CAMP LLC

Cellular V2X Device-to-Device Communication Consortium






# C-V2X Performance Assessment Project

**December 5, 2019**

# Project Overview / Status

# Technical Scope

- Conduct activities in the SOW addressing the evaluation of C-V2X technology and device-to-device (D2D) communication

- Objective evaluation of C-V2X communication technology, limited to 3GPP Release 14, mode 4, D2D communication, for V2X safety communication, by developing V2X functional and performance test procedures, conducting testing, conducting performance assessment, and documenting the results

# Project Tasks

Period of Performance: Oct 15, 2018 – Dec 31, 2019

- Task 1: Technical project management
- Task 2: Develop and document test cases and test procedures
- Task 3: C-V2X system acquisition and test software development
- Task 4: Vehicle and infrastructure system integration
- Task 5: Plan and conduct C-V2X testing
- Task 6: Data analysis and performance assessment
- Task 7: Develop potential extension plan

# Objective Testing

Aimed at understanding C-V2X system performance under these system factors:

- Channel bandwidth – 10 MHz and 20 MHz
- Payload variations – 200, 365, 1000 and 1400 bytes (1609.3 WSM max payload is 1400 bytes)
- Antenna integration – one Tx and one Rx (no receive diversity), one Tx and two Rx (diversity)
- Hybrid automatic repeat request (hybrid ARQ or HARQ) – On and Off (3GPP D2D Rel. 14 allows HARQ retransmit of one (1) as an option)
- Transmit power (unit) – 20 dBm (additional cable loss ~3dB, ~0dB antenna gain at Horizon)

# Testing Categories

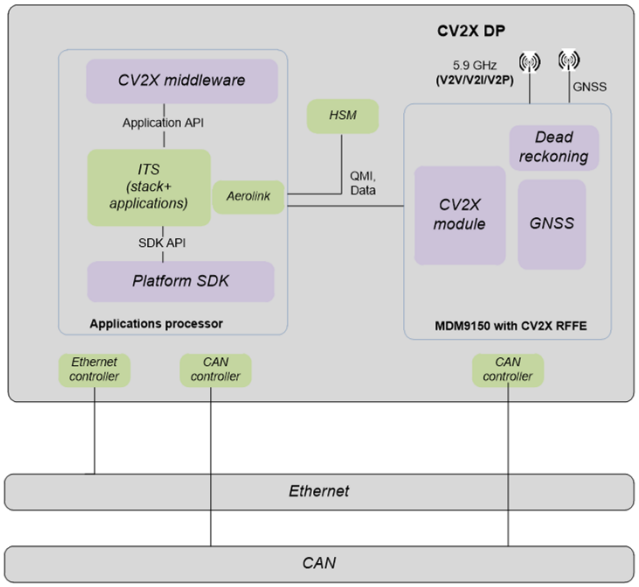
- Device Characterization
- Bench Testing
- Controlled Vehicle Testing – V2V & V2I Scenarios
- Mixed Traffic Vehicle Testing
- Congestion Control Testing

# Device Characterization

# C-V2X Development Platform (RRv1)

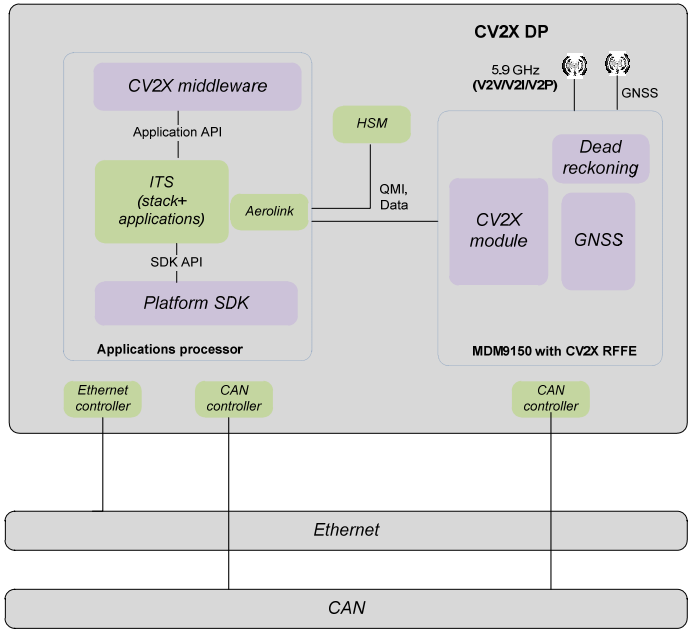
- Objectives
  - Serve as early OBU or RSU for C-V2X evaluation, trials and demonstration
  - Enable ITS stack vendors to port their stack and applications to function over the C-V2X PC5 Direct Communications

- Description
  - Platform consists of APQ 8096 (Applications Processor) and C-V2X 3GPP Single Channel Radio MDM 9160
  - Platform SDK to enable ITS stack vendors
  - Evaluation units supplied by Qualcomm come pre-loaded with ITS stack and applications from Savari
    - V2V Applications: FCW, EEBL, IMA, LTA, BSW, LCW
    - V2I Applications: SPAT/MAP etc.
  - Test Applications built using Platform SDK are also available for PC5 evaluation independent of ITS stack
  - CAN Functionality
    - Provides Multiple CAN buses and Multiple Options to connect to the Vehicle CAN Bus
  - Optional C-V2X Middleware to enable V2I, V2P, V2N Applications



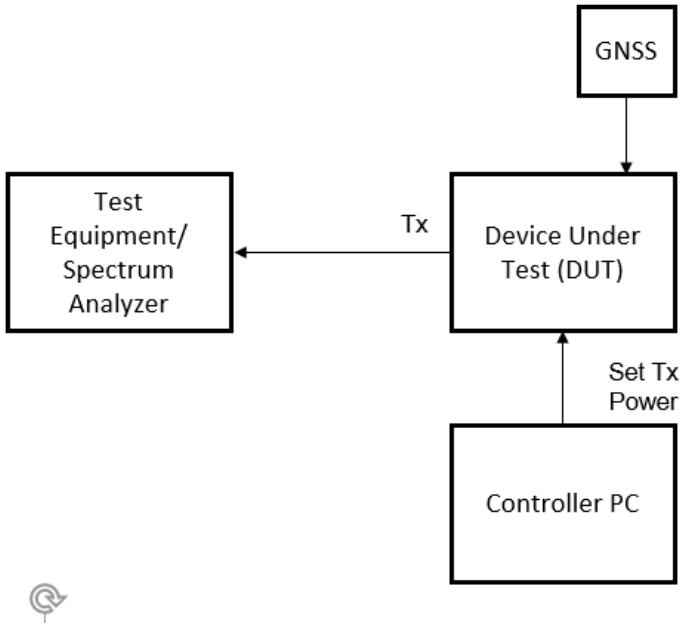

# C-V2X Development Platform (RRv1)

| Component | Description |
|---|---|
| Processor | Automotive Snapdragon820 (APQ8996)<br>1200 MHz ARM A7 (in MDM9150)+B2 |
| Memory | 2 GB (APQ) |
| Storage | 64 GB + 2 GB, microSD slot |
| Radio | PC5 Mode 4 |
| GNSS | Multi-constellation<br>Qualcomm QDR3 Dead Reckoning<br>XTRA + Time injection |
| Operational Temperature | “-40 to 85C” |
| Other Interfaces | USB 3.0 OTG, USB Host, 3x 1 Mbps CAN, 1000BT Ethernet, RS232 |
| Standards | 3GPP Rel 14, IEEE 1609.3, ETSI ITS G5, SAE J2735, SAE J3161 (draft) |
| Security | IEEE 1609.2 (Via Savari & On Board Security) |
| Wireless Connectivity | Automotive QCA6574AU<br>- Wi-Fi: 2.4 GHz, 802.11n, 2 x 2<br>- Bluetooth 4.2 + BLE |



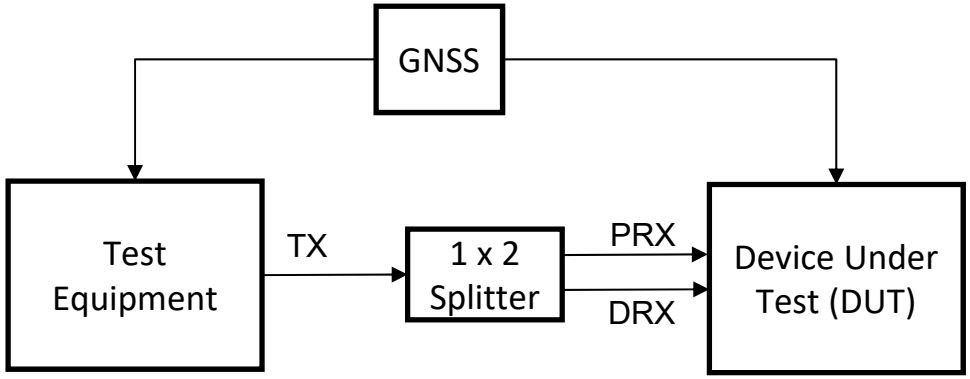

# Transmit Power Accuracy

- Commanded v/s Actual Power
  - Result: Output power within 0.5 dBm of commanded power setting



# Receiver Sensitivity Test – 3GPP

- Test Configuration: QPSK (1/3),Full BW, NO HARQ, 5% BLER
  - 10 MHz Min Req*: -90.4dBm, Result: Pass
  - 20 MHz Min Req*: -87.5dBm, Result: Pass




*Specified in TS 36.101 R14

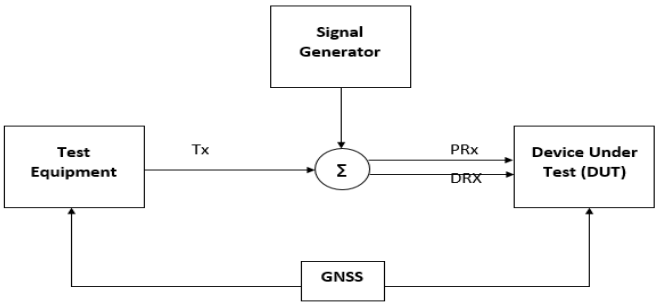
# TX Spectrum Emissions Mask – 10 MHz CH 184

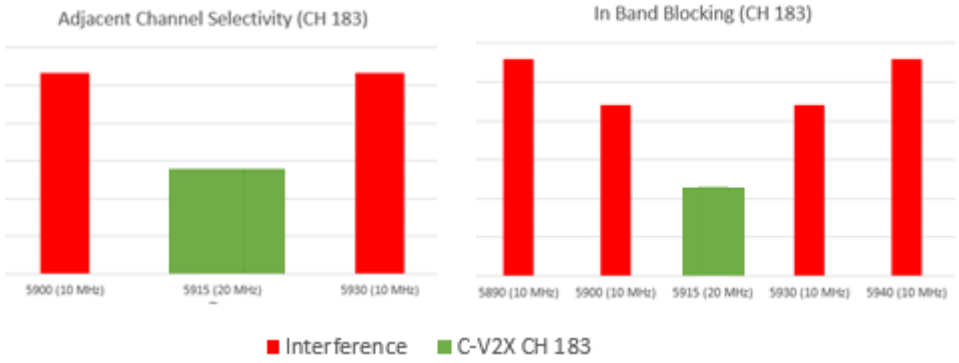
- 10 MHz – CH 184
  - Result : Device is able to meet FCC Class C mask at 20dBm TX Power
    - Tested for Full BW and NB Transmission aligned with the edges

- 20 MHz – CH 183 ( CH 182 + CH 184)
  - Result: Device is able to meet proposed C-V2X 20 MHz Transmit Mask at 20dBm TX Power
    - Tested for Full BW and NB Transmission aligned with the edges

# Adjacent Channel Selectivity and In Band Blocking

- Adjacent channel selectivity tests the OBU's ability to receive data, in the presence of an adjacent channel signal at a given frequency offset from the center frequency of the assigned channel, under conditions of ideal propagation and no added noise
- In Band blocking tests the OBU's ability to receive data, in the presence of an in-band interfering signal at +/-15MHz and +/-25MHz offset from the center frequency of the assigned channel, under conditions of ideal propagation and no added noise



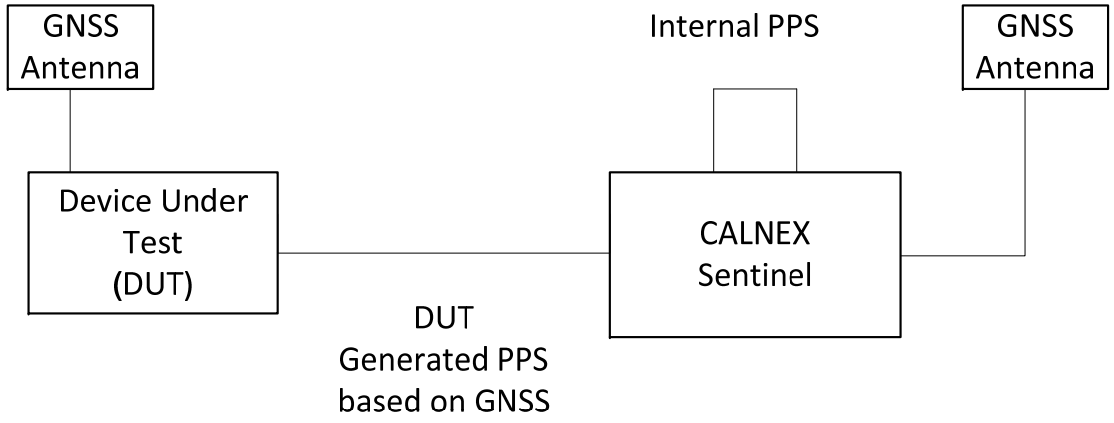




Results Summary

- ACS Result : Pass
- In Band Blocking Result: Pass
- Testing performed per 3GPP 36.521-1 Test Case 7.5G.1 & 7.6.1G.1.

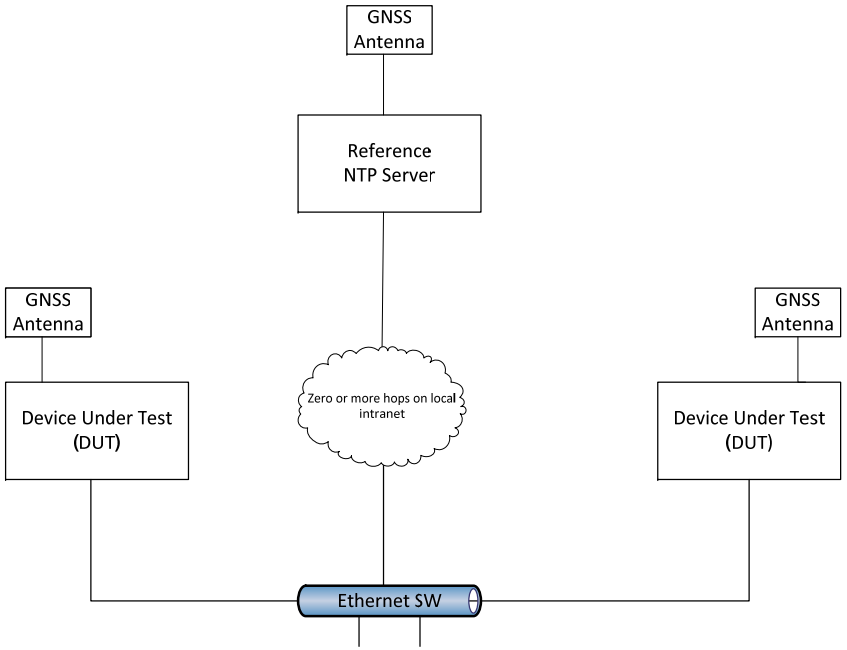
# Timing for C-V2X Transmission Synchronization (Open Sky)

- Allowed Timing Error +/-391ns
- Result : Pass. Measured timing error is always less than +/- 391ns



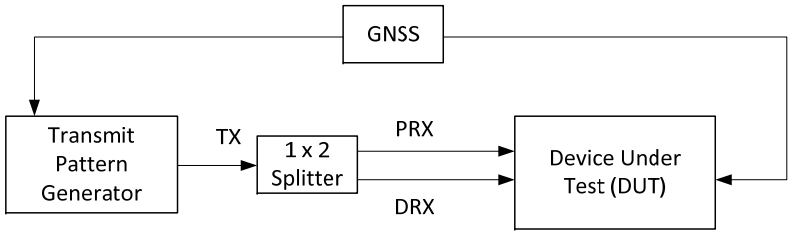
# System Clock Accuracy

- Measure ability of the C-V2X RR v1's platform system clock to sync within 1 ms of UTC
- Result: Platform's can sync within 1ms of Stratum 1 NTP servers within 1min after bootup



# Channel Busy Ratio (CBR)

- Verify OBU's ability to accurately measure Channel occupancy
- OBU should report CBR within +/- 3% (per 3GPP requirement )
- Result : Pass




| 60% Congestion | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Subframe 0 | Subframe 1 | Subframe 2 | Subframe 3 | Subframe 4 | Subframe 5 | Subframe 6 | Subframe 7 | Subframe 8 | Subframe 9 |
| **SC1** | SC1 | **SC1** | SC1 | **SC1** | SC1 | **SC1** | SC1 | **SC1** | **SC1** |
| **SC2** | SC2 | **SC2** | SC2 | **SC2** | SC2 | **SC2** | SC2 | **SC2** | **SC2** |
| **SC3** | SC3 | **SC3** | SC3 | **SC3** | SC3 | **SC3** | SC3 | **SC3** | **SC3** |
| **SC4** | SC4 | **SC4** | SC4 | **SC4** | SC4 | **SC4** | SC4 | **SC4** | **SC4** |
| **SC5** | SC5 | **SC5** | SC5 | **SC5** | SC5 | **SC5** | SC5 | **SC5** | **SC5** |
| **SC6** | SC6 | **SC6** | SC6 | **SC6** | SC6 | **SC6** | SC6 | **SC6** | **SC6** |
| **SC7** | SC7 | **SC7** | SC7 | **SC7** | SC7 | **SC7** | SC7 | **SC7** | **SC7** |
| **SC8** | SC8 | **SC8** | SC8 | **SC8** | SC8 | **SC8** | SC8 | **SC8** | **SC8** |
| **SC9** | SC9 | **SC9** | SC9 | **SC9** | SC9 | **SC9** | SC9 | **SC9** | **SC9** |
| **SC10** | SC10 | **SC10** | SC10 | **SC10** | SC10 | **SC10** | SC10 | **SC10** | **SC10** |
| Note: SC stands for subchannel. Each column above represents one TTI of 1ms. Bold font means blocked due to transmission. | | | | | | | | | |

- Testing Performed per TC 24.1.16 from 3GPP TS 36.523 for 30% and 60% CBR

# OBU Modem Parameters

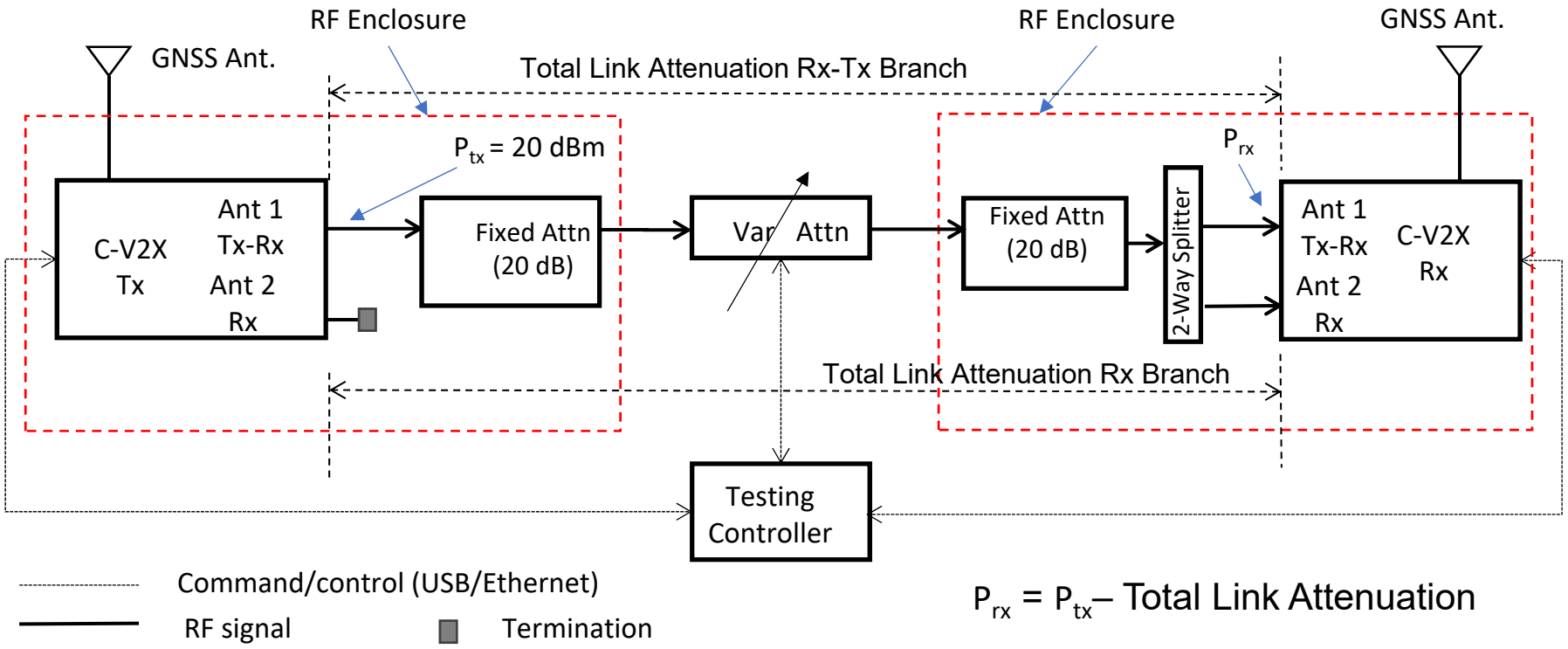
| | 20 MHz | | | | 10 MHz | | | |
|---|---|---|---|---|---|---|---|---|
| | Speed < 120kmph | | Speed > 120kmph | | Speed < 120kmph | | Speed > 120kmph | |
| Packet Size | MCS | Num Sub Channels | MCS | Num Sub Channels | MCS | Num Sub Channels | MCS | Num Sub Channels |
| 200 | 6 | 2 | 4 | 3 | 6 | 2 | 4 | 3 |
| 365 | 11 | 2 | 5 | 4 | 11 | 2 | 5 | 4 |
| 400 | 5 | 5 | 4 | 5 | 5 | 5 | 4 | 5 |
| 1000 | 5 | 10 | 5 | 10 | 11 | 5 | 5 | 5 |
| 1400 | 7 | 10 | 7 | 10 | 7 | 5 | 7 | 5 |

Sub-Channel Size = 10 RB

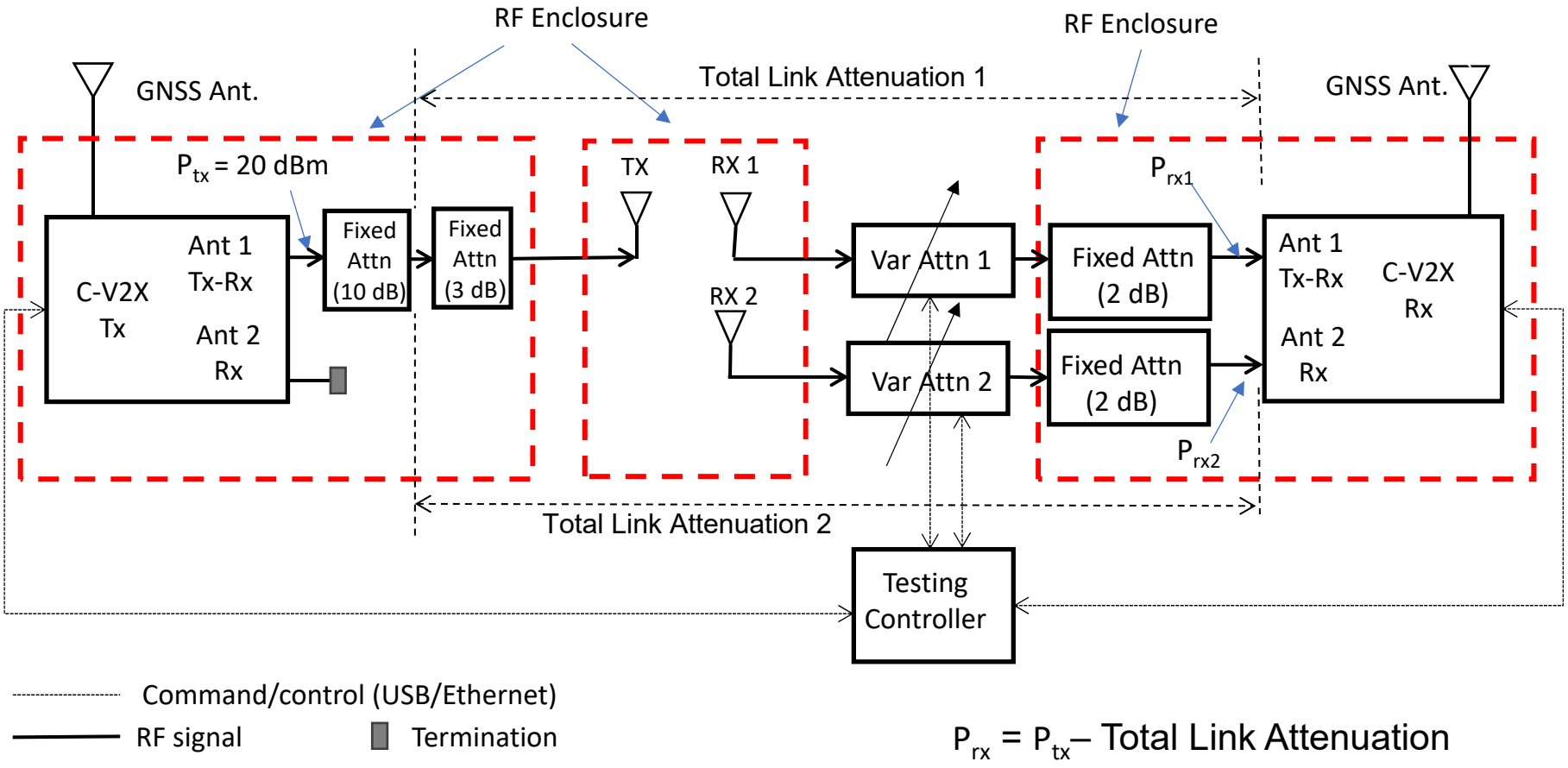
Note: The tabulated parameters were used for the lab, controlled and mixed traffic field testing. The parameters are subject to change pending future implementations and/or standards recommendations

# C-V2X Bench Testing and Results

# Bench Testing – Cabled (2Rx)



# Bench Testing – “Last Link Wireless” (2Rx)



# Bench Testing Summary

**Cabled, "Last Link Wireless" 2Rx power sensitivity at 10% PER**

| 10 MHz | | |
|---|---|---|
| | Cabled 2Rx | Wireless 2Rx |
| Pk. Size bytes | HARQ | HARQ |
| 200 | -105 dBm | -105 dBm |

| 20 MHz | | |
|---|---|---|
| | Cabled 2 Rx | Wireless 2Rx |
| Pk. Size byes | HARQ | HARQ |
| 200 | -104 dBm | -104 dBm |

**Inter Packet Gap (IPG) and Application Layer Latency**

- Average IPG is about 100 ms
- 95$^{th}$ Percentile Latency ~30 ms for 200B payload

Note: Bench re-testing will be conducted for 365B, and 1400B using latest software and configuration changes

Config Note : 200 bytes for 10 MHz and 20 MHz both use MCS 6 and 2 Subchannels with sub-channel size of 10 RB

# Controlled Vehicle Testing and Results

## FTTA Tests

Test Days: Sep 9 – Sep 13

# Test Setup

## Test Scenarios

| Scenario | Link Test |
|---|---|
| Line of Sight (LOS) | V2I & V2V |
| Non-Line of Sight (NLOS) | V2I & V2V |
| High Speed Opposite Direction | V2V |
| NLOS Intersection | V2V |

## Test Configurations

| Config Item | Values |
|---|---|
| Payload | 365, 1400 Byte |
| Antenna Diversity | 1 Rx, 2 Rx |
| HARQ | ON/OFF |
| Bandwidth | 20 MHz |
| Transmit Power (unit) | 20 dBm (additional ~3dB cable loss, ~0dB antenna gain at Horizon) |
| Inter-Transmit Time | 100 ms |

## OBE-Vehicle Mapping

| OBE ID | Vehicle/ RSU |
|---|---|
| 101 | Ford-1 |
| 12 | Ford-2 |
| 21 | GM-1 |
| 22 | GM-2 |
| 31 | HyundaiKia-1 |
| 32 | HyundaiKia-2 |
| 41 | Nissan-1 |
| 42 | Nissan-2 |
| 105 | RSU w/ ECO6-5900-RN (6 dBi gain Antenna) |
| 106 | RSU w/ ECO6-5500-RN (6 dBi gain Antenna) |

# Test Vehicles (1/2)

101

12

21

22

# Test Vehicles (2/2)

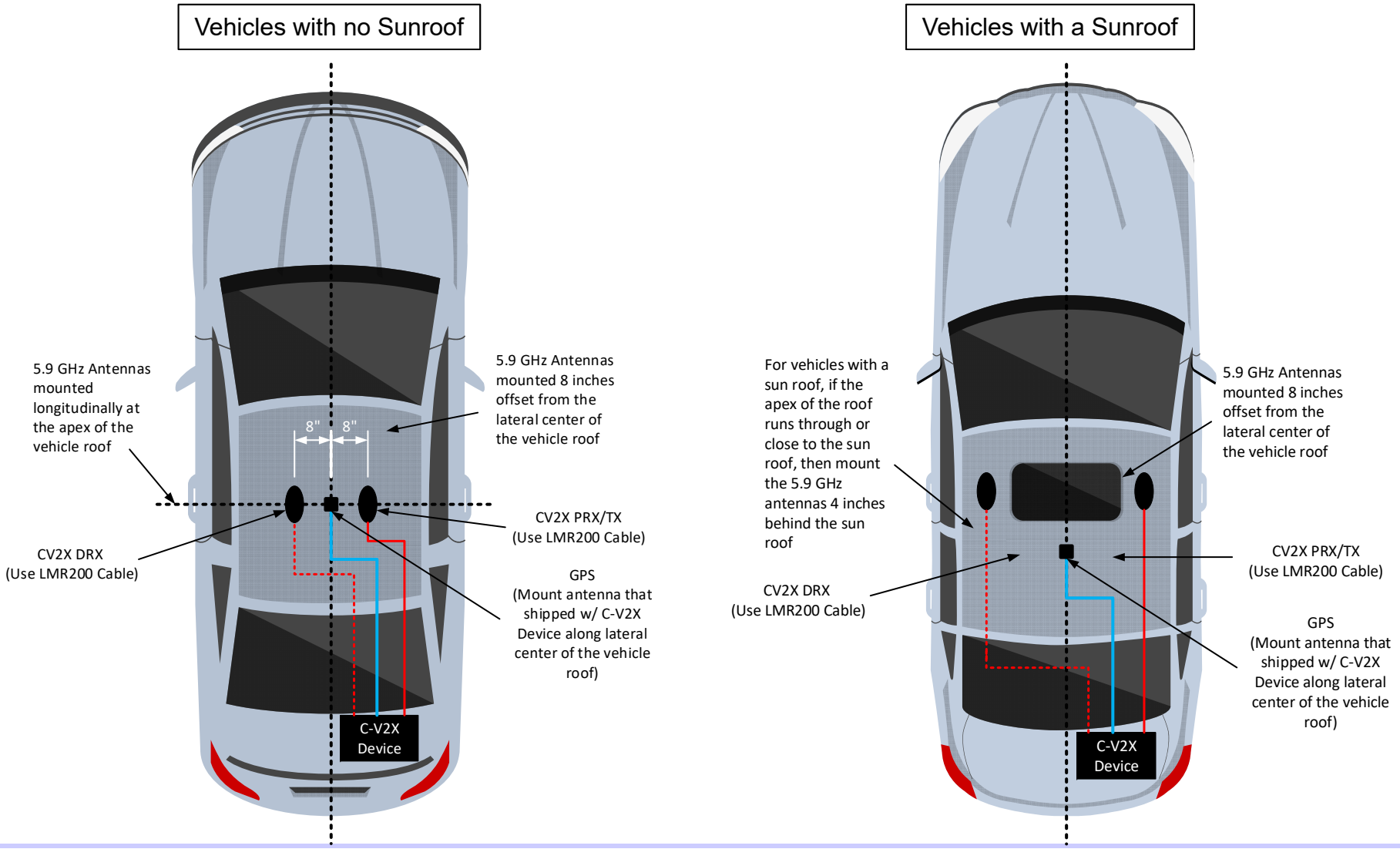
31

32

41

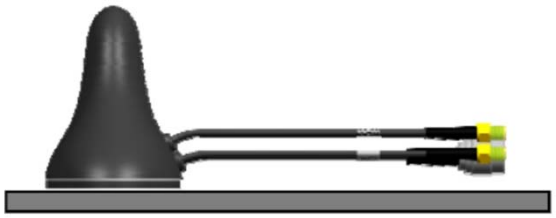
42

# Vehicle Antenna Placement



# Vehicle Radiated RF Power

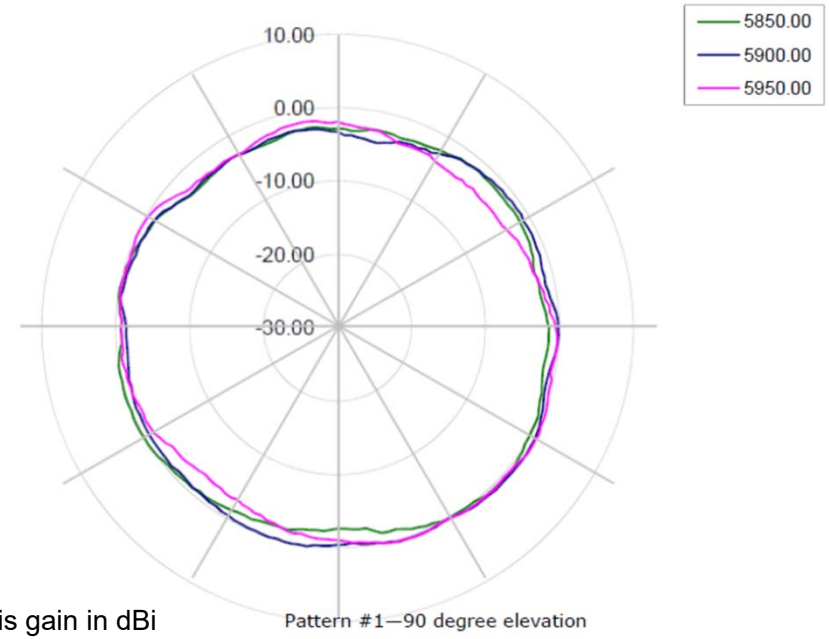
Radiated Power = Antenna Gain + Tx Power (unit) – Cable Loss
Tx Power (unit) = 20 dBm
Cable Loss (LMR 200, 3 meters) = ~ 3 dB
Antenna gain (horizon) = ~ 0 dBi
Radiated Power = ~ 17 dBm



Sketch #2—Mount on surface

Magnet Mount Antenna

**Radiation Pattern @ 5.85 GHz, 5.90 GHz, 5.95 GHz**



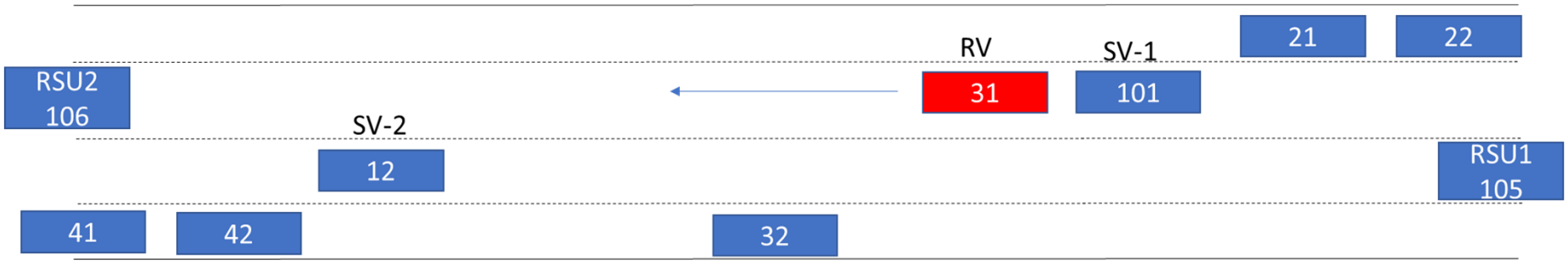

Pattern #1—90 degree elevation

The scale on the patterns is gain in dBi

These patterns were measured on a 1m diameter circular ground plane with the antenna in the center

# Test Setup: V2I & V2V LOS

- Primary OBEs: 31, 101, 12
- Primary RSEs: 105 & 106
- Background OBEs: 21, 22, 32, 41, 42

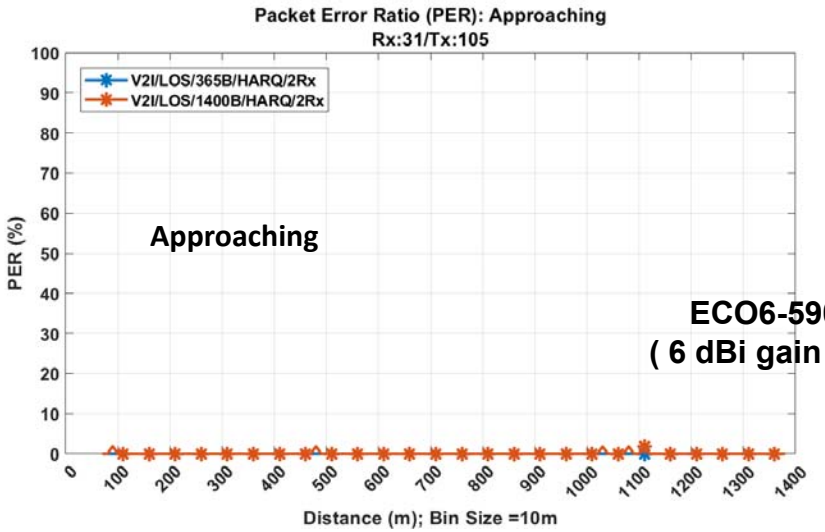


# V2I Line of Sight (LOS)

- 20 dBm/HARQ / 2Rx

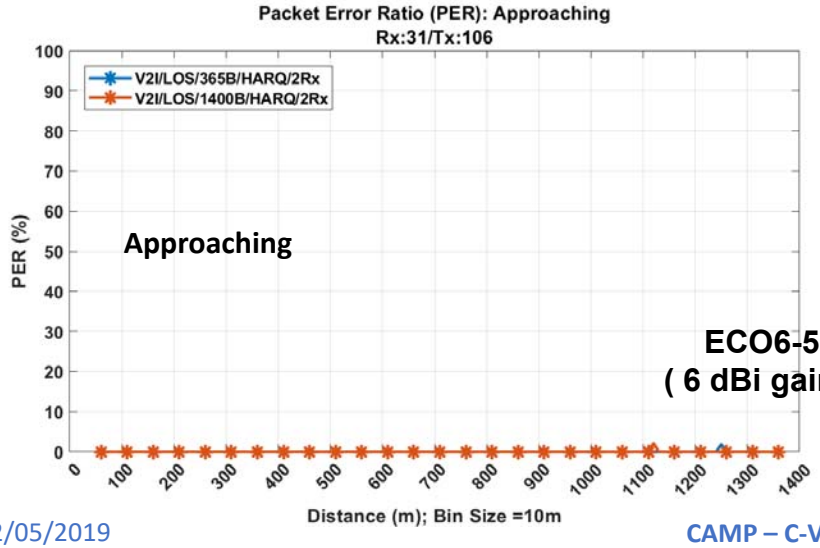
# V2I-LOS: HARQ/2Rx

## Moving Vehicle Receiving




**105**

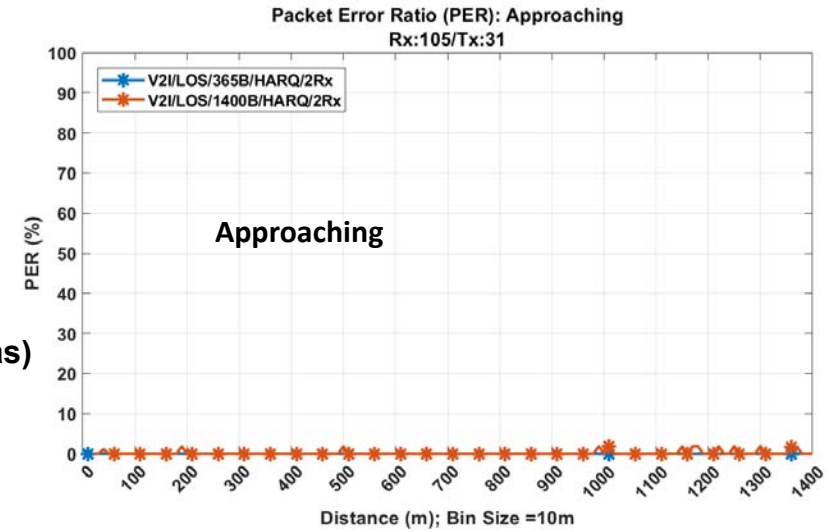
**ECO6-5900-RN**
**( 6 dBi gain antennas)**

