GEORGIA DOT RESEARCH PROJECT 22-28

Final Report

5.9GHZ INTERFERENCE RESILIENCY FOR CONNECTED VEHICLE EQUIPMENT

Georgia Department of Transportation

Office of Performance-based Management and Research
600 West Peachtree Street NW | Atlanta, GA 30308

November 2023

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.: FHWA-GA-23-2228	2. Government Accession No.: N/A	3. Recipient's Catalog No.: N/A
4. Title and Subtitle: 5.9GHz Interference Resiliency for Connected Vehicle Equipment		5. Report Date: November 2023 6. Performing Organization Code: N/A
7. Author(s): Billy Kihei (PI), Ph.D. Chase Barclay (Undergraduate Research Assistant) Jason Greaves-Taylor (Undergraduate Research Assistant)		8. Performing Organization Report No.: 22-28
9. Performing Organization Name and Address: Kennesaw State University 840 Polytechnique Lane Marietta, GA 30060		10. Work Unit No.: N/A 11. Contract or Grant No.: PI#0019320
12. Sponsoring Agency Name and Address: Georgia Department of Transportation (SPR) Office of Performance-based Management and Research 600 West Peachtree St. NW Atlanta, GA 30308		13. Type of Report and Period Covered: Final Report (December 2022 – December 2023) 14. Sponsoring Agency Code: N/A
15. Supplementary Notes: Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract:

There are new Wi-Fi channels in the 5.9GHz Dedicated Short Communications Band in the United States which once was licensed spectrum exclusively for IEEE 802.11p connected vehicle devices. Existing literature reports through simulations and modelling that unlicensed interference from low-cost Wi-Fi devices could degrade the quality of IEEE 802.11p communications. Furthermore, the introduction of Wi-Fi 6e has presented an additional form of interference to C-V2X technology. To date it has been challenging to perform unlicensed interference experimentation at scale due to the lack of low-cost Wi-Fi devices that can transmit in the new 5.9GHz Wi-Fi channels and Wi-fi 6e channels. With this work we report the actual interference effects using 25 real low-cost devices which have been modified to operate in the new 5.9GHz Wi-Fi channels and Wi-fi 6e channels and report the effects on commercial DSRC and C-V2X devices. Experimental observations both in lab and in the field show that infrastructure to vehicle messages have a higher likelihood of reception than vehicle to infrastructure messages during adjacent channel interference activity.

17. Keywords: Intelligent Transportation Systems, Connected Vehicle, Wireless Communications, DSRC, IEEE 802.11p, C-V2X, U-NII-4, U-NII-5, Wireless Interference		18. Distribution Statement: No restrictions.	
19. Security Classification (of this report): Unclassified	20. Security Classification (of this page): Unclassified	21. No. of Pages: 162	22. Price: Free

Form DOT F 1700.7 (8-72)

GDOT Research Project 22-28

Final Report

5.9GHZ INTERFERENCE RESILIENCY FOR CONNECTED VEHICLE EQUIPMENT

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November 2023

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LIST OF ACRONYMS

CV = Connected Vehicle

DSRC = Dedicated Short-Range Communications (IEEE 802.11p)

LTE-V2X = Long Term Evolution Vehicle to Everything Communications

3GPP = Third Generation Partnership Project

C-V2X = Cellular Vehicle to Everything Communications (3GPP Rel 14 Sidelink)

BSM = Basic Safety Message

SPAT = Signal Phase and Timing Message

MAP = MapData Messages

SRM = Signal Request Message

SSM = Signal Status Message

TIM = Traveler information Message

U-NII-4 = Unlicensed National Information Infrastructure 4

U-NII-5 = Unlicensed National Information Infrastructure 5

GHz = Giga Hertz

MHz = Mega Hertz

ACP = Adjacent Channel Power

ACPR = Adjacent Channel Power Ratio

OOBE = Out of Band Emissions

V2I = Vehicle to Infrastructure

I2V = Infrastructure to Vehicle

PRR = Packet Reception Rate

EXECUTIVE SUMMARY

Currently, there are not enough Wi-Fi devices operating around U-NII-4 Channels 180 to 184 and U-NII-5 (Wi-Fi 6e in 6GHz) channels to understand the impact to Connected Vehicle (CV) applications using IEEE 802.11p (Dedicated Short-Range Communications in U-NII-4 Channel 180) and 3GPP LTE-V2X Rel.14 (Cellular-Vehicle-to-Everything Communications in U-NII-4 Channel 183).

