



# C-V2X Performance Assessment Project

December 5, 2019

# Project Overview / Status

Note: For the purposes of this presentation,  
“Platoon” refers to a String of Vehicles.

# 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

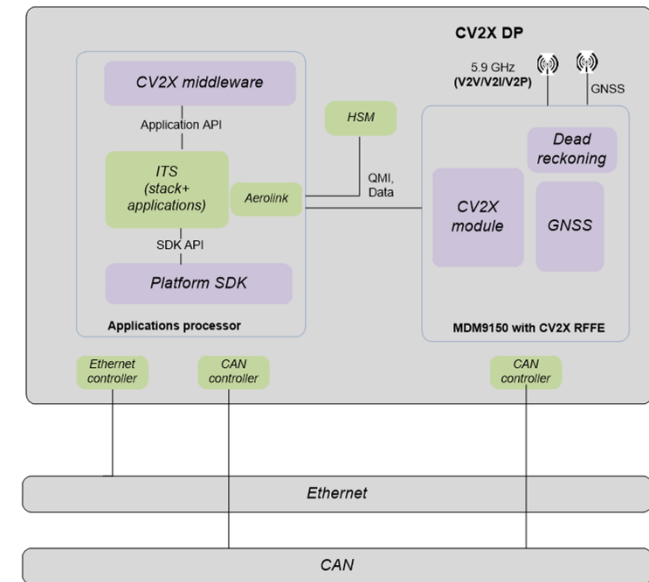
# C-V2X Development Platform (RRv1)

- 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

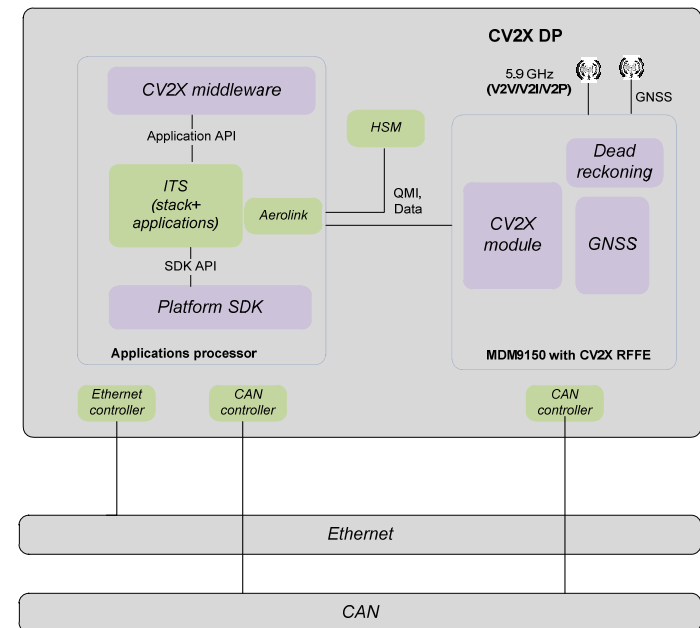
- Description

- 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



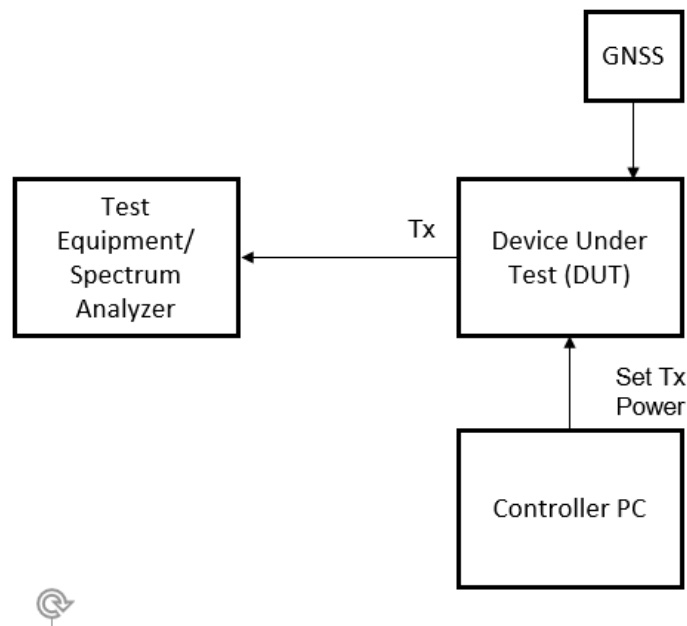
# C-V2X Development Platform (RRv1)

Component	Description
Processor	Automotive Snapdragon820 (APQ8996) 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 Qualcomm QDR3 Dead Reckoning 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 - Wi-Fi: 2.4 GHz, 802.11n, 2 x 2 - Bluetooth 4.2 + BLE



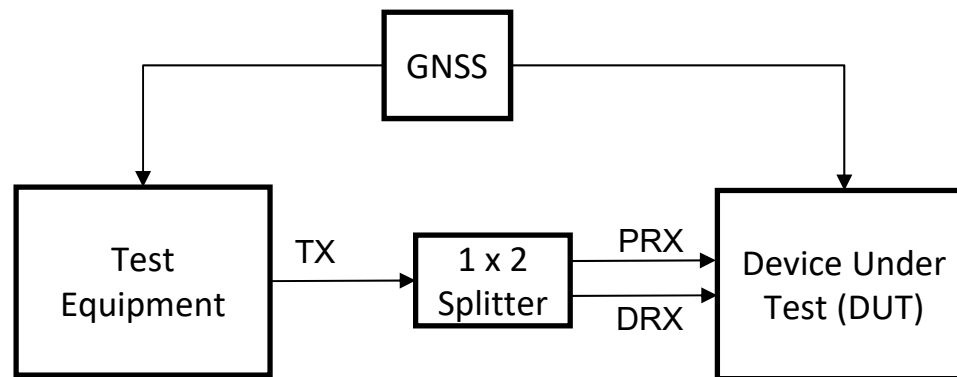
# Transmit Power Accuracy

- 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

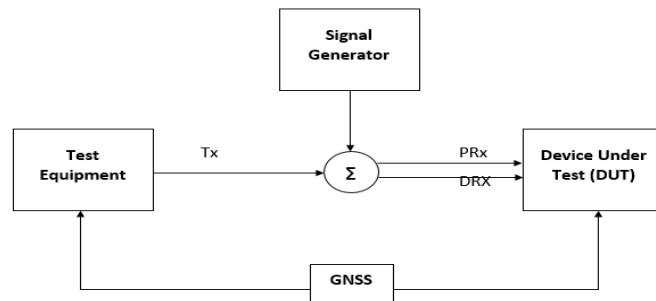
# TX Spectrum Emissions Mask – 10 MHz CH 184

- 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



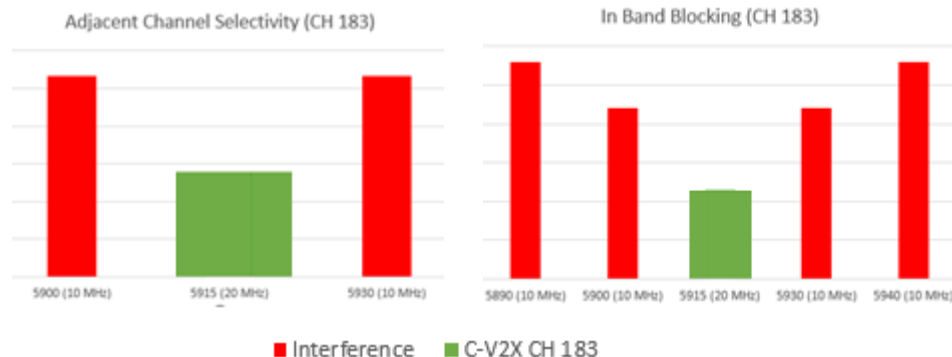
# Adjacent Channel Selectivity and In Band Blocking

- 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



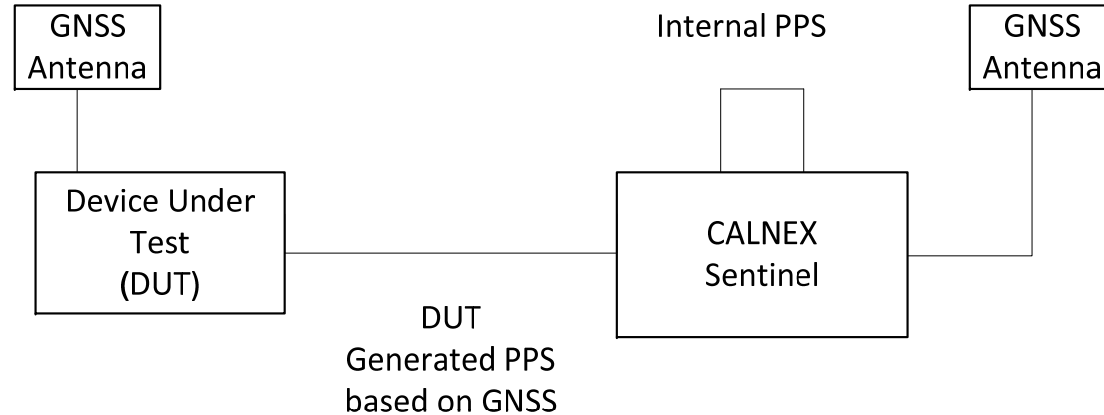
## Results Summary

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



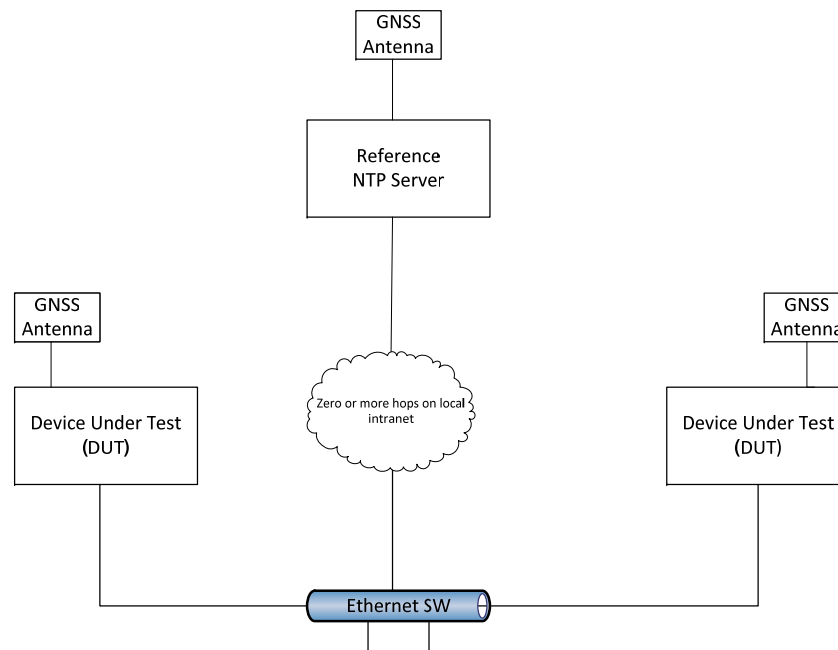
# Timing for C-V2X Transmission Synchronization (Open Sky)

- Allowed Timing Error  $\pm 391\text{ns}$
- Result : Pass. Measured timing error is always less than  $\pm 391\text{ns}$



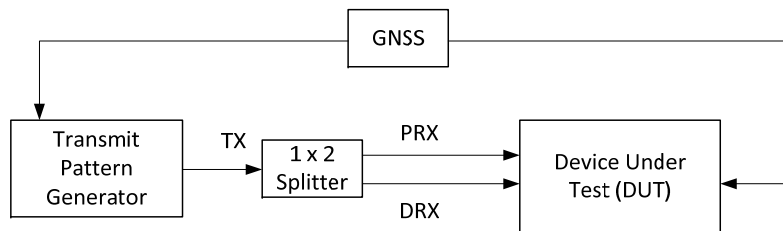
# System Clock Accuracy

- 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
<b>SC1</b>	SC1	<b>SC1</b>	SC1	<b>SC1</b>	SC1	<b>SC1</b>	SC1	<b>SC1</b>	<b>SC1</b>
<b>SC2</b>	SC2	<b>SC2</b>	SC2	<b>SC2</b>	SC2	<b>SC2</b>	SC2	<b>SC2</b>	<b>SC2</b>
<b>SC3</b>	SC3	<b>SC3</b>	SC3	<b>SC3</b>	SC3	<b>SC3</b>	SC3	<b>SC3</b>	<b>SC3</b>
<b>SC4</b>	SC4	<b>SC4</b>	SC4	<b>SC4</b>	SC4	<b>SC4</b>	SC4	<b>SC4</b>	<b>SC4</b>
<b>SC5</b>	SC5	<b>SC5</b>	SC5	<b>SC5</b>	SC5	<b>SC5</b>	SC5	<b>SC5</b>	<b>SC5</b>
<b>SC6</b>	SC6	<b>SC6</b>	SC6	<b>SC6</b>	SC6	<b>SC6</b>	SC6	<b>SC6</b>	<b>SC6</b>
<b>SC7</b>	SC7	<b>SC7</b>	SC7	<b>SC7</b>	SC7	<b>SC7</b>	SC7	<b>SC7</b>	<b>SC7</b>
<b>SC8</b>	SC8	<b>SC8</b>	SC8	<b>SC8</b>	SC8	<b>SC8</b>	SC8	<b>SC8</b>	<b>SC8</b>
<b>SC9</b>	SC9	<b>SC9</b>	SC9	<b>SC9</b>	SC9	<b>SC9</b>	SC9	<b>SC9</b>	<b>SC9</b>
<b>SC10</b>	SC10	<b>SC10</b>	SC10	<b>SC10</b>	SC10	<b>SC10</b>	SC10	<b>SC10</b>	<b>SC10</b>

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

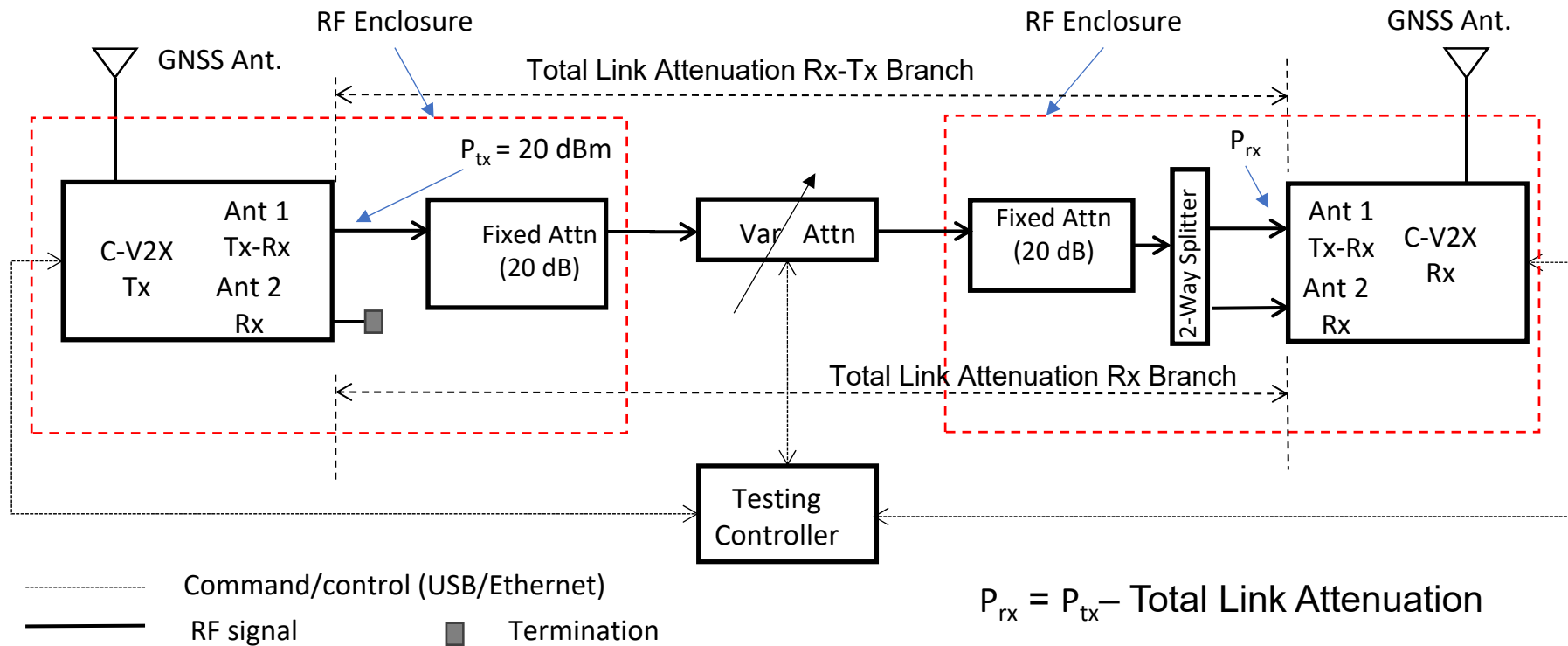
	20 MHz				10 MHz			
	Speed < 120kmph		Speed > 120kmph		Speed < 120kmph		Speed > 120kmph	
Packet Size	MCS	Num Sub Channels	MCS	Num Sub Channels	MCS	Num Sub Channels	MCS	Num Sub Channels
200	6	2	4	3	6	2	4	3
365	11	2	5	4	11	2	5	4
400	5	5	4	5	5	5	4	5
1000	5	10	5	10	11	5	5	5
1400	7	10	7	10	7	5	7	5

Sub-Channel Size = 10 RB

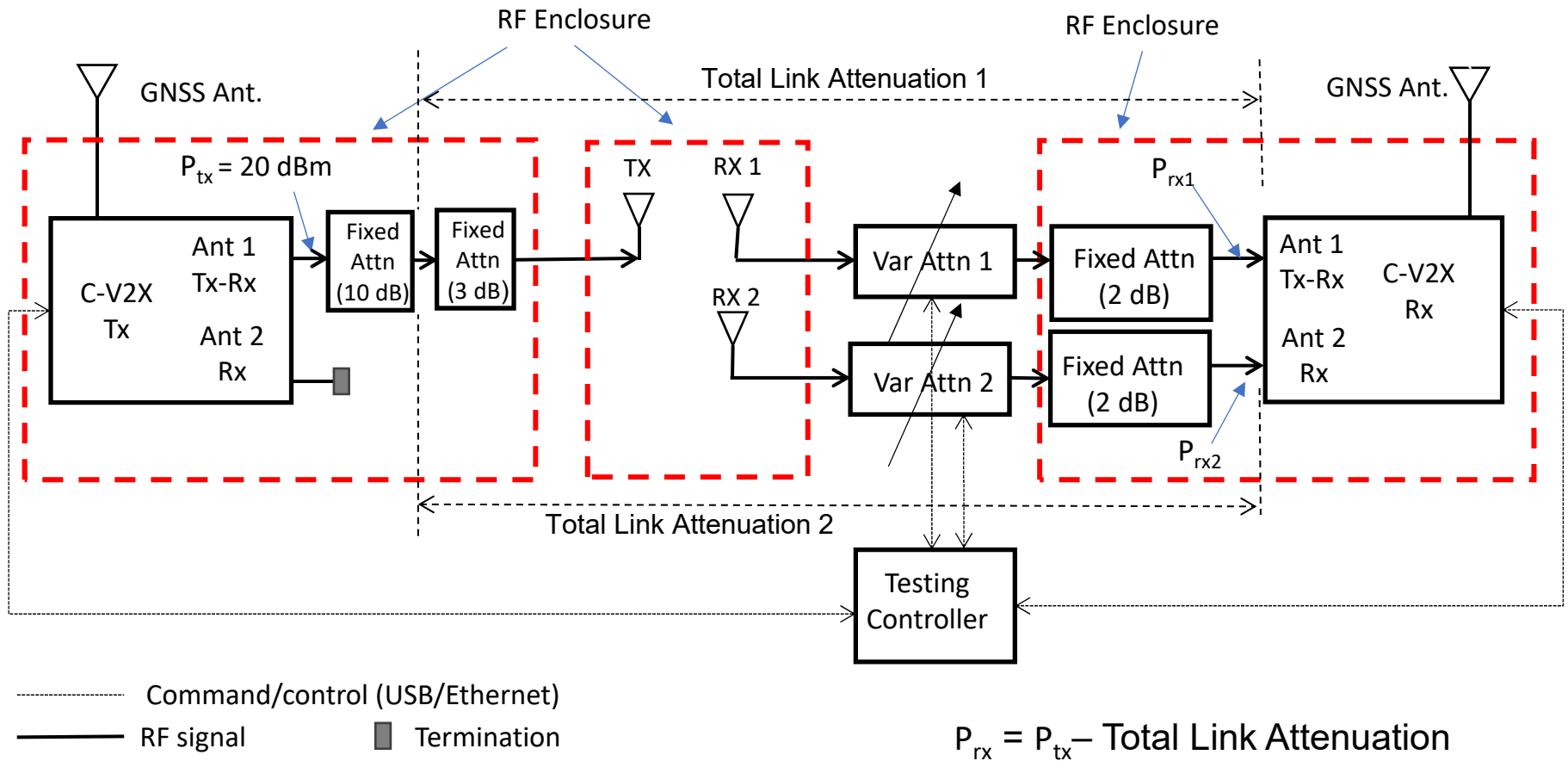
Note: The tabulated parameters were used for the lab, controlled and mixed traffic field testing. The parameters are subject to change pending future implementations and/or standards recommendations

# 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 bytes	HARQ	HARQ
200	-104 dBm	-104 dBm

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

- Average IPG is about 100 ms
- 95<sup>th</sup> 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



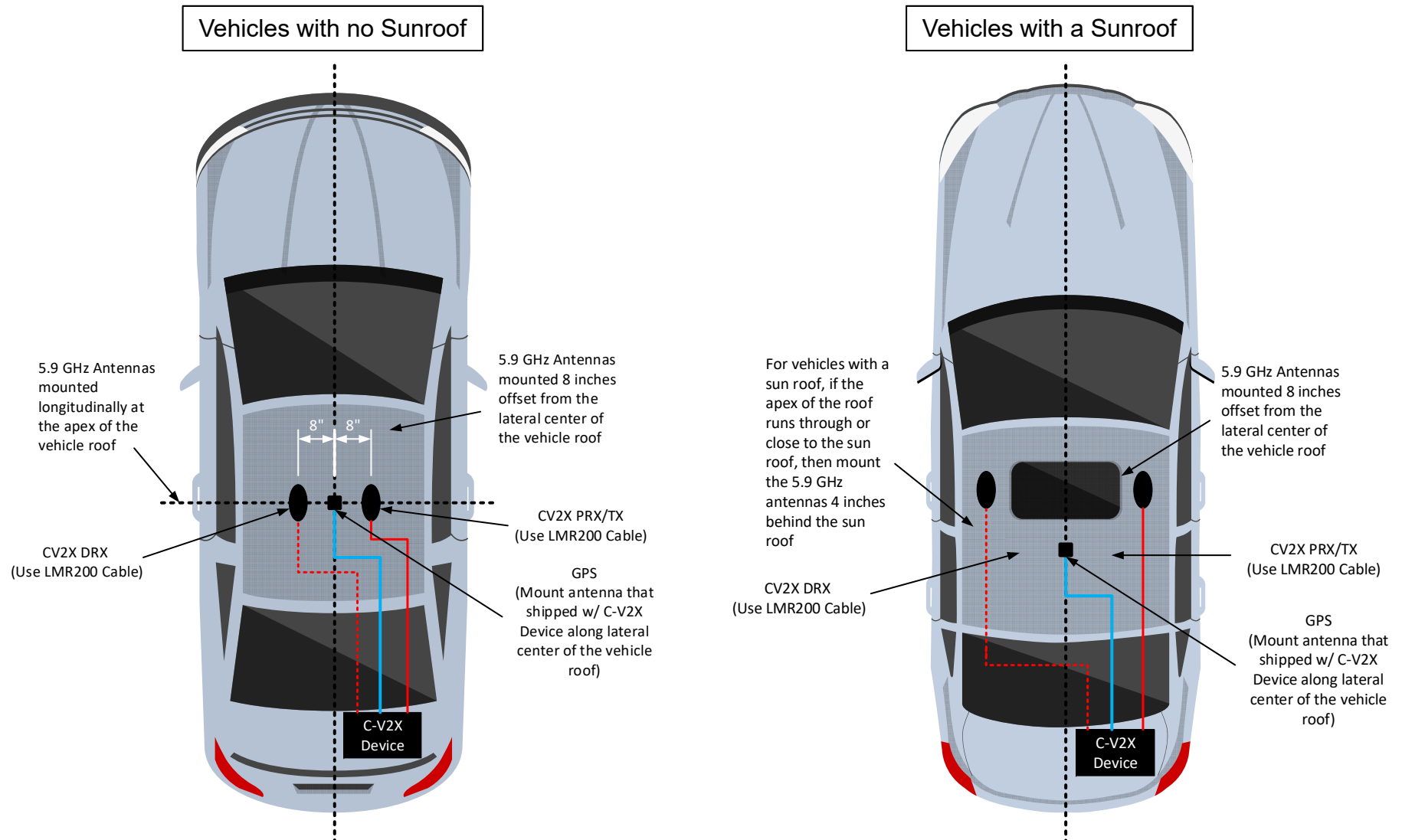
41



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

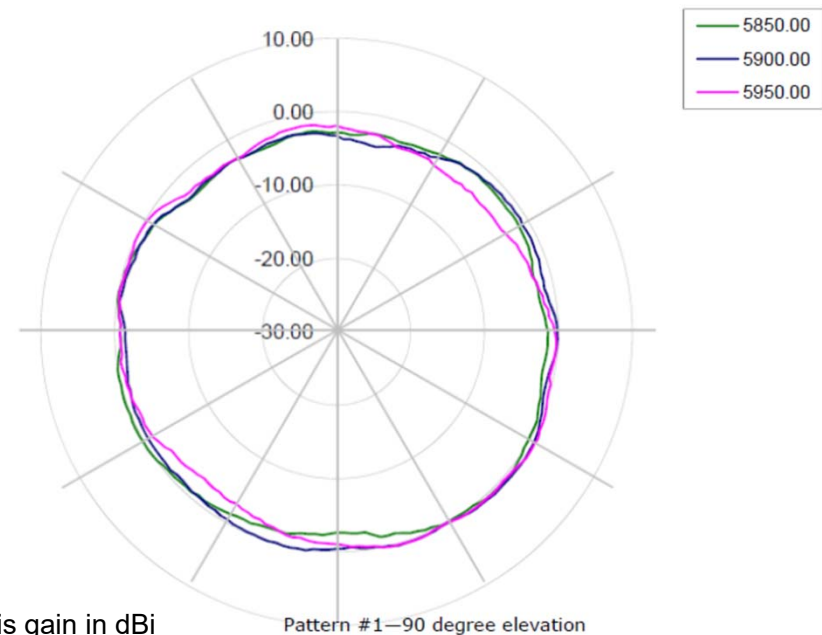
Radiated Power = ~ 17 dBm

Radiation Pattern @ 5.85 GHz, 5.90 GHz, 5.95 GHz



Sketch #2—Mount on surface

Magnet Mount Antenna



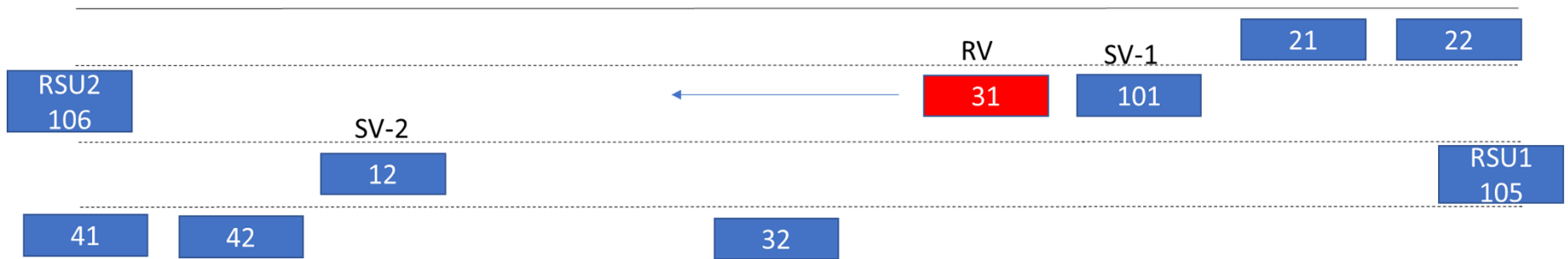
The scale on the patterns is gain in dBi

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





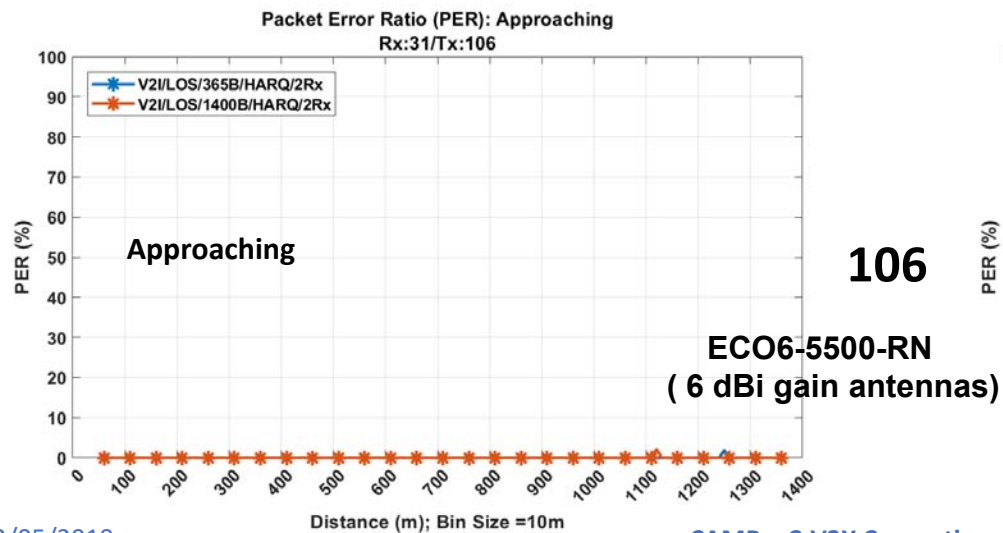
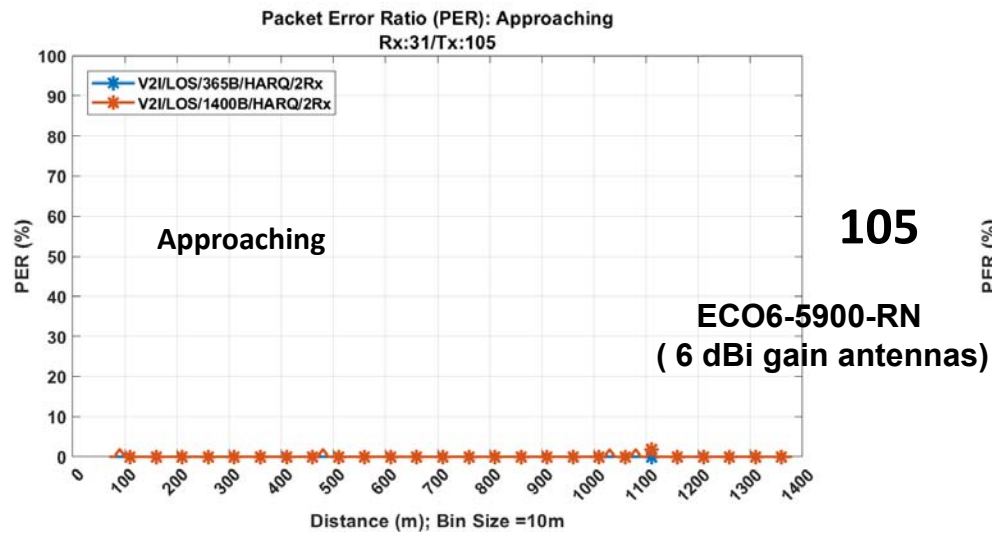


## V2I Line of Sight (LOS)

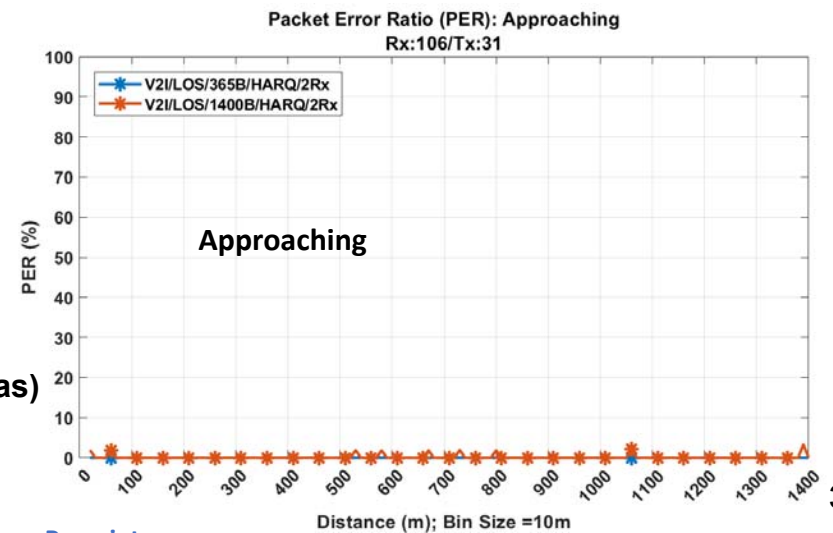
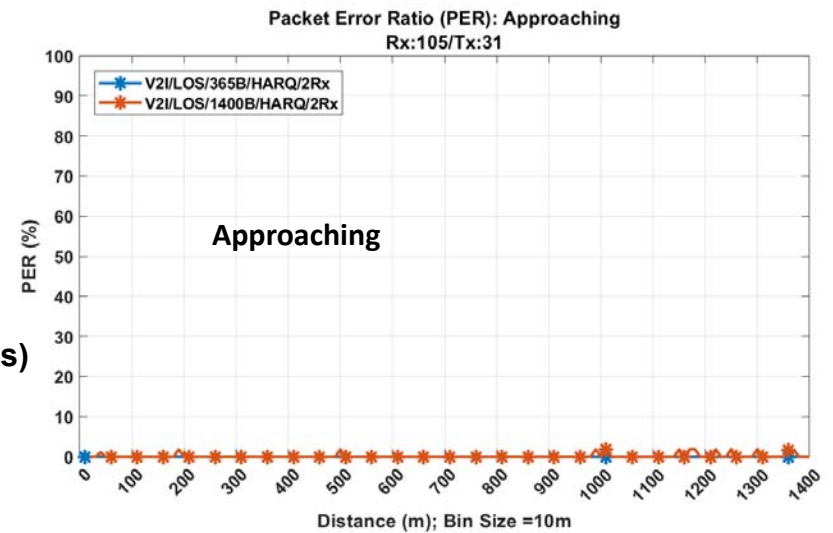
- 20 dBm/HARQ / 2Rx

# V2I-LOS: HARQ/2Rx

## Moving Vehicle Receiving



## RSU Receiving



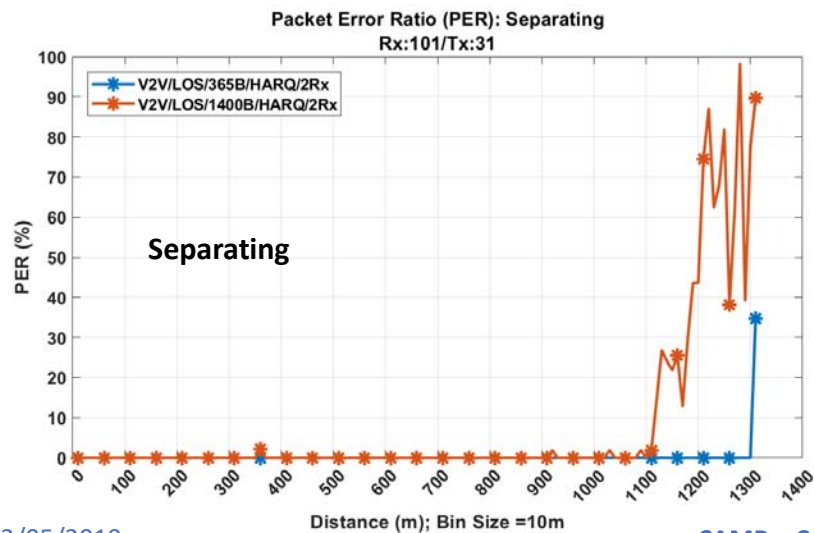
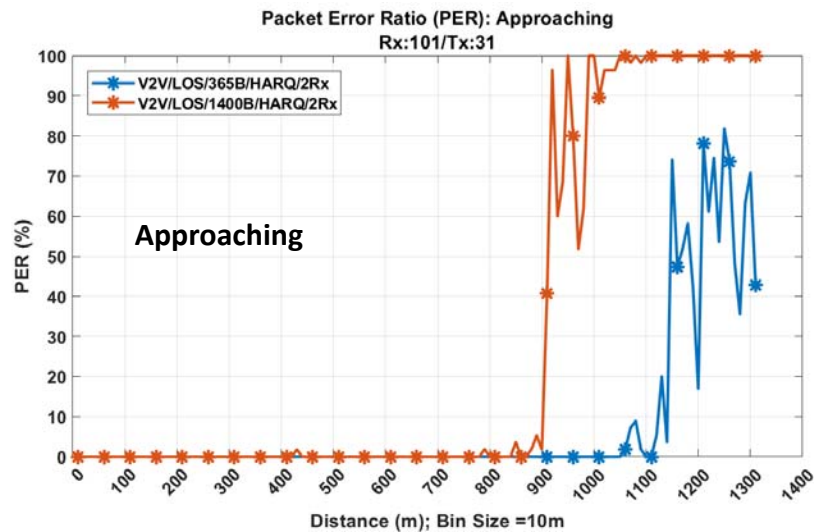


# V2V Line of Sight (LOS)

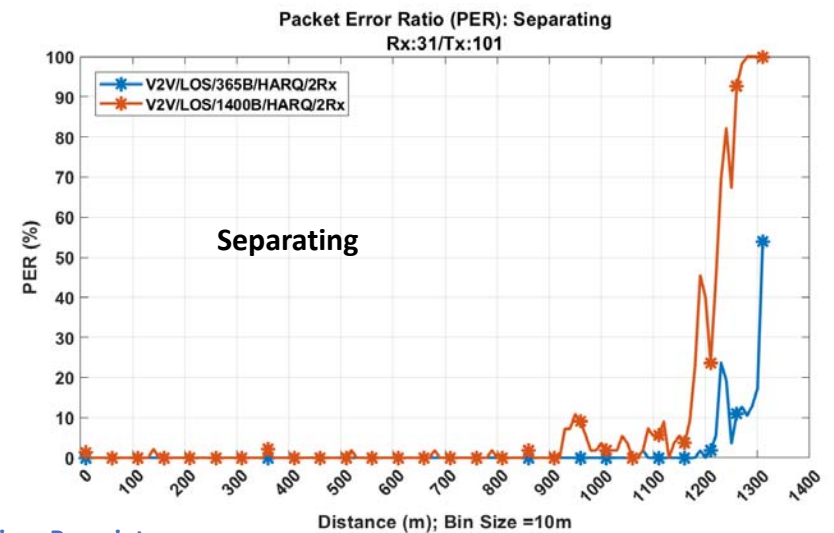
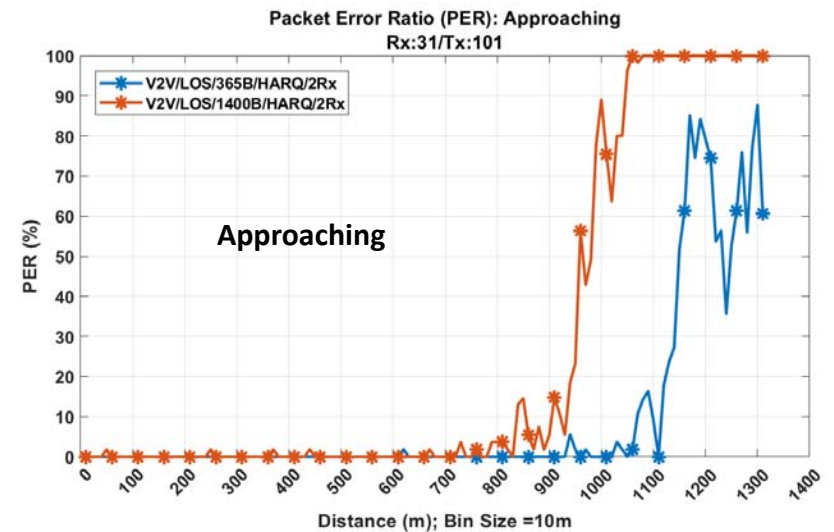
- 20 dBm/HARQ/2Rx

