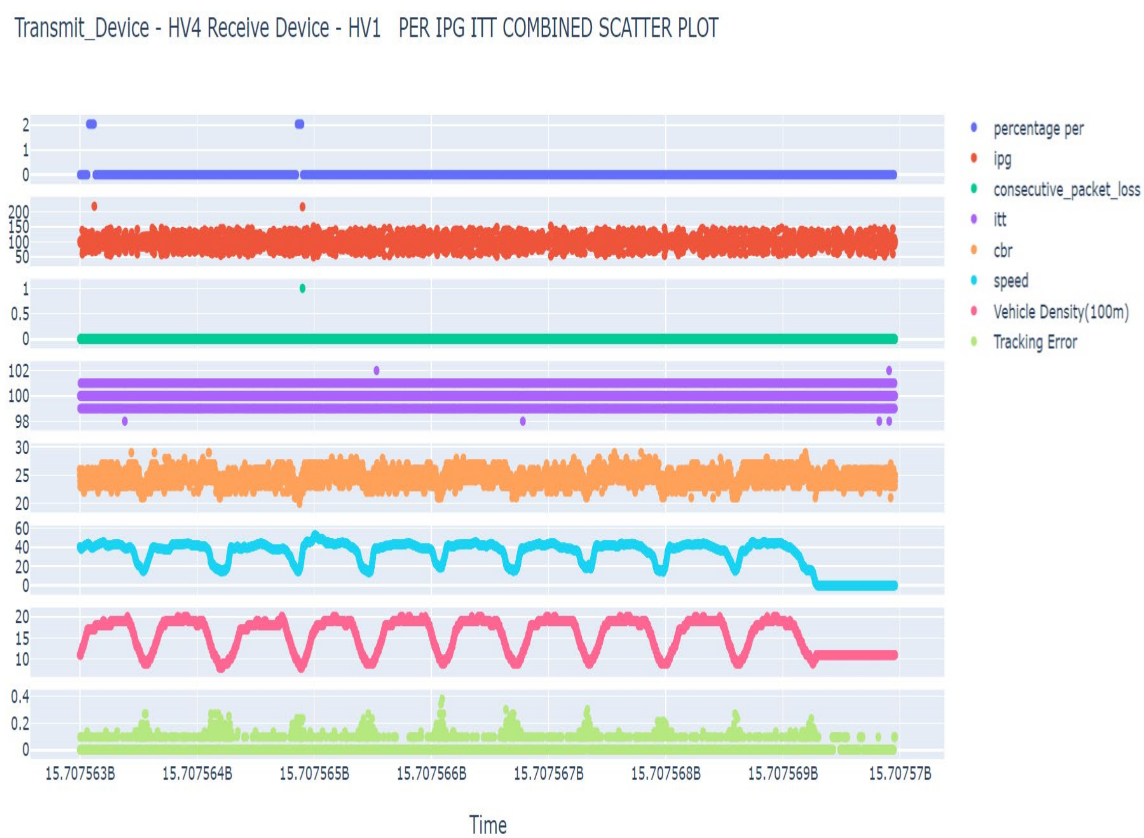


Figure 10-4 Field, four-car (600 m) – 1X transmission performance from HV4 to HV1

10.2.1.1.1 Key takeaways

- This system exhibits no packet loss 95% of the time in the congested environment where it was tested (as expected).
- CBR for this test is about 24%. The congestion control enabled case has no backoffs and the average CBR remains consistent.
- All links have less than 0.5% PER for both cases.
- The 95th percentile IPG shows zero packets were lost 95% of the time.
- The maximum IPG indicates that approximately 1-7 packets were lost consecutively for most links. The outlier for higher packet loss occurs in the case of lock-in between resources.
- ITT indicates that no backoffs were applied in this case, and that the DUT transmits at a nominal 100 ms periodicity even in the most congested areas of the track.
- The tracking error (ITS) was relatively low at the straight line and increased up to 0.4 around the edges of the track when the cars turned.

Simulation comparison

- CBR aligns well with simulation results where CBR was measured at approximately 25%.
- PER in simulation is slightly lower with a maximum below 0.5%.
- The 95th percentile IPG matches well between field tests and simulations.
- Outside a couple of outliers, the maximum IPG results align and are equal or less than 0.9 s.

10.2.1.2 2X load

Figure 10-5 shows performance between all transmitter-receiver DUT pairs in the 2X congestion control disabled and enabled scenarios.

CC Disabled, 2x load (50ms) - CBR: 48%

Percentage PER matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.41	0.53	0.34	2.31	3.24	2.93	3.65
HV2	0.01	nan	0.05	0.07	0.15	0.19	0.11	0.26
HV3	0.05	0.11	nan	0.03	0.39	1.73	1.38	0.95
HV4	0.11	0.14	0.07	nan	0.34	0.34	0.39	0.32
RV1	0.16	0.08	0.07	0.07	nan	0.88	0.18	0.12
RV2	0.07	0.11	0.72	0.04	0.76	nan	0.05	0.08
RV3	0.09	0.23	0.31	0.16	0.23	0.14	nan	0.66
RV4	0.24	0.14	0.12	0.12	0.3	0.22	0.14	nan

95th Percentile IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	120	121	120	126	126	126	126
HV2	120	nan	121	120	121	121	120	121
HV3	121	121	nan	121	121	125	125	125
HV4	120	120	119	nan	120	119	120	120
RV1	120	120	120	120	nan	120	120	120
RV2	120	120	121	120	121	nan	120	120
RV3	121	120	121	121	121	121	nan	121
RV4	120	120	120	120	120	121	120	nan

Max IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	816	512	412	905	1288	1286	1289
HV2	221	nan	221	250	226	252	247	516
HV3	217	221	nan	217	631	993	973	787
HV4	224	252	248	nan	517	486	492	491
RV1	222	222	221	221	nan	987	312	222
RV2	222	221	803	239	1002	nan	253	223
RV3	248	531	526	528	517	528	nan	749
RV4	517	403	309	301	559	312	488	nan

CC Enabled, 2x load (50ms) - CBR: 32%

Percentage PER matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.16	0.18	0.31	1.19	1.07	1.07	1.14
HV2	0.06	nan	0.06	0.09	0.08	0.14	0.09	0.15
HV3	0.05	0.05	nan	0.02	0.11	0.09	0.49	0.09
HV4	0.06	0.1	0.06	nan	0.5	0.72	0.86	0.53
RV1	0.61	0.07	0.03	0.09	nan	0.02	0.03	0.07
RV2	0.24	0.11	0.15	0.48	0.15	nan	0.07	0.17
RV3	0.07	0.11	0.22	0.63	0.18	0.02	nan	0.13
RV4	0.19	0.23	0.28	0.3	0.31	0.28	0.16	nan

95th Percentile IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	204	204	204	204	204	204	204
HV2	204	nan	204	204	204	204	204	204
HV3	204	204	nan	204	204	204	204	204
HV4	204	204	203	nan	204	204	204	204
RV1	205	205	206	205	nan	205	205	205
RV2	209	209	208	209	209	nan	209	209
RV3	209	209	209	209	209	208	nan	209
RV4	207	206	207	206	208	206	206	nan

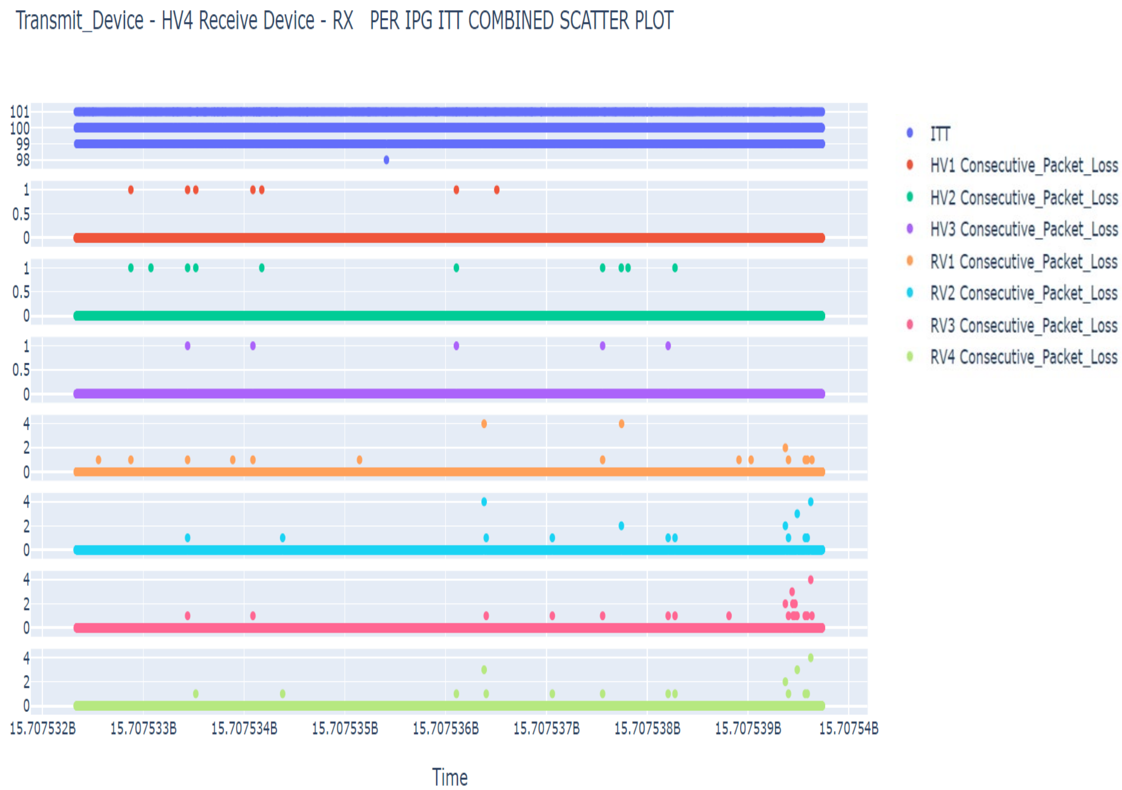
Max IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	421	419	719	718	721	726	722
HV2	319	nan	391	388	419	325	317	412
HV3	318	320	nan	319	332	317	395	316
HV4	420	414	420	nan	306	492	1093	324
RV1	1102	324	318	361	nan	314	317	419
RV2	420	420	423	606	424	nan	421	421
RV3	319	415	377	1110	414	311	nan	331
RV4	352	360	358	360	421	360	360	nan

Figure 10-5 Field, four-car (600 m) – 2X congestion control disabled/enabled performance

Figure 10-6 shows 2X CPL analysis for transmissions from HV4 toward other DUTs.

50 ms CC disabled



50 ms CC enabled

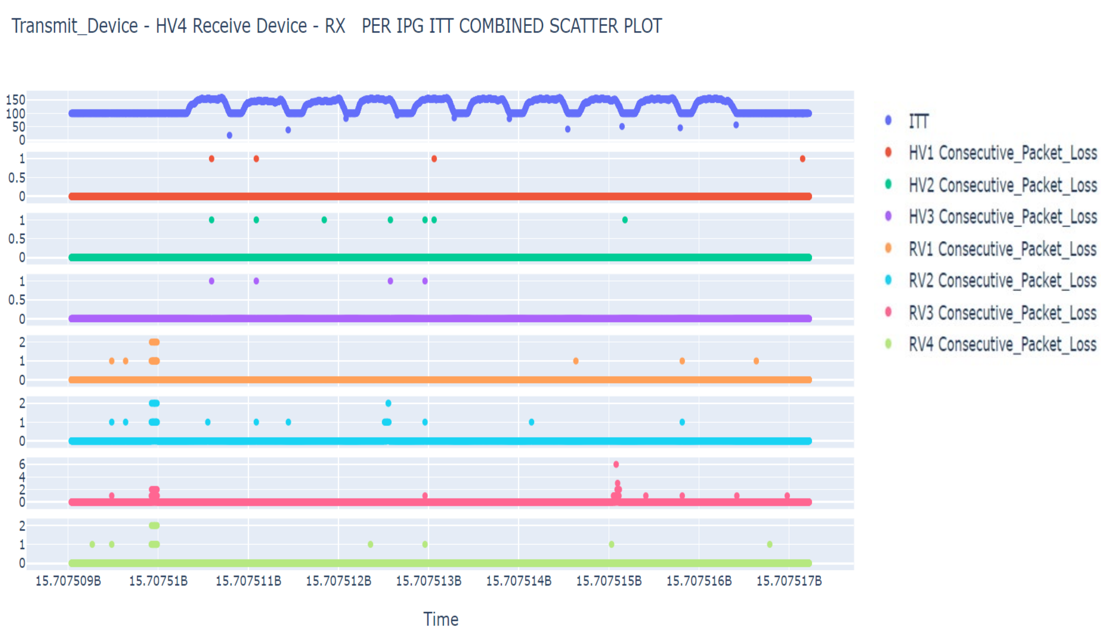


Figure 10-6 Field, four-car (600 m) – 2X CPL analysis

Figure 10-7 provides further analysis of transmission performance from HV4 to HV1 in the 2X congestion control enabled scenario.

