V2X Summit Speaker

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U.S. DOT LTE-V2X Testing:
Data Analysis and Observations

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COMMUNICATIONS FOR DEPLOYMENT

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Test Approach

U.S. DOT conducted LTE-V2X testing using devices procured from a wide range of vendors. Test configurations allowed for evaluation of radio performance in the presence of unlicensed interference, congestion and in limited real-world environments.

<u>Test methodology includes</u>:

- **Laboratory Device Performance Characterization** to quantify the baseline performance of the devices for comparison to performance under test conditions
- **Device/System Integration Testing** to ensure that all systems (including data collection systems and test command and control systems) are operating correctly with properly calibrated measurement equipment
- **Controlled Track Testing** using two basic scenarios that can scale to over 250 LTE-V2X transmitting and receiving devices (with an ability to emulate up to 3000 devices), including moving vehicles and generation of unlicensed UNII transmissions
- **Small-Scale Real-World Testing** to gather data on communications under conditions such as typical reflectivity and obstructions that complicate the RF environment (i.e., buildings, overpasses)

What are we testing?

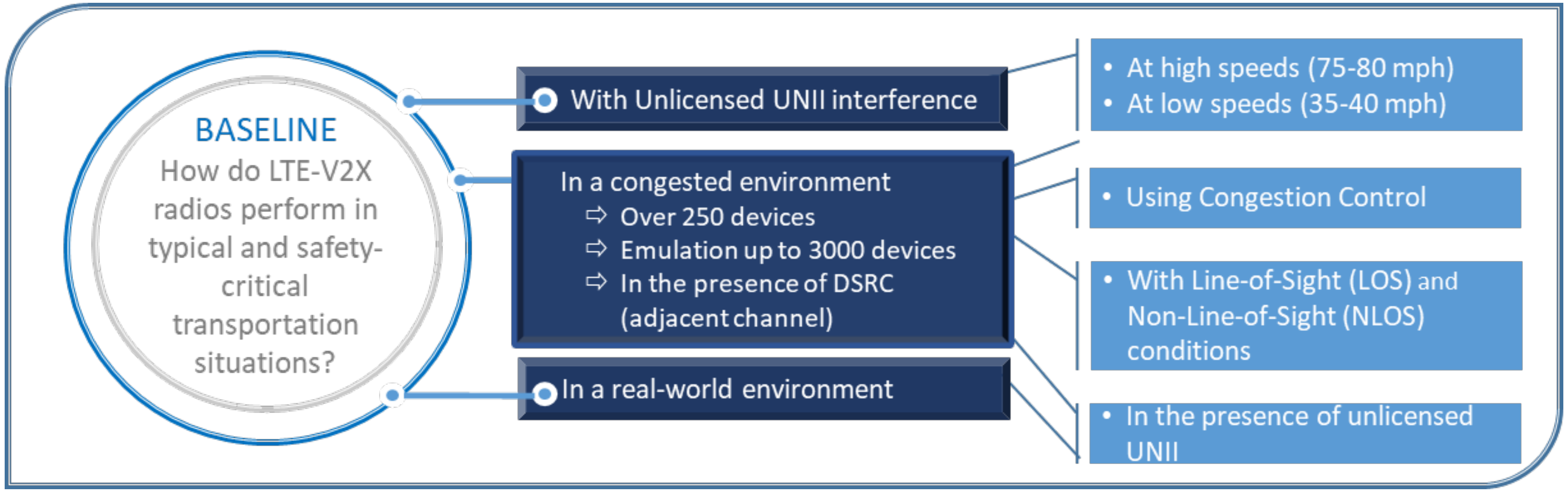
- **U.S. DOT testing focused on the performance of LTE-V2X communications**
- **Each test case was designed to isolate the impact of ...**

CONGESTION: *How do the devices perform in areas that represent dense traffic conditions?*

INTERFERENCE: *How do the radios perform in the presence of unlicensed interference from adjacent channels based on the FCC rulemaking?*

REAL-WORLD IMPACT: *How do the radios perform in natural driving environments?*

VENDOR DIVERSITY: *How do the radios perform when communicating with different vendors?*



Lab Characterization

- **U.S. DOT completed extensive characterization of each device before testing**
- **Devices used in the field met the minimum requirements for testing**

BASIC FUNCTIONALITY

- ✓ Turn On/Off
- ✓ Support for SAE J3161/1
- ✓ Select Tx/Rx Channel, Packet Length and Rate
- ✓ Position Information
- ✓ Change Data Rate / MCS
- ✓ Change Resource Block and Subframe Selection

RF CHARACTERIZATION

- ✓ Receiver Characterization
  - ✓ Rx Sensitivity
  - ✓ AWGN Interference
  - ✓ Noise Figure Extraction
- ✓ Transmitter Characterization
  - ✓ Transmit Power
  - ✓ Spectral Emission Mask
  - ✓ Adjacent Channel Leakage
  - ✓ EVM

ISSUES FOUND DURING CHARACTERIZATION

- GPS drift
- Radios not syncing the system time with the GPS time
- Leakage of energy out of ports that was unknown by vendors
- Significant length of time to get devices up and running
- Inability to hold a constant MAC or IPv6 address through power cycles
- Inability to transmit BSMs
- Significant power variation among devices + variation in receiver sensitivity

Controlled Track Testing

Test Configurations

- Broken into multiple scenarios, **measuring line of sight (LOS) and non-line of sight (NLOS) performance**
- Assess variations in communications between and among **vehicles operating up to 80 MPH** while surrounding onboard units (OBUs) are stationary (e.g. similar to idling traffic at an intersection) because LTE-V2X technology uses different modulations based on vehicle speed.
- Using each device's own settings based **on SAE J3161/1 parameter settings**, including use of the 20 MHz Channel 183 and an operational **congestion mitigation algorithm**
- Over **5 roadside units (RSUs)** set to transmit MAP (intersection geometry) messages, using larger (approximately 14,00 byte) MAP messages.
- Evaluate performance with and without **Unlicensed UNII transmissions**

Real-World Environment

Using a Connected Vehicle Pilot site in Tampa, Florida as a real-world location for communications performance testing. The data set allows for a fuller understanding of the propagation performance of LTE-V2X technologies outside of controlled conditions.

- Testing in an environment that offers **buildings and reflectivity**, as well as urban canyon effects, **overpasses**, foliage and weather variation, among **other typical conditions**.
- **Interference testing** to compare performance in different conditions (i.e. weather, time of day) as a baseline and then in the target area where unlicensed UNII interference was generated.

Figure 3: Test Track Scenario 3 Set-up

Number of LTE-V2X OBUs / RSUs	3 OBUs, 1 RSU
Payload	365 Byte (V2V) / 1400 Byte (I2V)
HARQ	ON
LTE-V2X Channels	CH 183
LTE-V2X Transmit Power	20 dBm
Unlicensed Wi-Fi Channel	20 MHz channel centered at 5.895 MHz / Also in the next adjacent channel CH177 Unlicensed Wi-Fi
Unlicensed Wi-Fi EIRP	OFF / 13 dBm /33 dBm / Max OOBE

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Assessment Metrics

PACKET ERROR RATE

The ratio of packets received to packets sent, over a window of time.