# V2V LOS: HARQ/2Rx 101 & 31

## Stationary Vehicle Receiving



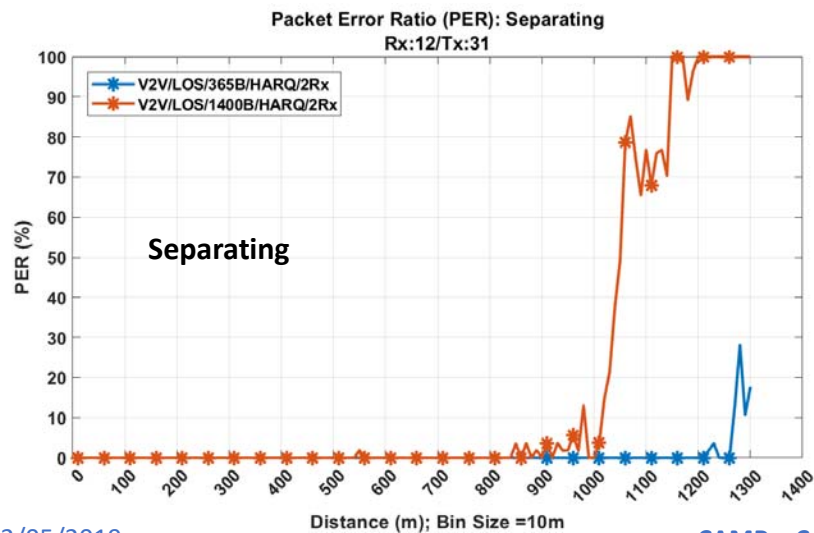
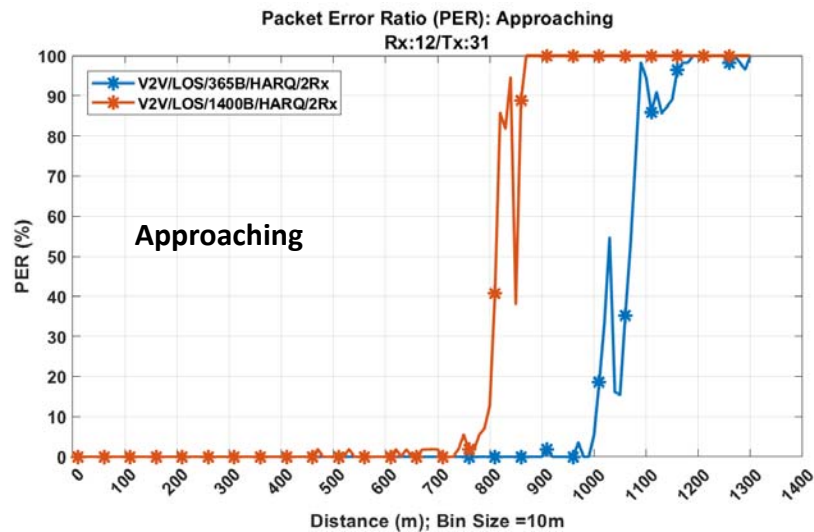
## Moving Vehicle Receiving



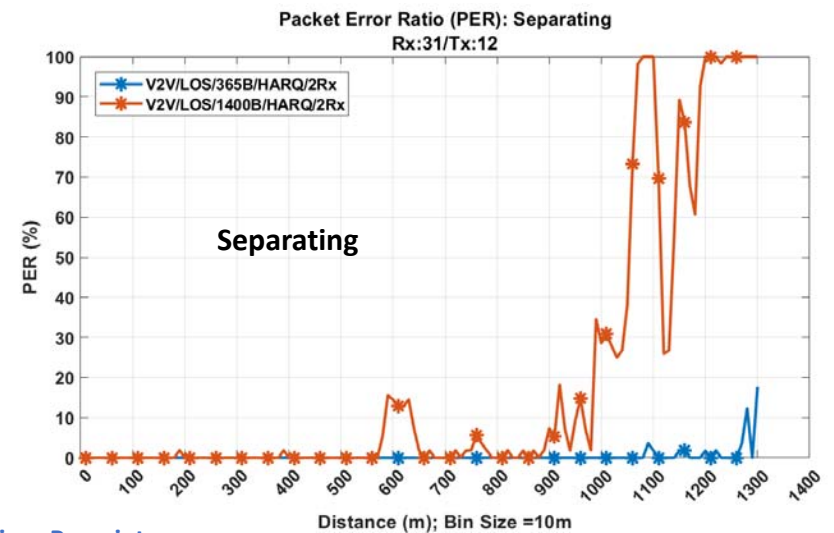
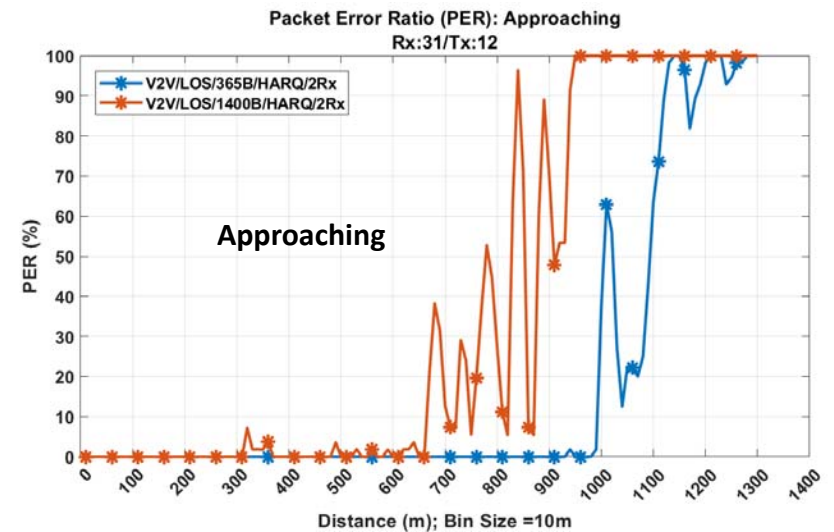


# V2V LOS: HARQ/2Rx 12 & 31

## Stationary Vehicle Receiving

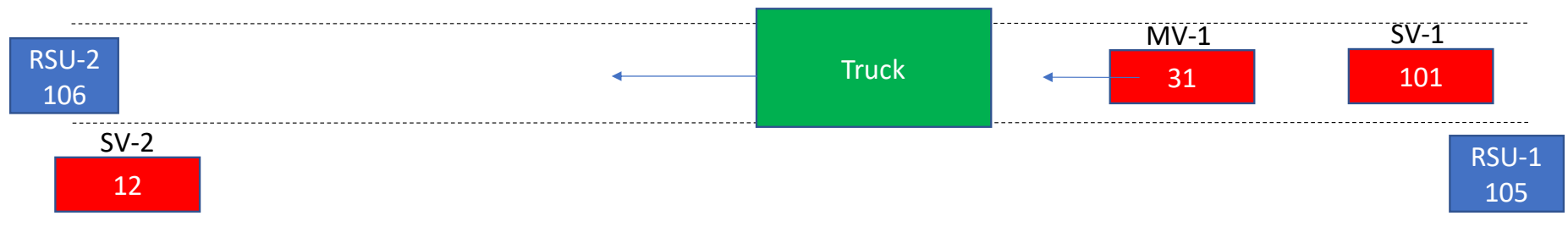


## Moving Vehicle Receiving



# Test Setup: V2I NLOS

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



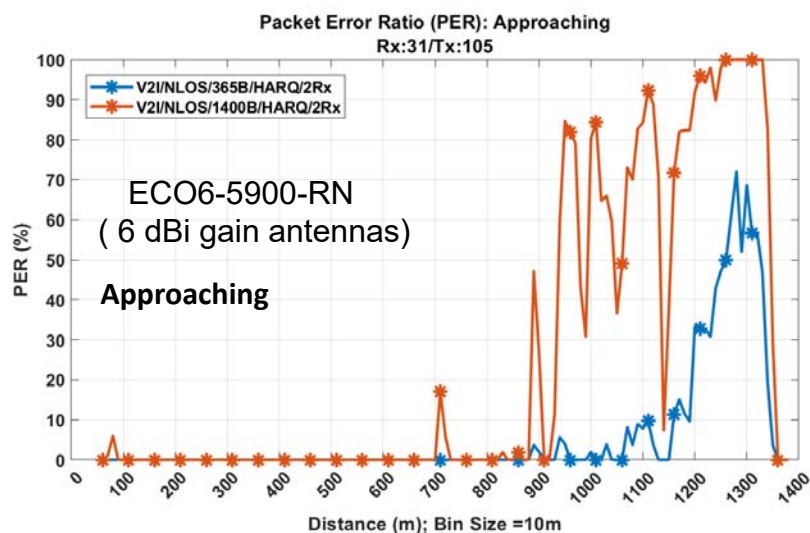


# V2I Non Line of Sight (NLOS)

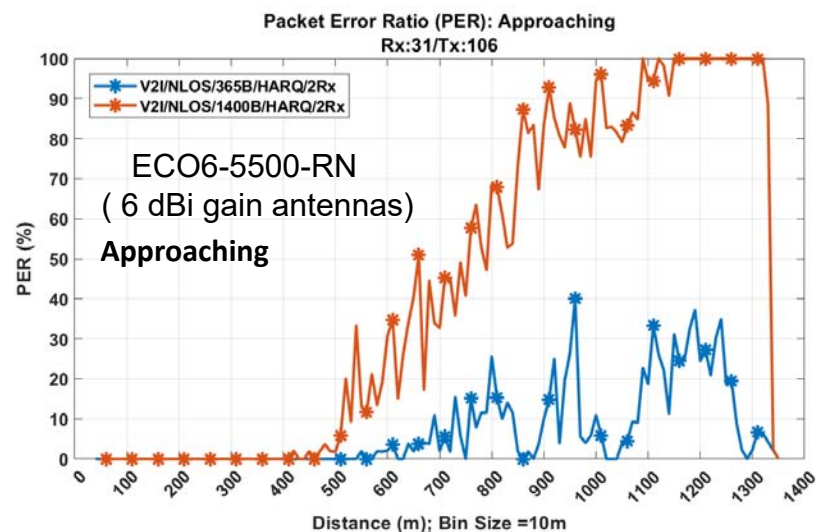
- 20 dBm/HARQ / 2Rx

# V2I NLOS: HARQ/2Rx

## Moving Vehicle Receiving

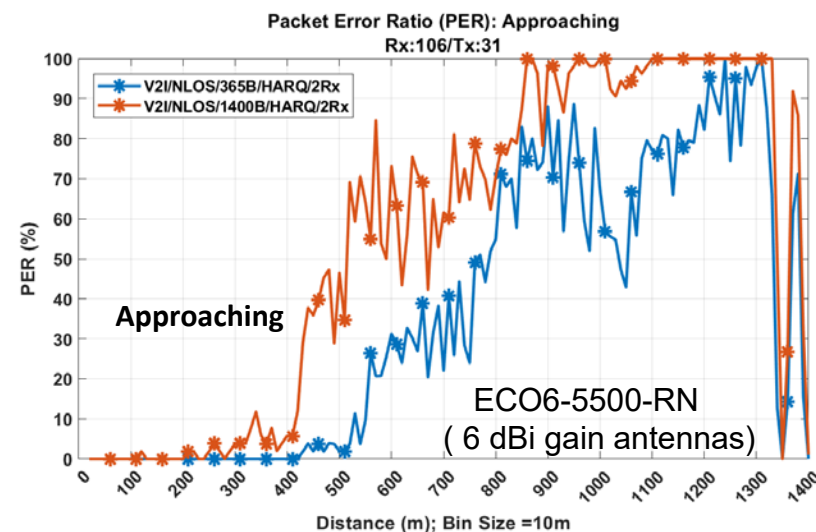
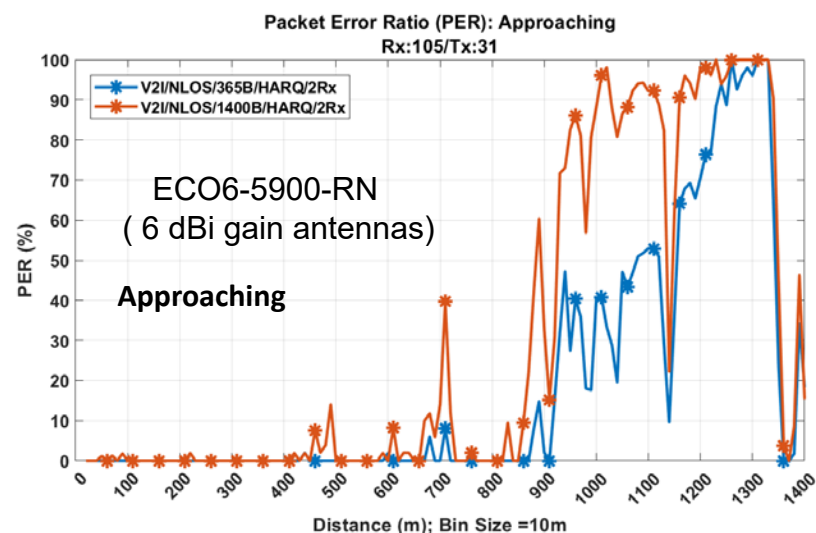


105



106

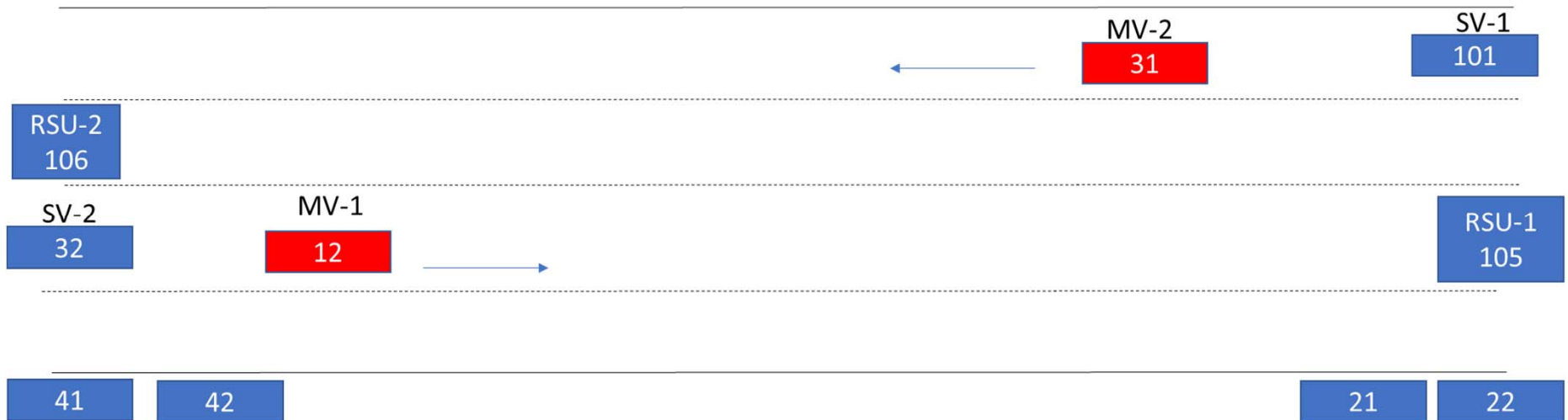
## RSU Receiving





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

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



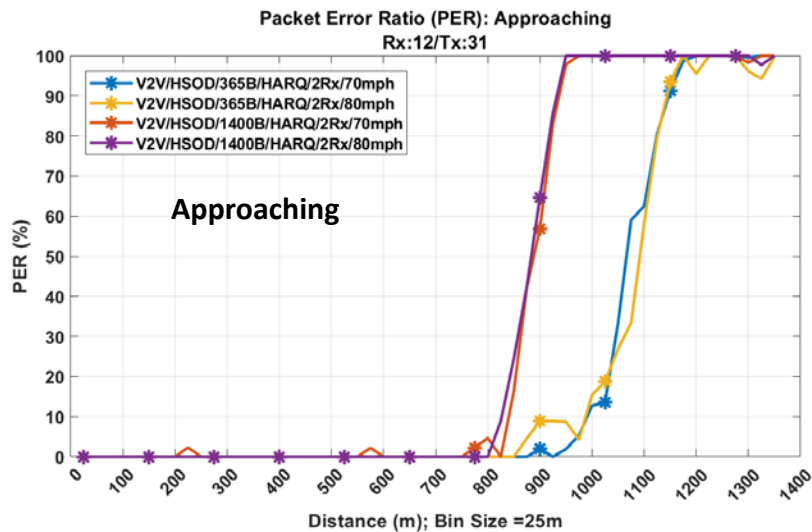


# V2V High Speed Opposite Direction (HSOD)

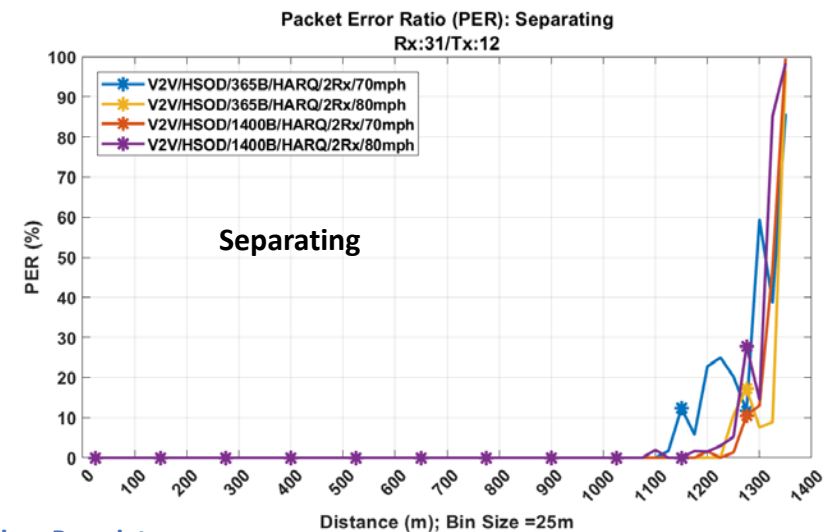
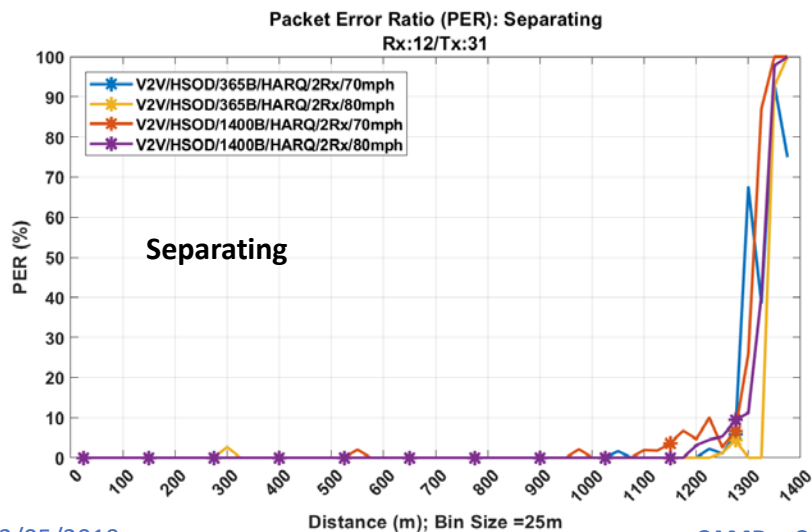
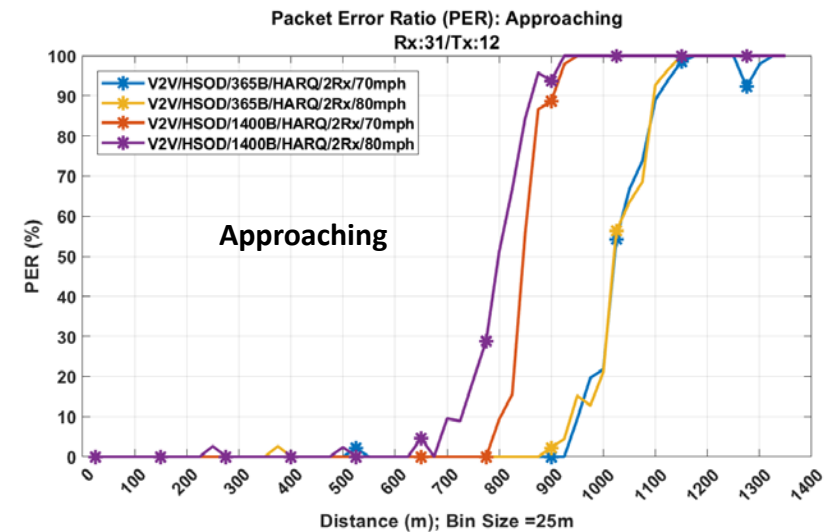
- 20 dBm/HARQ / 2Rx

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

## 12 Receiving

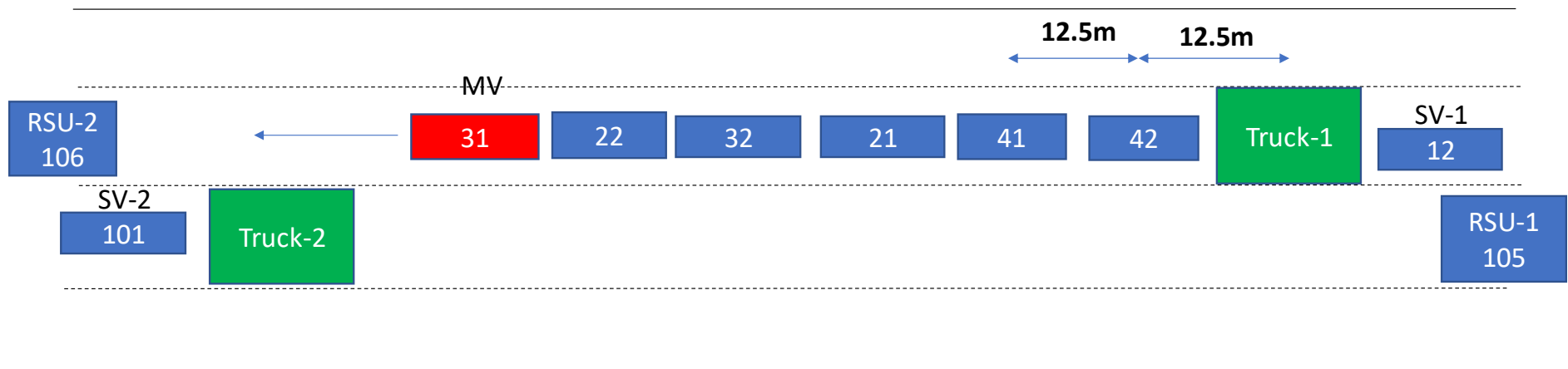


## 31 Receiving



# Test Setup: V2V NLOS

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





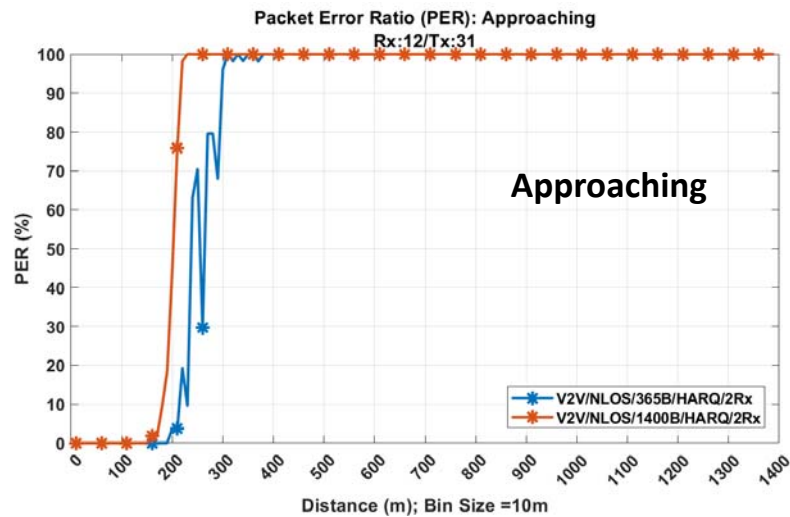
# V2V NLOS Same Lane Blocking

- 20 dBm/HARQ / 2Rx

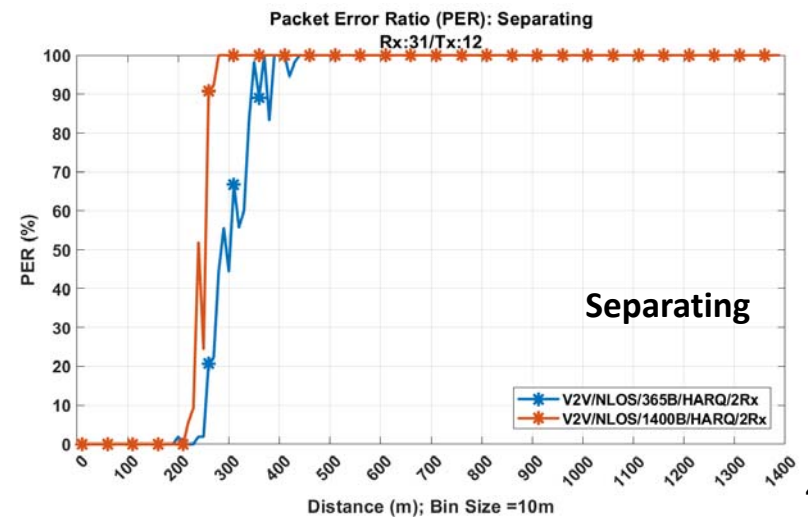
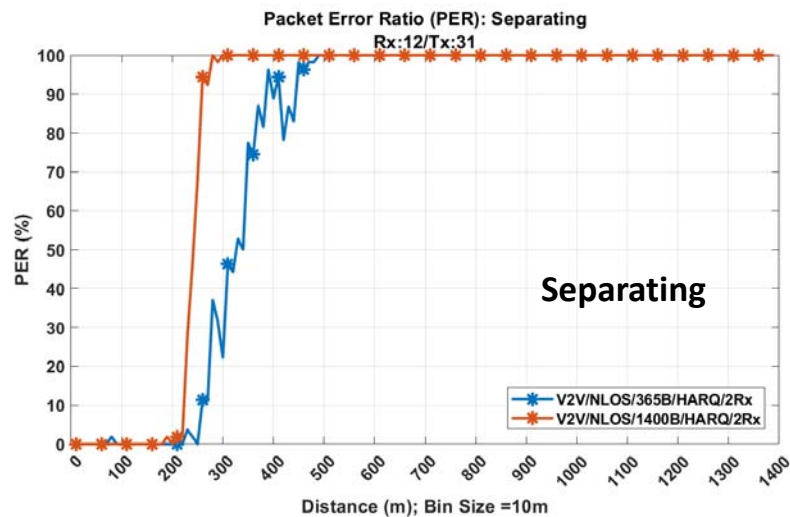
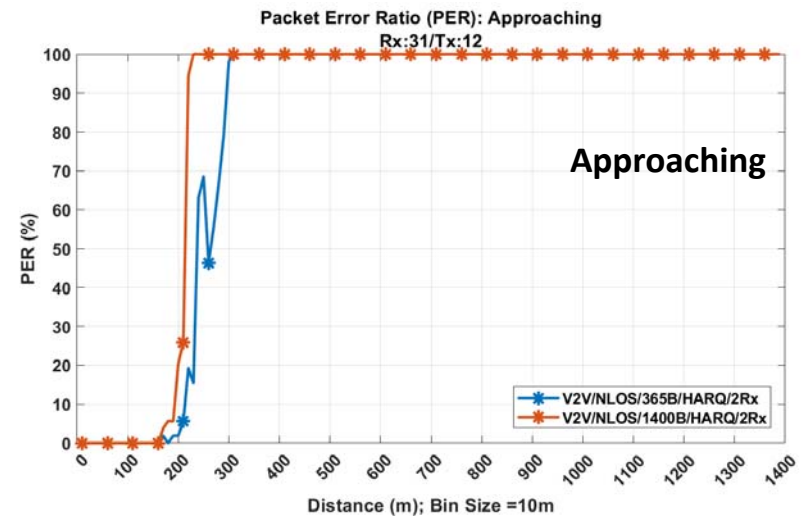
# V2V NLOS: HARQ/2Rx

## 31 MV & 12 SV

### Stationary Vehicle Receiving



### Moving Vehicle Receiving

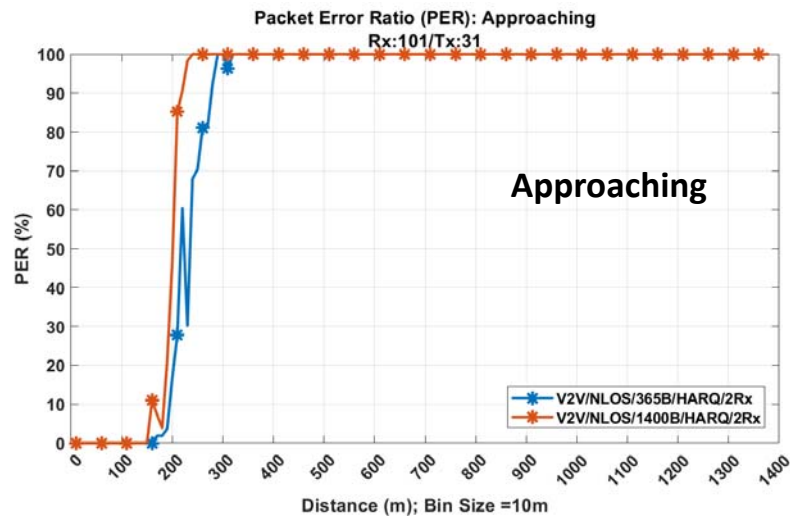




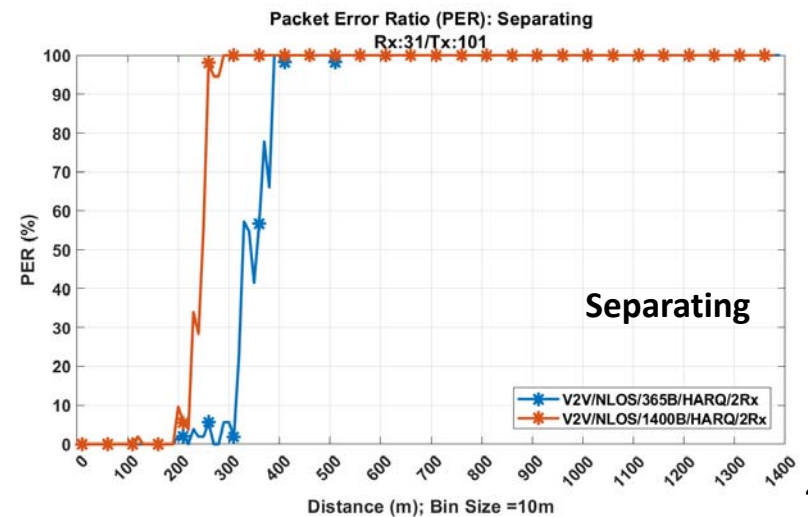
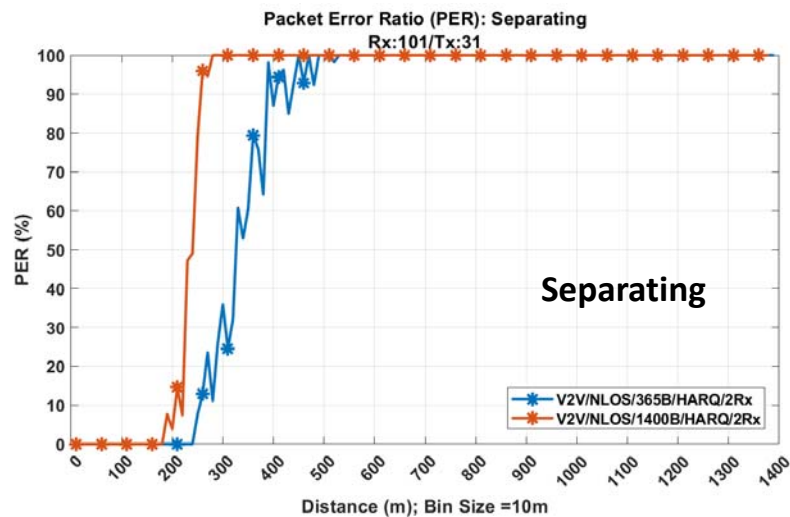
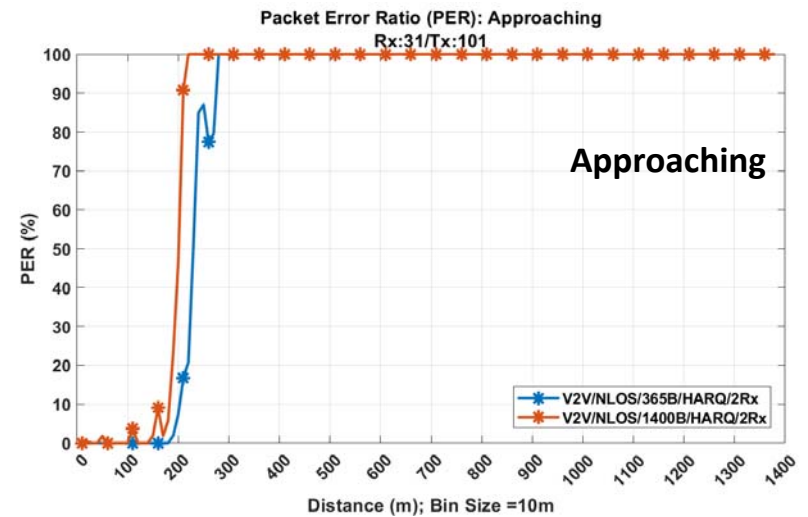
# V2V NLOS: HARQ/2Rx

## 31 MV & 101 SV

### Stationary Vehicle Receiving

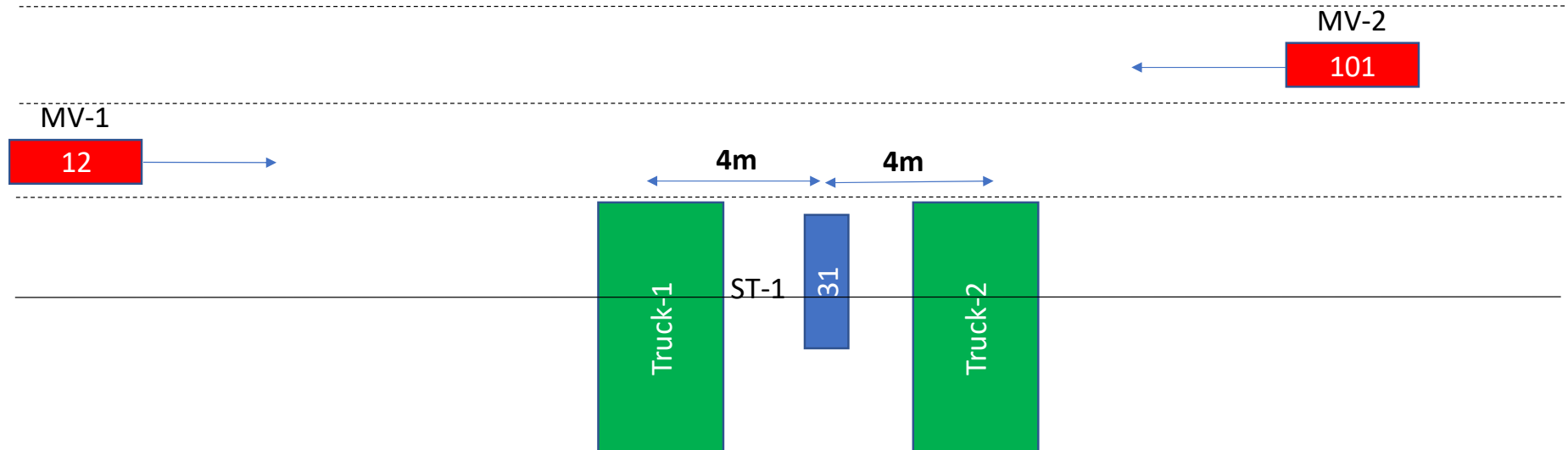


### Moving Vehicle Receiving



# Test Setup: V2V NLOS Intersection

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







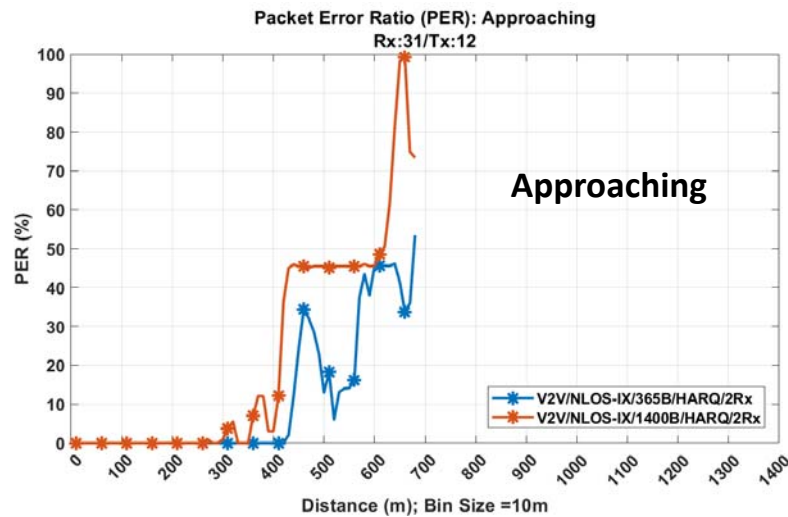
# V2V NLOS Intersection

- 20 dBm/HARQ / 2Rx

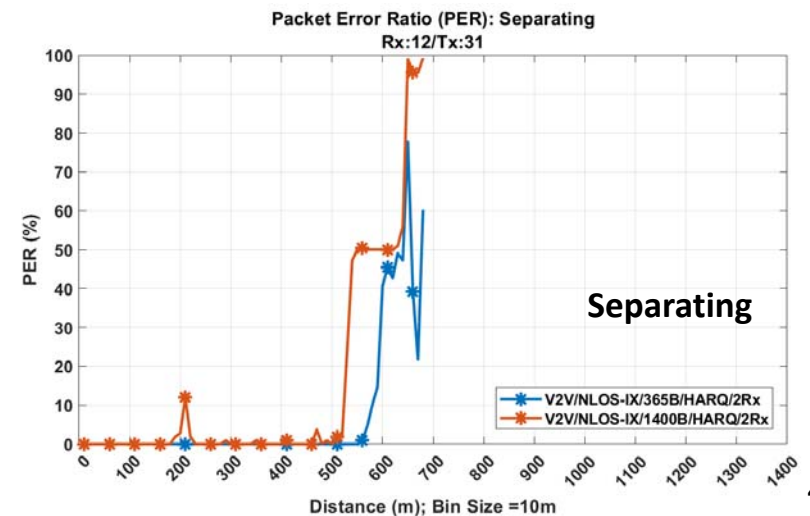
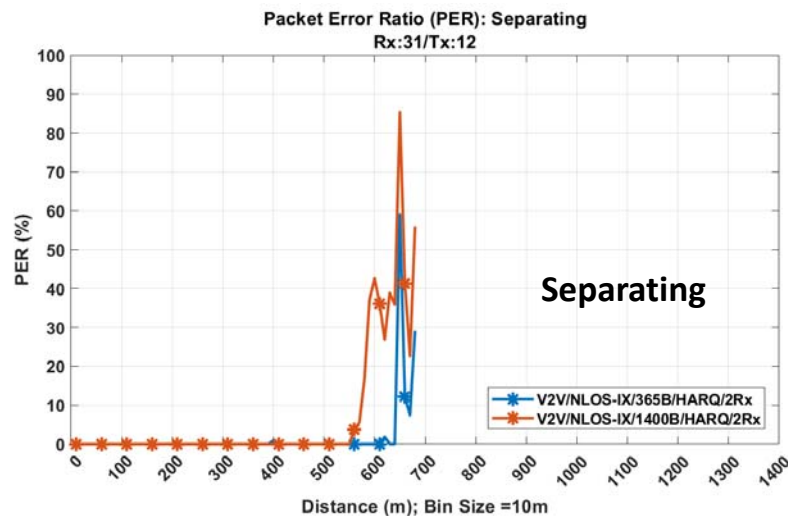
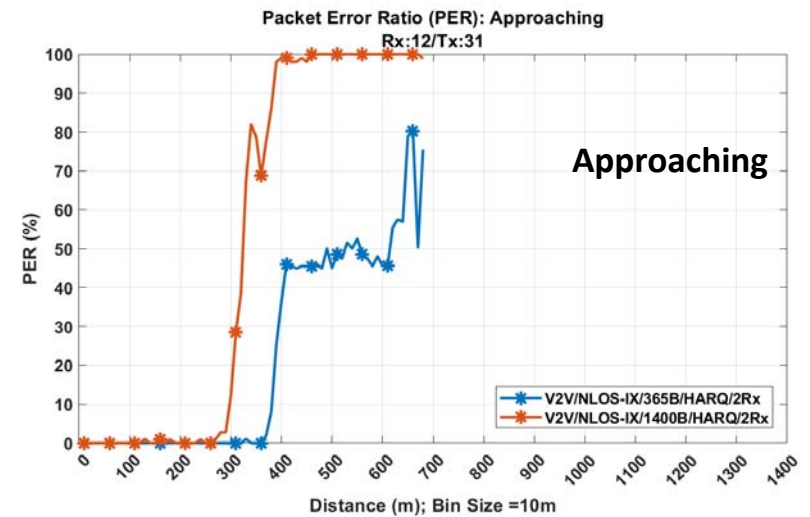
# V2V NLOS Intersection: HARQ/2Rx