This research deployed a density of real-world low-cost Wi-Fi 5 devices and Wi-Fi 6e devices in a laboratory setting and field deployment to understand the impact of low-cost unlicensed U-NII-4 and unlicensed U-NII-5 equipment causing adjacent channel interference from above and below the 5.9GHz Intelligent Transportation Systems (ITS) safety band.

The in-lab findings (without affects of movement or distance) identified:

- DSRC is more likely to be susceptible to U-NII-4 interference (Ch. 177 at 20MHz).
- C-V2X is not affected by U-NII-5 interference (Ch. 1 at 20MHz)
- If U-NII-4 interferers were to take Ch. 180, under low density of C-V2X devices, C-V2X is not affected by U-NII-4 interferers. Under moderate density of C-V2X devices, C-2X is slightly affected by U-NII-4. Under high density of C-V2X devices, the effects are not known.
- RSU antennas are more likely to capture adjacent channel power (ACP) interference than OBU antennas.

The field tests identified:

- ACP interference does not substantially impact Infrastructure to Vehicle (I2V) communications.

    - DSRC and C-V2X: CV applications that rely on SPAT, MAP,TIM,SSMs will likely perform as expected up to 25 U-NII-4 interferers.

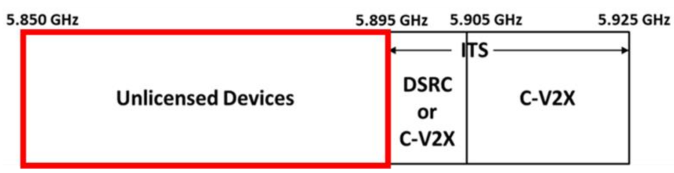
- ACP interference substantially impacts DSRC Vehicle to Infrastructure (V2I) communications.
- DSRC CV applications that rely on BSM, SRM will likely experience variations in performance depending on the Packet Reception Rate necessary for application performance.

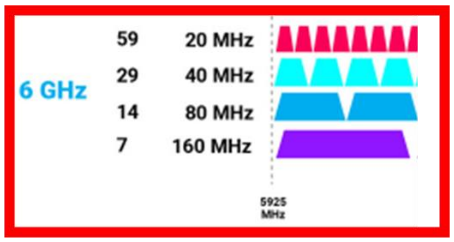
The findings suggest that suppressing ACP interference through tighter RF filtering could improve the reliability of CV equipment. However, there may still be risks of dropped packets due to low-cost U-NII-4 ACP interference. CV applications that require a specific PRR performance of V2I messages should respond flexibly to changes in ACP interference, which could be measured through a separate device deployed in the field. Ideally, the best solution is a guard band between CV spectrum and U-NII-4 spectrum.

CHAPTER 1. INTRODUCTION

OVERVIEW

Connected vehicle (CV) technologies will transform the way Georgians travel by providing safety, mobility, and environmental benefits. CV deployments in Georgia currently feature Roadside Unit (RSU) radios and a very small number of On-Board Vehicles. The RSUs operate in 30MHz of licensed bandwidth known as the 5.9GHz Safety Band. That 30MHz of spectrum allotment is critical for enabling CV applications to provide the benefits mentioned previously. However, that vital band of spectrum resides between two unlicensed Wi-Fi bands. This report details the effects of adjacent channel interference on the CV applications' performance.





The Georgia Department of Transportation (GDOT) supported a study to understand through simulation how the current 30MHz bandwidth can support CV application availability (1). To date, the US Department of Transportation has conducted field tests of in-band interference, and limited adjacent channel interference field tests that only feature one U-NII-4 interferer.

This project is a broader study using real-world interference with actual low-cost U-NII-4 and U-NII-5 device saturations on the 30MHz licensed 5.9GHz Safety Band.

FINAL REPORT STRUCTURE

The structure of this report encompasses seven chapters that describe the in-lab and field tests. Chapter 2 provides a literature review covering interference reports on CV equipment. Chapter 3 describes equipment used in the in-lab study. Chapter 4 reviews the in-lab studies, methodology, and results. Chapter 5 describes equipment used in the field tests.