INTER-PACKET GAP

The time between successive packets received.

CONSECUTIVE PACKETS MISSED

The number of times at least two consecutive packets are missed.

TRANSMIT TIME INTERVAL

The time between successive packets sent.

CHANNEL BUSY RATIO

The amount of time the channel is busy.

IMPACT OF UNII INTERFERENCE

BACKGROUND

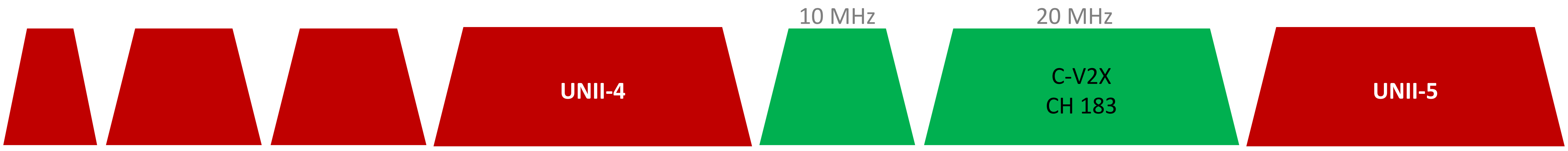
On May 3, 2021, the Federal Communications Commission (FCC) published in the Federal Register a First Report and Order (R&O) that became effective on July 2, 2021. The R&O reallocated 45 MHz of the 5.890 to 5.950 GHz spectrum ("Safety Band") to unlicensed UNII uses.

- The FCC shifted the vehicle-to-everything (V2X) communications technology to the remaining 30 MHz of the 5.9 GHz band. **FCC chose 4G long-term evolution V2X (or LTE-V2X)**, which is part of an emerging cellular V2X (C-V2X) set of technologies.
- The "guard band" that had existed between the lower end of the original Safety Band and the unlicensed UNII band has been removed, **raising concerns about potential out-of-band emissions (OOBE) from unlicensed UNII** operating just below the new (30 MHz) V2X band (5.895 to 5.925 GHz).
- The FCC proposes to **remove the priority for the safety-of-life and public safety messages**, raising concern over how such messages may be affected by other V2X messages or by unlicensed UNII transmissions.

UNII INTERFERENCE: Band Plan

In 2020, the FCC issued a Report & Order to **reallocate 45 MHz of the Safety Band for Unlicensed Use**, preserving only 30 MHz for vehicle and infrastructure communications.

Dedicated V2X communications must operate in this 30 MHz space, with **DSRC in 180 transitioning to C-V2X**



U.S. DOT tested the **performance of LTE-V2X radios in the presence of unlicensed UNII**, both above and below Channel 183

IMPACT OF UNII INTERFERENCE: Moving Vehicle Performance

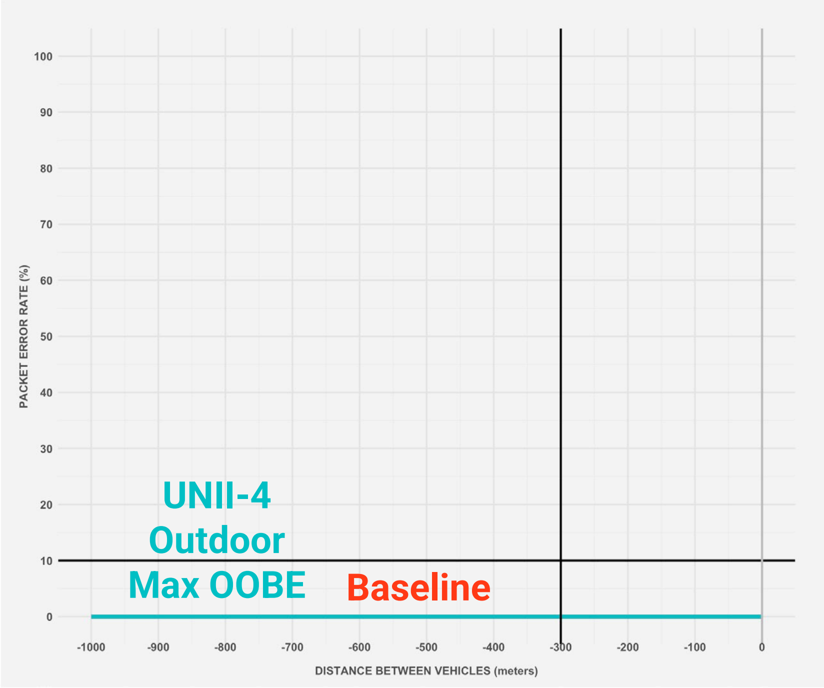
The charts below show the **packet error rate** (the percentage of sent messages that were never received) **between two vehicles approaching each other at high-speed** (80 MPH) under various interference settings (***without any congestion***).

IMPACT OF UNII-4 at Max OOBE on CH 177:

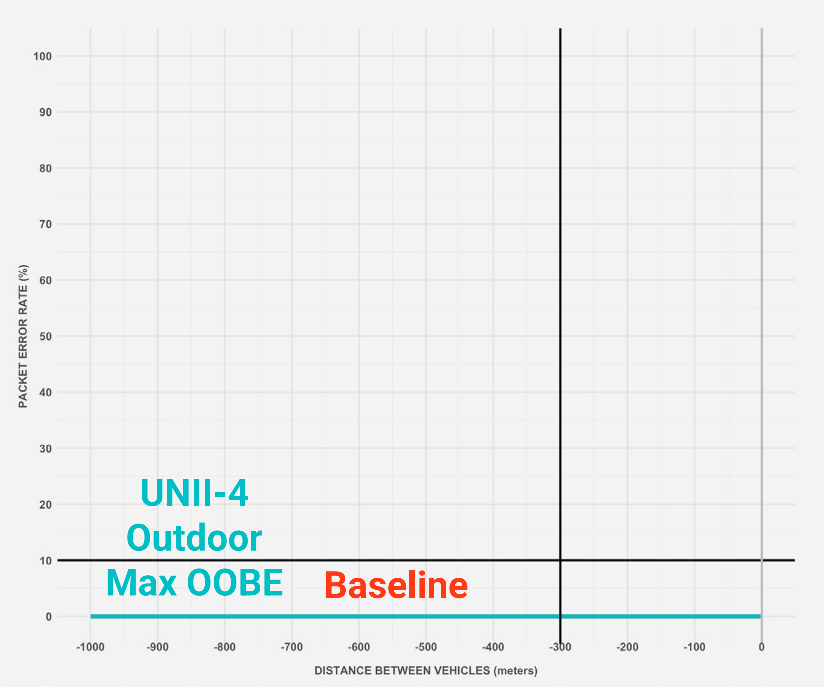
Interference representing an **outdoor access point operating below Channel 183 had no impact**.