50 ms CC enabled detailed test metric analysis

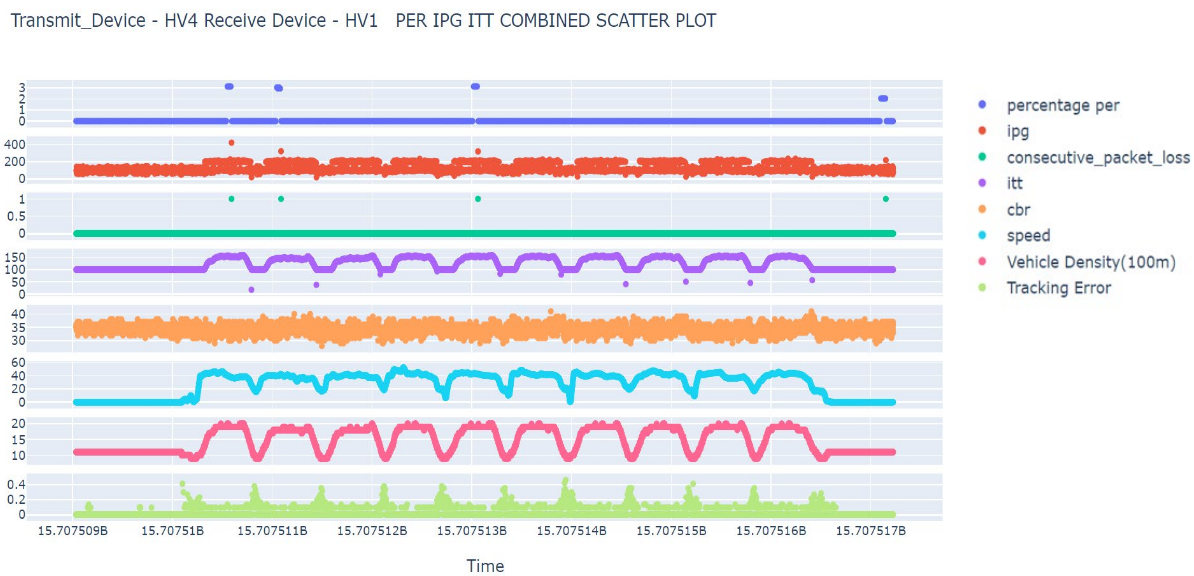


Figure 10-7 Field, four-car (600 m) – 2X transmission performance from HV4 to HV1

10.2.1.2.1 Key takeaways

- This system performed as expected: 48% congestion with congestion control disabled with zero packet loss 95% of the time on congestion control enabled and disabled cases.
- CBR for this test is 48% with congestion control disabled. The congestion control enabled case caused CBR to drop to 32% as all devices backoff to a lower value.
- Intra-platoon DUT links which are closest with respect to each other (75 m separation) have good PER performance of less than 1% for both cases. PER performance drops in the case of inter-platoon DUTs with a PER up to ~3.75% for the congestion control disabled case, and ~1.25% for the congestion control enabled case.
- The 95th percentile IPG shows zero packets were lost 95% of the time.
- The maximum IPG indicates that approximately 1-7 packets were lost consecutively for most links.
- ITT indicates that backoffs applied in this case are as expected, i.e., DUT backoff to ITT of 168 ms from a nominal 100 ms in the most congested areas of the track.
- The tracking error (ITS) was relatively low at the straight line and increased up to 0.4 around the edges of the track when the cars turned.

Simulation comparison

- CBR aligns well with simulation results where CBR reduces from 47% to 33% after enabling congestion control.
- PER in the simulation is lower with a maximum of 0.7%.
- The 95th percentile IPG matches well between field tests and simulations.
- Maximum IPG in the simulations is less than 0.9 s across all links. This aligns well with the field results where, outside of three outliers at 1.3 s, maximum IPG is less than 1.1 s across all other links.

10.2.1.3 5X load

Figure 10-8 shows performance between all transmitter-receiver DUT pairs in the 5X congestion control disabled and enabled scenarios.

CC Disabled, 2x load (50ms) - CBR: 87%

Percentage PER matrix

	HV1	HV2	HV3	HV4	RV2	RV3	RV4
HV1	nan	5.48	0.58	3.03	0.58	2.68	2.45
HV2	3.88	nan	5.05	4.22	4.8	0.26	3.81
HV3	0.89	10.3	nan	1.32	3.6	5.67	8.46
HV4	4.03	9.25	1.64	nan	5.61	7.44	9.83
RV2	4.11	17.2	9.7	12.3	nan	14.7	15.9
RV3	8.59	2.3	7.84	7.74	8.42	nan	2.19
RV4	8.93	8.5	9.48	11.8	12.4	1.34	nan

95th Percentile IPG matrix

	HV1	HV2	HV3	HV4	RV2	RV3	RV4
HV1	nan	132	124	131	125	127	127
HV2	126	nan	129	126	127	120	126
HV3	121	132	nan	122	126	128	127
HV4	132	137	126	nan	132	133	138
RV2	127	216	135	138	nan	204	215
RV3	137	122	134	132	138	nan	125
RV4	135	136	137	138	152	125	nan

Max IPG matrix

	HV1	HV2	HV3	HV4	RV2	RV3	RV4
HV1	nan	1212	1048	1056	1051	1055	1050
HV2	1246	nan	1327	2314	2314	783	1422
HV3	1039	2724	nan	1220	1260	1985	2724
HV4	1272	1523	849	nan	1536	1523	1512
RV2	1427	2346	1995	3303	nan	2046	2052
RV3	1436	1338	1504	1504	1230	nan	1199
RV4	3378	2191	2580	4991	2572	914	nan

CC Enabled, 2x load (50ms) - CBR: 32%

Percentage PER matrix

	HV1	HV2	HV4	RV1	RV2	RV3	RV4
HV1	nan	2.37	2.1	1.8	0.53	1.58	2.72
HV2	1.96	nan	1.8	0.8	1.8	0.9	1.75
HV4	1.79	2.92	nan	2.15	1.95	2.32	3.29
RV1	2.1	1.25	2.15	nan	2.45	3.6	4.8
RV2	1.28	5.05	4.41	4.75	nan	4.93	5.61
RV3	2.41	0.9	1.9	5.21	2.46	nan	0.67
RV4	2.02	1.43	2.6	4.62	2.39	0.37	nan

95th Percentile IPG matrix

	HV1	HV2	HV4	RV1	RV2	RV3	RV4
HV1	nan	414	414	414	410	412	415
HV2	419	nan	415	414	416	415	415
HV4	408	409	nan	409	408	408	409
RV1	410	410	411	nan	413	415	423
RV2	409	419	417	416	nan	416	420
RV3	431	425	428	582	432	nan	425
RV4	415	415	416	431	416	413	nan

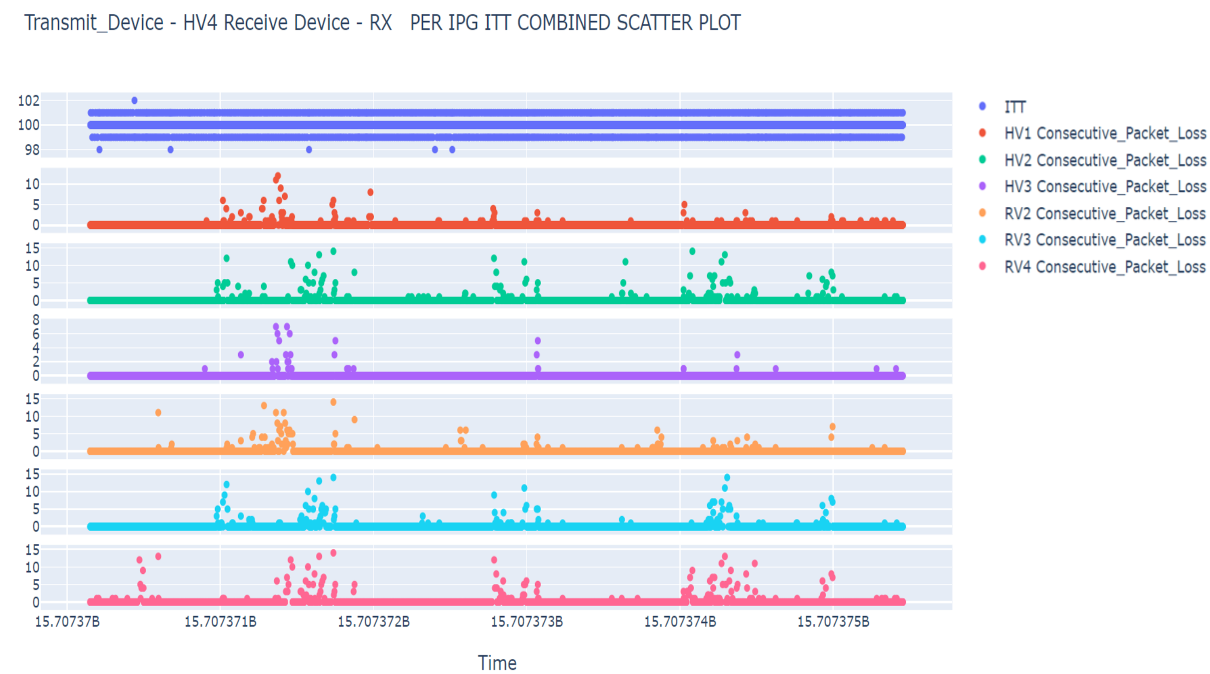
Max IPG matrix

	HV1	HV2	HV4	RV1	RV2	RV3	RV4
HV1	nan	1431	1117	818	812	811	828
HV2	1020	nan	1116	788	1022	1136	1113
HV4	1162	836	nan	907	1155	792	1115
RV1	1033	1142	1020	nan	1322	1134	1135
RV2	1117	1603	1620	1614	nan	1220	1622
RV3	1085	842	1609	1619	850	nan	845
RV4	1103	819	989	1121	1122	816	nan

Figure 10-8 Field, four-car (600 m) – 5X congestion control disabled/enabled performance

Figure 10-9 shows 5X CPL analysis for transmissions from HV4 toward other DUTs.