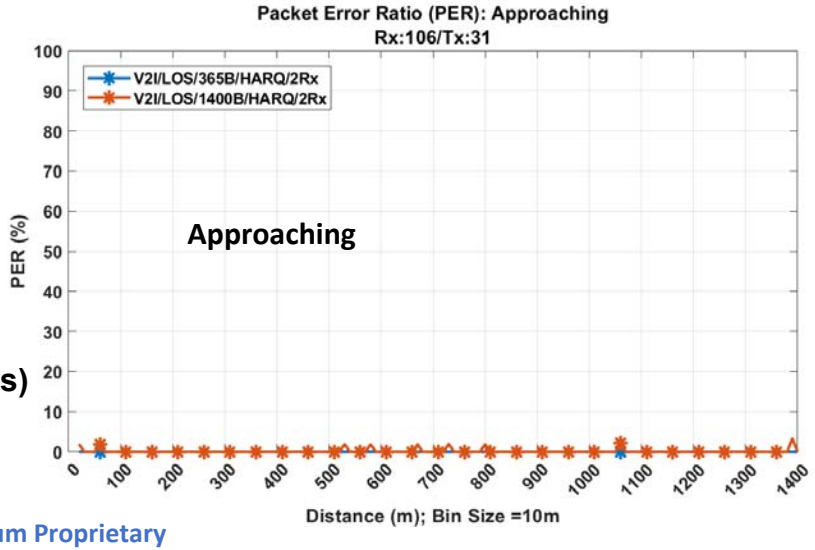



**106**

**ECO6-5500-RN**
**( 6 dBi gain antennas)**

## RSU Receiving



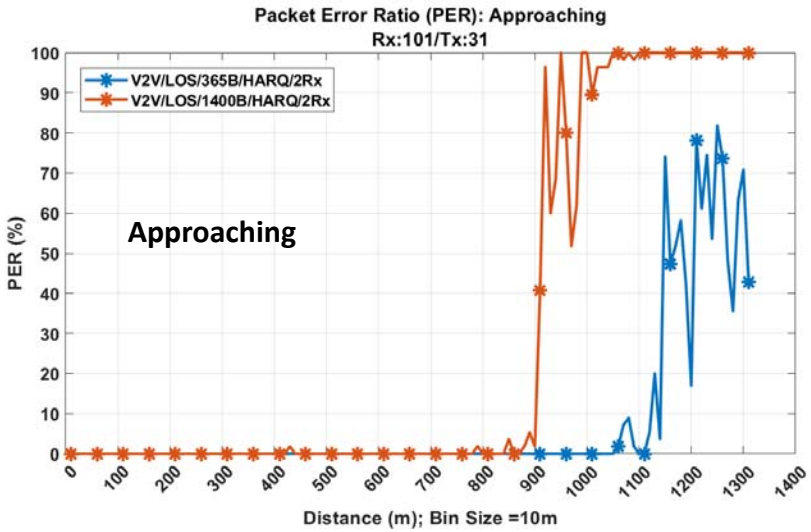



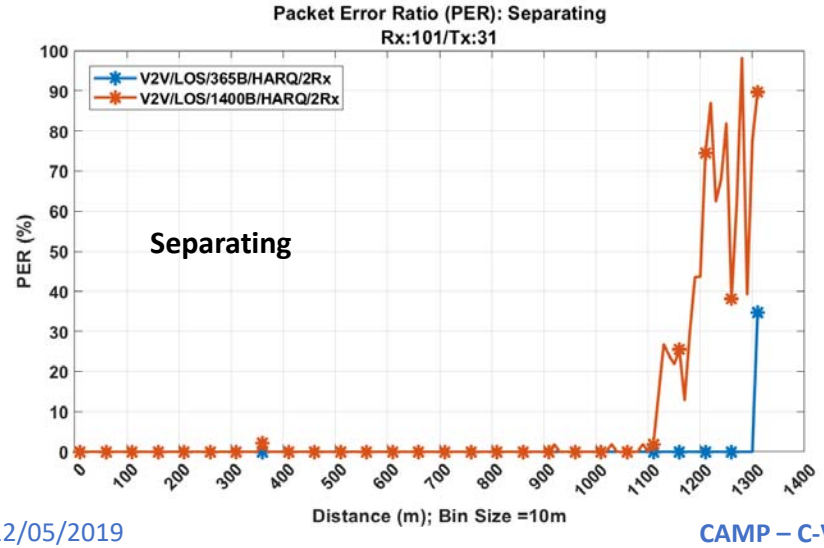
# V2V Line of Sight (LOS)

- 20 dBm/HARQ/2Rx

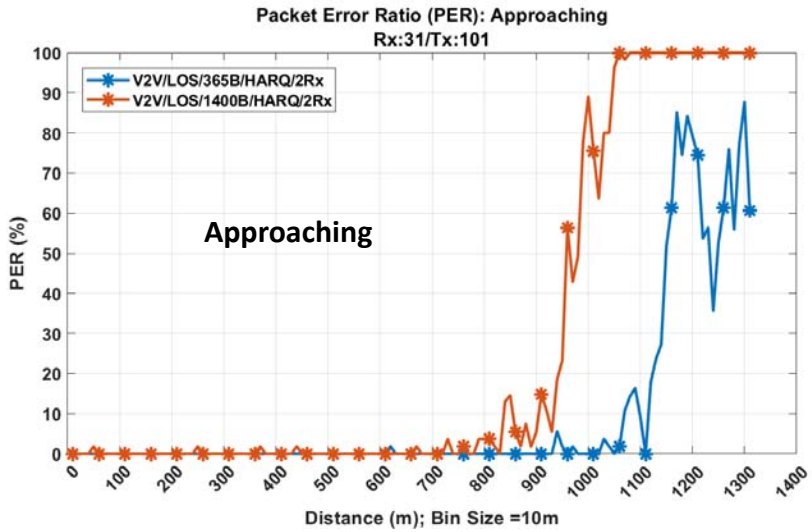
# V2V LOS: HARQ/2Rx
# 101 & 31

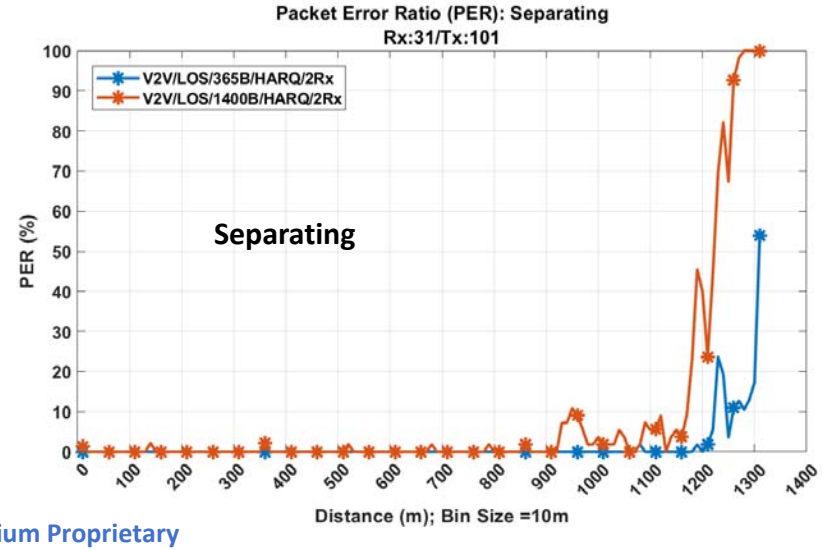
## Stationary Vehicle Receiving



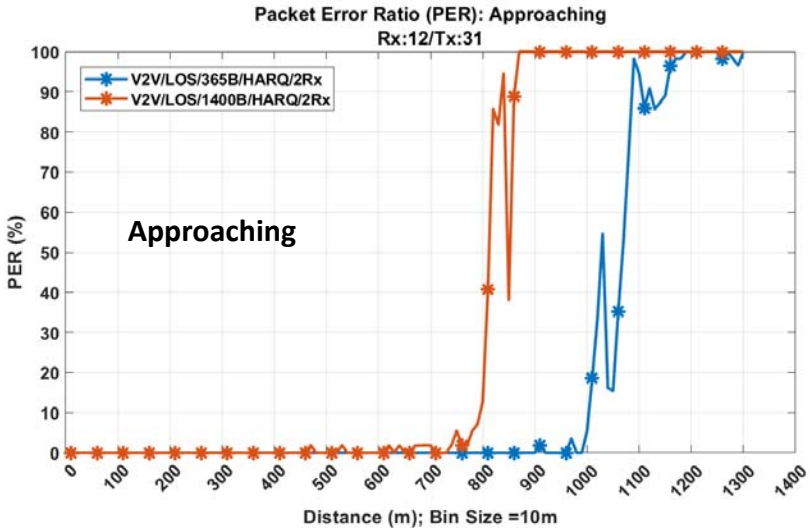

## Moving Vehicle Receiving

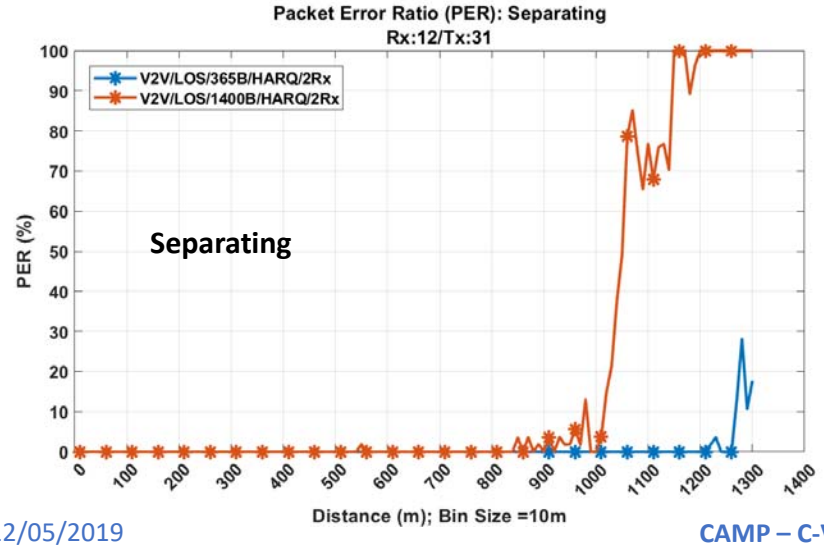


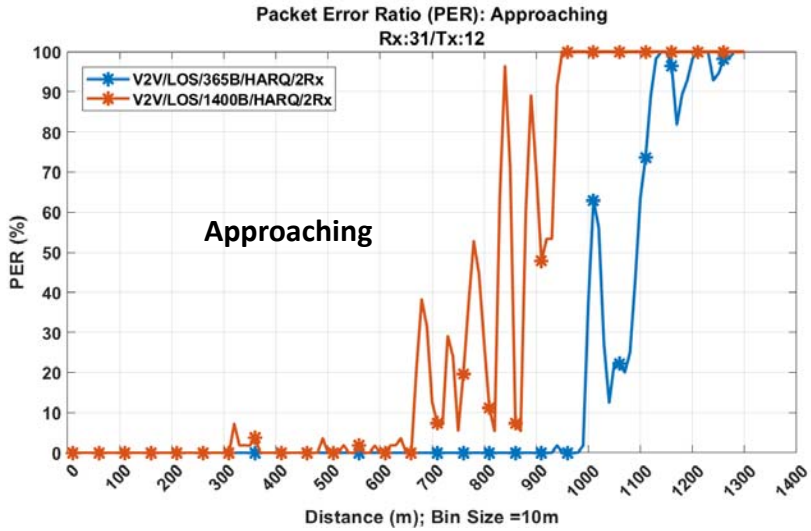
# V2V LOS: HARQ/2Rx
# 12 & 31

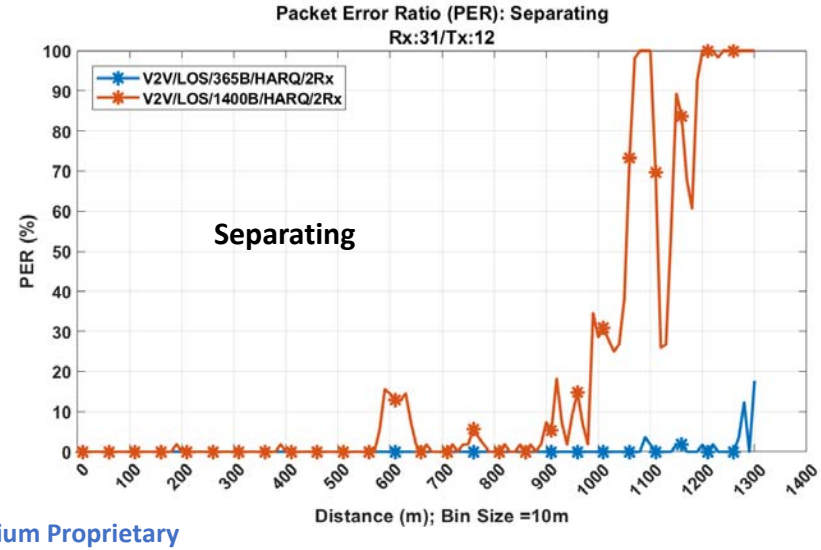
## Stationary Vehicle Receiving



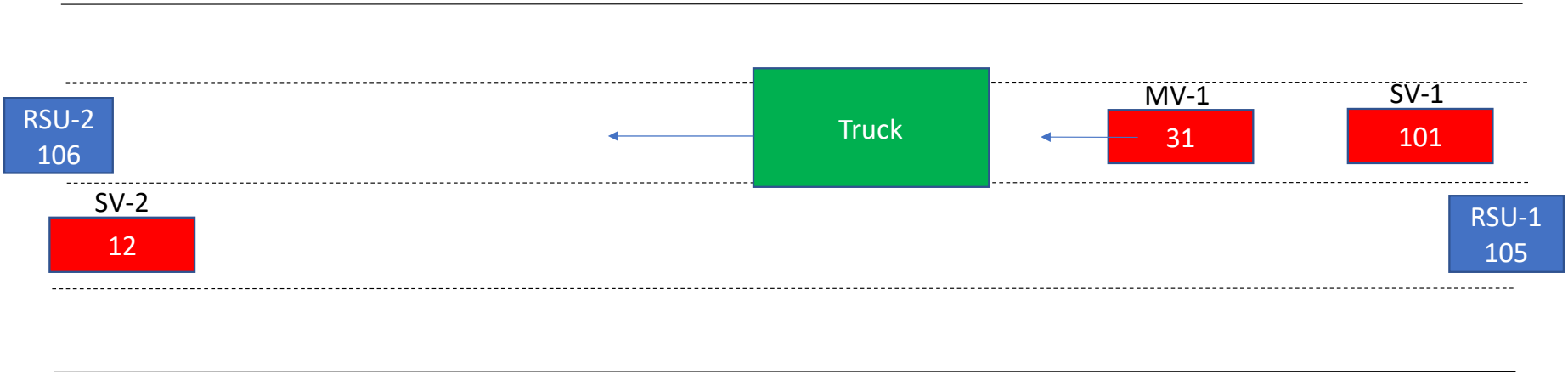

## Moving Vehicle Receiving



# Test Setup: V2I NLOS

- Primary OBE: 31
- RSEs: 105 & 106
- Background OBEs: 12, 101

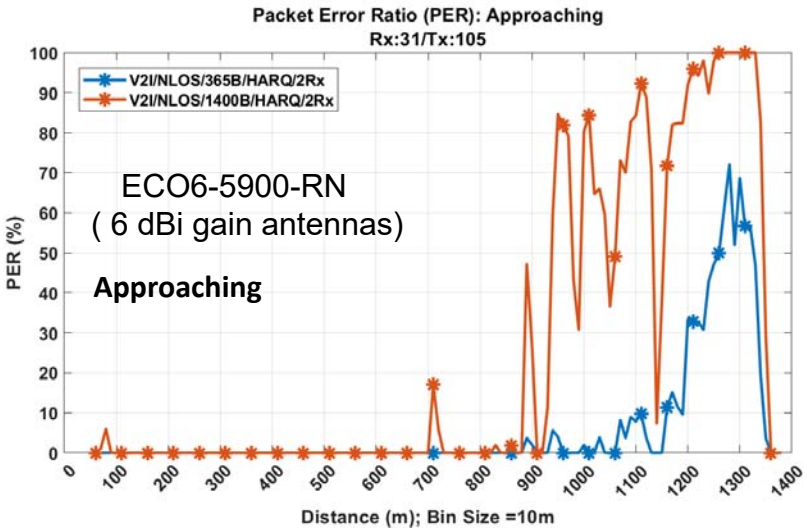



# V2I Non Line of Sight (NLOS)

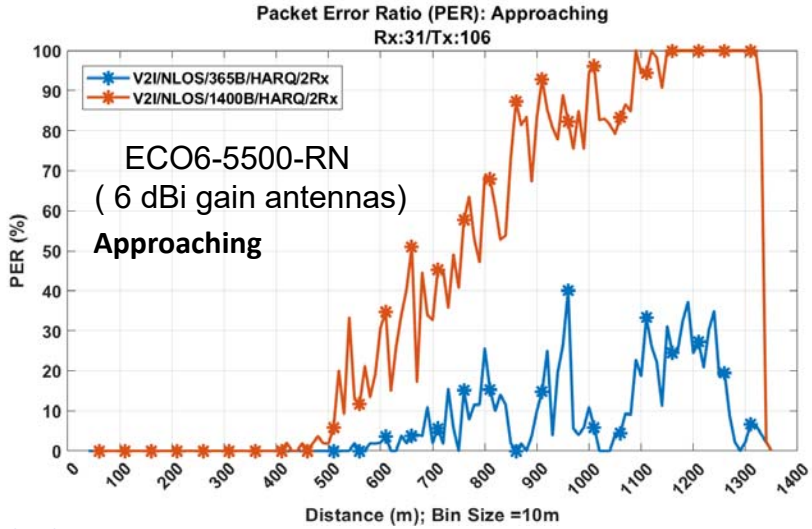
- 20 dBm/HARQ / 2Rx

# V2I NLOS: HARQ/2Rx

## Moving Vehicle Receiving

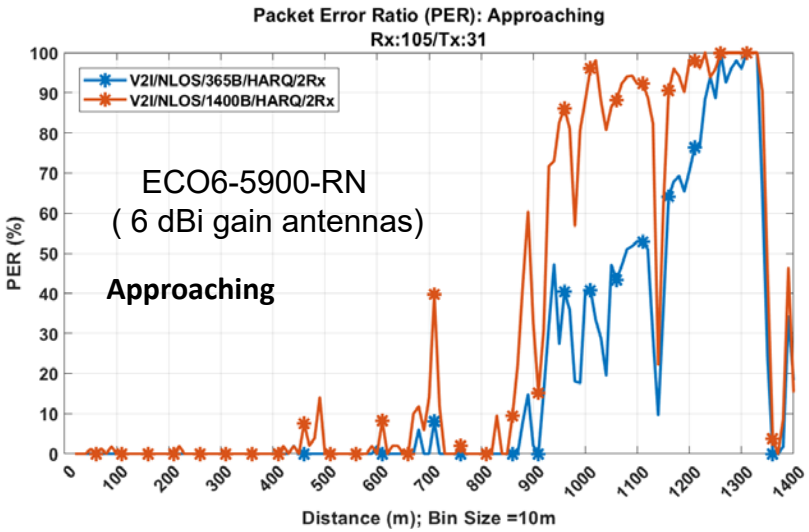


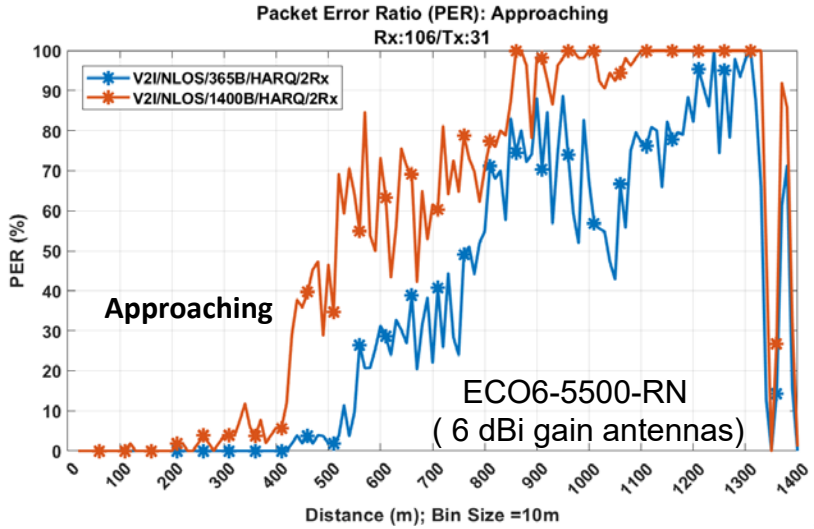

105




106

## RSU Receiving



# Test Setup: V2V High Speed Opposite Direction (HSOD)

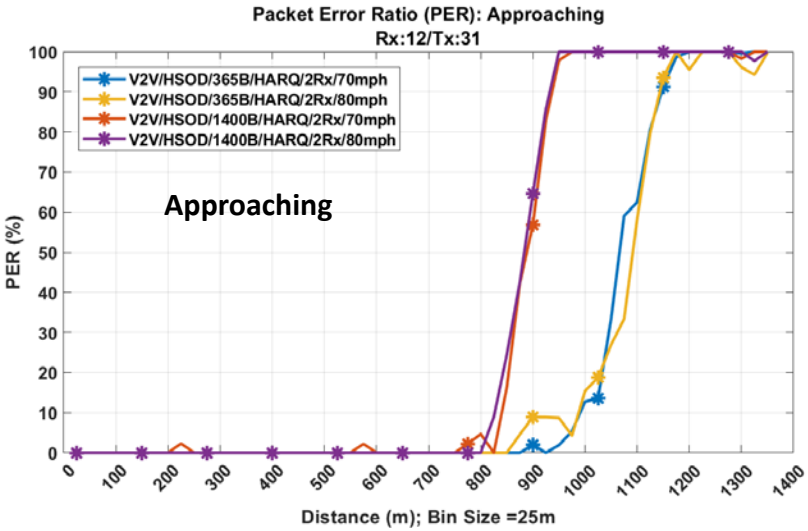
- Primary OBEs: 31 , 12
- Background RSEs: 105 & 106
- Background OBEs: 101, 21, 22, 32, 41, 42

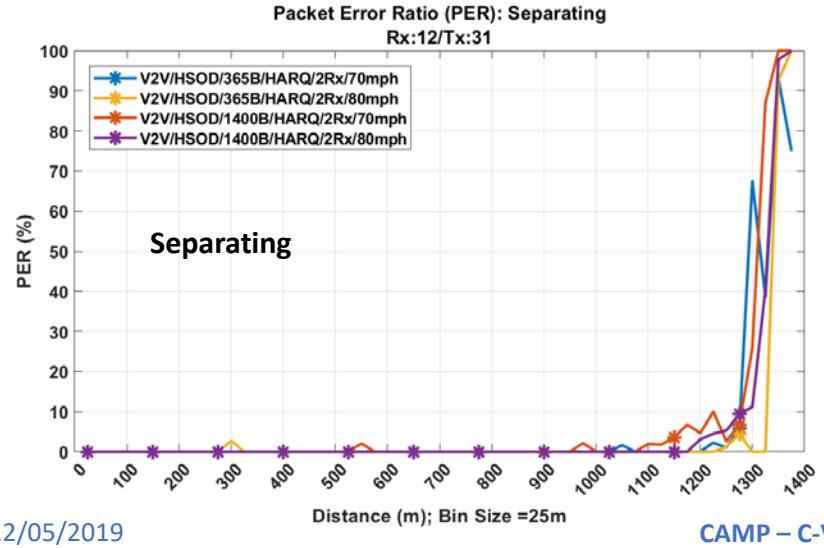
# V2V High Speed Opposite Direction (HSOD)

- 20 dBm/HARQ / 2Rx

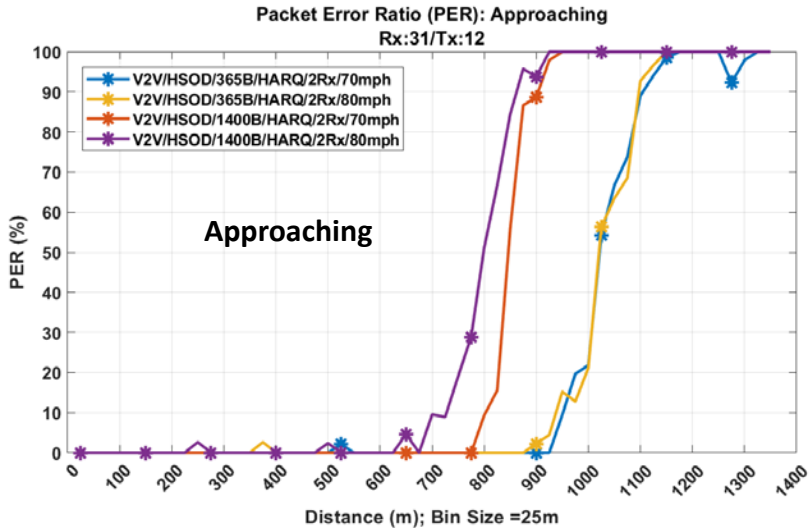
# V2V HSOD : HARQ/2Rx/80 mph-vs-70 mph 12 & 31

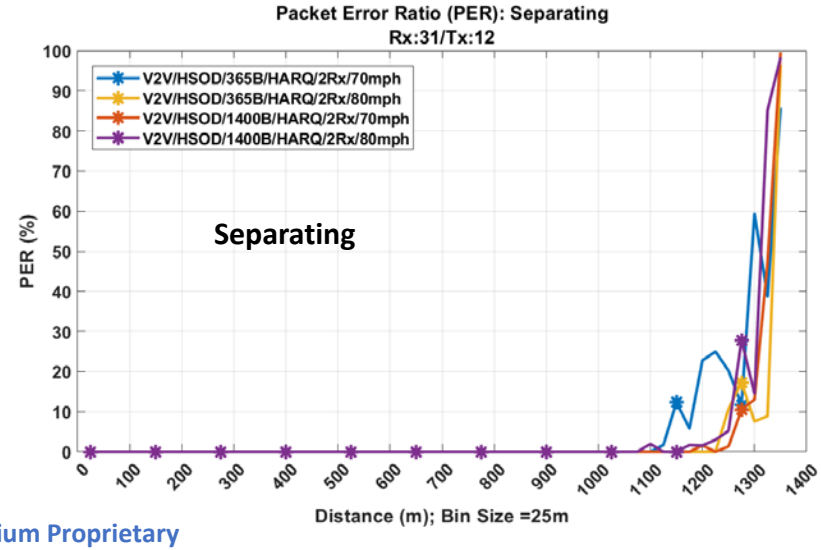
## 12 Receiving



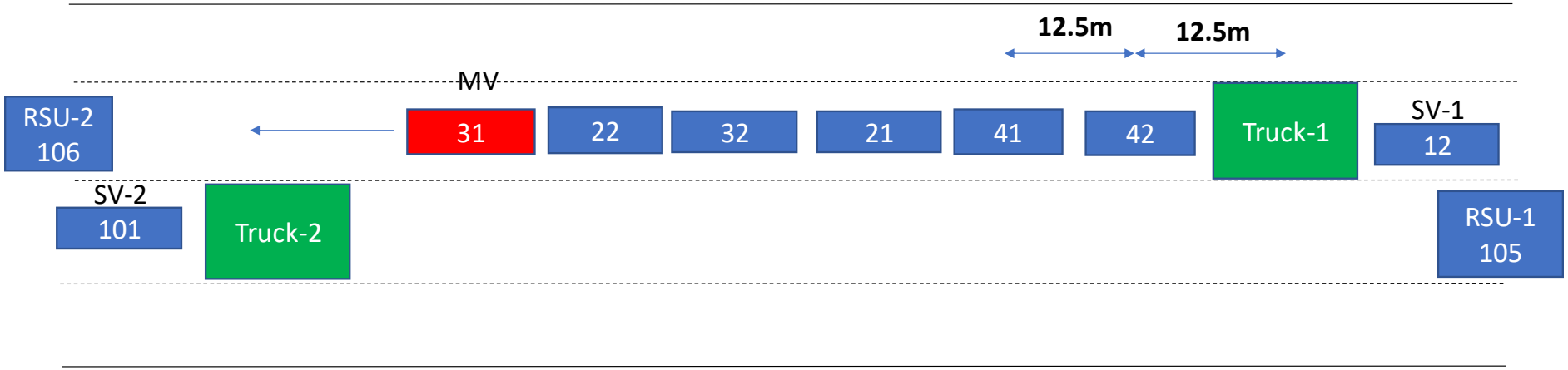

## 31 Receiving



# Test Setup: V2V NLOS

- Primary OBEs: 31, 12, 101
- Background RSEs: 105 & 106
- Background OBEs: 21, 22, 32, 41, 41

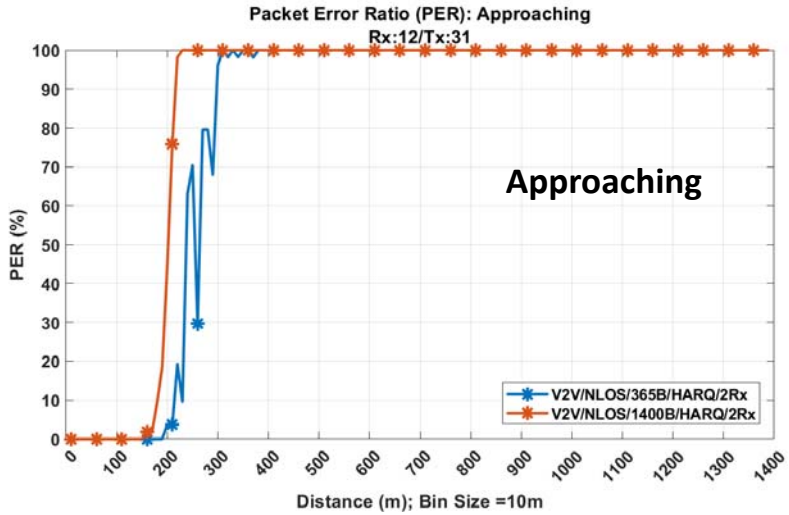


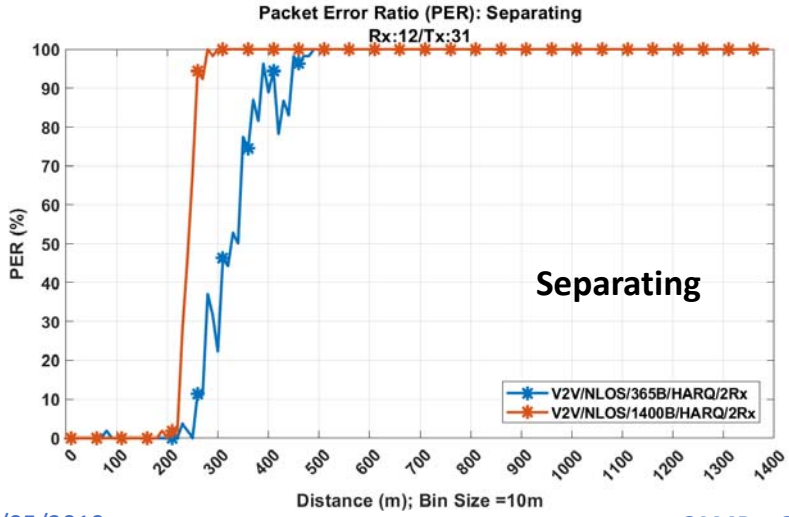

# V2V NLOS Same Lane Blocking

- 20 dBm/HARQ / 2Rx

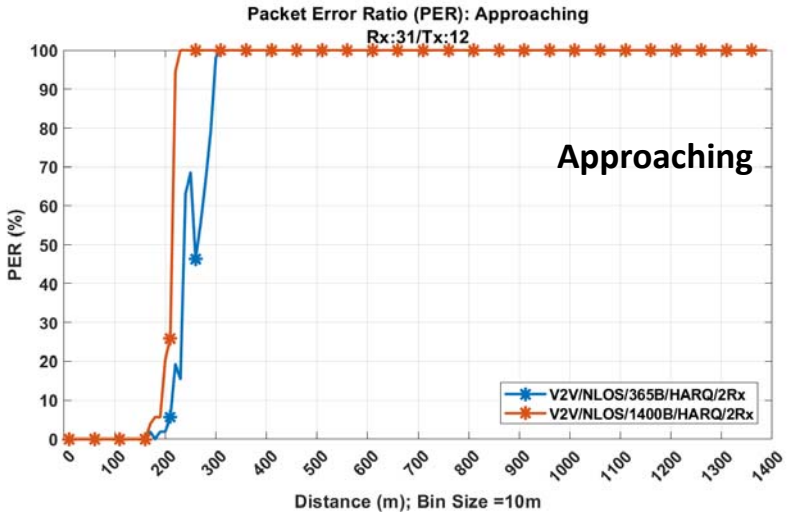
# V2V NLOS: HARQ/2Rx
# 31 MV & 12 SV

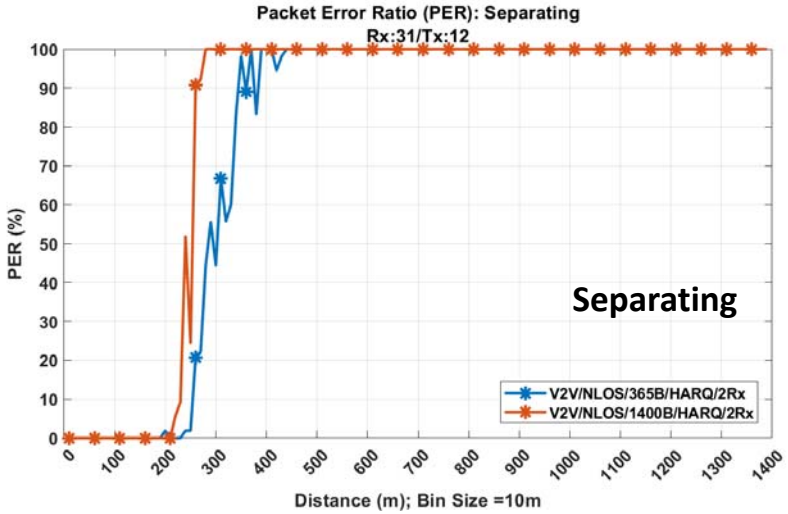
## Stationary Vehicle Receiving



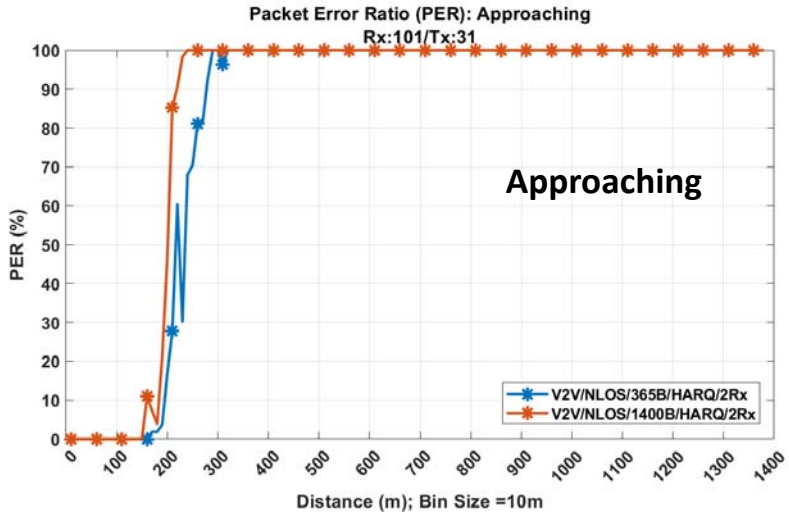

## Moving Vehicle Receiving

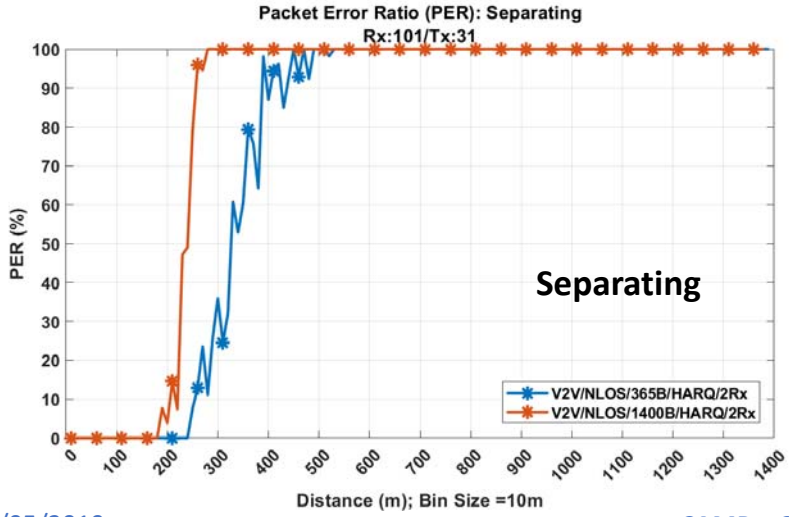


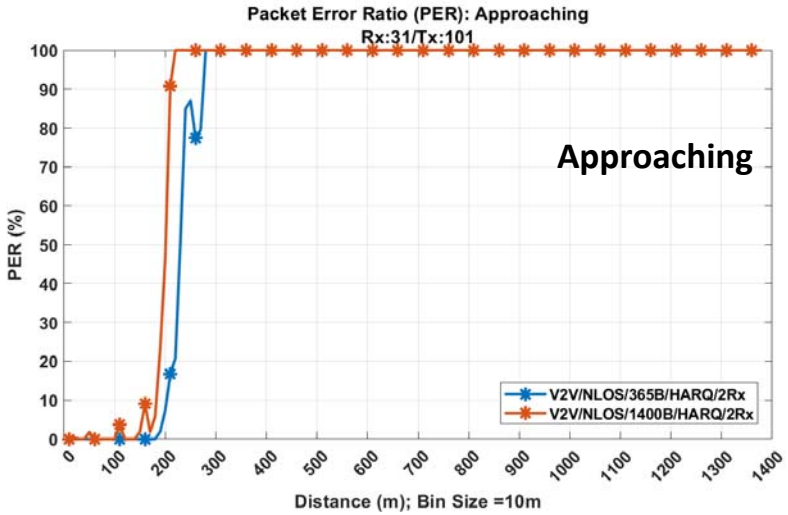
# V2V NLOS: HARQ/2Rx
# 31 MV & 101 SV

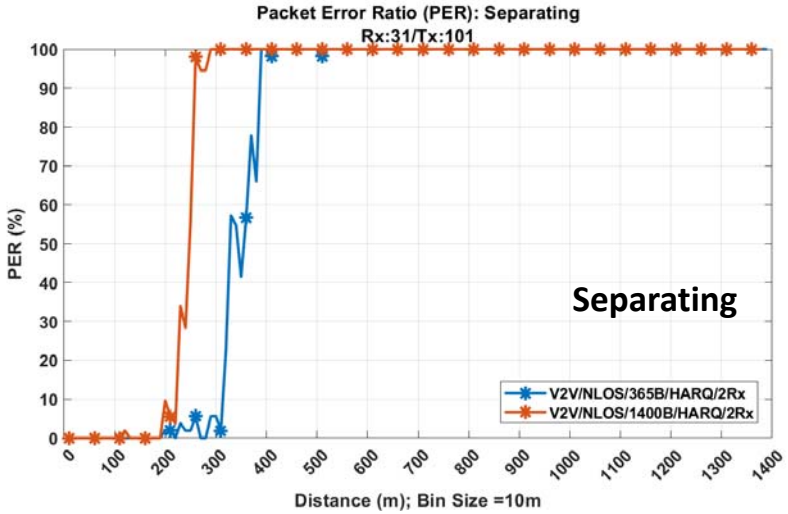
## Stationary Vehicle Receiving



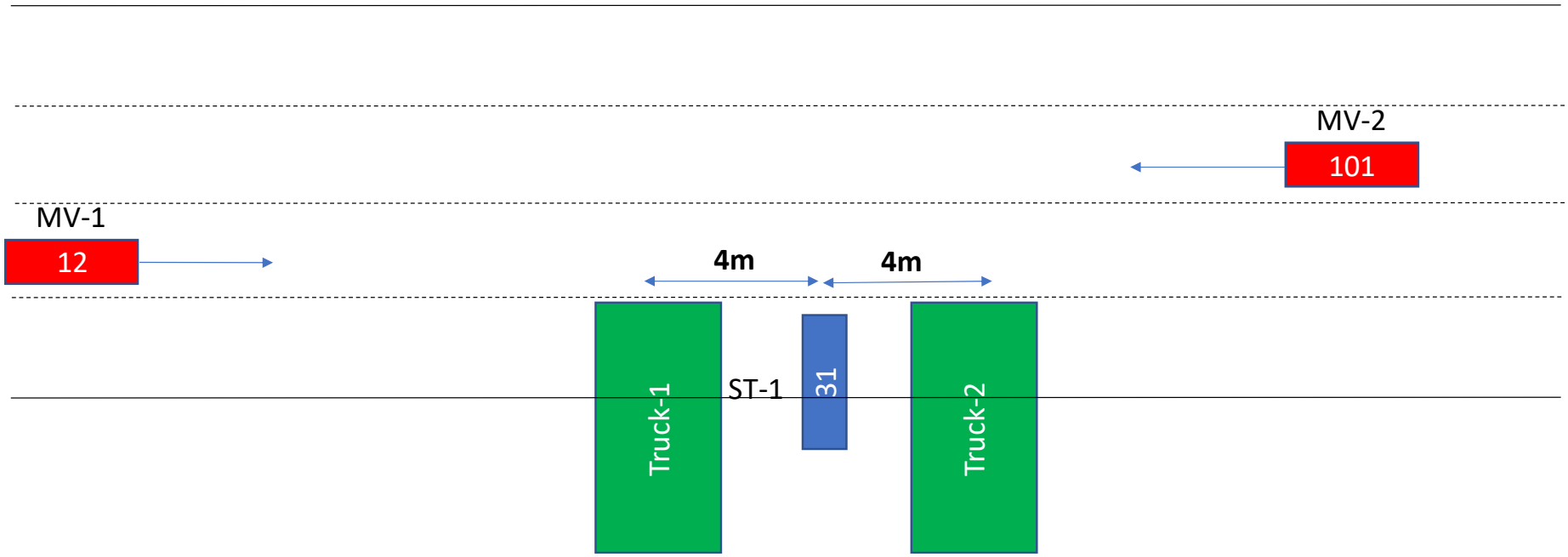

## Moving Vehicle Receiving



# Test Setup: V2V NLOS Intersection

- Primary OBEs: 31 & 12
- Backup OBE: 101

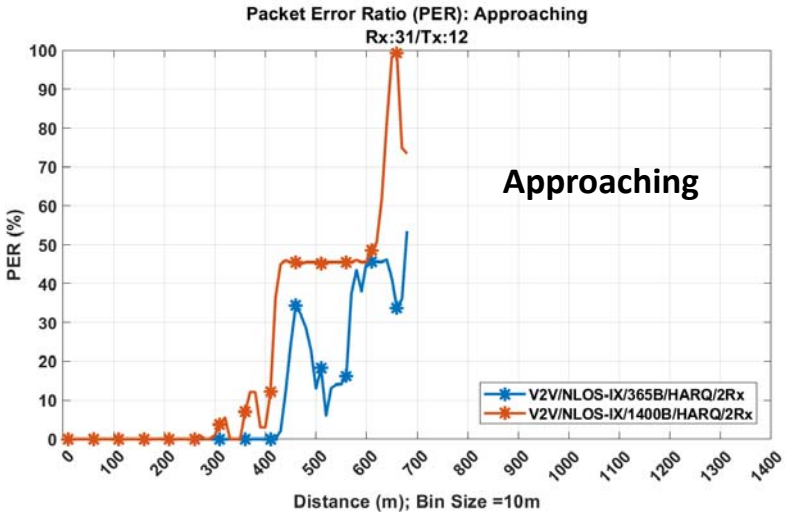


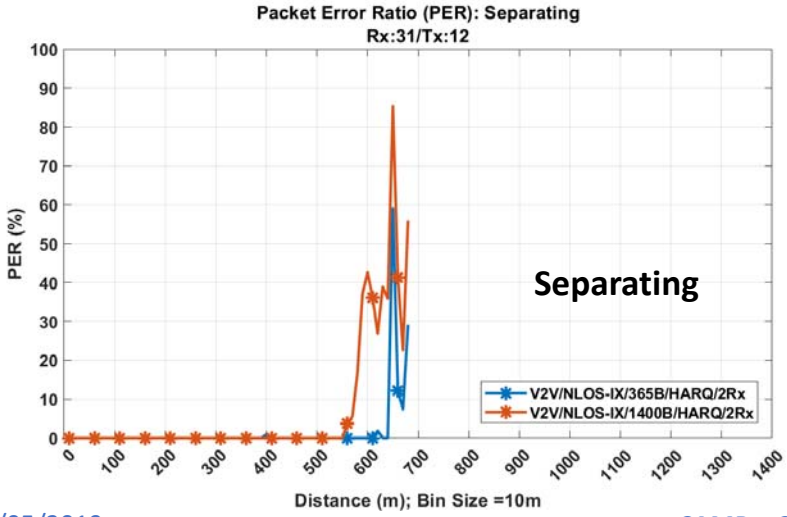
# V2V NLOS Intersection

- 20 dBm/HARQ / 2Rx

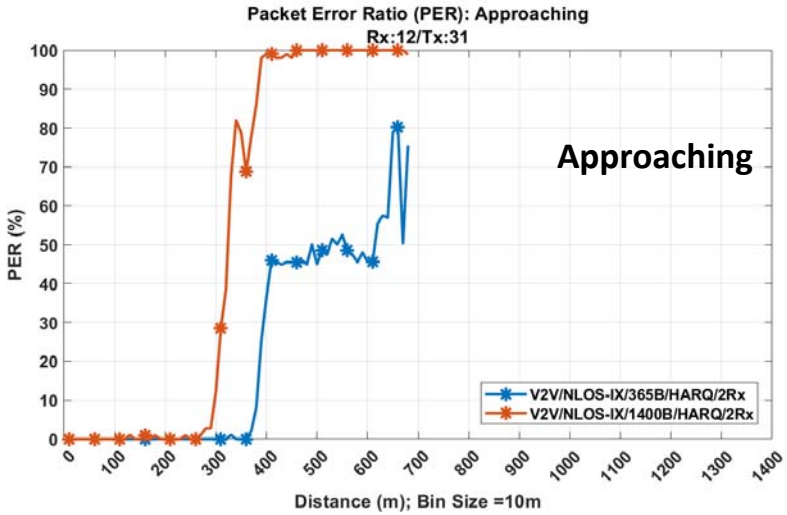
# V2V NLOS Intersection: HARQ/2Rx
# 31 MV & 12 SV