The moving vehicles were able to **communicate without packet loss up to 1000 meters apart**, the same as the baseline

High-Speed Vehicle 1 to High-Speed Vehicle 2
Packet Error Rate (with only 2 vehicles)



High-Speed Vehicle 2 **to High-Speed Vehicle 1**
Packet Error Rate (with only 2 vehicles)



IMPACT OF UNII INTERFERENCE: with congestion

The charts below show the **packet error rate** (the percentage of sent messages that were never received) **between two vehicles approaching each other at high-speed** (80 MPH) under various interference settings (***with 250 surrounding radios***).

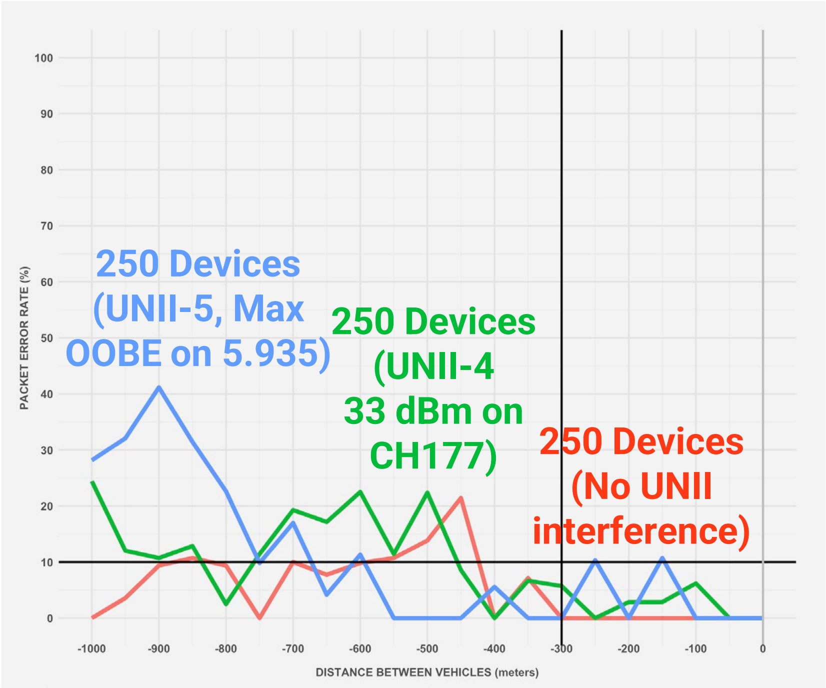
IMPACT OF UNII + CONGESTION

The combination of interference and congestion **reduces communications range**.

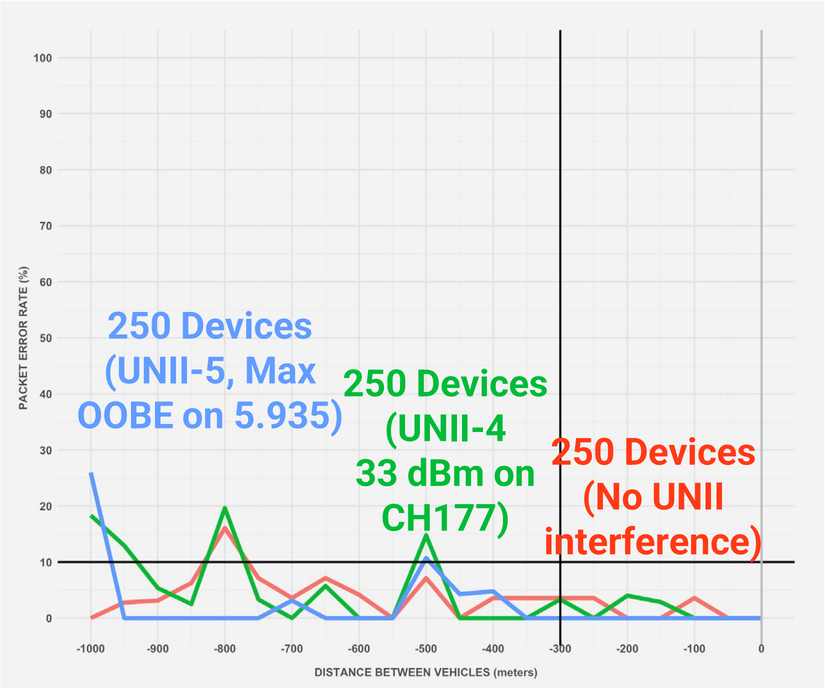
However, the moving vehicles were mostly effective in **communicating within 300 meters** in the presence of both UNII interference and 250-device congestion.

UNII-5 centered at 5.935 impacted one of the vehicles ability to receive messages more than the other

High-Speed Vehicle 1 to High-Speed Vehicle 2
Packet Error Rate (with 250 surrounding radios)



High-Speed Vehicle 2 **to High-Speed Vehicle 1**
Packet Error Rate (with 250 surrounding radios)



IMPACT OF CONGESTION ON LTE-V2X

IMPACT OF CONGESTION: Channel 183 Saturation Point

TESTING DIFFERENT CONGESTION LEVELS

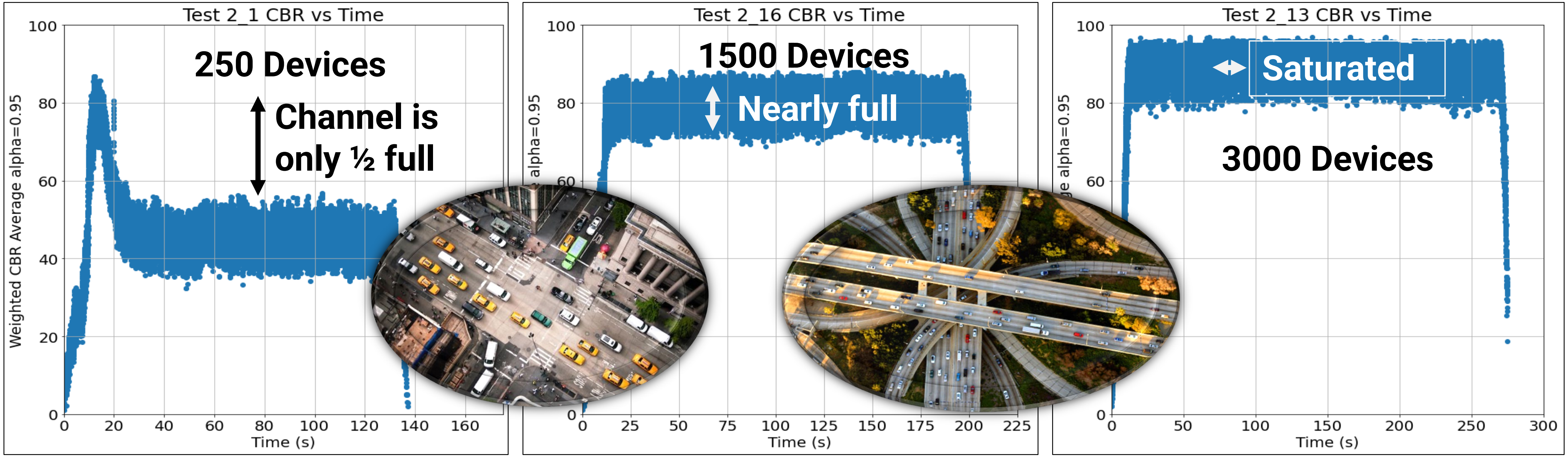
Using over 250 actual radios, U.S. DOT tested under various congestion settings by changing the number of messages each device was transmitting.