20 ms CC disabled



20 ms CC enabled

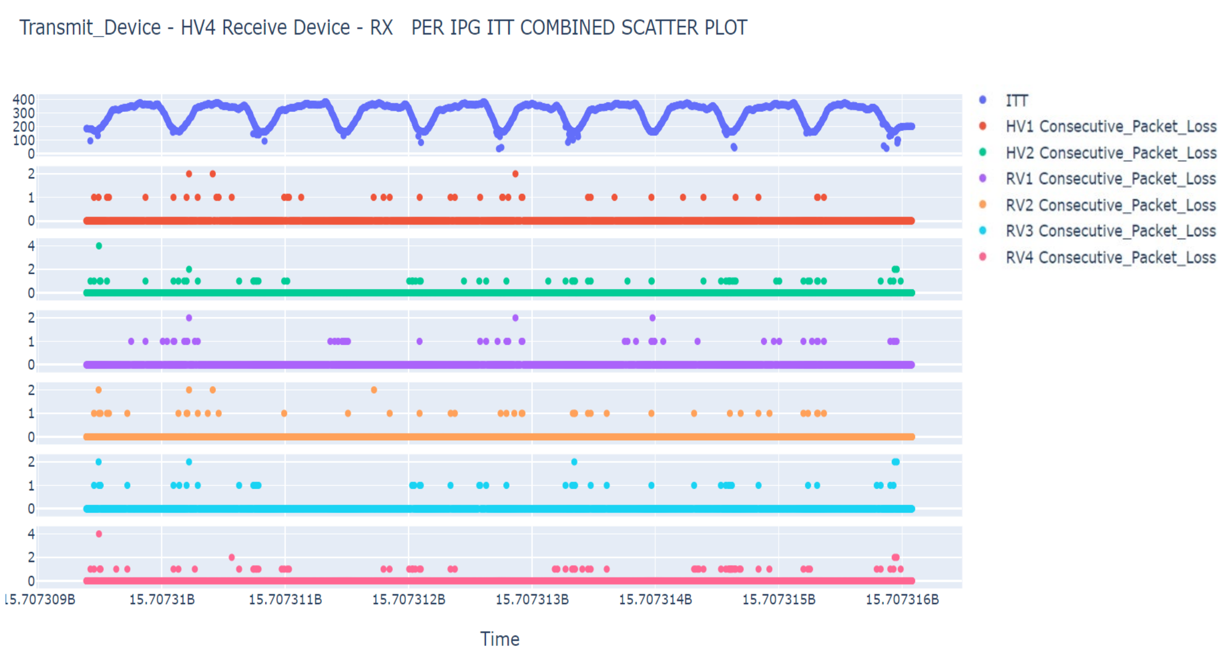


Figure 10-9 Field, four-car (600 m) – 5X CPL analysis

Figure 10-10 describes further analysis of transmission performance from HV4 to HV1 in the 5X congestion control enabled scenario.

20 ms CC enabled detailed test metric analysis

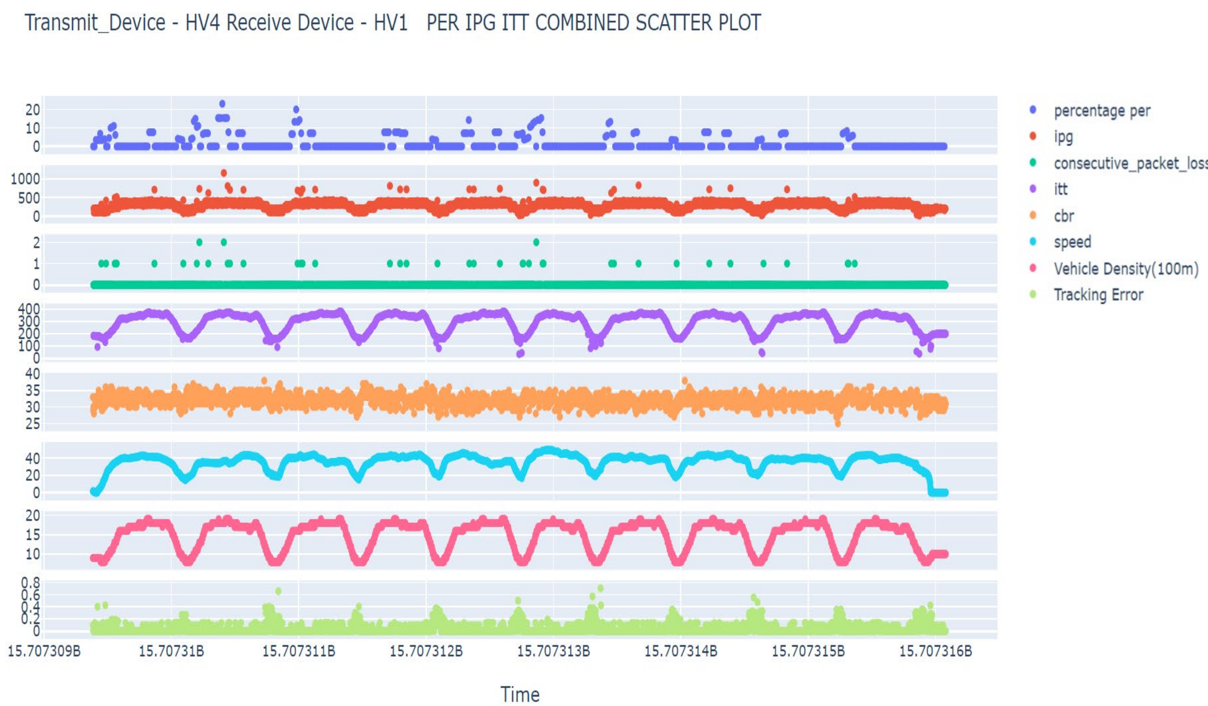


Figure 10-10 Field, four-car (600 m) – 5X transmission performance from HV4 to HV1

10.2.1.3.1 Key takeaways

- CBR for this test is 87% with congestion control disabled. The congestion control enabled case causes CBR to drop to 32% as all the devices backoff to a higher ITT.
- PER performance congestion control disabled:
  - PER performance is well-bounded for most links showing PER at less than 10%. The maximum PER goes up to 17% and is seen on an inter-platoon DUT (DUTs that are not close to each other).
  - An RV1 log was not collected for this test.
- PER performance congestion control enabled:
  - Dramatic improvement in overall PER performance seen with maximum PER less than 6%.
  - An HV3 log was not collected for this test.
- IPG performance congestion control disabled:
  - The 95th percentile IPG shows no packet loss 95% of the time. However, there are still many instances where a consecutive loss of 20+ packets can be seen.
  - Some links show a higher maximum IPG than acceptable for a safety application owing to higher PER on those links.
- IPG performance congestion control enabled:
  - The 95th percentile IPG shows a loss of (at most) 1 packet.
  - The maximum IPG indicates a consecutive loss of 3-4 packets (helped by Mute and Listen Optimizations).

Simulation comparison

- CBR is aligned between field tests and simulations:
  - Field tests: CBR is ~87% and ~32% for congestion control disabled and enabled.
  - Simulations: CBR is ~82% and ~29% for congestion control disabled and enabled.
- Peak PER across all links in the congestion control disabled case is 17% in the field test, versus 13% in the simulations. Peak PER across all links in the congestion control enabled case is 5.6% in the field test, versus 2.8% in the simulations. The field tests and simulations show the same trend in terms of PER improvement.
- The 95th percentile IPG peaks at approximately 150 ms for the congestion control disabled case, and 500 ms for the congestion control enabled case in both field tests and simulations.
- In the field tests (outside an outlier of 5 s), the maximum IPG is approximately 3.3 s for the congestion control disabled case, and 1.6 s for the congestion control enabled case. In simulations, the maximum IPG is approximately 3 s for the congestion control disabled case, and 1.2 s for the congestion control enabled case. Field tests and simulations show good alignment and highlight the same PER improvement trend.
- Generally, CBR and the 95th percentile IPG and maximum IPG show a satisfactory alignment between the simulation and field test results.

10.2.1.4 Key takeaways

- For 1X and 2X emulation modes, all metrics look acceptable for both congestion control disabled and enabled, with PER at less than 1%. The 95th percentile IPG indicates no packet loss.
- For the 5X emulation mode with congestion control disabled, PER ranges from 1-17% as distance between cars increase. With congestion control enabled, PER drops significantly to about 1-5% for all links. The 95th percentile IPG indicates 1-3 loss of packets (at most).
- For all scenarios, results were in line with simulation results for CBR, PER, and IPG within an acceptable margin of error.

10.2.2 Hard-braking in congestion (600 m)

For a detailed test description, see Section 10.3.2.

10.2.2.1 2X load

Figure 10-11 shows performance between all transmitter-receiver DUT pairs in the 2X congestion control disabled and enabled scenarios.

CC Disabled, 2x load (50ms) - CBR: 48%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	0	0	0.49	0.49	0.98	0.49	0

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	108	109	111	109	108	108	109

Critical Event MAX IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV1	nan	204	204	210	217	222	216	205

CC Enabled, 2x load (50ms) - CBR: 32%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	0	0	0	0	0	0	0

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	109	108	109	109	109	109	109

Critical Event MAX IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV1	nan	121	114	116	115	114	114	114

Figure 10-11 Field, hard-braking (600 m) – 2X congestion control disabled/enabled performance

10.2.2.2 5X load

Figure 10-12 shows performance between all transmitter-receiver DUT pairs in the 5X congestion control disabled and enabled scenarios.

CC Disabled, 5x load (20ms) - CBR: 87%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	6.15	9.5	11.2	0	0.56	1.12	12.8

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	125	211	221	110	108	110	220

Critical Event MAX IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV1	nan	513	228	323	123	217	212	320

CC Enabled, 5x load (20ms) - CBR: 32%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV3	RV4	RV5	RV6
HV	nan	1.13	0.56	0	0	1.69	2.26

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV3	RV4	RV5	RV6
HV	nan	109	109	109	109	109	111

Critical Event MAX IPG matrix

	HV	RV	RV1	RV3	RV4	RV5	RV6
HV1	nan	221	215	115	115	222	221

Figure 10-12 Field, hard-braking (600 m) – 5X congestion control disabled/enabled performance

10.2.2.3 Key takeaways

- In the 2X congestion control disabled and enabled scenario, cases perform equally well for critical messages with PER being less than 1% for all links. The 95th percentile IPG indicates no packet loss.
- For 5X emulation mode without congestion control, PER ranges between 0.5-12% for critical messages. With congestion control turned on, PER is limited to less than 2.3%. The 95th percentile IPG indicates no packet loss.

10.3 300 m test results

This section presents simulation results for the 300 m track length scenario. Simulations were run with the congestion control algorithm enabled and disabled.

10.3.1 Four-Car Moving Platoon test (25 MPH)

In this test, there are four moving vehicles performing loops around a 300 m track. KPIs were only collected between DUTs for every pair-wise link.

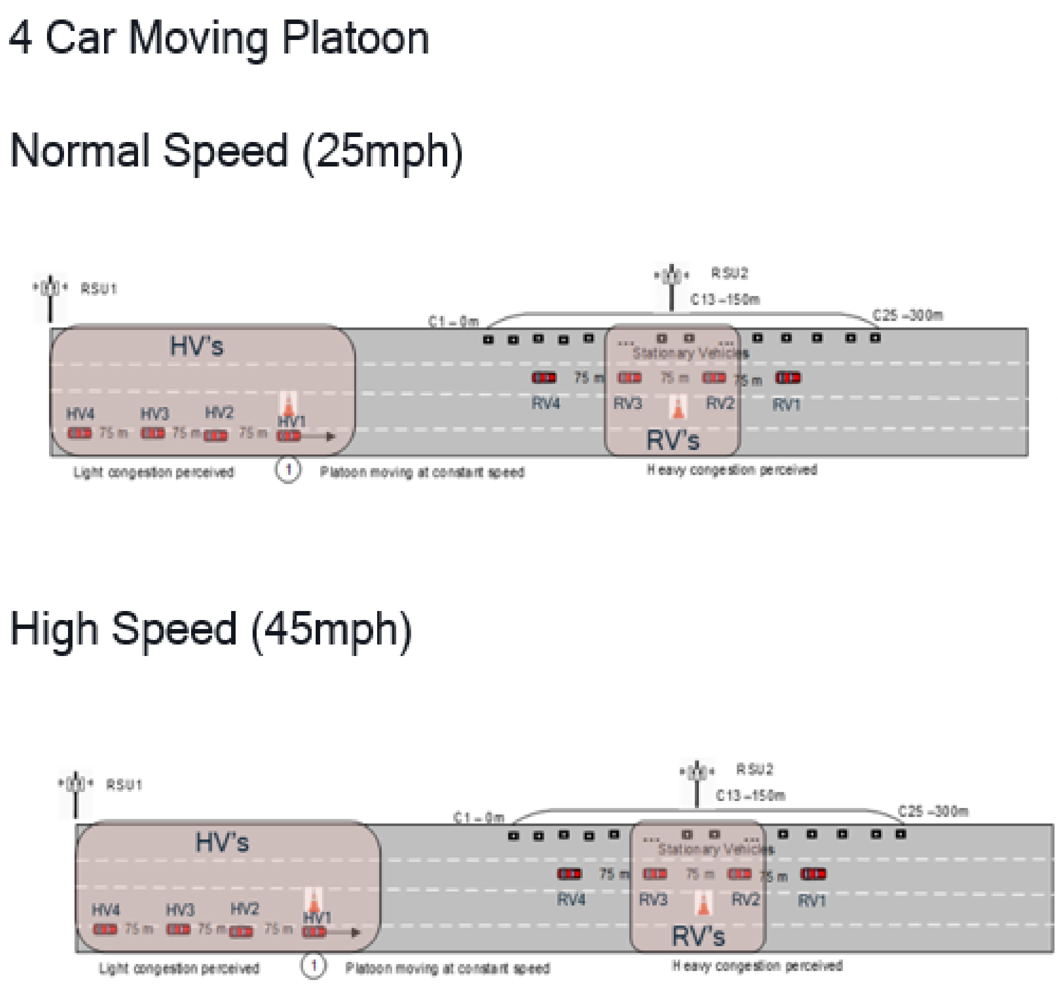


Figure 10-13 Field – Four-car moving platoon test (25 MPH)

10.3.1.1 1X load

Figure 10-14 shows performance between all transmitter-receiver DUT pairs in the 1X congestion control disabled and enabled scenarios.