## 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



Group A: Ford1, GM1, HK1, Nissan1



Group B: Ford2, GM2, HK2, Nissan2



# 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

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# Mixed Traffic Testing Summary

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

EAST ROUTE	365 Byte	1400 Byte	WEST ROUTE	365 Byte	1400 Byte
	2 Rx	2 Rx		2 Rx	2 Rx
Total Sent BSM	59119	56591	Total Sent BSM	74418	87758
Total Received BSM	59116	56575	Total Received BSM	74417	87717
Failure Count	3	16	Failure Count	1	41
PER [%]	0.005	0.028	PER [%]	0.001	0.047
Avg IPG [ms]	100.2	97.13	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	WEST ROUTE	365 Byte	1400 Byte
	2 Rx	2 Rx		2 Rx	2 Rx
Total Sent BSM	58064	57841	Total Sent BSM	74417	88047
Total Received BSM	58061	57825	Total Received BSM	74412	87966
Failure Count	3	16	Failure Count	5	81
PER [%]	0.005	0.028	PER [%]	0.006	0.092
Avg IPG [ms]	100.3	94.54	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	WEST ROUTE	365 Byte	1400 Byte
	2 Rx	2 Rx		2 Rx	2 Rx
Total Sent BSM	58980	56115	Total Sent BSM	74417	87987
Total Received BSM	58976	56101	Total Received BSM	74395	86915
Failure Count	4	14	Failure Count	22	1072*
PER [%]	0.007	0.025	PER [%]	0.029	1.22
Avg IPG [ms]	100.3	97.40	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

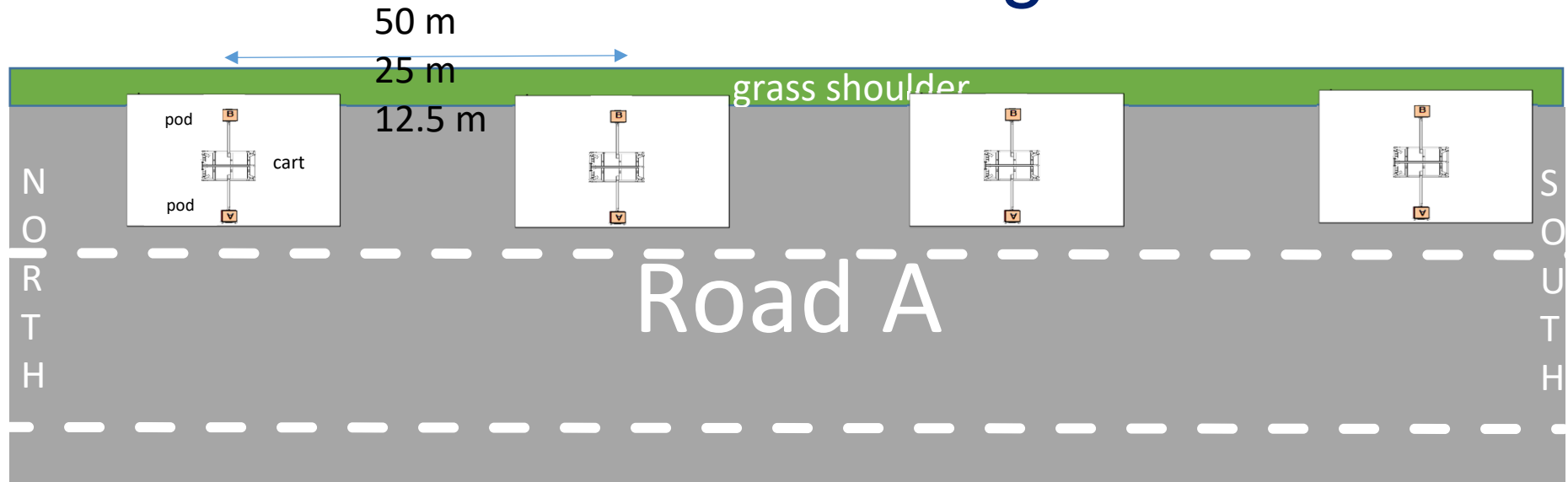
# Congestion Control Test Results Fowlerville Test Track

Test dates: 10/28-11/1

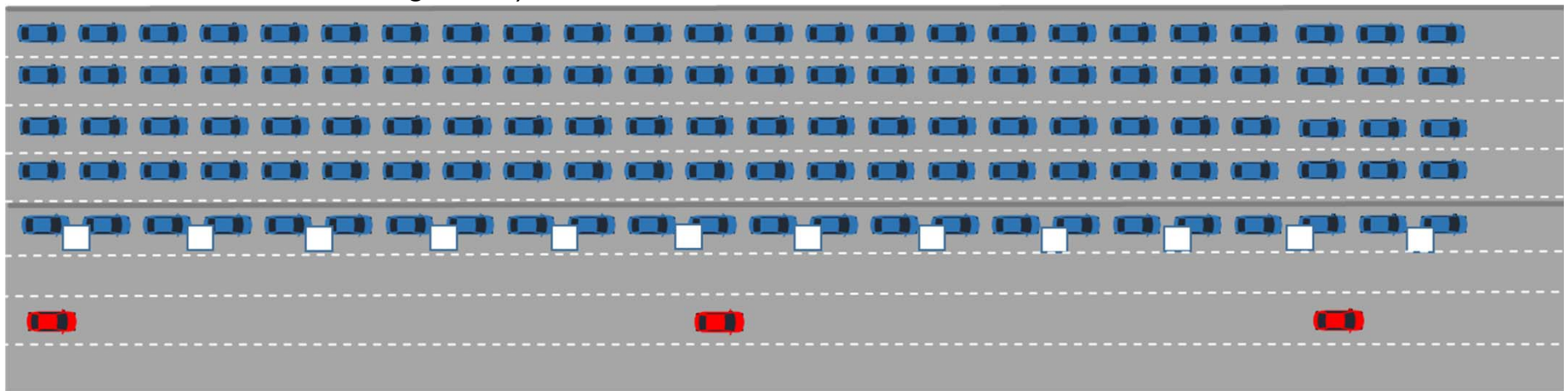
# Test Overview

- 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)

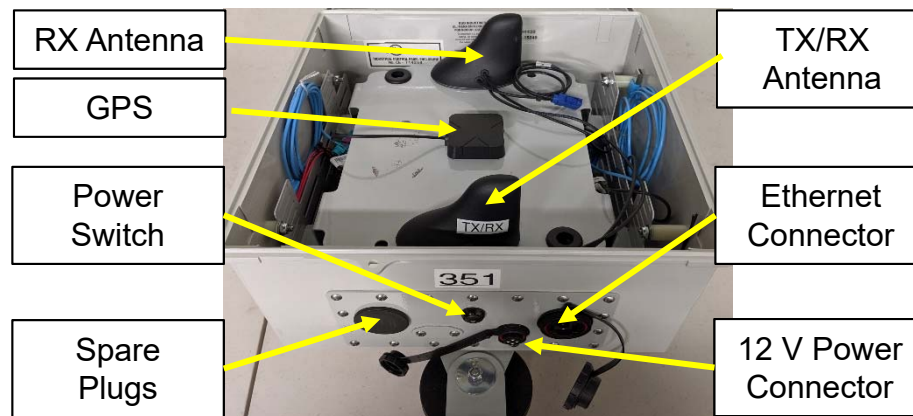
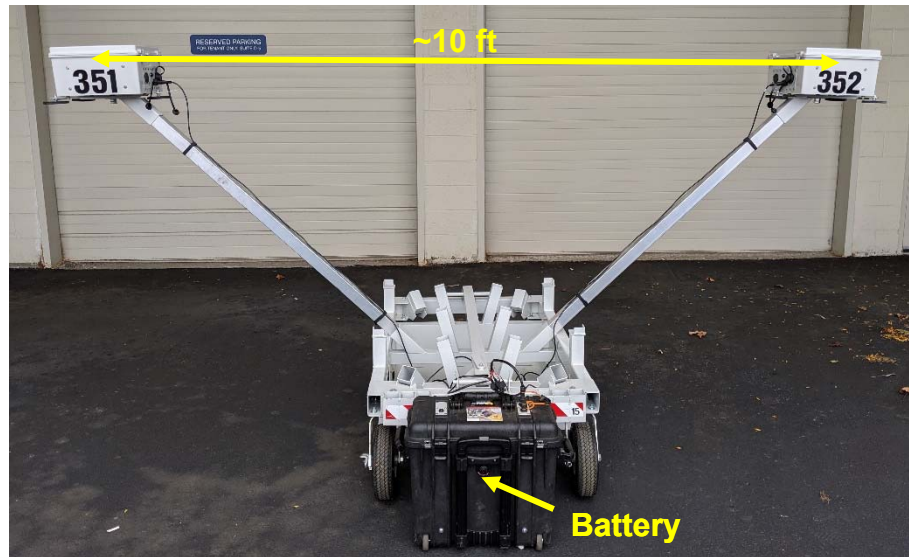
# Cart and Pod Arrangement



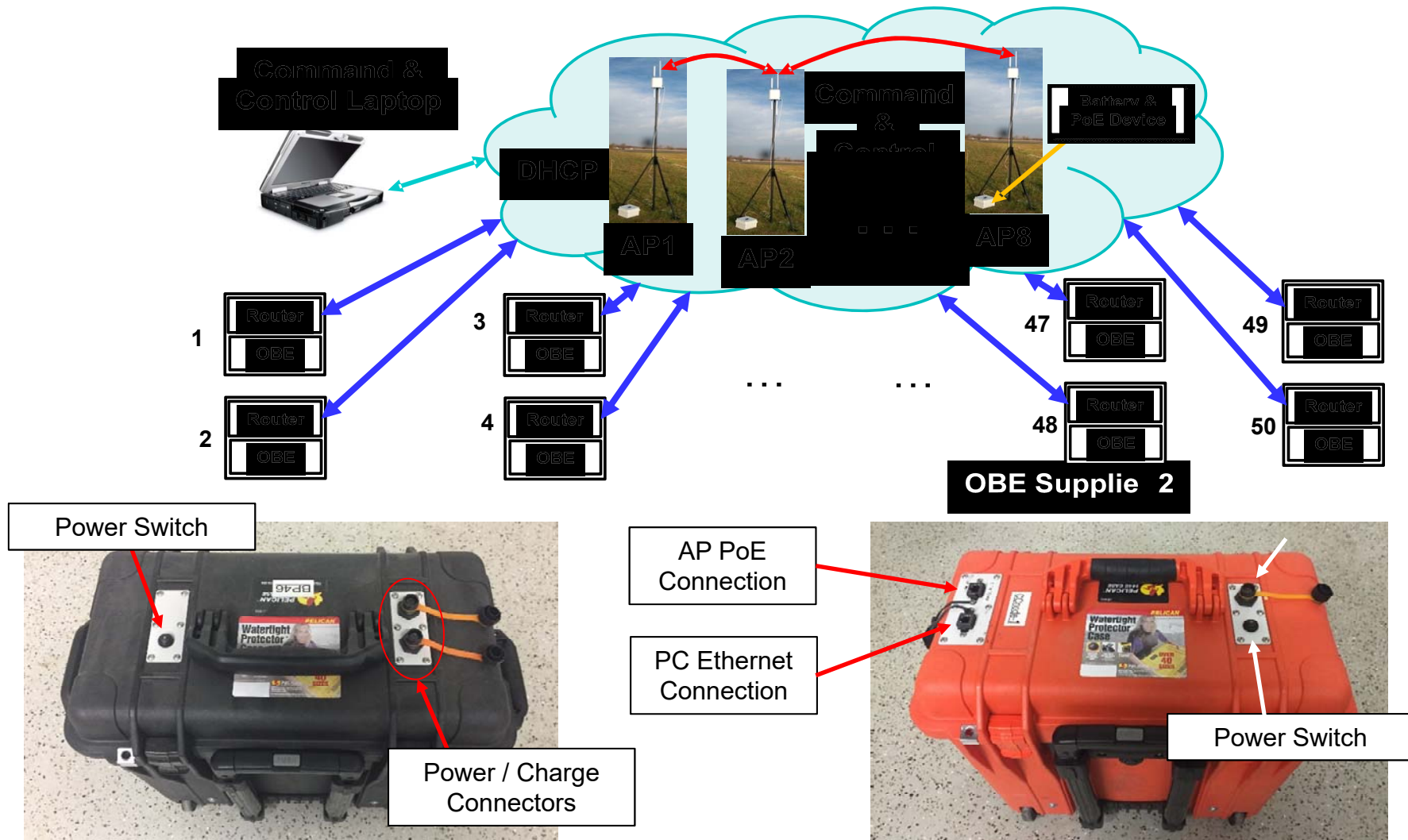
- Heaviest congestion (5X nominal rate) emulates 5 adjacent lanes and 10 vehicles per cart (blue vehicles illustrate congestion)



# Carts/Pods/Batteries

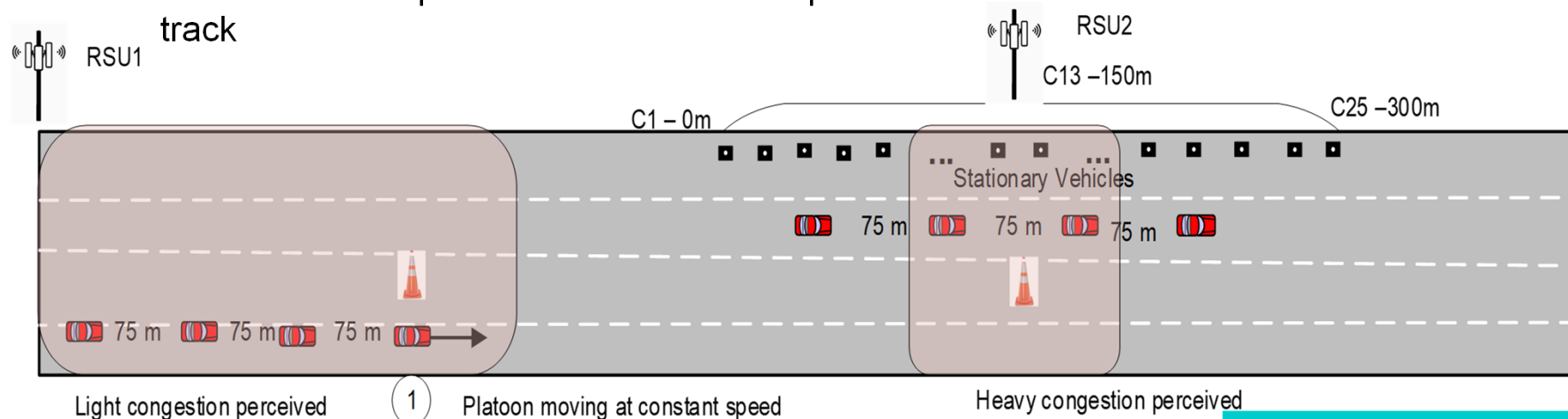


# Wireless Mesh: Connecting Pods to C&C Laptop



# 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

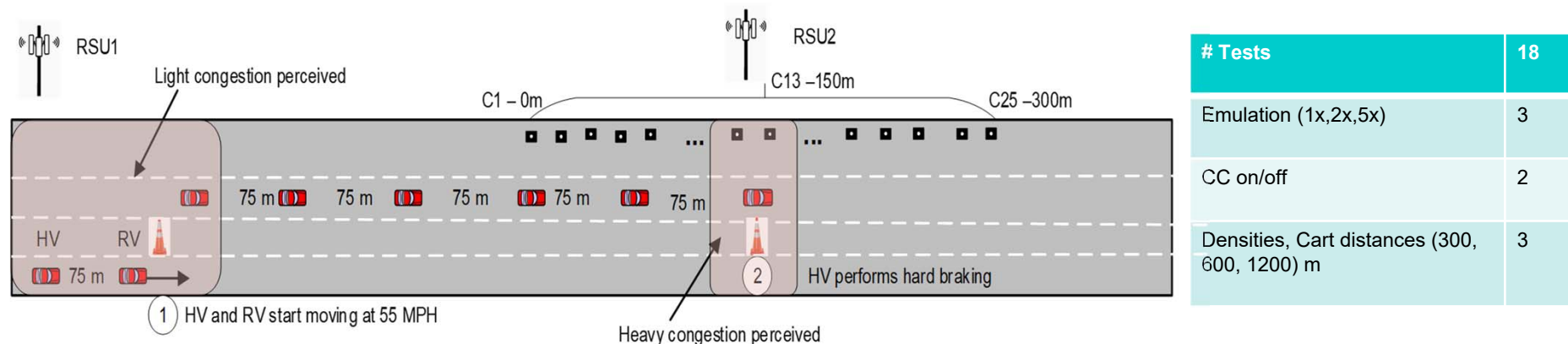


- 8 vehicles + 2 RSU collect logs for KPI post-processing

# Tests	36
Emulation (1x,2x,5x)	3
CC on/off	2
Densities, 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



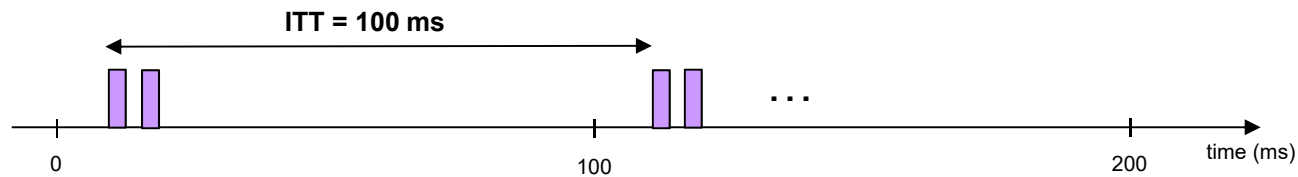


# Additional Details

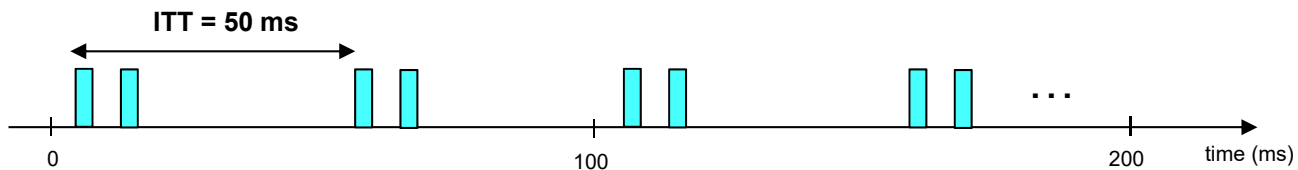
- All transmission are in CH183 (20 MHz), HARQ is always on and all packet have the same size of 365 bytes
- Congestion control is implemented as per SAE J3161/1
- We use live BSM mode to incorporate CAN data for critical event testing
- Data is logged for presenting the following KPIs
  - Steady state 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

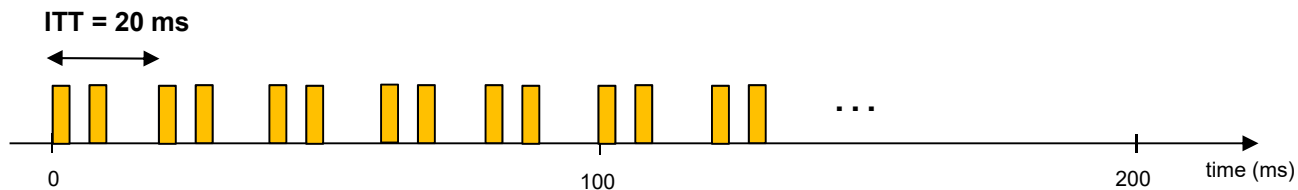
- Inter-Transmit Time (ITT) varies as a function of emulation level
- 1X emulation: 50 congesting pods and 10 OBUs each generate 2 transmissions per 100 ms (1 original plus HARQ retransmission)



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

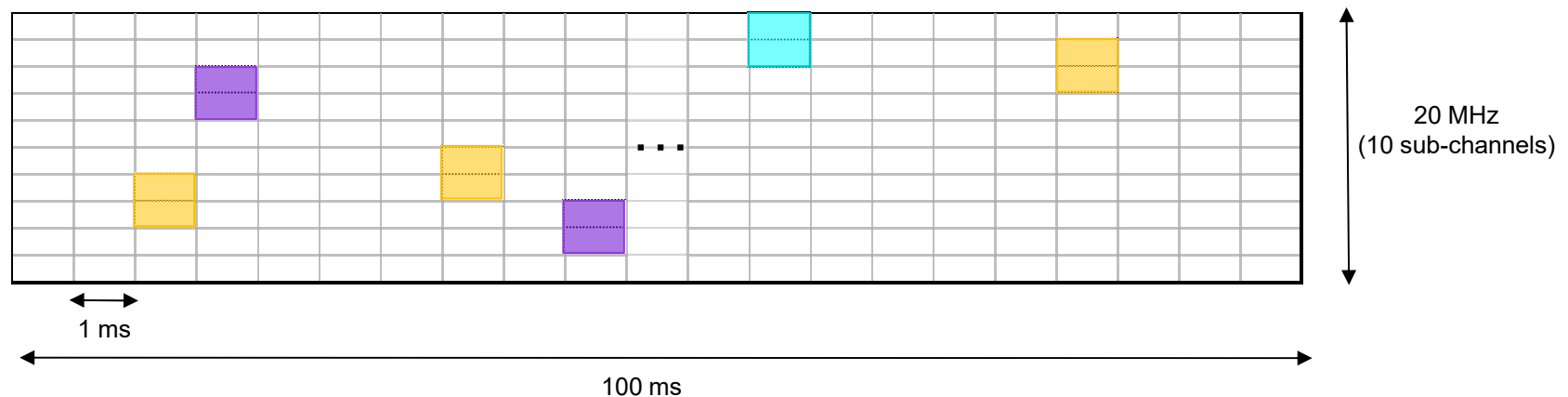


- 5X emulation: 50 congesting pods each generate 10 transmissions per 100 ms



# 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<sup>(\*)</sup>

- 1X emulation:

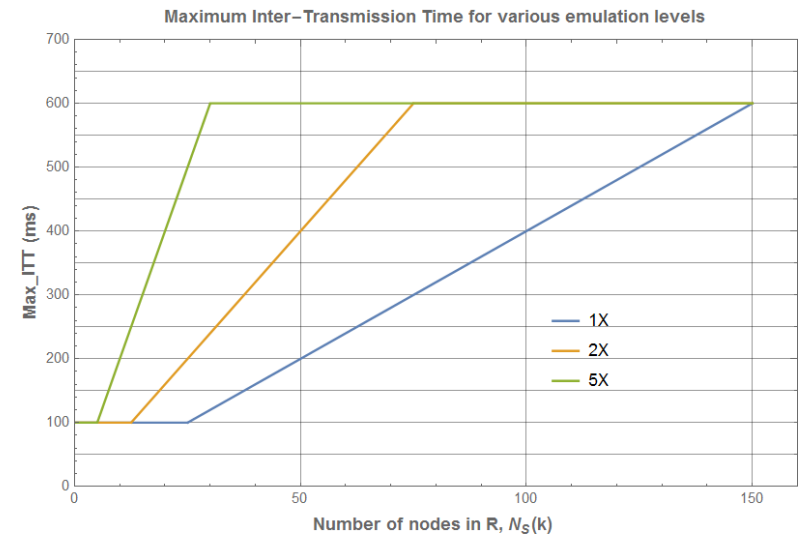
$$\bullet \quad Max\_ITT(k) = \begin{cases} 100 & N_s(k) \leq 25 \\ 100 \times \frac{N_s(k)}{25} & 25 < N_s(k) < 150 \\ 600 & 150 \leq N_s(k) \end{cases}$$

- 2X emulation:

$$\bullet \quad Max\_ITT(k) = \begin{cases} 100 & N_s(k) \leq 12.5 \\ 100 \times \frac{N_s(k)}{12.5} & 12.5 < N_s(k) < 75 \\ 600 & 75 \leq N_s(k) \end{cases}$$

- 5X emulation:

$$\bullet \quad Max\_ITT(k) = \begin{cases} 100 & N_s(k) \leq 5 \\ 100 \times \frac{N_s(k)}{5} & 5 < N_s(k) < 30 \\ 600 & 30 \leq N_s(k) \end{cases}$$



<sup>(\*)</sup> Congesting pods behave in a similar way except they further scale down Max\_ITT in proportion to the emulation factor



# Congestion Control Platoon Test

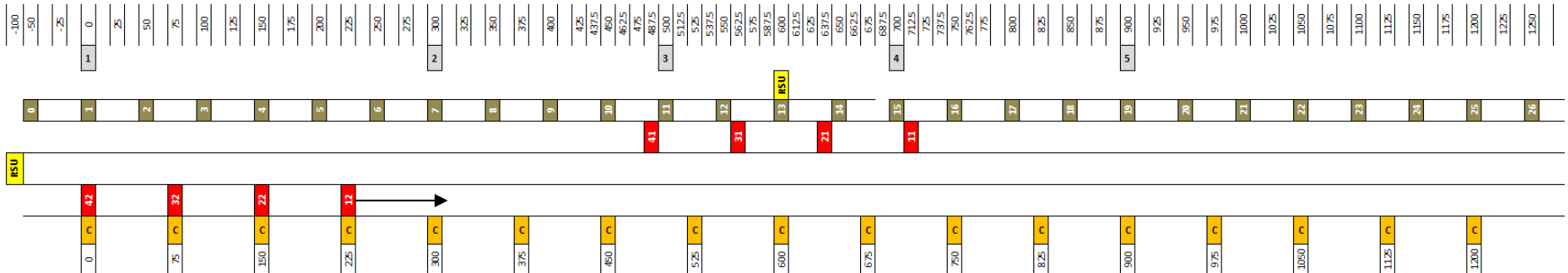
- 4-vehicle platoon, 20/80 mph

# Platoon Test

Congestion Spread 1200m  
Speed 20mph

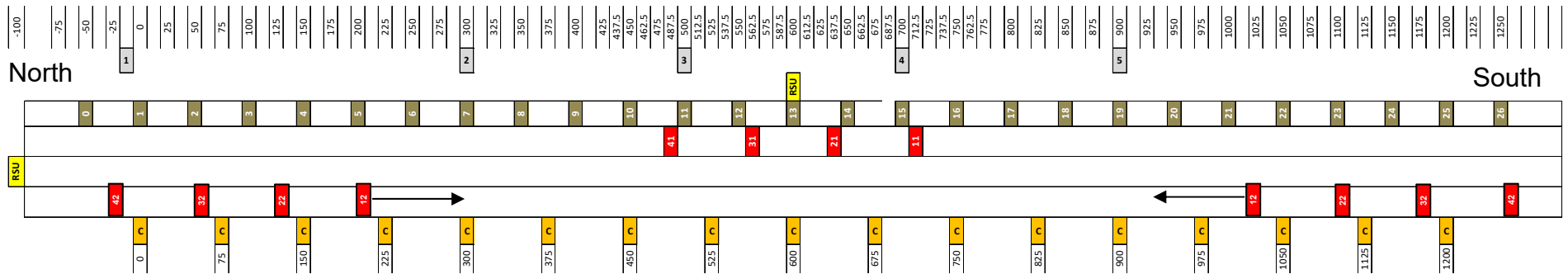
# Test Setup: Platoon 1200m

- 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

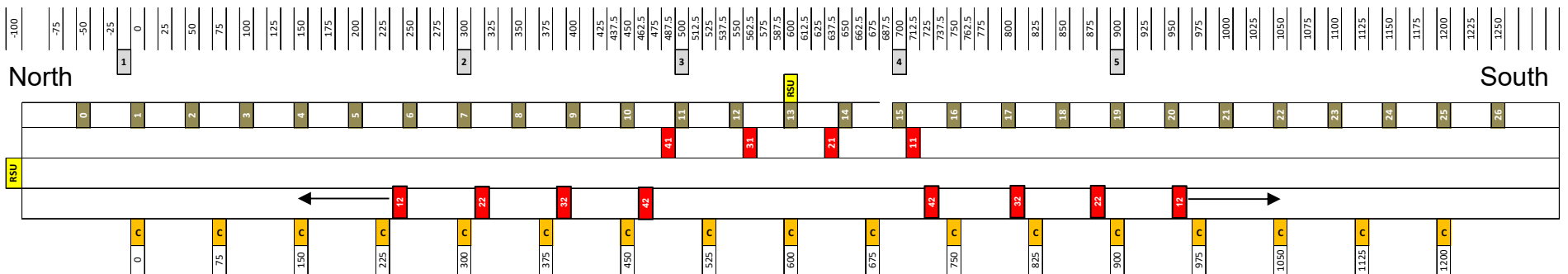


# Explanation of the Graphs – Platoon Direction

- Approaching North->South and South->North



- Separating North->South and South->North





# Max\_ITT Estimate for Vehicle 11 at 5X Emulation

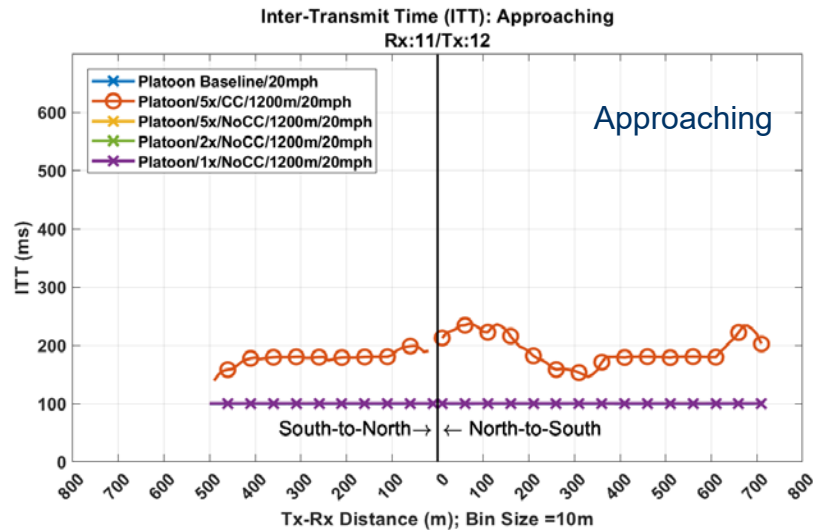
- When the platoon is away Vehicle 11 receives
  - 4 carts (7 pods)\*
  - 1 vehicle
  - $\text{Max\_ITT}(k) = 100 \times 8/5 = 160 \text{ ms}$
- When the platoon is partially overlapping Vehicle 11 receives
  - 4 carts (7 pods)\*
  - 4 vehicles
  - $\text{Max\_ITT}(k) = 100 \times 11/5 = 220 \text{ ms}$



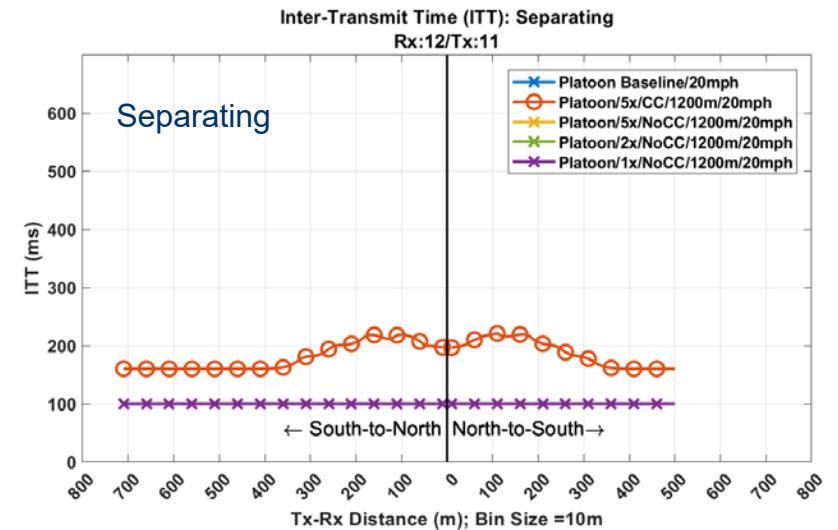
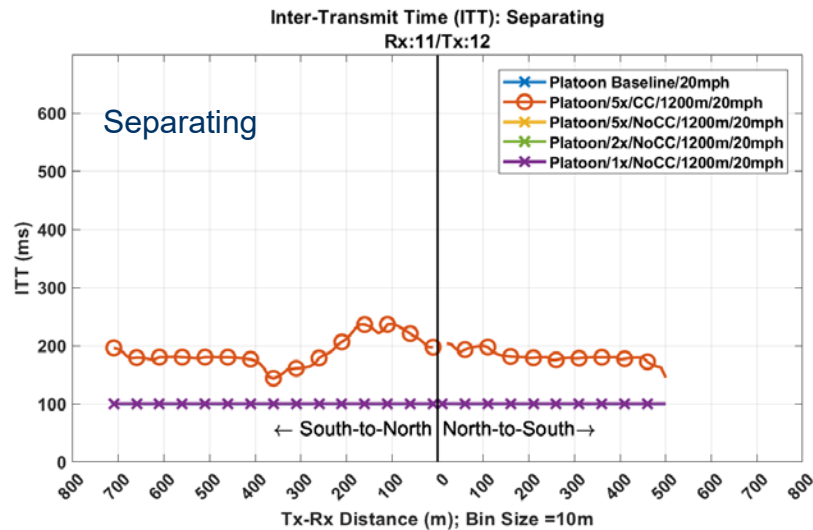
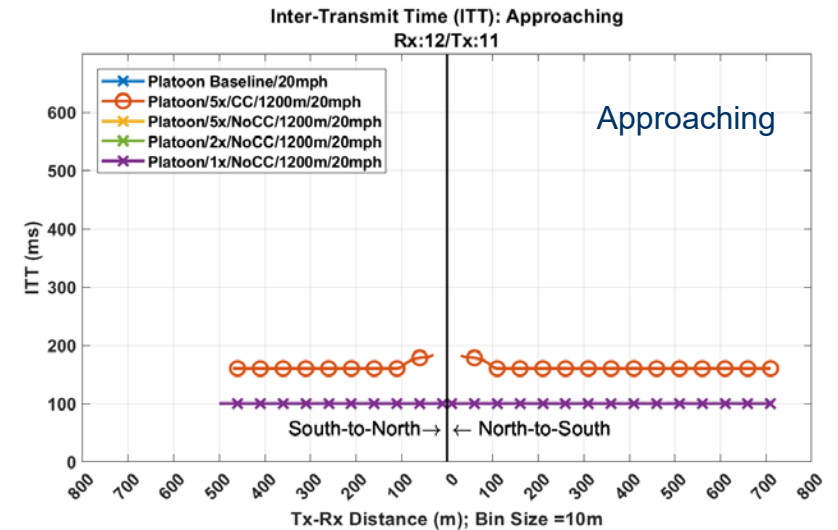
\* A pod on cart 14 was turned off during the test

# ITT – Platoon Test – 1200m

## Stationary Vehicle Receiving



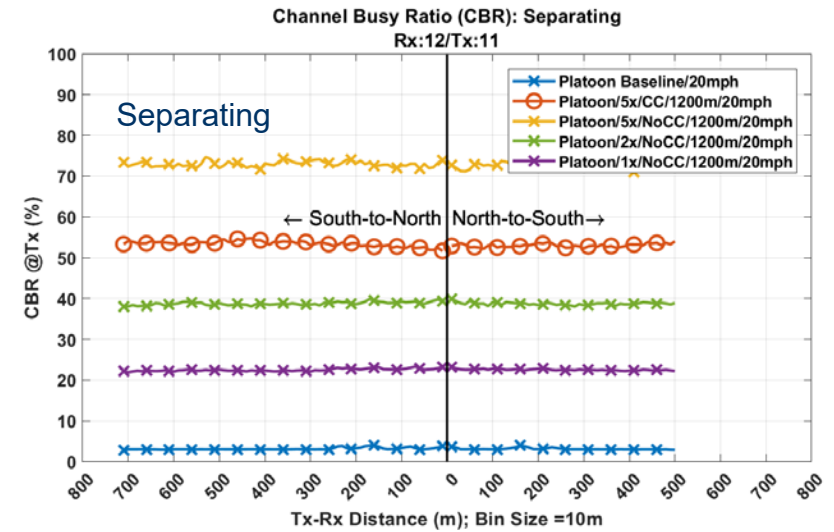
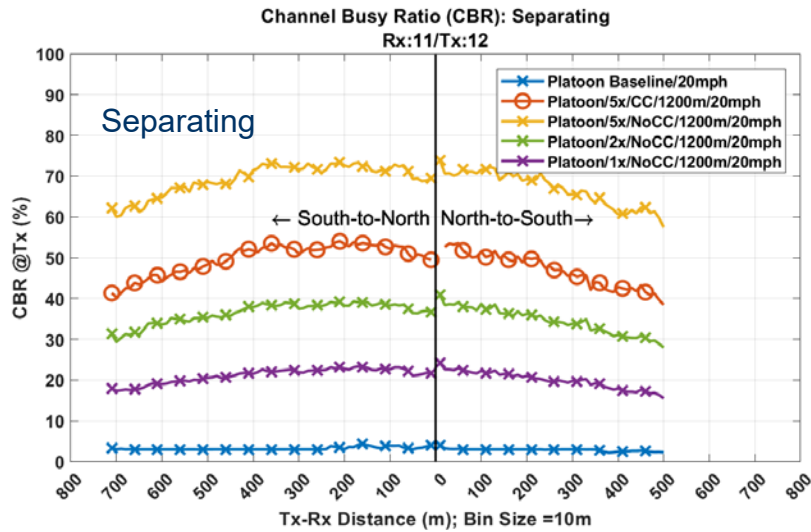
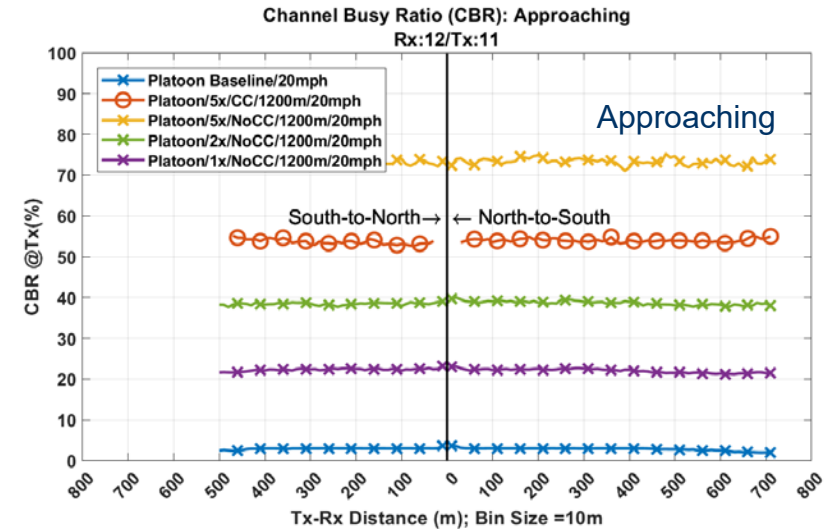
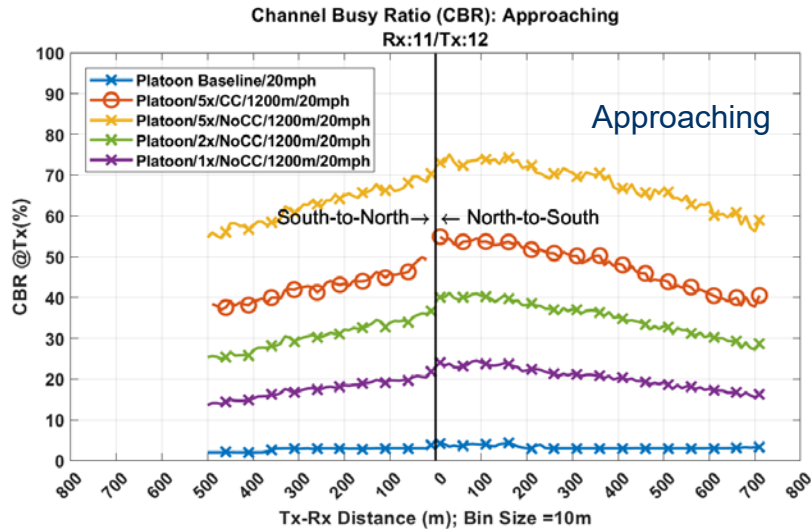
## Moving Vehicle Receiving