Chapter 6 reviews the field tests, methodology, and results. Finally, chapter 7 summarizes the research and offers multiple recommendations for future studies. The appendix and references and are found at the end of this report.

CHAPTER 2. LITERATURE REVIEW

Connected vehicle (CV) technologies can transform road travel by providing safety, mobility, and environmental benefits. CV deployments based on 5.9GHz Dedicated Short Range Communications (DSRC) based on IEEE 802.11p currently feature Roadside Unit (RSU) radios and a very small number of On-Board Units (OBU). The RSUs operate in 10MHz of licensed bandwidth known as the 5.9GHz Safety Band Channel 180. That 10MHz of spectrum allotment is critical for enabling CV applications to provide the benefits mentioned previously until IEEE 802.11p is sunset, in favor of Cellular-Vehicle-to-Everything (LTE-V2X Rel 14) technology. However, as seen in Figure 1, that vital DSRC channel 180 of spectrum resides above Wi-Fi bands (U-NII-4 devices), which could cause adjacent channel interference and significantly degrade the CV communication performance.

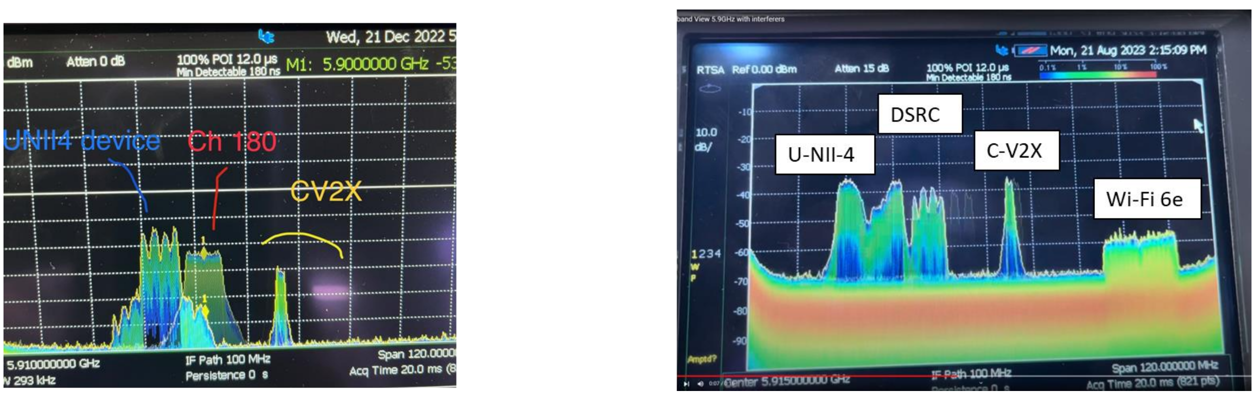


Figure 1. Photos. Low-cost and aged U-NII-4 devices can show large out-of-band-emissions, which degrade IEEE 802.11p communications. Wi-Fi 6e U-NII-5 devices have a large guard band to C-V2X.

There are not enough Wi-Fi devices operating around Unlicensed National Information Infrastructure (U-NII) U-NII-4 Channel 180 to understand the impact to CV communications. This work experimentally observes the effects of up to 25 U-NII-4 low-cost Wi-Fi devices in a lab setting to understand the impact of adjacent channel interference on channel 180 communications. Studies to date do not consider a saturation of real-world interference devices in the unlicensed Wi-Fi bands below the 5.9GHz Intelligent Transportation Systems (ITS) safety band. This is due to an unavailability of consumer Wi-Fi devices that operate in the lower 40MHz of the previous 5.9GHz ITS Safety Band, and a lack of real low-cost device degradation over time, in which spectrum emissions can exceed the regulatory mask that they were originally certified under. The objective of this work assesses the resiliency of IEEE 802.11p communications to adjacent channel interference by reporting real-world packet adjacent channel power ratio (ACPR) and providing empirical models for packet reception rate during U-NII-4 Wi-Fi interference.

The Georgia Department of Transportation (GDOT) is currently supporting an on-going study to understand through simulation how the current 30MHz bandwidth can support CV application availability [1]. However, a broader study needs to be conducted on real-world interference with actual device saturation in the adjacent unlicensed band.