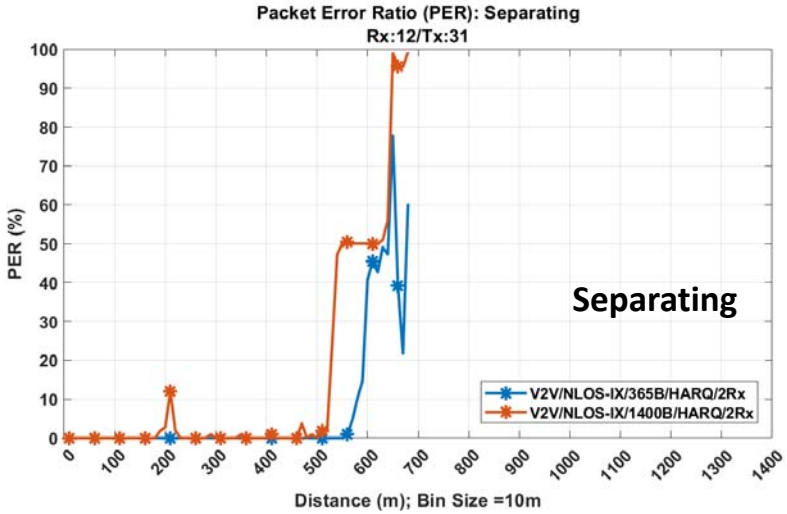
## Stationary Vehicle Receiving




## Moving Vehicle Receiving



# Controlled Vehicle Testing Summary

## Communication Range [meter] (@ PER < 10%)

| TEST SCENARIOS | 365 Byte | 1400 Byte |
|---|---|---|
| V2I NLOS | 1160 | 710 |
| V2V LOS | 1070 | 840 |
| V2V HSOD | 940 | 800 |
| V2V NLOS | 220 | 200 |
| V2V NLOS-Intersection | 440 | 370 |

*** Results for the recommended HARQ-2Rx configuration**

# Mixing Traffic Testing and Results
# Michigan East and West Routes

HARQ, 20 dBm

Test Days: Sep 17 – Sep 18



# Mixed Traffic Testing

20 dBm/HARQ

# Testing Categories: Mixed Traffic Testing

- Vehicle Testing Under Mixed Traffic Conditions: Real-world Test Parameters
- Performance drives re-tests on Sep 17 and Sep18 - Automotive Events (AE) support with drivers; 6/7 trips each route
- C-V2X system settings: HARQ, 20 MHz, 365/1000/1400B payloads, 1Rx/2Rx
- **Group A:** Ford1, GM1, HK1, Nissan1, **Group B:** Ford2, GM2, HK2, Nissan2; Benchmark: PER vs Range, IPG vs Range, Latency

East Route


West Route


**City Navigator North America NT 2020.1**

# Mixed Traffic Testing Summary

## Link Statistics Between Lead Vehicle and the First Following Vehicle

| EAST ROUTE | 365 Byte | 1400 Byte |
|---|---|---|
| | 2 Rx | 2 Rx |
| Total Sent BSM | 59119 | 56591 |
| Total Received BSM | 59116 | 56575 |
| Failure Count | 3 | 16 |
| PER [%] | 0.005 | 0.028 |
| Avg IPG [ms] | 100.2 | 97.13 |

| WEST ROUTE | 365 Byte | 1400 Byte |
|---|---|---|
| | 2 Rx | 2 Rx |
| Total Sent BSM | 74418 | 87758 |
| Total Received BSM | 74417 | 87717 |
| Failure Count | 1 | 41 |
| PER [%] | 0.001 | 0.047 |
| Avg IPG [ms] | 100.0 | 100.0 |

**HARQ-2Rx is the recommended configuration**

# Mixed Traffic Testing Summary

## Link Statistics Between Lead Vehicle and the Second Following Vehicle

| EAST ROUTE | 365 Byte | 1400 Byte |
|---|---|---|
| | 2 Rx | 2 Rx |
| Total Sent BSM | 58064 | 57841 |
| Total Received BSM | 58061 | 57825 |
| Failure Count | 3 | 16 |
| PER [%] | 0.005 | 0.028 |
| Avg IPG [ms] | 100.3 | 94.54 |

| WEST ROUTE | 365 Byte | 1400 Byte |
|---|---|---|
| | 2 Rx | 2 Rx |
| Total Sent BSM | 74417 | 88047 |
| Total Received BSM | 74412 | 87966 |
| Failure Count | 5 | 81 |
| PER [%] | 0.006 | 0.092 |
| Avg IPG [ms] | 100.0 | 100.1 |

**HARQ-2Rx is the recommended configuration**

# Mixed Traffic Testing Summary

## Link Statistics Between Lead Vehicle and the Third Following Vehicle

| EAST ROUTE | 365 Byte | 1400 Byte |
|---|---|---|
| | 2 Rx | 2 Rx |
| Total Sent BSM | 58980 | 56115 |
| Total Received BSM | 58976 | 56101 |
| Failure Count | 4 | 14 |
| PER [%] | 0.007 | 0.025 |
| Avg IPG [ms] | 100.3 | 97.40 |

| WEST ROUTE | 365 Byte | 1400 Byte |
|---|---|---|
| | 2 Rx | 2 Rx |
| Total Sent BSM | 74417 | 87987 |
| Total Received BSM | 74395 | 86915 |
| Failure Count | 22 | 1072* |
| PER [%] | 0.029 | 1.22 |
| Avg IPG [ms] | 100.0 | 101.2 |

**HARQ-2Rx is the recommended configuration**

* Communication link was broken for a short period of time due to potential NLOS between TX-RX pair

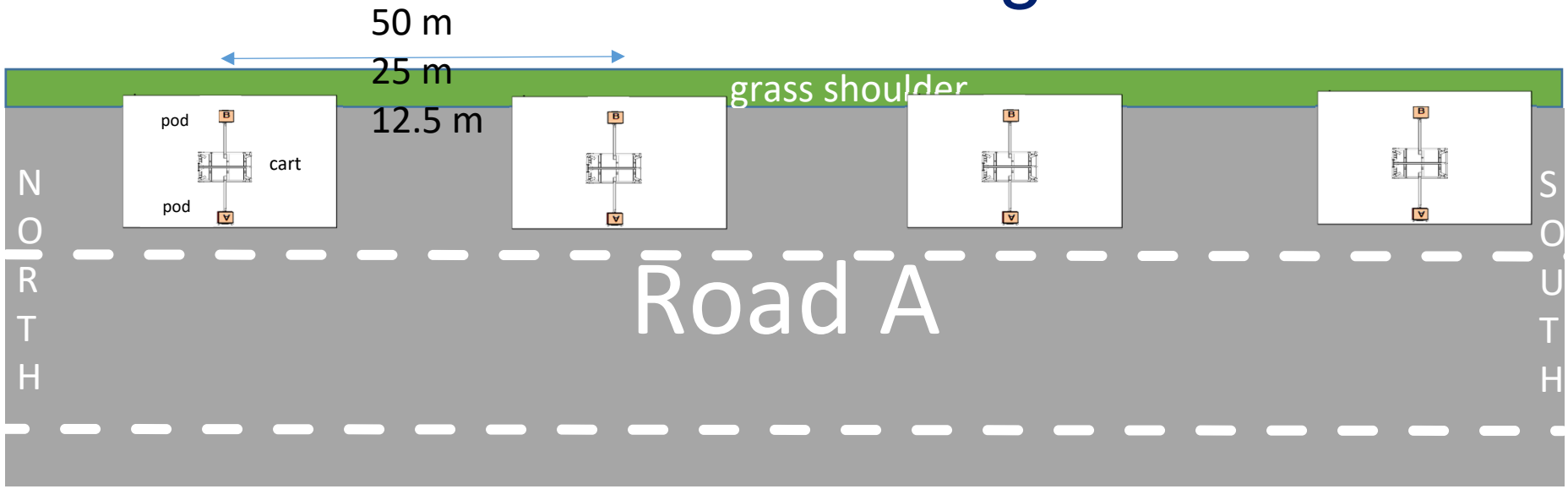
# Congestion Control Test Results
# Fowlerville Test Track

Test dates: 10/28-11/1

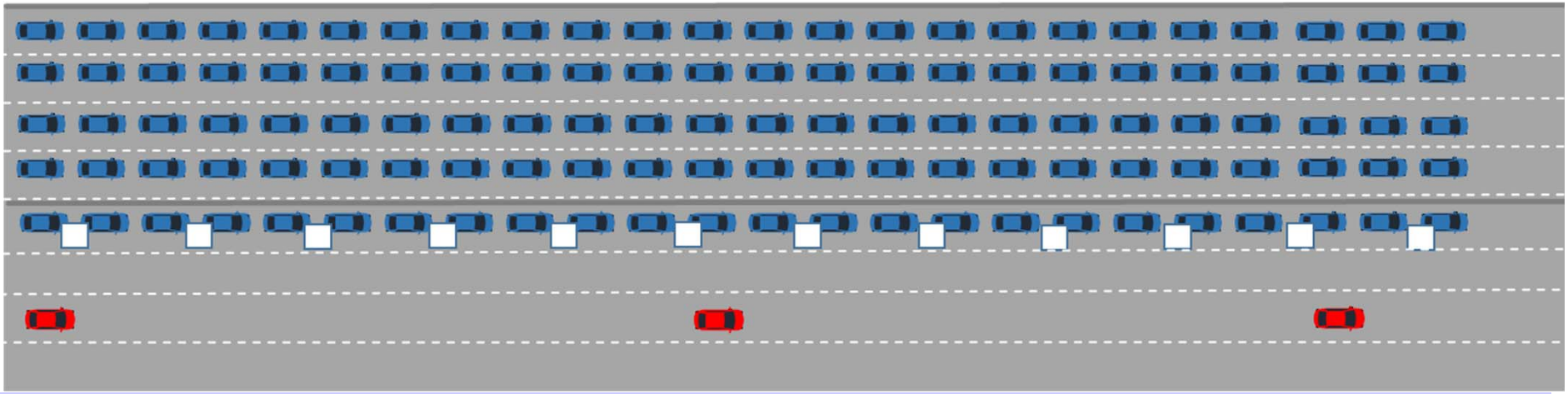
# Test Overview

- Test objective is to assess C-V2X system performance in several congested scenarios and compare cases with congestion control turned ON and OFF
- Field test is performed with up to 60 devices (50 congestion generation pods, 8 vehicles, 2 RSUs) at FTTA test track in Michigan
- Setup can emulate up to 260 units including stationary and moving vehicles
- **Test variables**
  - Congestion pods on/off
  - Congestion control on/off
  - Three (3) level of load (each congestion pod generates at 1x, 2x or 5x the nominal rate)
  - Three (3) node densities (congestion pods spread over 300m, 600m, or 1200m)
  - Two (2) vehicle speeds (20 MPH, 80 MPH)
- **Baseline Test:** The 50 congestion pods are turned off
- **Platoon Test**: Four (4) vehicles moving in a platoon at 20 MPH (congestion pods turned on)
- **High speed Test**: Four (4) vehicles moving in a platoon at 80 MPH (congestion pods turned on)
- **Critical Event Test**: Two (2) vehicles moving in a platoon, one vehicle experiences hard braking event (congestion pods turned on)
- **Stationary Test**: Six (6) stationary vehicles experiencing different congestion levels with OBUs at designated spots (congestion pods turned on)

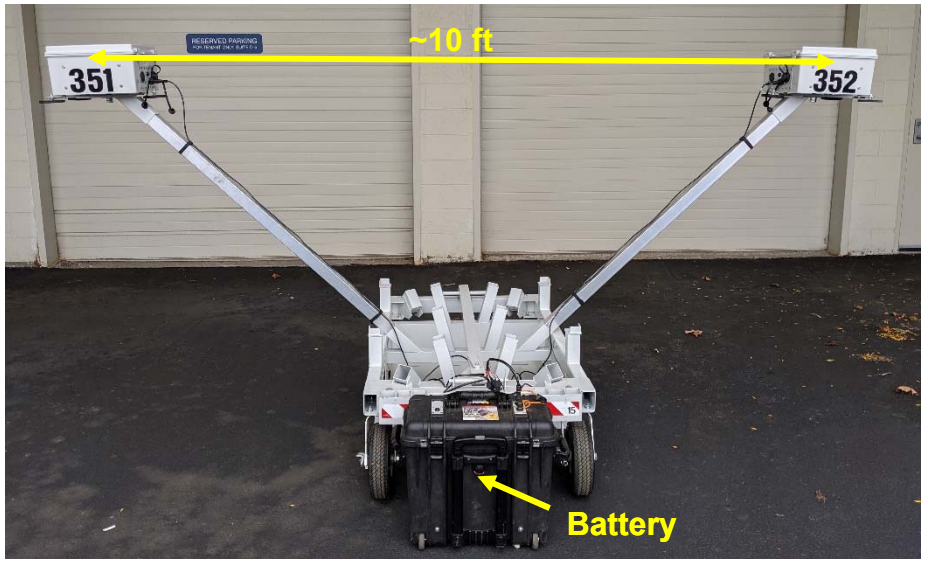
# Cart and Pod Arrangement

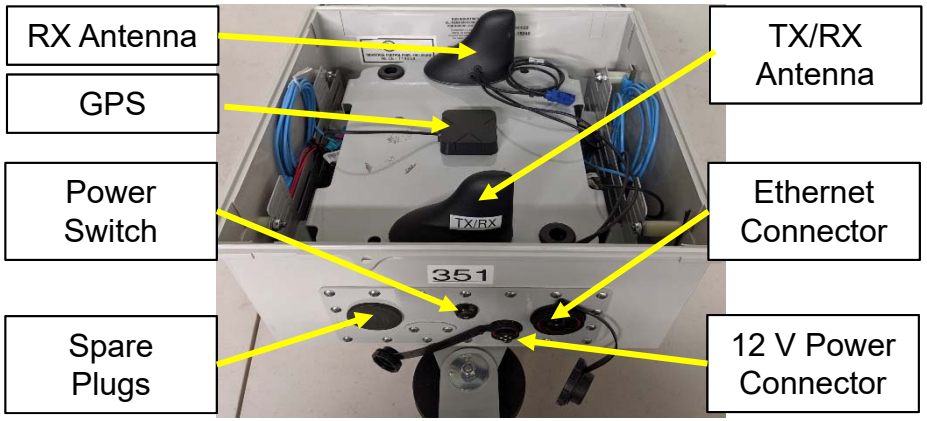



- Heaviest congestion (5X nominal rate) emulates 5 adjacent lanes and 10 vehicles per cart (blue vehicles illustrate congestion)

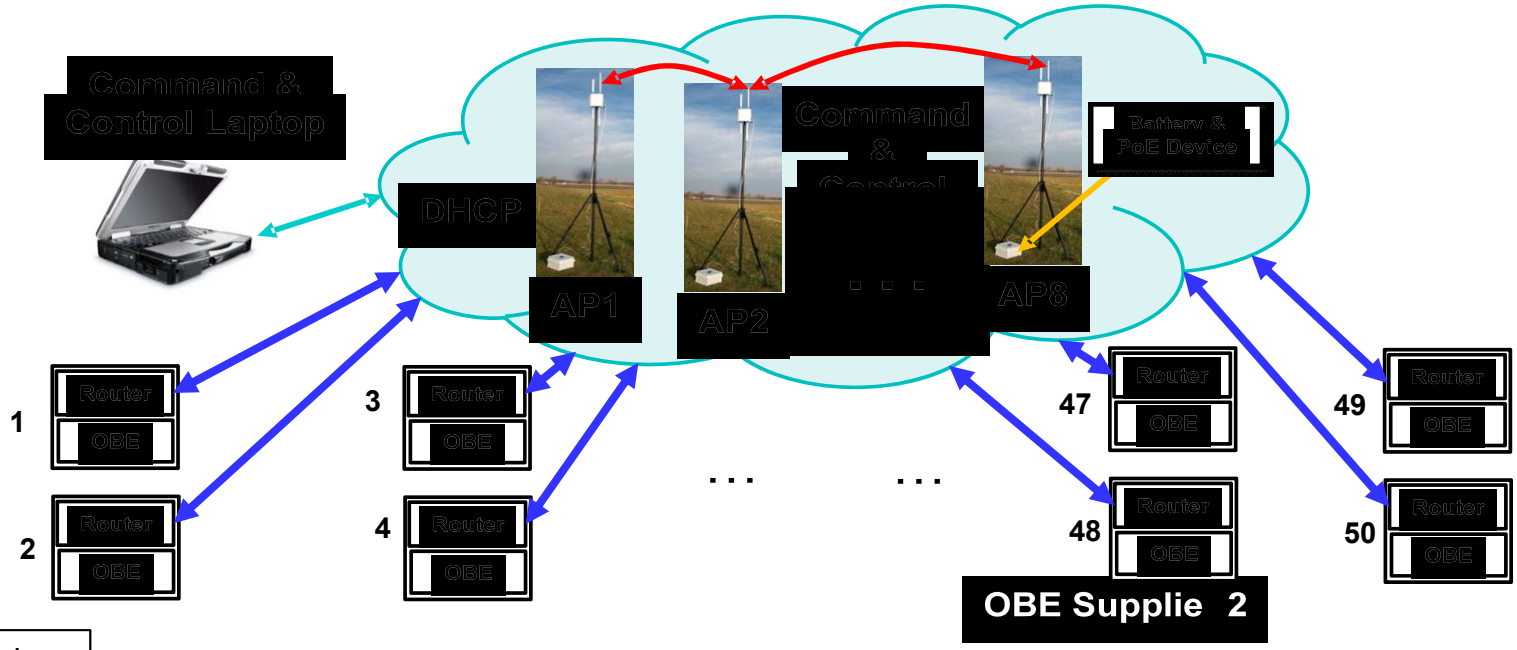


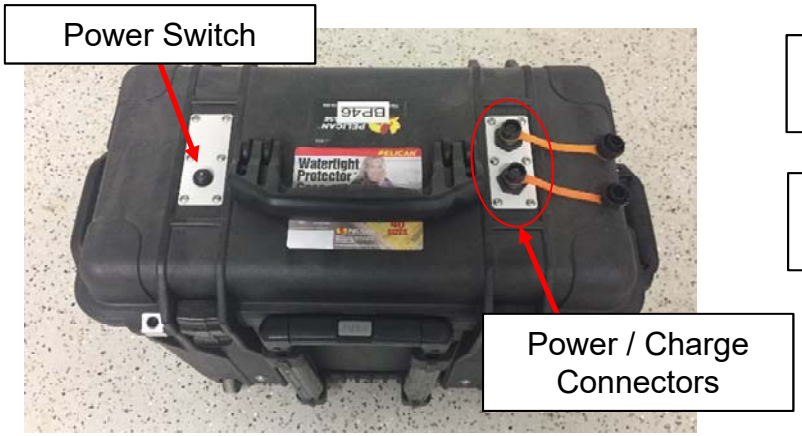
# Carts/Pods/Batteries



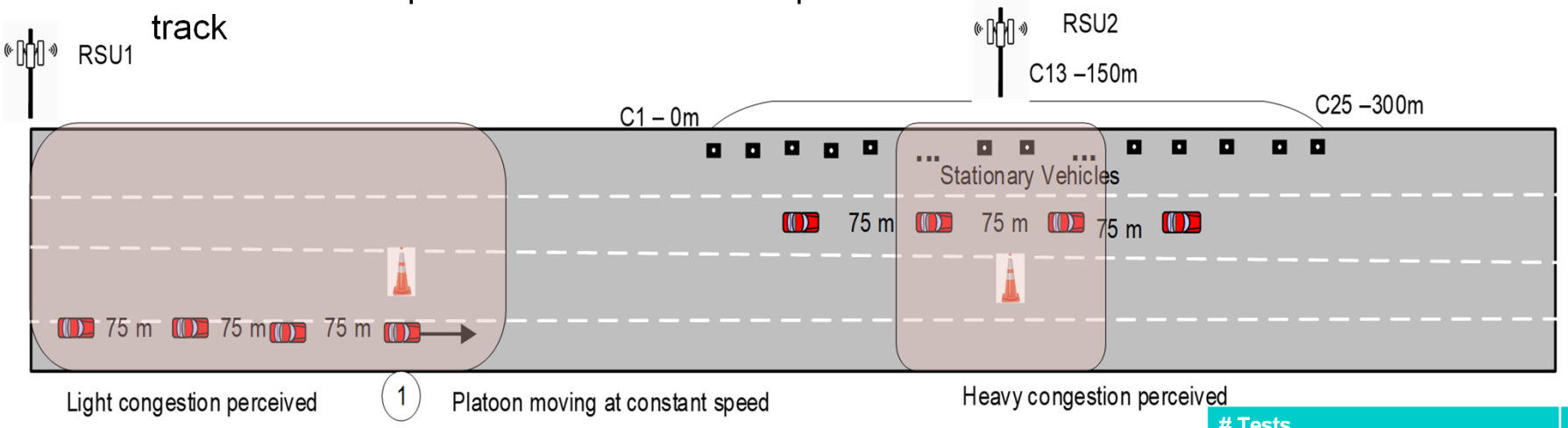
# Wireless Mesh: Connecting Pods to C&C Laptop




# Platoon Test + High-speed Test

- 4 moving vehicles in a platoon
  - Initially baseline test with congestion pods turned off
  - Move at 20 MPH and 80 MPH
- For each vehicle in the platoon, 4 static vantage points provide continuous distance vs PER performance
- Additional static points are the two RSUs positioned in the center and at one end of the test track

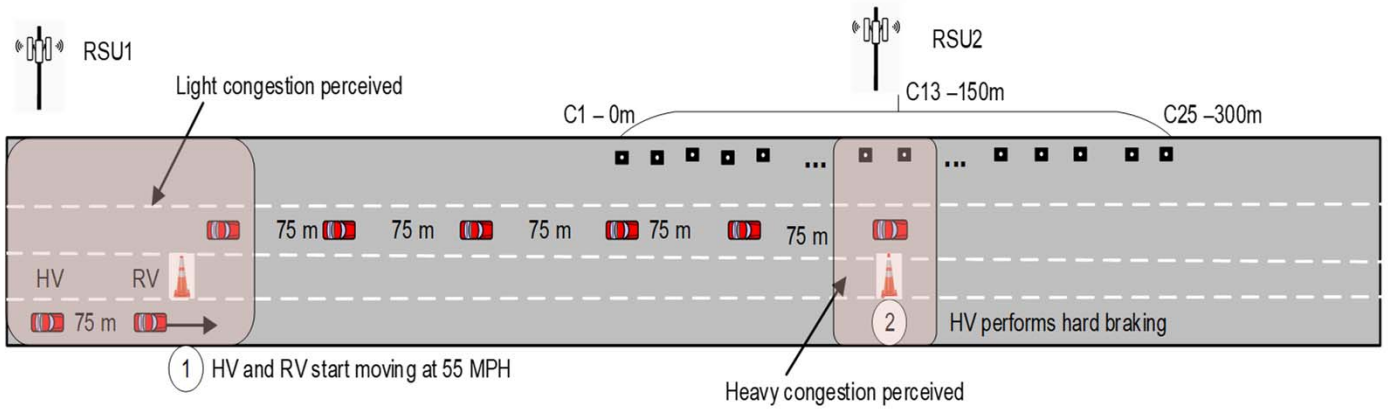



- 8 vehicles + 2 RSU collect logs for KPI post-processing

| # Tests | 36 |
|---|---|
| Emulation (1x,2x,5x) | 3 |
| CC on/off | 2 |
| Densities,<br>Cart distances (300, 600, 1200) m | 3 |
| Speed thresholds (20 , 80) MPH | 2 |

# Stationary Test + Critical Event Test

- 6 Stationary (transmitting/receiving) vehicles plus 2 RSUs providing performance from 8 vantage points with varying levels of congestion experienced
  - Initial baseline test with congestion pods off
- 2 Moving (transmitting/receiving) vehicles where the HV experiences critical event at the location of heaviest congestion whereas the RV continues moving smoothly
- This tests how well the critical event at the HV is detected by the RV and the 6 stationary vehicles experiencing different congestion levels
- Moving HV and RV provide a continuum of distance bins for various KPIs to and from stationary vehicles
- 8 vehicles + 2 RSU collect logs for KPI post-processing




| # Tests | 18 |
|---|---|
| Emulation (1x,2x,5x) | 3 |
| CC on/off | 2 |
| Densities, Cart distances (300, 600, 1200) m | 3 |

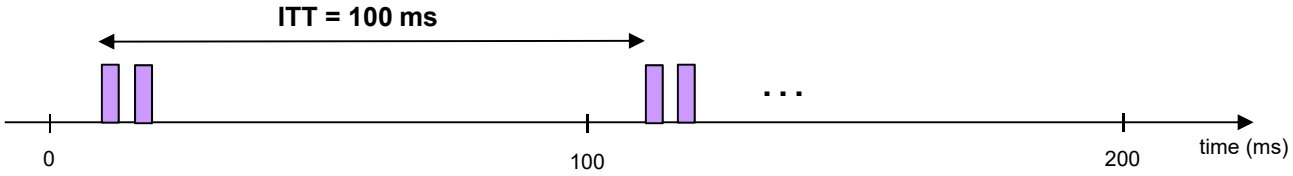
# Additional Details

- All transmission are in CH183 (20 MHz), HARQ is always on and all packet have the same size of 365 bytes
- Congestion control is implemented as per SAE J3161/1
- We use live BSM mode to incorporate CAN data for critical event testing
- Data is logged for presenting the following KPIs
  - Steady state PER vs distance
  - Information Age
  - Inter-Packet Gap
  - Channel Busy Ratio (CBR)
  - Inter-Transmit Time (ITT)
  - Packer Failure Count for critical events

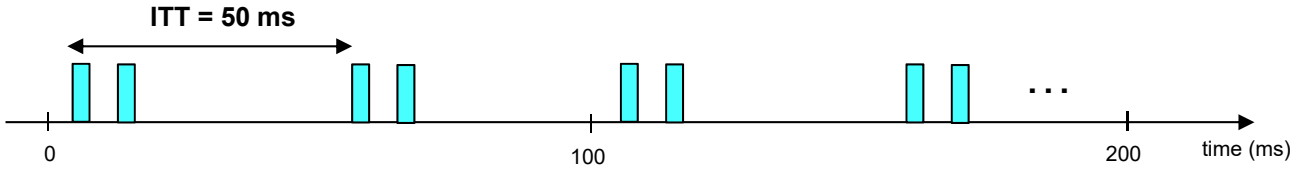
# Time Characterization of Load

- Inter-Transmit Time (ITT) varies as a function of emulation level

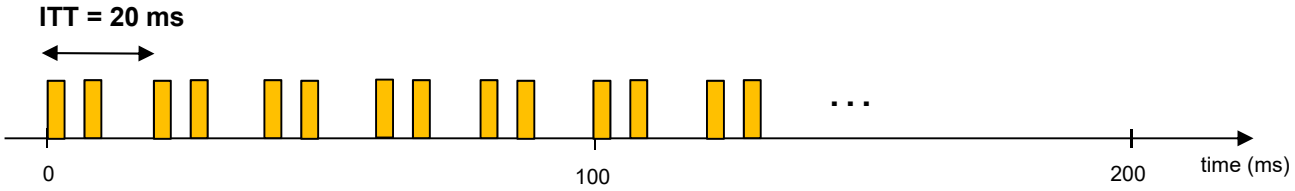
- 1X emulation: 50 congesting pods and 10 OBUs each generate 2 transmissions per 100 ms (1 original plus HARQ retransmission)




- 2X emulation: 50 congesting pods each generate 4 transmissions per 100 ms

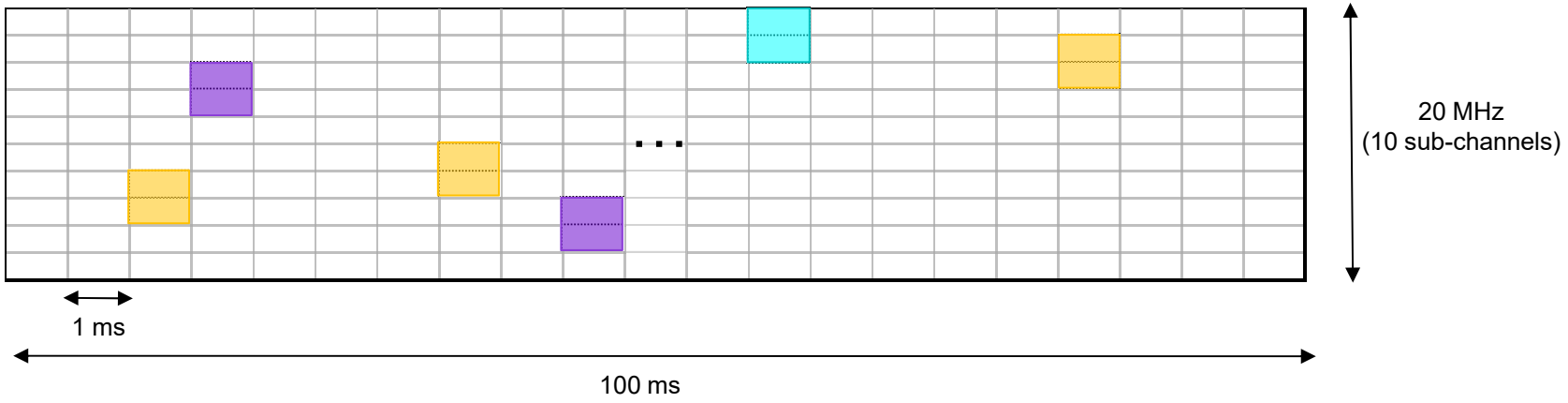



- 5X emulation: 50 congesting pods each generate 10 transmissions per 100 ms



# Congestion Control Test Load Estimate

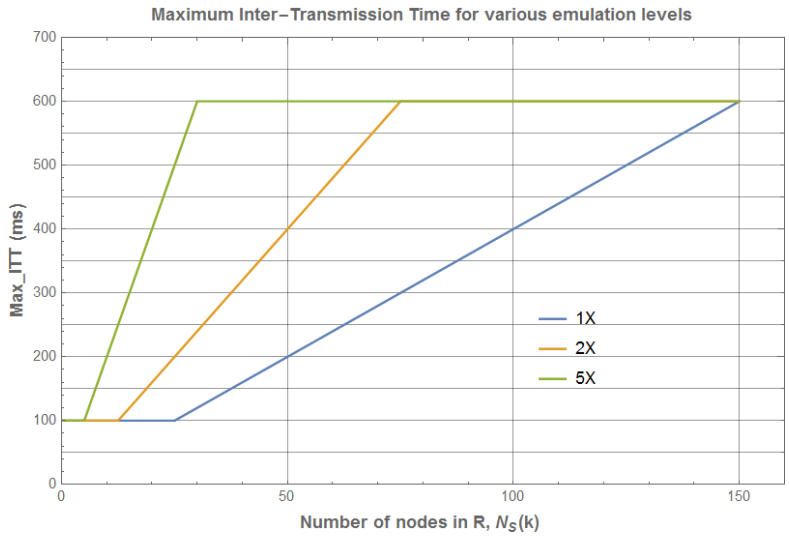
- We compute the offered load by the 50 congestion generating pods and 10 OBUs (8 vehicles + 2 RSUs) – assuming no congestion control
- Each BSM transmission occupies 2 sub-channels => in 100 ms the 20-MHz channel can carry 500 BSM without overlap
- 1X emulation:
  - 50 congesting pods and 10 OBUs each generate 2 transmissions per 100 ms (1 original plus HARQ retransmission)
  - Offered load of 120 transmissions per 100 ms results in **24% normalized offered load**
- 2X emulation:
  - 50 congesting pods each generate 4 transmissions per 100 ms; 10 OBUs each generate 2 transmissions per 100 ms
  - Offered load of 220 transmissions per 100 ms results in **44% normalized offered load**
- 5X emulation:
  - 50 congesting pods each generate 10 transmissions per 100 ms; 10 OBUs each generate 2 transmissions per 100 ms
  - Offered load of 520 transmissions per 100 ms results in **104% normalized offered load**



# J3161 Congestion Control: Rate Control Part

- Each receiving vehicle OBU monitors BSMs over a period of 1 seconds and records the number, $N_s(k)$, of different transmitting OBUs it receives from within radius R=100 m
- Since each congesting pod is received by its neighbors as a single transmitter, BSM rate as a function of congestion needs to be adjusted based on the emulation level (1X, 2X, 5X)
- Max Inter-Transmit Time (Max_ITT) for vehicle OBUs varies as a function of $N_s(k)$, as follows(*)

- 1X emulation:
  - $$Max\_ITT(k) = \begin{cases} 100 & Ns(k) \le 25 \\ 100 \times \frac{Ns(k)}{25} & 25 < Ns(k) < 150 \\ 600 & 150 \le Ns(k) \end{cases}$$
- 2X emulation:
  - $$Max\_ITT(k) = \begin{cases} 100 & Ns(k) \le 12.5 \\ 100 \times \frac{Ns(k)}{12.5} & 12.5 < Ns(k) < 75 \\ 600 & 75 \le Ns(k) \end{cases}$$
- 5X emulation:
  - $$Max\_ITT(k) = \begin{cases} 100 & Ns(k) \le 5 \\ 100 \times \frac{Ns(k)}{5} & 5 < Ns(k) < 30 \\ 600 & 30 \le Ns(k) \end{cases}$$




(*) Congesting pods behave in a similar way except they further scale down Max_ITT in proportion to the emulation factor

# Congestion Control Platoon Test

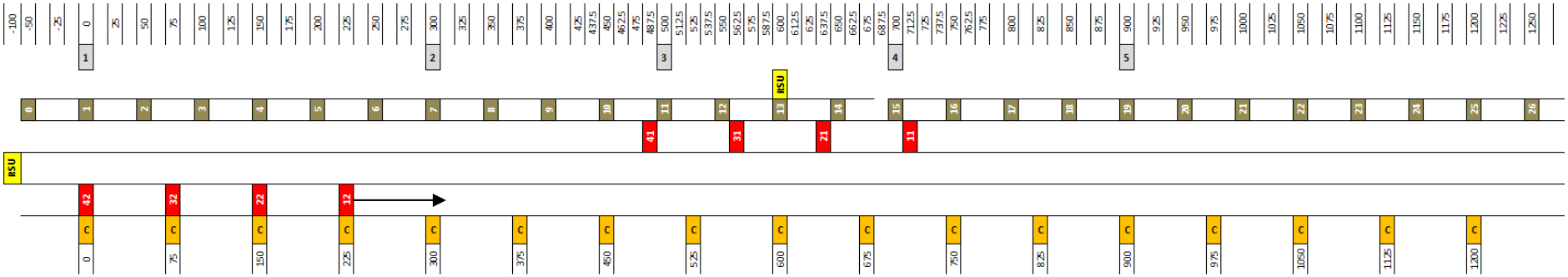
- 4-vehicle platoon, 20/80 mph

# Platoon Test

# Congestion Spread 1200m
# Speed 20mph

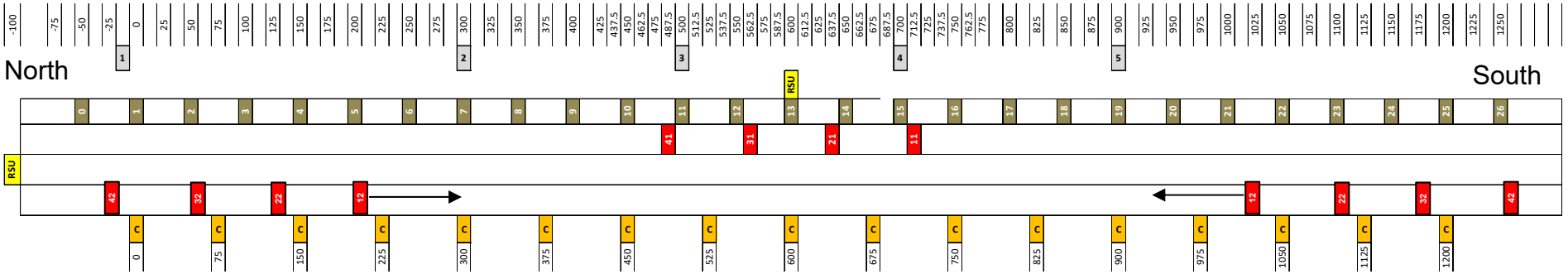
# Test Setup: Platoon 1200m

- Stationary OBEs: 11, 21, 31, 41
- Platoon OBEs: 12, 22, 32, 42
- Congestion Carts: 0-26 (start at -50m)
- Cart 13 at 600m (center of the test track)
- Results shown for (Vehicle 11,Vehicle 12) pair

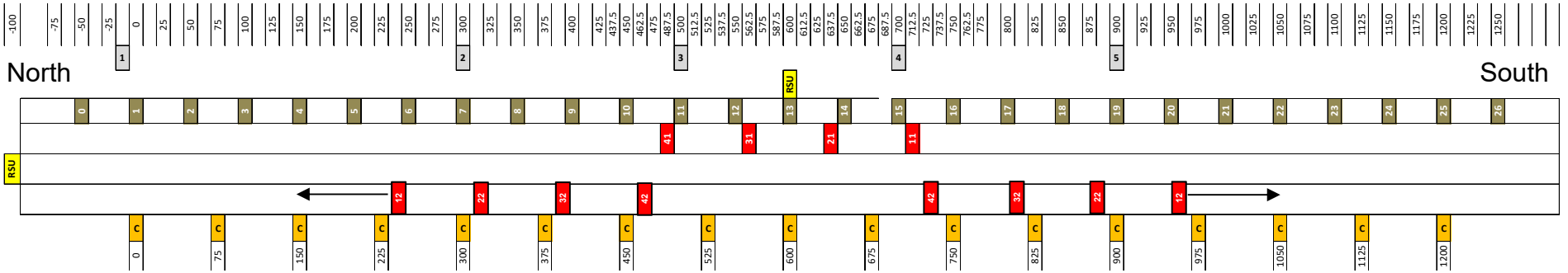


# Explanation of the Graphs – Platoon Direction

- Approaching North->South and South->North

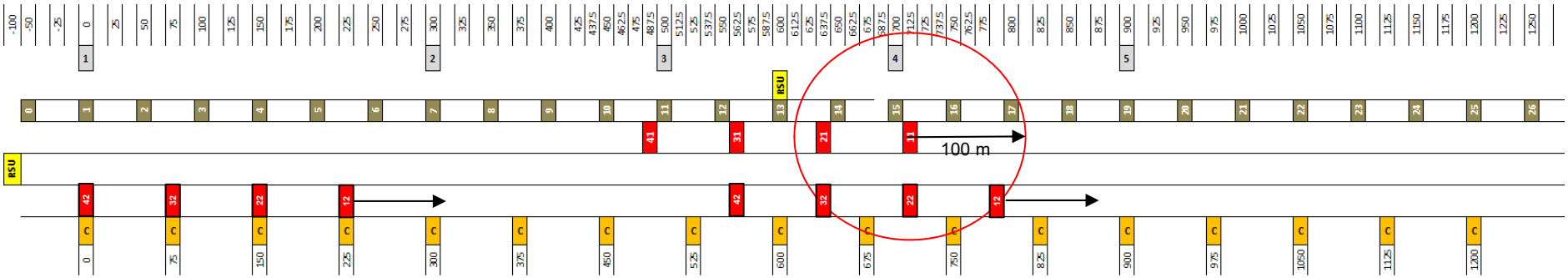



- Separating North->South and South->North



# Max_ITT Estimate for Vehicle 11 at 5X Emulation

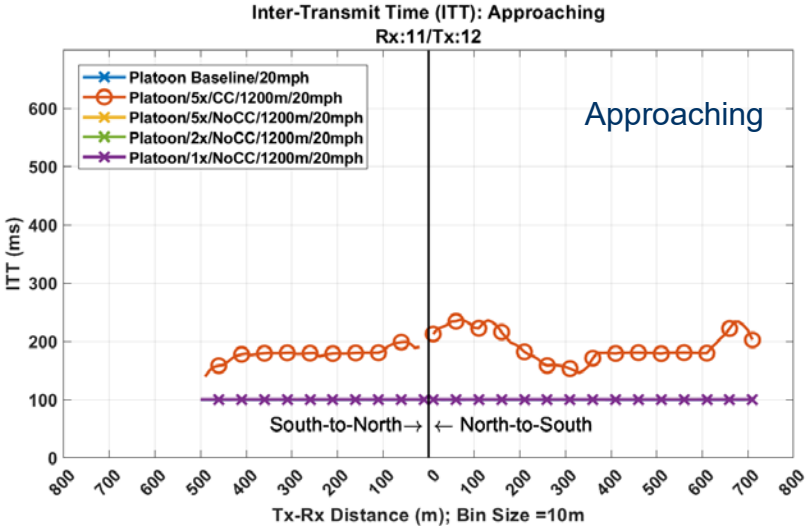
- When the platoon is away Vehicle 11 receives
  - 4 carts (7 pods)*
  - 1 vehicle
  - Max_ITT(k) = 100 x 8/5 = 160 ms
- When the platoon is partially overlapping Vehicle 11 receives
  - 4 carts (7 pods)*
  - 4 vehicles
  - Max_ITT(k) = 100 x 11/5 = 220 ms