# CBR – Platoon Test – 1200m

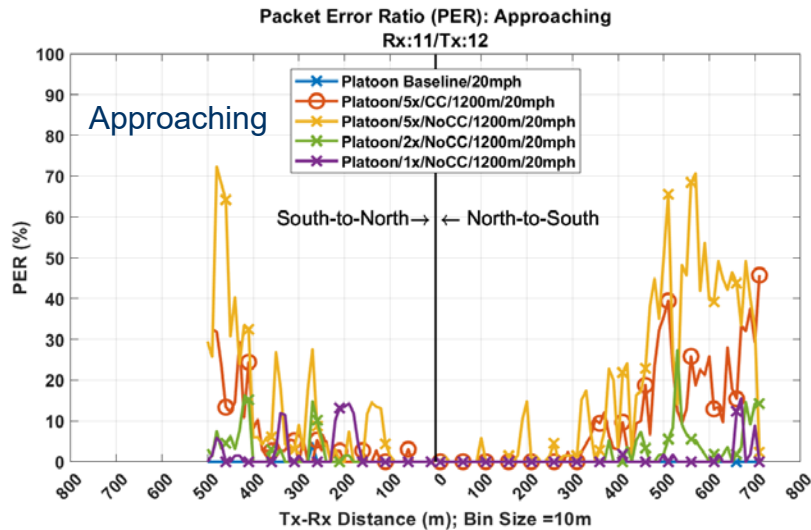
Stationary Vehicle Receiving

Moving Vehicle Receiving

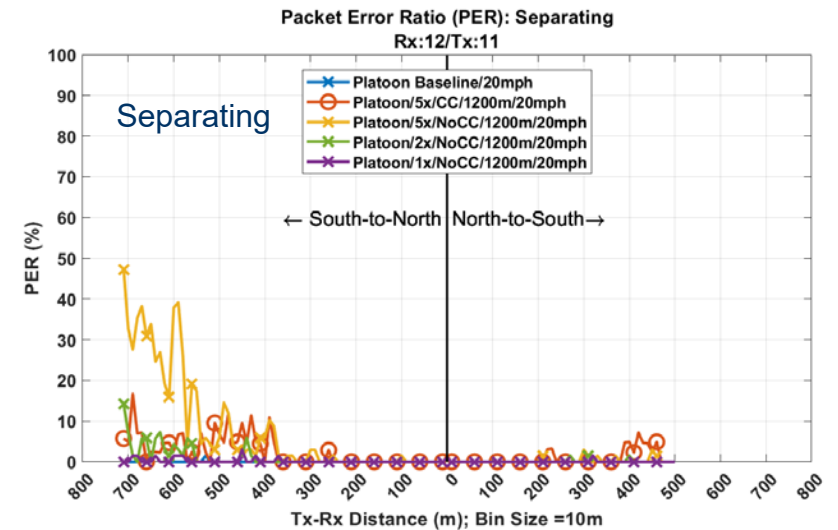
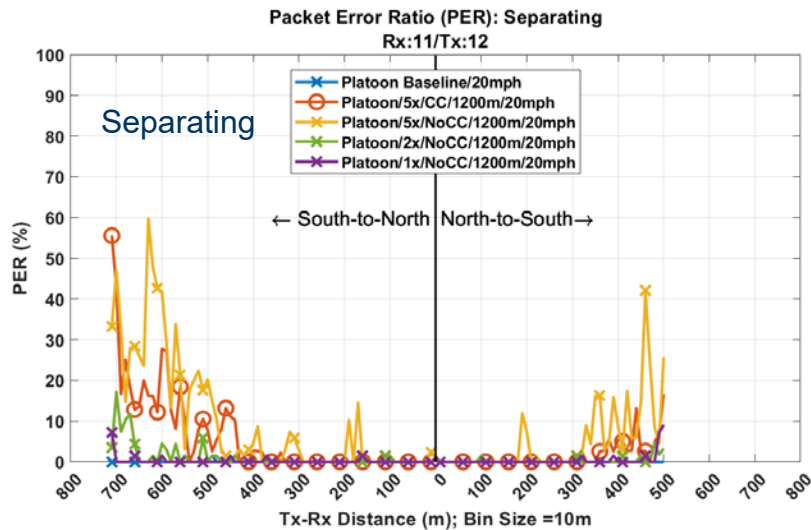
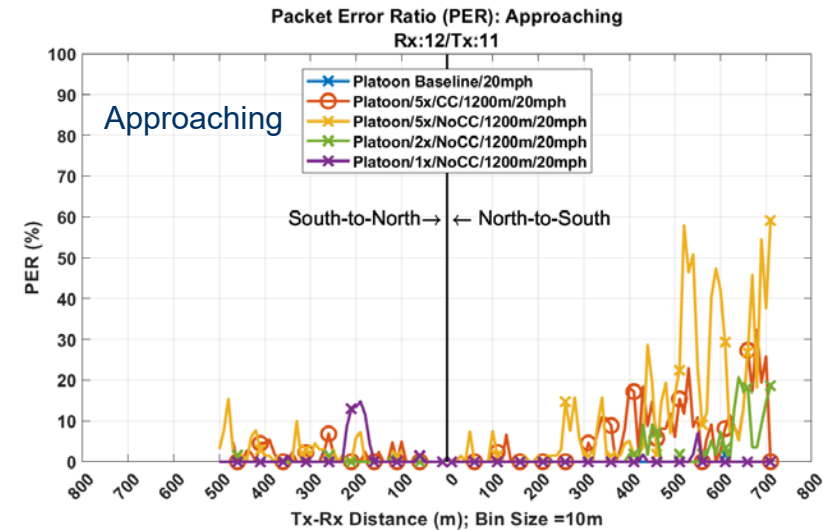


# PER – Platoon Test – 1200m

## Stationary Vehicle Receiving

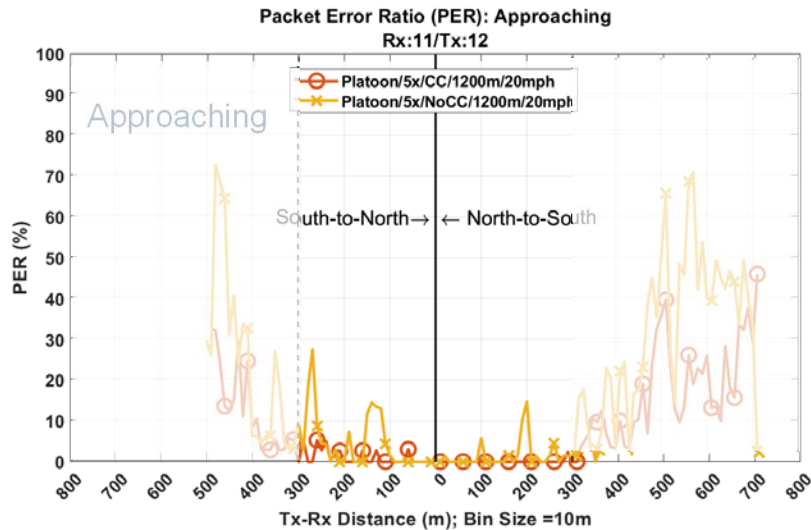


## Moving Vehicle Receiving

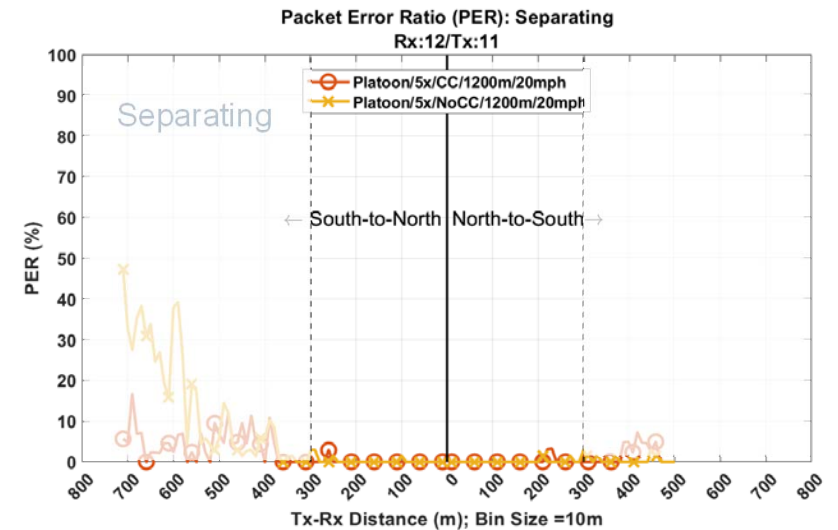
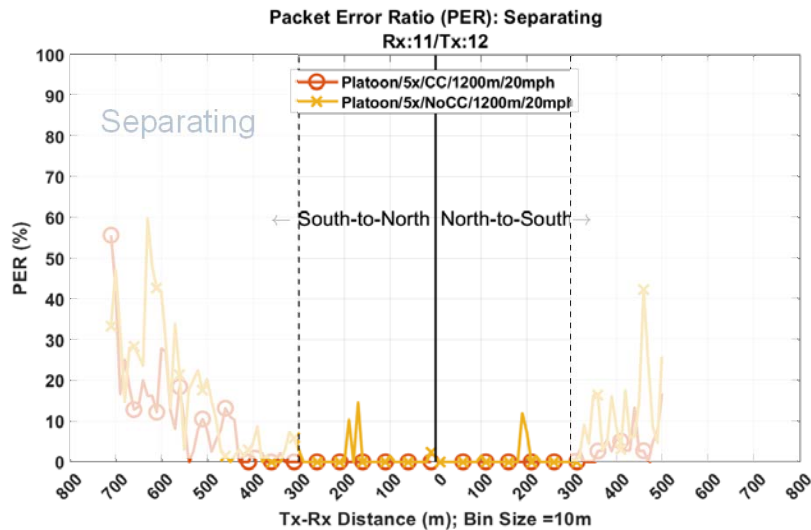
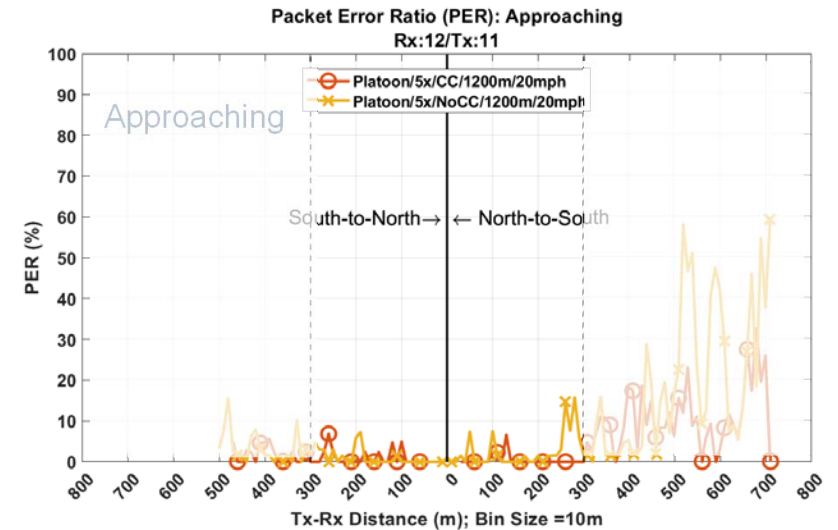


# PER – Platoon Test – 1200m

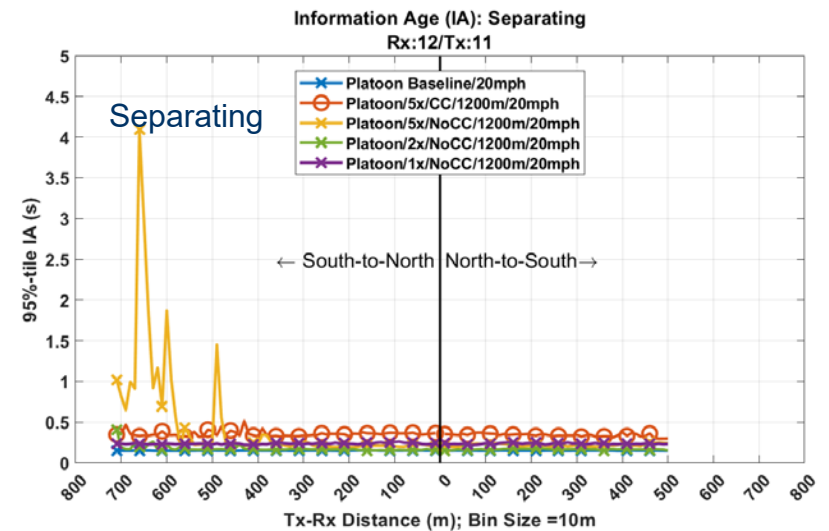
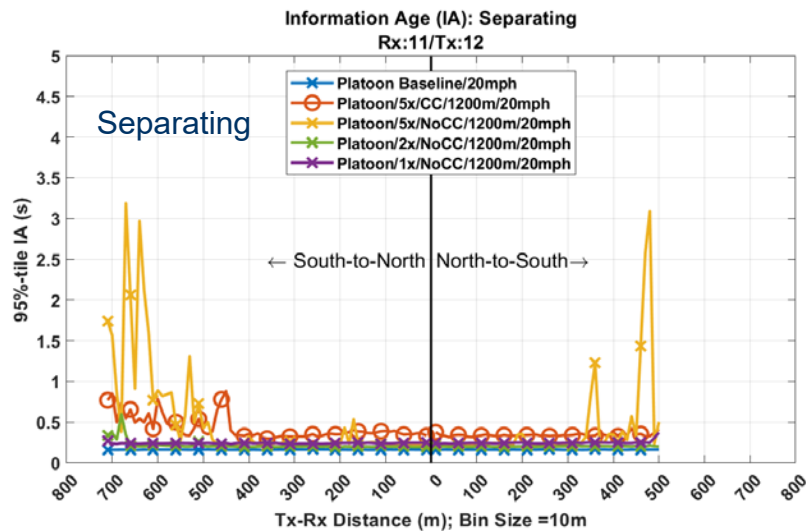
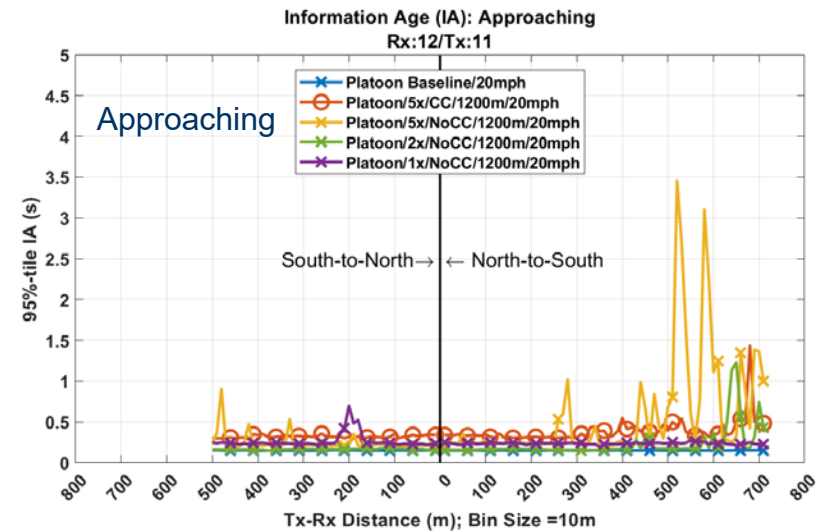
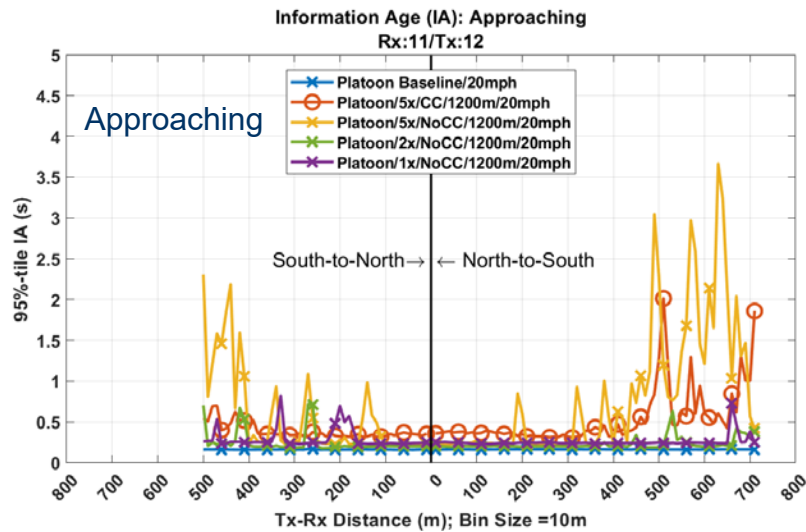
## Stationary Vehicle Receiving



## Moving Vehicle Receiving



# IA – Platoon Test – 1200m

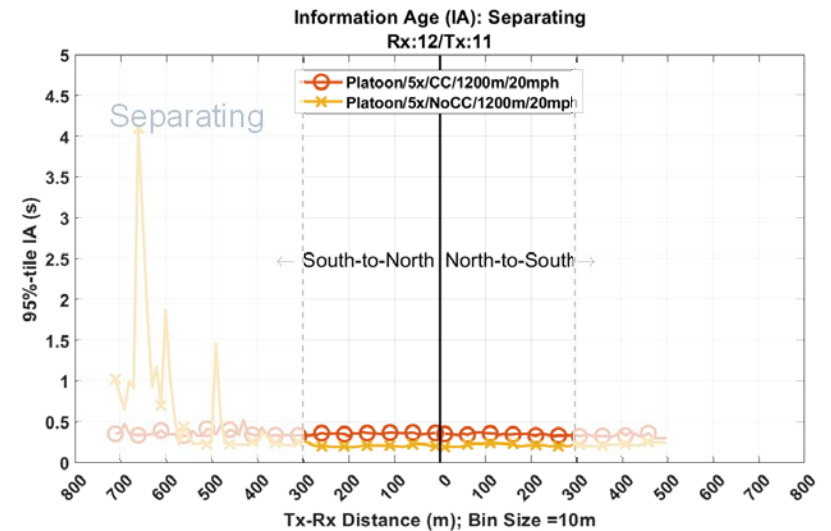
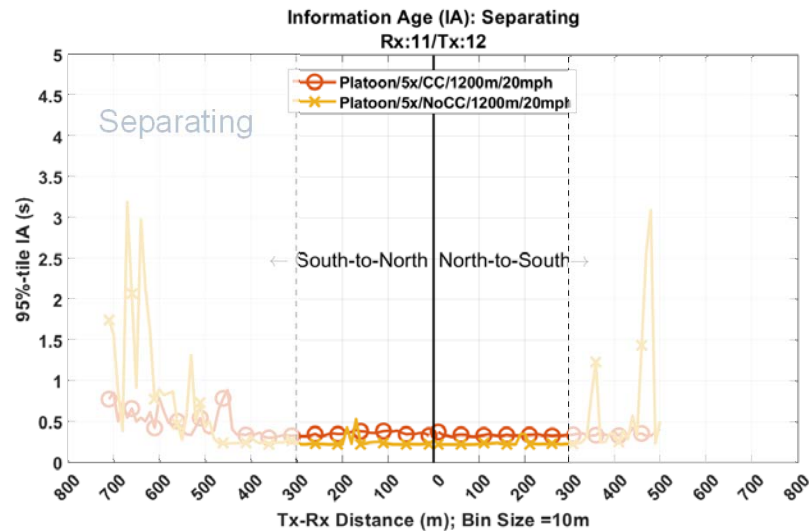
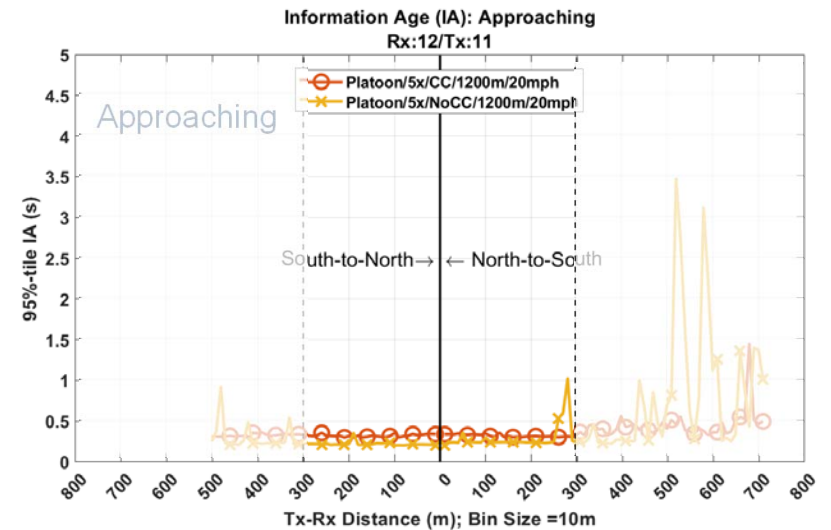
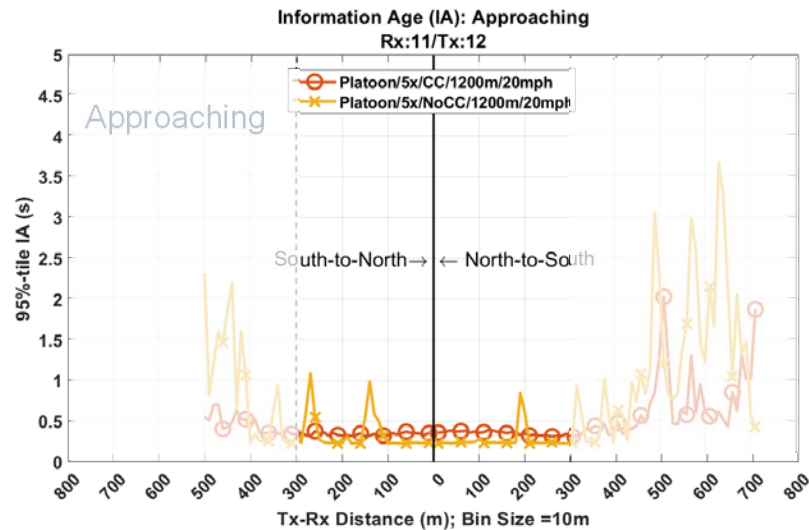




# IA – Platoon Test – 1200m

Stationary Vehicle Receiving

Moving Vehicle Receiving



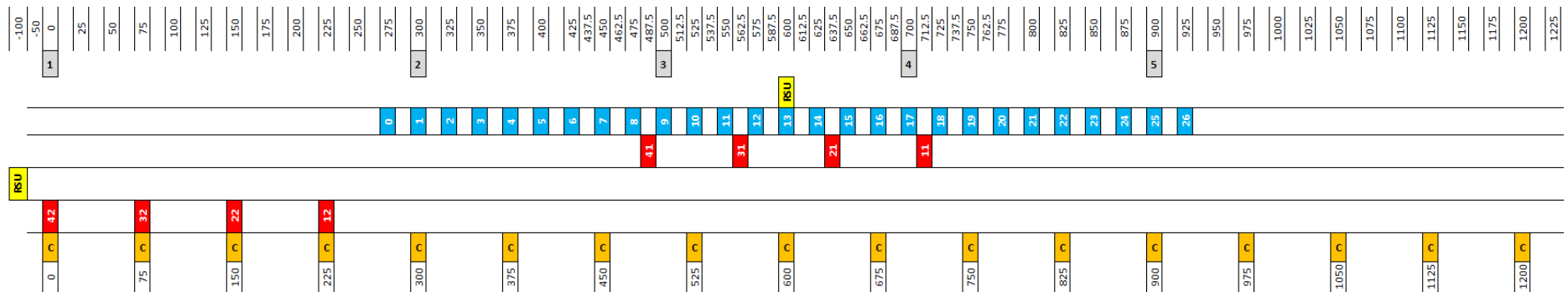


# Platoon Test

Congestion Spread 600m  
Speed 20mph

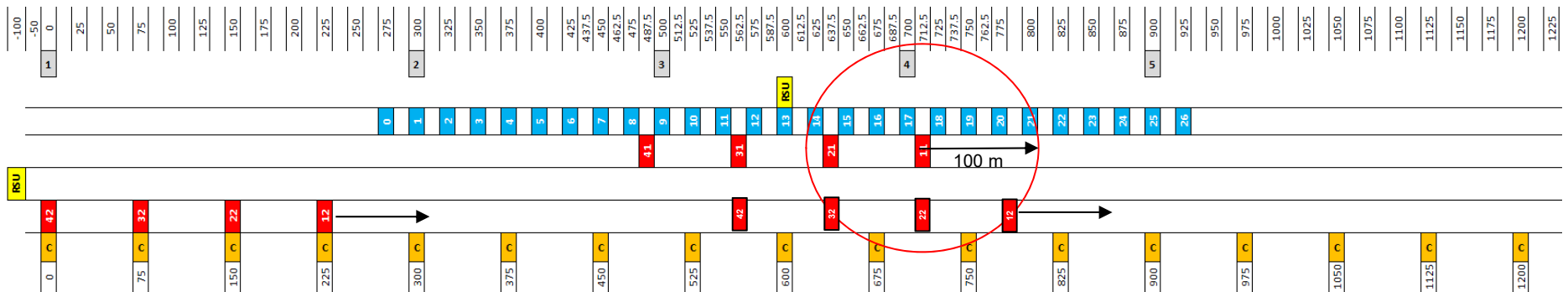
# Test Setup: Platoon 600m

- 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

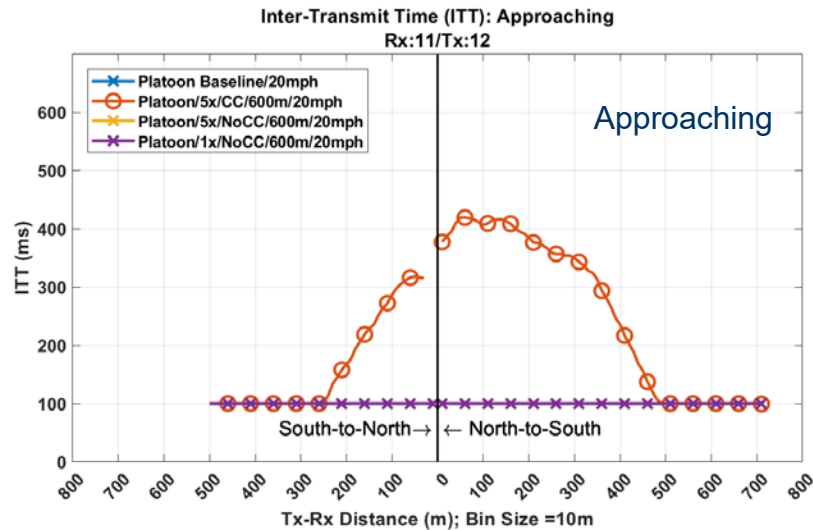
- When the platoon is away vehicle 11 observes
  - ~8 carts (15 OBUs)\*
  - 1 vehicle
  - $\text{Max\_ITT}(k) = 100 \times 16/5 = 320 \text{ ms}$
- When the platoon is partially overlapping vehicle 11 observes
  - ~8 carts (15 OBUs)\*
  - 4 vehicles
  - $\text{Max\_ITT}(k) = 100 \times 19/5 = 380 \text{ ms}$



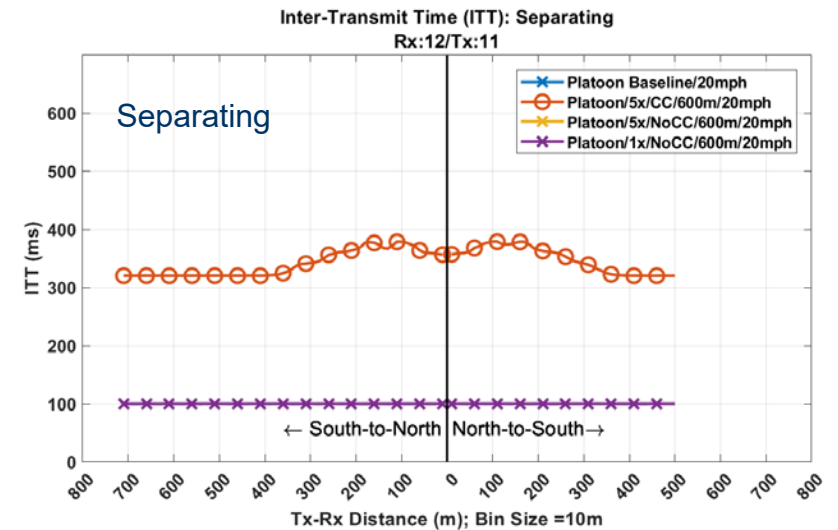
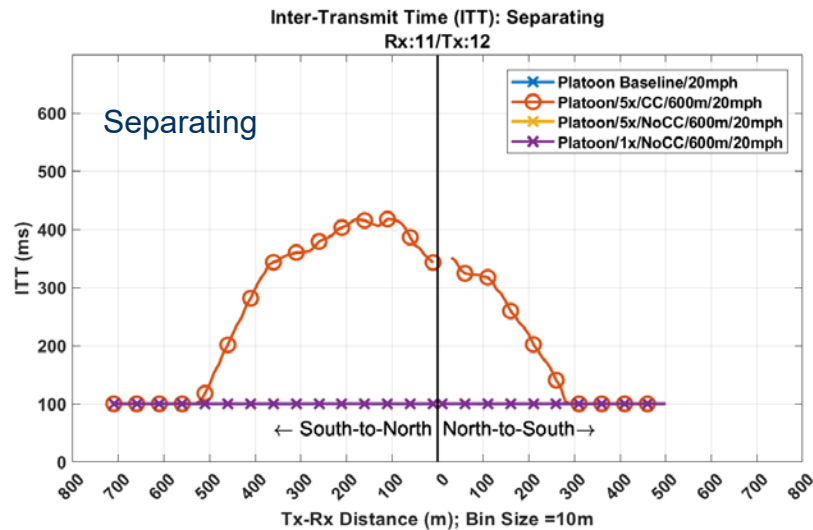
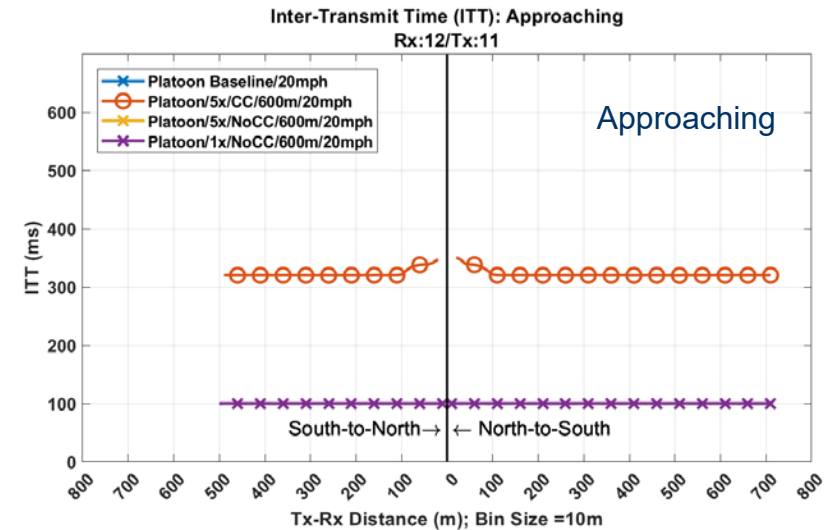
\* A pod on cart 20 was turned off during the test

# ITT – Platoon Test – 600m

## Stationary Vehicle Receiving

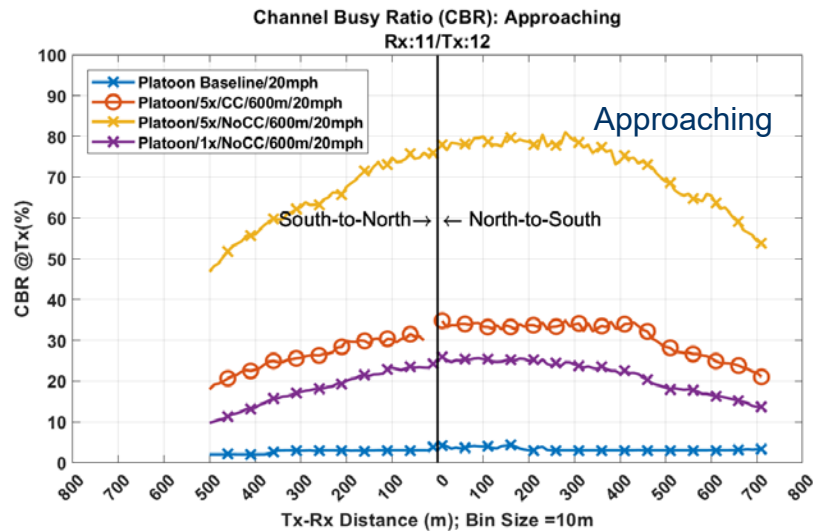


## Moving Vehicle Receiving

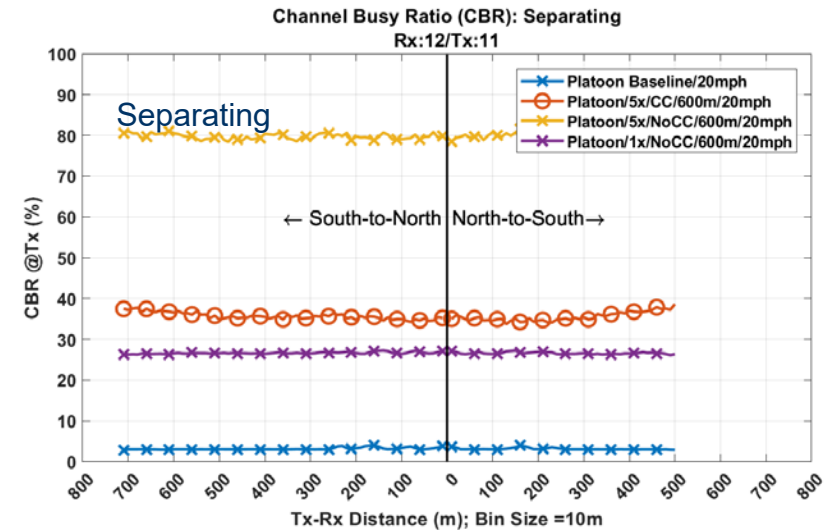
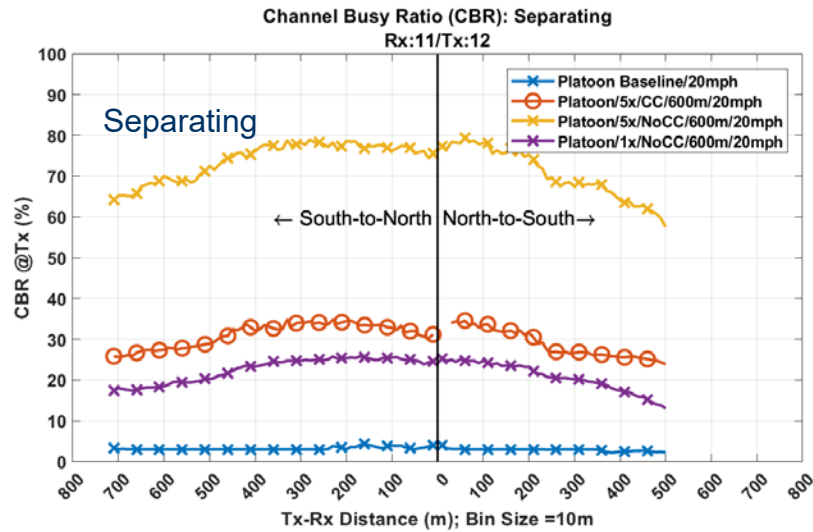
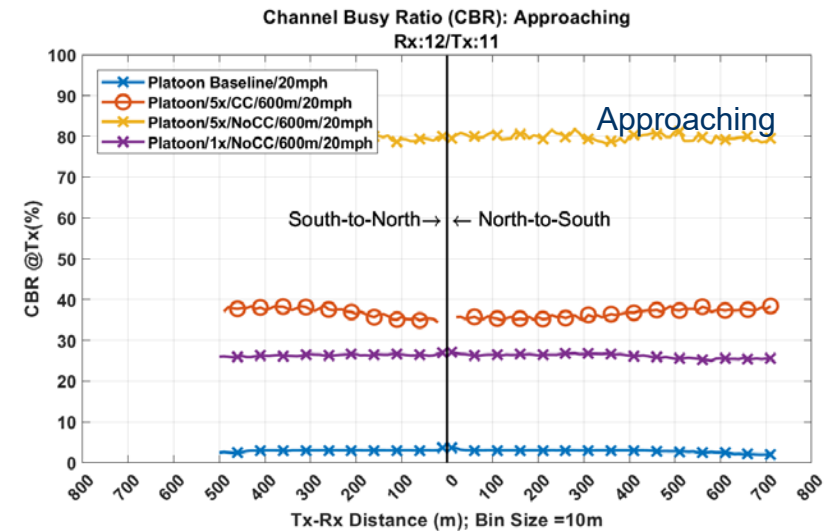


# CBR – Platoon Test – 600m

## Stationary Vehicle Receiving

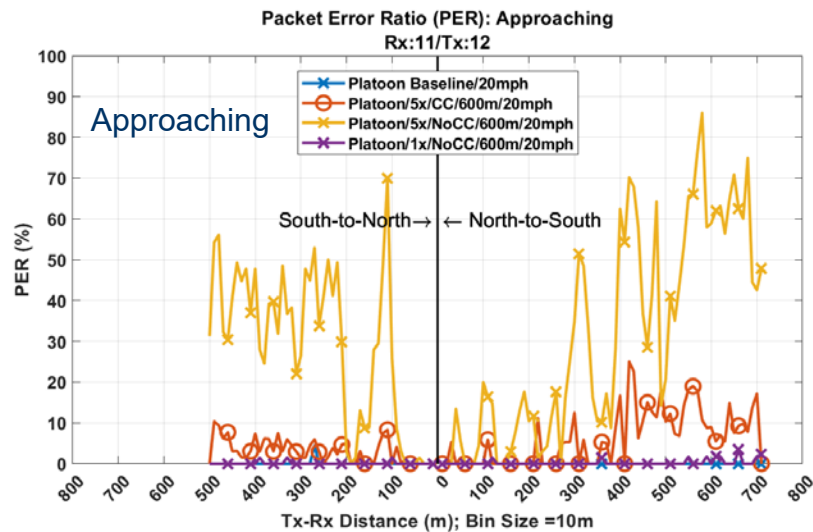


## Moving Vehicle Receiving

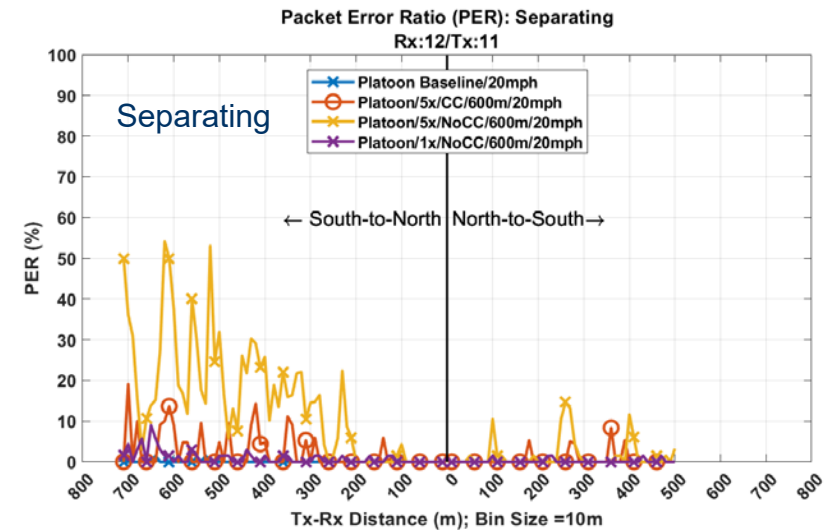
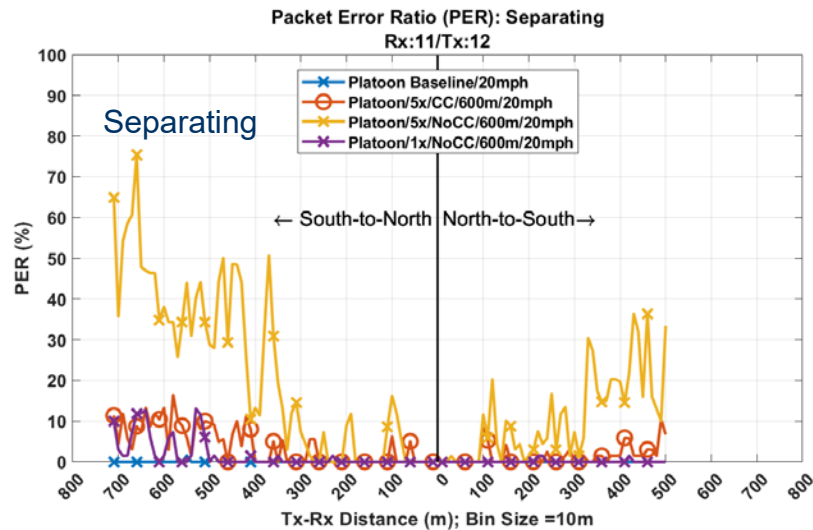
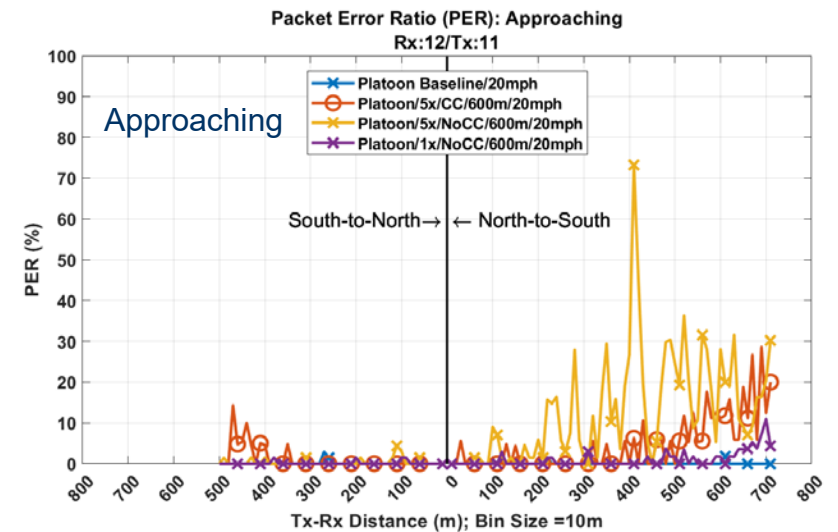