Row headings are the transmit devices and the column headings denote receiving devices. From top to bottom, these tables provide the average PER, 95th percentile IPG, and maximum IPG between the DUTs.

CC Disabled, 1x load (100ms) - CBR: 24%

Percentage PER matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.06	0.07	0.29	0.29	0.29	0.29	0.29
HV2	0.03	nan	0.03	0.26	0.15	0.09	0.06	0.05
HV3	0.06	0.02	nan	0	0.08	0.26	0.05	0.17
HV4	0.1	0.07	0.05	nan	0.07	0.07	0.2	0.1
RV1	0.04	0.06	0.03	0.02	nan	0.02	0.19	0.07
RV2	0.05	0.07	0.29	0.05	0.07	nan	0.07	0.08
RV3	0.06	0.1	0.08	0.1	0.27	0.04	nan	0.03
RV4	0.07	0.1	0.07	0.06	0.17	0.31	0.04	nan

95th Percentile IPG matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	124	124	125	125	124	125	124
HV2	121	nan	120	121	121	121	121	121
HV3	119	119	nan	119	120	120	119	120
HV4	121	121	121	nan	121	122	122	121
RV1	121	121	121	121	nan	121	122	122
RV2	120	120	120	120	120	nan	119	120
RV3	120	120	120	120	121	121	nan	121
RV4	120	120	120	120	120	120	120	nan

Max IPG matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	241	240	729	980	1197	1192	1192
HV2	223	nan	233	739	381	223	217	219
HV3	224	221	nan	150	222	898	222	816
HV4	226	225	224	nan	228	228	336	223
RV1	230	249	234	217	nan	218	225	224
RV2	219	223	904	218	237	nan	238	241
RV3	219	227	223	237	437	219	nan	219
RV4	223	223	222	219	226	722	221	nan

CC Enabled, 1x load (100ms) - CBR: 23%

Percentage PER matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.12	0.09	0.18	0.09	0.08	0.1	0.08
HV2	0.06	nan	0.16	0.12	0.16	0.1	0.14	0.1
HV3	0.07	0.09	nan	0.03	0.04	0.04	0.1	0.07
HV4	0.18	0.08	0.01	nan	0.09	0.14	0.27	0.03
RV1	0.03	0.03	0.03	0.04	nan	0.04	0.07	0.12
RV2	0.1	0.12	0.1	0.17	0.12	nan	0.2	0.23
RV3	0.09	0.04	0.09	0.26	0.51	0.13	nan	0.07
RV4	0.05	0.07	0.04	0.09	0.15	0.12	0.08	nan

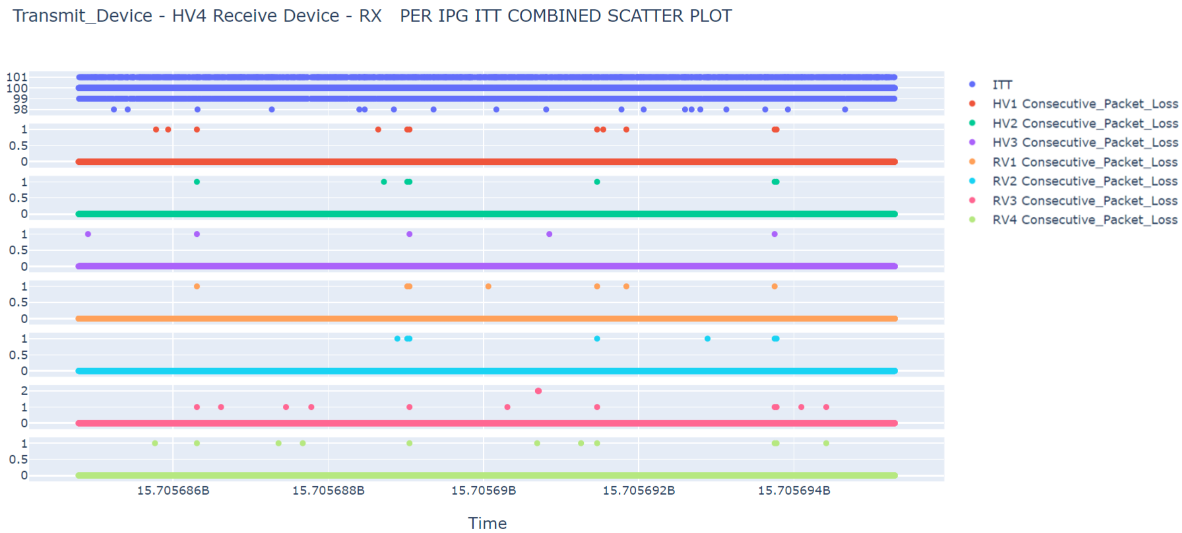
95th Percentile IPG matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	203	203	203	203	203	203	203
HV2	203	nan	203	203	203	203	203	203
HV3	203	203	nan	203	203	203	203	203
HV4	203	202	202	nan	202	202	202	203
RV1	205	205	204	204	nan	204	204	205
RV2	208	208	208	208	208	nan	208	208
RV3	205	205	205	205	205	205	nan	205
RV4	120	120	120	120	120	120	120	nan

Max IPG matrix								
	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	337	338	337	337	323	324	331
HV2	332	nan	729	319	421	328	334	319
HV3	319	728	nan	233	247	237	321	322
HV4	338	321	320	nan	328	321	798	318
RV1	313	314	313	316	nan	325	322	318
RV2	317	322	319	676	320	nan	324	322
RV3	319	318	318	592	512	321	nan	413
RV4	226	256	256	257	256	256	300	nan

Figure 10-14 Field, four-car (300 m) – 1X congestion control disabled/enabled performance

Figure 10-15 shows 1X CPL analysis for transmissions from HV4 toward all other DUTs. The top plot shows ITT at HV4. The subsequent seven plots show the CPLs between HV4 and other DUTs.

100 ms CC disabled



100 ms CC enabled

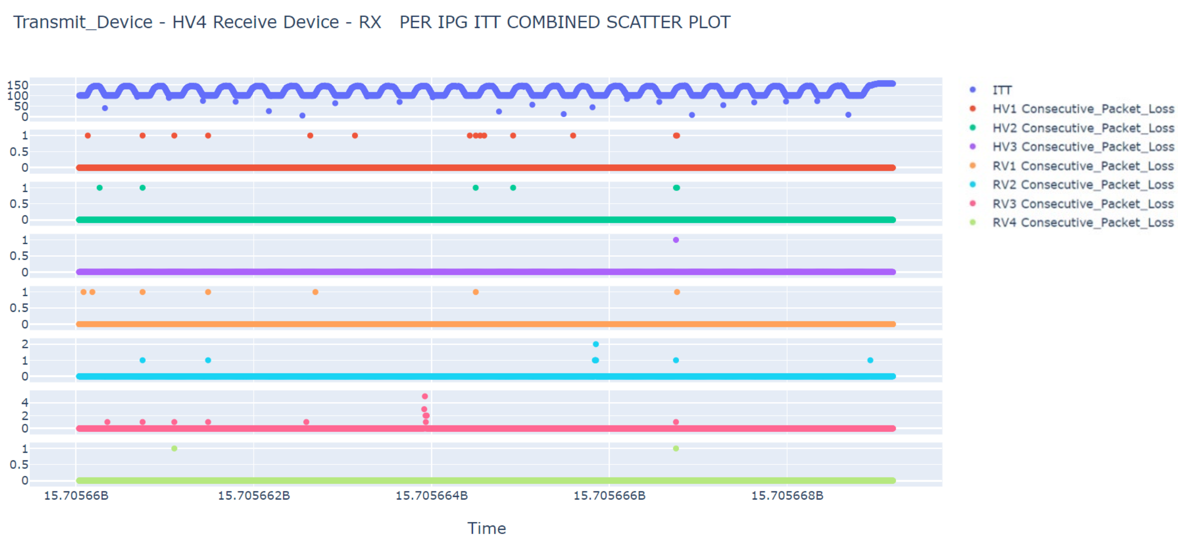


Figure 10-15 Field, four-car (300 m) – 1X CPL analysis

Figure 10-16 provides further analysis of transmission performance from HV4 to HV1 in the 1X congestion control enabled scenario. The plots cover these metrics:

- Modem: CBR, CPL
- ITS: PER, IPG, ITT, vehicle density, and tracking error (measured directly by ITS stack)

100 ms CC enabled detailed test metric analysis

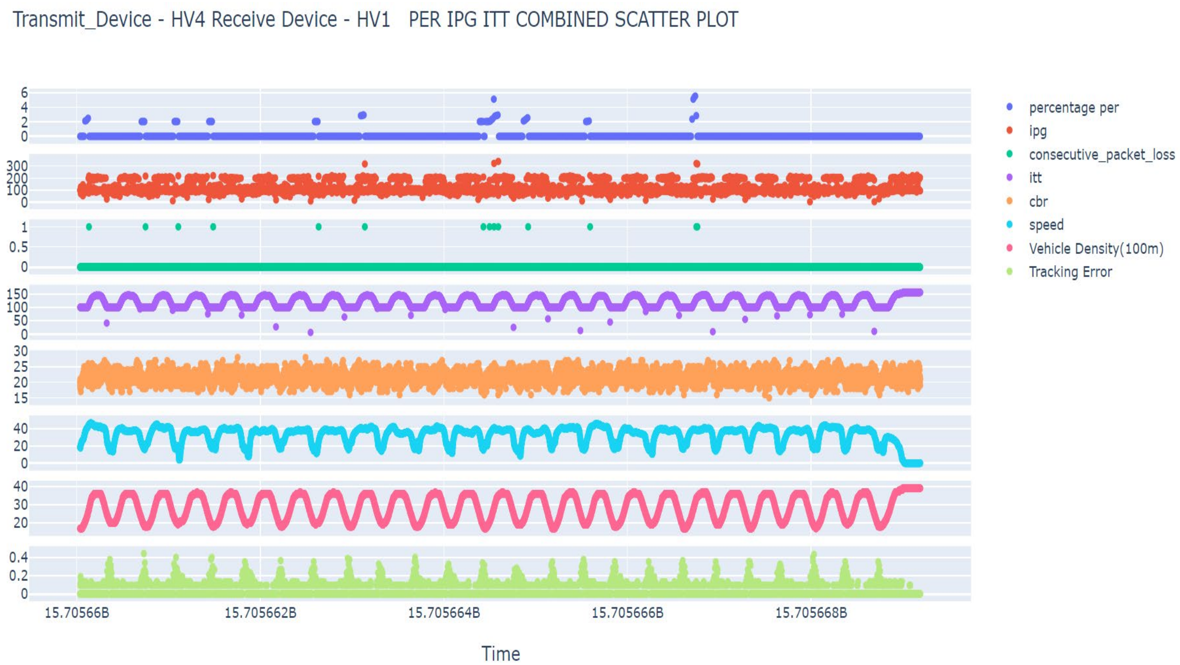


Figure 10-16 Field, four-car (300 m) – 1X transmission performance from HV4 to HV1

10.3.1.1.1 Key takeaways

- CBR for this test is approximately 23-24%. The congestion control enabled case does not cause extremely high backoffs and the average CBR remains fairly consistent.
- All links have less than 1% PER for both cases.
- The 95th percentile IPG shows that no packets were lost 95% of the time.
- The maximum IPG indicates that approximately 3-5 packets (at most) were lost consecutively for most links (largely helped by Mute and Listen Optimizations).
- ITT indicates that the backoffs applied in this case are not severe. DUT backoffs to an ITT of 150 ms from a nominal 100 ms even in the most congested areas of the track.
- Tracking error (ITS) was relatively low at the straight line and increased up to 0.4 around the edges of the track when the cars turned.