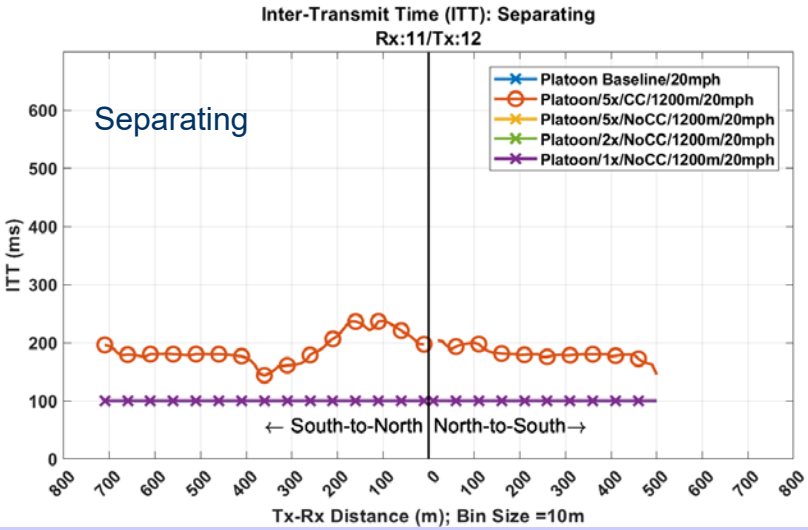



* A pod on cart 14 was turned off during the test

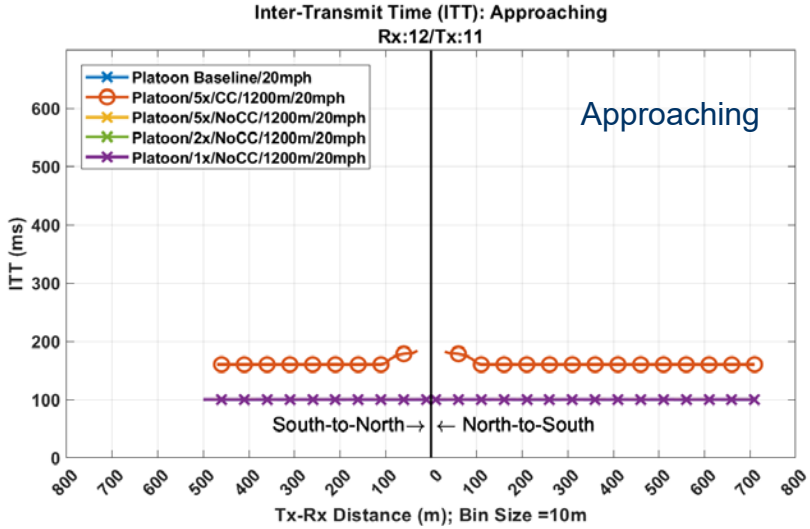
# ITT – Platoon Test – 1200m

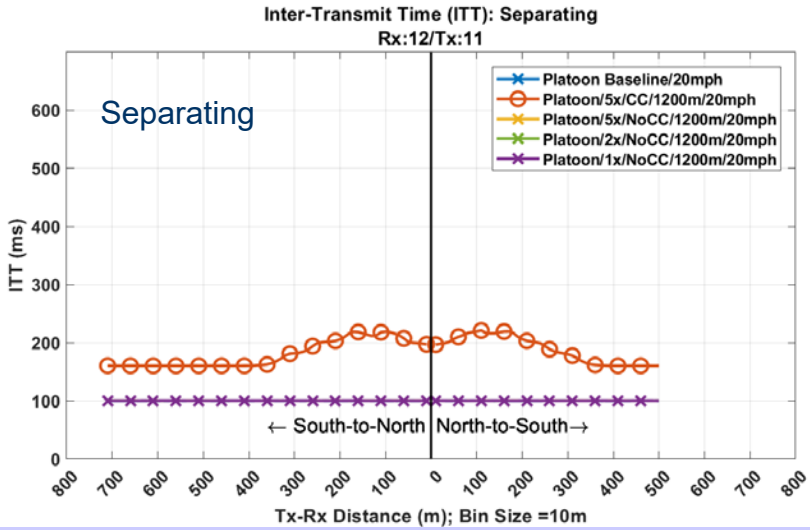
## Stationary Vehicle Receiving



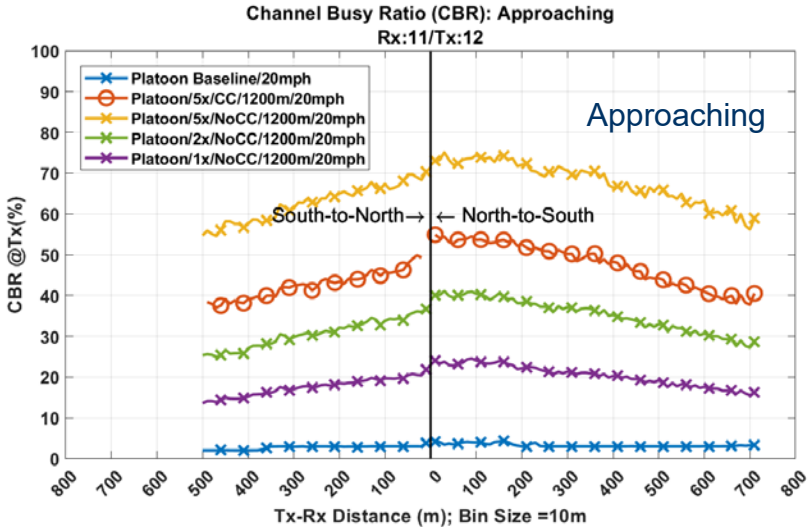

## Moving Vehicle Receiving

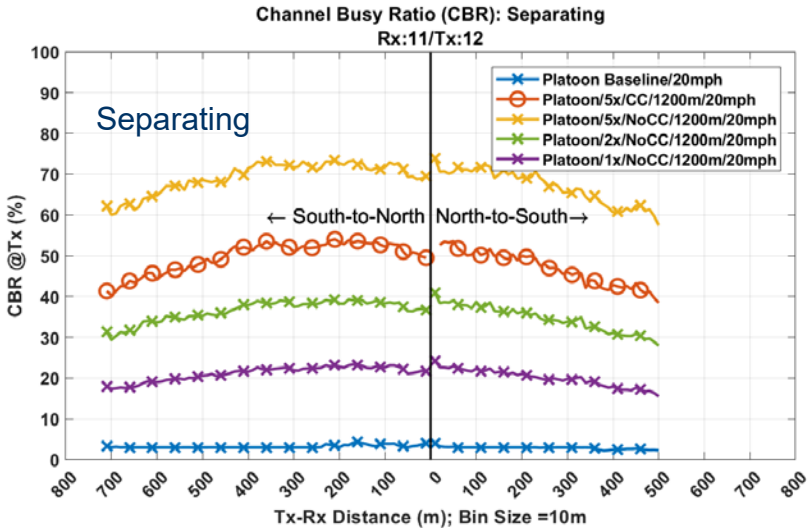


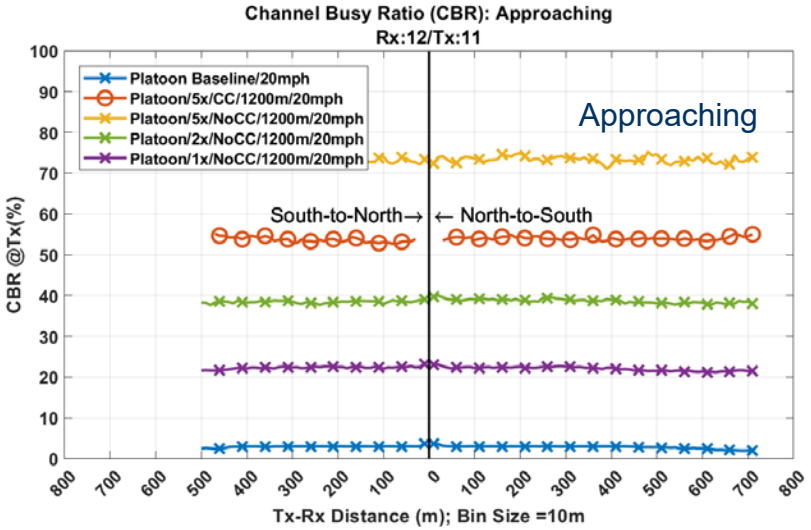
# CBR – Platoon Test – 1200m

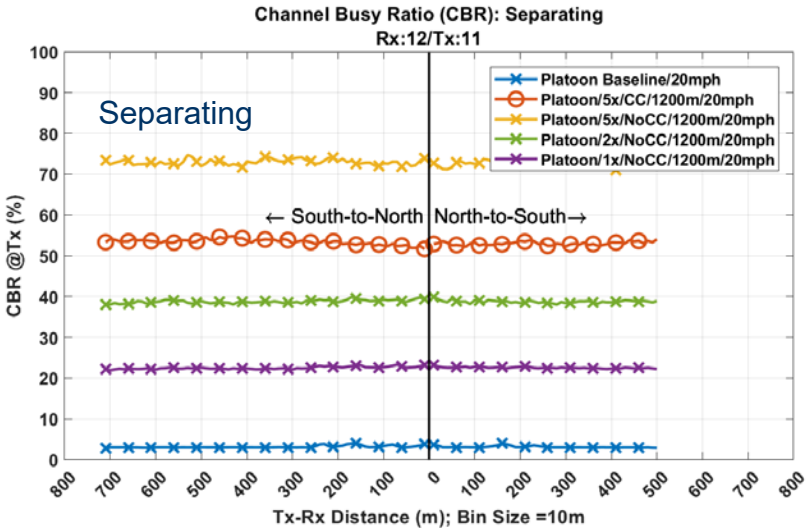
## Stationary Vehicle Receiving



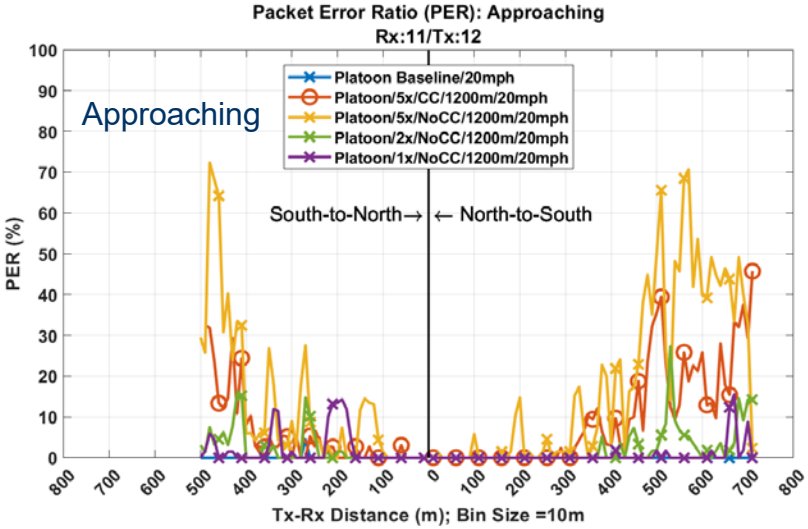

## Moving Vehicle Receiving

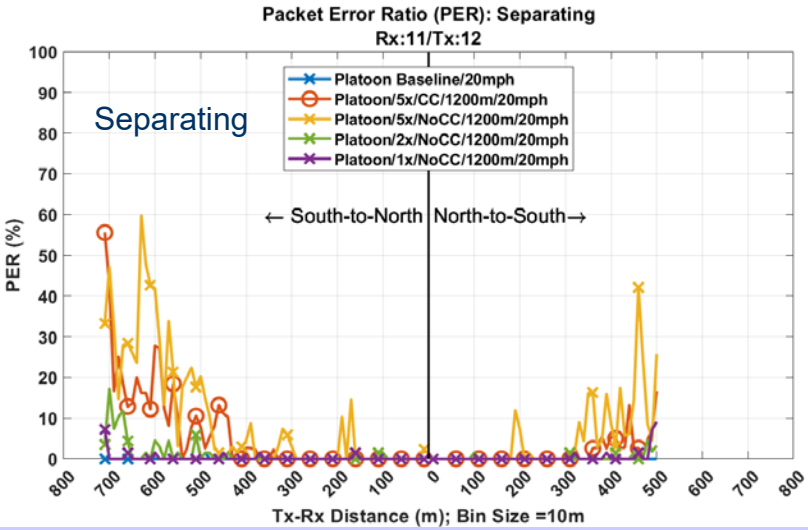


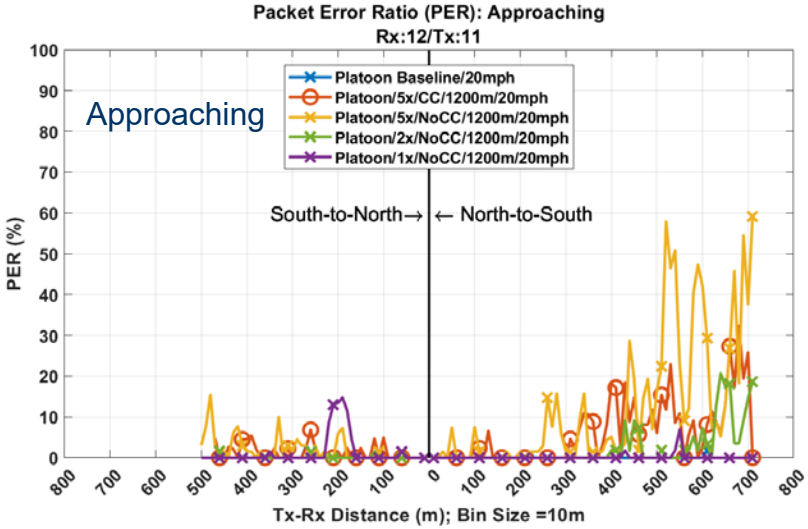
# PER – Platoon Test – 1200m

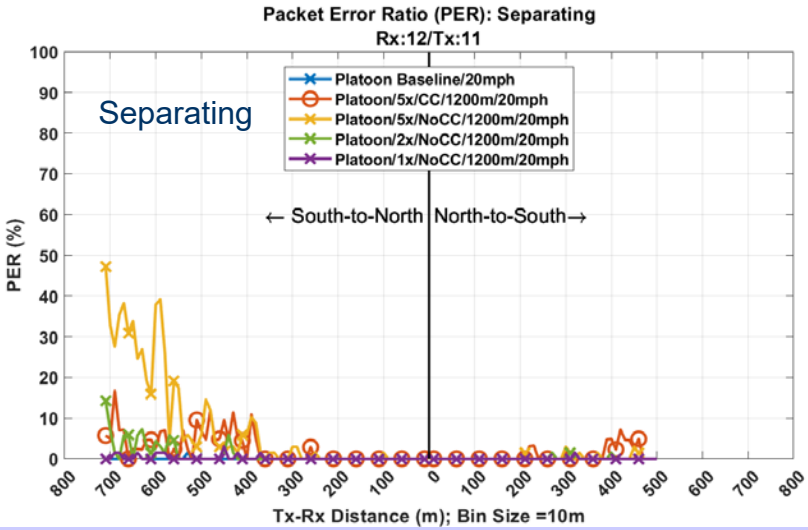
## Stationary Vehicle Receiving



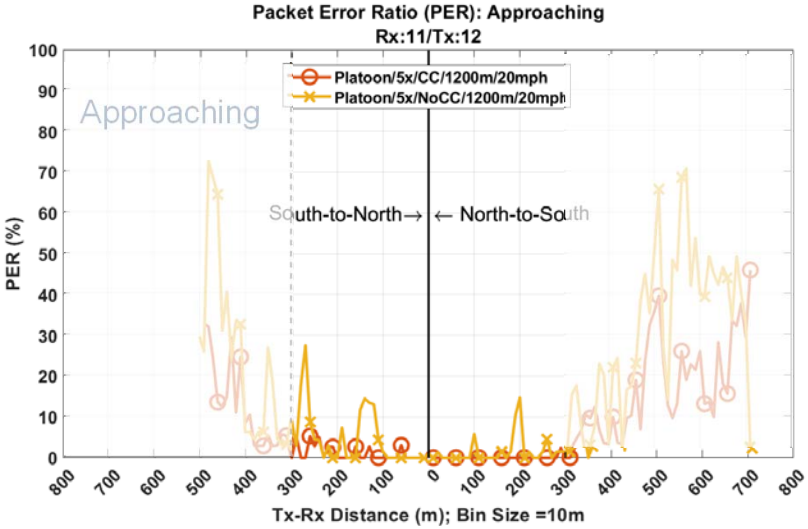

## Moving Vehicle Receiving

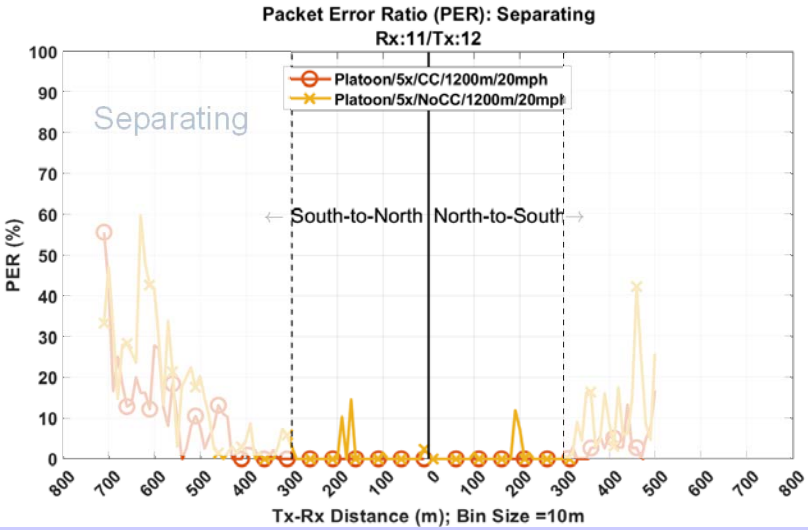


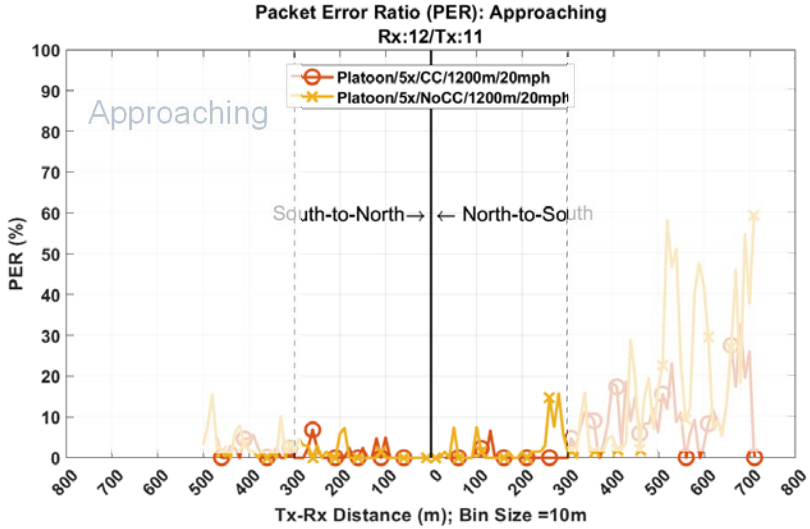
# PER – Platoon Test – 1200m

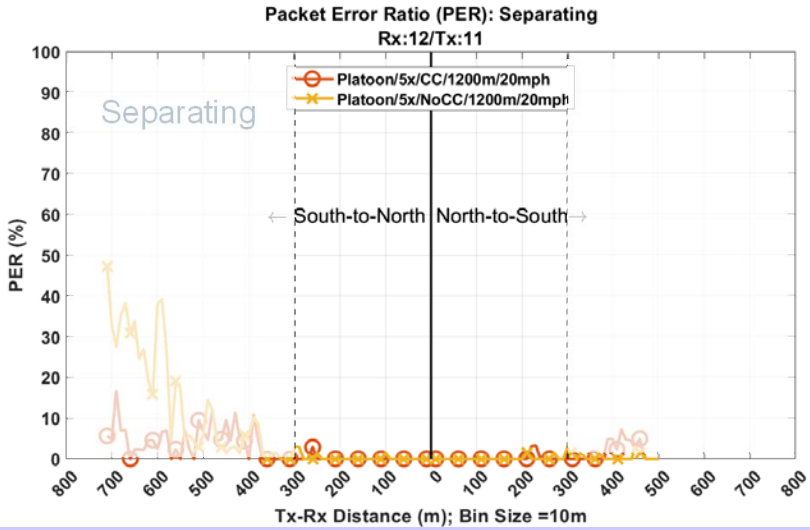
## Stationary Vehicle Receiving



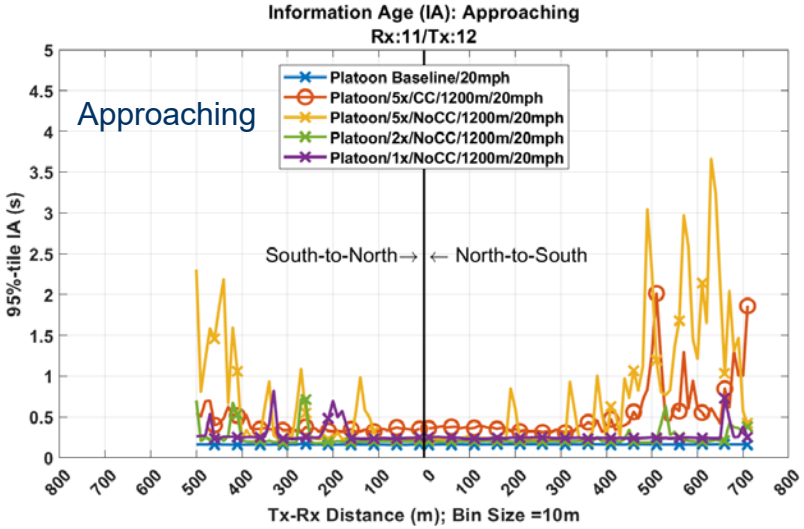



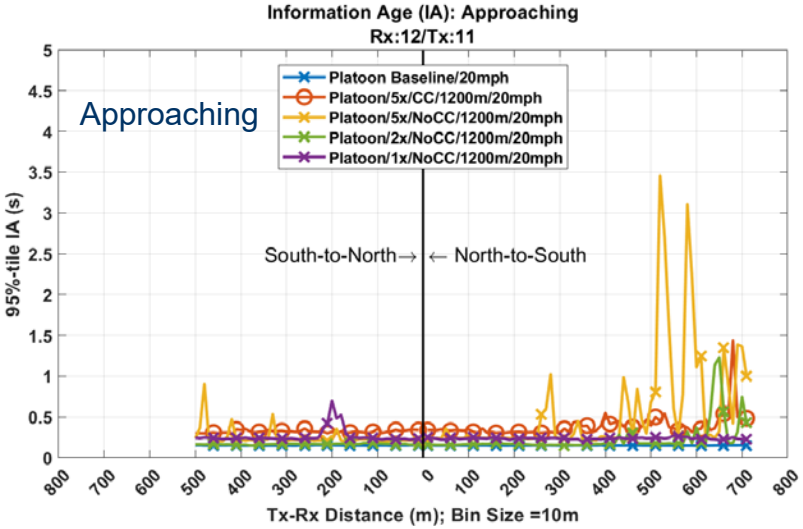

## Moving Vehicle Receiving

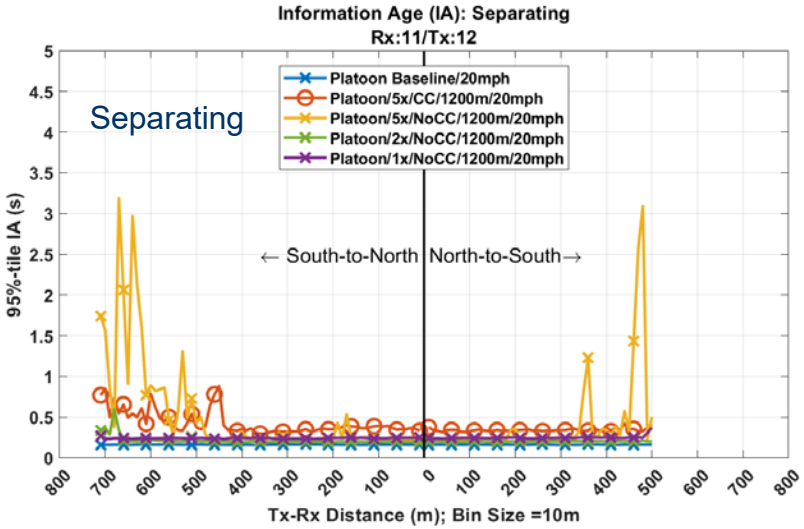


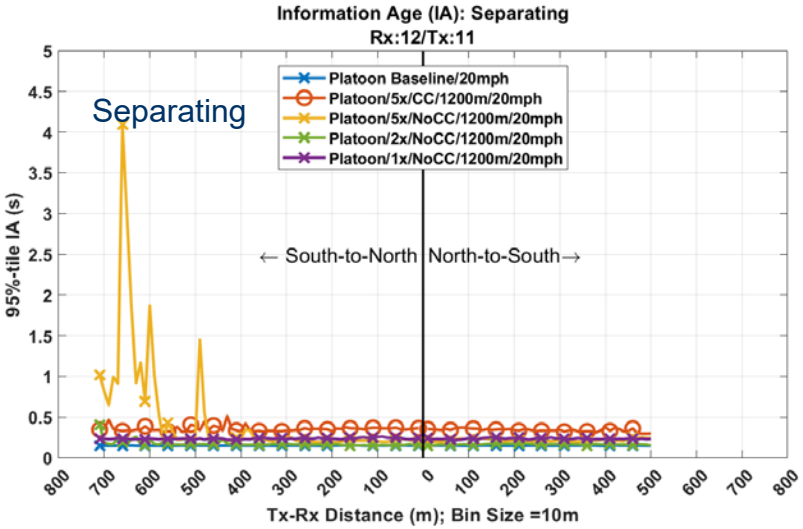



# IA – Platoon Test – 1200m



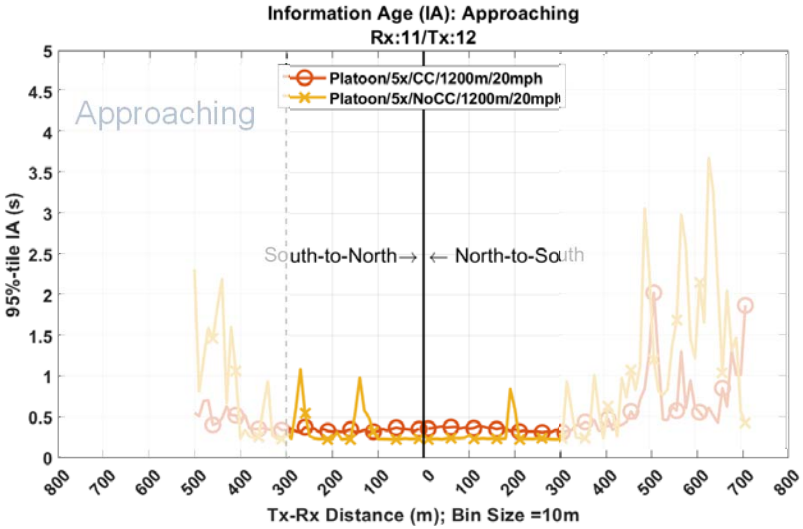



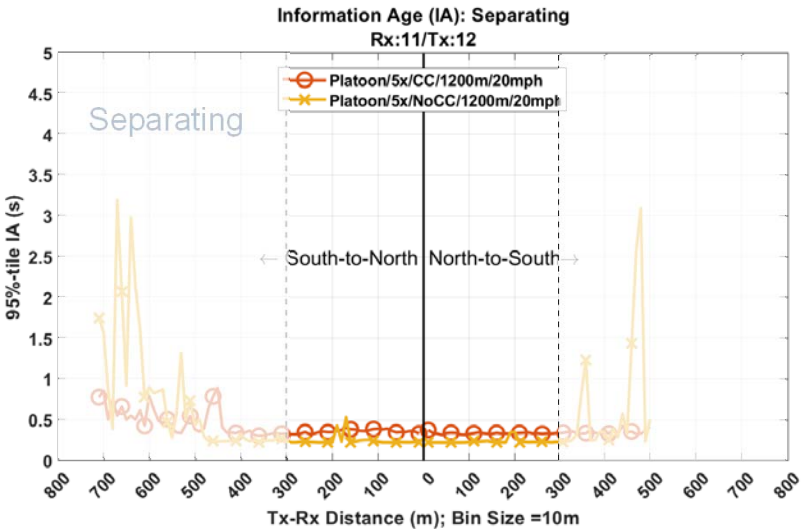



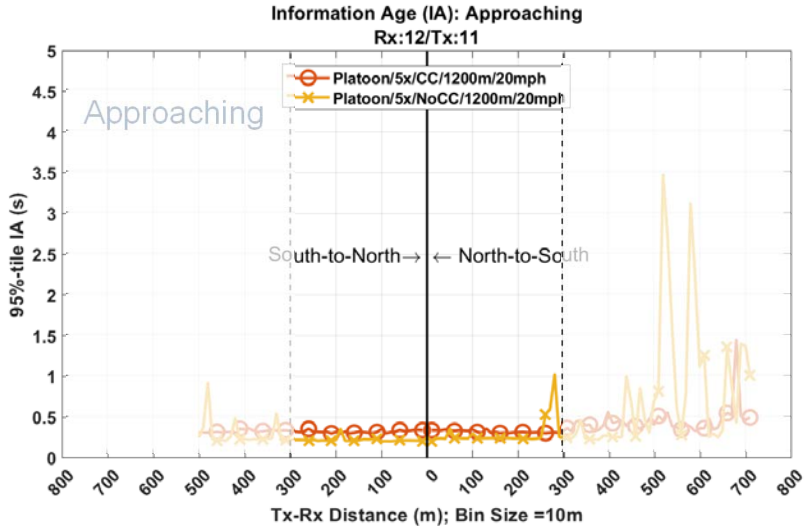
# IA – Platoon Test – 1200m

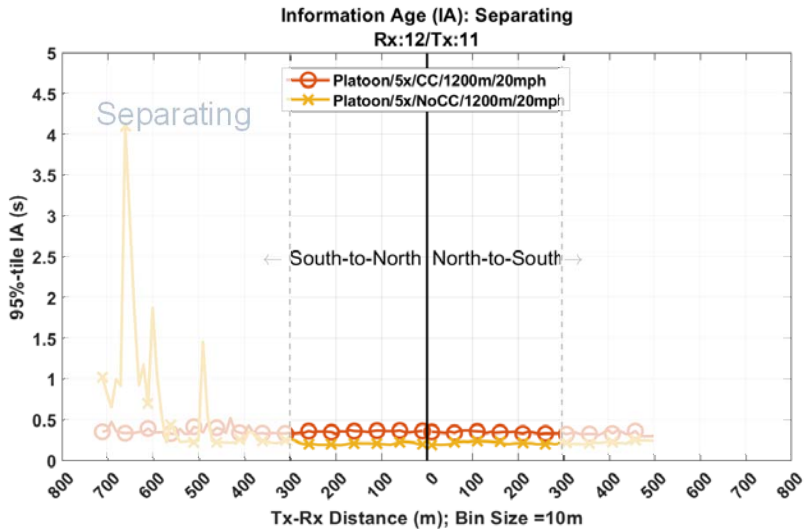
## Stationary Vehicle Receiving




## Moving Vehicle Receiving



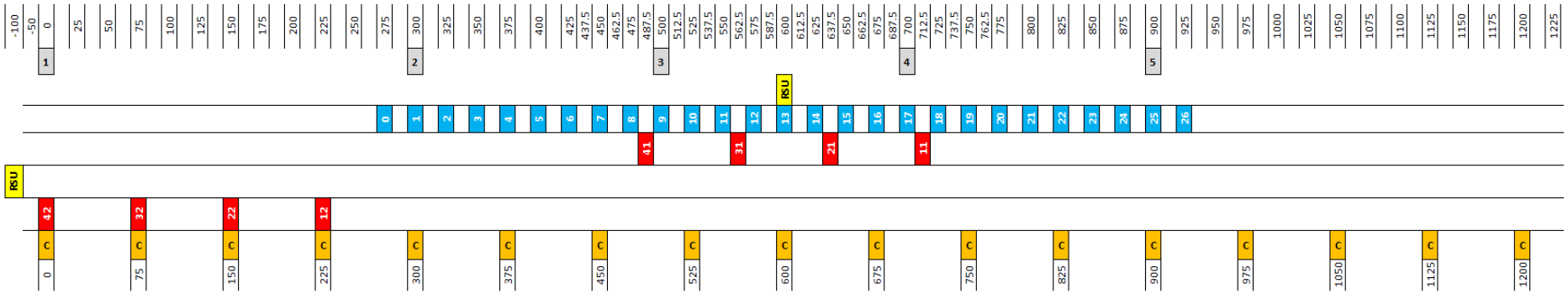



# Platoon Test

# Congestion Spread 600m
# Speed 20mph

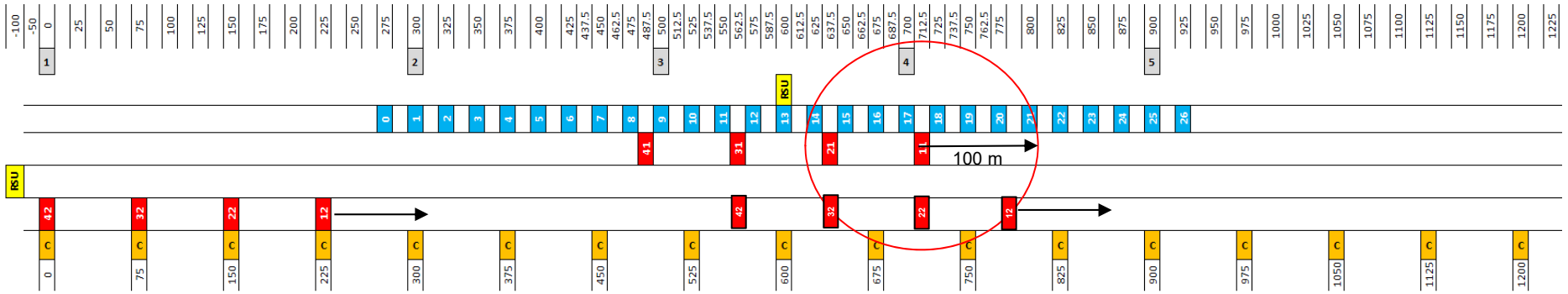
# Test Setup: Platoon 600m

- Stationary OBEs: 11, 21, 31, 41
- Platoon OBEs: 12, 22, 32, 42
- Congestion Carts: 0-26 (start at 275m)
- Cart 13 at 600m (center of the test track)
- Results shown for (Vehicle 11, Vehicle 12) pair



# Max_ITT Estimate for Vehicle 11 at 5X Emulation

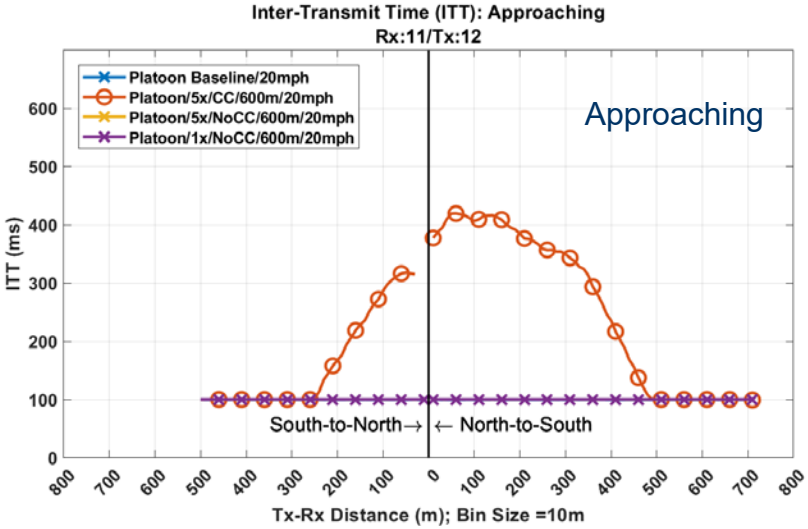
- When the platoon is away vehicle 11 observes
  - ~8 carts (15 OBUs)*
  - 1 vehicle
  - Max_ITT(k) = 100 x 16/5 = 320 ms
- When the platoon is partially overlapping vehicle 11 observes
  - ~8 carts (15 OBUs)*
  - 4 vehicles
  - Max_ITT(k) = 100 x 19/5 = 380 ms