# PER – Platoon Test – 600m

## Stationary Vehicle Receiving

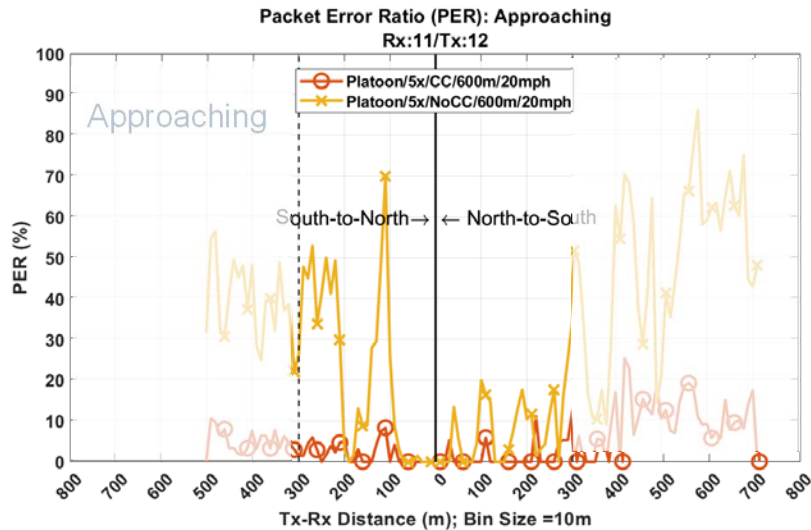


## Moving Vehicle Receiving

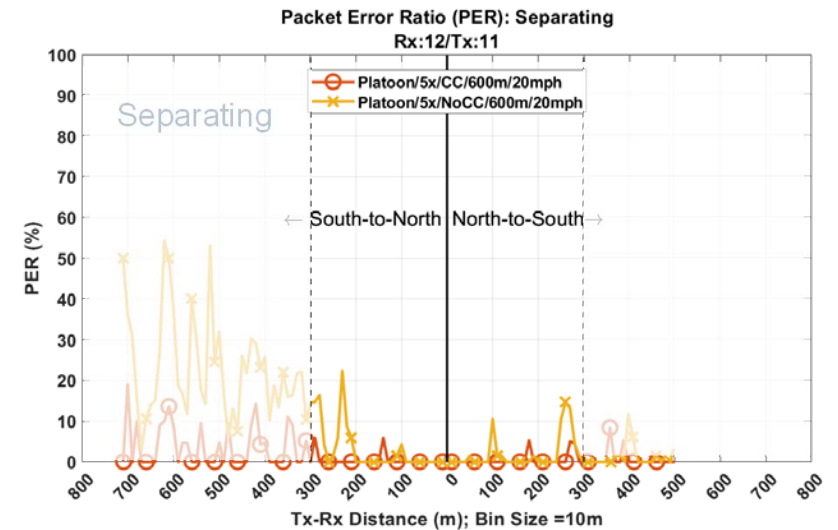
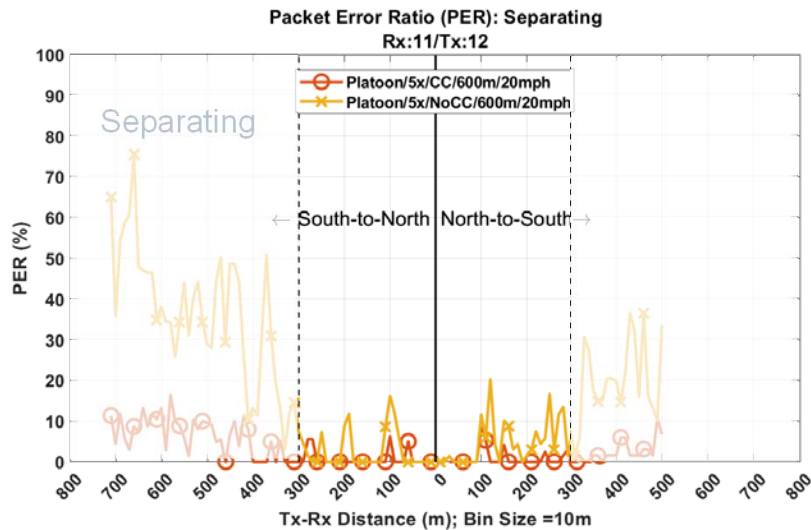
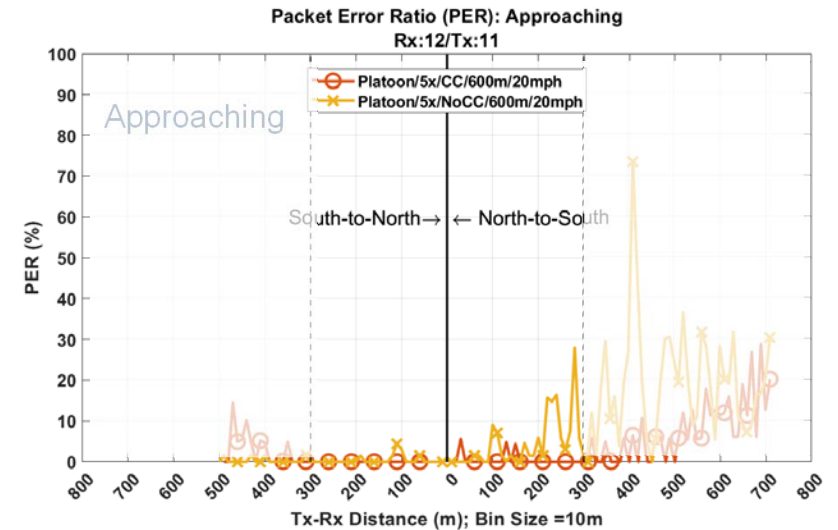


# PER – Platoon Test – 600m

## Stationary Vehicle Receiving



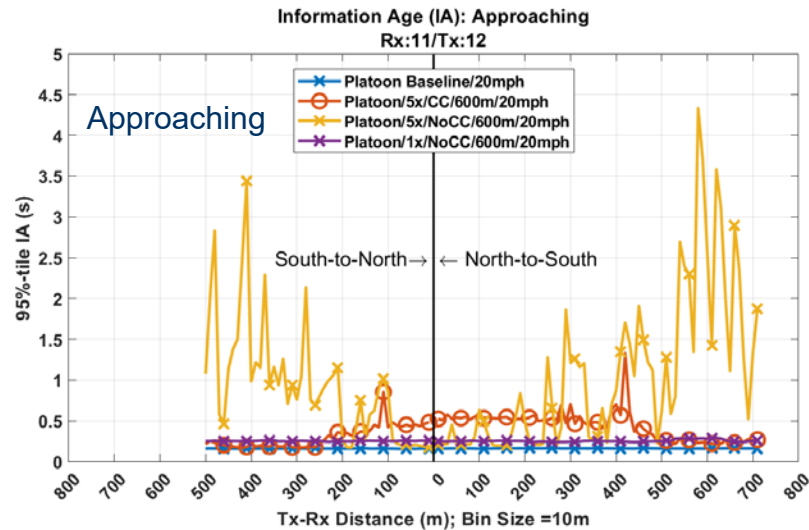
## Moving Vehicle Receiving



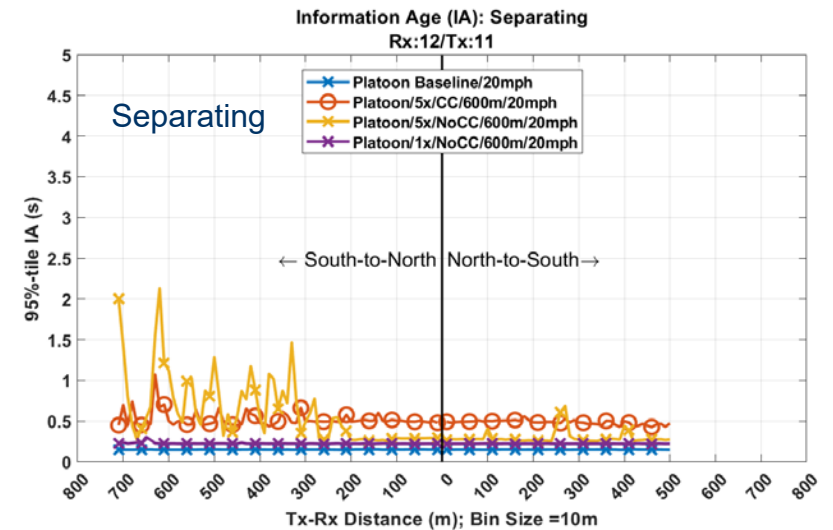
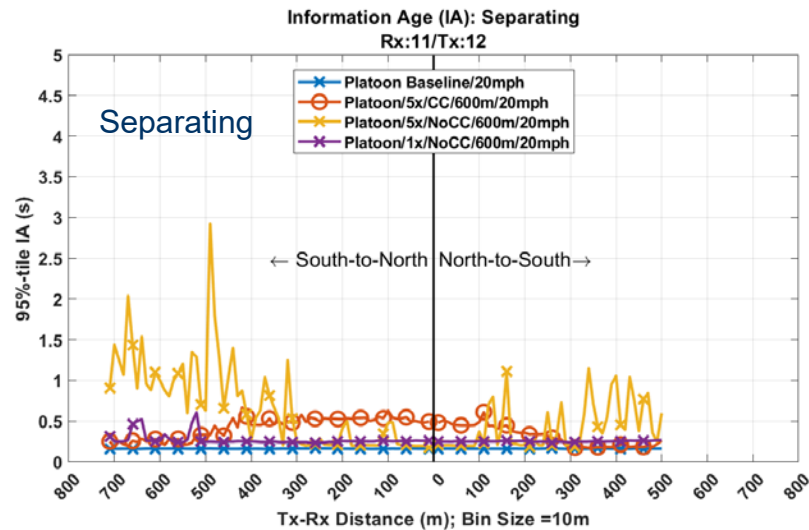
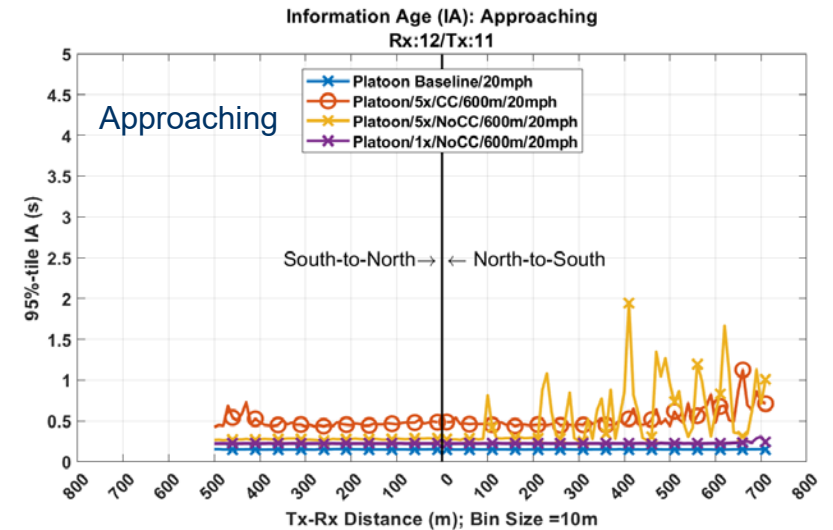


# IA – Platoon Test – 600m

## Stationary Vehicle Receiving



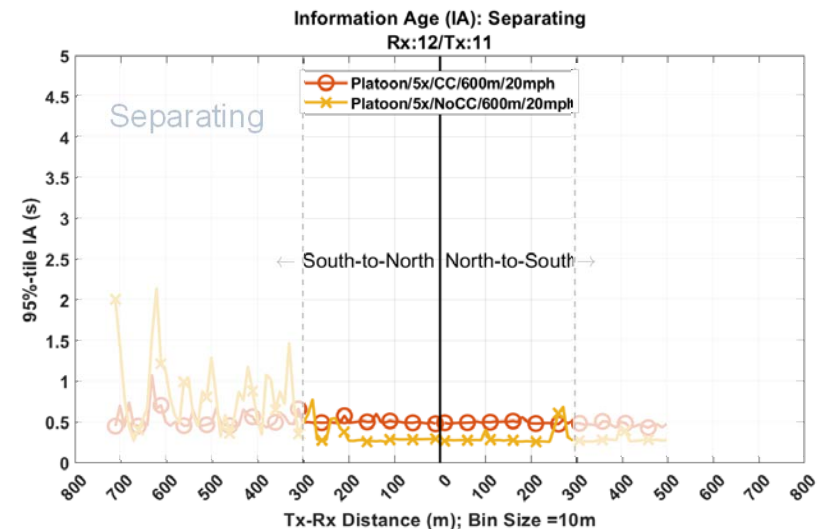
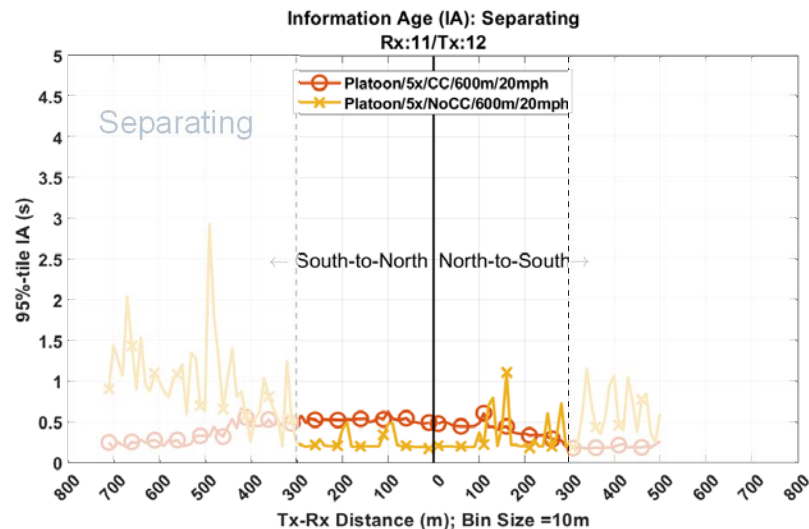
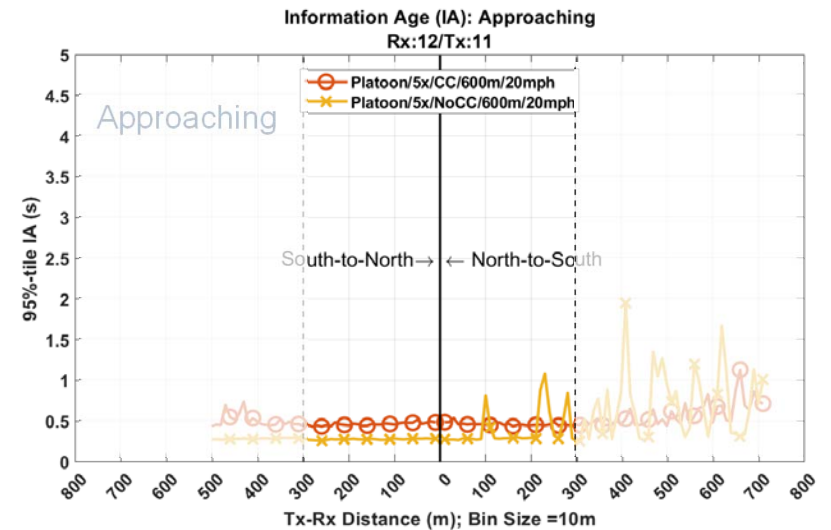
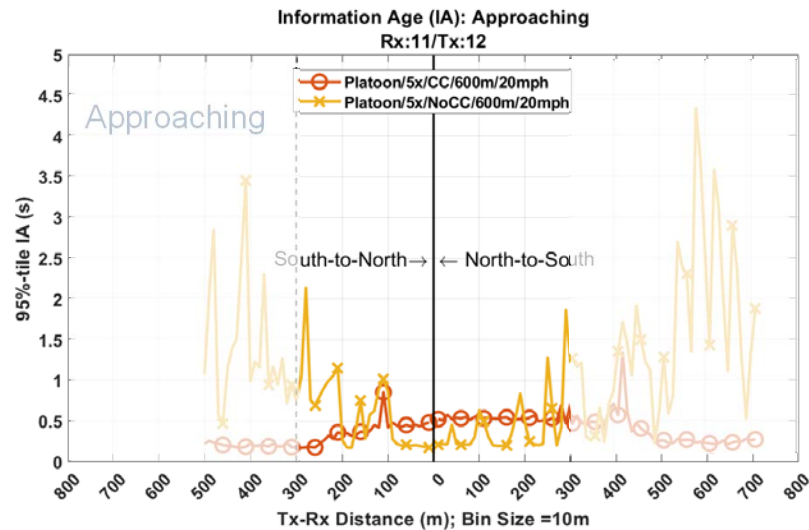
## Moving Vehicle Receiving



# IA – Platoon Test – 600m

Stationary Vehicle Receiving

Moving Vehicle Receiving

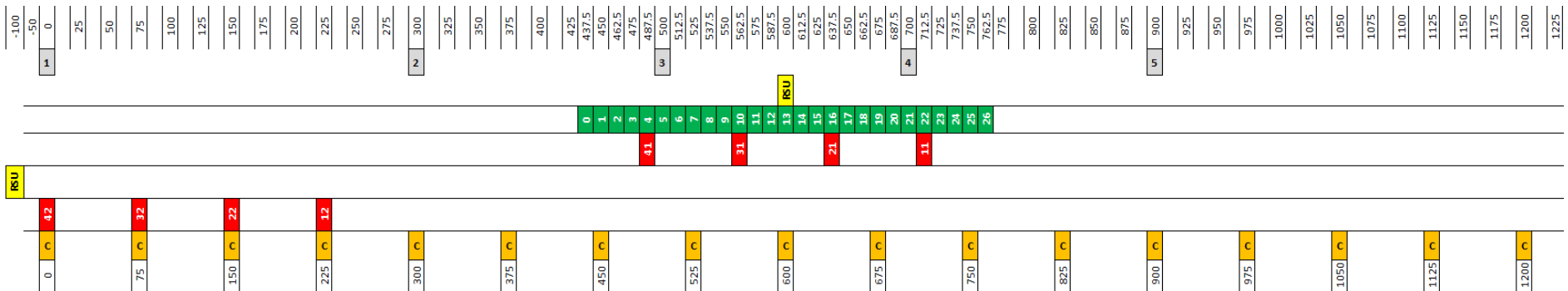


# Platoon Test

Congestion Spread 300m  
Speed 20mph

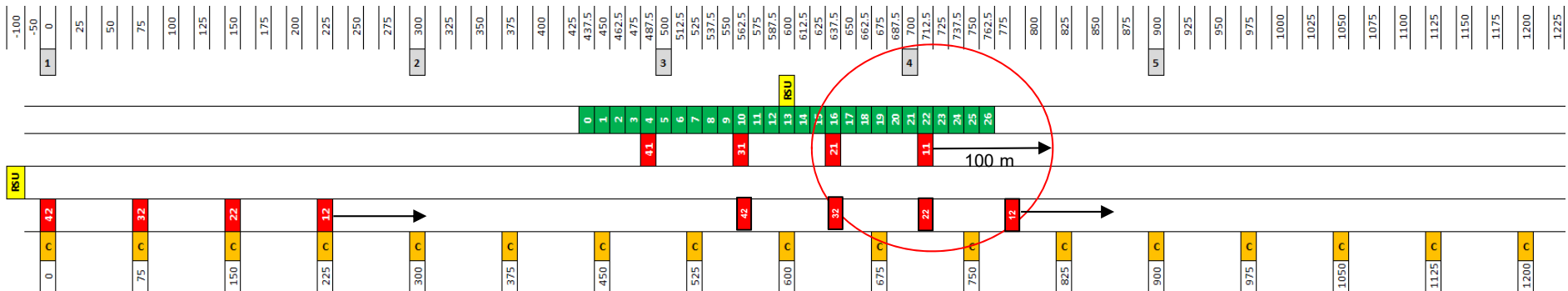
# Test Setup: Platoon 300m

- 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



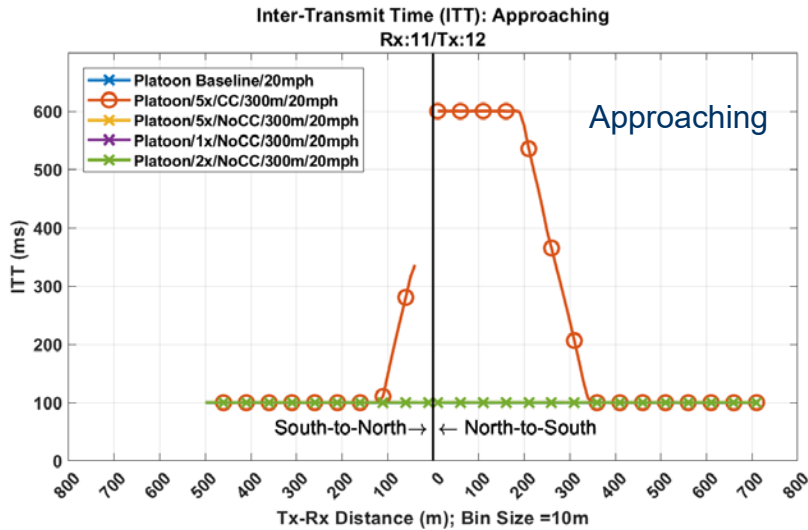
# Max\_ITT Estimate for Vehicle 11 at 5X Emulation

- When the platoon is away vehicle 11 observes
  - ~12 carts (24 OBUs)
  - 1 vehicle
  - $\text{Max\_ITT}(k) = 100 \times 25/5 = 500 \text{ ms}$
- When the platoon is partially overlapping vehicle 11 observes
  - ~12 carts (24 OBUs)
  - 4 vehicles
  - $\text{Max\_ITT}(k) = 100 \times 28/5 = 560 \text{ ms}$

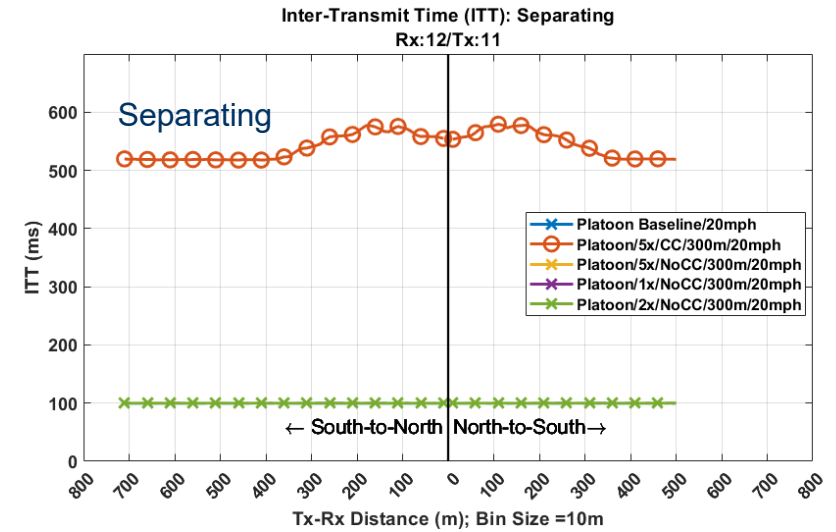
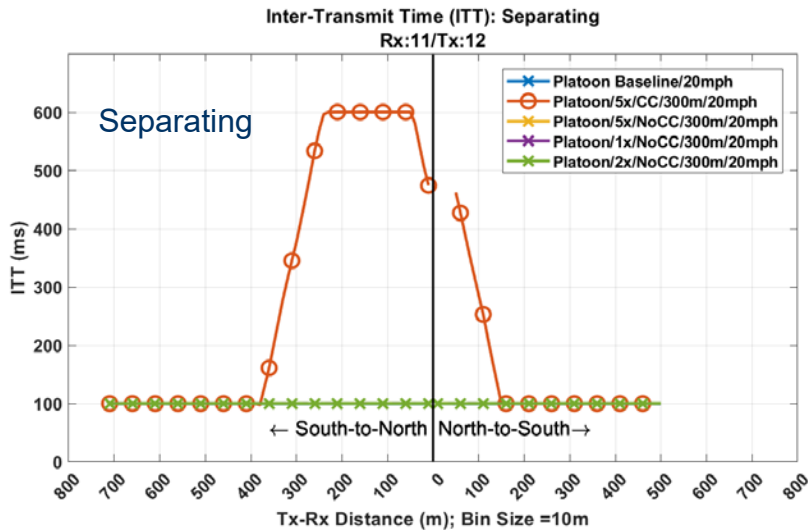
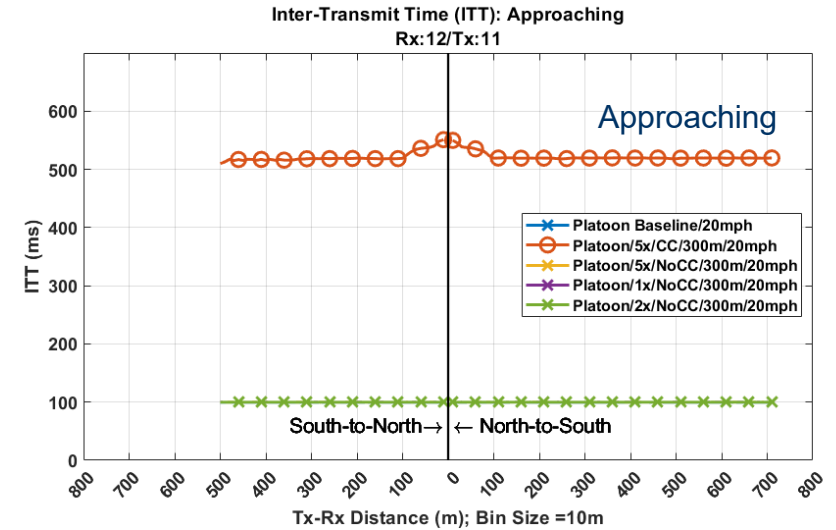


# ITT – Platoon Test – 300m

## Stationary Vehicle Receiving



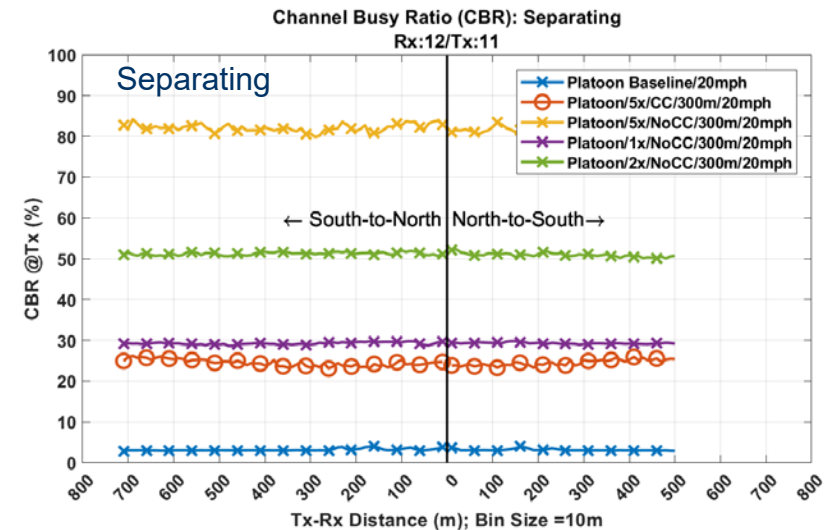
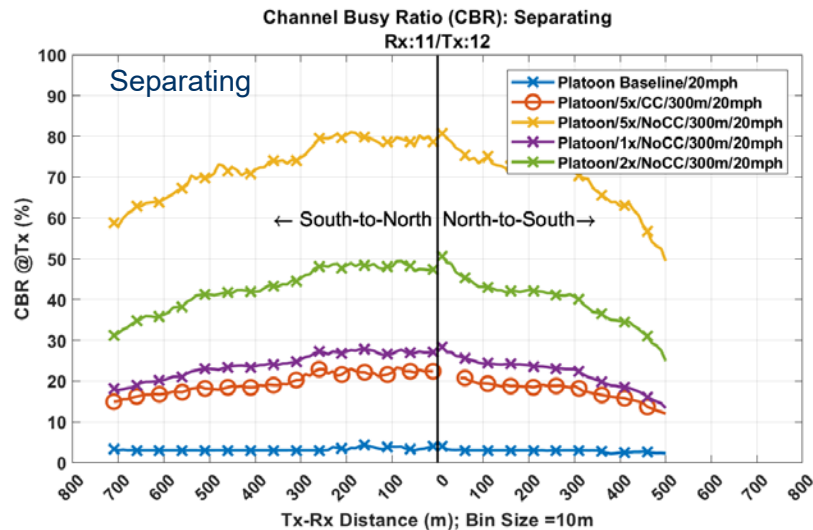
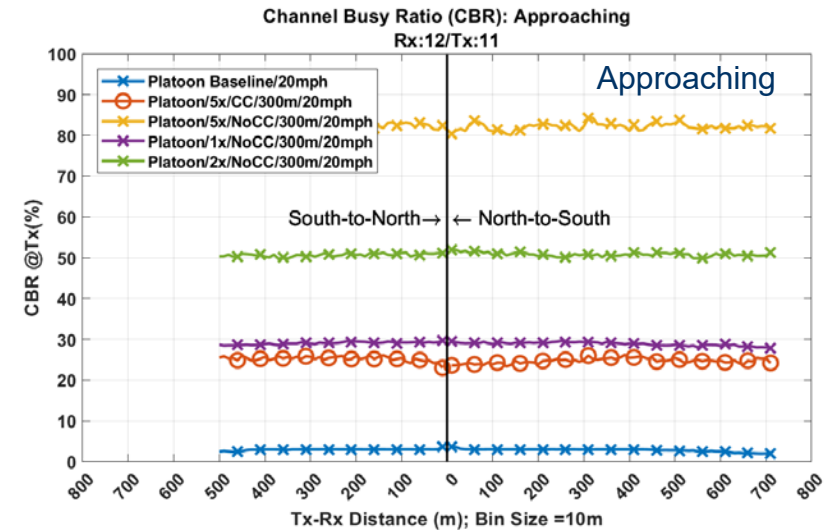
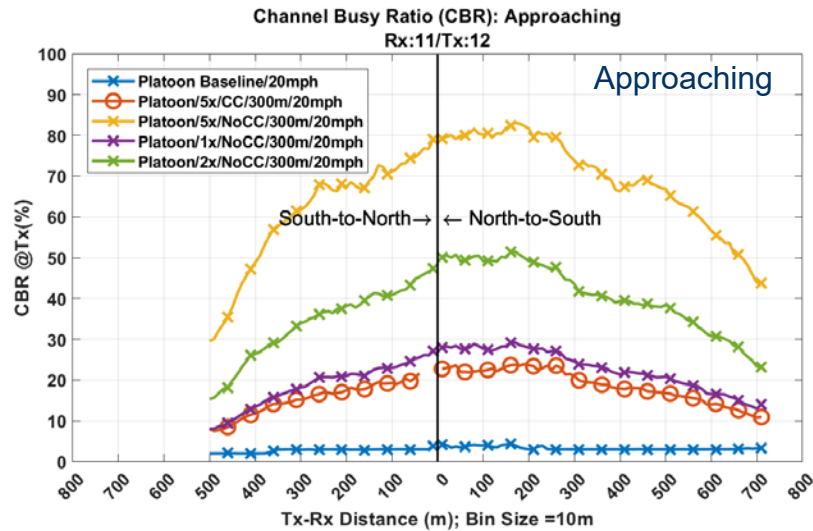
## Moving Vehicle Receiving



# CBR – Platoon Test – 300m

## Stationary Vehicle Receiving

## Moving Vehicle Receiving

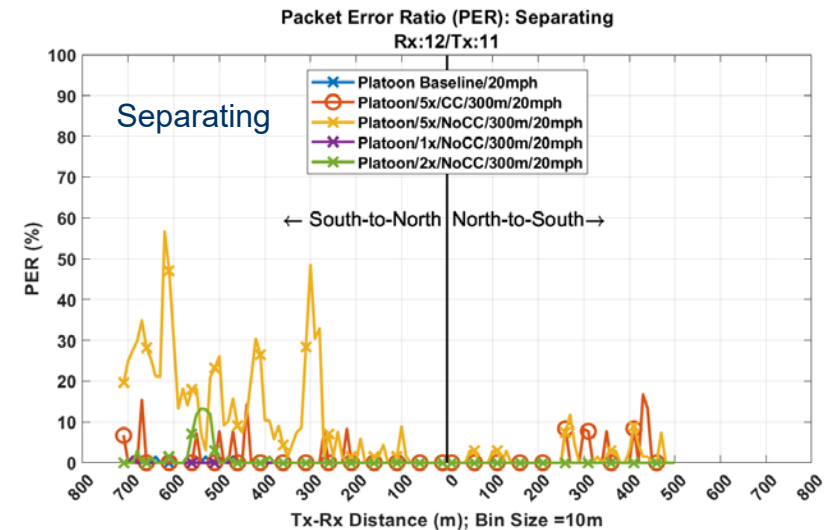
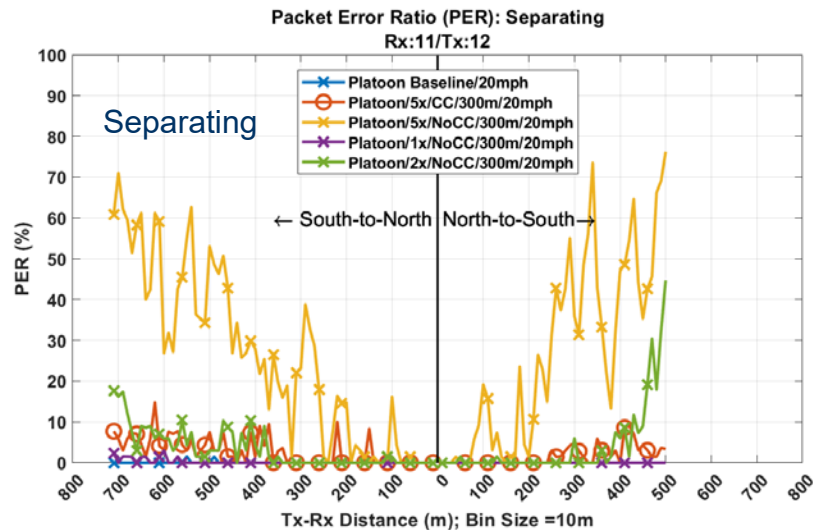
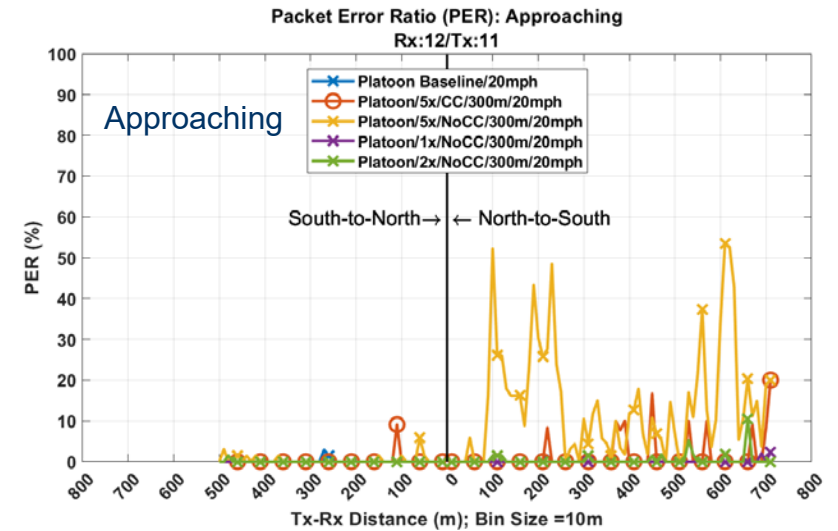
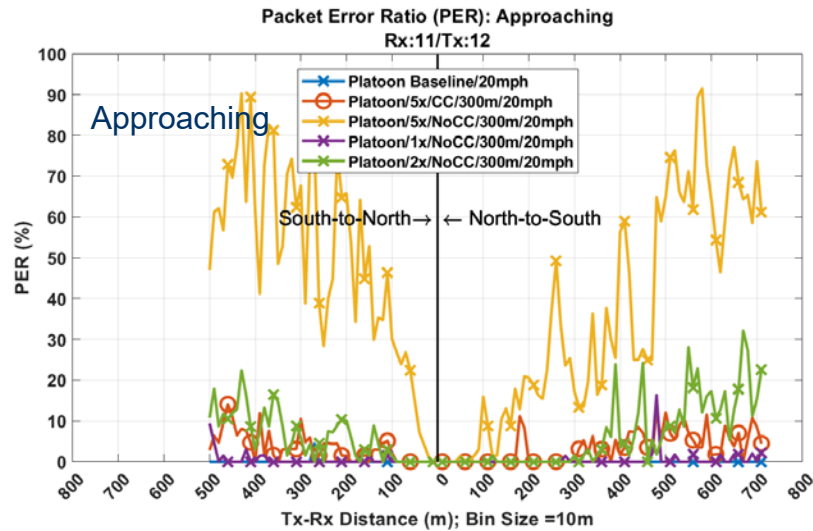