*U.S. DOT purposefully tested to see how the radios perform **when Channel 183 reached different capacity levels**.*

CHANNEL BUSY RATIO

The **metric used to determine when a channel has reached saturation** (or is too full) is called the *Channel Busy Ratio*.

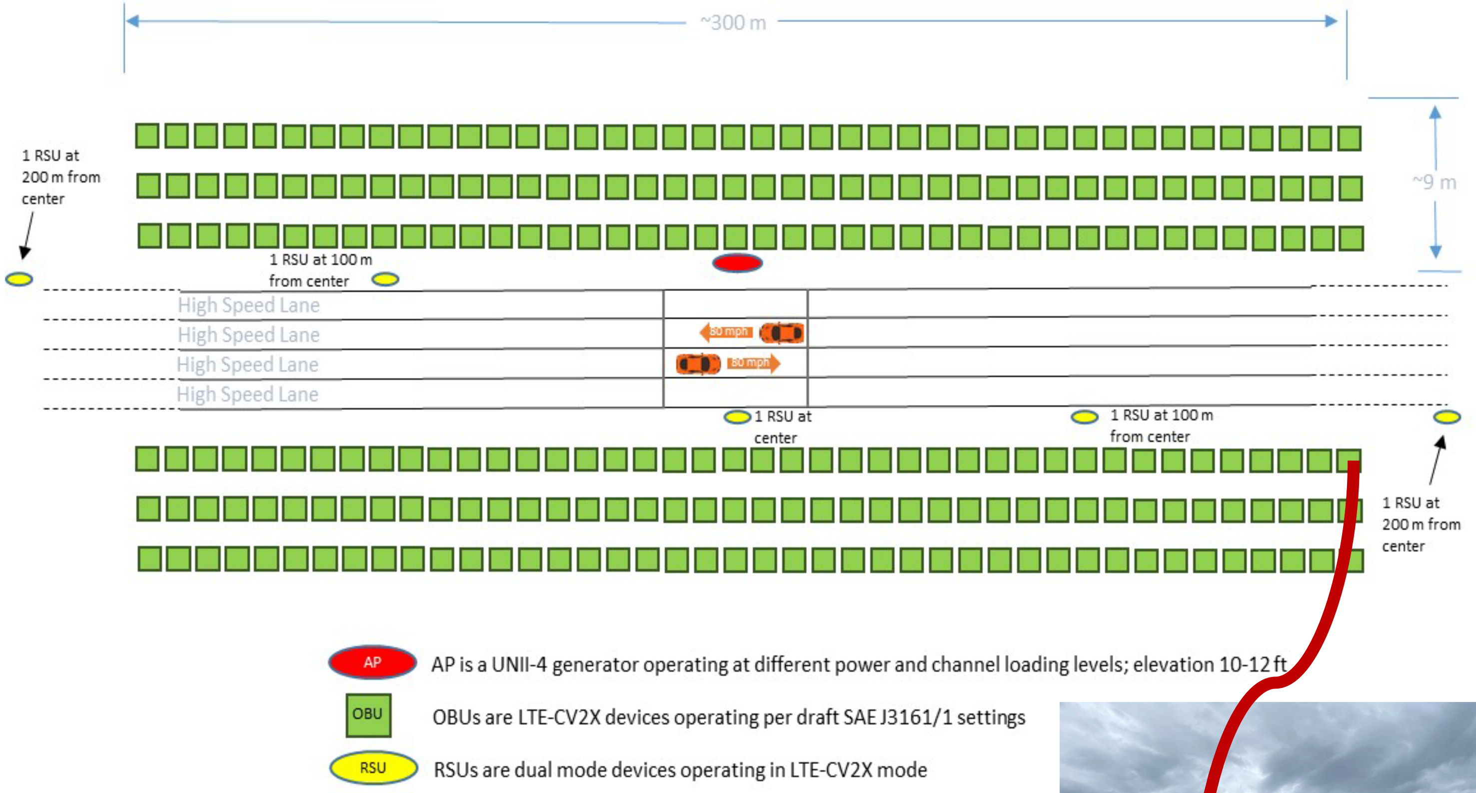
*100% means channel is completely saturated. *These channel busy ratio charts represent three test cases with 250 devices transmitting at different TTIs (with congestion control activated).*



IMPACT OF CONGESTION: How the test setup emulated congestion

Willow Grove Closed Track Testing

- ✓ 2 vehicles approaching each other at 80 MPH (closing speed 160 MPH)
- ✓ With 220+ stationary OBUs and 30+ RSUs (a total of over 250 devices) transmitting and receiving under different mitigation settings
- ✓ By changing the transmission time interval of the stationary devices, U.S. DOT could emulate different levels of congestion
- ✓ Most radios were equipped with congestion mitigation algorithms



IMPACT OF CONGESTION: Moving Vehicle Performance

The charts below show the **packet error rate** (the percentage of sent messages that were never received) **between two vehicles approaching each other at high-speed** (80 MPH) under various congestion settings (*without unlicensed interference*).