10.3.1.2 2X load

Figure 10-17 shows performance between all transmitter-receiver DUT pairs in the 2X congestion control disabled and enabled scenarios.

CC Disabled, 2x load (50ms) - CBR: 48%

Percentage PER matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.08	0.18	0.2	0.16	0.11	0.28	0.17
HV2	0.09	nan	0.07	0.06	0.09	0.12	0.07	0.34
HV3	0.27	0.03	nan	0.04	0.2	0.08	0.18	0.11
HV4	0.11	0.08	0.01	nan	0.26	0.59	0.48	0.07
RV1	0.13	0.06	0.09	0.29	nan	0.09	0.72	0.33
RV2	0.12	0.1	0.09	0.11	0.21	nan	0.14	0.22
RV3	0.16	0.19	0.13	0.47	0.53	0.21	nan	0.03
RV4	0.34	0.82	0.31	0.21	0.54	0.73	0.18	nan

95th Percentile IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	121	121	121	121	121	121	121
HV2	120	nan	120	120	120	120	120	120
HV3	120	120	nan	120	121	120	121	120
HV4	120	120	120	nan	120	120	120	120
RV1	121	120	121	120	nan	121	125	121
RV2	120	120	120	120	120	nan	120	120
RV3	122	121	121	122	124	122	nan	121
RV4	120	120	120	120	121	121	120	nan

Max IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	224	546	547	224	224	546	547
HV2	246	nan	501	225	246	231	240	1161
HV3	513	218	nan	222	524	224	407	492
HV4	348	222	210	nan	444	764	1020	222
RV1	221	222	223	822	nan	221	792	504
RV2	323	490	396	310	528	nan	491	510
RV3	545	508	247	1033	641	545	nan	223
RV4	618	1235	552	245	499	532	517	nan

CC Enabled, 2x load (50ms) - CBR: 23%

Percentage PER matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.16	0.31	0.16	0.2	0.27	0.11	0.11
HV2	0.09	nan	0.02	0.12	0.09	0.14	0.16	0.07
HV3	0.23	0.07	nan	0.05	0.09	0.11	0.11	0.14
HV4	0.16	0.07	0.04	nan	0.16	0.18	0.13	0.11
RV1	0.2	0.23	0.25	0.28	nan	0.31	0.56	0.51
RV2	0.09	0.12	0.19	0.12	0.19	nan	0.22	0.37
RV3	0.28	0.28	0.22	0.11	0.53	0.33	nan	0.25
RV4	0.13	0.15	0.2	0.16	0.37	0.44	0.11	nan

95th Percentile IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	310	311	310	311	311	311	310
HV2	315	nan	316	316	315	315	316	315
HV3	312	312	nan	311	312	312	312	312
HV4	313	313	312	nan	314	313	313	313
RV1	311	311	311	311	nan	311	312	312
RV2	397	396	397	396	396	nan	396	397
RV3	318	318	318	318	320	319	nan	318
RV4	211	211	211	211	212	212	211	nan

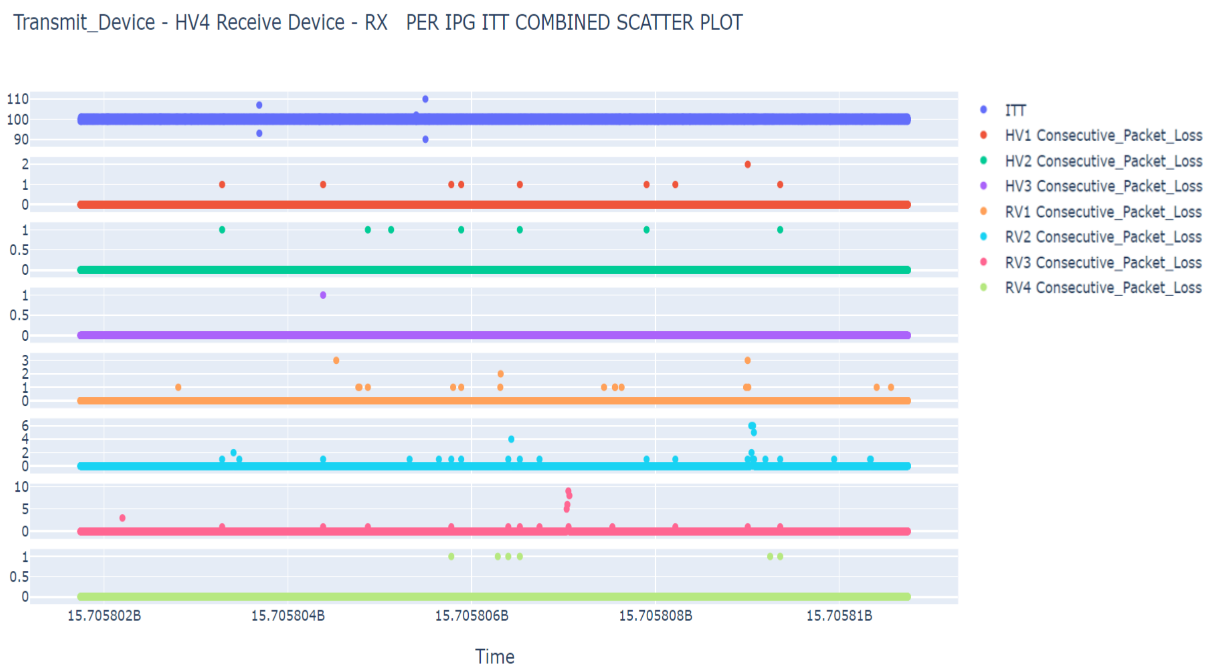
Max IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	618	948	623	717	618	623	718
HV2	610	nan	517	614	613	421	614	515
HV3	620	620	nan	621	619	619	614	620
HV4	616	620	413	nan	517	522	616	615
RV1	619	617	542	618	nan	623	623	624
RV2	621	620	622	620	717	nan	622	720
RV3	623	622	621	616	623	623	nan	632
RV4	416	421	323	321	428	420	417	nan

Figure 10-17 Field, four-car (300 m) – 2X congestion control disabled/enabled performance

Figure 10-18 shows 2X CPL analysis for transmissions from HV4 toward all other DUTs.

50 ms CC disabled



50 ms CC enabled

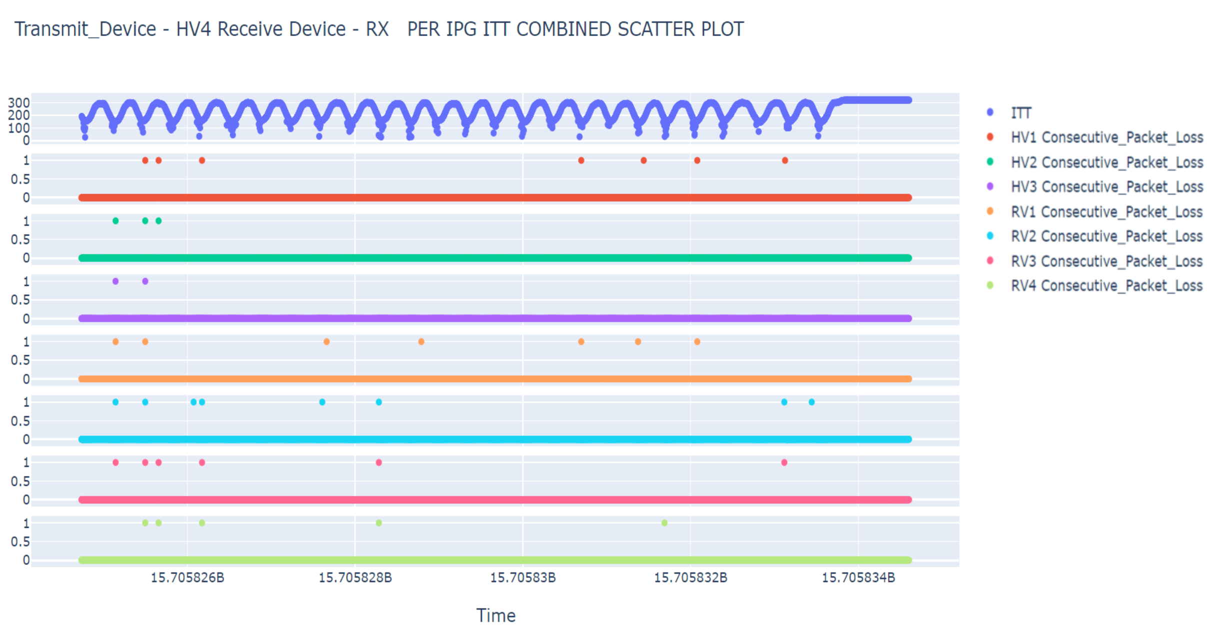


Figure 10-18 Field, four-car (300 m) – 2X CPL analysis

Figure 10-19 provides further analysis of transmission performance from HV4 to HV1 in the 2X congestion control enabled scenario.

50 ms CC enabled detailed test metric analysis

Figure 10-19 Field, four-car (300 m) – 2X transmission performance from HV4 to HV1

10.3.1.2.1 Key takeaways

- CBR for this test is 48% with congestion control disabled. The congestion control enabled case causes CBR to drop to 23% as all devices backoff to a lower value.
- All links have less than 1% PER for both cases.
- The 95th percentile IPG shows zero packets were lost 95% of the time.
- The maximum IPG indicates that approximately 3-5 packets (at most) were lost consecutively for most links.
- ITT indicates that backoffs applied in this case are as expected, i.e., DUT backoff to ITT of 300 ms from a nominal 100 ms in the most congested areas of the track.
- Tracking error (ITS) was relatively low at the straight line and increased up to 0.4-0.6 around the edges of the track when the cars turned.

10.3.1.3 5X load

Figure 10-20 shows performance between all transmitter-receiver DUT pairs in the 5X congestion control disabled/enabled scenarios.