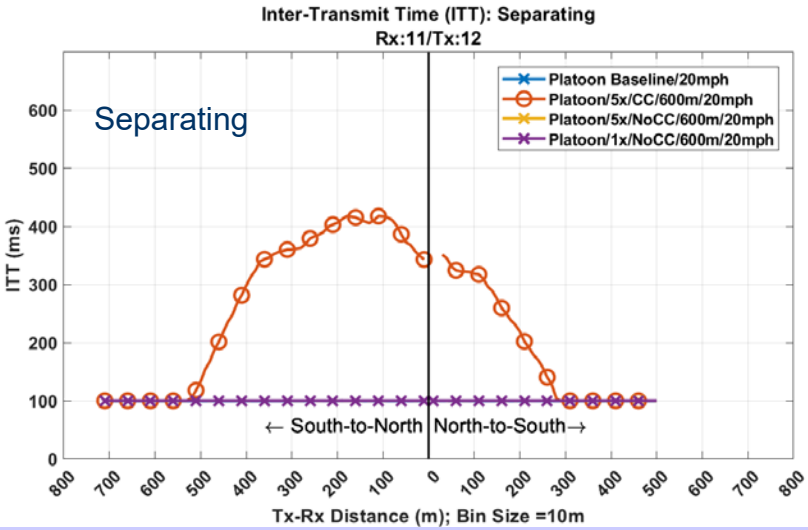



* A pod on cart 20 was turned off during the test

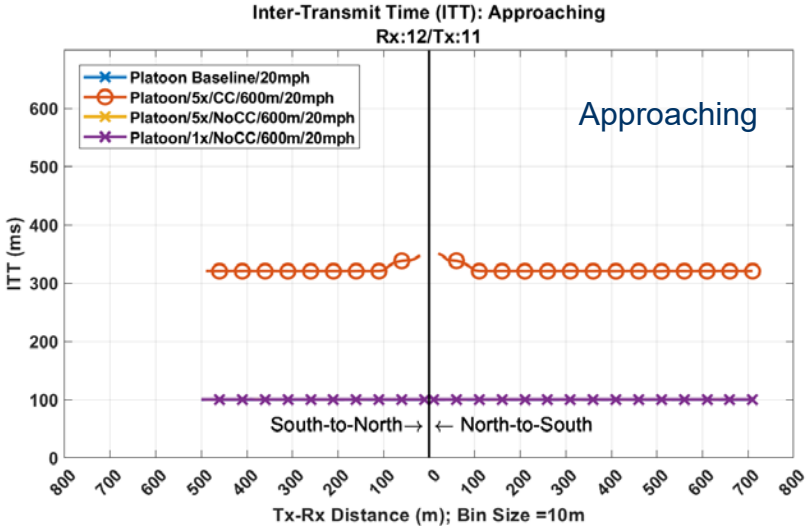
# ITT – Platoon Test – 600m

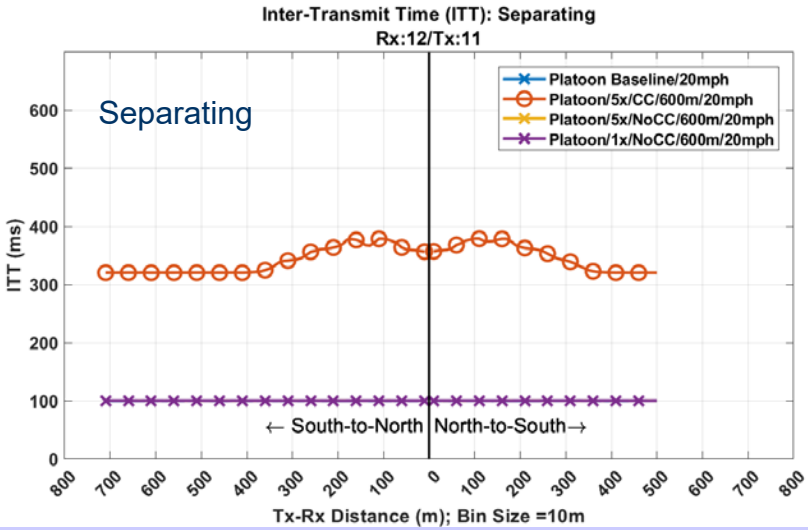
## Stationary Vehicle Receiving



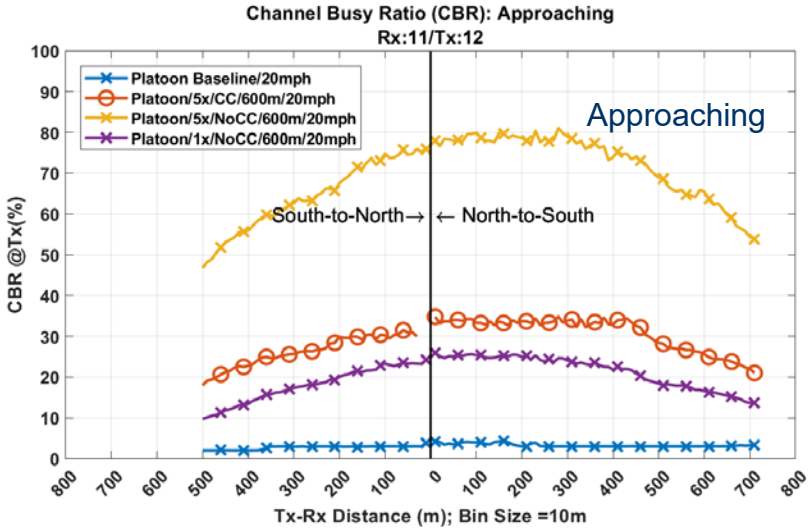

## Moving Vehicle Receiving

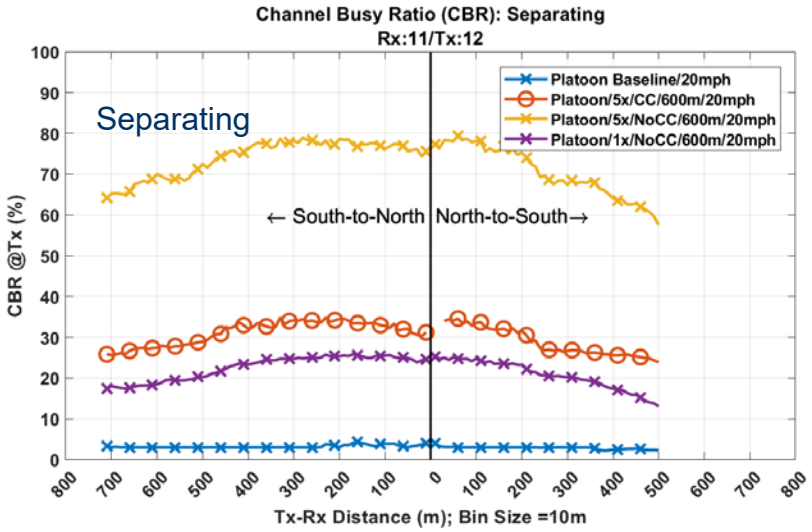


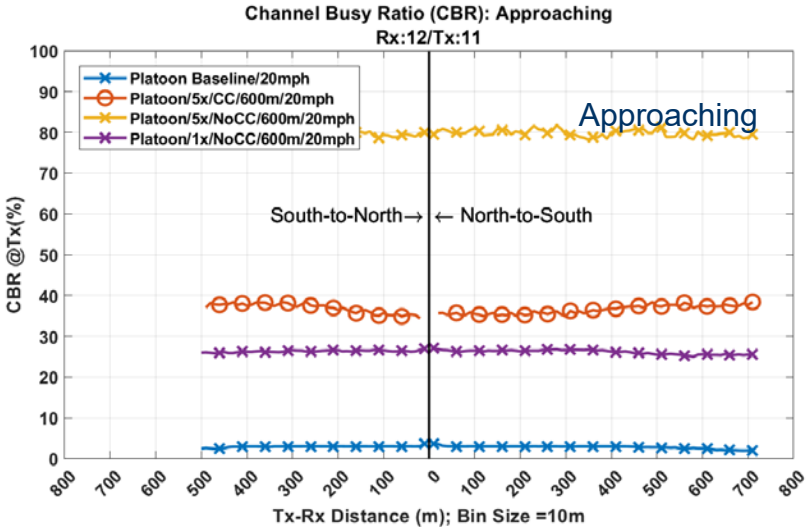
# CBR – Platoon Test – 600m

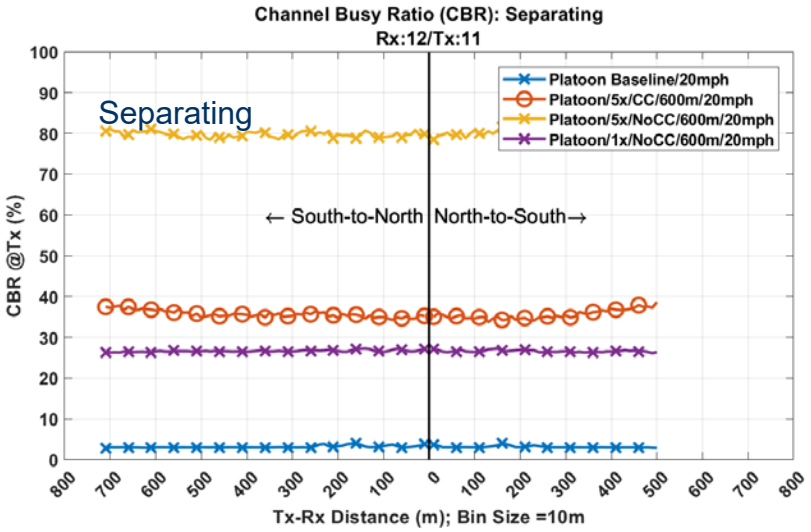
## Stationary Vehicle Receiving



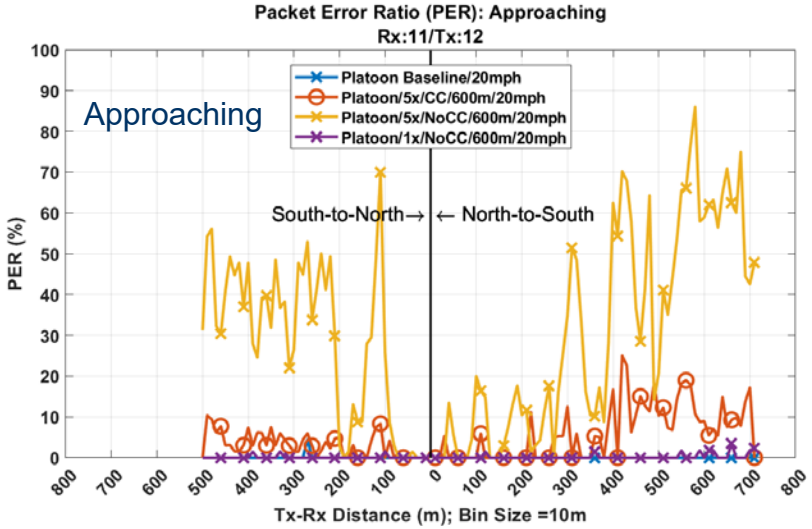

## Moving Vehicle Receiving

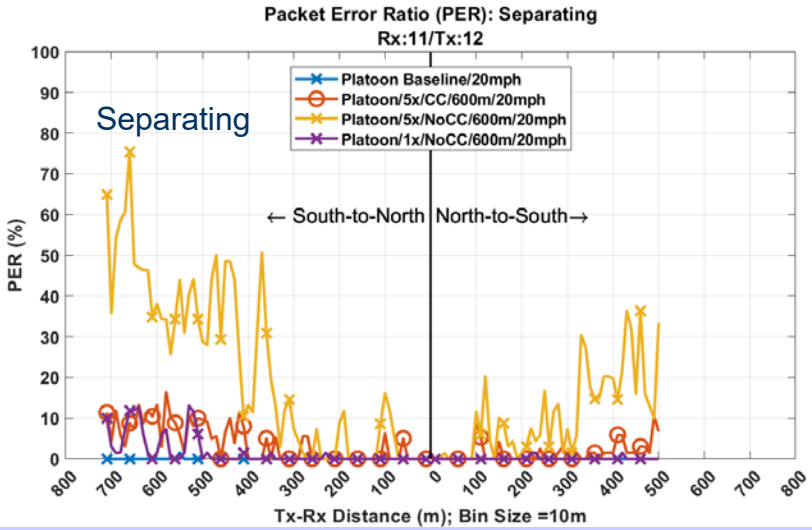


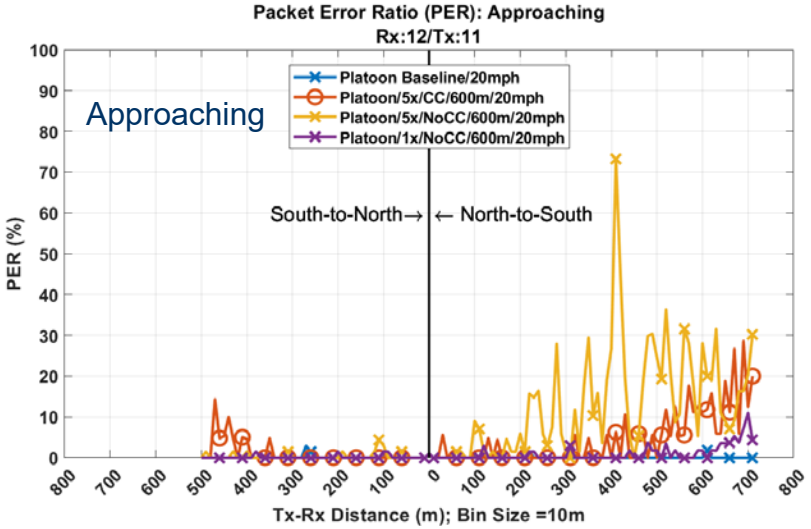
# PER – Platoon Test – 600m

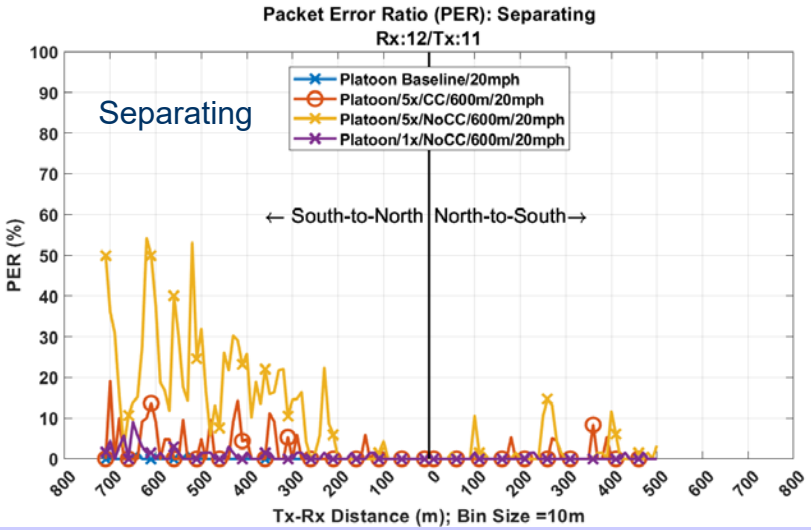
## Stationary Vehicle Receiving



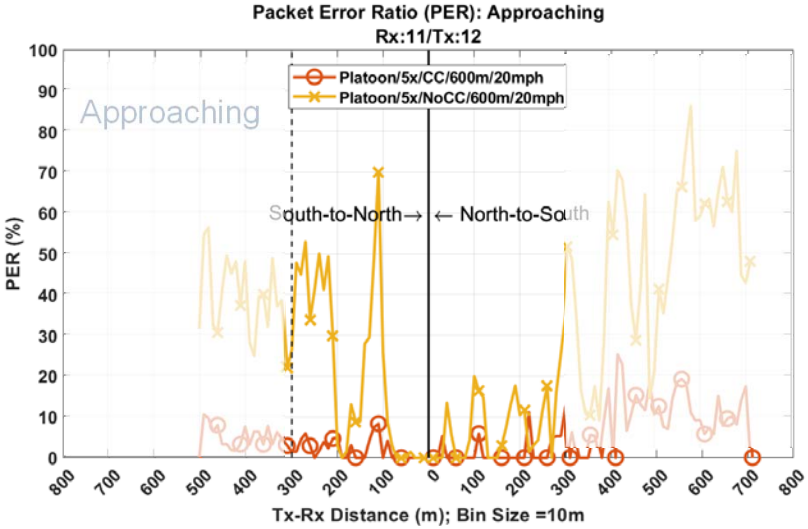

## Moving Vehicle Receiving

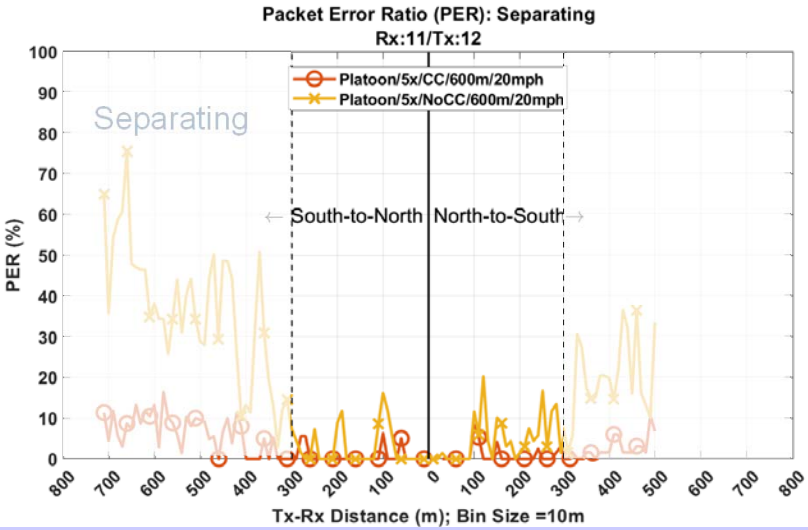


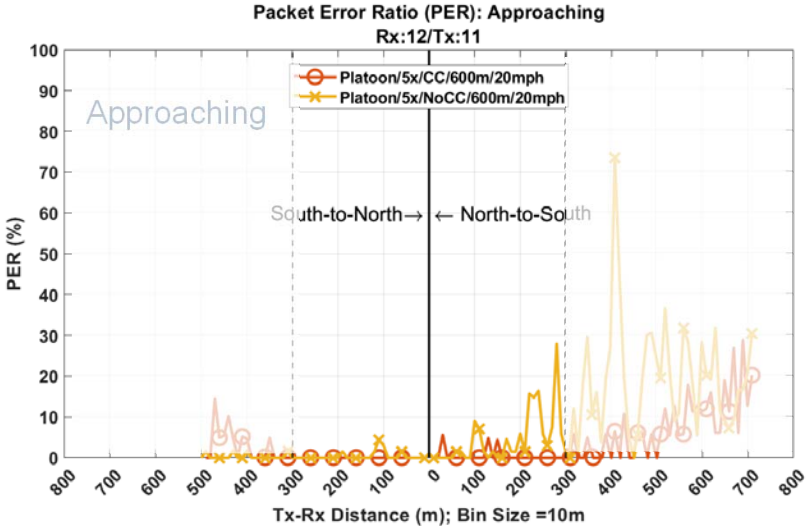
# PER – Platoon Test – 600m

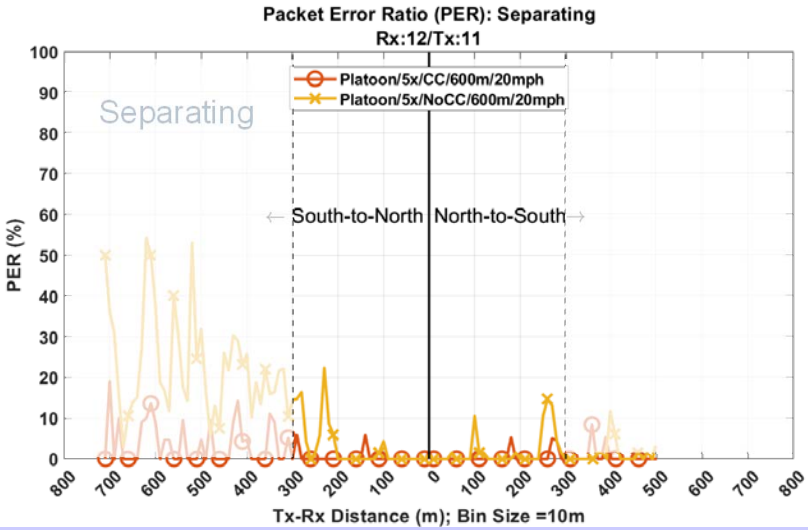
## Stationary Vehicle Receiving



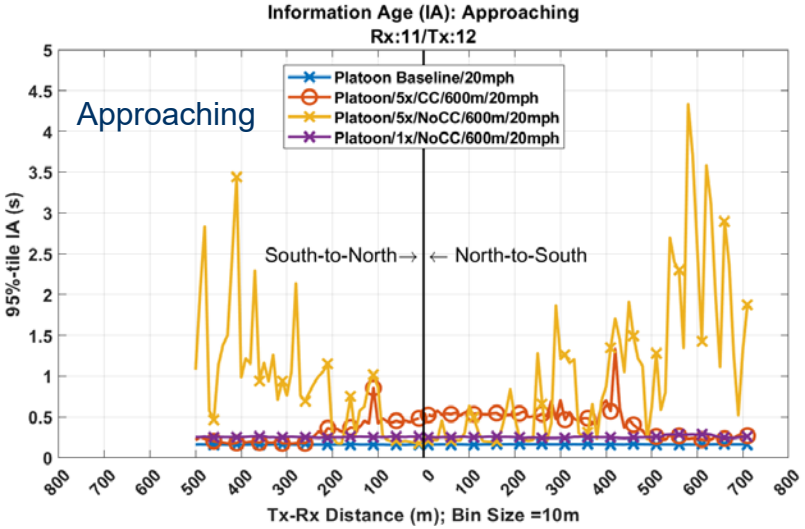

## Moving Vehicle Receiving

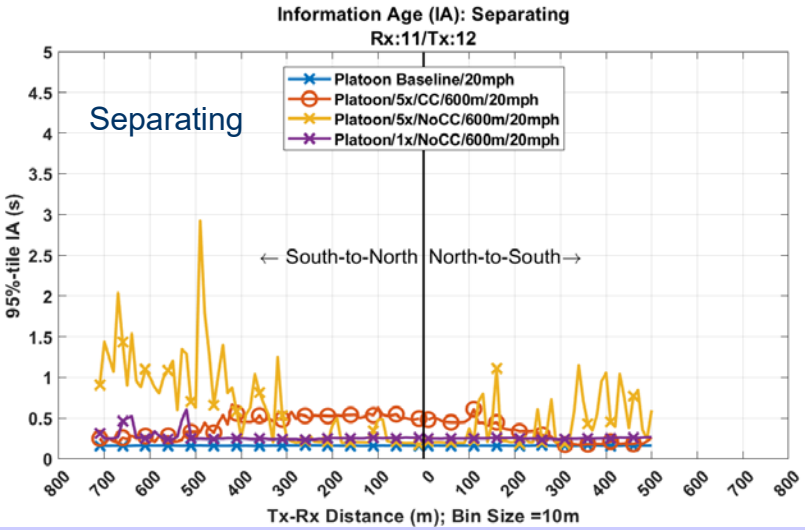


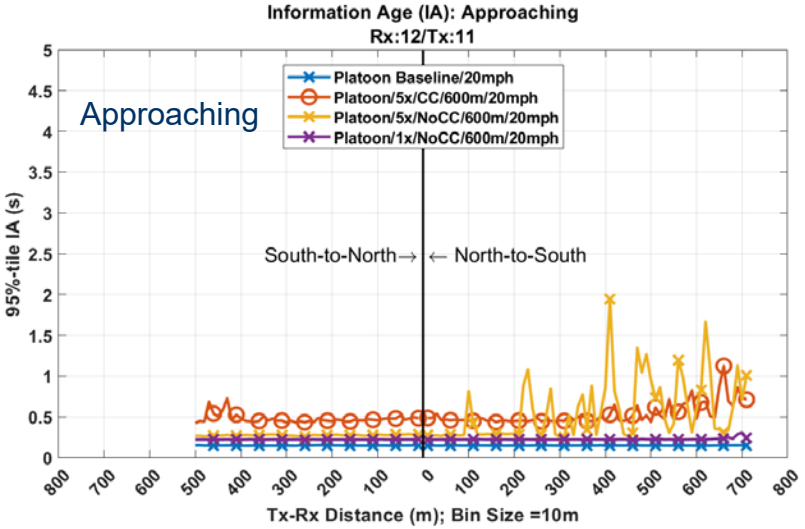
# IA – Platoon Test – 600m

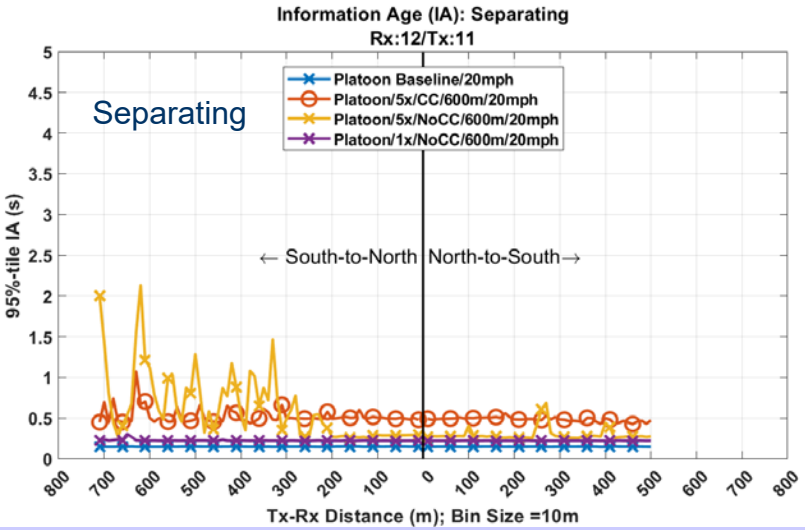
## Stationary Vehicle Receiving



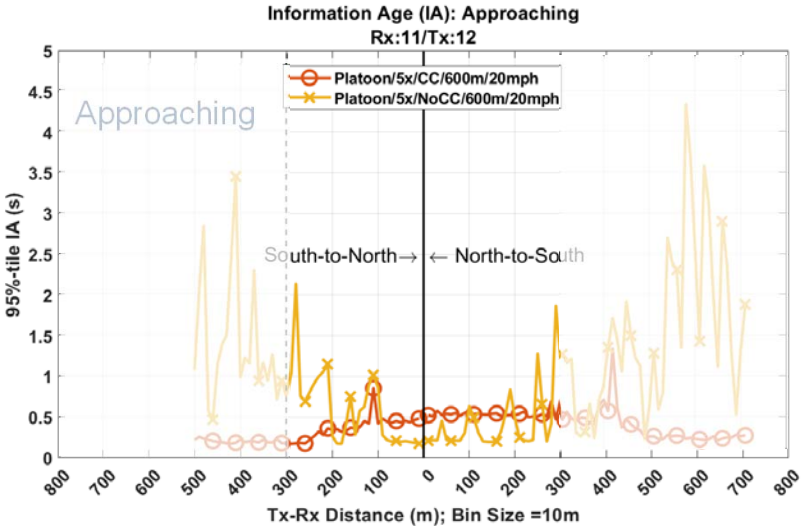

## Moving Vehicle Receiving

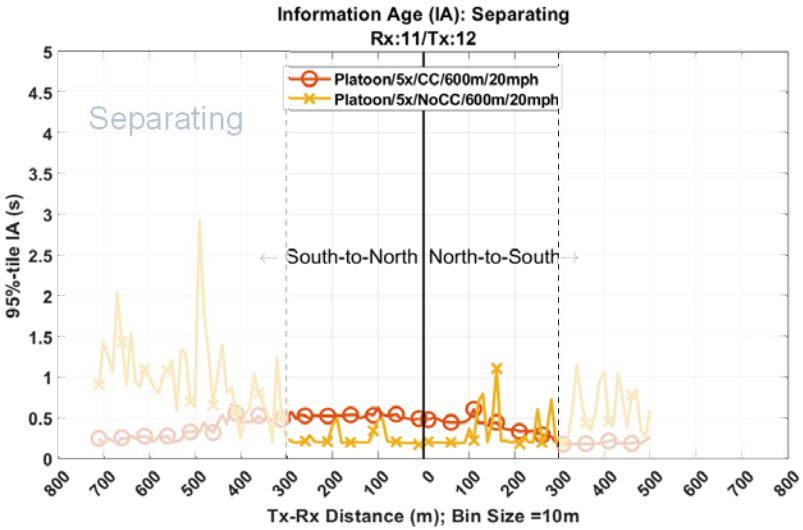


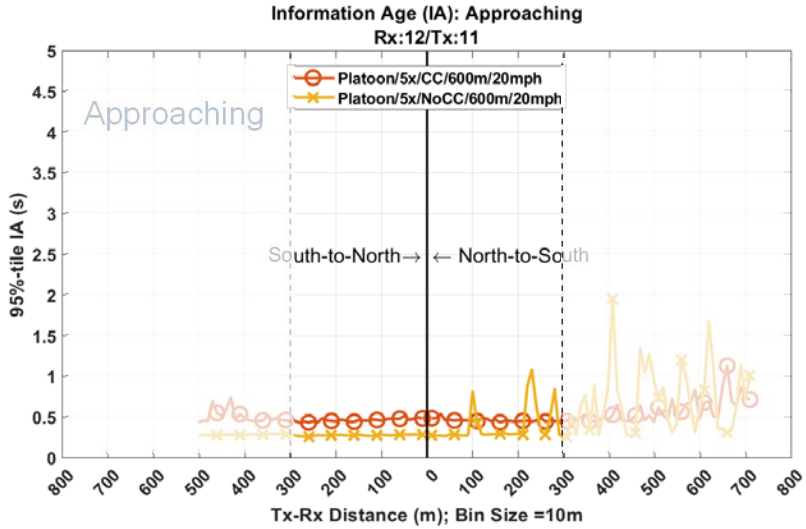
# IA – Platoon Test – 600m

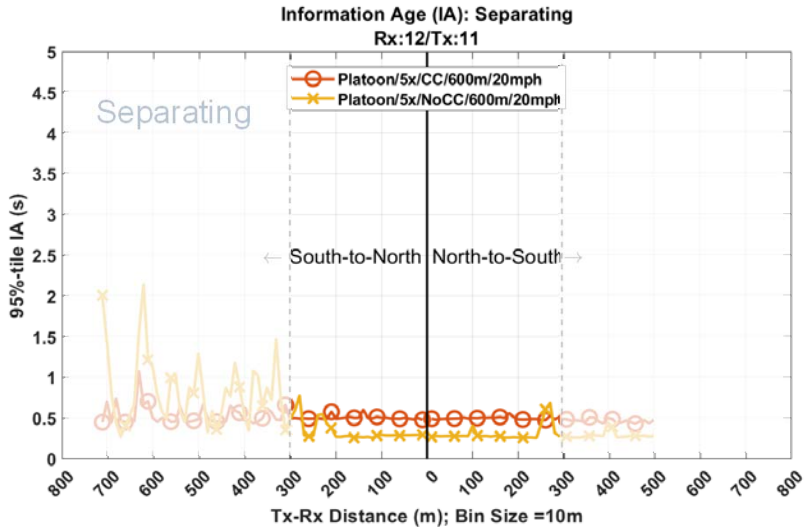
## Stationary Vehicle Receiving




## Moving Vehicle Receiving



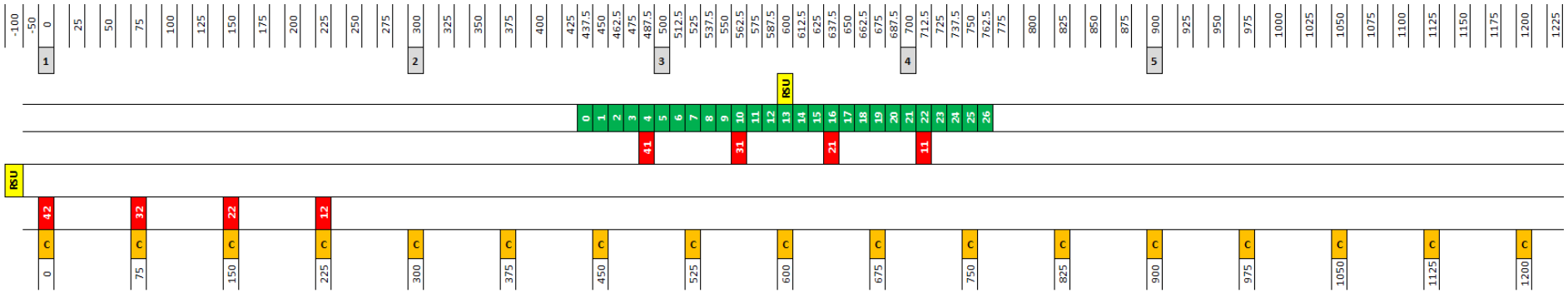



# Platoon Test

# Congestion Spread 300m
# Speed 20mph

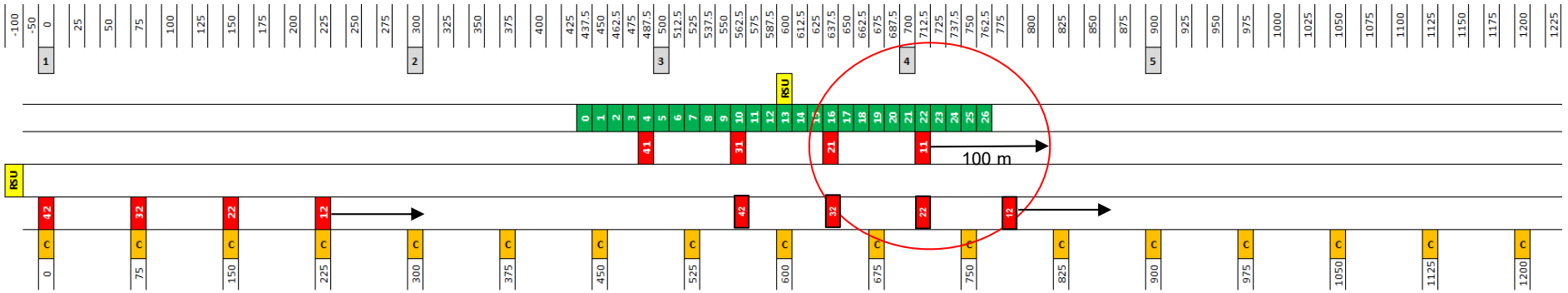
# Test Setup: Platoon 300m

- Stationary OBEs: 11, 21, 31, 41
- Platoon OBEs: 12, 22, 32, 42
- Congestion Carts: 0-26 (start at 437.5m)
- Cart 13 at 600m (center of the test track)
- Results shown for ( Vehicle 11, Vehicle 12) pair



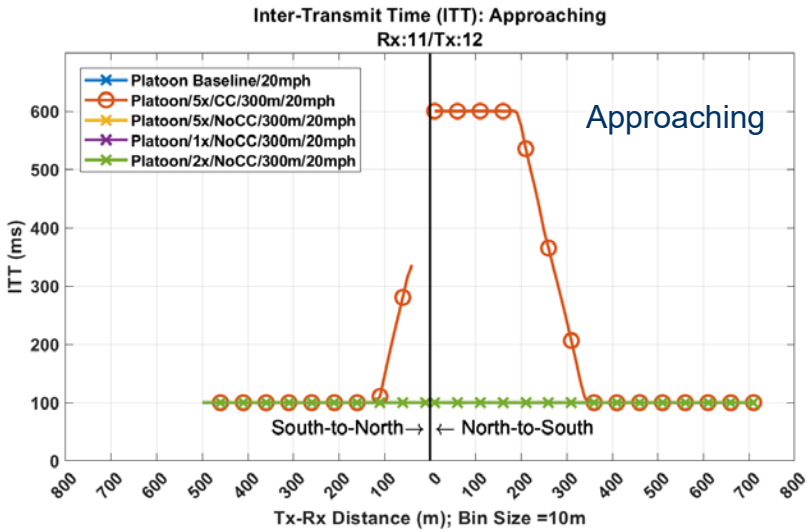
# Max_ITT Estimate for Vehicle 11 at 5X Emulation

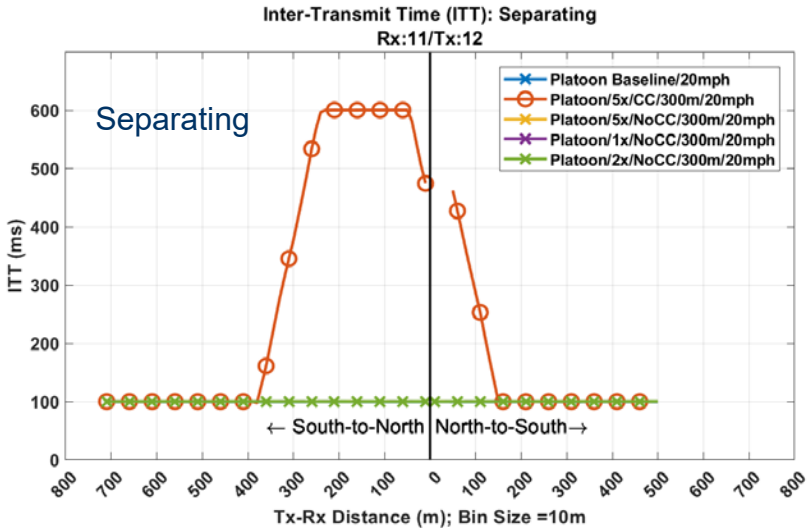
- When the platoon is away vehicle 11 observes
  - ~12 carts (24 OBUs)
  - 1 vehicle
  - Max_ITT(k) = 100 x 25/5 = 500 ms
- When the platoon is partially overlapping vehicle 11 observes
  - ~12 carts (24 OBUs)
  - 4 vehicles
  - Max_ITT(k) = 100 x 28/5 = 560 ms