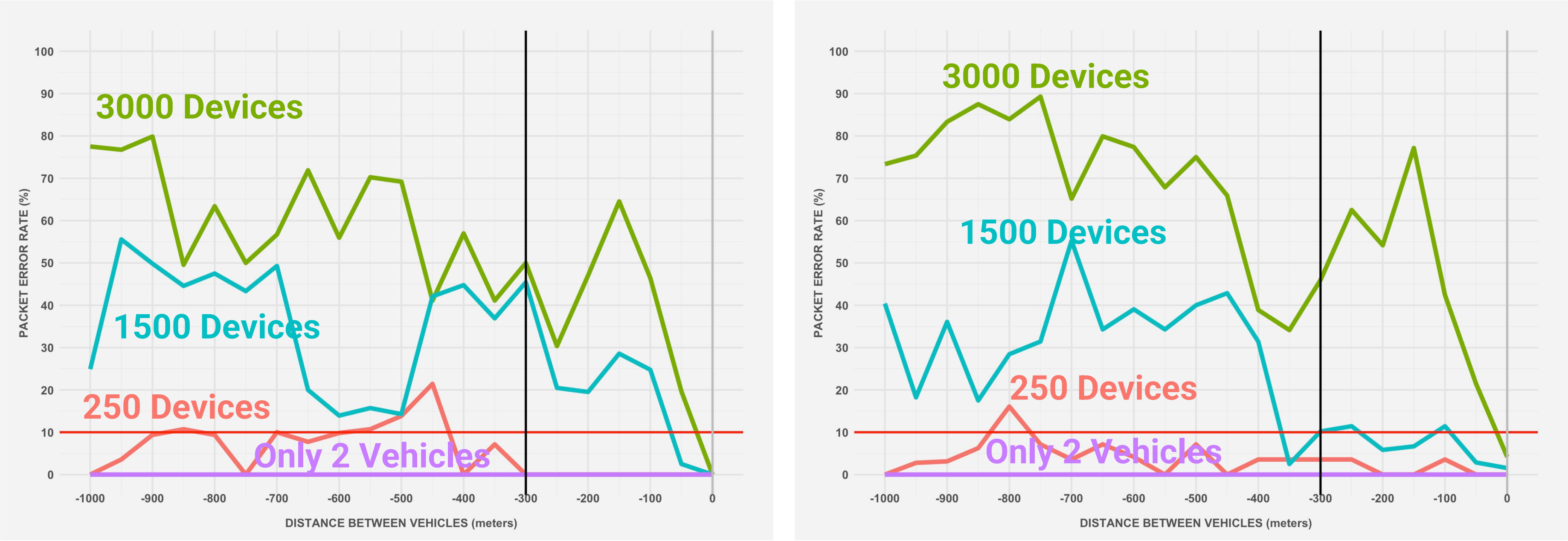
IMPACT OF CONGESTION

Only when emulating **1500+ devices was performance significantly impacted** between the moving vehicles.

At 250 devices, range was reduced to **450 meters** for one vehicle and **800 meters** for the other, but performance was acceptable within 300 meters

High-Speed Vehicle 2 receiving (from MV1)
Average Packet Error Rate across 5 trials (50 m bins)

High-Speed Vehicle 1 receiving (from MV2)
Average Packet Error Rate across 5 trials (50 m bins)



IMPACT OF CONGESTION: Stationary Devices (emulating vehicles)

PERFORMANCE OF DEVICES ON PODS

The devices placed on pods to emulate vehicles in traffic were **impacted by congestion more than unlicensed interference.**

Over 1/3 of the pod pairings had a PER > 10% with **250 radios** broadcasting at the same time.

- This percentage is skewed by the poor performance **of one particular cross-vendor pairing**.

Nearly 80% of pairings had a PER > 10% when emulating **3000 radios**.

Test Case	Vehicle Mean TTI (ms)	Vehicle Mean IPG (ms)	Vehicle Mean PER (%)	ALL Static C-V2X Devices Mean PER (%)	Static Devices Percentage of pairs with PER > 10%
250 Actual Radios	142.04	143.25	0.62	11.77	38.66
250 Radios Emulating 1500 Radios	141.61	168.69	14.92	14.10	45.67
250 Radios Emulating 3000 Radios	135.24	221.68	53.57	38.37	79.28

**Statistics for when vehicles were within 300 meters of each other*

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REAL-WORLD ENVIRONMENT

Vehicle-to-Vehicle, Nominal Line-of-Sight

<u>Test methodology:</u>

- **Two vehicles** traveling together, **one vehicle** stationary near an intersection, **RSU at intersection**.
- **Visualizations** of all the communication pairs were plotted for **qualitative evaluation**.
- **Individual transmit and receive log files** are also available to provide a qualitative view of radio data delivery performance.

<u>Test questions:</u>

- *Did the equipment experience any **interaction with the radio environment**, was there any **impact on performance** due to the built environment?*
- *What was the **qualitative impact** of <u>expected interference</u> from **UNII activity**?*

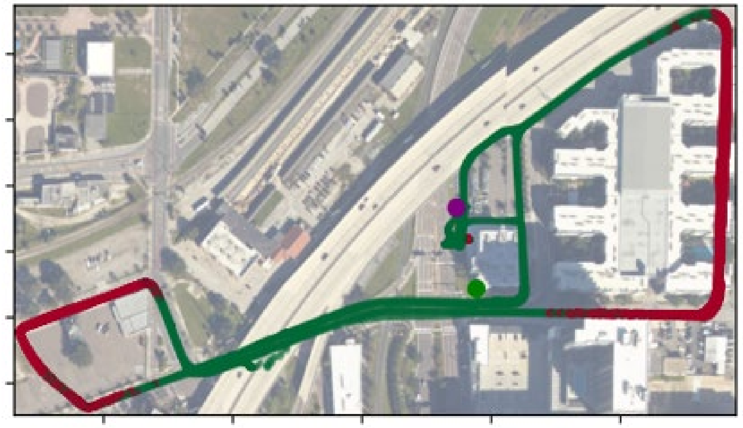
<u>General Observations:</u>

- The useful range of the medium was **reduced to around 350 meters** by the combined effects of the built environment.
- An **interference source** near one of the communicating partners **shortened the useful range** even further.

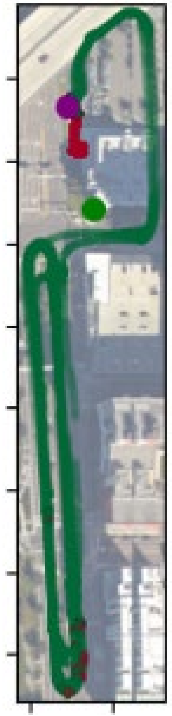
Vehicle-to-Vehicle, Nominal Line-of-Sight – Tampa Example

Visualization Examples

Moving vehicle to stationary, Twiggs route



Moving vehicle, Meridian route



Moving vehicle to moving vehicle

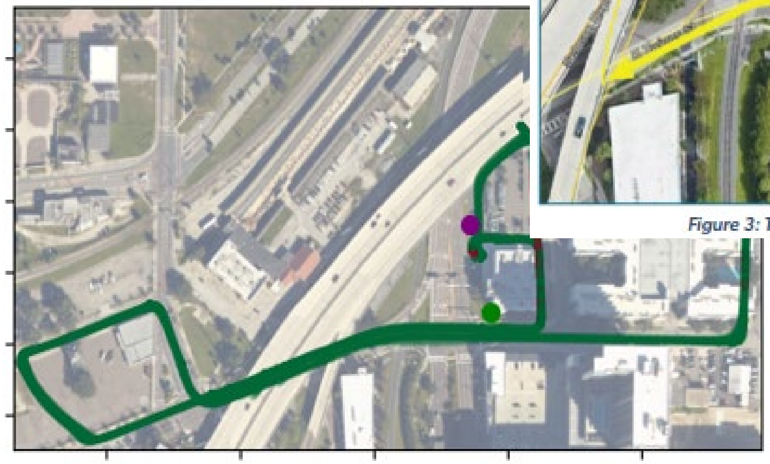
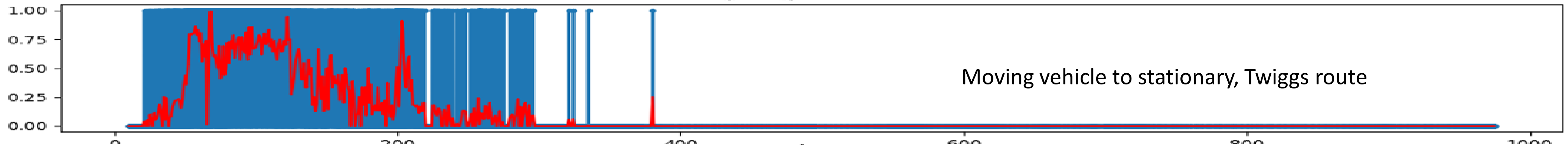
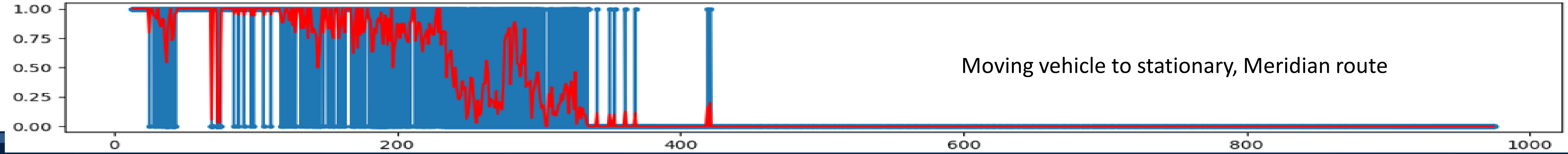