CC Disabled, 5x load (20ms) - CBR: 87%

Percentage PER matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	6.27	10.2	16.3	23.9	15.4	14.2	11.2
HV2	12.7	nan	2.61	13.6	24.5	23.1	32.1	29.3
HV3	7.76	1.46	nan	2.32	12.2	12.3	15.8	14.1
HV4	13.8	8.08	2.93	nan	12	12.4	16.9	13.9
RV1	15.4	7.91	9.19	8.95	nan	9.3	31.6	30.7
RV2	6	6.14	5.52	5.19	7.37	nan	8.25	15.3
RV3	10.3	18.7	12.4	17.7	39	10.7	nan	2.14
RV4	22.7	32.8	28.3	31.5	49.1	44	13.1	nan

95th Percentile IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	137	150	215	217	163	166	152
HV2	162	nan	121	173	222	217	333	314
HV3	132	120	nan	121	156	141	157	150
HV4	174	138	125	nan	152	156	215	166
RV1	186	156	157	157	nan	156	409	413
RV2	132	132	130	131	135	nan	137	210
RV3	149	216	150	215	499	145	nan	122
RV4	222	387	312	366	802	667	156	nan

Max IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	1523	1860	5538	4495	2828	3989	2275
HV2	3755	nan	1494	3264	4362	4098	4753	3991
HV3	2525	983	nan	2053	3504	3879	4366	4973
HV4	2299	2004	1998	nan	2208	2297	3402	3498
RV1	4205	1780	2018	2923	nan	2018	4219	5022
RV2	2315	1897	3181	1999	1859	nan	2305	2982
RV3	2178	3979	4093	3273	4970	2015	nan	1218
RV4	2591	3389	3797	3390	4434	5688	1620	nan

CC Enabled, 5x load (20ms) - CBR: 22%

Percentage PER matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	0.39	0.61	1.29	1.29	1.61	1.72	1.32
HV2	0.96	nan	0.14	0.64	2.64	3.14	2.78	2.71
HV3	0.69	0.15	nan	0.04	1.27	2	1.96	1.71
HV4	1.19	0.52	0.23	nan	1.71	2.29	2.13	2.23
RV1	1.08	0.74	1.18	1.13	nan	0.74	2.5	2.6
RV2	0.83	0.74	0.88	0.93	0.64	nan	0.34	1.42
RV3	1.18	1.28	1.57	1.62	2.55	0.59	nan	0.54
RV4	2.52	2.61	2.52	2.4	3.7	3.2	1.68	nan

95th Percentile IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	622	623	626	624	627	627	628
HV2	625	nan	622	623	631	632	631	632
HV3	625	623	nan	623	626	629	628	627
HV4	622	619	619	nan	626	628	627	628
RV1	638	637	638	637	nan	637	640	640
RV2	638	638	637	637	637	nan	636	638
RV3	638	639	639	640	641	637	nan	638
RV4	501	503	502	501	505	504	498	nan

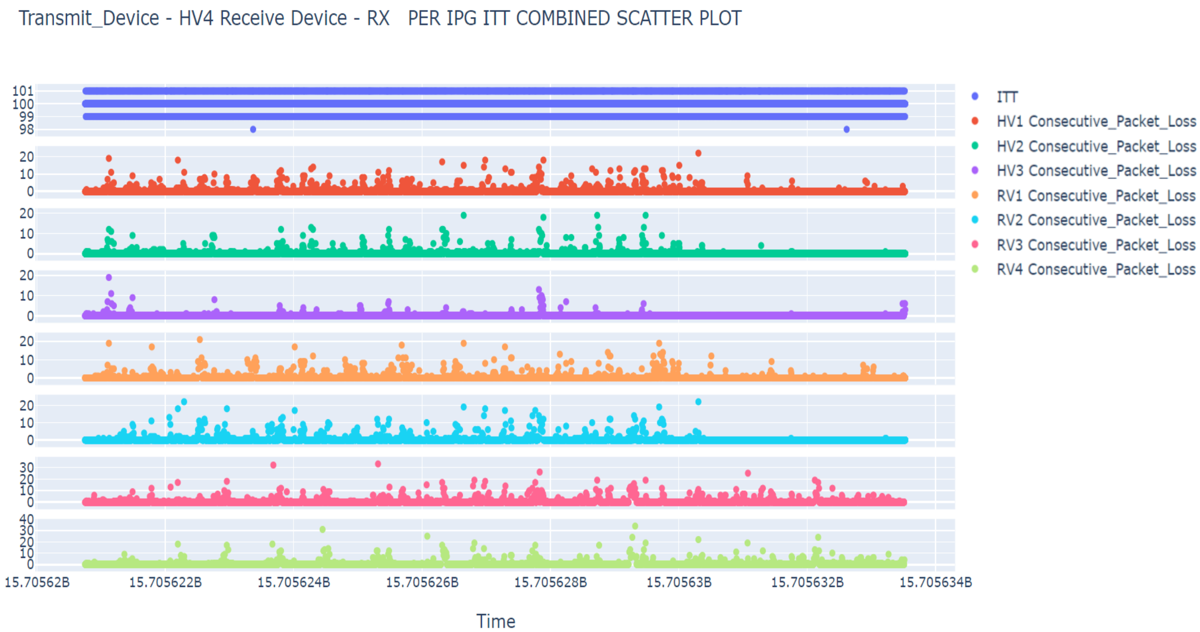
Max IPG matrix

	HV1	HV2	HV3	HV4	RV1	RV2	RV3	RV4
HV1	nan	1467	1234	1468	1465	1226	1249	1232
HV2	1623	nan	1222	1255	1587	1248	1249	1250
HV3	1826	1259	nan	1222	1825	1803	1258	1257
HV4	1745	1746	1106	nan	1239	1237	1743	1265
RV1	1813	1809	1811	1811	nan	1240	1812	1811
RV2	1240	1247	1244	1860	1244	nan	1239	2427
RV3	1836	1839	1836	1836	2381	1835	nan	1837
RV4	1117	840	1115	1115	1316	1300	1300	nan

Figure 10-20 Field, four-car (300 m) – 5X congestion control disabled/enabled performance

Figure 10-21 shows 5X CPL analysis for transmissions from HV4 toward all other DUTs.

20 ms CC disabled



20 ms CC enabled

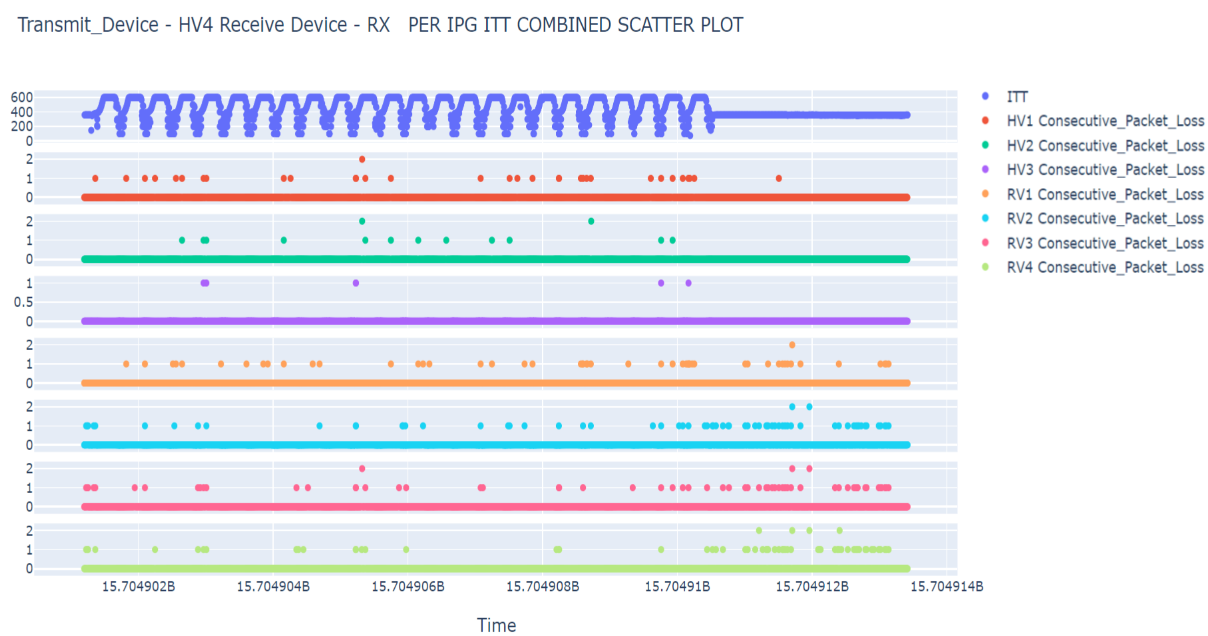


Figure 10-21 Field, four-car (300 m) – 5X CPL analysis

Figure 10-22 provides further analysis of transmission performance from HV4 to HV1 in the 5X congestion control enabled scenario.

20 ms CC enabled detailed test metric analysis

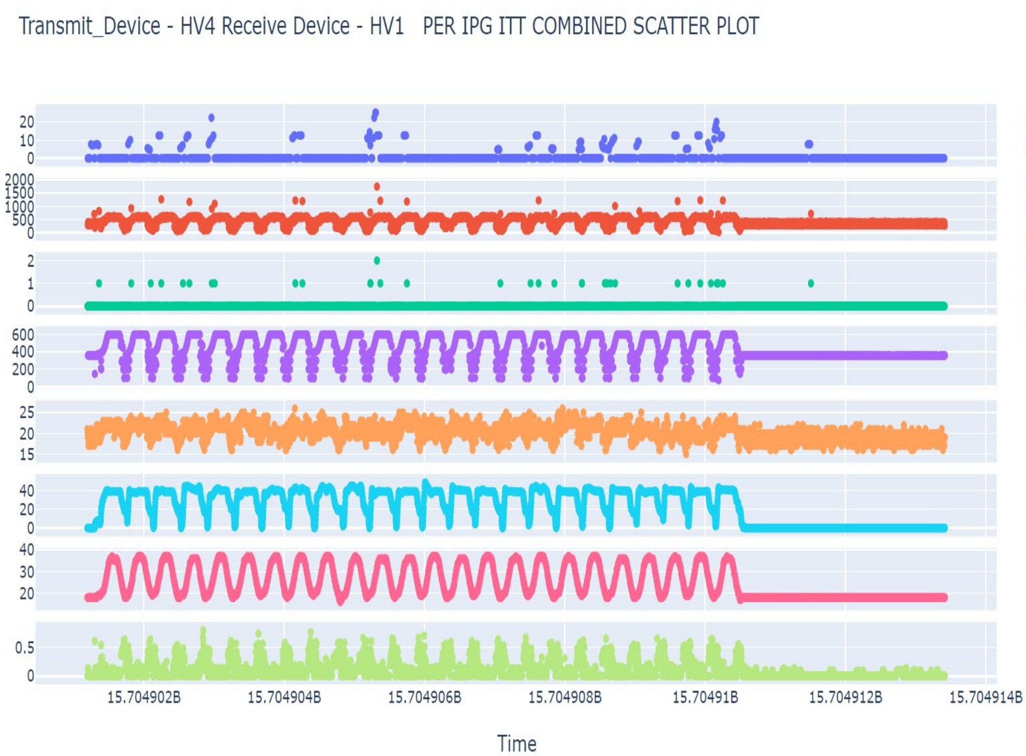


Figure 10-22 Field, four-car (300 m) – 5X transmission performance from HV4 to HV1

10.3.1.3.1 Key takeaways

- CBR for this test is 87% with congestion control disabled. The congestion control enabled case causes CBR to drop to 22% as all devices backoff to a higher ITT.
- PER performance congestion control disabled:
  - Intra-platoon DUT links which are closest with respect to each other (75 m separation) have good PER performance of less than 7%. PER performance drops drastically beyond that point. Successive DUTs have PER of 15%, 23%, and up to 40% for the furthest links.
  - Inter-platoon links have an average PER of approximately 25%.
- PER performance congestion control enabled
  - Intra-platoon DUTs improve PER performance with PER between 0-1.5%.
  - Inter-platoon links also see dramatic improvements with PER between 1-2.5%.
- IPG performance congestion control disabled:
  - The 95th percentile IPG shows consecutive loss of 8-10 packets. However, there are still many instances where a consecutive loss of 30-40 packets can be seen.
  - Due to high PER, there are many areas where IPG is much higher than acceptable for a safety application.

- IPG performance congestion control enabled:
  - The 95th percentile IPG shows zero packet loss 95% of the time.
  - The maximum IPG indicates that approximately 3-5 packets were lost consecutively for most links (largely helped by the Mute and Listen Optimizations).

10.3.1.4 Key takeaways

- In 1X and 2X emulation modes, PER and IPG performance are extremely good for both congestion control disabled and enabled cases. PER remains less than 1% for most links. The 95th percentile IPG shows zero packet loss 95% of the time. CBR with congestion control enabled drops to about 23-24%, while congestion control disabled cases have a CBR of approximately 25% and 48%,respectively.
- In 5X emulation mode, CBR drops from 87% (congestion control disabled) to 25% with congestion control enabled as devices backoff to 600 ms from the nominal 100 ms periodicity.
  - PER significantly improves with congestion control disabled, showing PER of about 15-40% while congestion control enabled reduced PER approximately 1.5-2% for most links.
  - With congestion control enabled, the 95th percentile IPG indicates no packet loss. With congestion control disabled, 8-10 packets were lost consecutively.
- 5X results show worse metrics than the equivalent case with the 600 m track length where less densification was observed. The overall CBR is also lower as devices back off more (compared to the 600 m case), due to higher densification.
- Congestion-based rate control helps improve all metrics in 5X emulation mode.