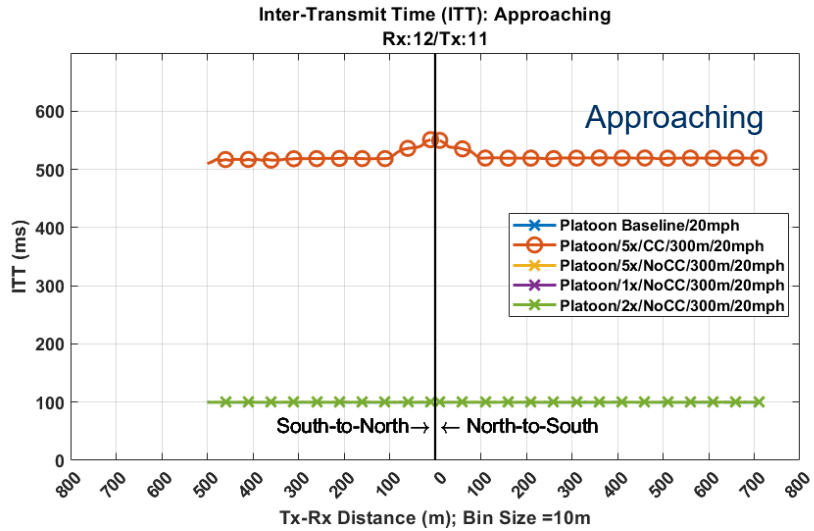
# ITT – Platoon Test – 300m

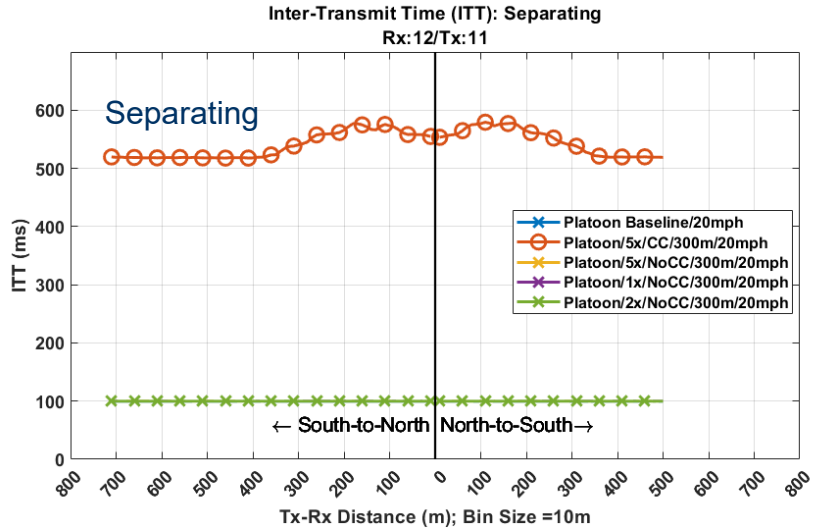
## Stationary Vehicle Receiving



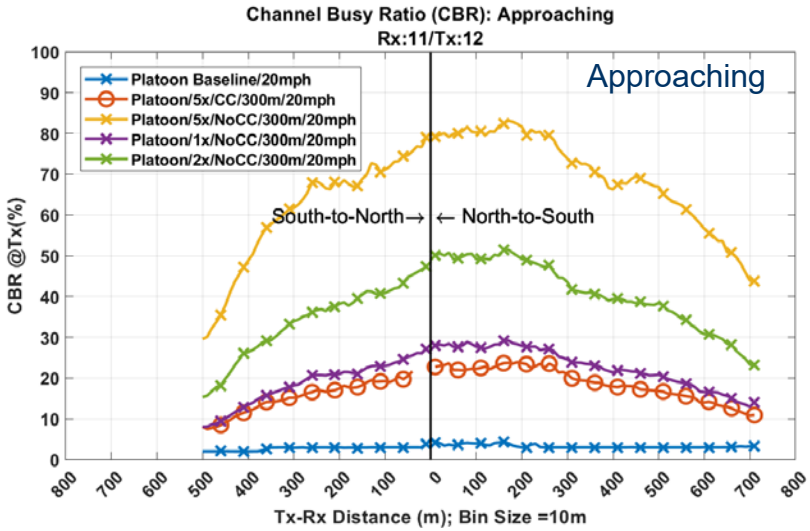

## Moving Vehicle Receiving

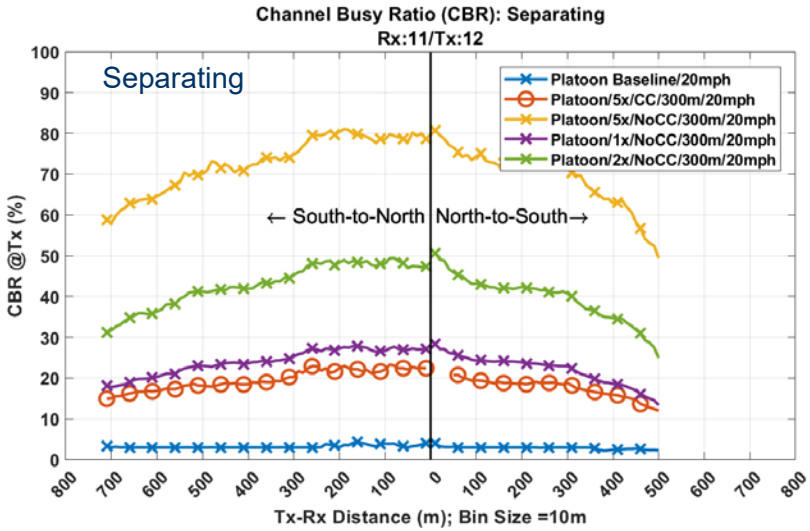


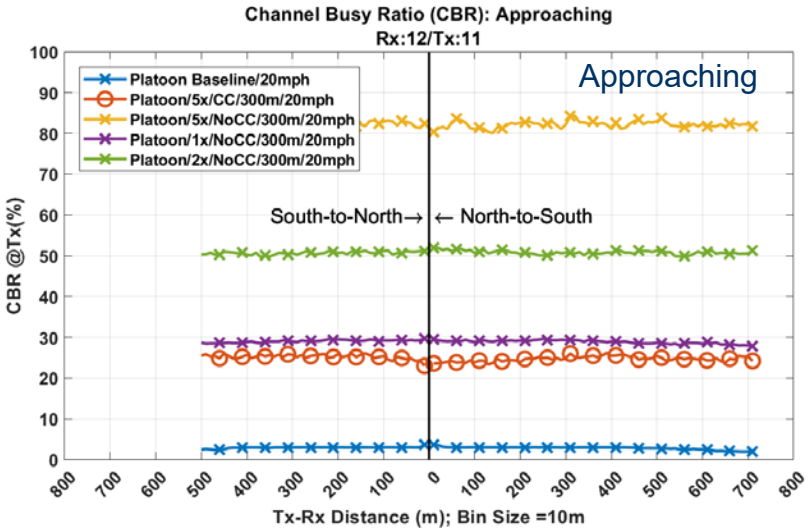
# CBR – Platoon Test – 300m

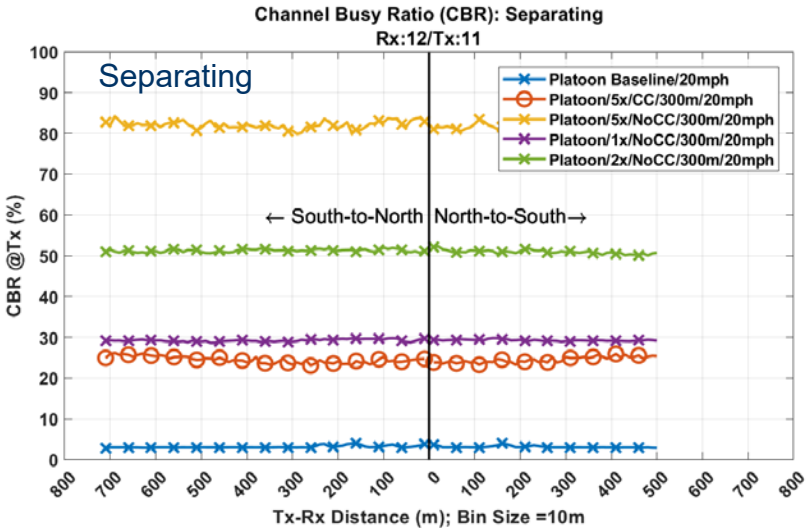
## Stationary Vehicle Receiving



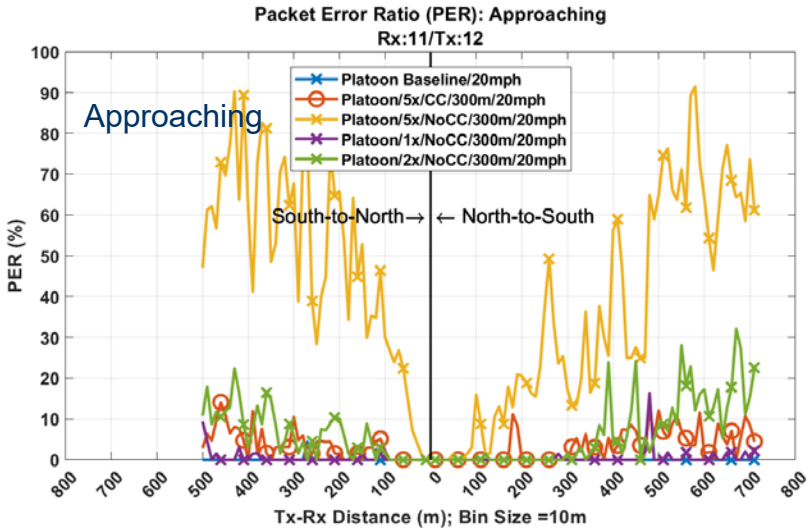

## Moving Vehicle Receiving

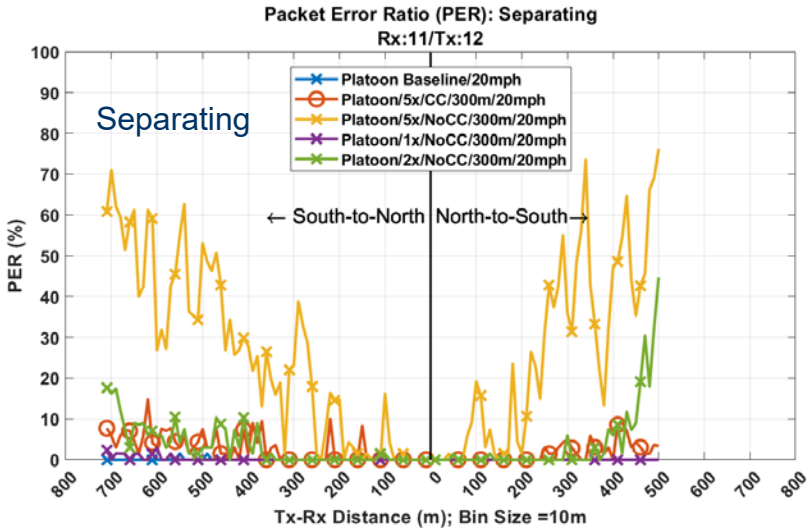


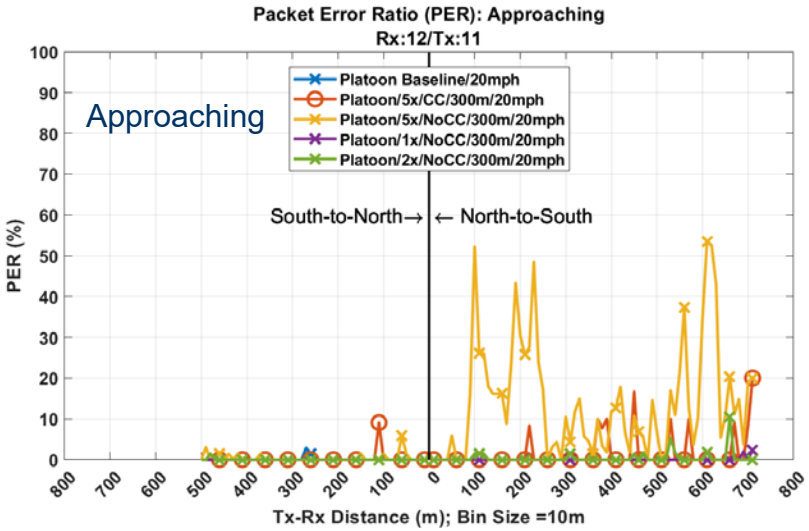
# PER – Platoon Test – 300m

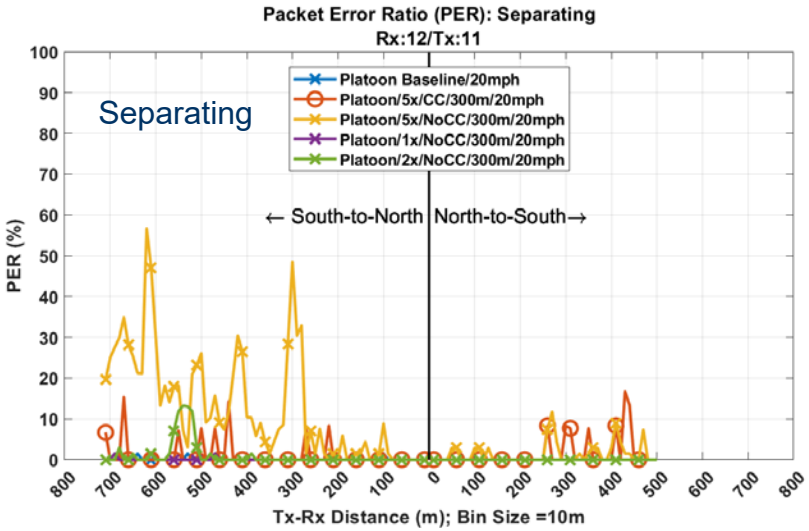
## Stationary Vehicle Receiving



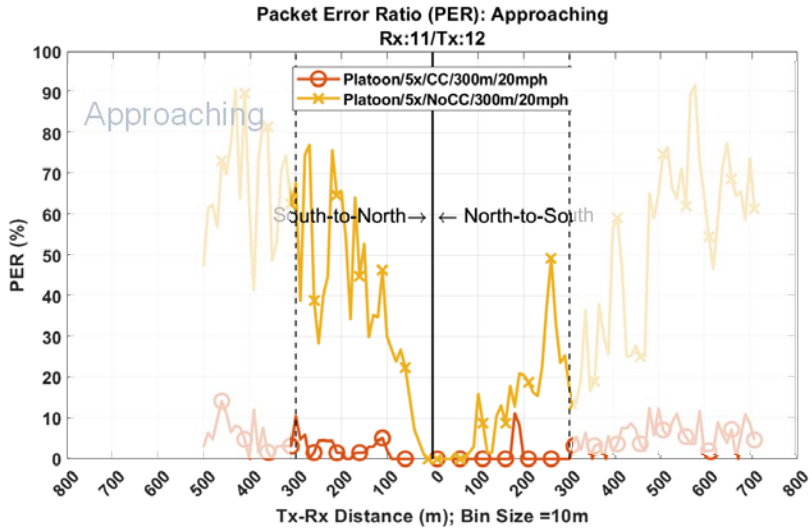

## Moving Vehicle Receiving

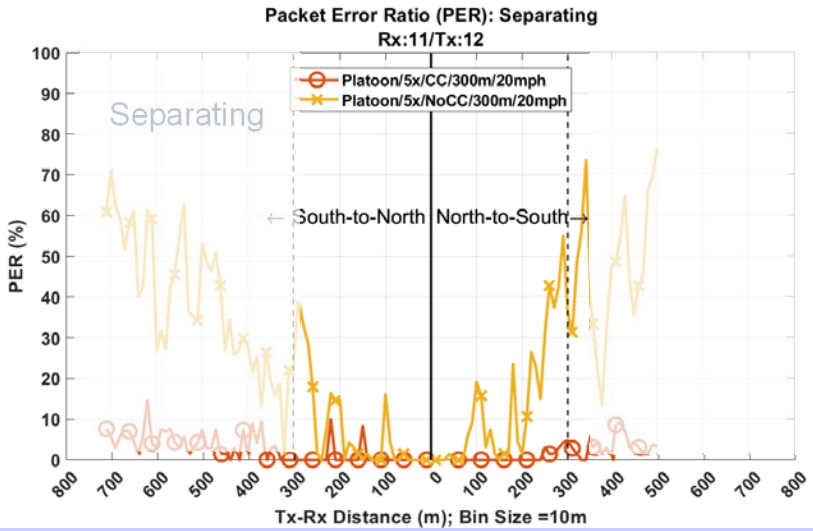


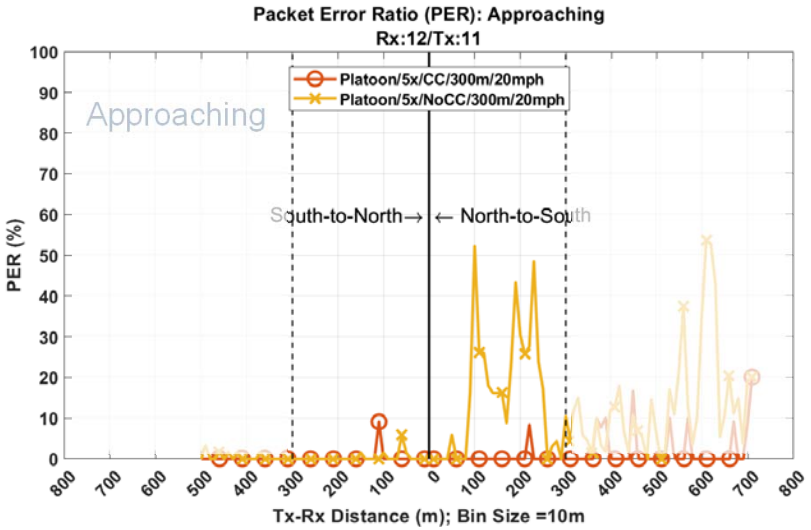
# PER – Platoon Test – 300m

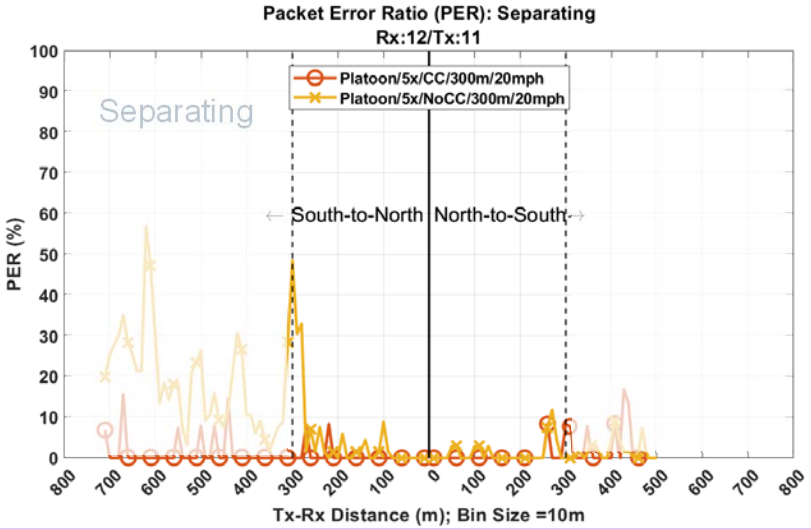
## Stationary Vehicle Receiving



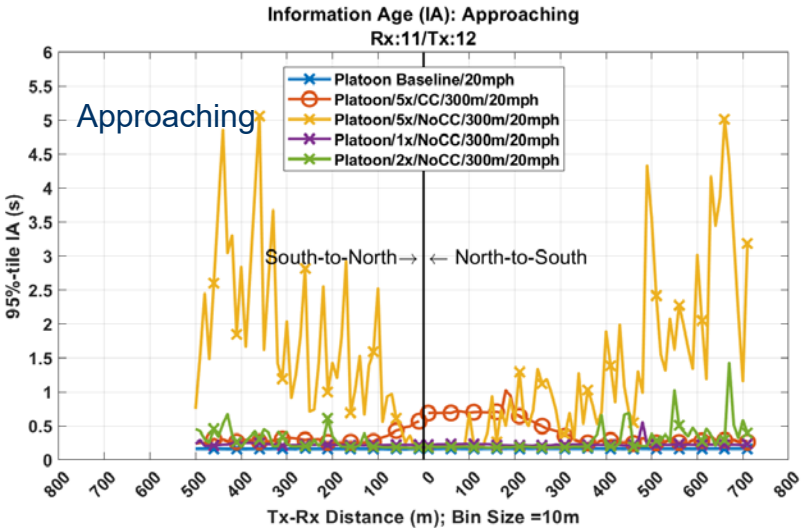

## Moving Vehicle Receiving

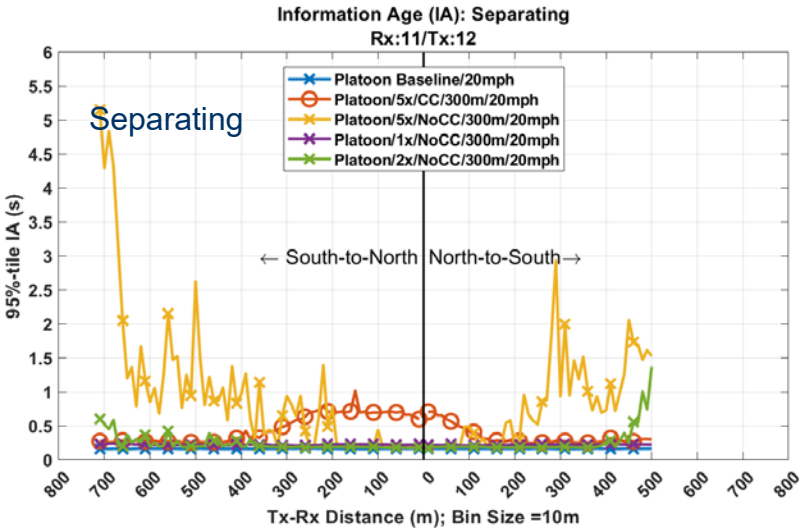


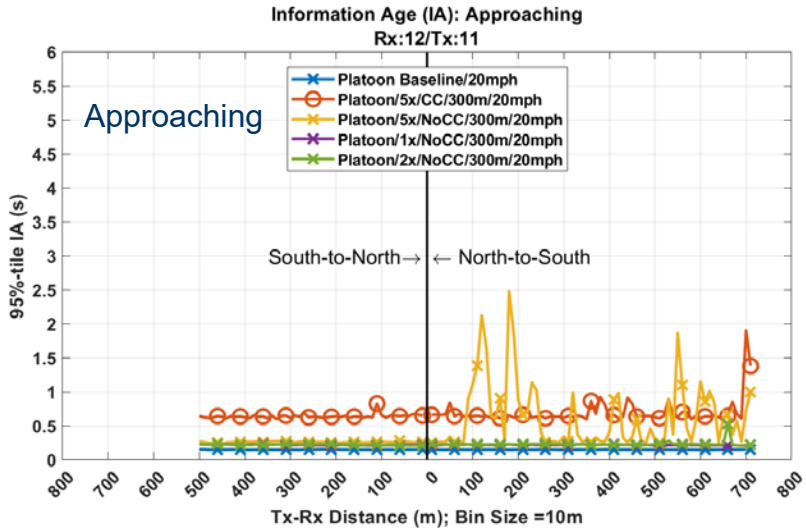
# IA – Platoon Test – 300m

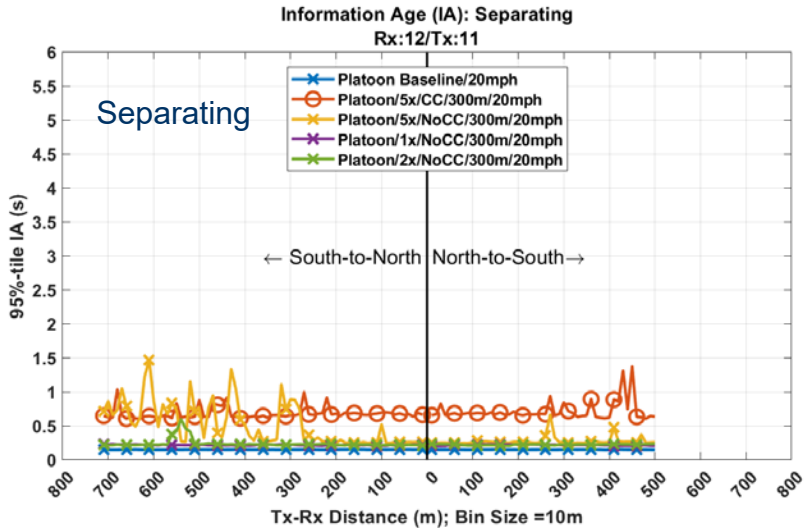
## Stationary Vehicle Receiving



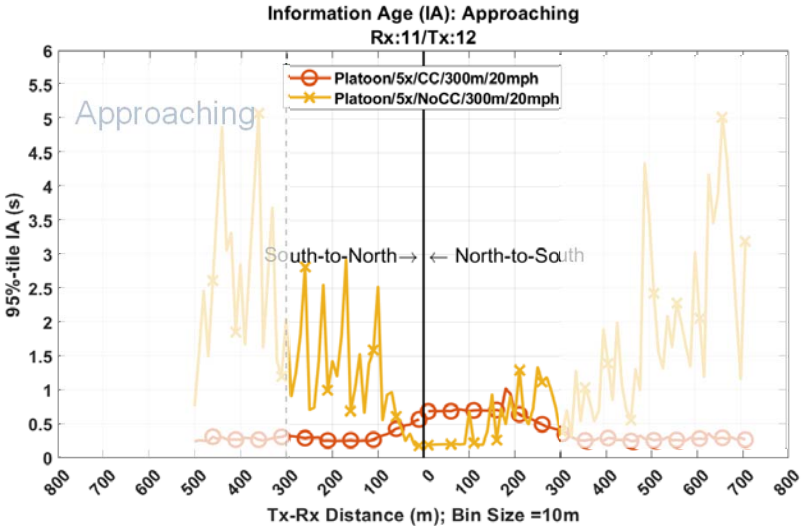

## Moving Vehicle Receiving

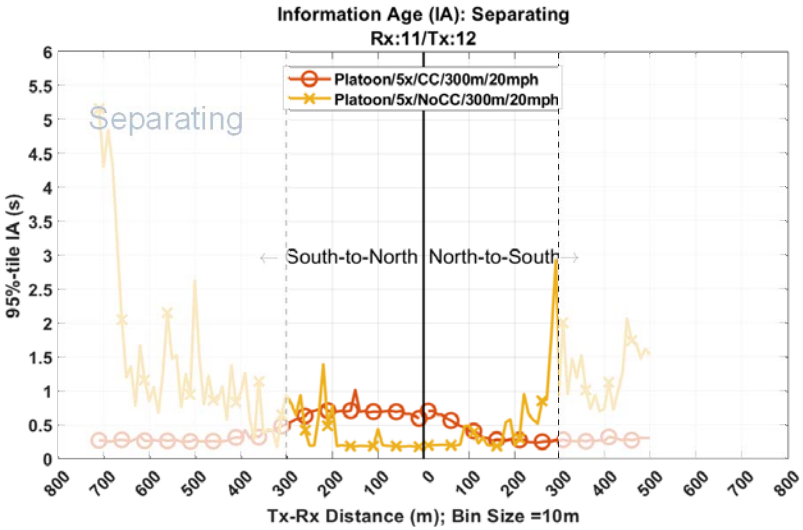


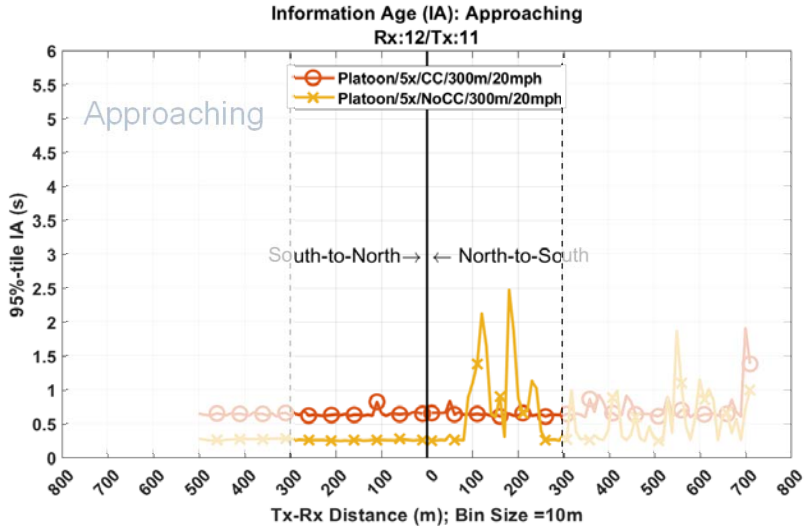
# IA – Platoon Test – 300m

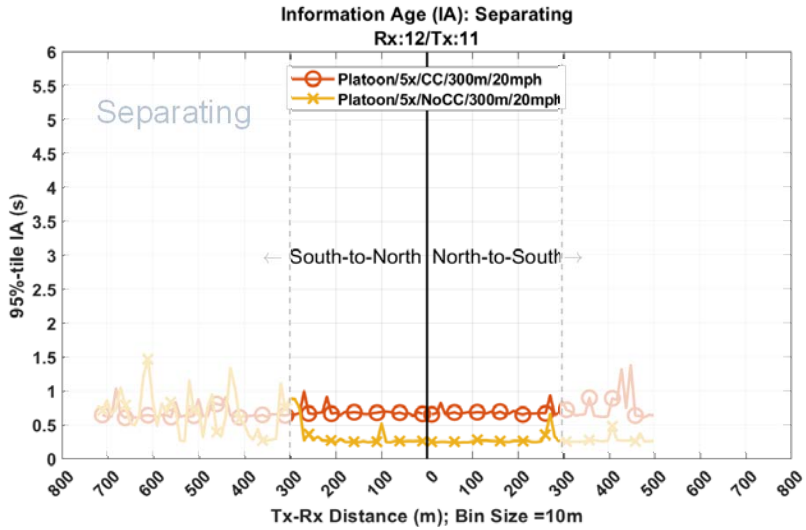
## Stationary Vehicle Receiving




## Moving Vehicle Receiving



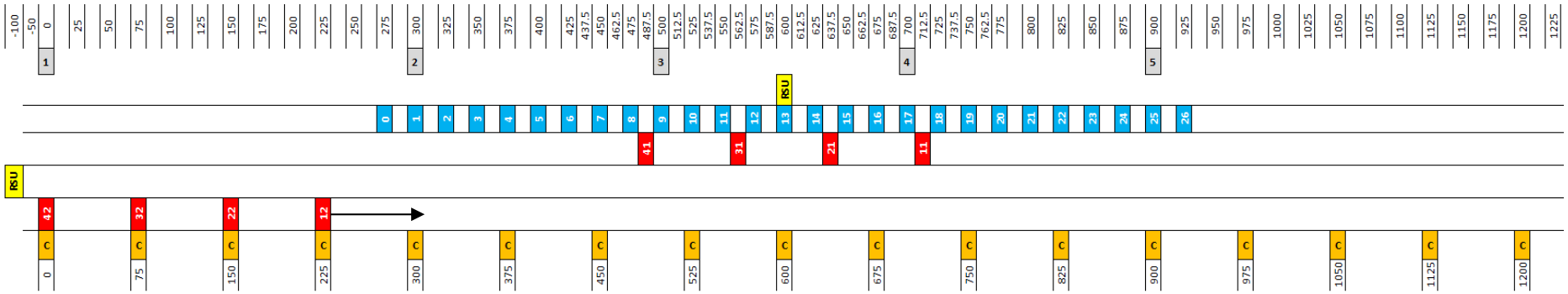



# High Speed Test

# Congestion Spread 600m
# Speed 80mph

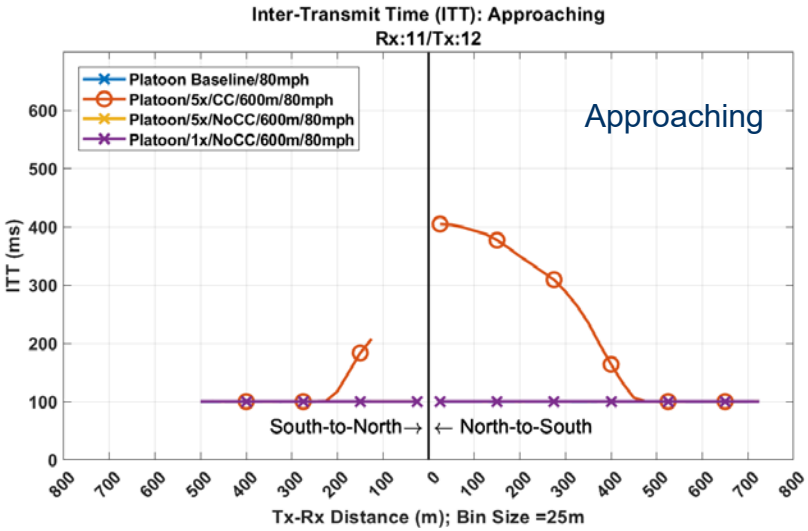
# Test Setup: High Speed, 600m

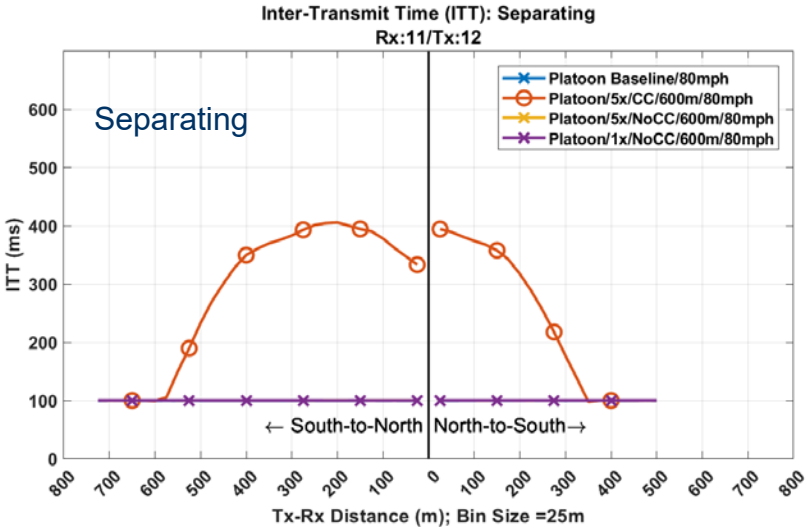
- Stationary OBEs: 11, 21, 31, 41
- Platoon OBEs: 12, 22, 32, 42
- Congestion Carts: 0-26 (start at 275m)
- Cart 13 at 600m (center of the test track)
- Results shown for (Vehicle 11, Vehicle 12) pair