Figure 3: Test Track Scenario 3 Set-up

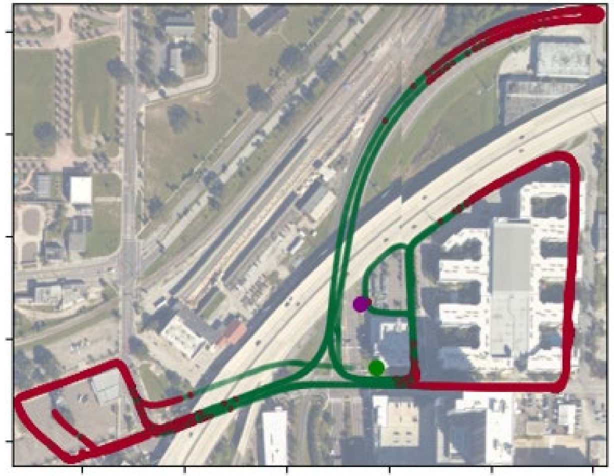




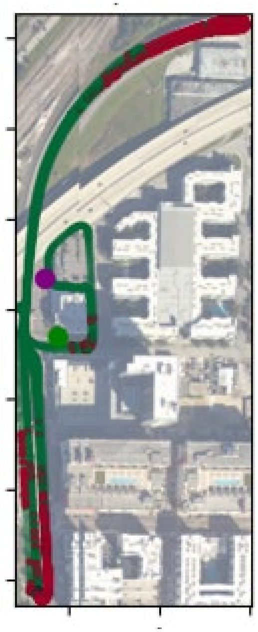
Vehicle-to-Vehicle, Nominal Line-of-Sight – Tampa Example, Interference

Visualization Examples

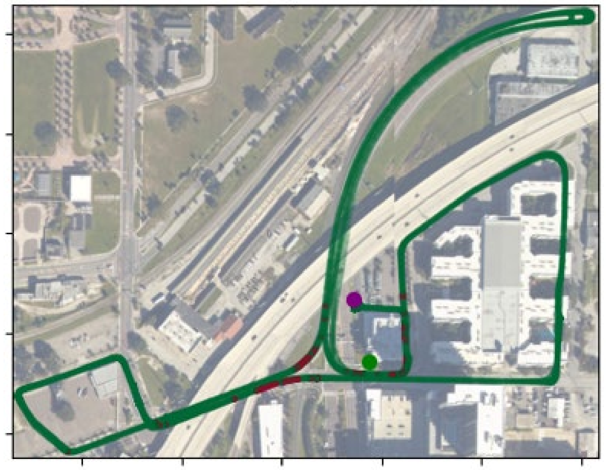
Moving vehicle to stationary, Twiggs route

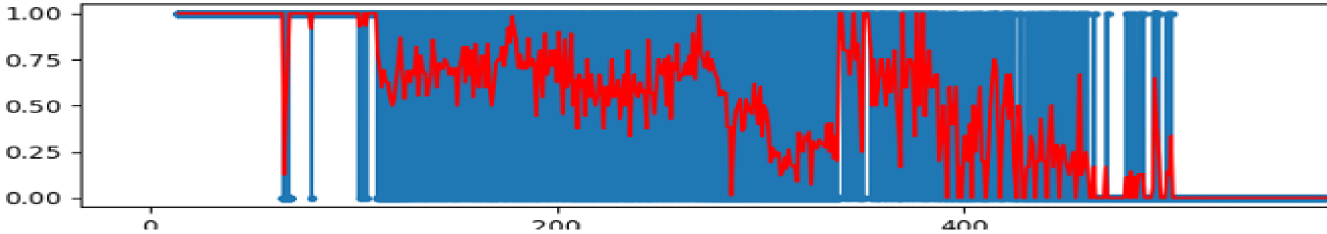


Moving vehicle, Meridian route

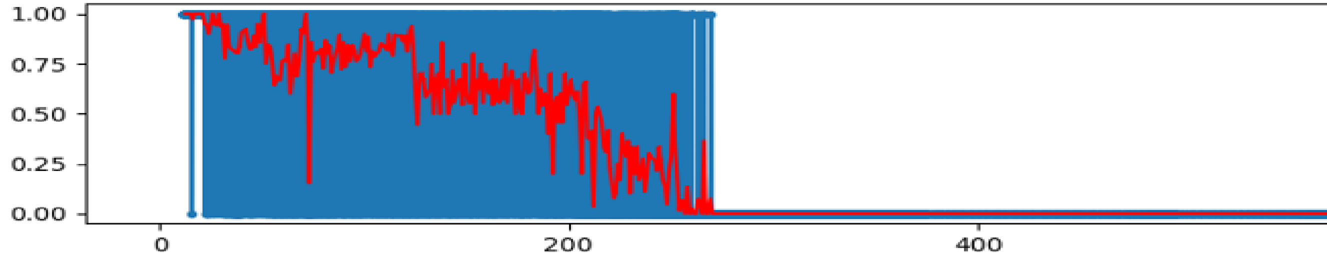


Moving vehicle to moving vehicle, Twiggs route





Moving vehicle to stationary, no interference, Twiggs route



Moving vehicle to stationary, with interference, Twiggs route

Vehicle-to-Vehicle, Obstructed Line-of-Sight

Test methodology:

- **Two vehicles** traveling near each other with line-of-sight obstructed by the built environment.
- Conducted in various locations in **Tampa**, **NAS Willow Grove**, and **Turner Fairbank Highway Research Center** where there was a variety of building construction and site usage types – modern commercial building construction, older construction, massive structures, open park-like sites, and different levels of foliage.
- **Animated visualizations** of the successful propagations were created for qualitative evaluation.
- Individual transmit and receive log files are available as well as the animated visualizations of the data delivery performance.