# PER – Platoon Test – 300m

Stationary Vehicle Receiving

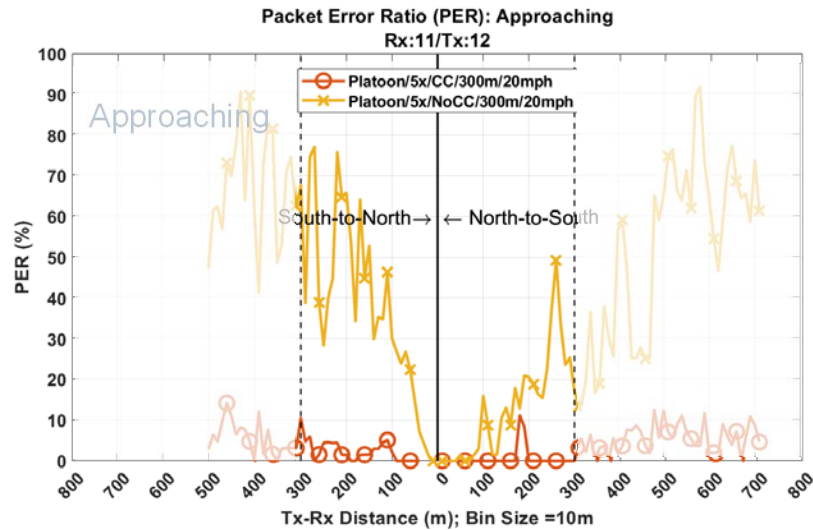
Moving Vehicle Receiving



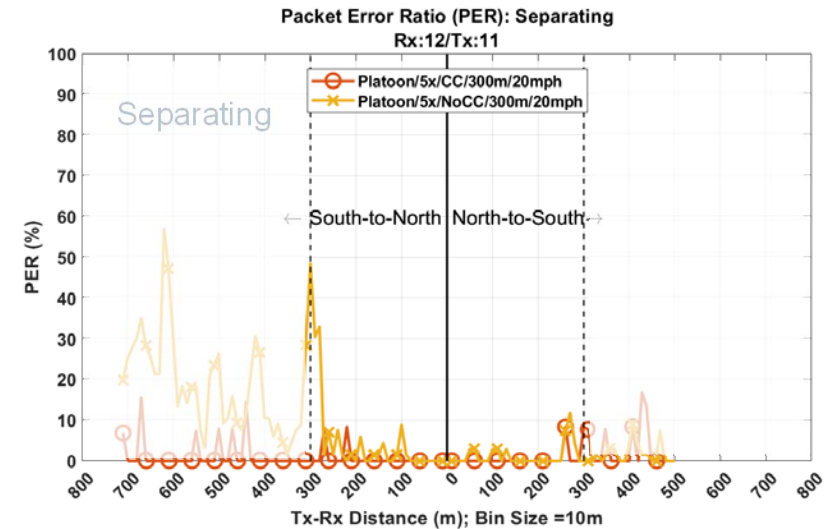
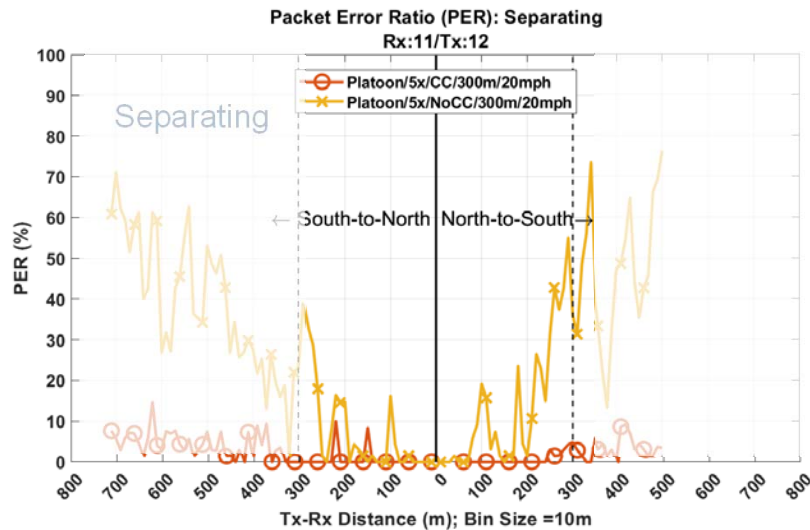
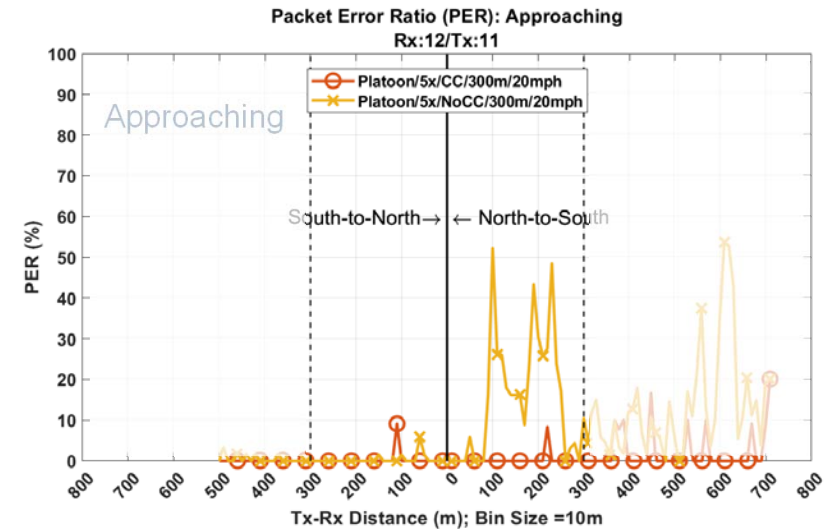


# PER – Platoon Test – 300m

## Stationary Vehicle Receiving



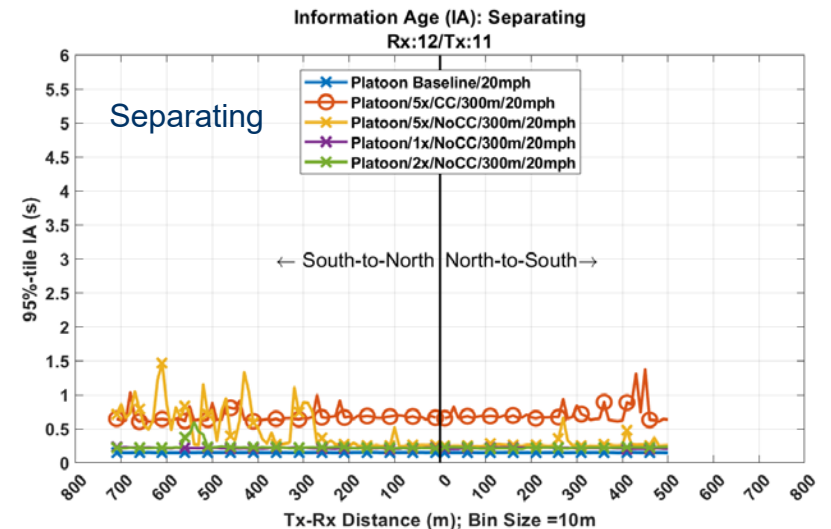
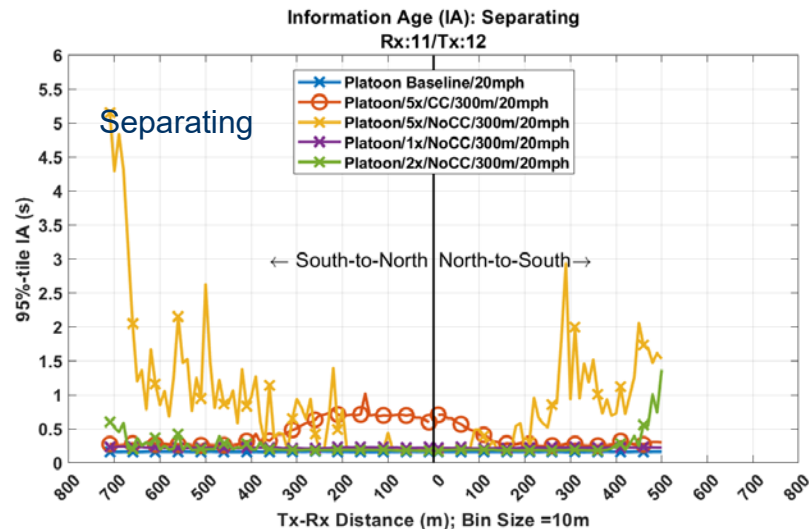
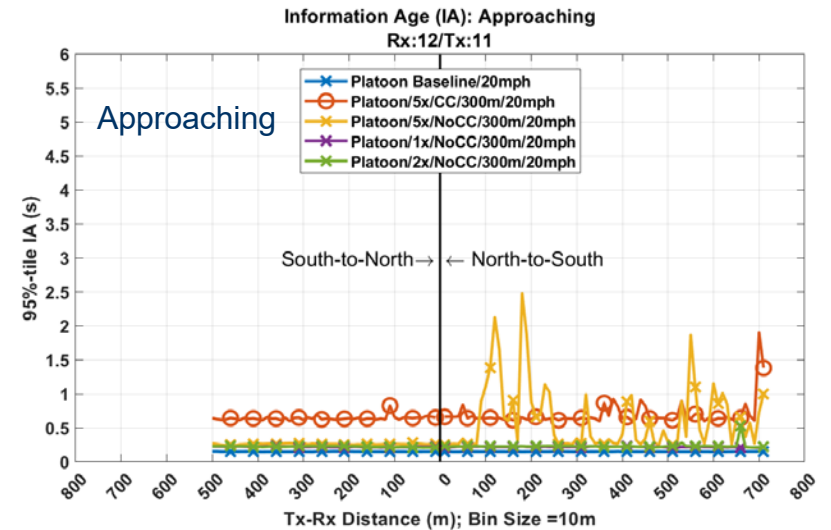
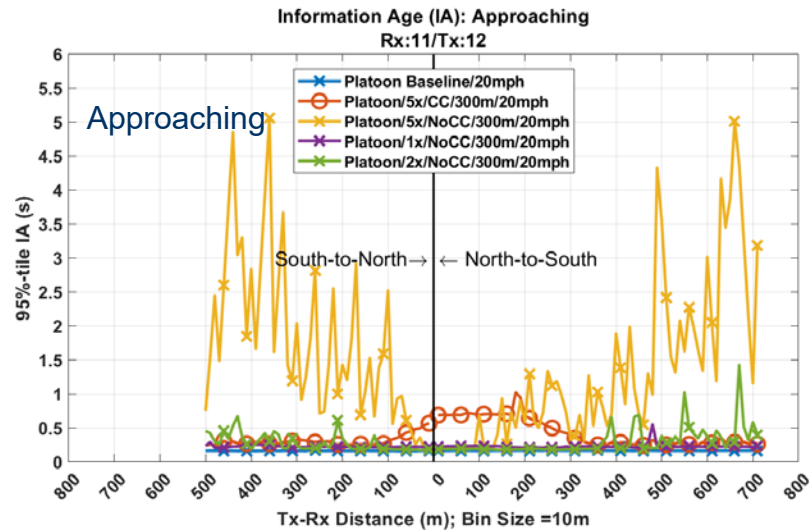
## Moving Vehicle Receiving



# IA – Platoon Test – 300m

Stationary Vehicle Receiving

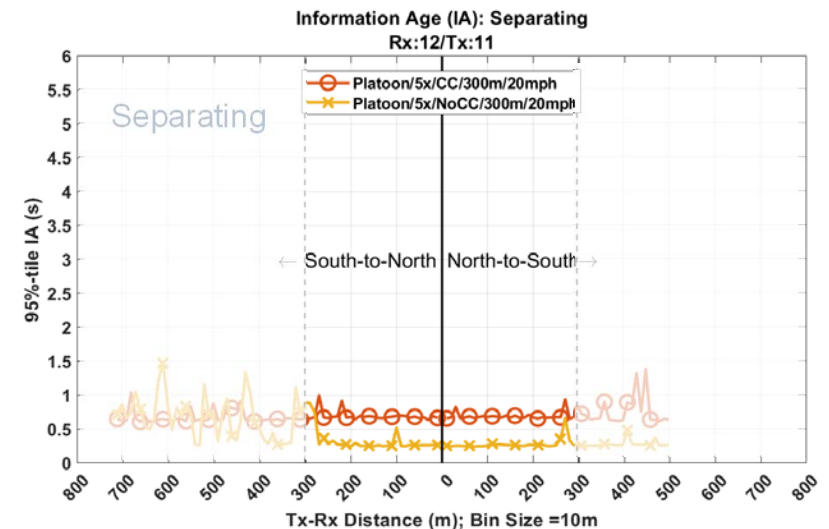
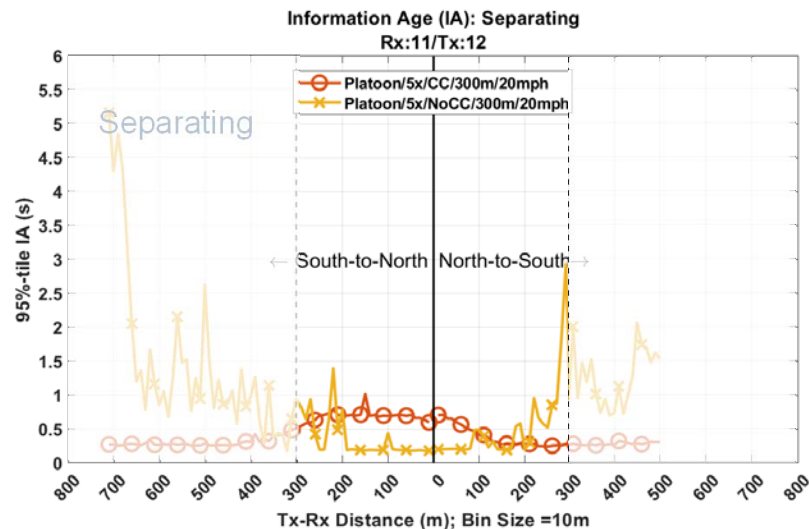
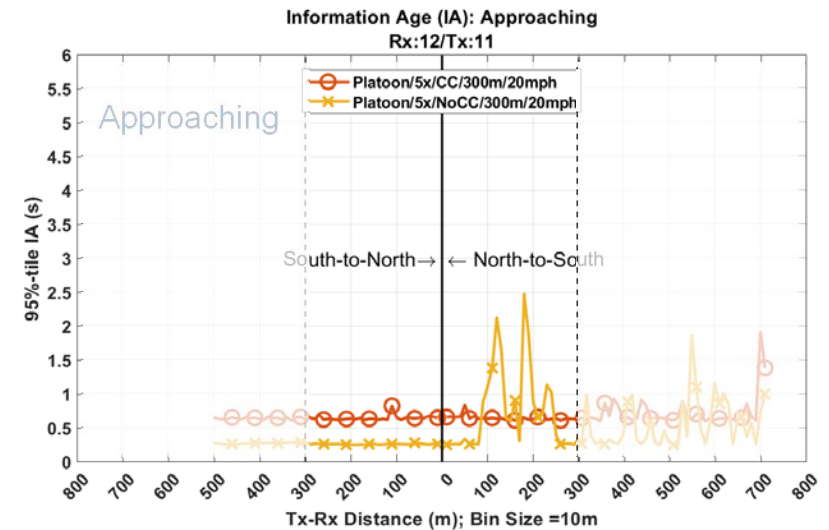
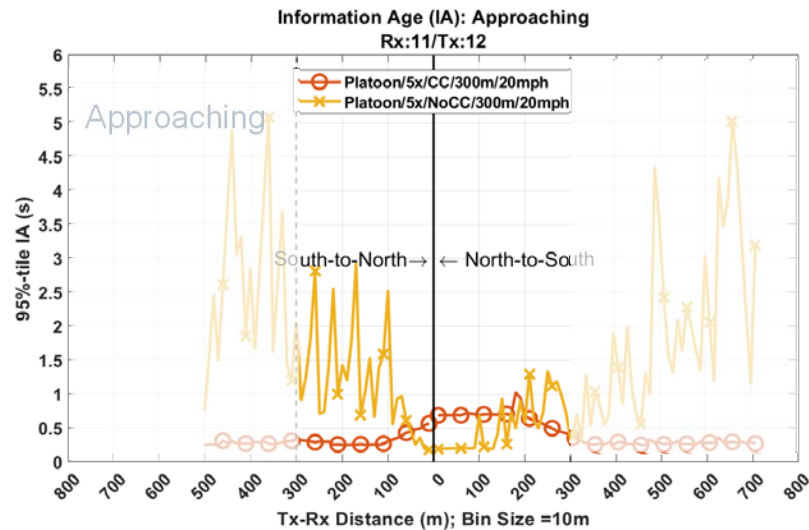
Moving Vehicle Receiving



# IA – Platoon Test – 300m

Stationary Vehicle Receiving

Moving Vehicle Receiving

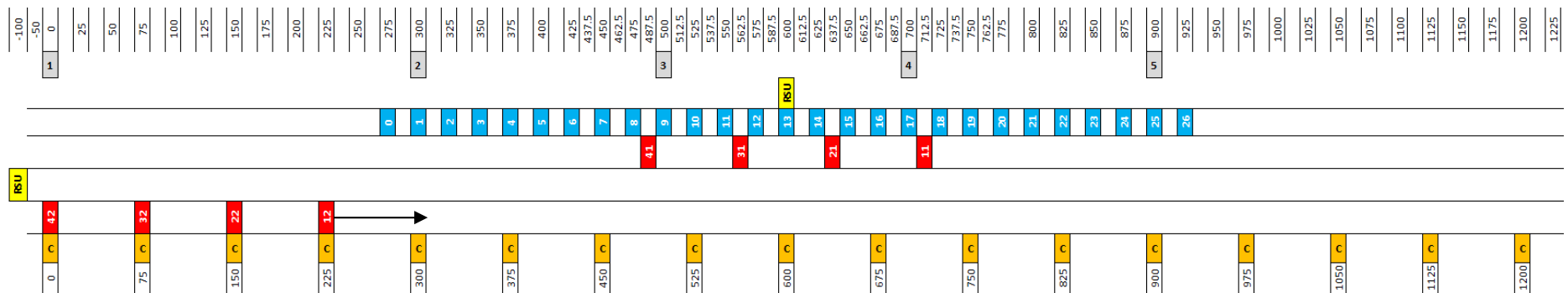


# High Speed Test

Congestion Spread 600m  
Speed 80mph

# Test Setup: High Speed, 600m

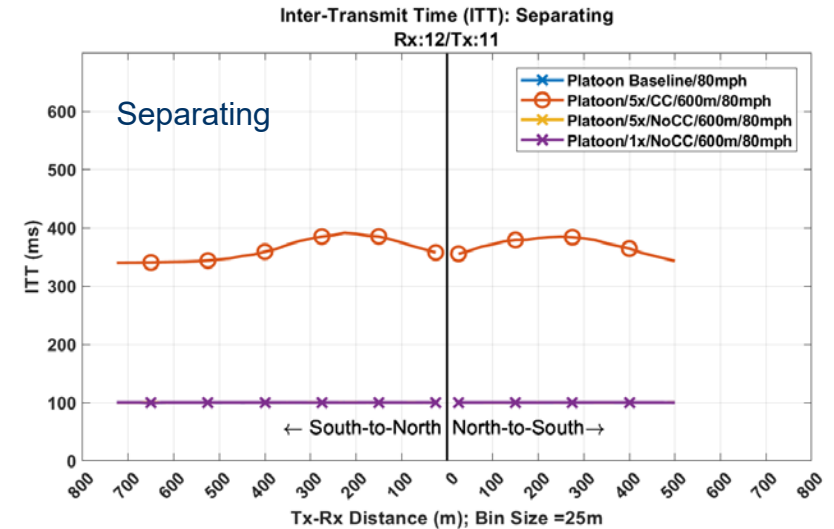
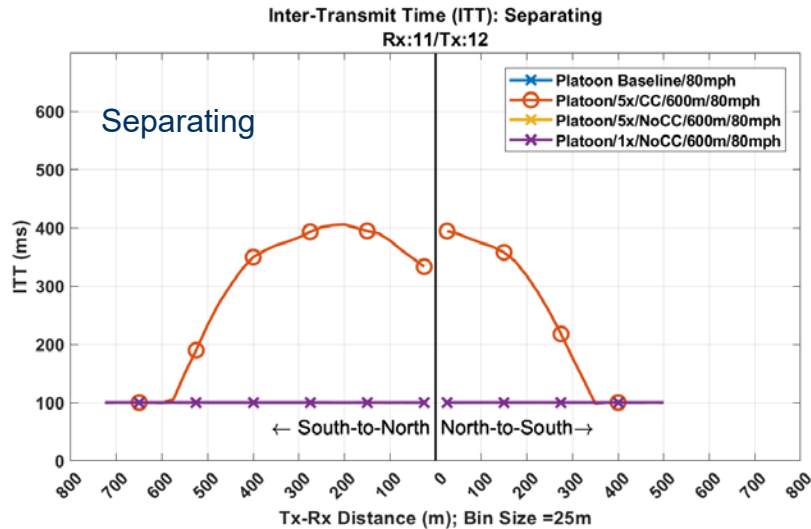
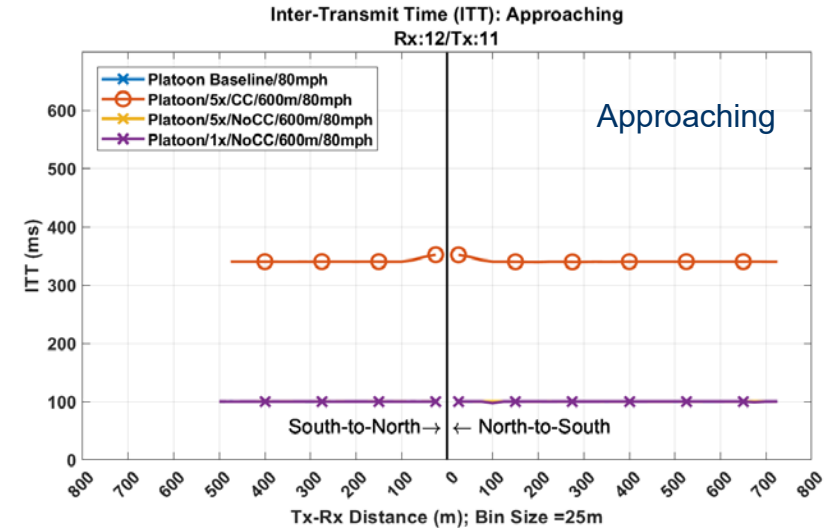
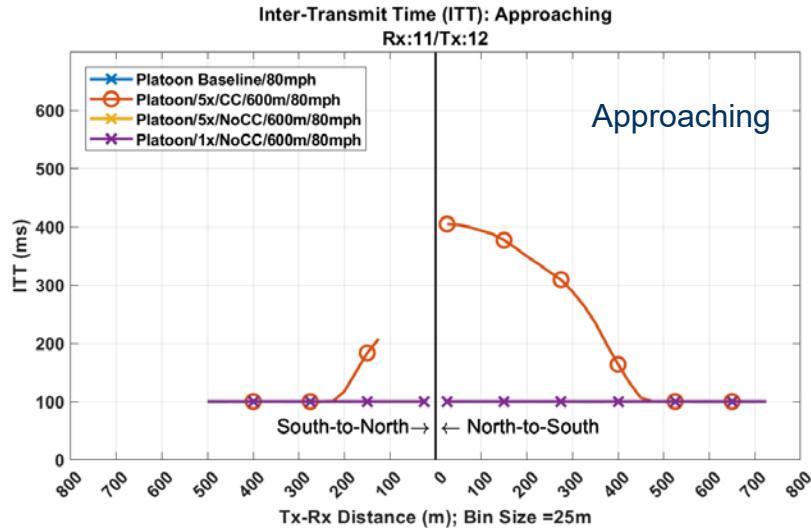
- Stationary OBEs: 11, 21, 31, 41
- Platoon OBEs: 12, 22, 32, 42
- Congestion Carts: 0-26 (start at 275m)
- Cart 13 at 600m (center of the test track)
- Results shown for (Vehicle 11, Vehicle 12) pair



# ITT – High Speed Test – 600m

Stationary Vehicle Receiving

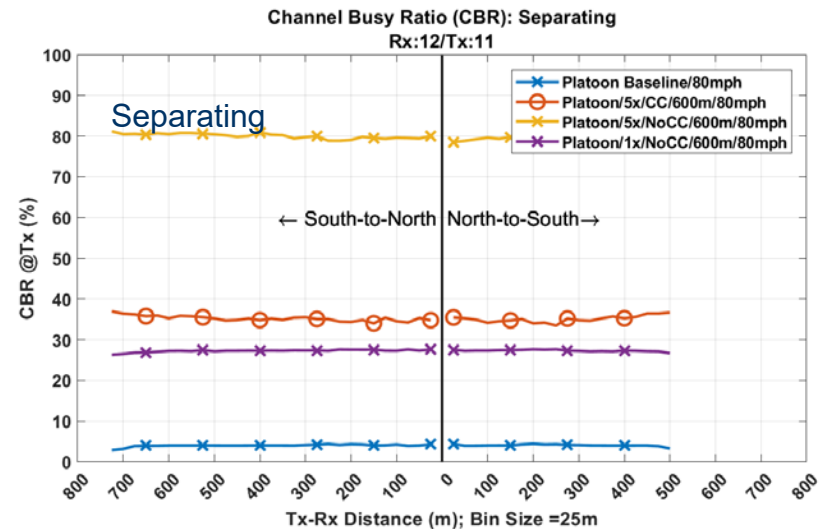
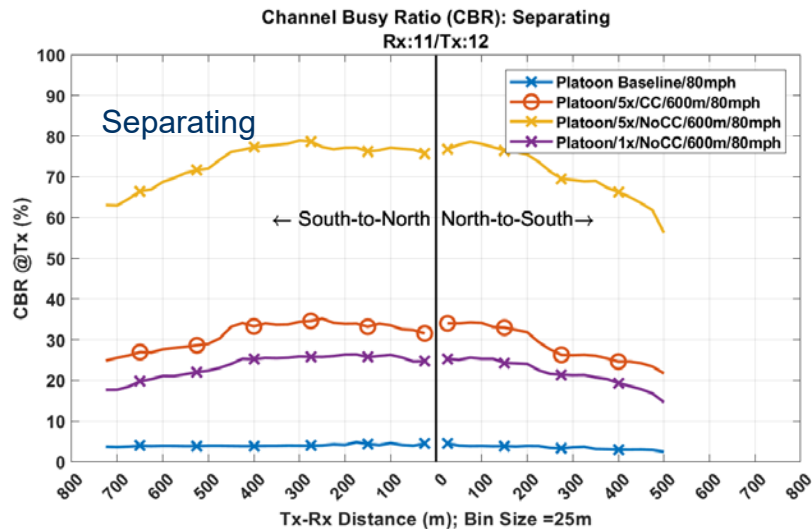
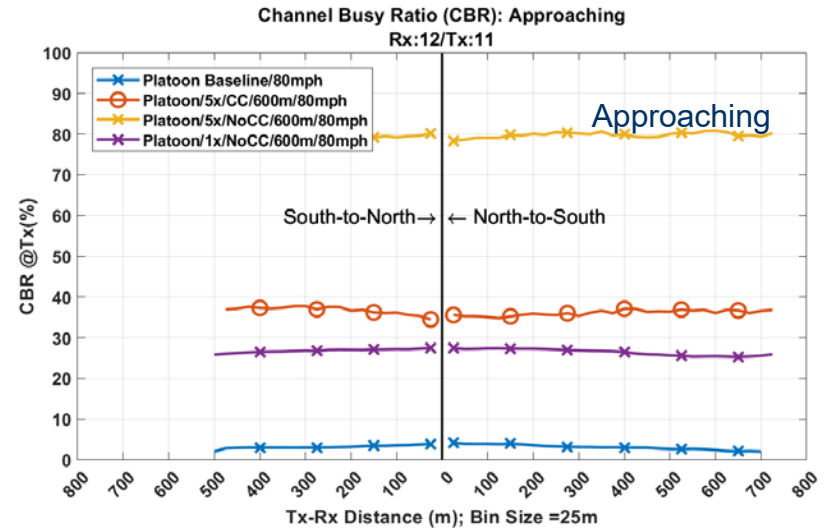
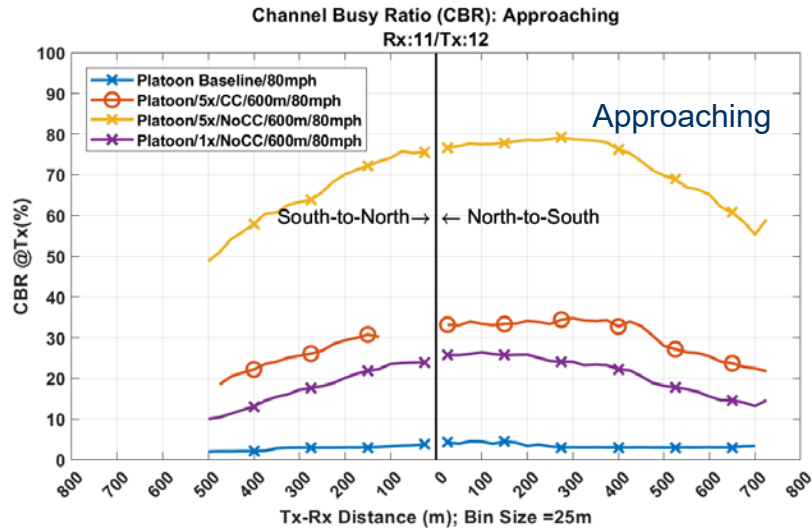
Moving Vehicle Receiving



# CBR – High Speed Test – 600m

## Stationary Vehicle Receiving

## Moving Vehicle Receiving

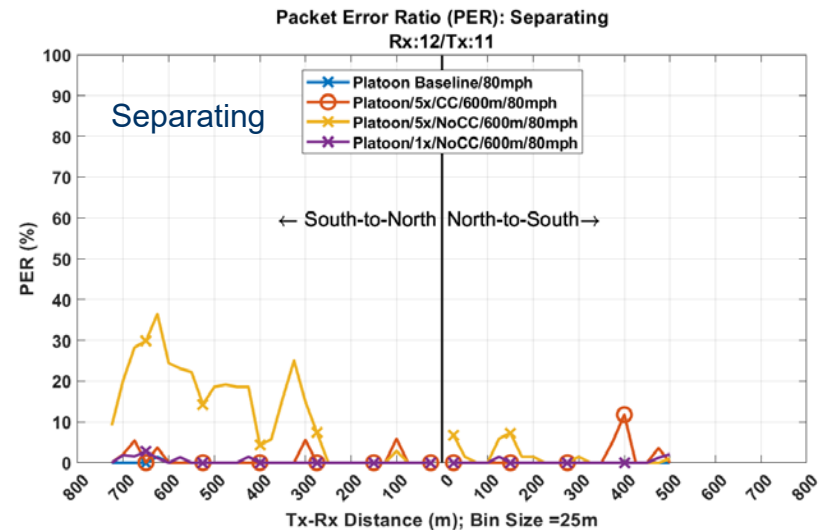
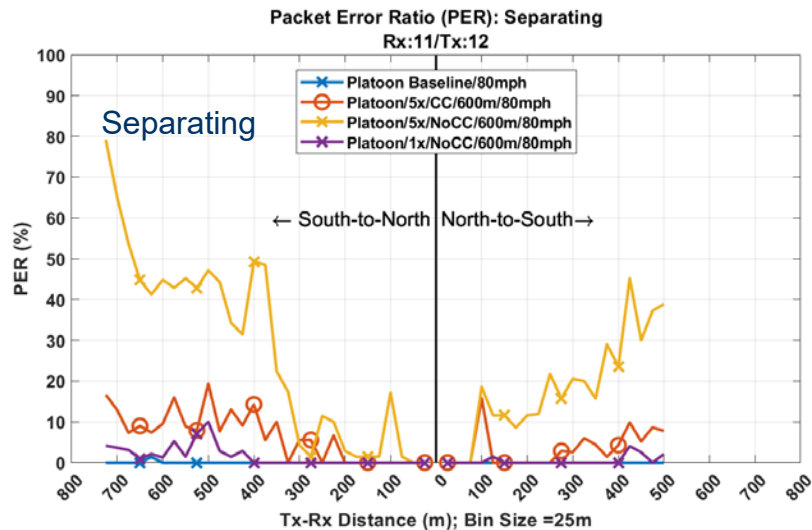
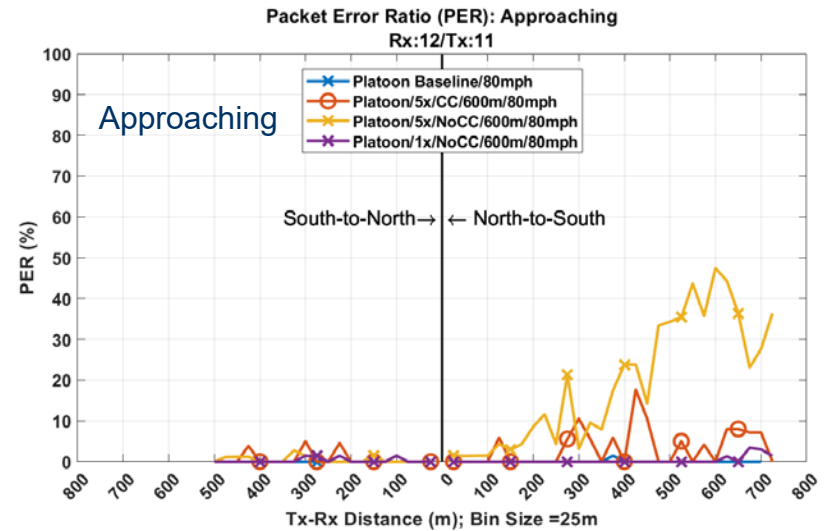
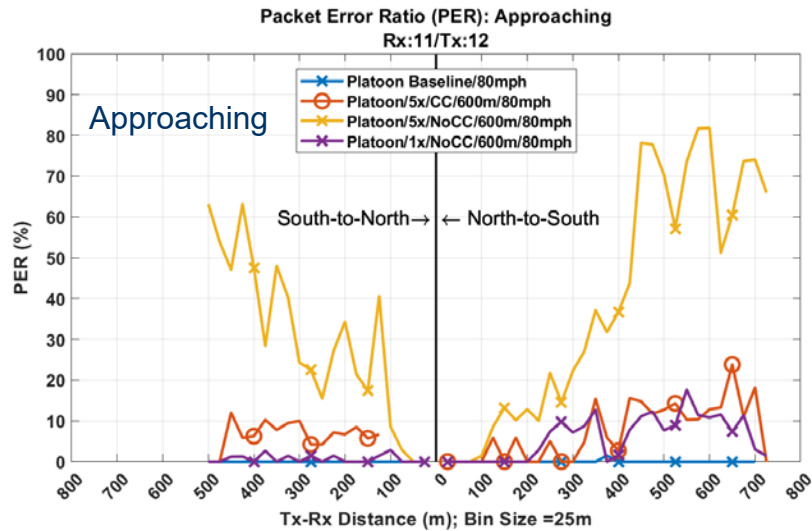




# PER – High Speed Test – 600m

## Stationary Vehicle Receiving

## Moving Vehicle Receiving

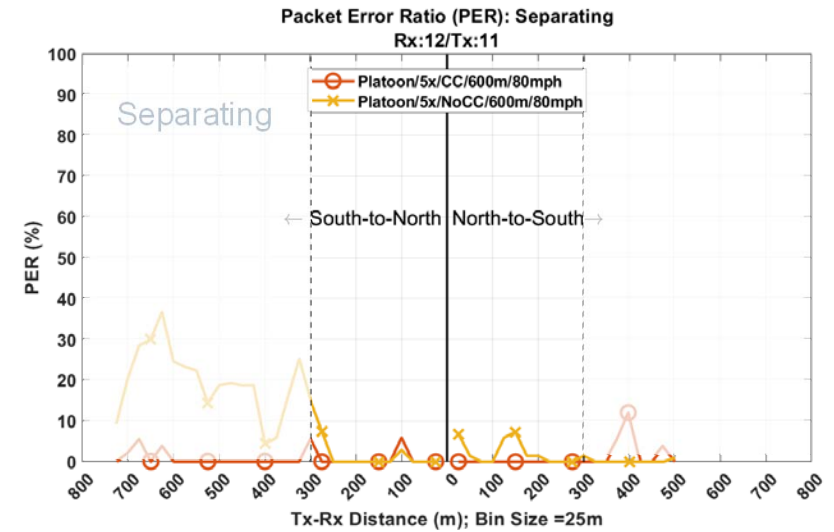
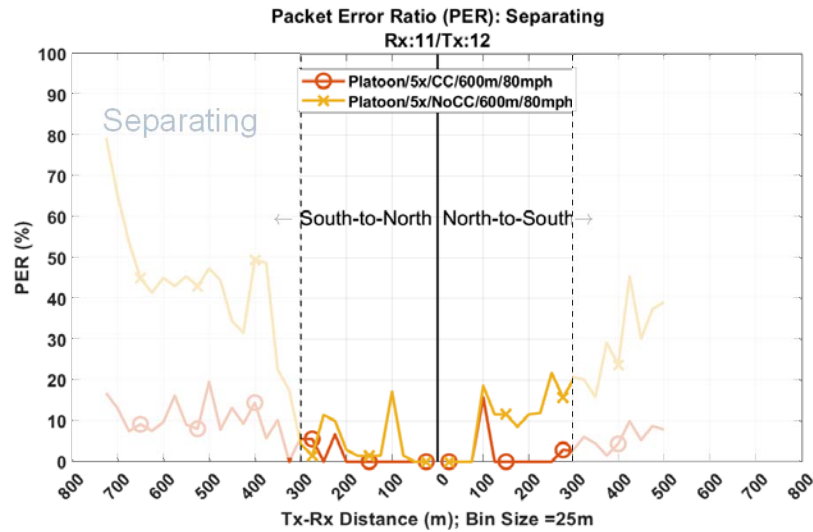
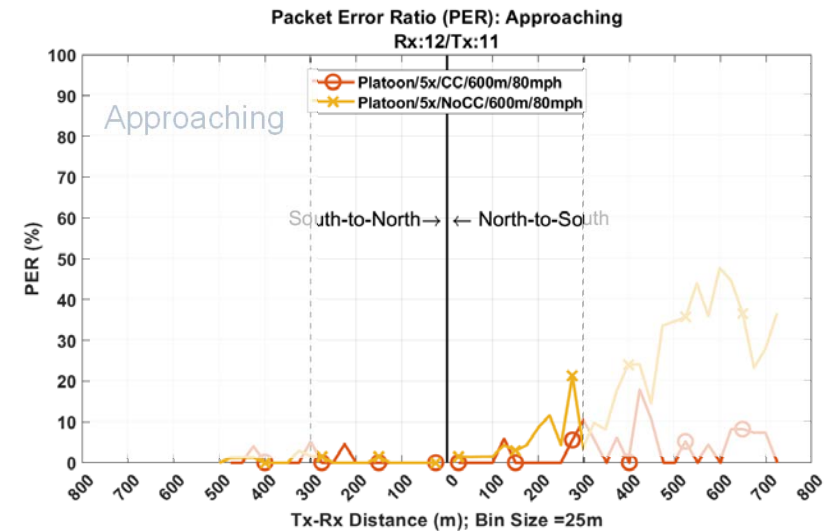
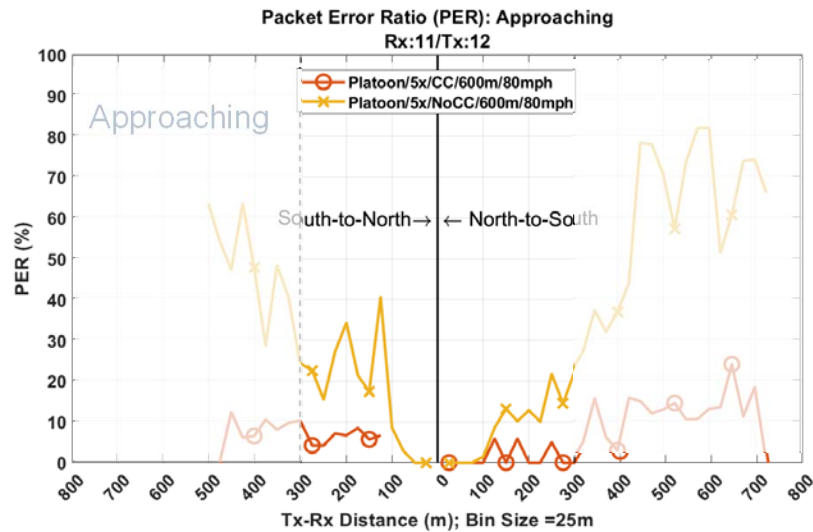