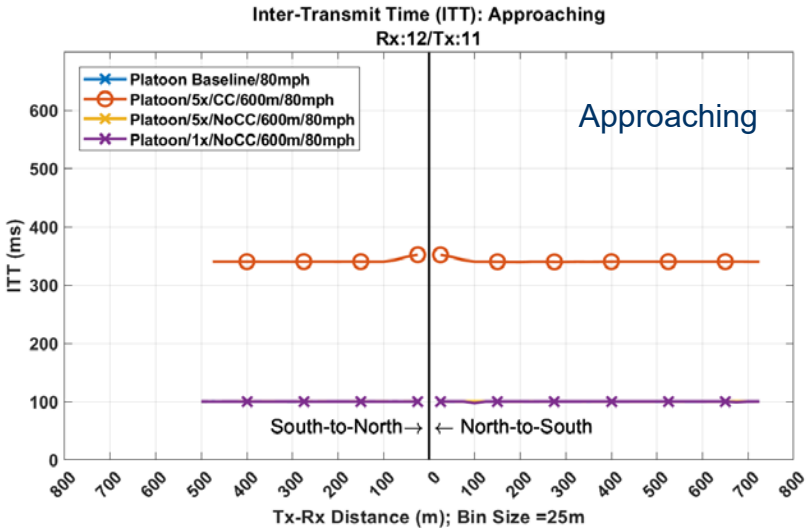
# ITT – High Speed Test – 600m

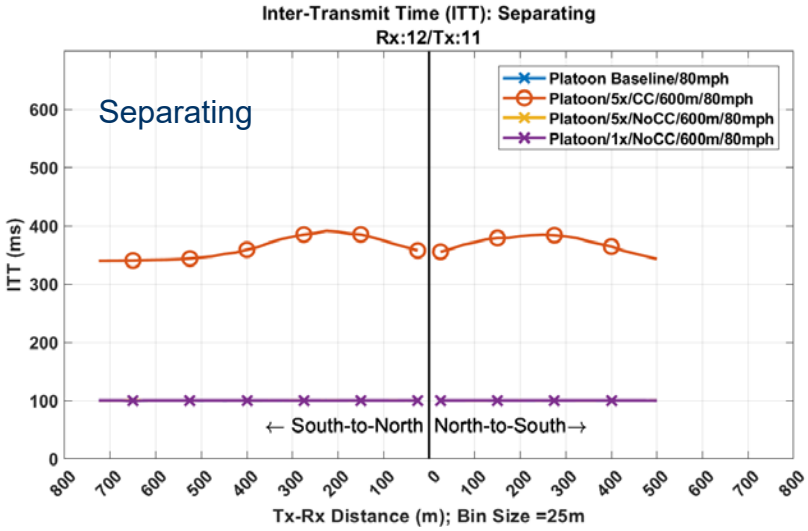
## Stationary Vehicle Receiving



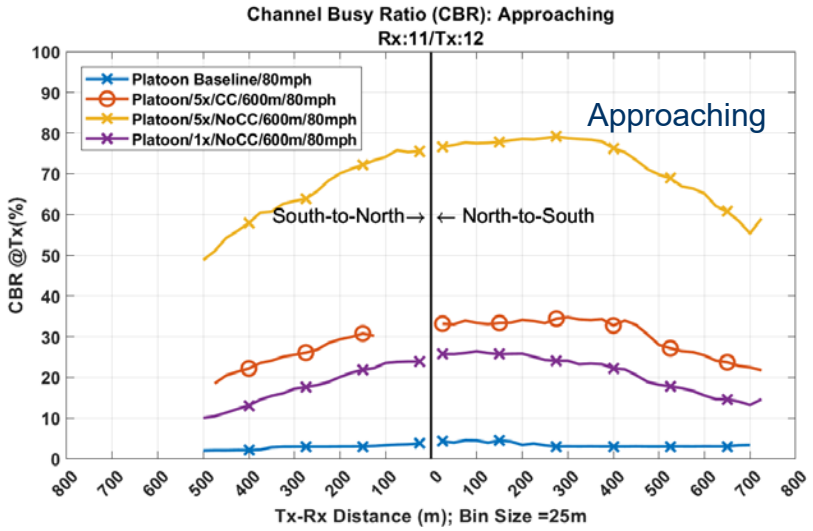

## Moving Vehicle Receiving

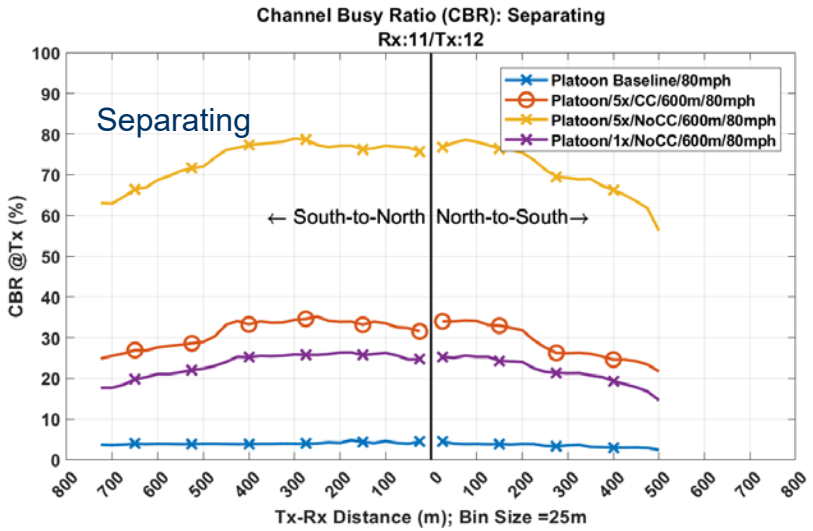


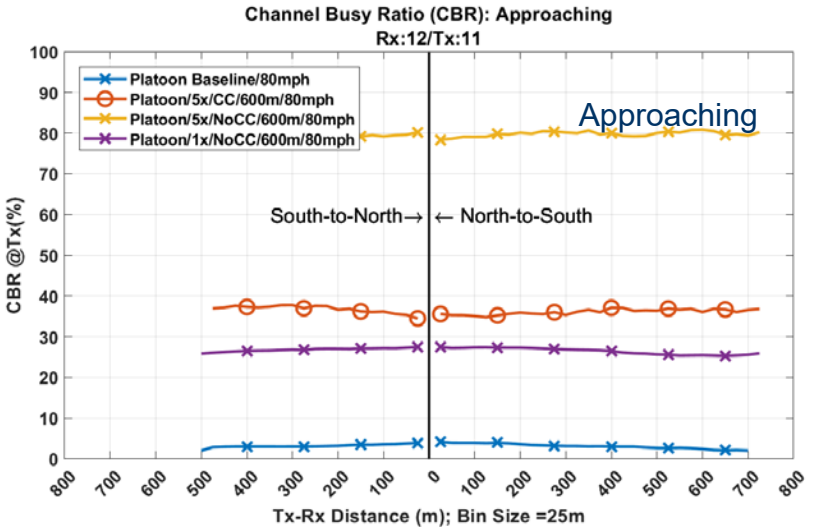
# CBR – High Speed Test – 600m

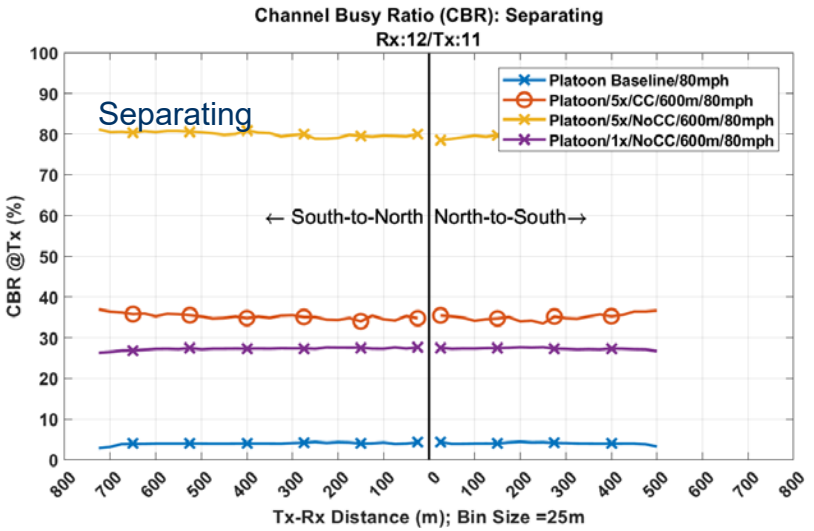
## Stationary Vehicle Receiving



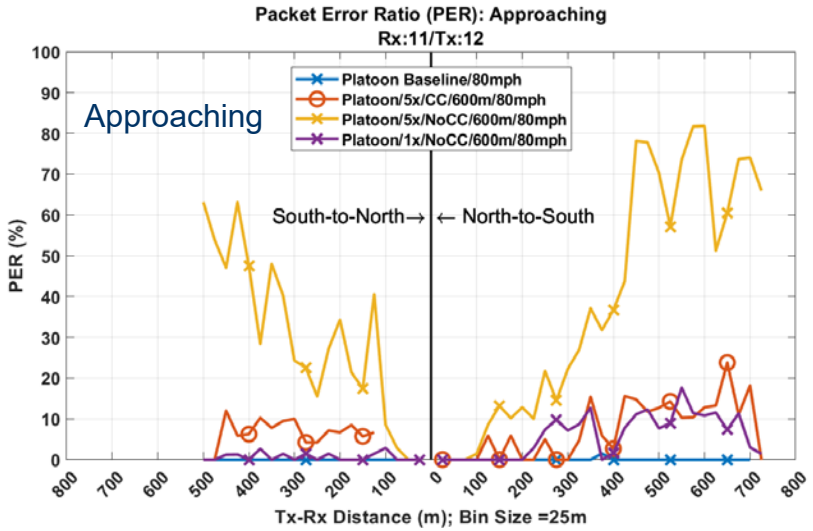

## Moving Vehicle Receiving

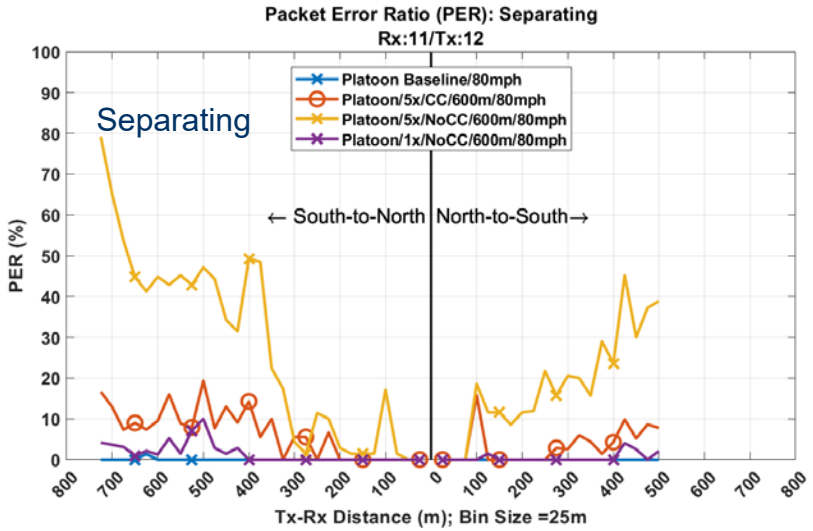


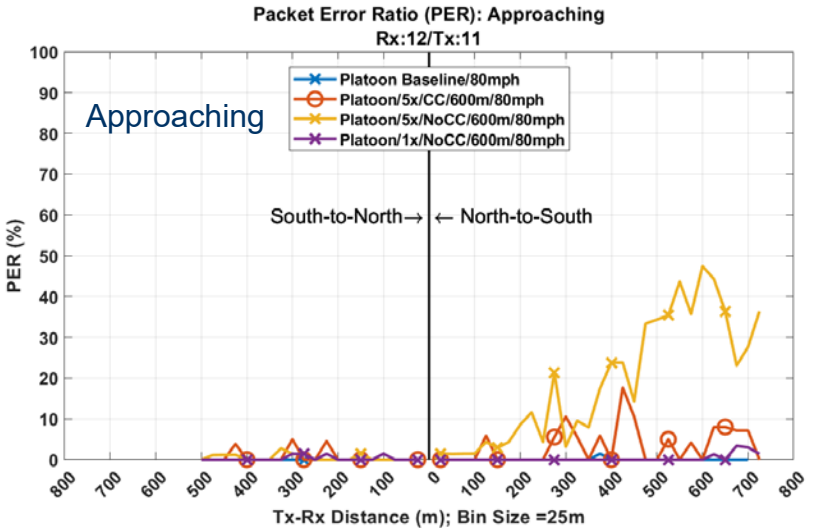
# PER – High Speed Test – 600m

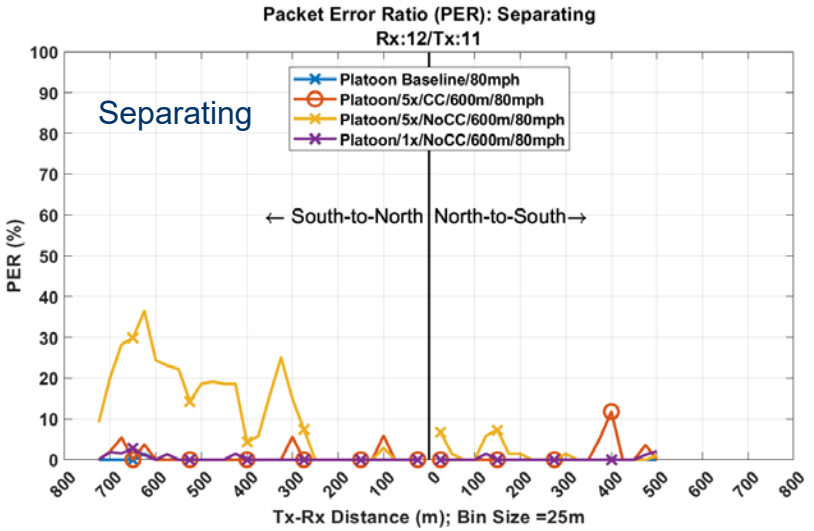
## Stationary Vehicle Receiving



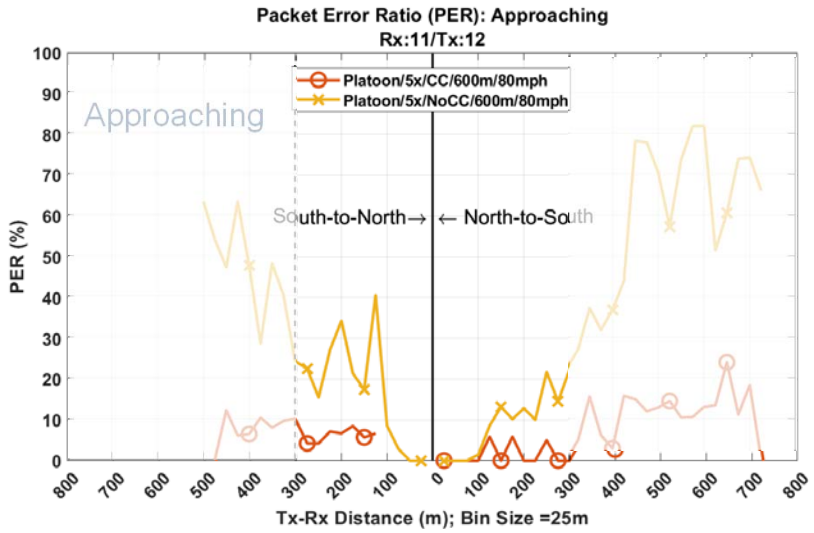

## Moving Vehicle Receiving

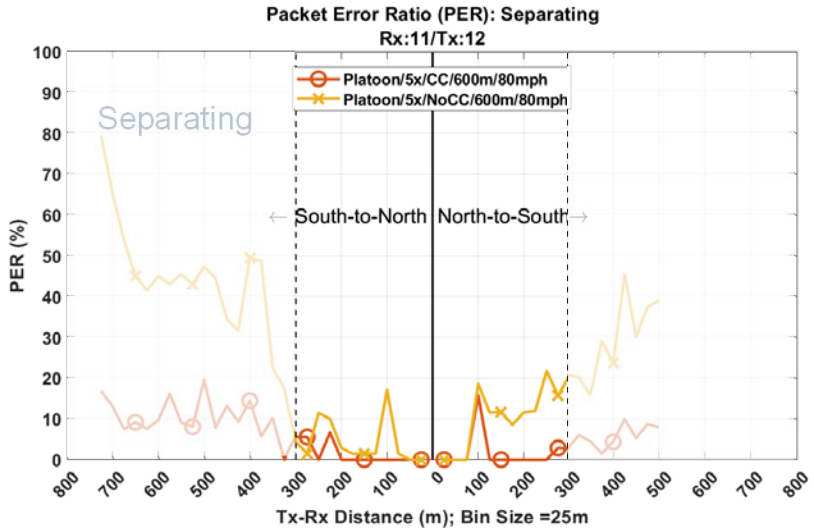


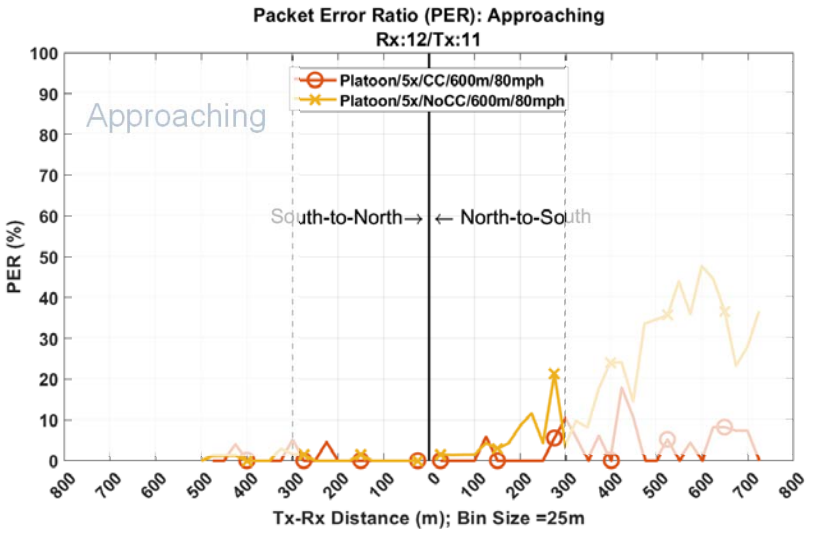
# PER – High Speed Test – 600m

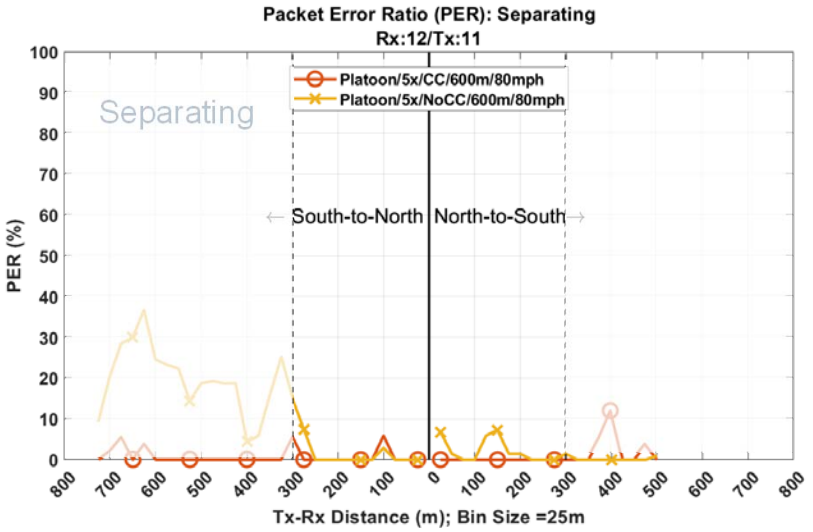
## Stationary Vehicle Receiving



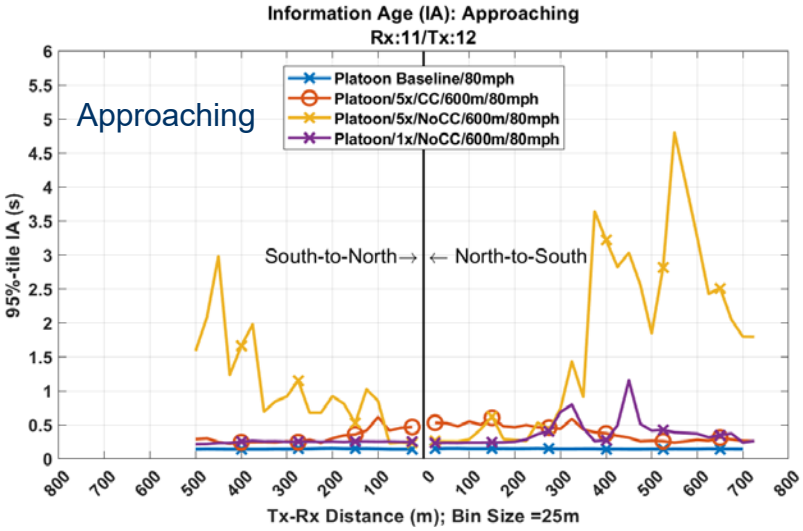

## Moving Vehicle Receiving

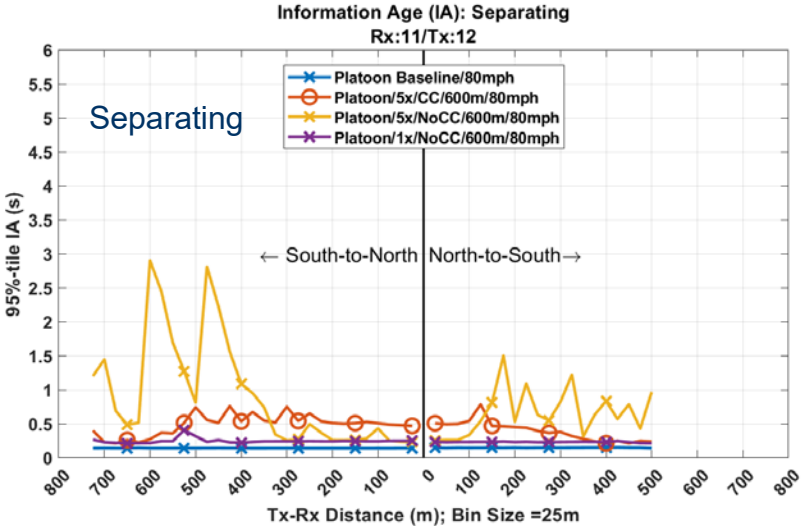


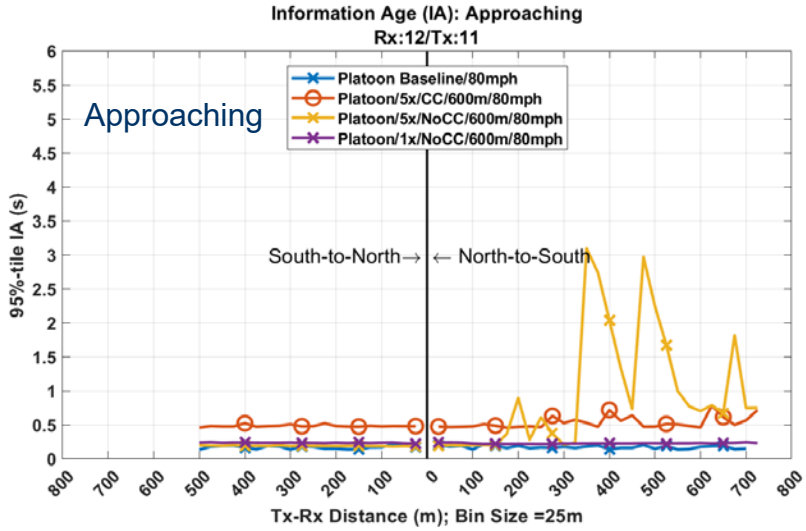
# IA – High Speed Test – 600m

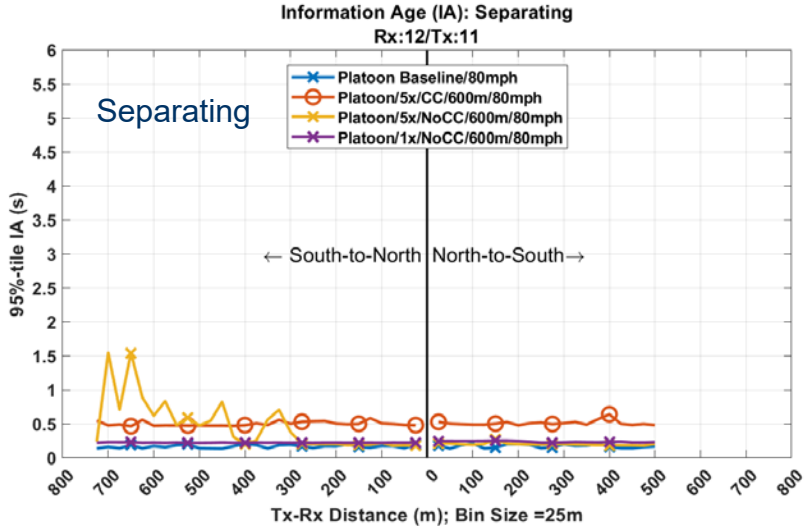
## Stationary Vehicle Receiving



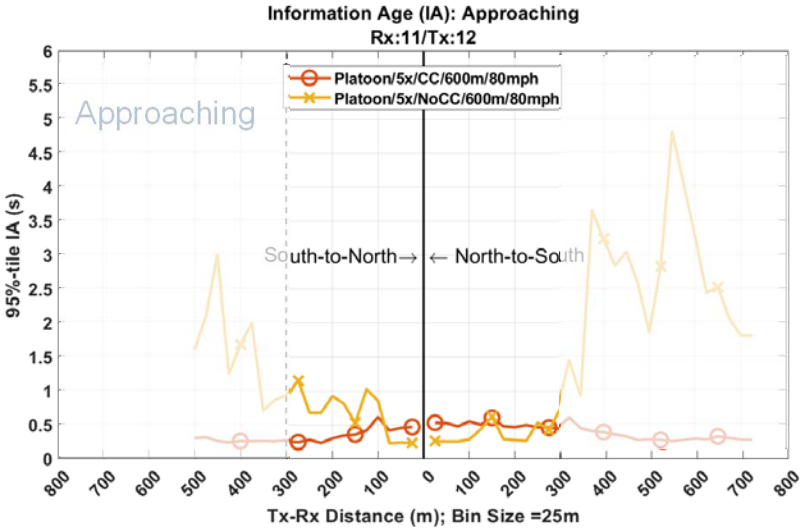

## Moving Vehicle Receiving

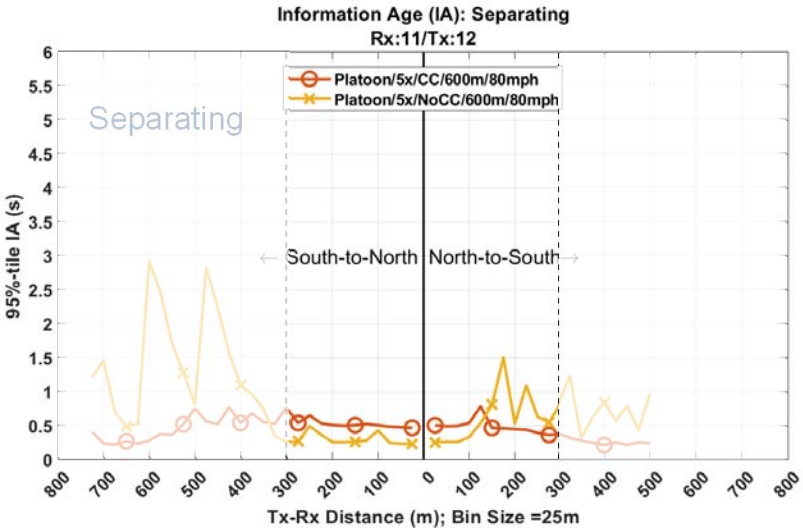


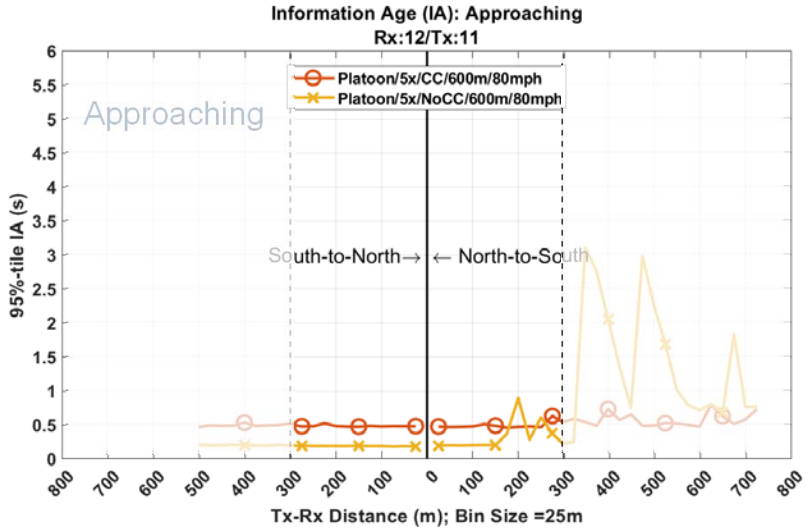
# IA – High Speed Test – 600m

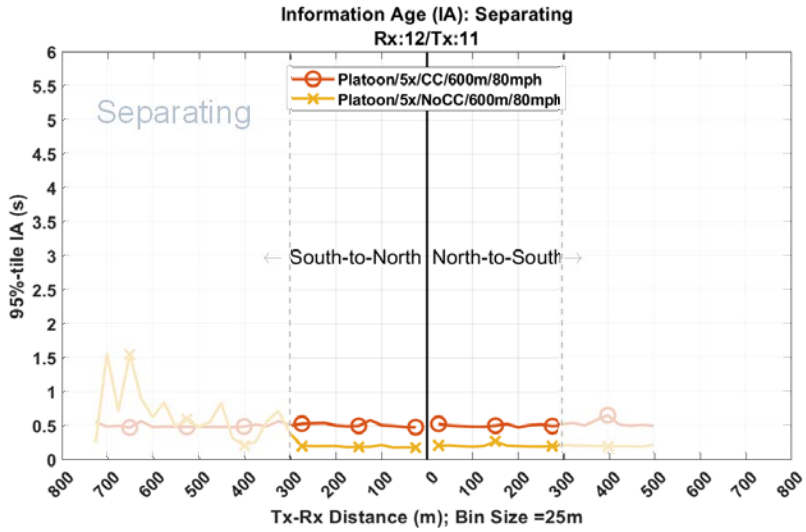
## Stationary Vehicle Receiving




## Moving Vehicle Receiving



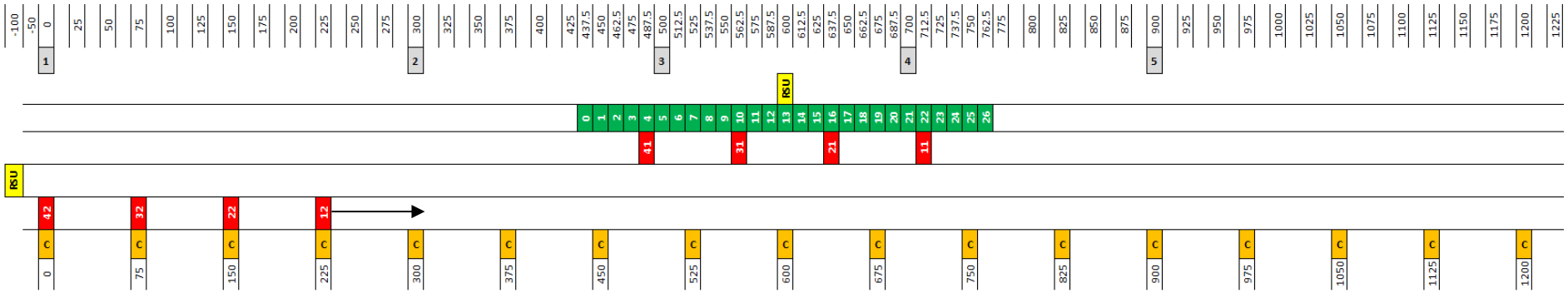



# High Speed Test

# Congestion Spread 300m
# Speed 80mph

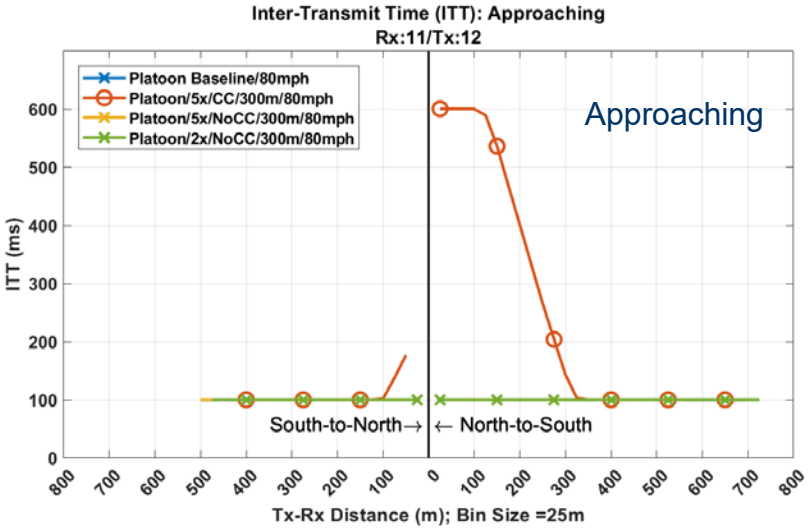
# Test Setup: High Speed Test, 300m

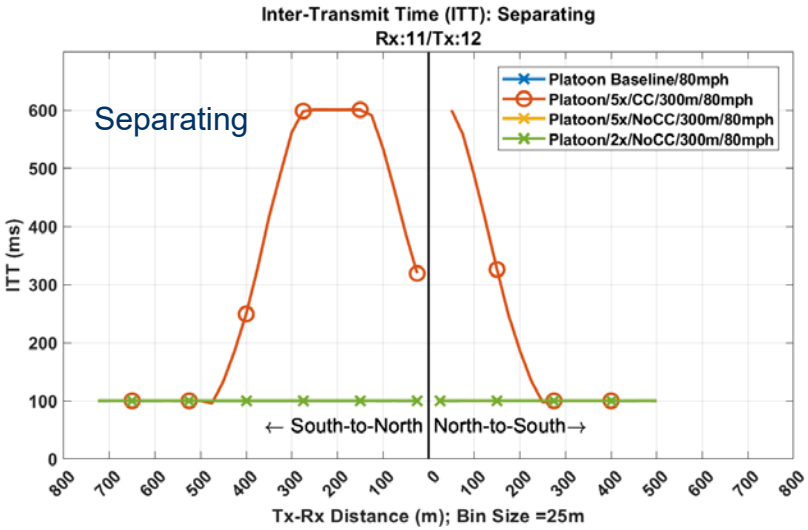
- Stationary OBEs: 11, 21, 31, 41
- Platoon OBEs: 12, 22, 32, 42
- Congestion Carts: 0-26 (start at 437.5m)
- Cart 13 at 600m (center of the test track)
- Results shown for (Vehicle 11,Vehicle 12) pair



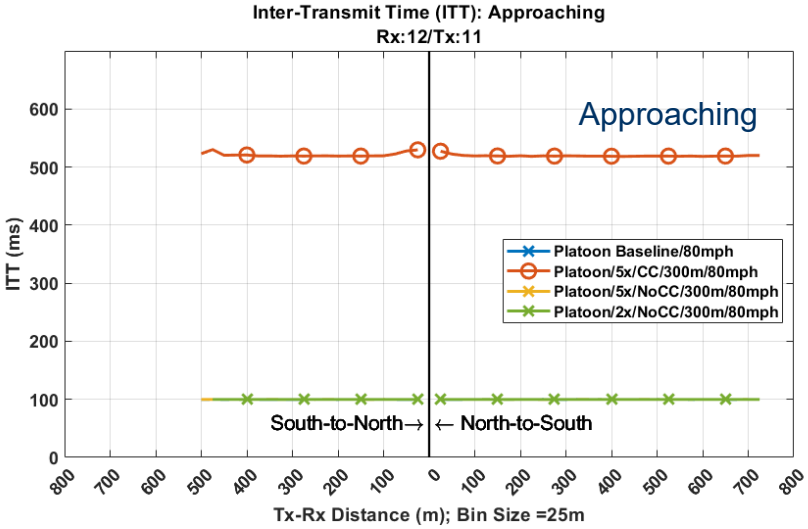
# ITT – High Speed Test – 300m

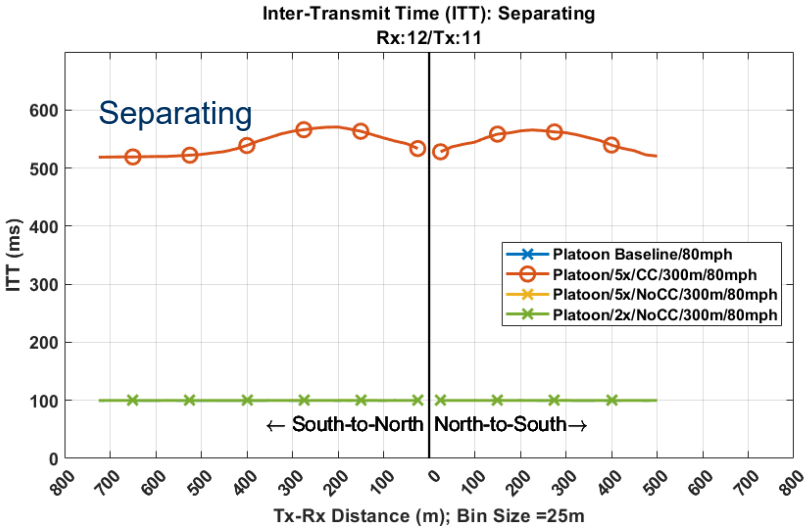
## Stationary Vehicle Receiving



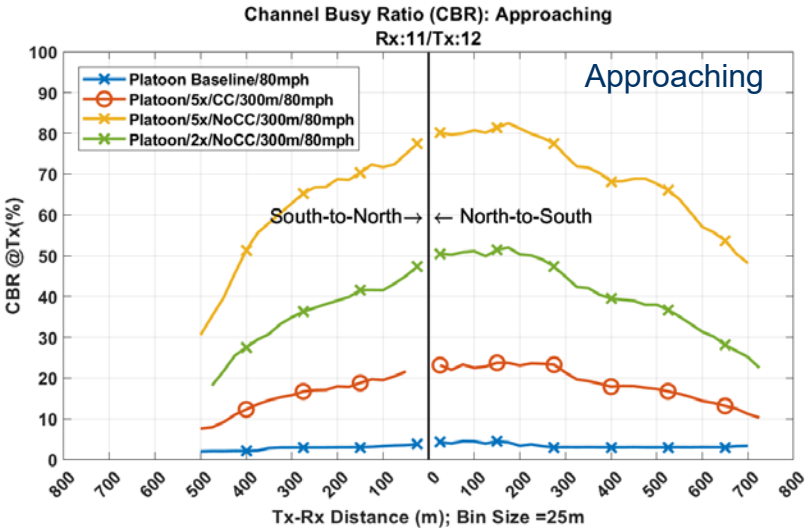

## Moving Vehicle Receiving

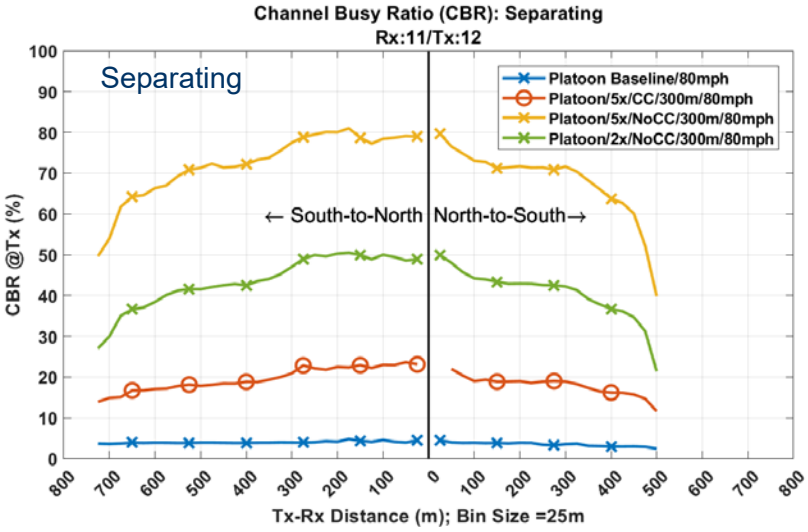


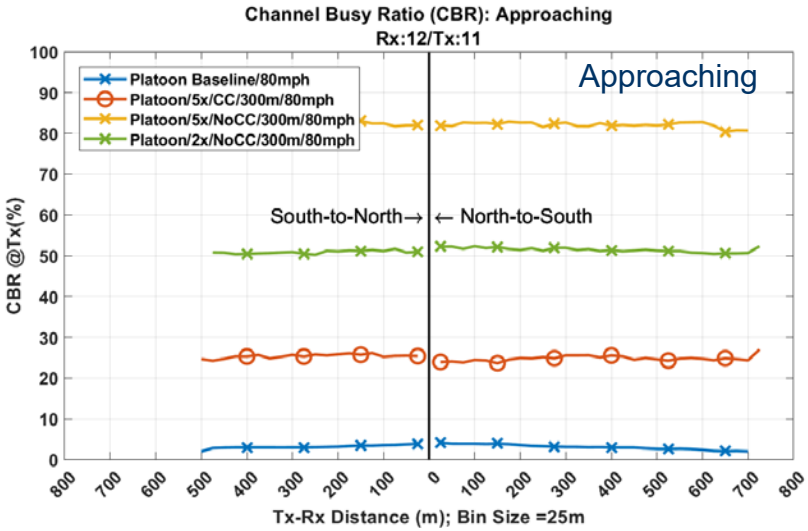
# CBR – High Speed Test – 300m

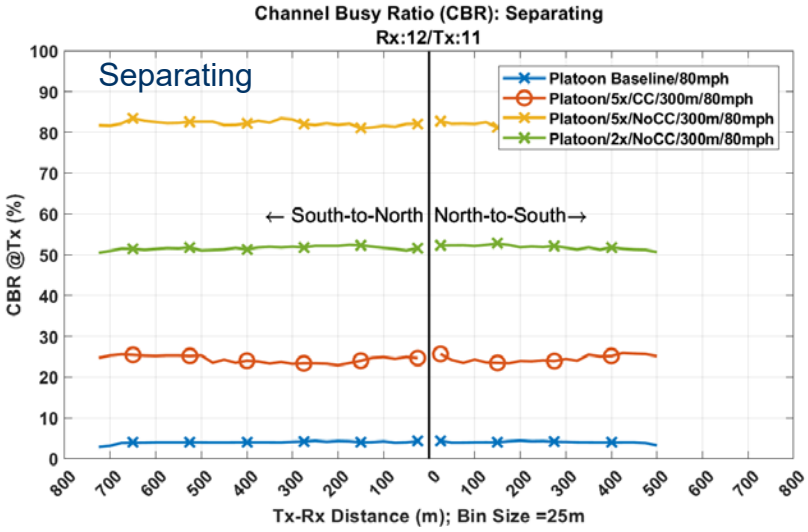
## Stationary Vehicle Receiving



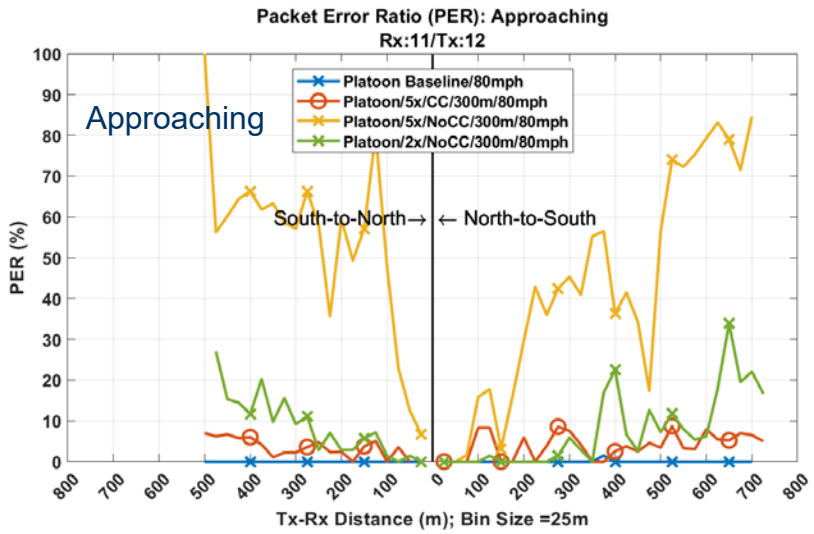

## Moving Vehicle Receiving

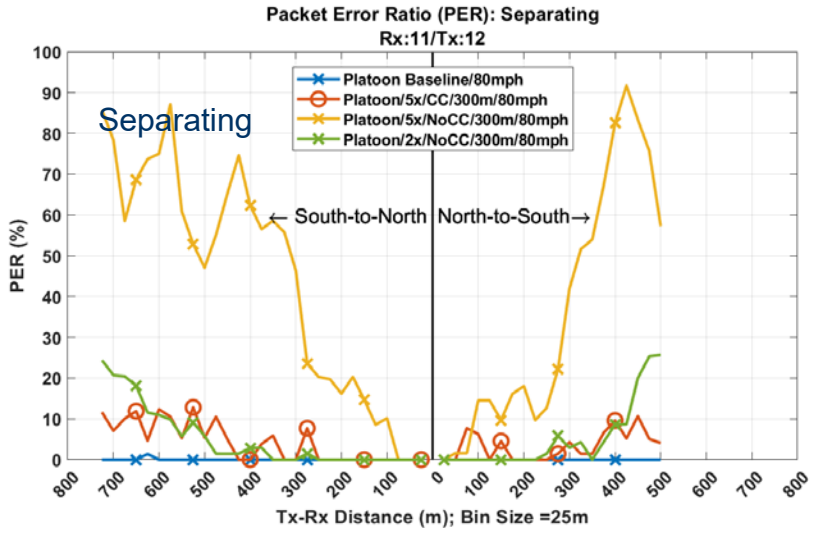


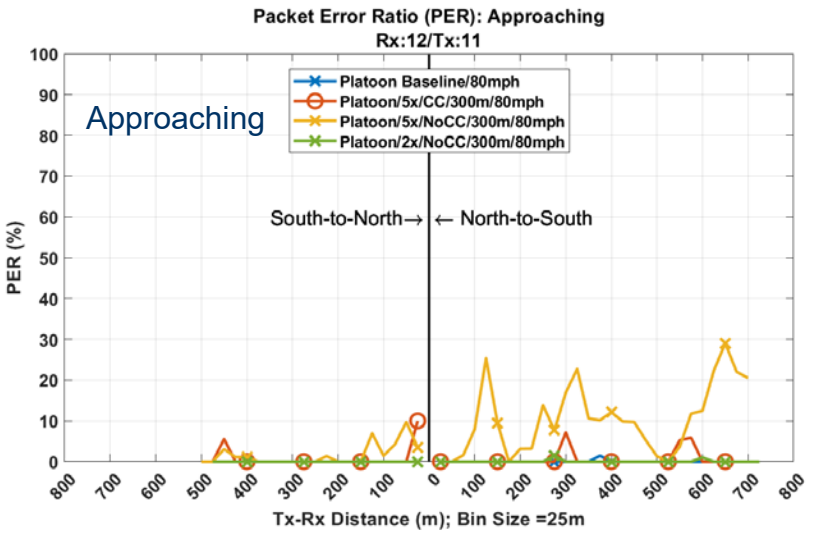
# PER – High Speed Test – 300m

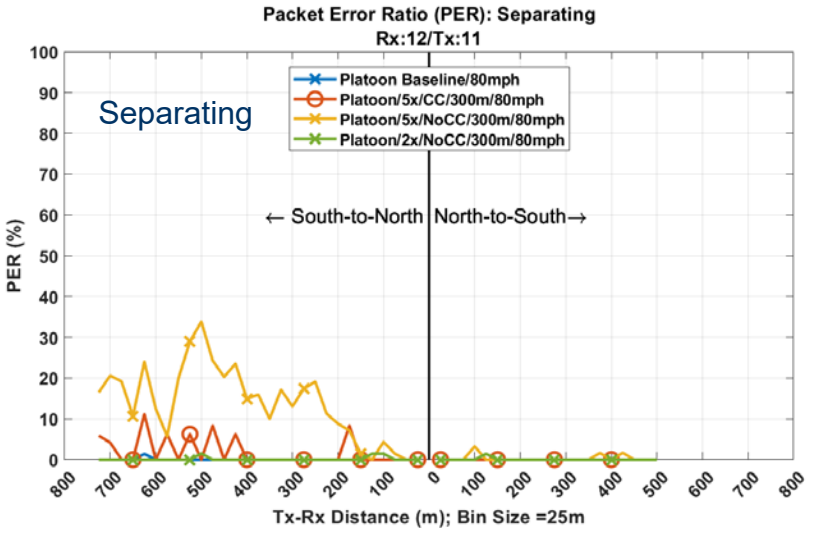
## Stationary Vehicle Receiving



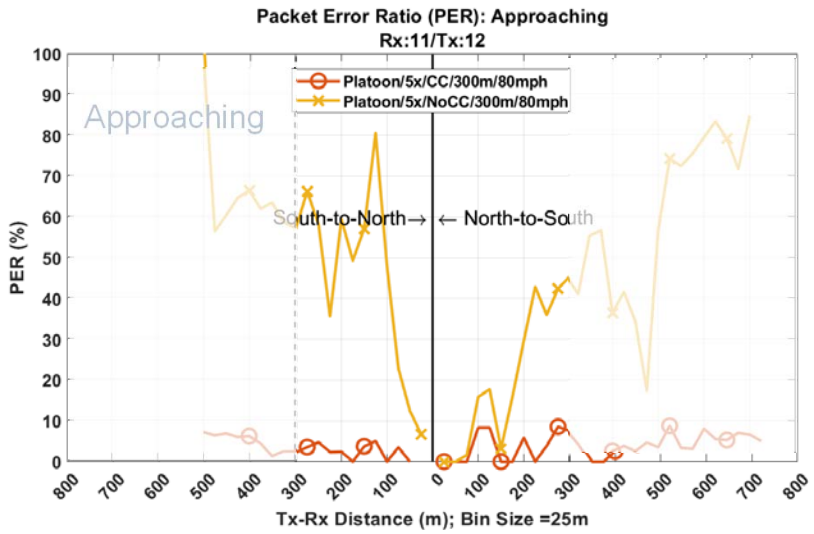

## Moving Vehicle Receiving

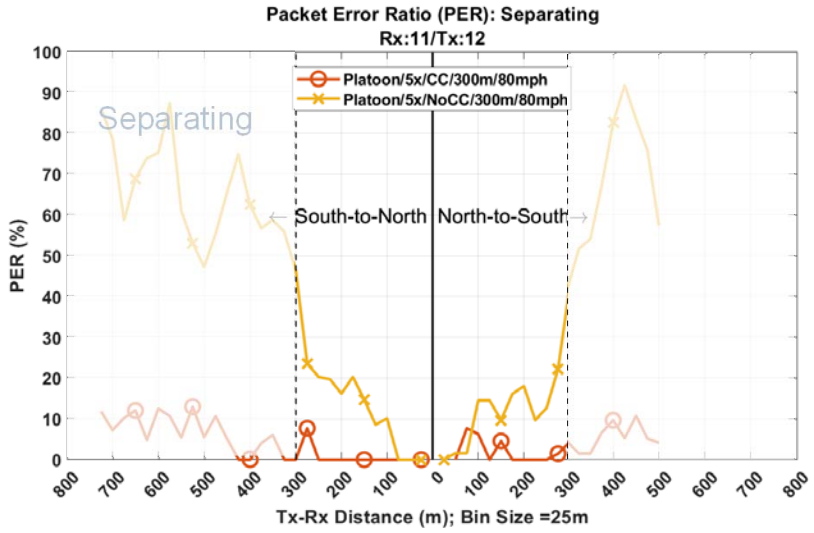


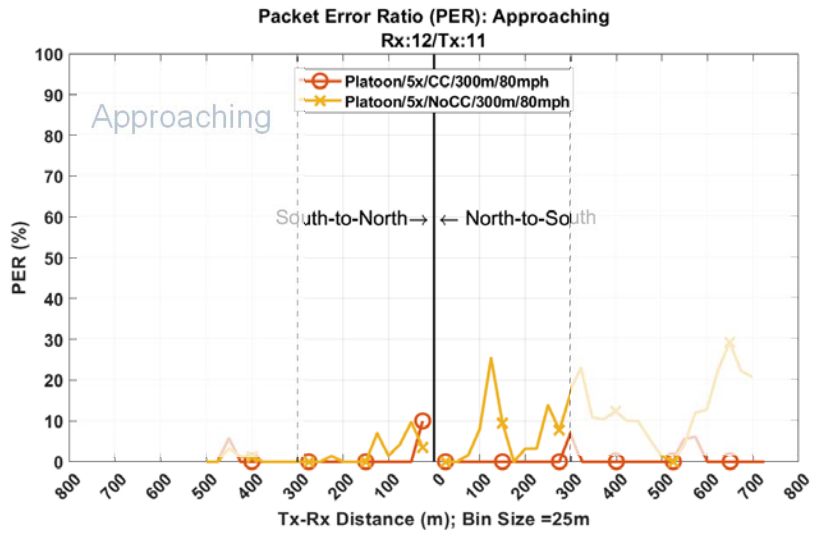
# PER – High Speed Test – 300m

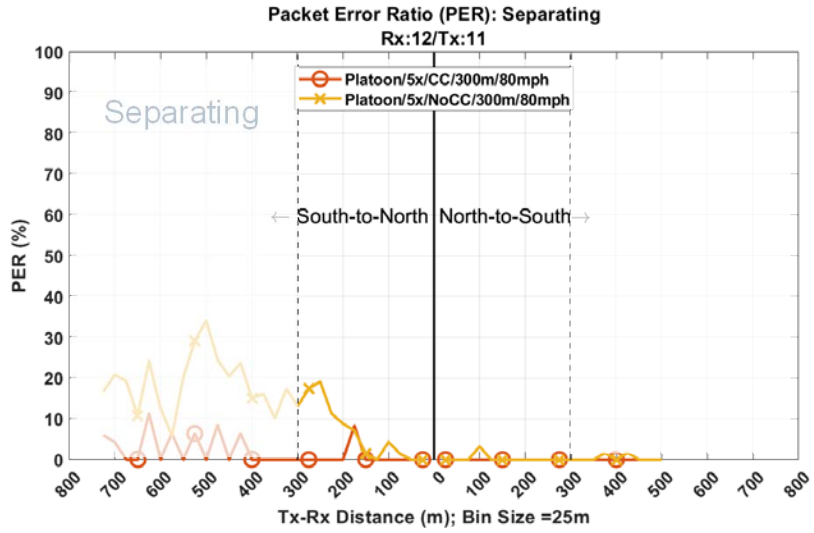
## Stationary Vehicle Receiving



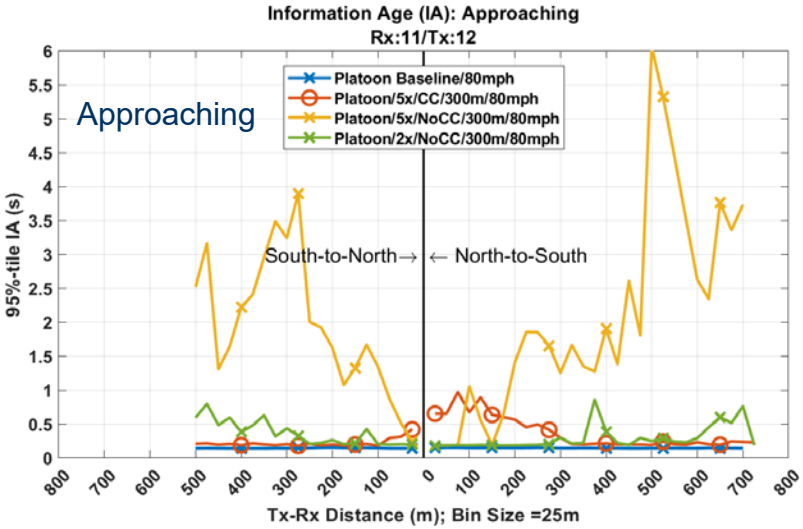

## Moving Vehicle Receiving

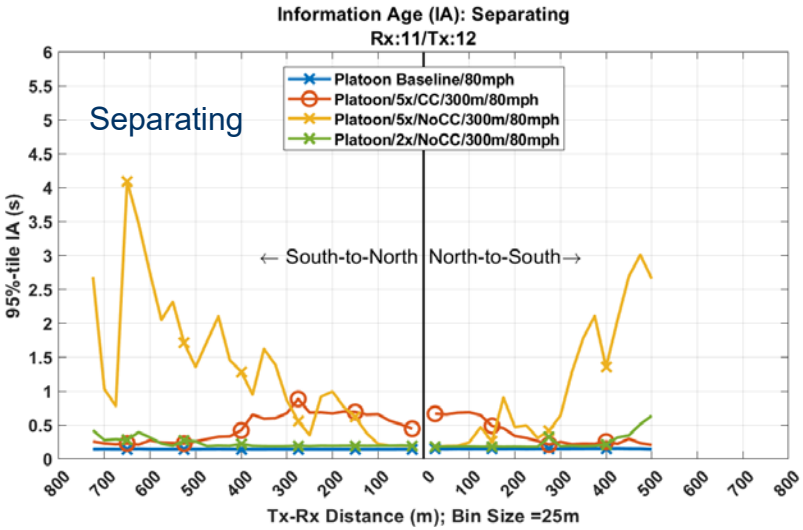


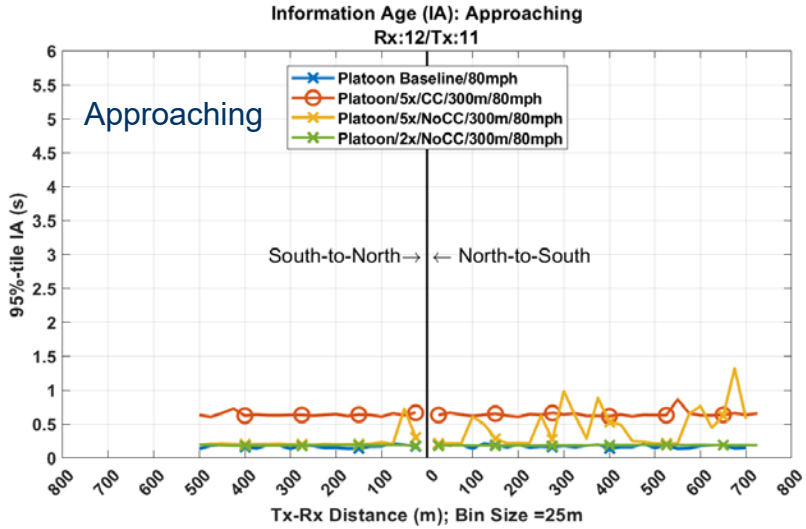
# IA – High Speed Test – 300m

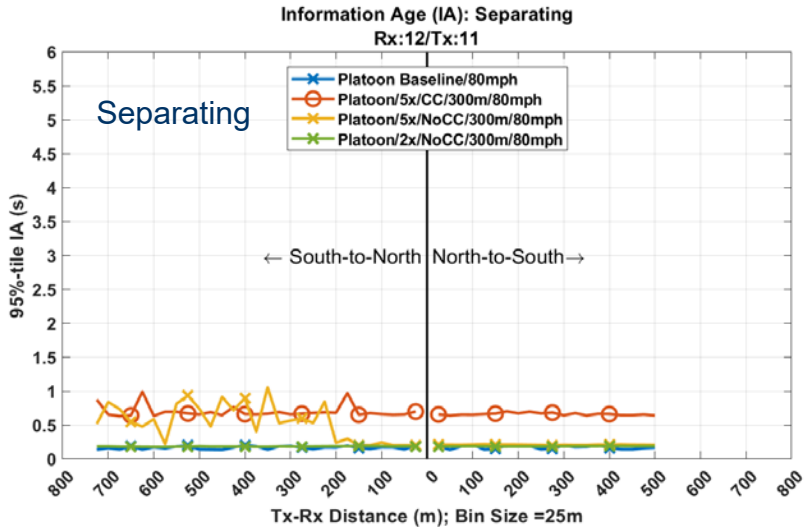
## Stationary Vehicle Receiving



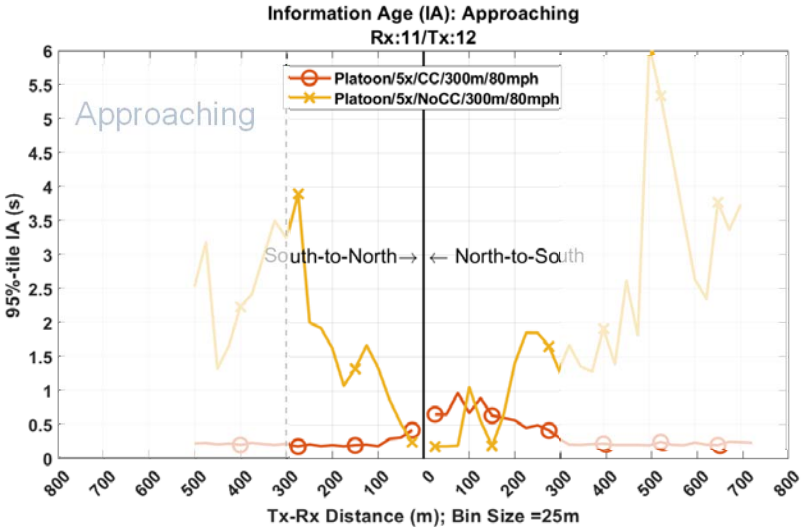

## Moving Vehicle Receiving

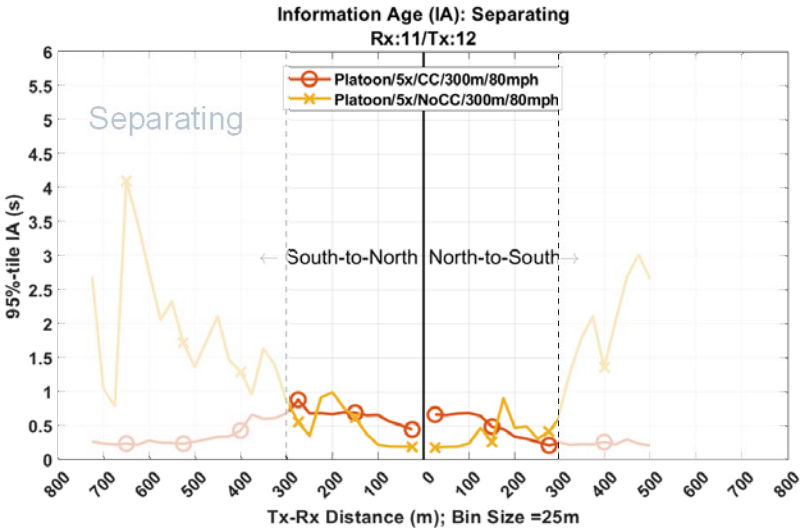


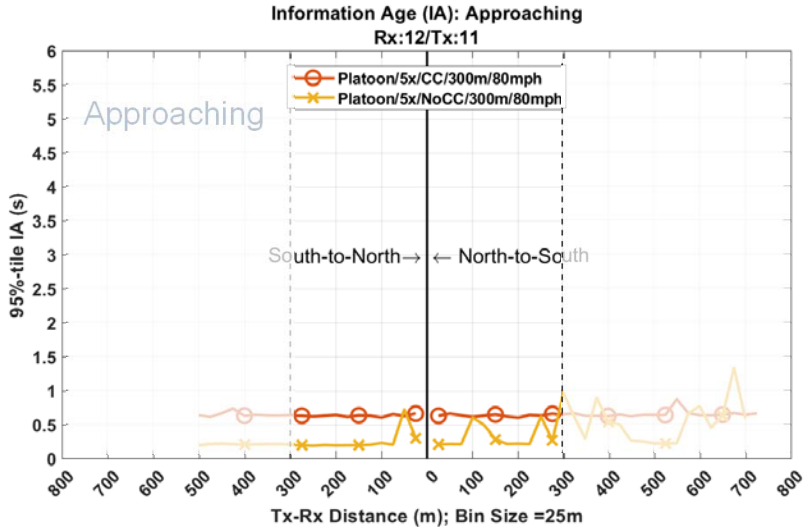
# IA – High Speed Test – 300m

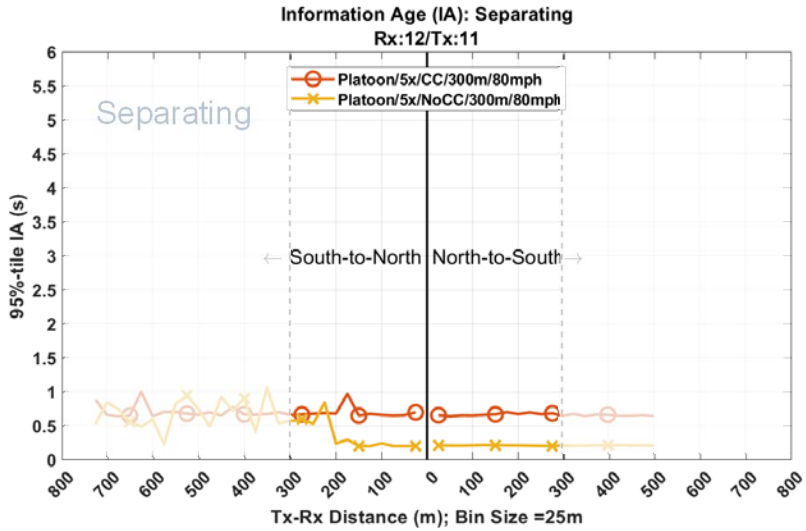
## Stationary Vehicle Receiving




## Moving Vehicle Receiving




# Congestion Test
# Critical Event Test

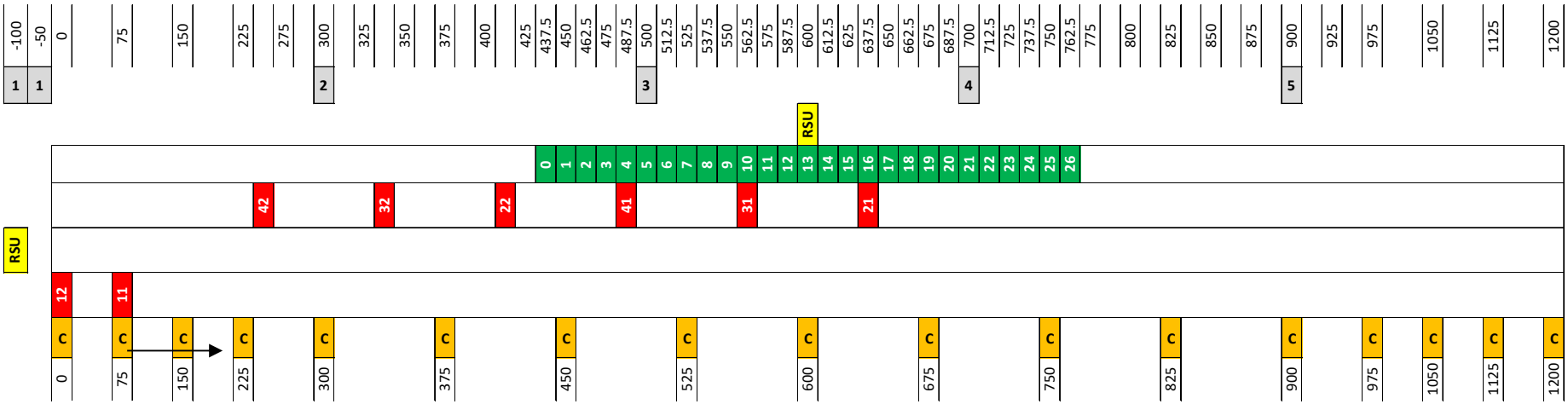
- 2 vehicle platoon, 55 mph, hard brake in the middle of the test track