10.3.2 Hard-braking in congestion (300 m)

This test has six stationary (transmitting/receiving) vehicles providing performance from six vantage points with varying levels of congestion. This test provides a large number of steady-state PER samples for the intra-stationary group.

There are two moving (transmitting/receiving) vehicles where only HV performs a critical event in the heaviest congestion. RV continues moving.

A critical event such as a hard-brake under test is functionally equivalent to a rapid lane change test (as it decreases ITT) where a vehicle switches between lanes at a high speed. This also tests how well the critical event HV was heard by the stationary vehicles experiencing different levels.

The moving RV provides a continuum of distance bins for PER to and from stationary vehicles for transient PER versus distance.

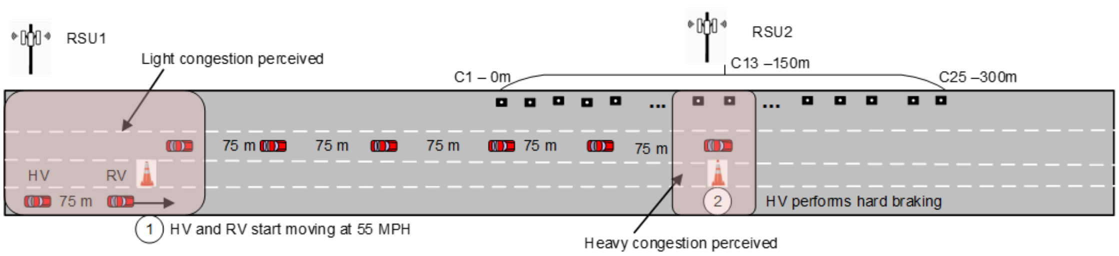


Figure 10-23 Hard-braking in congestion (300 m) overview

10.3.2.1 1X load

This test was run for both disabled and enabled congestion control algorithms and results were compared.

Figure 10-24 shows performance between all transmitter receiver DUT pairs. Row headings are the transmit device and the column headings denote the receiving device.

CC Disabled, 1x load (100ms) - CBR: 24%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	0	0	0	0	0	0

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	109	111	109	111	109	109

Critical Event MAX IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	115	115	115	115	115	115

Critical Event MAX ITT matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	101	101	101	101	101	101

CC Enabled, 1x load (100ms) - CBR: 23%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	0	0.49	0	0	0.98	0

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	109	109	110	109	110	109

Critical Event MAX IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	116	116	116	116	222	115

Critical Event MAX ITT matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	101	101	101	101	101	101

Figure 10-24 Field, hard-braking (300 m) – 1X congestion control disabled/enabled performance

10.3.2.2 2X load

This test was run for both disabled and enabled congestion control algorithms and results were compared.

Figure 10-25 shows performance between all transmitter receiver DUT pair. Row headings are the transmit device and the column headings denote the receiving device.

CC Disabled, 2x load (50ms) - CBR: 48%

Critical Event Percentage PER matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	0	1.35	0.9	0	0.45	0	0

Critical Event 95th Percentile IPG matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	109	109	109	109	110	108	109

Critical Event MAX IPG matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	114	224	226	115	220	113	114

Critical Event MAX ITT matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	101	101	101	101	101	101	101

CC Enabled, 2x load (50ms) - CBR: 22%

Critical Event Percentage PER matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	0	0	0.4	0.4	0.4	0.79	0

Critical Event 95th Percentile IPG matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	109	109	109	109	109	109	109

Critical Event MAX IPG matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	117	115	219	219	206	216	121

Critical Event MAX ITT matrix	HV	RV	RV1	RV2	RV3	RV4	RV5	RV6
HV	nan	101	101	101	101	101	101	101

Figure 10-25 Field, hard-braking (300 m) – 2X congestion control disabled/enabled performance

10.3.2.3 5X load

This test was run for both disabled and enabled congestion control algorithms, and results were compared.

Figure 10-26 shows performance between all transmitter receiver DUT pair. Row headings are the transmit device and the column headings denote the receiving device.

CC Disabled, 5x load (20ms) - CBR: 87%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	5.76	23.1	18.3	4.41	25.4	13.2

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	114	230	222	114	227	218

Critical Event MAX IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	527	522	713	228	720	595

Critical Event MAX ITT matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	101	101	101	101	101	101

CC Enabled, 5x load (20ms) - CBR: 22%

Critical Event Percentage PER matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	0.37	0.73	0.73	0.37	0.73	0.73

Critical Event 95th Percentile IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	109	110	110	110	111	110

Critical Event MAX IPG matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	239	239	239	243	242	241

Critical Event MAX ITT matrix

	HV	RV	RV1	RV2	RV3	RV4	RV6
HV	nan	231	231	231	231	231	231

Figure 10-26 Field, hard-braking (300 m) – 5X congestion control disabled/enabled performance

10.3.2.4 Key takeaways

- Hard-braking events were sent as critical messages with event driven flows.
- For emulation modes 1X and 2X, performance was very good for all cases. PER remains mostly less than 1% for most links.
- In 5X emulation mode with congestion control disabled, critical messages experience high PER between 5-25%. Congestion control enabled PER was less than 1% for all links.

Simulation comparison

- Compared to the 600 m congestion control disabled scenario, the same would range between 0.5-12%, indicating that less densification improves performance, as expected.
- The congestion control algorithm throttles normal BSM generation rates, effectively improving performance of critical messages which are sent with the nominal 100 ms periodicity for the duration of the critical event.

10.3.3 Non-line of sight test in congestion

In this test, there are four moving vehicles in a platoon that provides transient PER samples against stationary vehicles.

Two stationary vehicles were placed on either end of a line of sight blocker, i.e., a large van, on a single lane. Performance is measured between stationary cars for congestion impact.

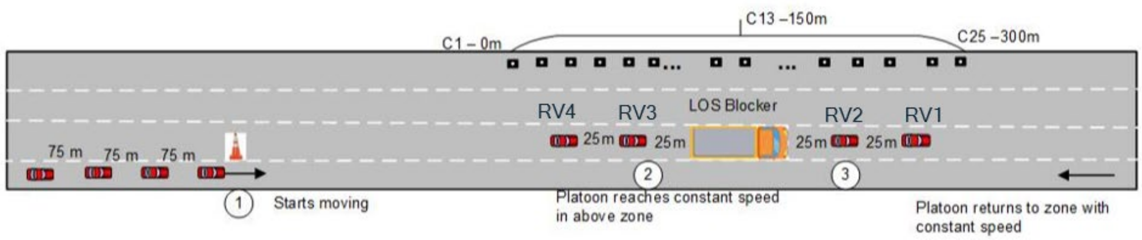


Figure 10-27 NLOS test overview

NOTE: This test was only performed for the highly congested 5X load case. QTI anticipated this would be the most stressful scenario among the available configurations.

10.3.3.1 5X load

This test was run for both disabled and enabled congestion control algorithms and results were compared.

Figure 10-27 shows RV1 and RV2 in LOS while RV3 and RV4 are in LOS. Pair RV3-4 and RV1-2 have a LOS blocker between them.

Figure 10-28 shows performance between any transmitter receiver DUT pair. Row headings are the transmit device and the column headings denote the receiving device.

CC Disabled, 5x load (20ms) - CBR: 87%

Percentage PER matrix

	RV1	RV2	RV3	RV4
RV1	nan	2.17	47.1	46.6
RV2	1.96	nan	53.5	51.3
RV3	60.1	47.8	nan	5.15
RV4	49.3	49.2	5.21	nan

95th Percentile IPG matrix

	RV1	RV2	RV3	RV4
RV1	nan	115	729	715
RV2	114	nan	822	846
RV3	1085	720	nan	121
RV4	737	720	119	nan

Max IPG matrix

	RV1	RV2	RV3	RV4
RV1	nan	1073	3894	5707
RV2	1410	nan	4218	4219
RV3	3899	3275	nan	1327
RV4	3330	3857	1339	nan

Max ITT matrix

	RV1	RV2	RV3	RV4
RV1	nan	101	101	101
RV2	101	nan	101	101
RV3	101	101	nan	101
RV4	101	101	101	nan

CC Enabled, 5x load (20ms) - CBR: 23%

Percentage PER matrix

	RV1	RV2	RV3	RV4
RV1	nan	0.17	2.43	2.78
RV2	0	nan	3.14	3.14
RV3	2.78	2.09	nan	0.87
RV4	2.61	2.26	0.52	nan

95th Percentile IPG matrix

	RV1	RV2	RV3	RV4
RV1	nan	633	637	640
RV2	631	nan	639	638
RV3	639	640	nan	635
RV4	636	636	633	nan

Max IPG matrix

	RV1	RV2	RV3	RV4
RV1	nan	1186	1787	1786
RV2	645	nan	1243	2410
RV3	1240	1242	nan	1247
RV4	1245	1821	1209	nan

Max ITT matrix

	RV1	RV2	RV3	RV4
RV1	nan	601	601	601
RV2	601	nan	601	601
RV3	601	601	nan	601
RV4	601	601	601	nan

Figure 10-28 NLOS – Stationary vehicle KPI comparison

The performance comparison focuses mainly on stationary cars because moving cars average out their metrics by virtue of moving in loops around the test track.

Performance Comparison between NLOS Links in Congestion RV2 vs RV3

Scenario	Emulated Cars	Percentage CBR	Percentage PER	Maximum Consecutive Packet Losses	95th Percentile IPG	95th Percentile ITT
20ms CC Disabled	258	87	47	37	728	101
20ms CC Enabled	258	23	2.4	5	625	601

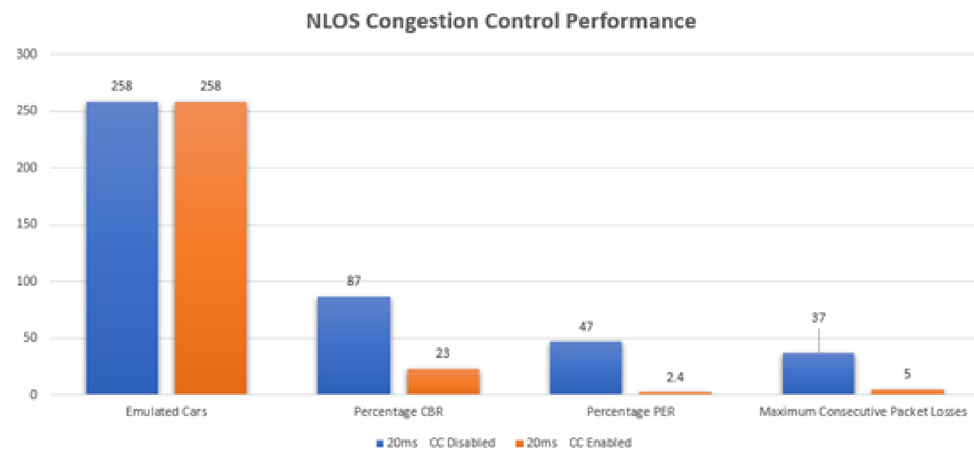


Figure 10-29 NLOS links performance comparison

10.3.3.2 Key takeaways

- Congestion control significantly improves C-V2X performance under NLOS scenarios. Without congestion control, NLOS components perform poorly in PER and IPG metrics.

Without congestion control, PER can be as high as 47% with 95th percentile IPG indicating a loss of 6-10 consecutive packets. With congestion control enabled, PER drops significantly to about 2.4% and 95th percentile IPG indicates that no packets were lost.

11 Conclusion

Through a series of simulations and lab and field tests, this report shows that C-V2X performs well under loaded conditions. This is demonstrated by well-understood KPIs that quantitatively measure performance for all scenarios.

SAE congestion control was triggered and effective in lowering PER and IPG, while ensuring vehicle safety communication between C-V2X nodes in congested scenarios. This is also validated by results that were compared to simulation results for additional validation.

11.1 Lab and field tests

VeCTR is the main lab test setup that generated lab test results for this report. The field test setup provided all the field test results presented.

Results show the effectiveness of using SAE congestion control with C-V2X to reduce the system load, and enable satisfactory communication at a median PER of 3% between a home and remote vehicle at 75 m, and a 95 dB path loss from each other.