# PER – High Speed Test – 600m

Stationary Vehicle Receiving

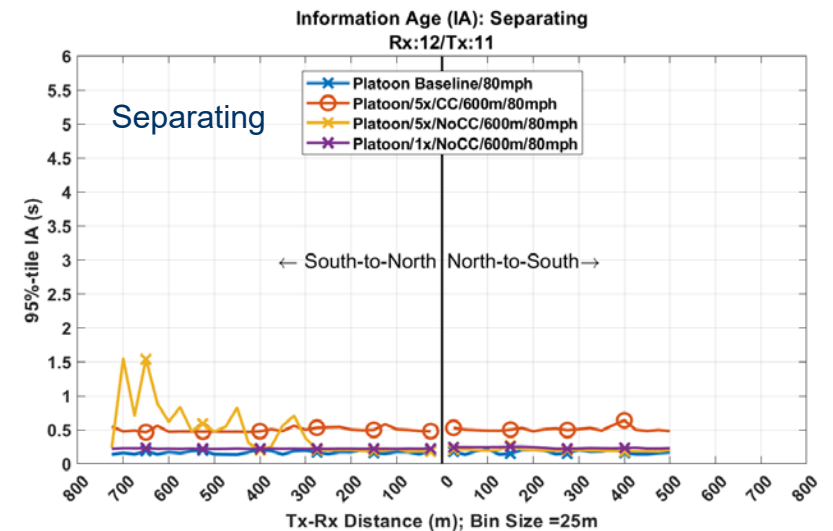
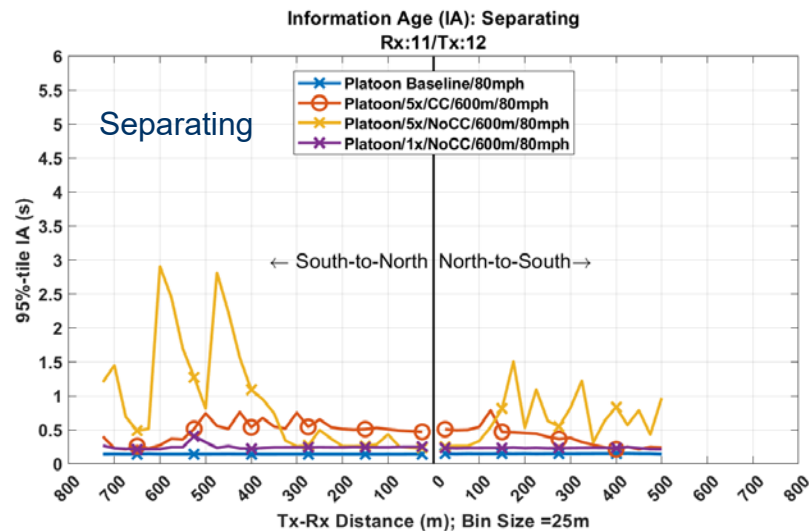
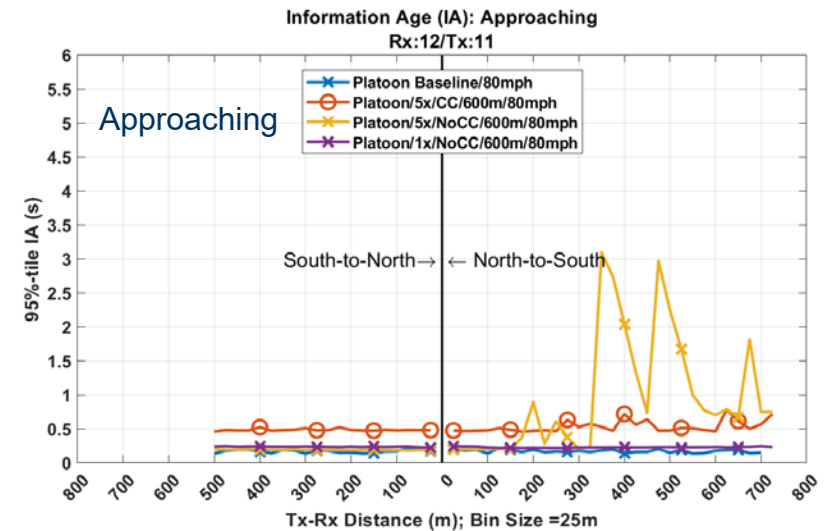
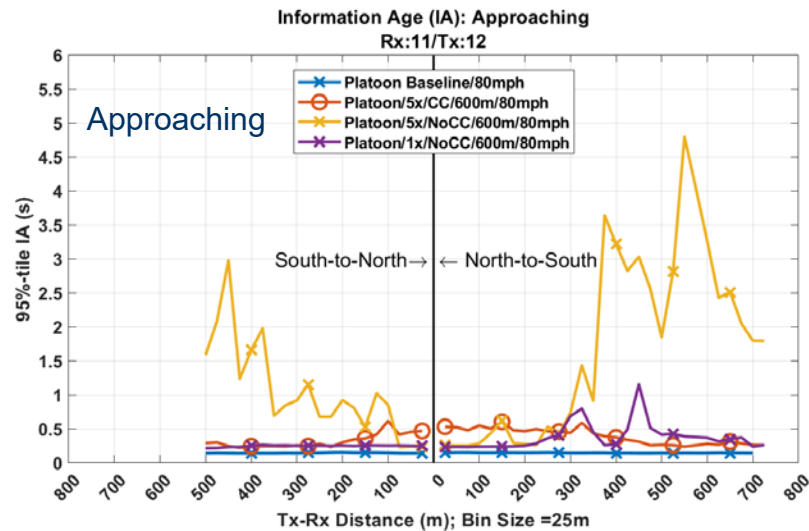
Moving Vehicle Receiving



# IA – High Speed Test – 600m

Stationary Vehicle Receiving

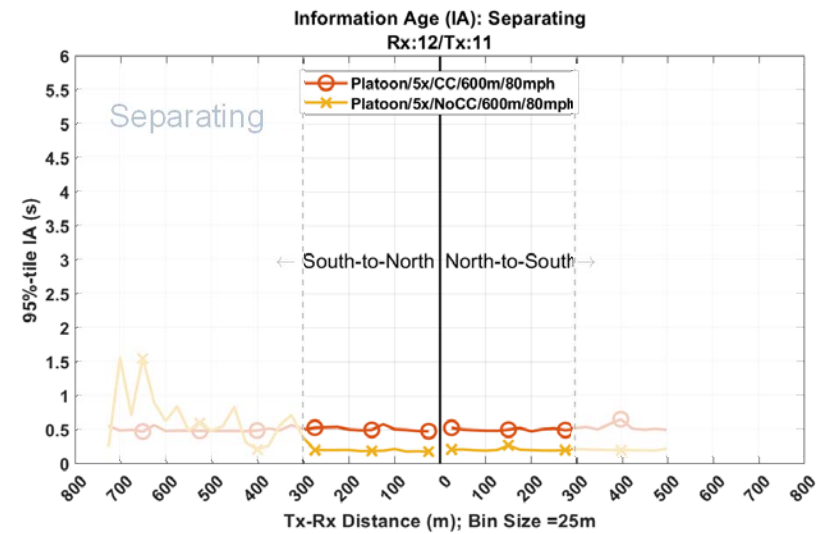
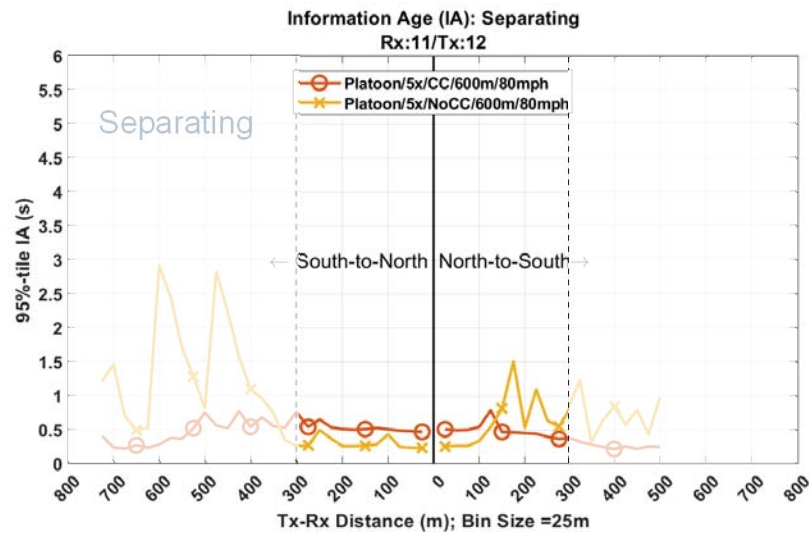
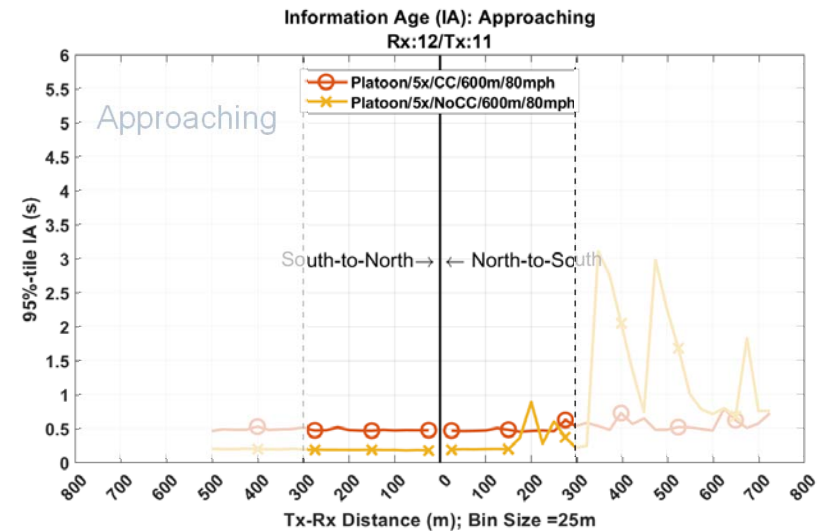
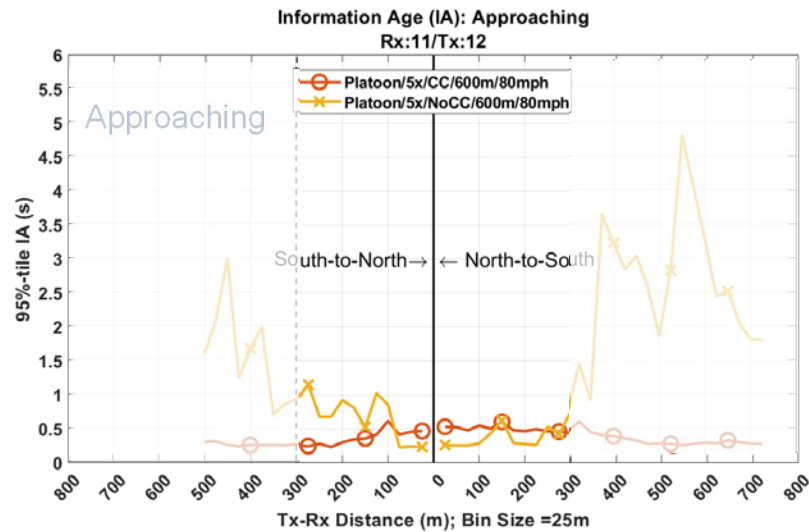
Moving Vehicle Receiving



# IA – High Speed Test – 600m

Stationary Vehicle Receiving

Moving Vehicle Receiving

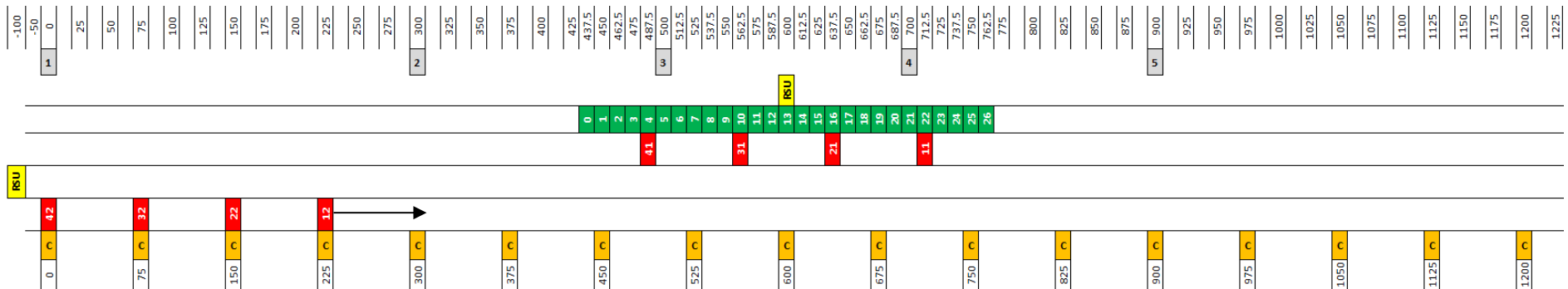


# High Speed Test

Congestion Spread 300m  
Speed 80mph

# Test Setup: High Speed Test, 300m

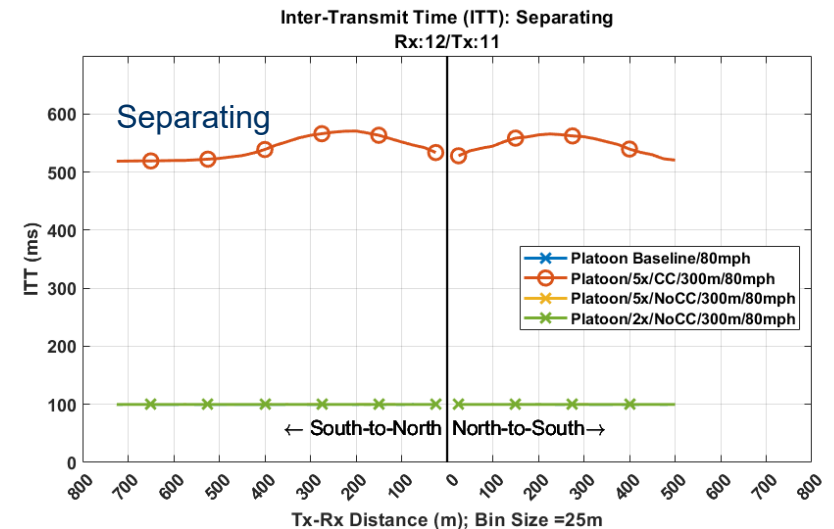
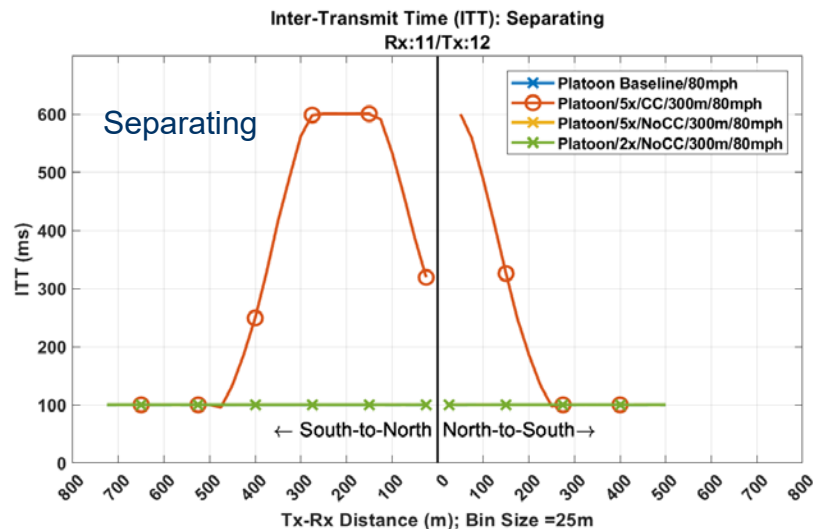
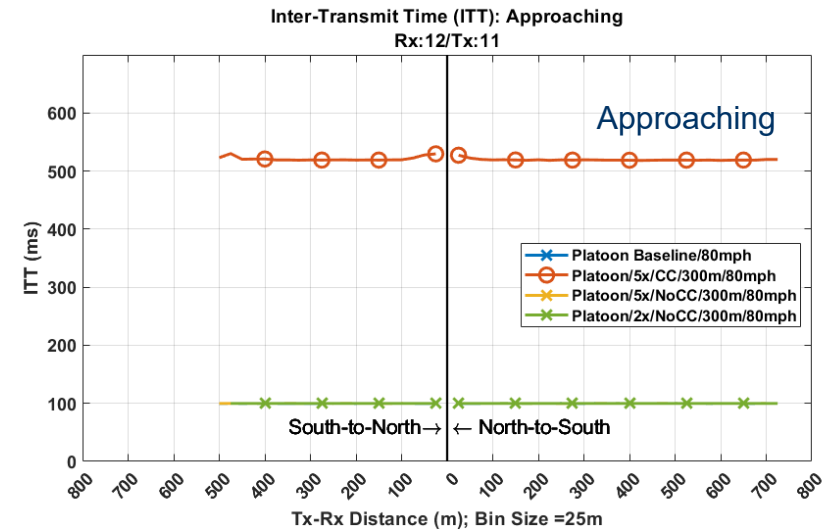
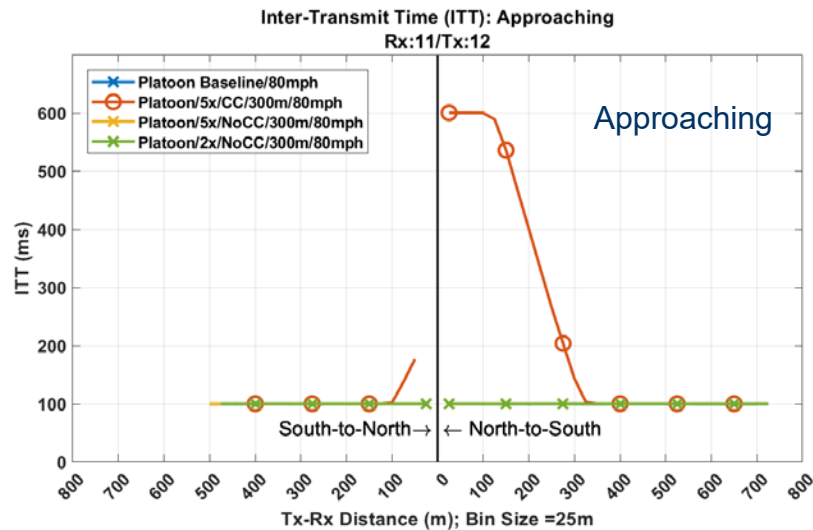
- Stationary OBEs: 11, 21, 31, 41
- Platoon OBEs: 12, 22, 32, 42
- Congestion Carts: 0-26 (start at 437.5m)
- Cart 13 at 600m (center of the test track)
- Results shown for (Vehicle 11, Vehicle 12) pair



# ITT – High Speed Test – 300m

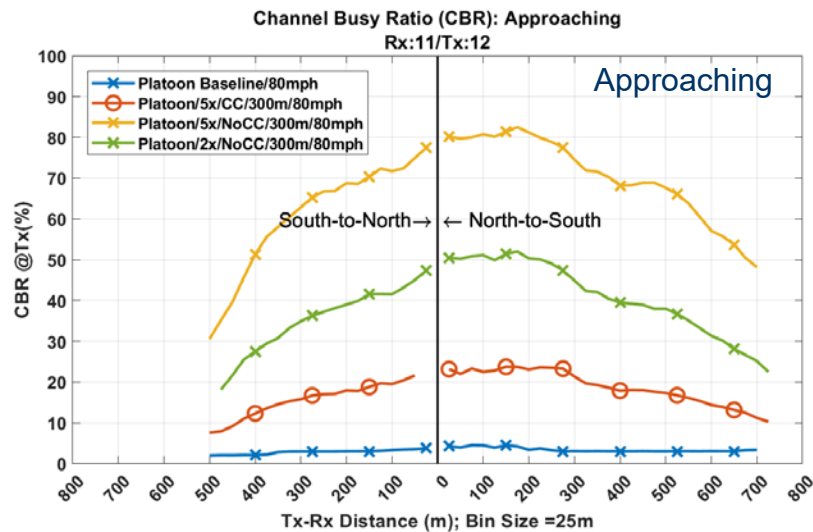
Stationary Vehicle Receiving

Moving Vehicle Receiving

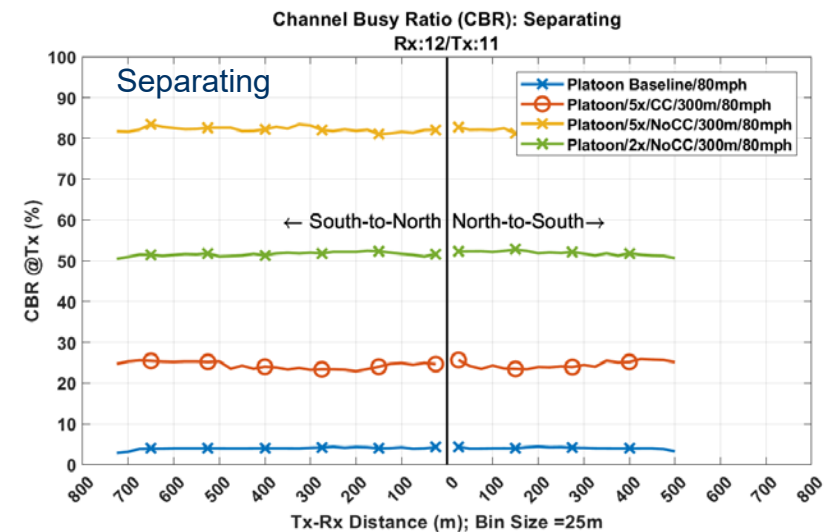
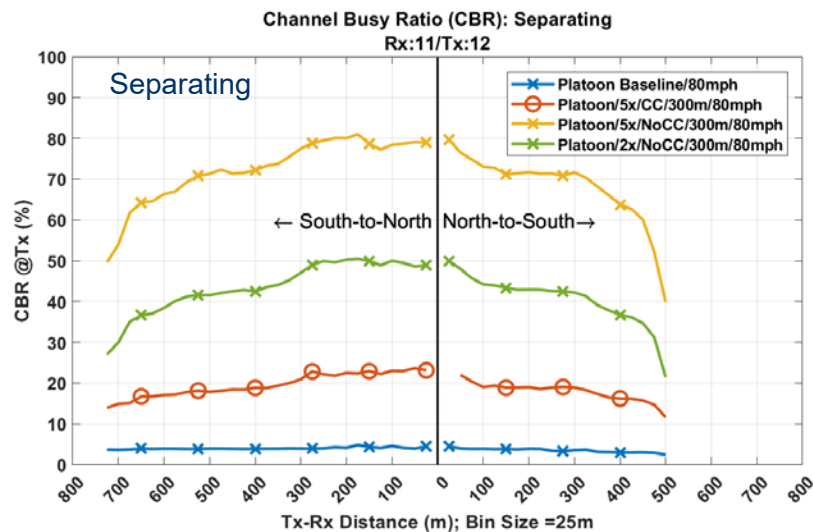
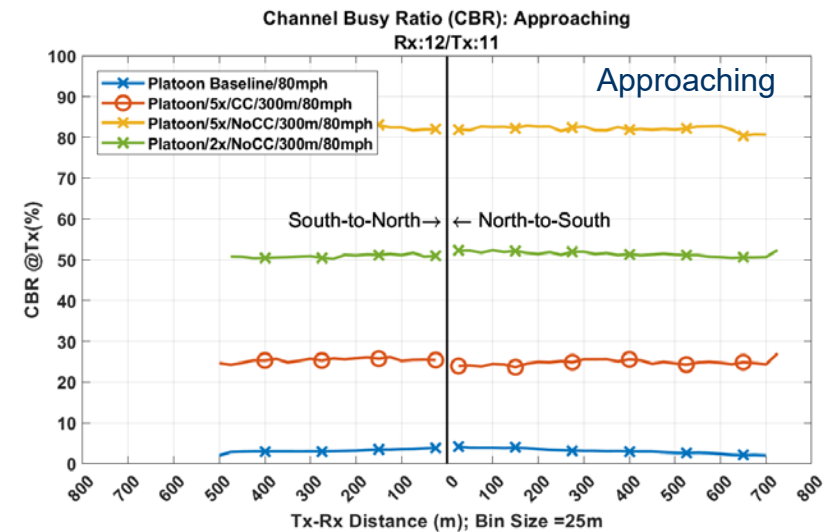


# CBR – High Speed Test – 300m

## Stationary Vehicle Receiving



## Moving Vehicle Receiving

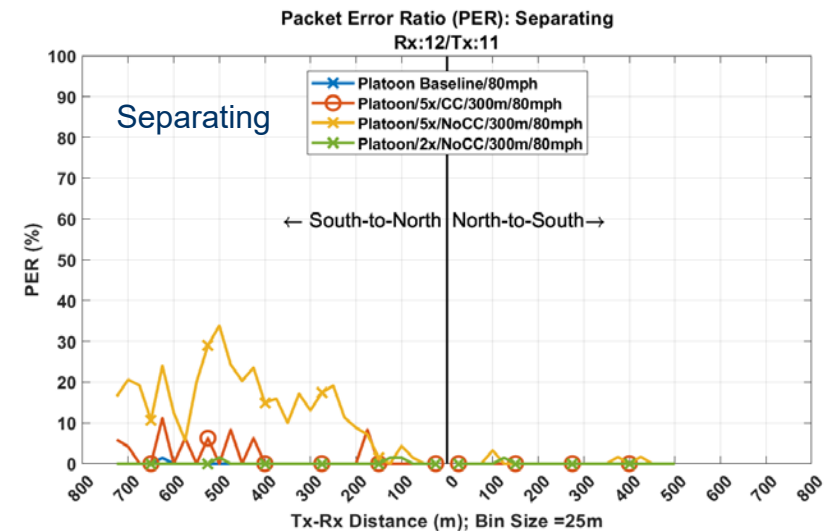
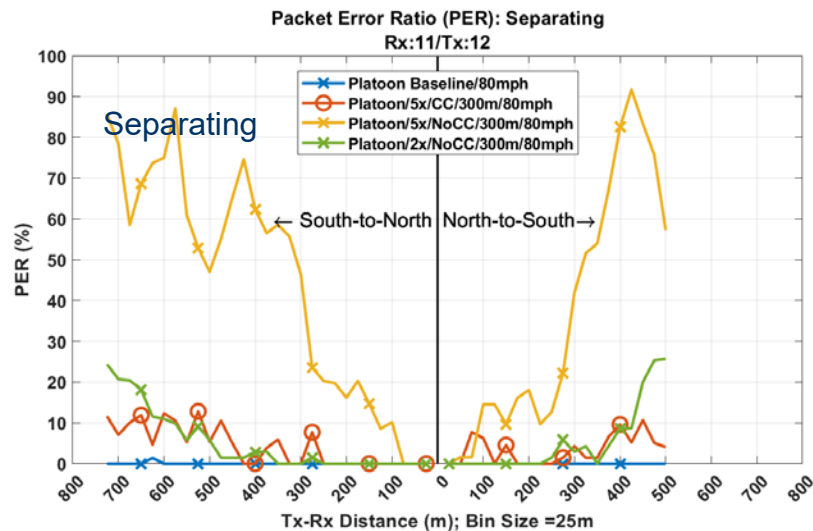
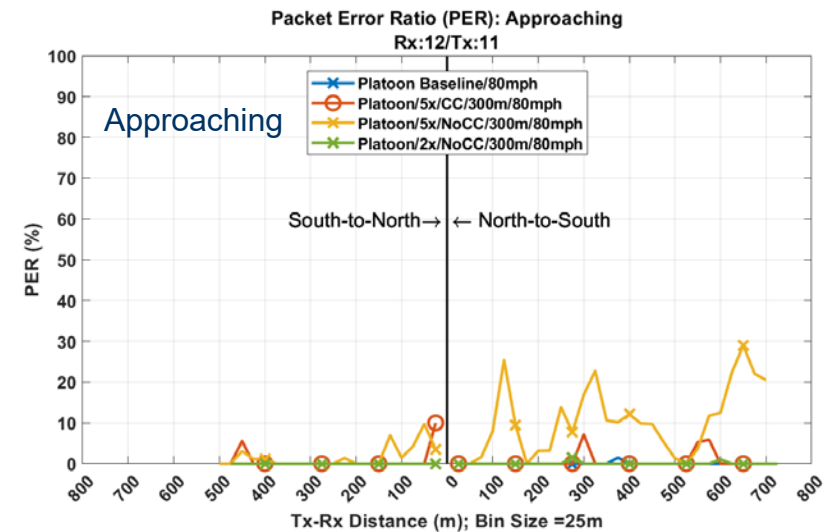
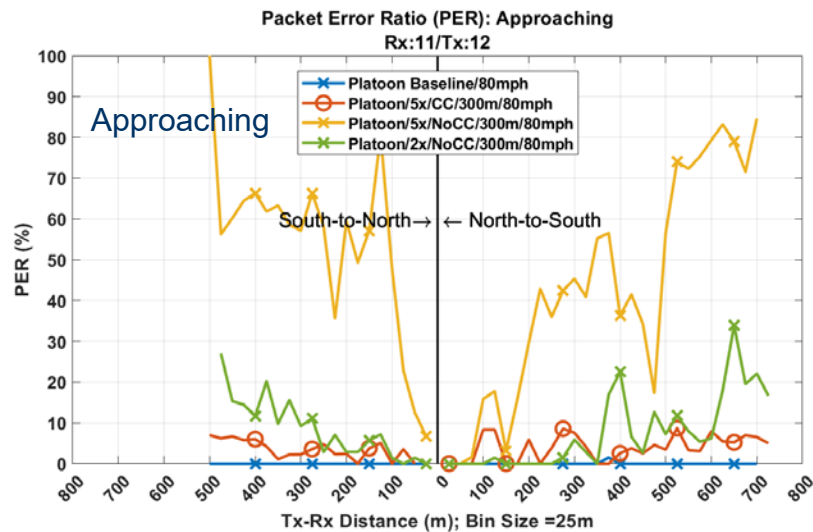




# PER – High Speed Test – 300m

Stationary Vehicle Receiving

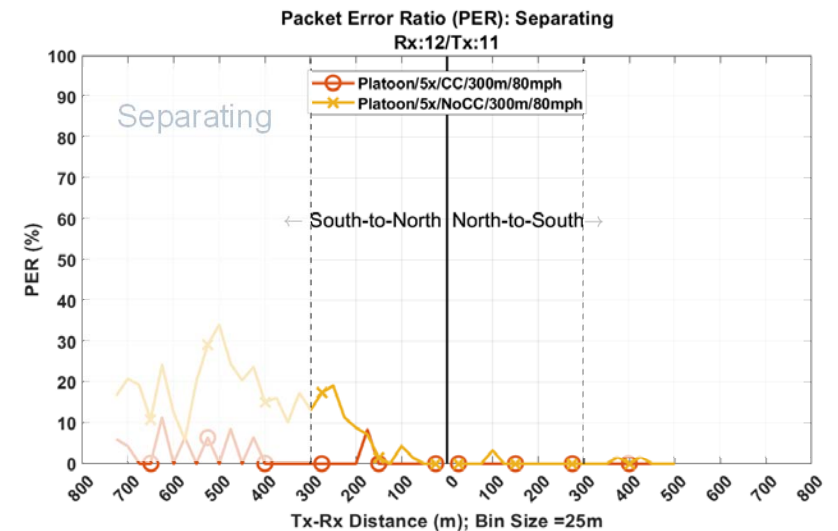
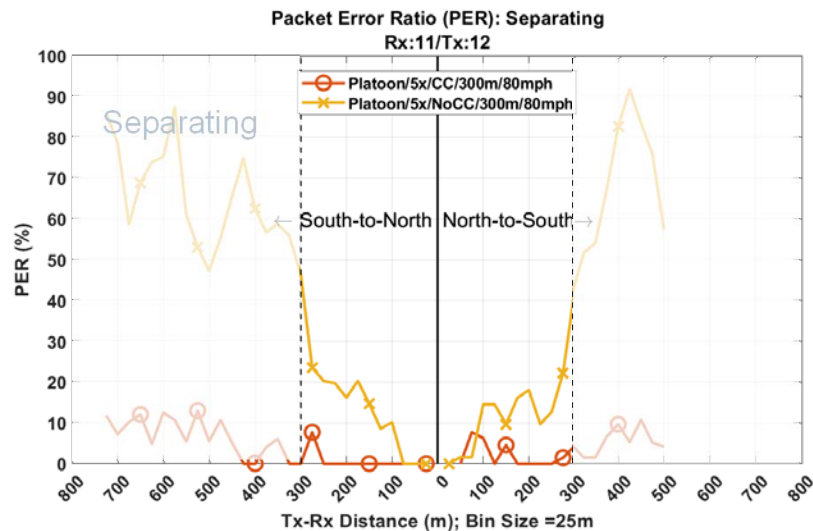
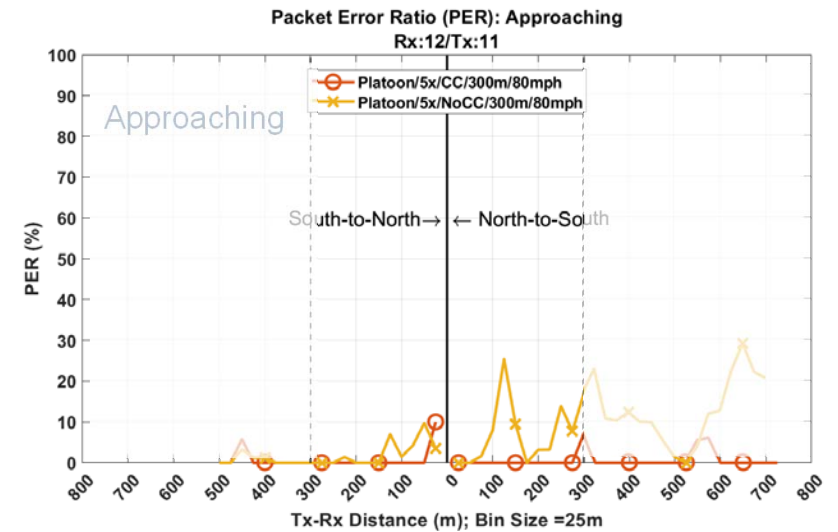
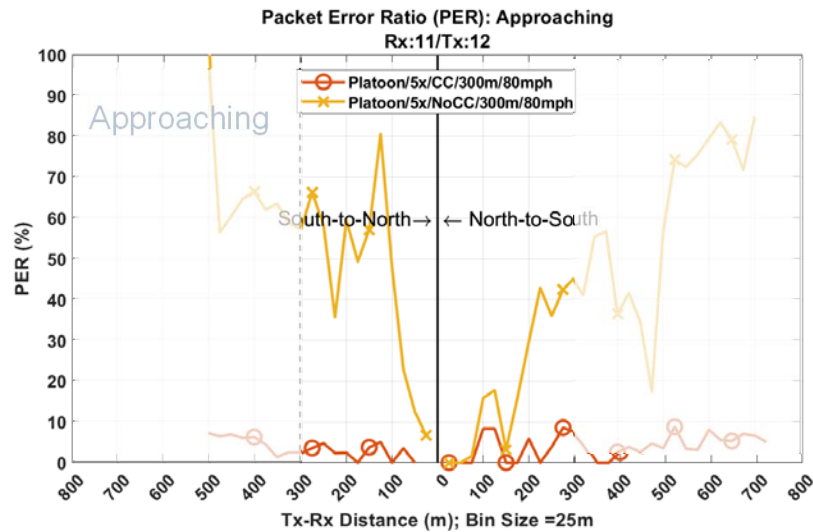
Moving Vehicle Receiving



# PER – High Speed Test – 300m

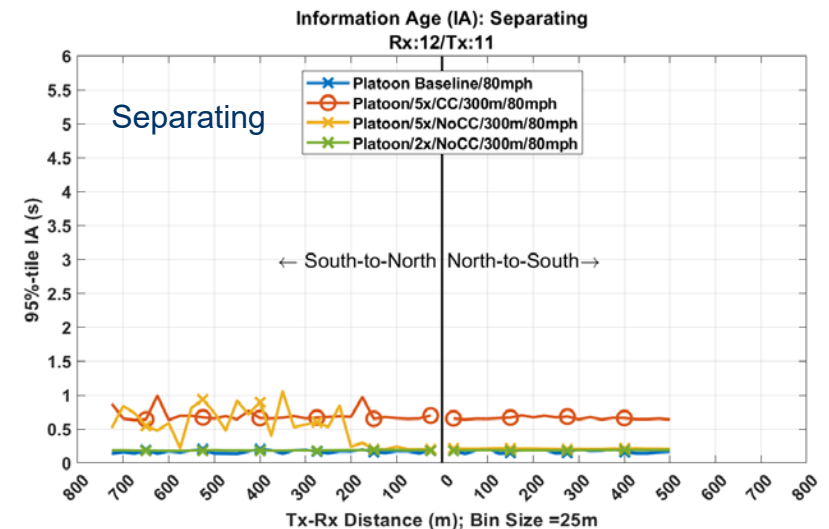
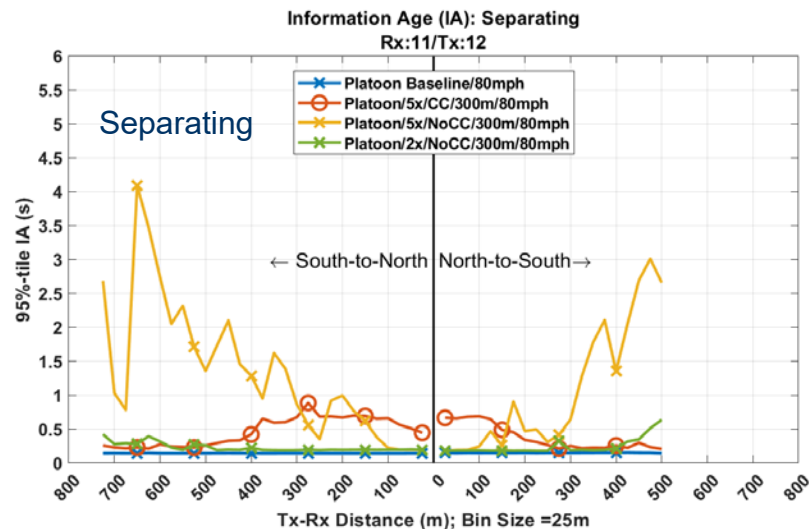
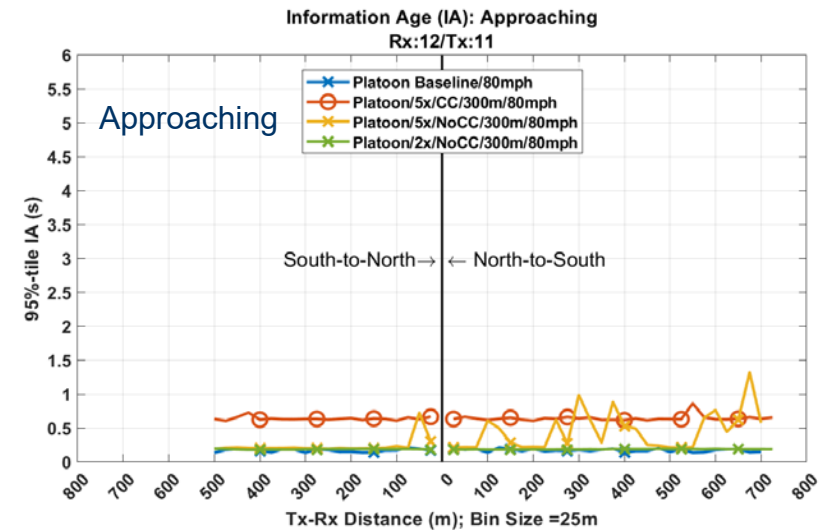
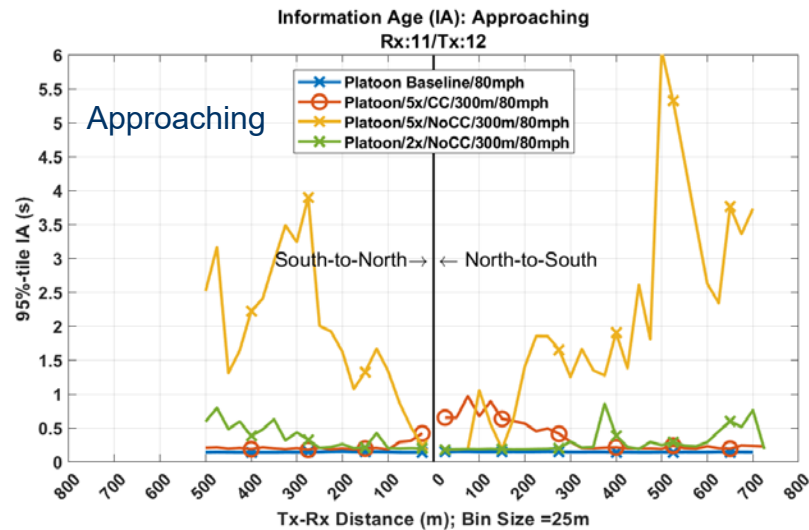
Stationary Vehicle Receiving