# Critical Event Test

# Congestion Spread 300m
# Speed 55mph

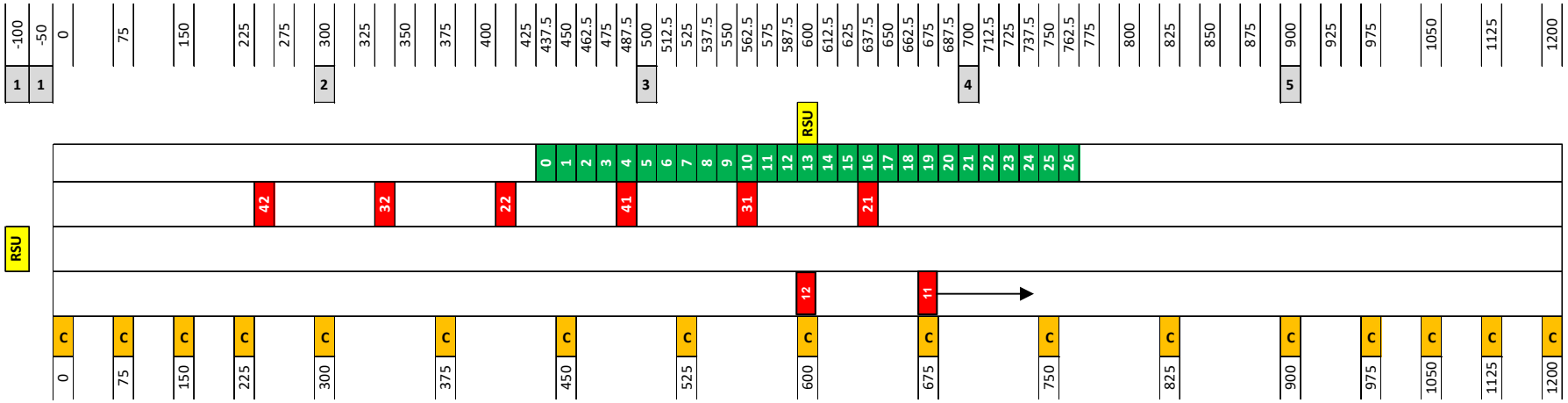
# Critical Event Test: 300m

- Stationary OBEs: 21, 31, 41, 22, 32, 42
- Platoon OBEs: 11, 12
- Congestion Carts: 0-26 (start at 437.5m)
- Cart 13 at 600m (center of the test track)



# Test Details: 300m

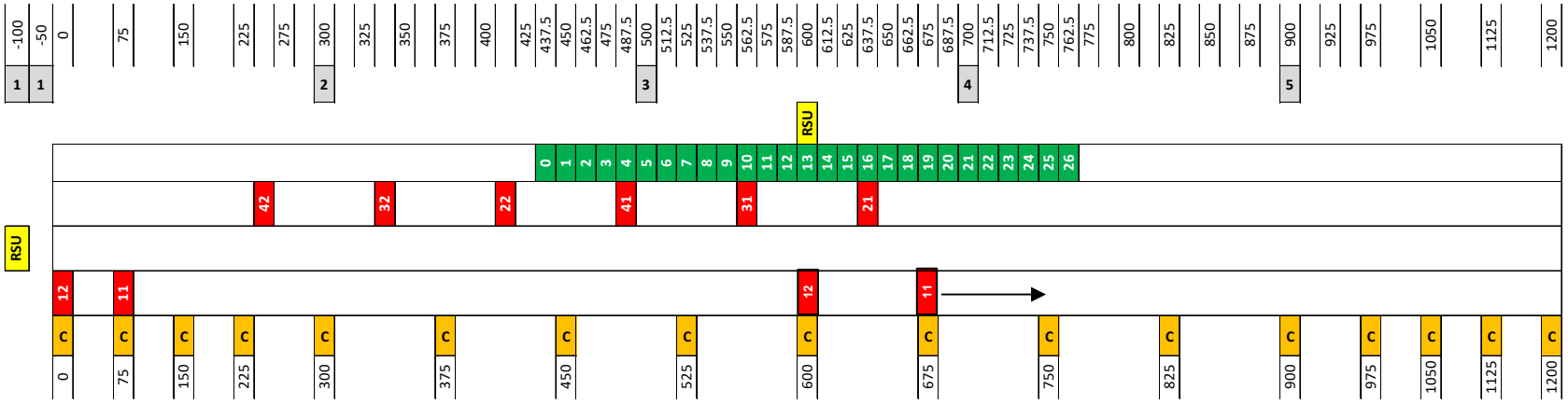
- In the North->South direction following vehicle (V12) brakes in the middle of the test track




- In the South->North vehicles swap order and vehicle 11 performs hard brake

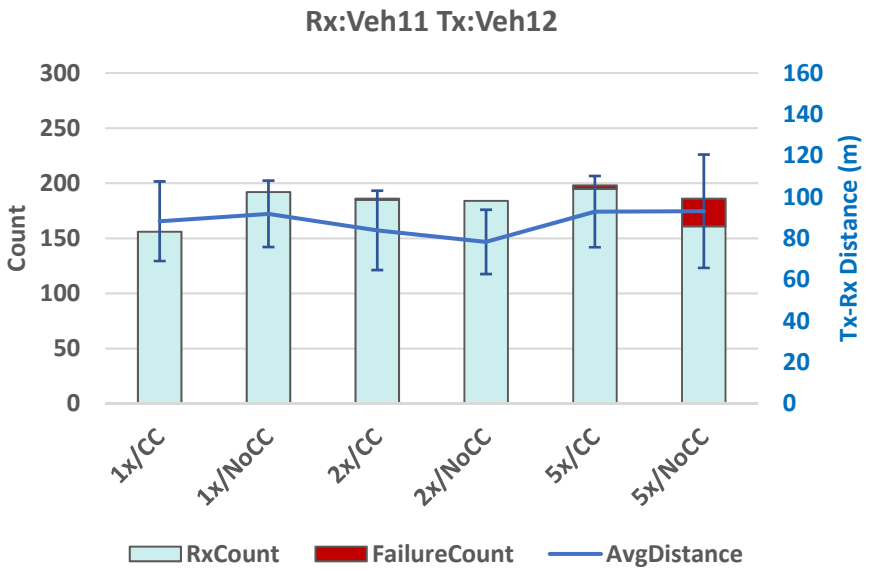
# Results Preview: 300m

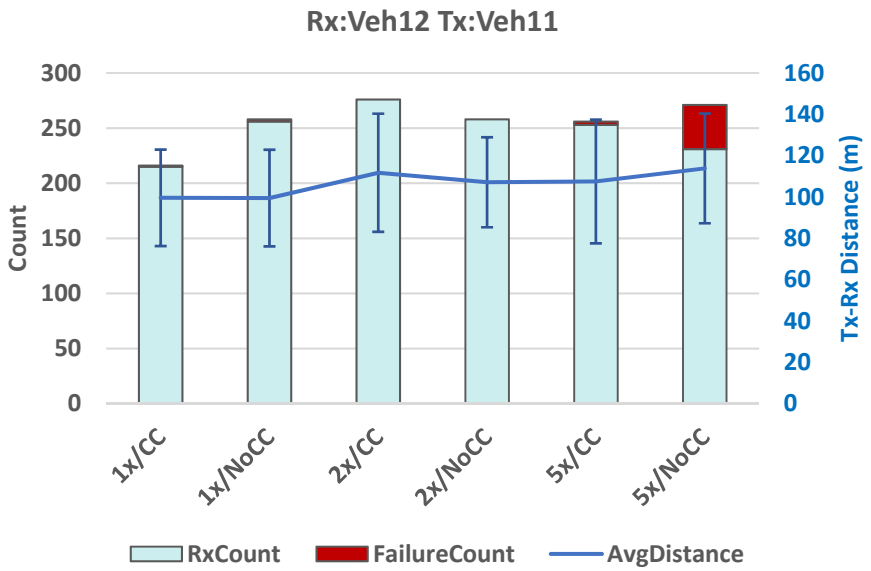
- We are showing results in two sets
- <u>Set 1</u>
  - Count of packets transmitted and failed between Vehicle 11 and Vehicle 12
- <u>Set 2</u>
  - Count of packets transmitted from either or Vehicle 11 and Vehicle 12 and received by the stationary vehicles 21, 31, 41, 22, 32, and 42
- For each set we vary the offered load and turn CC on/off



# Critical Event – 300m / 55mph

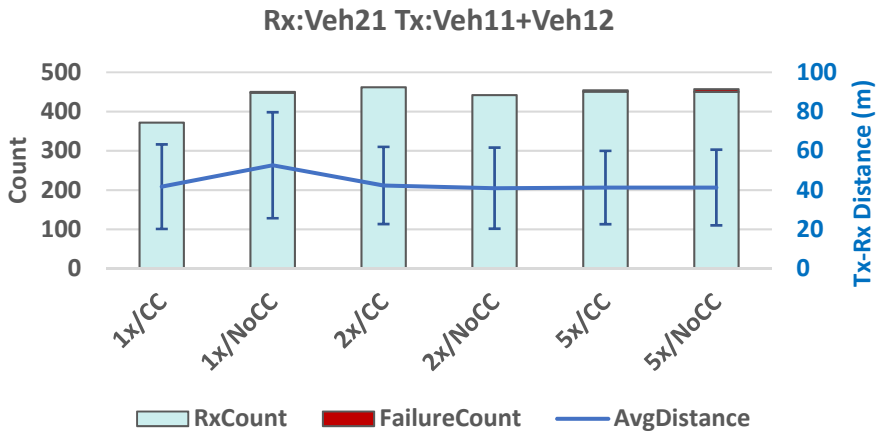
## Moving Vehicle Receiving From Hard Braking Transmitter Vehicle

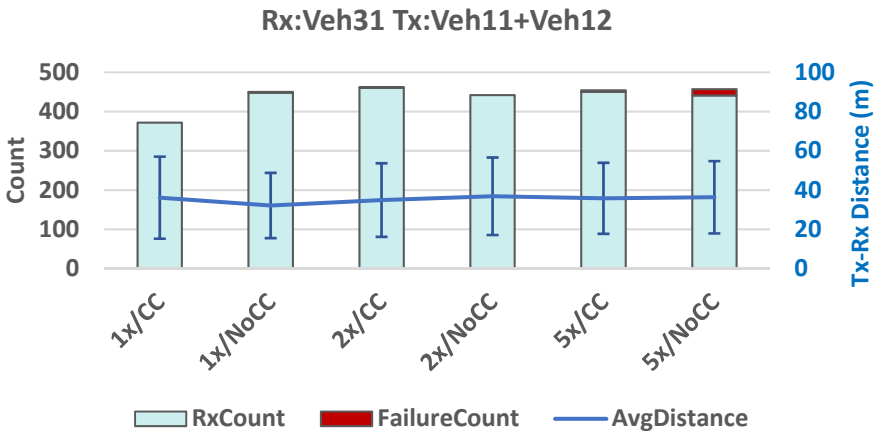


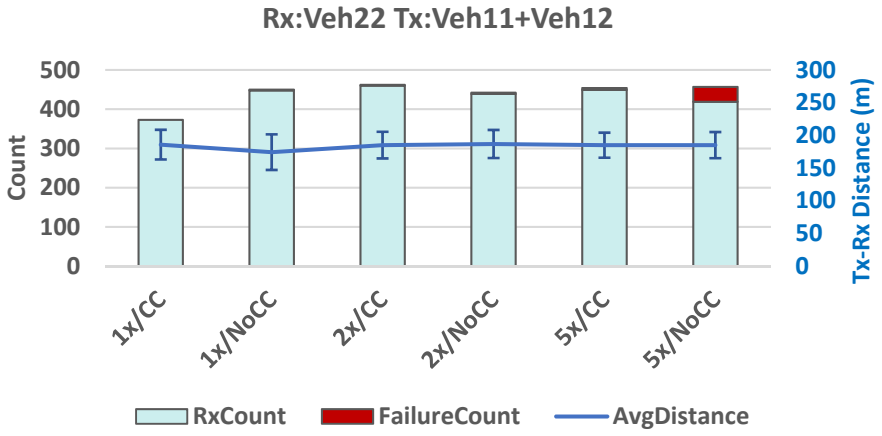



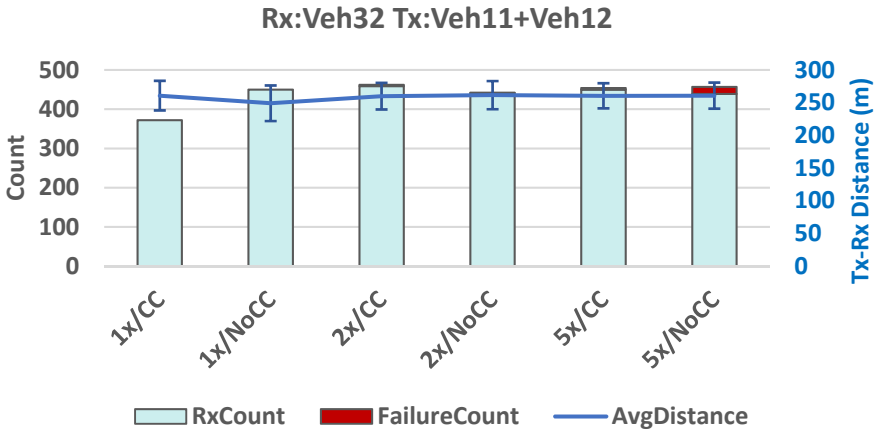
# Critical Event – 300m / 55mph

## Stationary Vehicle Receiving From Hard Braking Transmitter Vehicle



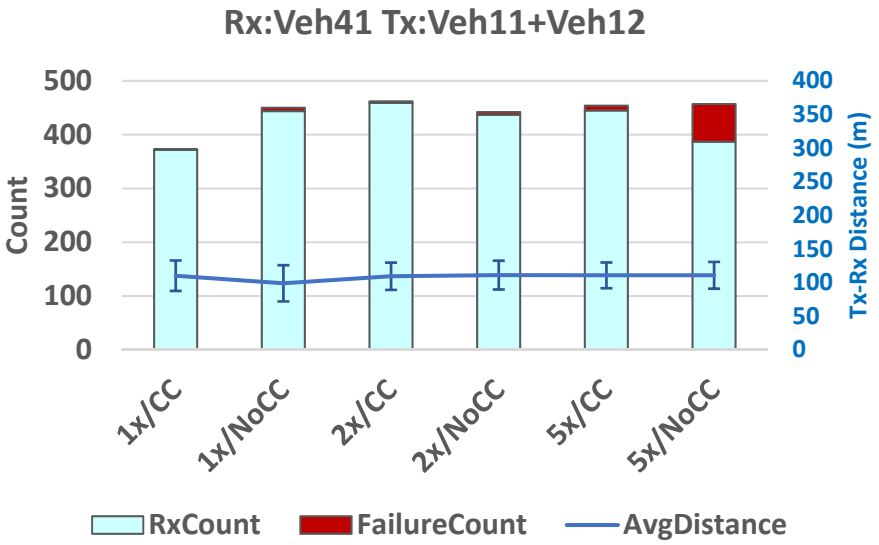



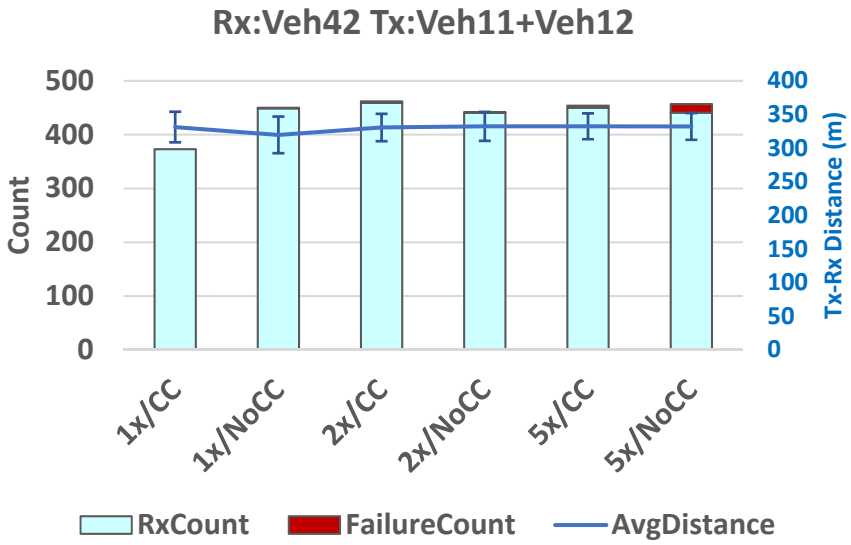



# Critical Event – 300m / 55mph

## Stationary Vehicle Receiving From Hard Braking Transmitter Vehicle



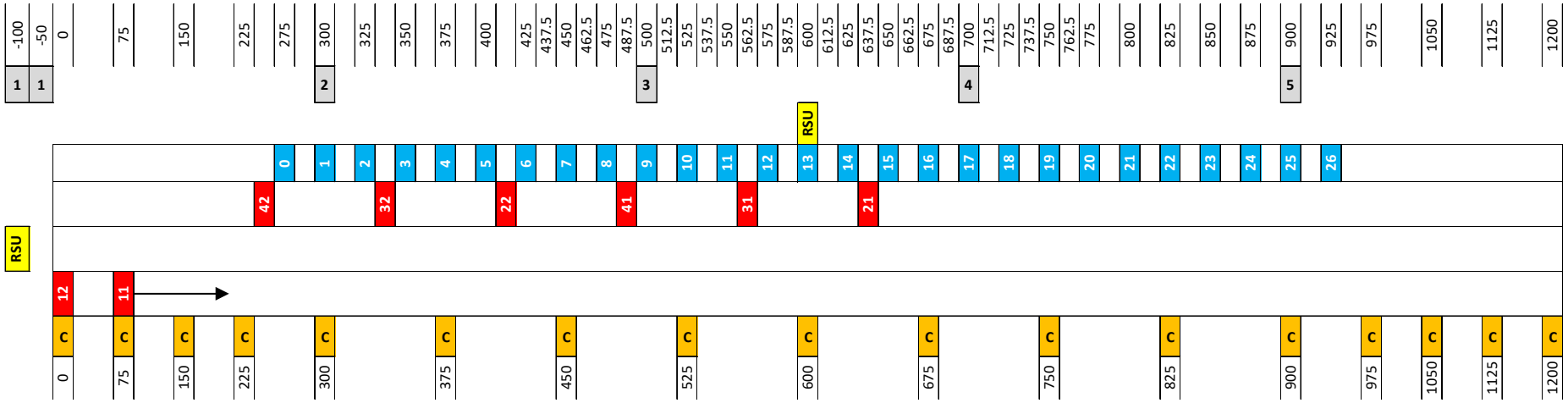



# Critical Event Test

# Congestion Spread 600m
# Speed 55mph

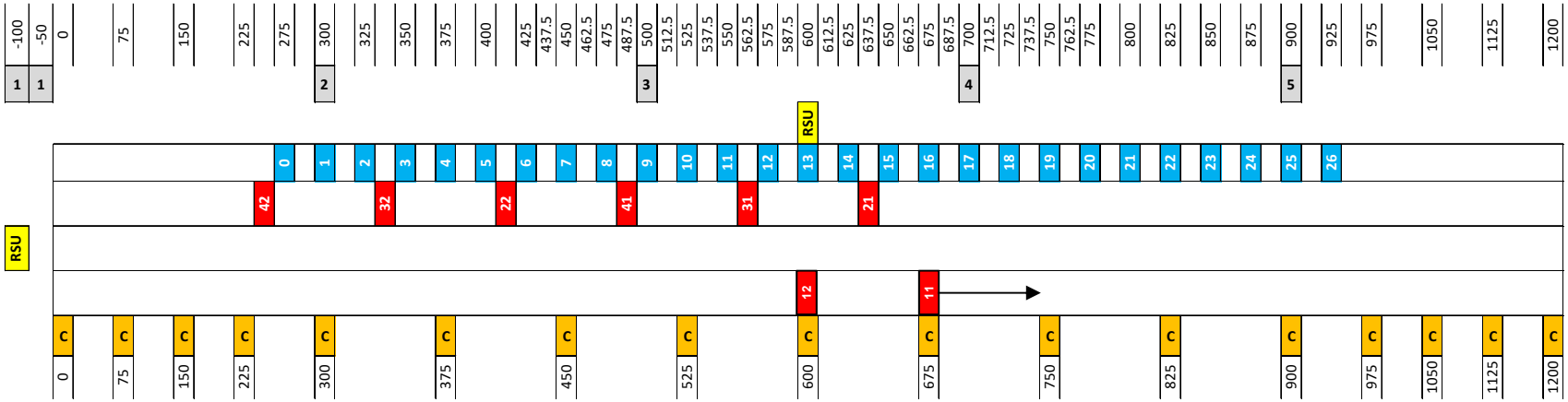
# Critical Event Test: 600m

- Stationary OBEs: 21, 31, 41, 22, 32, 42
- Platoon OBEs: 11, 12
- Congestion Carts: 0-26 (start at 275m)
- Cart 13 at 600m (center of the test track)



# Test Details: 600m

- In the North->South direction following vehicle (V12) brakes in the middle of the test track




- In the South->North vehicles swap order and vehicle 11 performs hard brake

# Results Preview: 600m

- We are showing results in two sets
- <u>Set 1</u>
  - Count of packets transmitted and failed between Vehicle 11 and Vehicle 12
- <u>Set 2</u>
  - Count of packets transmitted from either or Vehicle 11 and Vehicle 12 and received by the stationary vehicles 21, 31, 41, 22, 32, and 42
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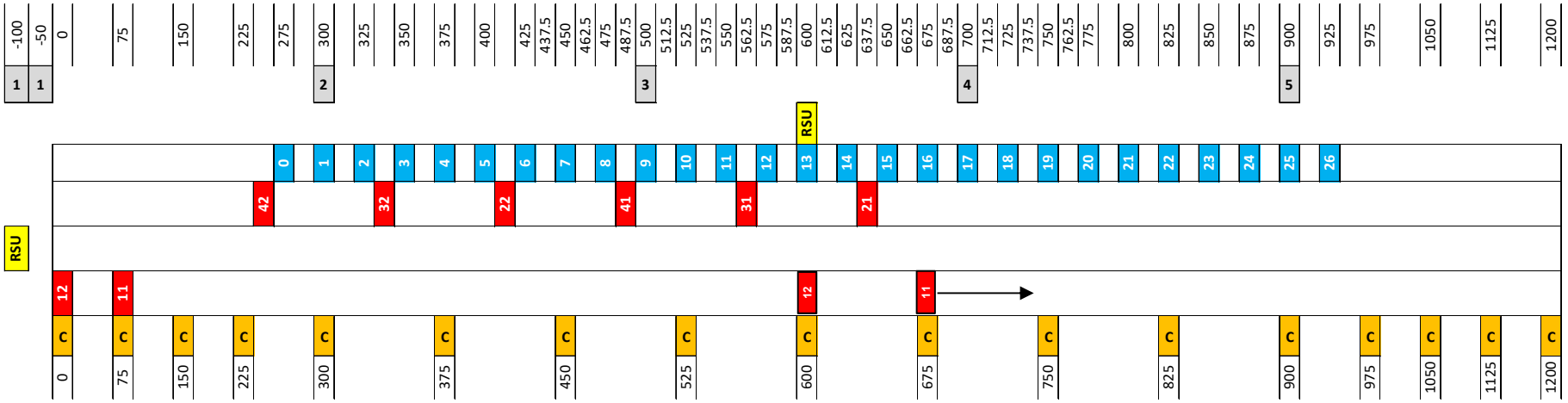
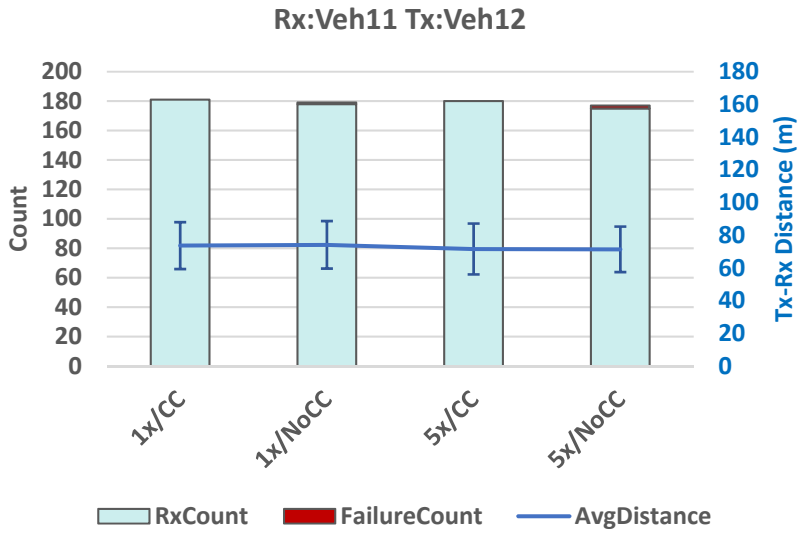
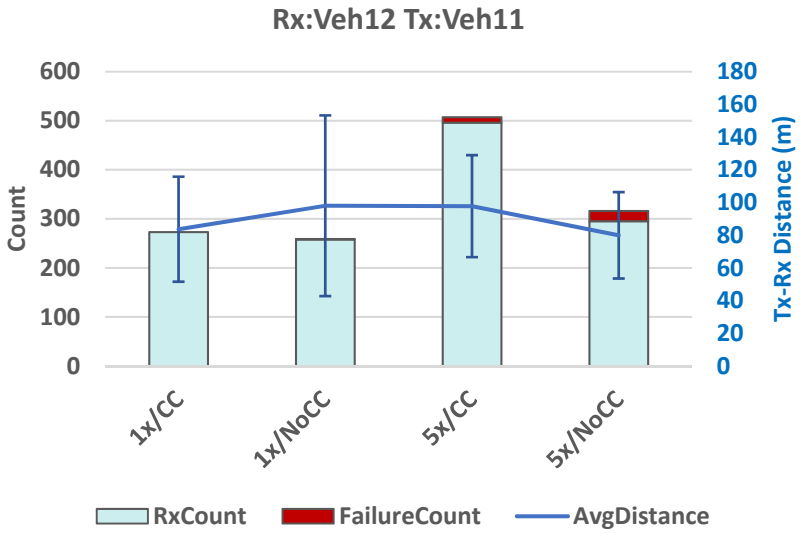


# Critical Event – 600m / 55mph

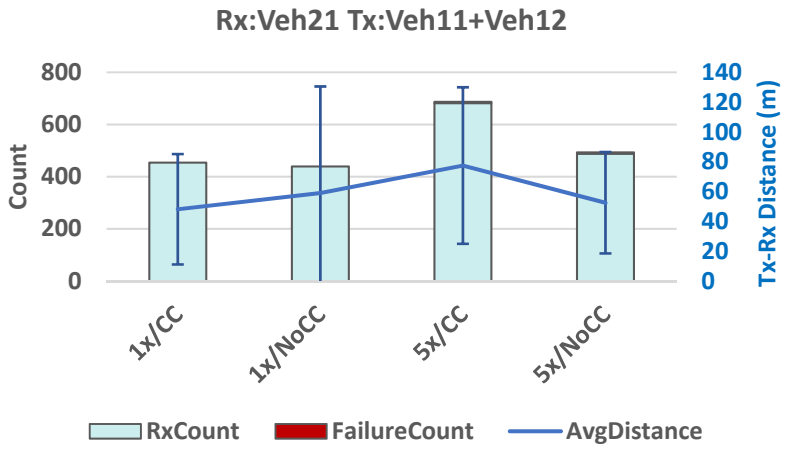
## Moving Vehicle Receiving From Hard Braking Transmitter Vehicle

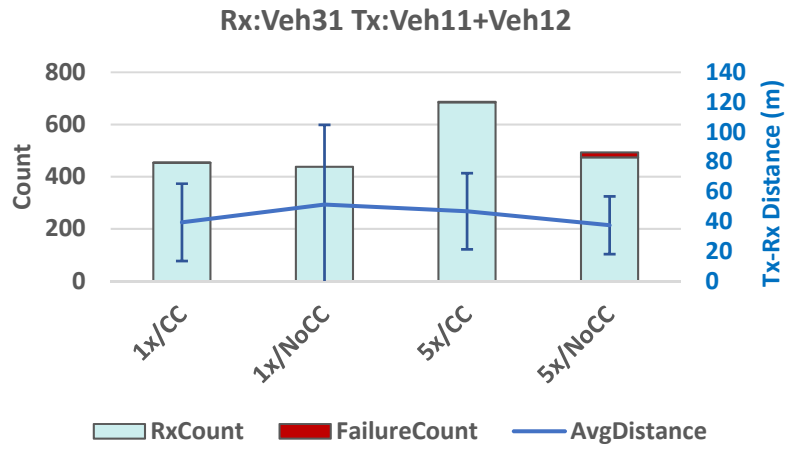


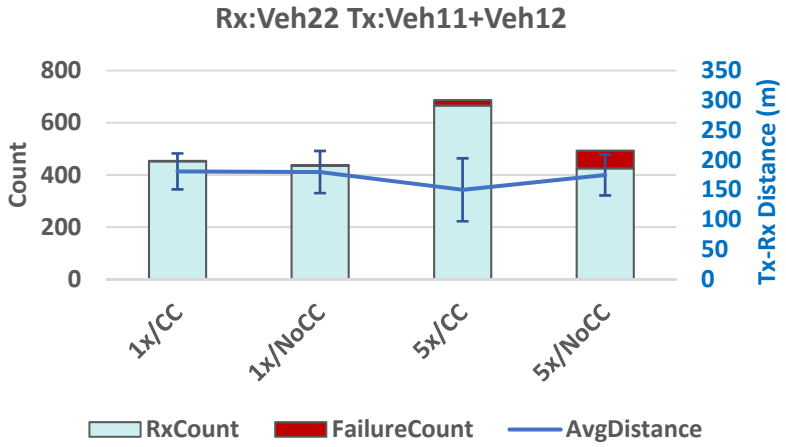



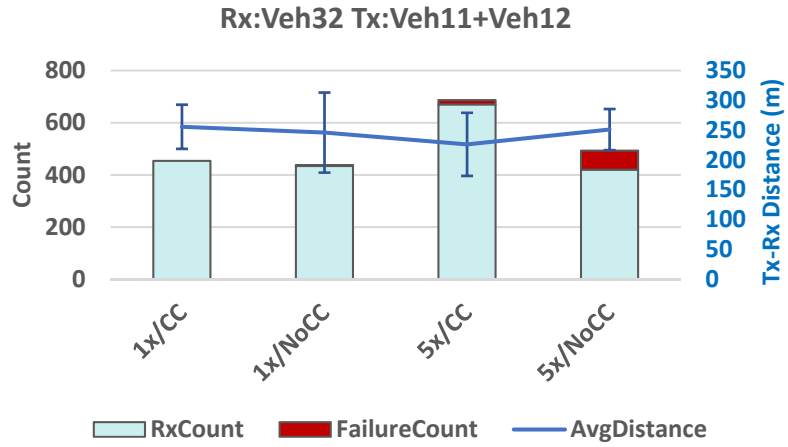
# Critical Event – 600m / 55mph

## Stationary Vehicle Receiving From Hard Braking Transmitter Vehicle



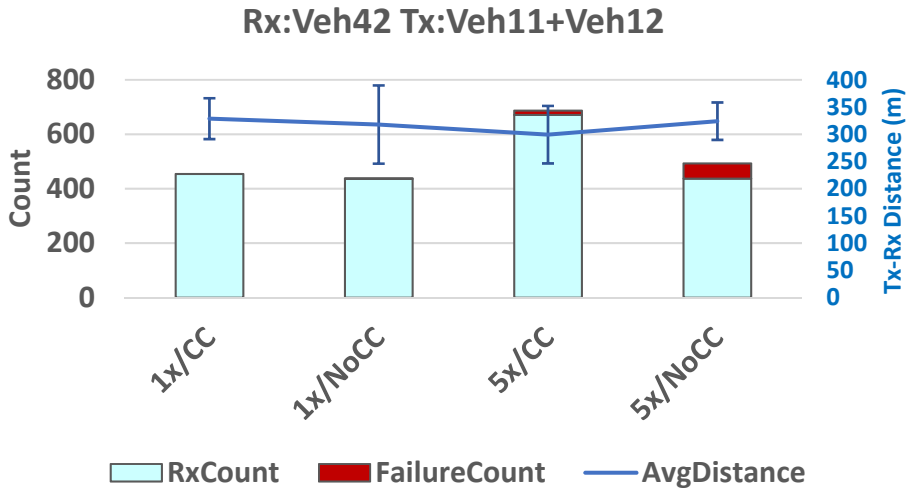



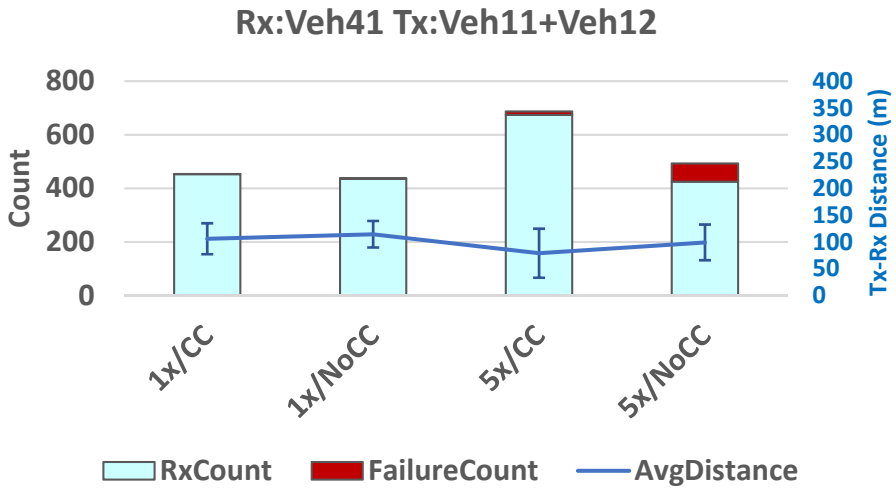



# Critical Event – 600m / 55 mph

## Stationary Vehicle Receiving From Hard Braking Transmitter Vehicle



# Summary and Discussion

# KPI Summary

## Max PER and max (95 per IA) <=300m(*)

| Test Scenarios | CC OFF | | CC ON | |
|---|---|---|---|---|
| | PER | IA | PER | IA |
| 5X emulation , 20 mph,1200m | 30% | 1.1s | <10% | 400ms |
| 5X emulation , 20 mph, 600m | 70%(**) | 2.1s | <10% | 900ms |
| 5X emulation , 80 mph, 600m | 40%(**) | 1.5s | 10% | 600ms |
| 5X emulation , 20 mph, 300m | 77% | 3s | 10% | 1s |
| 5X emulation , 80 mph, 300m | 80% | 4s | 10% | 1s |

(*) The maximum measured values in the 300m range were used in this table
(**) 80mph uses more robust MCS which could cause PER inversion

# Objective Testing Observations

- Device characterization confirms device meets 3GPP and FCC class C requirements
- Bench testing with Cabled and “Last Link Wireless” tests shows:
  - Good Receive Sensitivity (i.e. -105 dBm for 200B with 10 MHz, HARQ, 2Rx; -104 dBm for 200B with 20 MHz, HARQ, 2Rx )
  - Average Inter-Packet-Gap (IPG) is about 100 ms
  - 95% Latency is ~30ms for 200B payload
- Based on controlled vehicle re-testing with few vehicles, transmit power of 20 dBm, HARQ on, 20 MHz BW
  - one Tx and one Rx (no receive diversity) shows good LOS performance
  - one Tx and two Rx (diversity) shows good NLOS performance (recommended)
- Based on mixed traffic vehicle re-testing, with transmit power of 20 dBm, HARQ on, 20 MHz BW, C-V2X shows good communication performance in mixed real-world traffic
- Based on congestion testing with the equivalent load of up to 260 OBEs on a stretch of road of length 1.3 km C-V2X communication performance was shown
  - To perform reliably when CC is turned on for offered load conditions greater than 100%
  - To have predictable performance based on observed basic KPIs (e.g., Max_ITT)
  - To have graceful performance degradation up to and beyond 100% offered load

# OBU Modem Parameters Recommendations

| | 20 MHz | | | | 10 MHz | | | |
|---|---|---|---|---|---|---|---|---|
| | Speed < 120kmph | | Speed > 120kmph | | Speed < 120kmph | | Speed > 120kmph | |
| Packet Size | MCS | Num Sub Channels | MCS | Num Sub Channels | MCS | Num Sub Channels | MCS | Num Sub Channels |
| 200 | 6 | 2 | 6 | 2 | 6 | 2 | 6 | 2 |
| 365 | 11 | 2 | 7 | 3 | 11 | 2 | 7 | 3 |
| 400 | 5 | 5 | 4 | 5 | 5 | 5 | 4 | 5 |
| 1000 | 5 | 10 | 5 | 10 | 11 | 5 | 5 | 5 |
| 1400 | 7 | 10 | 7 | 10 | 7 | 5 | 7 | 5 |

Sub-Channel Size = 10 RB

Note: The tabulated parameters were used for the congestion testing and represent the final recommendation of the project. The parameters are subject to change pending future implementations and/or standards recommendations.