The tests were extended later to show good performance with up to an additional 15 dB path loss between the two devices, and differentiated performance for critical BSMs versus normal BSMs. This initial set of results also validates the simulation results presented to 5GAA for a more extensive 1,940 car scenario. The simulations and lab results match at the PER and CBR levels.

The field test setup that generated results for this report found that 50 background devices generated similar loads to the VeCTR setup on 300 m or 600 m test tracks. A variety of scenarios were tested, including four HVs and four RVs, either mobile or stationary, at various points along the track.

Lab tests emulating CAMP scenarios conducted by field tests used the field test setup and a path loss model determined from field measurements. VeCTR is also used for these tests.

The background devices emulated 48 (1X emulation), 96 (2X), and 240 (5X) devices, generating a total offered load between 19.2% and 96% in the 20 MHz carrier used in these tests. 1X and 2X results in this setup showed good performance with or without congestion control.

The 5X emulation mode shows the benefits of enabling congestion control. In 5X, the congestion control algorithm results in devices backing off to 600 ms from the nominal 100 ms BSM transmission periodicity. This results in CBR dropping from 87% with congestion control disabled, to about 24% with congestion control enabled. PER improves significantly from about 4-5% to less than 1% between the host and remote vehicle under test.

These tests showcase that C-V2X performs well without congestion control enabled for the 1X and 2X cases, while the 5X case shows the benefits of enabling congestion control.

11.2 Field tests

Field tests generated results for the 600 m and 300 m test tracks.

Results are preceded with simulation results for the four-car platoon test on the 600 m track.

11.2.1 600 m

Field test results on the 600 m test track are presented for two scenarios:

- In the four-car platoon test, four host vehicles move at a fixed distance of 75 m from each other, and repeatedly cover the track in both directions. Four remote vehicles are placed at a fixed distance across the track. The 50 background devices line the test track and generate 1X, 2X or 5X load.
  - In 1X and 2X emulation modes, all metrics look acceptable for both congestion control disabled and enabled. PER is less than 1% and 95th percentile IPG indicates packet loss at that percentile.
  - In 5X emulation mode with congestion control disabled, PER ranges from 1% to 17% as the distance between cars increase. With congestion control enabled, PER drops significantly to a range of 1% to 5% for all links and 95th percentile IPG indicates no packet loss at that percentile.
  - For all scenarios, results are in line with the simulation results for CBR, PER, and IPG.
- While testing hard-braking in congested environments, a moving device repeatedly brakes hard and reception statistics are collected at a nearby device. The device generates critical BSMs during hard-braking.
  - In 2X emulation mode with congestion control enabled or disabled, delivery of the critical BSMs perform equally well. PER is less than 1% for all links and 95th percentile IPG indicates no packet loss.
  - In 5X emulation mode without congestion control, PER ranges between 5% and 12% for critical messages. With congestion control turned on in the 5X emulation test, PER is limited to less than 2.3% and 95th percentile IPG indicates no packet loss.

11.2.2 300 m

Field test results on the 300 m test track are presented for three scenarios:

- In the four-car platoon test, results show similar trends to the 600 m scenarios but with higher PER in the 5X scenario without congestion control because of higher densification.
- While testing hard-braking in a congested environment, the observations seen for the 600 m case are repeated with the following differences: at 5X emulation, PER is higher between 5% and 25% without congestion control, but lowers to less than 1% due to higher backoff when congestion control is enabled.
  - Compared to the 600 m scenario, higher PER without congestion control and higher backoff with congestion control are due to higher density in this scenario.
- In an NLOS congestion test scenario, a large van separates two sets of stationary vehicles while a four-car platoon passes by. Congestion control significantly improves performance of NLOS links with congestion.
  - Without congestion control, NLOS components have a bad performance in terms of PER and IPG metrics. PER is as high as 47% with 95th percentile IPG, indicating a loss of 6-10 consecutive packets.
  - With congestion control enabled, PER drops significantly to approximately 2.4%, and the 95th percentile IPG indicates no packet loss 95% of the time.

A References

A.1 References and standards

Document	URL
Standards	
LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements (3GPP TS 36.214 version 14.2.0 Release 14)	https://portal.3gpp.org/
Study on LTE-based V2X services (3GPP TR 36.885)	http://www.3gpp.org/
On-Board System Requirements for V2V Safety Communications (SAE J2945/1_201603)	https://www.sae.org/
On-Board System Requirements for LTE V2X V2V Safety Communications (SAE J3161/1)	https://www.sae.org/
Related documents	
V2X Functional and Performance Test Report (5GAA TRP-170142)	https://5gaa.org/
V2X Functional and Performance Test Procedures – Selected Assessment of Device to Device Communication Aspects (5GAA P-180092)	https://5gaa.org/
C-V2X Performance Assessment Project	https://pronto-core-cdn.prontomarketing.com/
Vehicle-To-Vehicle Communication Technology for Light Vehicles (NHTSA-2015-0060)	https://www.nhtsa.gov/
Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application (DOT HS 812 014)	https://www.nhtsa.gov/

A.2 Acronyms and definitions

Term	Definition
5GAA	5G Automotive Association
ADB	Android Debug Bridge
AWGN	Additive White Gaussian Noise
BSM	Basic safety message
CAMP	Crash Avoidance Metrics Partners LLC
CBR	Channel busy ratio
CDF	Cumulative distribution function
CPL	Consecutive packet loss
C-V2X	Cellular vehicle-to-everything
DUT	Device under test
GNSS	Global Navigation Satellite System
HARQ	Hybrid automatic repeat request
HV	Host vehicle
IA	Information age
IPC	Inter-packet count
IPG	Inter-packet gap
ITT	Inter-transmit time
ITS	Intelligent Transportation System
KPI	Key performance indicator
LOS	Line-of-sight
MCS	Modulation coding scheme
NLOS	Non-line of sight
OBU	On board unit
OTA	Over-the-air
PER	Packet error rate
RB	Resource block
RF	Radio frequency
RSRP	Reference Signal Received Power
RV	Remote vehicle
SAE International	Standards developing organization for engineering professionals
SPS	Semi-persistent scheduling
UE	User equipment
UTC	Coordinated Universal Time
V2V	Vehicle-to-vehicle
VA	Variable attenuator
VeCTR	Vehicular Congestion Test Rack

B Configuration Parameters

B.1 Radio resource configuration pre-configuration parameters

The following configuration from SAE J3161/1 is used for congestion testing:

```
{
 v2x-PreconfigFreqList-r14 {
  {
   v2x-CommPreconfigGeneral-r14 {
    rohc-Profiles-r12 {
     profile0x0001-r12 FALSE,
     profile0x0002-r12 FALSE,
     profile0x0004-r12 FALSE,
     profile0x0006-r12 FALSE,
     profile0x0101-r12 FALSE,
     profile0x0102-r12 FALSE,
     profile0x0104-r12 FALSE
    },
    carrierFreq-r12 55140,
    maxTxPower-r12 23,
    additionalSpectrumEmission-r12 32,
    sl-bandwidth-r12 n100,
    tdd-ConfigSL-r12 {
     subframeAssignmentSL-r12 none
    },
    reserved-r12 '0000000000000000000'B
   },
   v2x-CommRxPoolList-r14 {
    {
     sl-Subframe-r14 bs20-r14 : 'FFFFF'H,
     adjacencyPSCCH-PSSCH-r14 TRUE,
     sizeSubchannel-r14 n10,
     numSubchannel-r14 n10,
     startRB-Subchannel-r14 0,
     dataTxParameters-r14 23
    }
   },
   v2x-CommTxPoolList-r14 {
    {
     sl-Subframe-r14 bs20-r14 : 'FFFFF'H,
     adjacencyPSCCH-PSSCH-r14 TRUE,
     sizeSubchannel-r14 n10,
     numSubchannel-r14 n10,
     startRB-Subchannel-r14 0,
     dataTxParameters-r14 23,
```

```
      threshS-RSSI-CBR-r14 9,
      cbr-pssch-TxConfigList-r14 {
       {
        priorityThreshold-r14 8,
        defaultTxConfigIndex-r14 1,
        cbr-ConfigIndex-r14 0,
        tx-ConfigIndexList-r14 {
         0,
         1
        }
       }
      },
      syncAllowed-r14 {
       gnss-Sync-r14 true
      }
     }
    },
    p2x-CommTxPoolList-r14 {
     {
      sl-Subframe-r14 bs10-r14 : '0000000000'B,
      adjacencyPSCCH-PSSCH-r14 FALSE,
      sizeSubchannel-r14 n4,
      numSubchannel-r14 n1,
      startRB-Subchannel-r14 0,
      dataTxParameters-r14 -126
     }
    },
    v2x-ResourceSelectionConfig-r14 {
     pssch-TxConfigList-r14 {
      {
       typeTxSync-r14 gnss,
       thresUE-Speed-r14 kmph120,
       parametersAboveThres-r14 {
        minMCS-PSSCH-r14 0,
        maxMCS-PSSCH-r14 7,
        minSubChannel-NumberPSSCH-r14 1,
        maxSubchannel-NumberPSSCH-r14 5,
        allowedRetxNumberPSSCH-r14 n1
       },
       parametersBelowThres-r14 {
        minMCS-PSSCH-r14 5,
        maxMCS-PSSCH-r14 11,
        minSubChannel-NumberPSSCH-r14 1,
        maxSubchannel-NumberPSSCH-r14 2,
        allowedRetxNumberPSSCH-r14 n1
       }
      }
     },
```

```
thresPSSCH-RSRP-List-r14 {
 2,
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      11,
      11,
      11,
      11,
      11
     },
     restrictResourceReservationPeriod-r14 {
      v1
     },
     probResourceKeep-r14 v0dot8,
     sl-ReselectAfter-r14 n5
    },
    syncPriority-r14 gnss,
    offsetDFN-r14 0
   }
  },
  cbr-PreconfigList-r14 {
   cbr-RangeCommonConfigList-r14 {
    {
     65,
     100
    }
   },
   sl-CBR-PSSCH-TxConfigList-r14 {
    {
     cr-Limit-r14 10000,
     tx-Parameters-r14 {
      minMCS-PSSCH-r14 0,
      maxMCS-PSSCH-r14 28,
      minSubChannel-NumberPSSCH-r14 1,
      maxSubchannel-NumberPSSCH-r14 10,
      allowedRetxNumberPSSCH-r14 n1,
      maxTxPower-r14 txPower-r14 : 23
     }
    },
    {
```

```
        cr-Limit-r14 400,
        tx-Parameters-r14 {
         minMCS-PSSCH-r14 0,
         maxMCS-PSSCH-r14 28,
         minSubChannel-NumberPSSCH-r14 1,
         maxSubchannel-NumberPSSCH-r14 10,
         allowedRetxNumberPSSCH-r14 n1,
         maxTxPower-r14 txPower-r14 : 23
        }
       }
      }
     }
    }
```

B.2 Device configurator

Many tools that enable device control while running VeCTR were developed internally by QTI. These tools are either device handlers or log analyzers.

B.2.1 Device handlers

Device handlers allow for control of the UE in every aspect while testing.

Table B-1 provides details of critical device handlers.

Table B-1 Critical device handlers

Device handler	Function

UE configurator	All devices on VeCTR system are configured automatically from a remote location. Configuration includes the following:
	▪ Software updates, including (but not limited to) loading or updating:
	  ▫ Device software needed for UE operation
	  ▫ ITS Stack software
	  ▫ Modem binaries
	▪ Modem config:
	  ▫ Modifies and edits v2x.xml pre-configuration automatically
	  ▫ Loads other modem related parameters and RF calibration related configurations and files

Log collector	Validates system behavior of the and enables debug during testing. Can collect logs from the following areas: ▪ Modem level logs, i.e., QXDM Professional™ Tool ▪ ITS application logs, i.e., Interop CSVs from SI ▪ Application processor Linux system logs ▪ Android Debug Bridge (ADB) logs system
UE scenario controller	Allows user to control UE to ensure that UE can be distributed in time and scale would not any stop test execution. Can perform the following actions: ▪ Controls modem for fine-tuned action ▪ Packet periodicity, MAX_ITT, VehicleDensityCoefficient, Packet Priority, Congestion Control, etc. ▪ Executes ADB commands or Linux shell commands on the UE, i.e., starting SI ▪ Controls UE power