Test questions:

- *Did the equipment **experience any interaction with the radio environment**, was there any **impact on performance** due to the **built environment**?*
- *Was the **radio line-of-sight** significantly different than **visual line-of-sight**?*

General observation:

- Only the **most substantial environmental objects** attenuated the medium to the point where useful communication was not possible.

Vehicle-to-Vehicle, Obstructed Line-of-Sight – TFHRC Example

Visualization Examples

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Documentation and Data

Anonymized test data is available in two forms on the V2X website:

- Over **11 TB of data** in total
  - Data was collected for each of the 250+ devices under test (transmits and receipts)
- A **data primer** is included on the website to map each test case to the relevant dataset, along with a data dictionary to provide an understanding of the metadata.

The data is available in two formats:

- **Moving vehicle data** shows the transmissions and receipts between the two moving vehicles under test in each test case.
- **Raw data** for each transmitter-receiver pairing is available on a public Amazon Web Services bucket (instructions for how to access are included on the website)

ITS/V2X TESTING WEBSITE

MOVING VEHICLE DATA

Data to analyze **the performance of the moving vehicles** in each test case can be found in CSV files on the ITS/V2X TESTING Website

LARGE-SCALE CONTROLLED FIELD DATA

This U.S. DOT large-scale controlled field testing moves beyond the reliance on simulation to collect and present real-world measurements taken under challenging transportation conditions. The large-scale field test set-up will mimic the following use cases:

1. Crash-imminent scenarios where there are widely differing vehicle speeds with the vehicles involved in the potential conflict situation—with and without line-of-sight; with and without the presence of unlicensed Wi-Fi.
2. Crash-imminent scenarios where the density of vehicles causes congested conditions in the wireless communications—with and without line-of-sight; with and without the presence of unlicensed Wi-Fi.

The data collected from these tests is provided below:

- Scenario 1 Moving Vehicle Data
- Scenario 2 Moving Vehicle Data
- Scenario 3 Moving Vehicle Data
- Scenario 4 Moving Vehicle Data

RAW DATA: Amazon Web Services

The raw data for all of the devices under test (250+ devices) **can be found on Amazon Web Services**.

Detailed instructions are provided for gaining free access to the site and downloading the data.

Name ▲	Type
ClosedTestTrack1/	Folder
ClosedTestTrack2/	Folder
RealWorld1/	Folder

Data is organized in folders (explained in the **Data Primer** provide on the website).

Each dataset corresponds to a test case detailed in the **USDOT LTE V2X TEST PARAMETERS** spreadsheet found on the website.

Additional Test Cases

Data on the following use cases is available online:

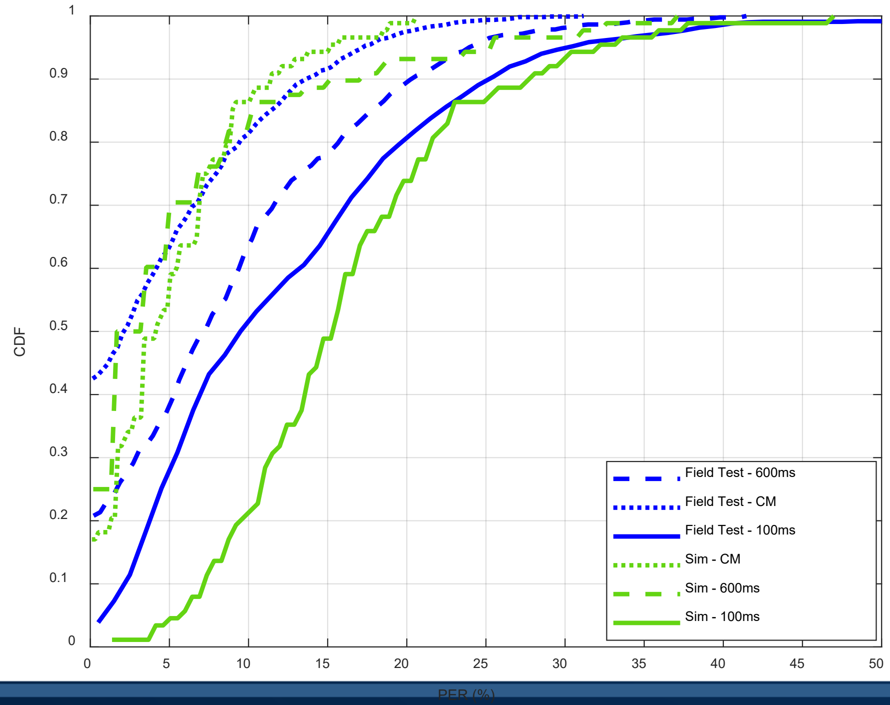
- ✓ In-Vehicle Interference testing
- ✓ Attenuated Line-of-Sight Testing
- ✓ The presence of DSRC operating adjacent to Channel 183
- ✓ Signal Violation Warning Testing
- ✓ Additional RSU analysis
- ✓ Impact of varying payload size, and SPS flows
- ✓ Different test configurations

TESTING OBSERVATIONS: Simulation Results

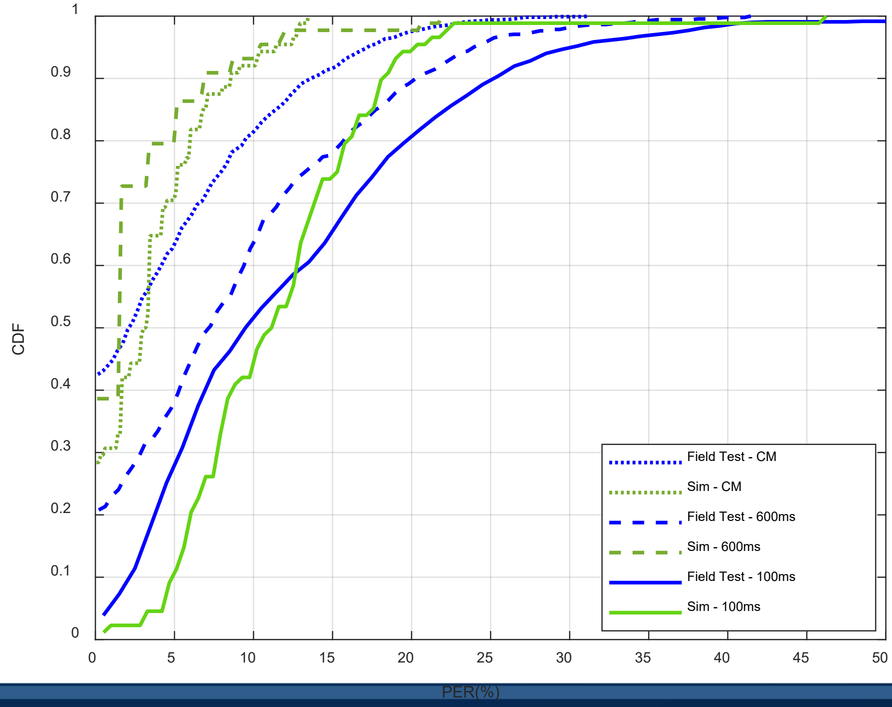
• U.S. DOT has been working with NTIA to validate simulation results.