Moving Vehicle Receiving



# IA – High Speed Test – 300m

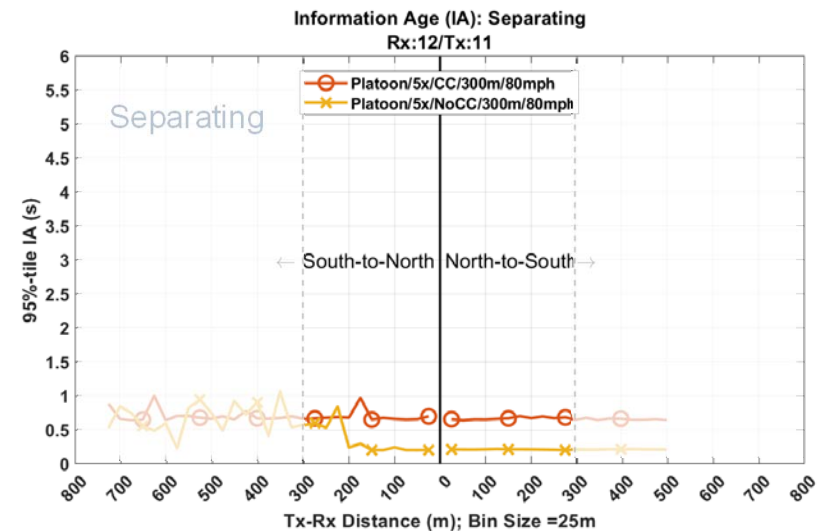
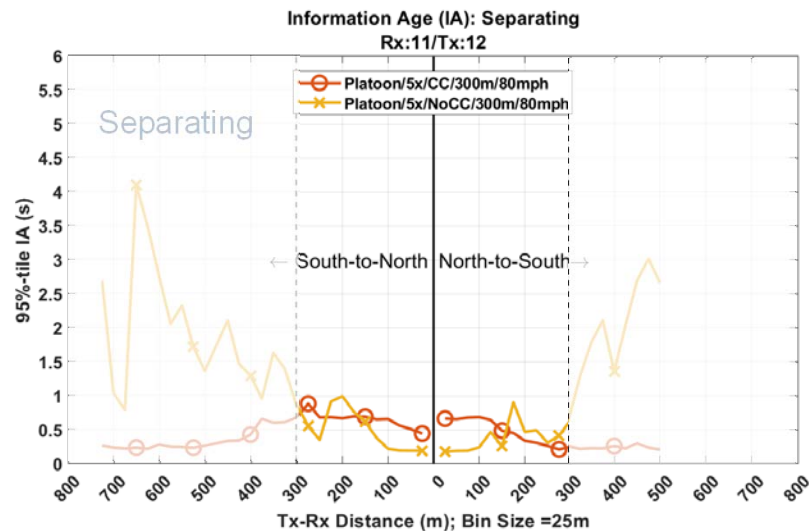
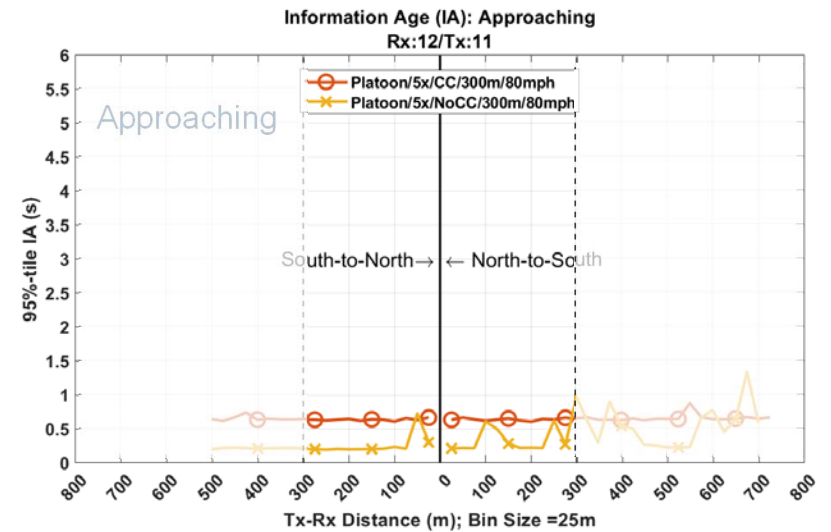
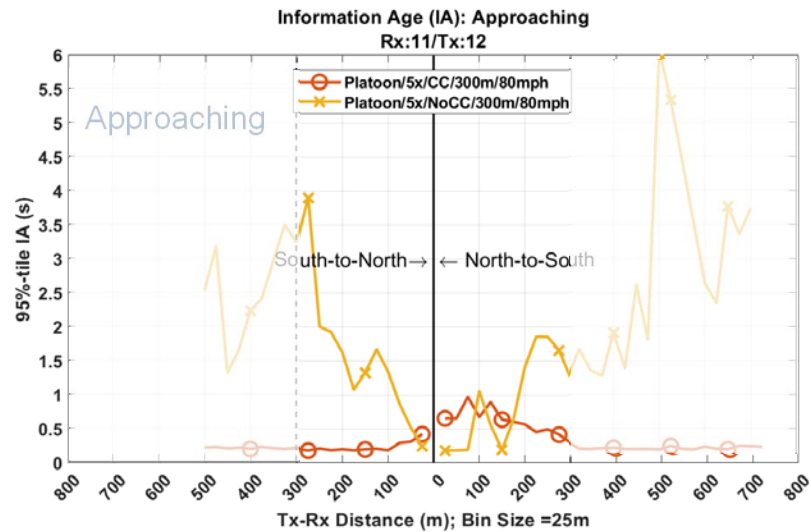
## Stationary Vehicle Receiving      Moving Vehicle Receiving



# 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

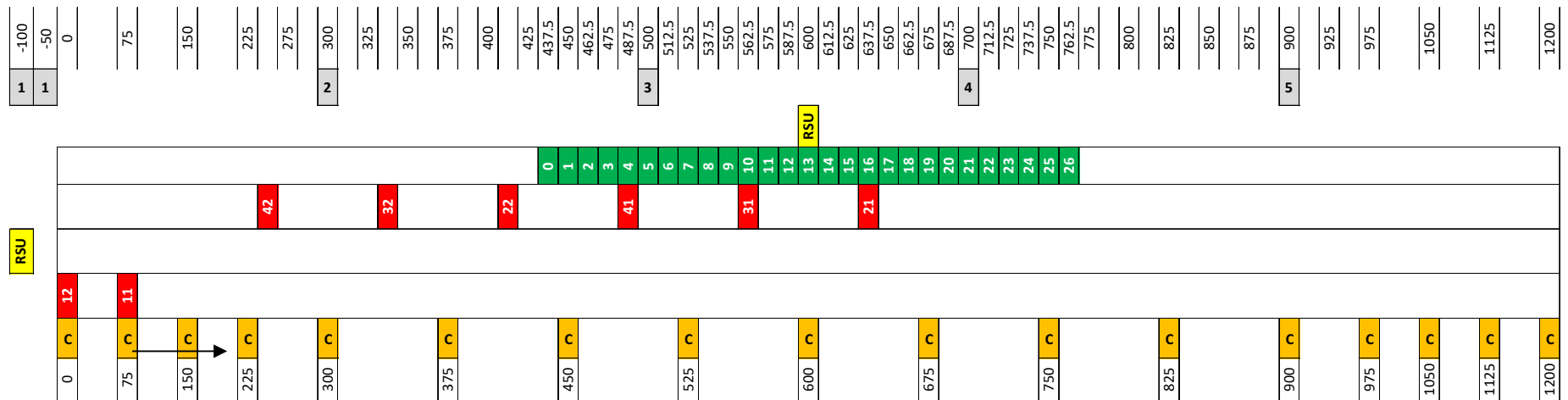


# Critical Event Test

Congestion Spread 300m  
Speed 55mph

# Critical Event Test: 300m

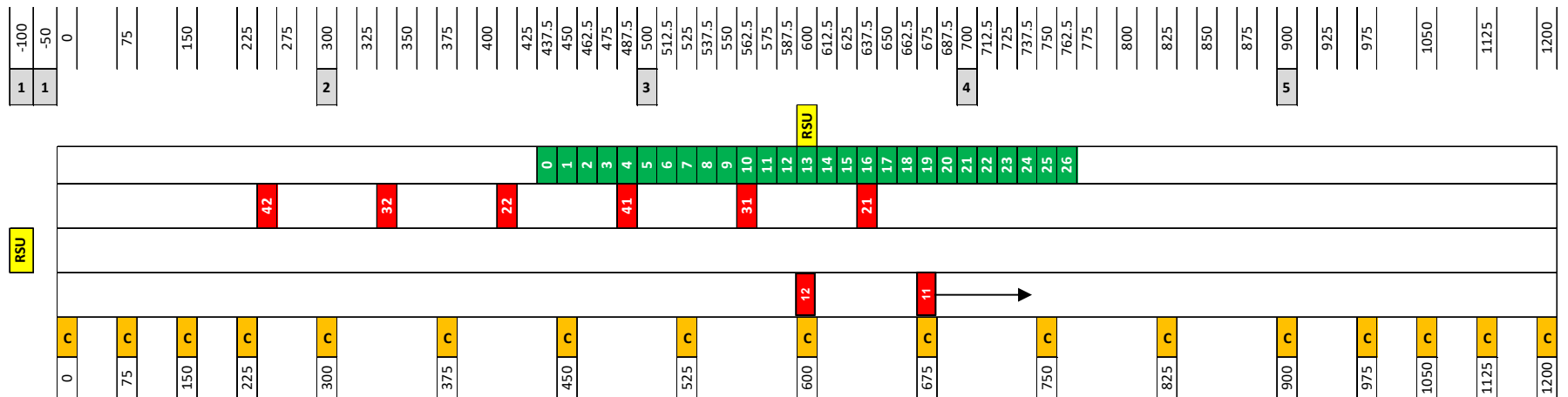
- Stationary OBEs: 21, 31, 41, 22, 32, 42
- Platoon OBEs: 11, 12
- Congestion Carts: 0-26 (start at 437.5m)
- Cart 13 at 600m (center of the test track)





# Test Details: 300m

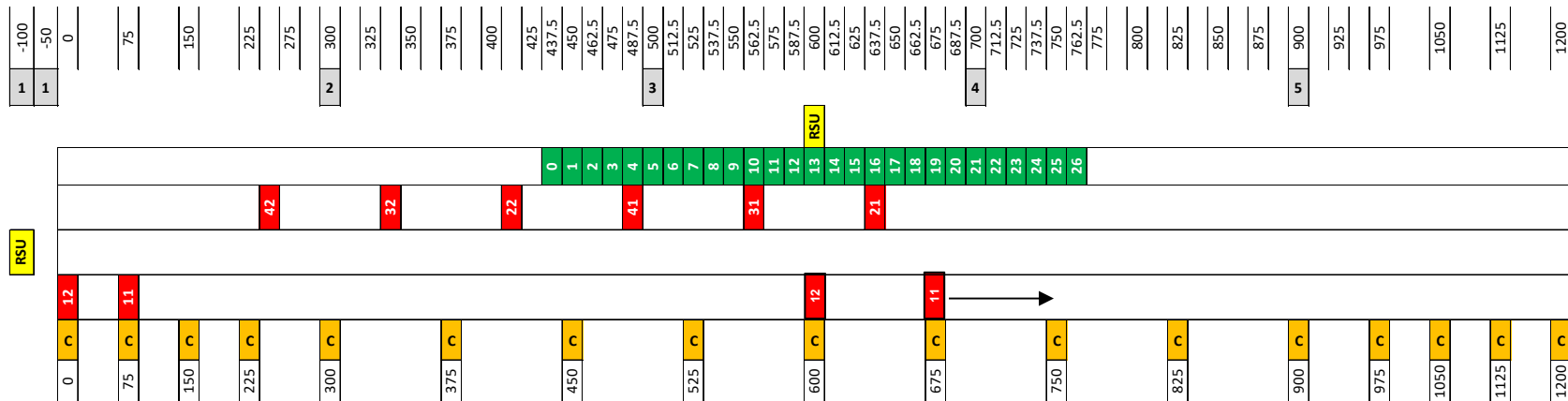
- In the North->South direction following vehicle (V12) brakes in the middle of the test track



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

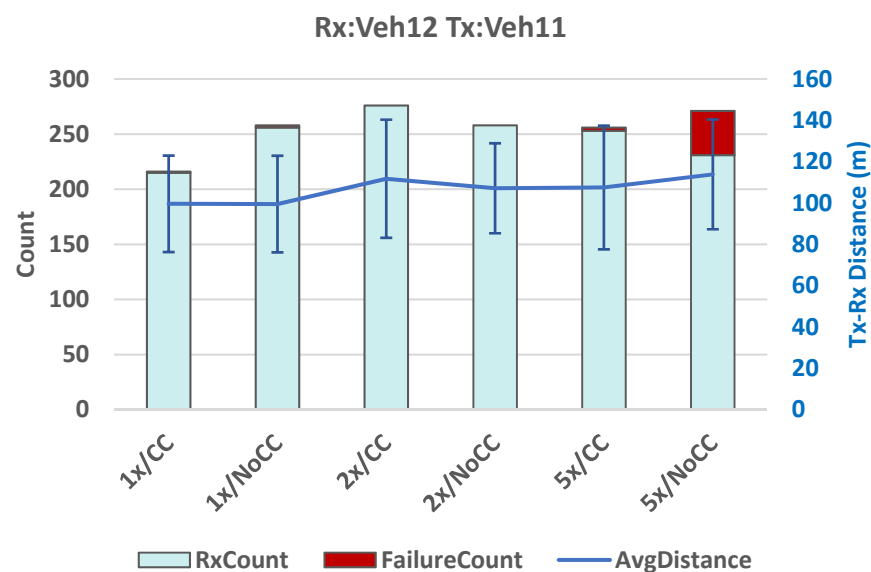
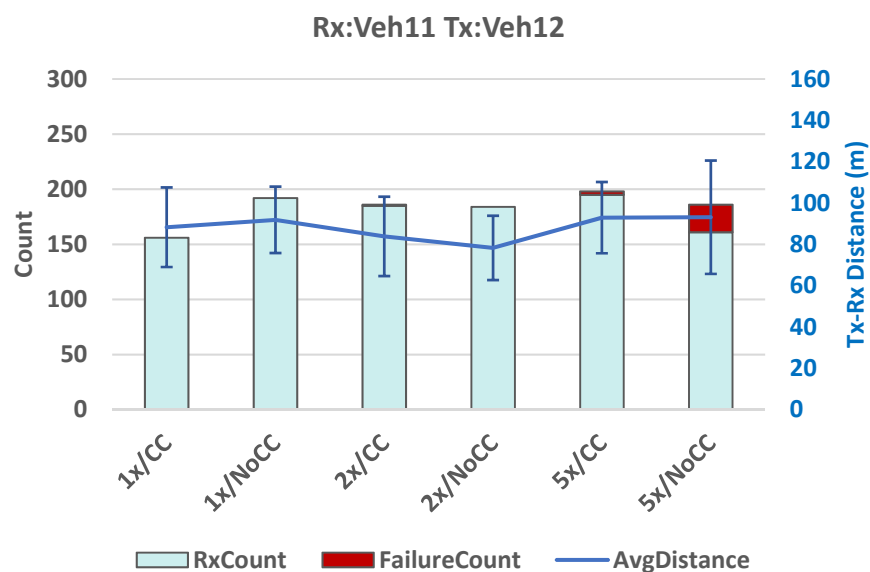
# Results Preview: 300m

- We are showing results in two sets
- Set 1
  - Count of packets transmitted and failed between Vehicle 11 and Vehicle 12
- Set 2
  - 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



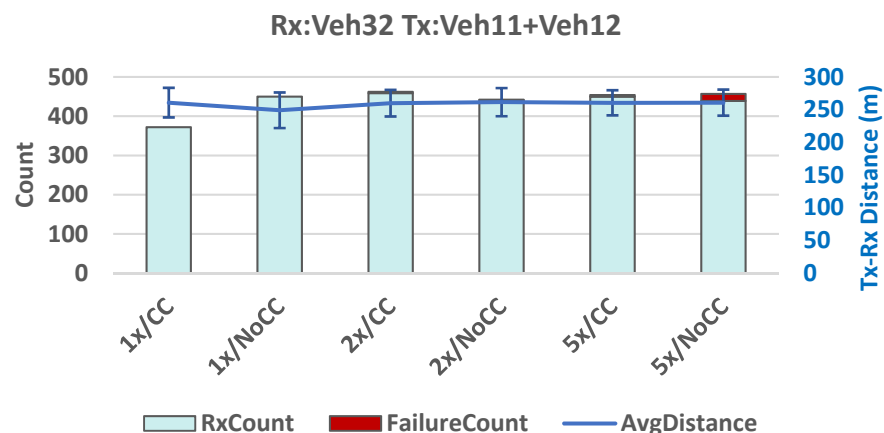
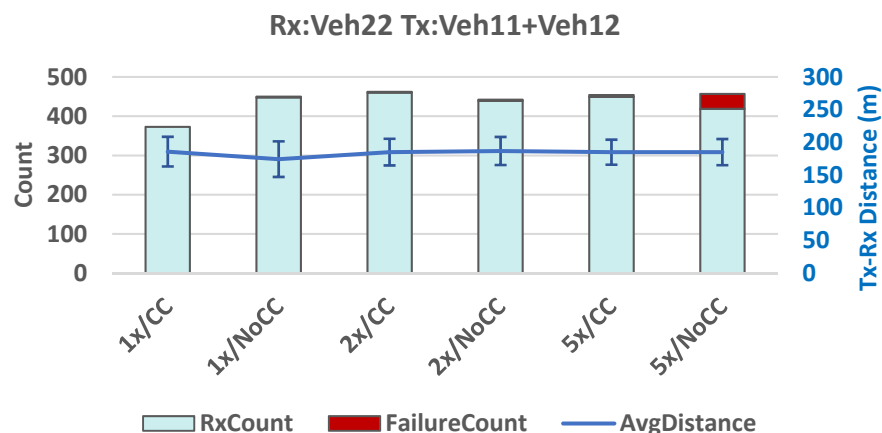
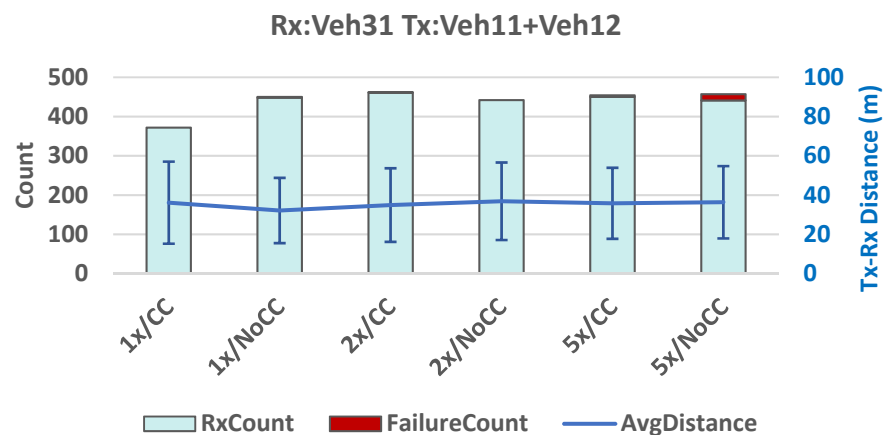
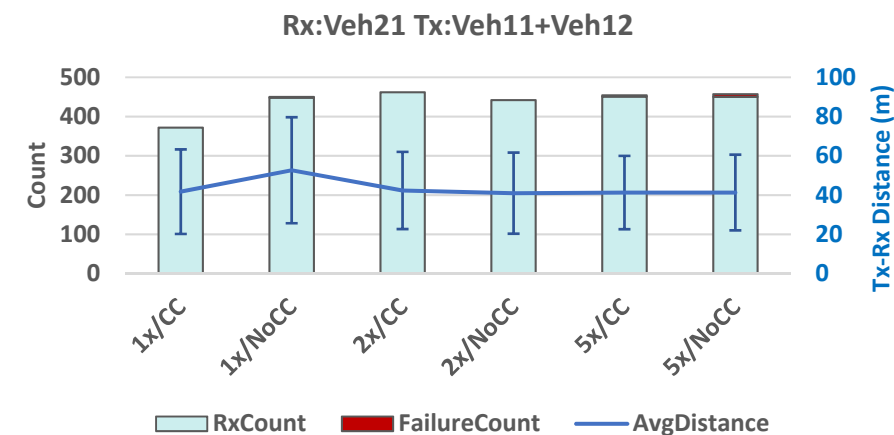
# Critical Event – 300m / 55mph

## Moving Vehicle Receiving From Hard Braking Transmitter Vehicle



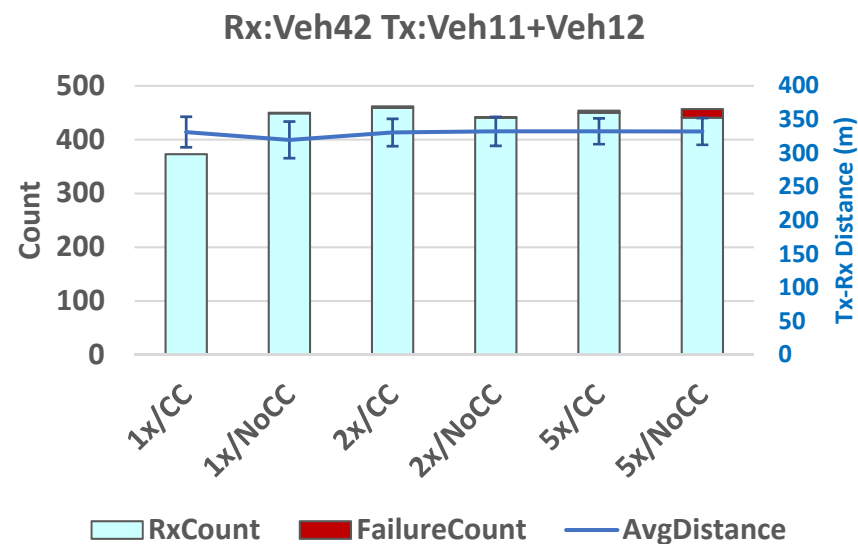
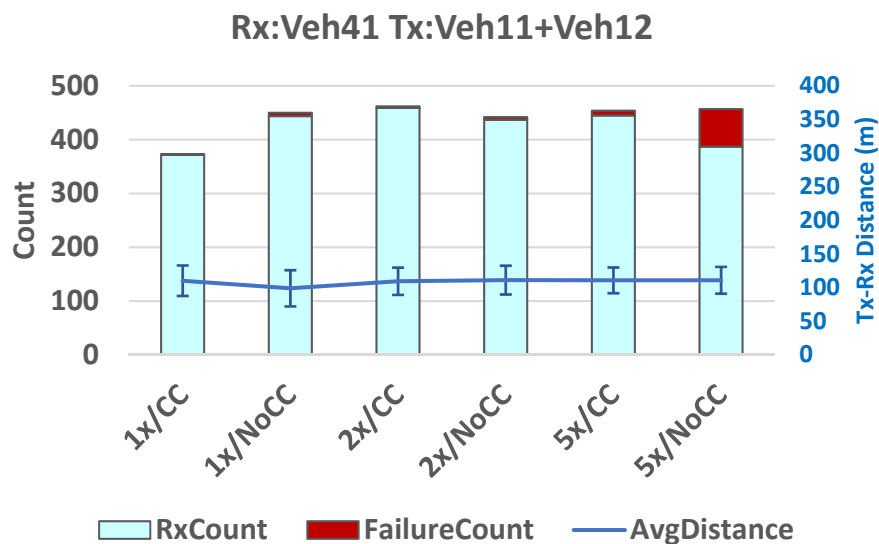
# Critical Event – 300m / 55mph

## Stationary Vehicle Receiving From Hard Braking Transmitter Vehicle



# Critical Event – 300m / 55mph

## Stationary Vehicle Receiving From Hard Braking Transmitter Vehicle

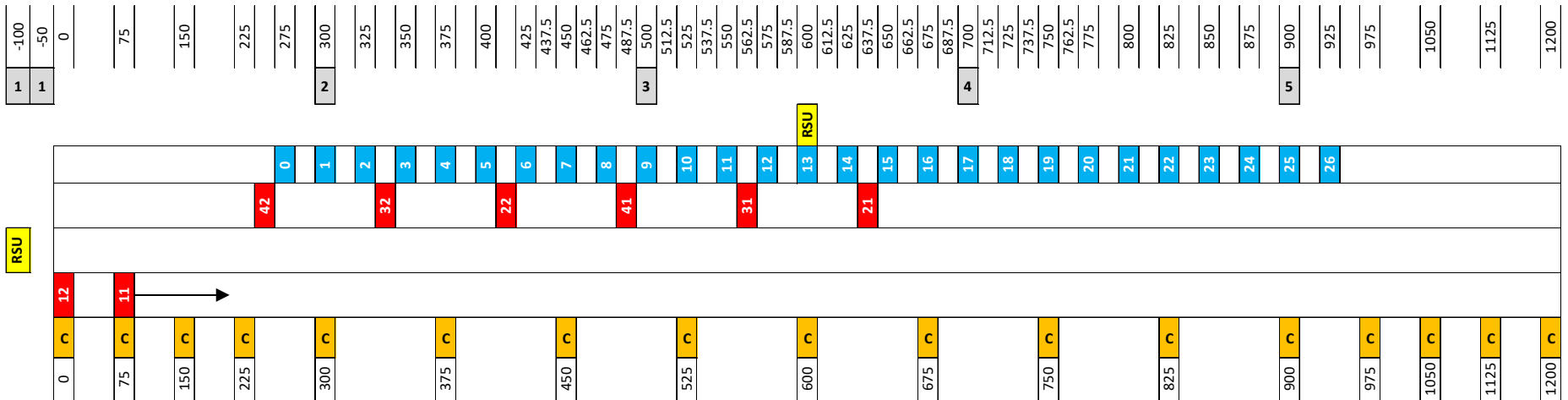


# Critical Event Test

Congestion Spread 600m  
Speed 55mph

# Critical Event Test: 600m

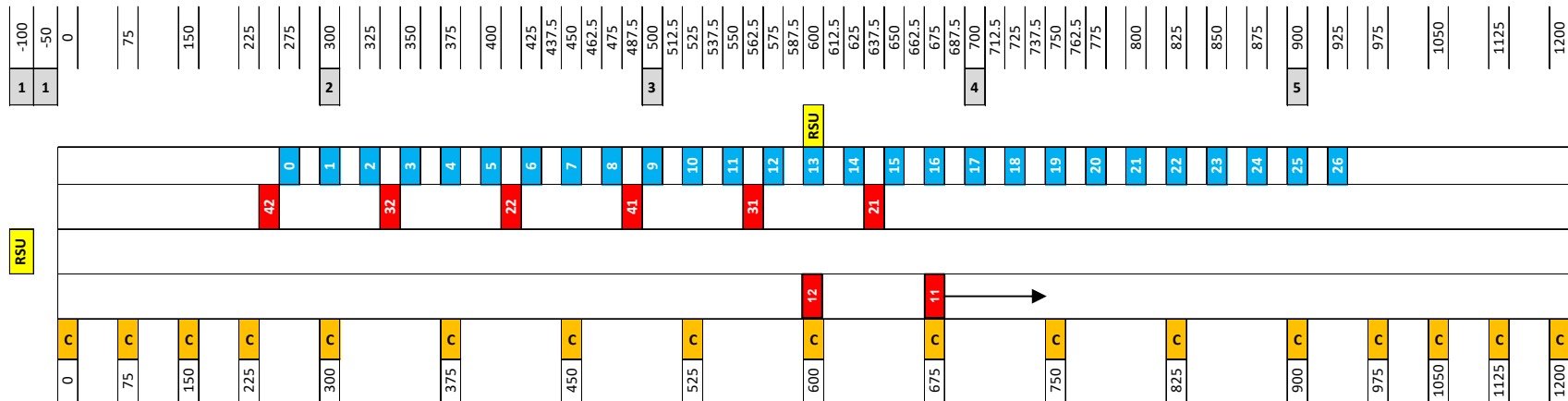
- Stationary OBEs: 21, 31, 41, 22, 32, 42
- Platoon OBEs: 11, 12
- Congestion Carts: 0-26 (start at 275m)
- Cart 13 at 600m (center of the test track)





# Test Details: 600m

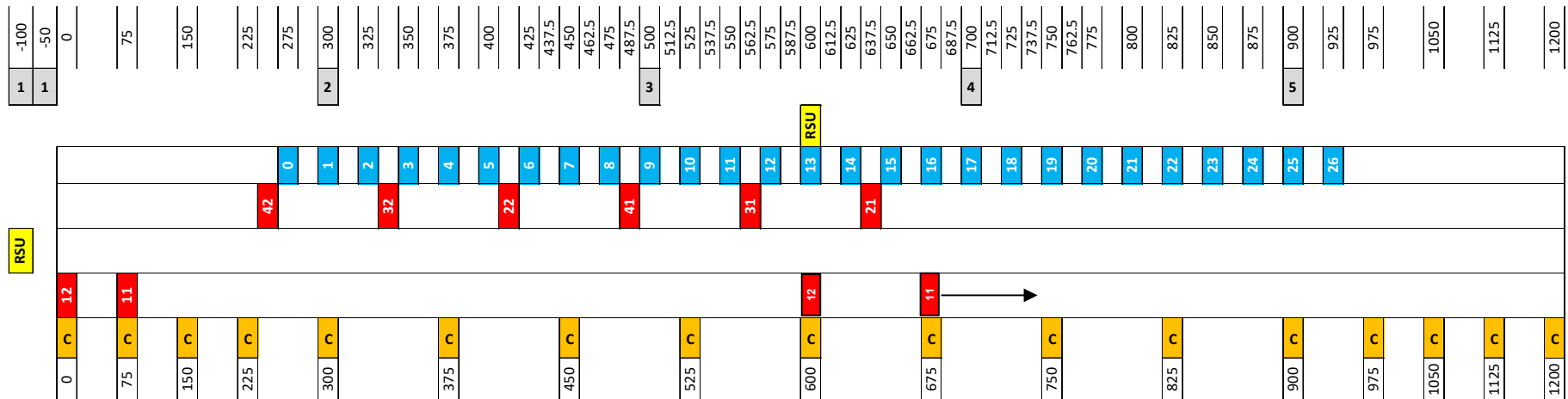
- In the North->South direction following vehicle (V12) brakes in the middle of the test track



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

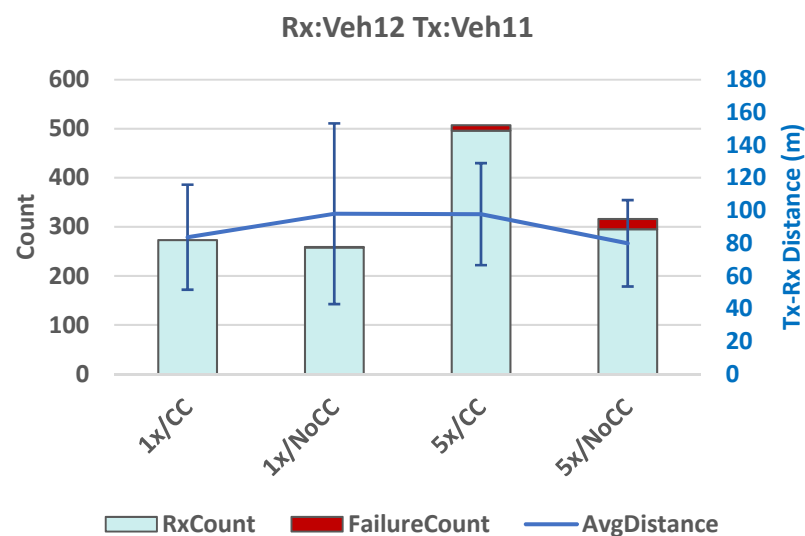
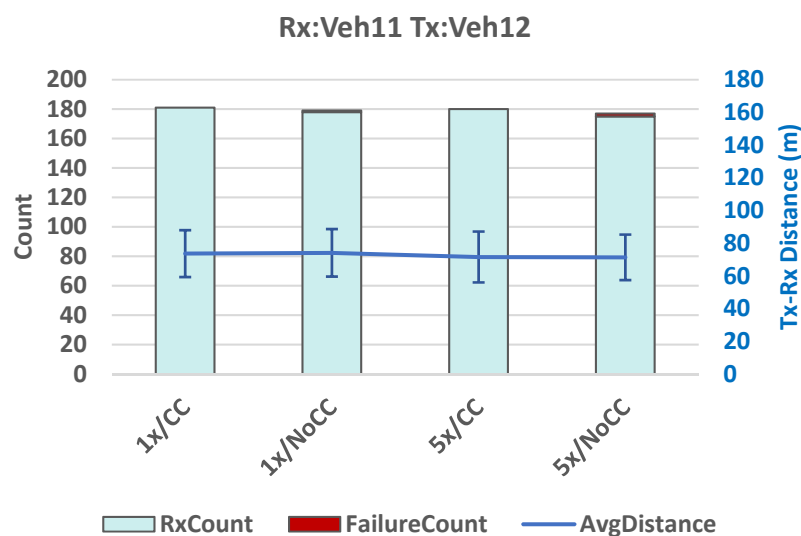
# Results Preview: 600m

- We are showing results in two sets
- Set 1
  - Count of packets transmitted and failed between Vehicle 11 and Vehicle 12
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  - 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



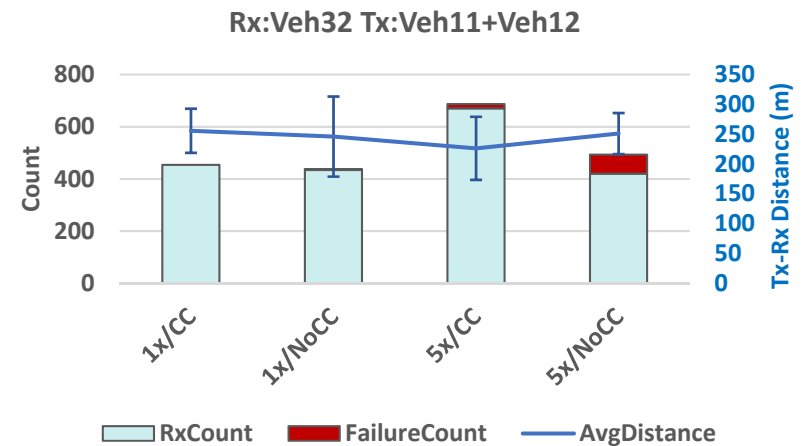
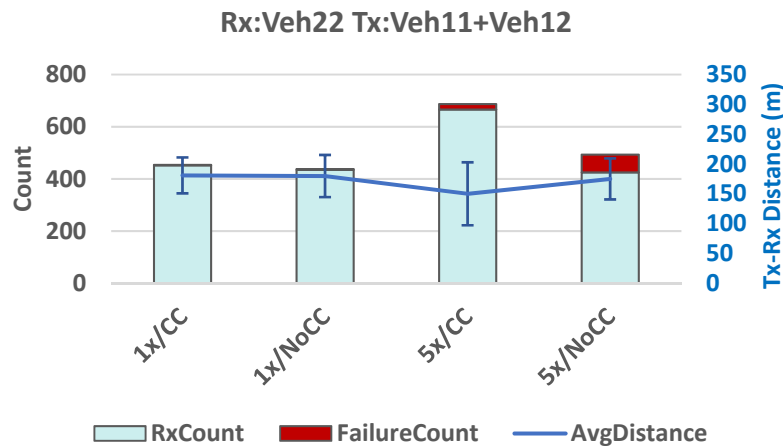
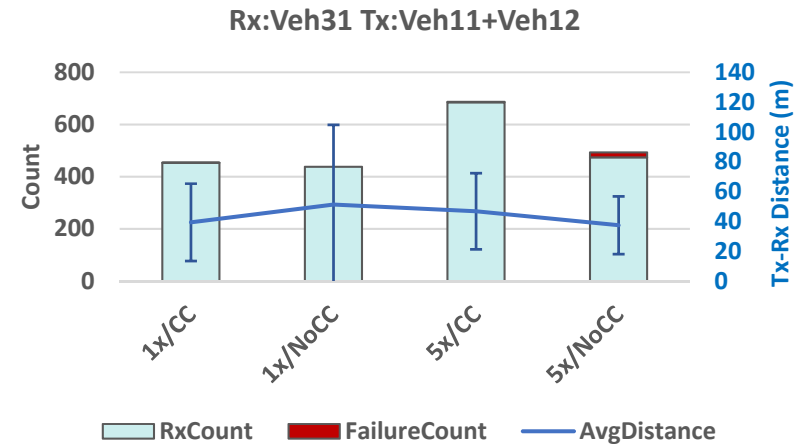
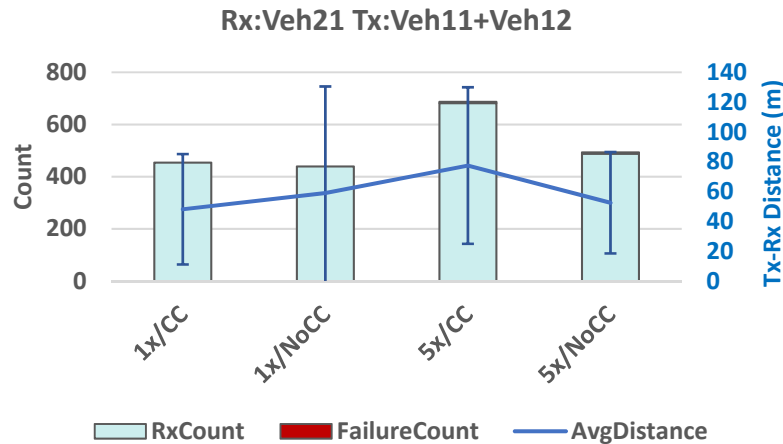
# Critical Event – 600m / 55mph

## Moving Vehicle Receiving From Hard Braking Transmitter Vehicle



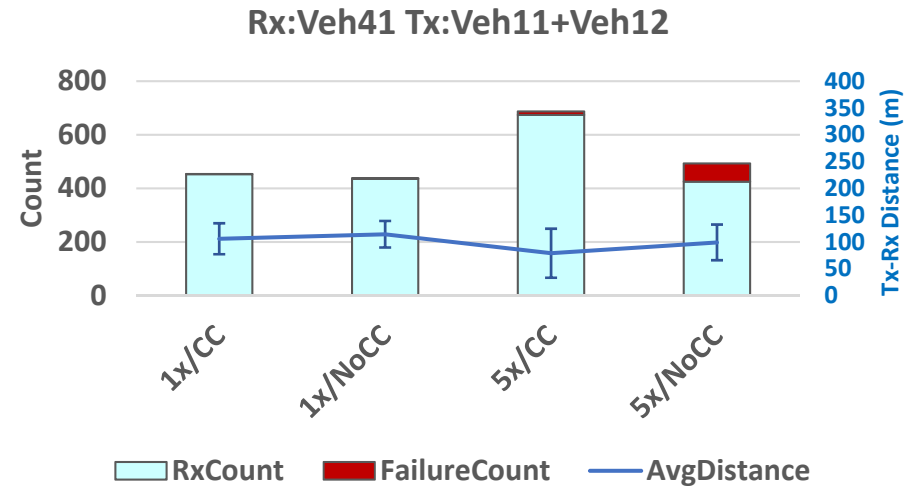
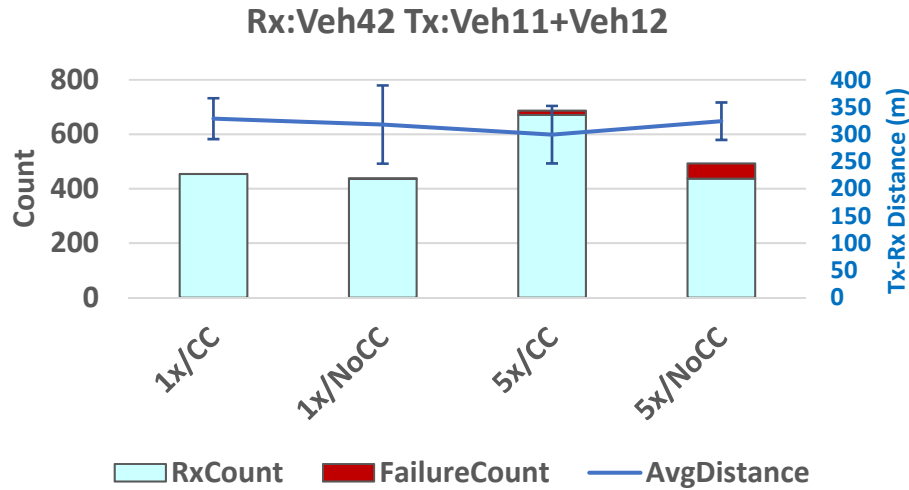
# Critical Event – 600m / 55mph

## 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<sup>(\*)</sup>

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.