- The simulation results almost **match the field test results on the 100 ms tests**
- Results with emulation and **1500 devices** deployment scenario show that **emulation performs better than simulation**. This is expected because in emulation six devices emulated by a single device cannot interfere with each other. However, in real deployment, any devices can interfere with any device

With Extended Vehicle-A Channel Model



With Rician Channel Model



LTE-V2X TESTING OBSERVATIONS

TESTING OBSERVATIONS: Summary

U.S. DOT testing focused on the lower layers of the protocol – mainly, the physical and data link layers – our results indirectly inform us how safety applications would work. **Importantly,** the test results provide **critical insight into the timeliness and reliability of the data** that safety applications rely on to issue crash-imminent warnings.

IMPACT OF INTERFERENCE

- **Unlicensed interference** from either an indoor or outdoor access point on the channels adjacent to Channel 183 **had little impact on radio performance**.
- The **combination of unlicensed interference and congestion** (~250 radios) reduced the effective communications range between the moving vehicles; however, vehicles were able to communicate within 300 meters in low-to-moderate congestion levels.

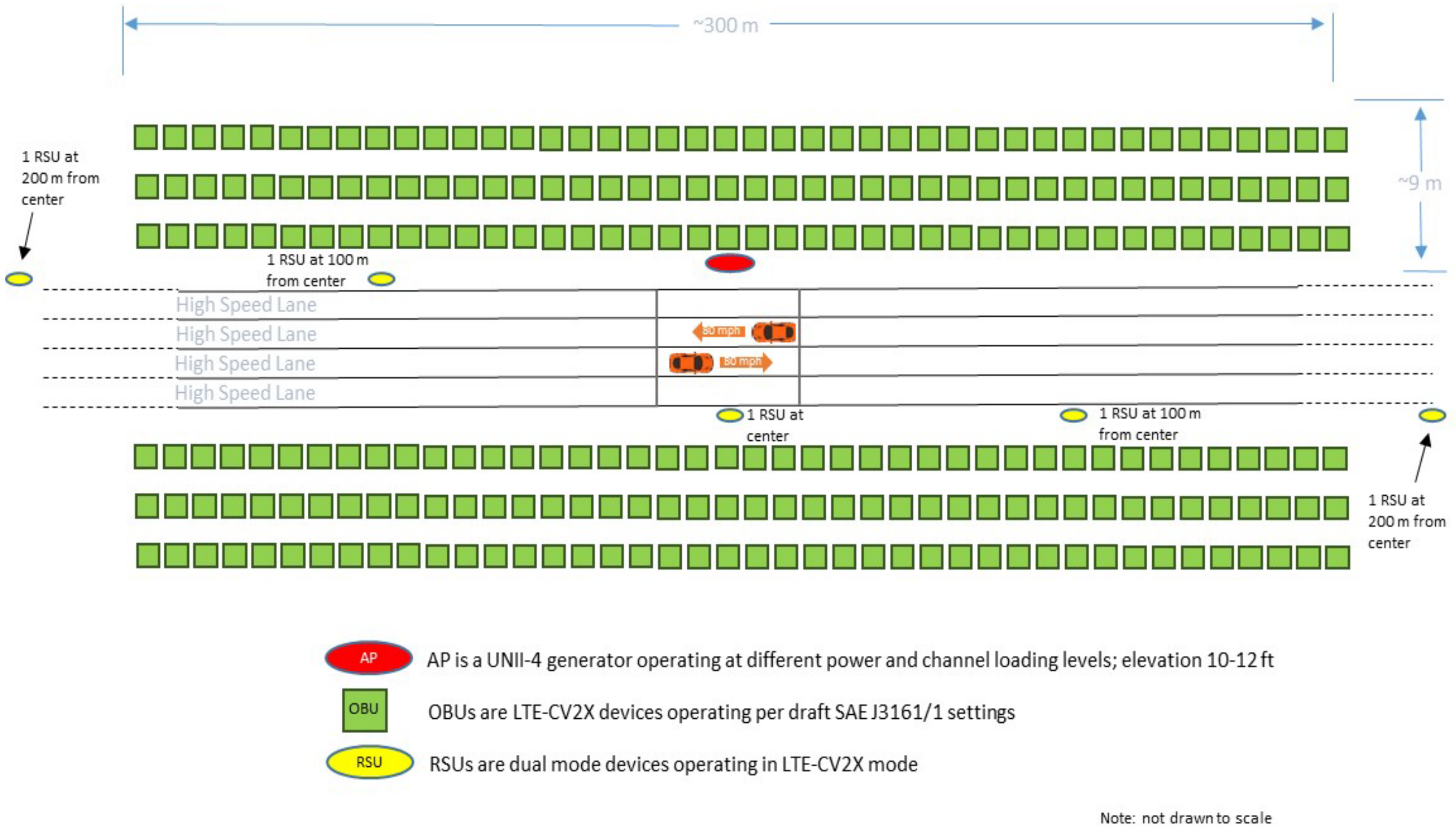
IMPACT OF CONGESTION

- Communications performance between the two moving vehicles was only **significantly impacted when emulating extreme congestion levels of 1500-3000 radios** (6x to 12x emulation of 250 radios).
- Channel 183 reached **near saturation point when emulating 6x 250 radios** (~1500 radios), which significantly impacted performance between the moving vehicles.

TESTING OBSERVATIONS: Summary

IMPACT OF CONGESTION (continued…)

- As congestion increases, the **number of devices effectively receiving BSMs from the vehicle drops**.
- The **number of times *zero* static devices receive from a vehicle** also increases with heavy congestion. This is important because every time this occurs, the static device does not hear from the vehicle for 36 meters of travel.
- Increasing **congestion affects the receiver count substantially more compared to interference** in this analysis.



TESTING OBSERVATIONS: Technology Challenges

SKIPPED TRANSMISSIONS. Throughout testing, devices randomly stopped transmitting for several seconds. This occurred across different test cases, test environments and with multiple vendors.

CONGESTION CONTROL. The congestion control algorithm took longer to activate than expected within the moving vehicles. Often the vehicles did not change their respective TTIs until they had already passed each other.

INTEROPERABILITY: Additional testing is needed using different chipsets. U.S. DOT testing included multiple LTE-V2X vendors (using both vehicle-based OBUs and infrastructure-based roadside units) with the same underlying chipset. Performance varied across vendors.

POTENTIAL NEXT STEPS

- ✓ Additional testing with **newer software***
- ✓ **Optimization** within the radio layers might further improve performance
- ✓ **Improved GPS** and location awareness
- ✓ **Certification:** developing robust test procedures, **cross-vendor** conformance testing

**U.S. DOT tested with devices procured in 2020 that contain software versions that have since been updated by the vendors and could possibly address some of the challenges highlighted on this slide.*