Carnegie Mellon University recently completed a study that used extensive simulations to identify and assess alternative ways to meet the spectrum needs of connected vehicles in a reduced 30MHz bandwidth, while also providing spectrum for Wi-Fi [2]. The researchers further developed additional simulations to understand other spectrum options amid interference [3].

WSP USA studied the impacts of 5.9GHz spectrum changes on CV applications [4]. A final report is being prepared, however, a white paper from the study reported that the impact of real-world saturation interference has not yet been tested, evaluated, or resolved [5].

Virginia Tech [6] simulated the impact of adjacent channel Wi-Fi transmissions surrounding the 5.9GHz ITS safety band on Cellular-Vehicle-to-Everything (C-V2X) operations. The main concern is that out-of-band-emissions (OOBE) are linked to device cost, such that low-cost devices tend to possess lower quality radio frequency filters (RF), which can cause more power to radiate outside the desired channel. In their simulations they assume the worst-case spectral mask. Our work presented reports the effects of saturation of real-world low-cost devices to verify if these assumptions are true for IEEE 802.11p.

The US Department of Transportation (USDOT) [7] published a report examining the potential impact of interference from unlicensed users on traffic safety in the safety band. The report presents an analysis of the effects of such interference due to adjacent channels *within* the 5.9GHz ITS Safety Band but did not perform any analysis on adjacent channel interference due to unlicensed devices, referred to as ambient noise. We report that the ambient noise due to low-cost Wi-Fi devices operating in 5.9GHz presents a significant degradation to IEEE 802.11p communications operating in Channel 180.

The USDOT published another report examining the potential interference that may arise from the proposed changes to the Out of Band Emissions (OOBE) rules in 2016 [8]. The analysis focuses on the adjacent channel interference caused by the new Out-of-band-emissions (OOBE) mask of U-NII-3 devices transmitting near the original lower 5.9 GHz band (Channel 172). The conclusions found that the new OOBE limits potentially increase interference to DSRC (ch.172), but the specific level was not able to be established without studying specific deployment scenarios and conducting further analysis with real devices. The report neglects to consider how radio frequency components age, in which spectrum masks over time create larger a OOBE than when first certified by the federal communications commission (FCC). Furthermore, the report neglects to effects of low-cost devices unlicensed U-NII devices that use inferior components that what pass certification, what we refer to in this work as: imposter devices.

A study by independent researchers carried out the experimental work called out for by [8] to investigate the potential impact of adjacent channel interference from Wi-Fi emissions on the performance of DSRC [9]. To evaluate the performance of DSRC in the presence of adjacent channel Wi-Fi interference, the researchers conducted measurements by placing DSRC in channel 172 and configuring 802.11ac Wi-Fi in channels 169 (20 MHz bandwidth) and 167 (40 MHz bandwidth) to simulate different deployment scenarios. The results showed that when DSRC transmit power was increased to 33 dBm, even Wi-Fi transmitters in close proximity to the DSRC receiver had minimal impact, achieving Packet Delivery Ratios (PDR) higher than 80\% for DSRC transmitter-receiver distances up to 415 meters. The study concluded that Wi-Fi adjacent channel interference did not significantly affect DSRC performance under reasonable DSRC channel conditions. However, the authors noted that their measurements were conducted in a lab environment without considering signal fading effects. They emphasized the need for further field tests in real-world settings, taking into account various factors such as multiple nearby Wi-Fi devices, mobility of DSRC devices, and Non-Line-of-Sight conditions to provide more conclusive results and insights for practical deployment.

The Vehicle-to-Vehicle Communications Research Project (V2V-CR) reported on the impact of cross-channel interference from Wi-Fi emissions on IEEE 802.11p devices [10]. According to the report, cross-channel interference from 802.11ac devices can affect DSRC performance at distances of up to 500 meters, with a typical range between 200 and 300 meters. The degree of interference is closely related to the spectral occupancy of 802.11ac emissions, with greater adherence to spectral mask requirements leading to more significant interference effects. However, the study acknowledges that the testing distances used may result in stronger DSRC Received Signal Strength (RSS) levels than what may be experienced at longer ranges or in non-line-of-sight (NLOS) environments. The authors faced challenges in obtaining prototype devices for "Detect and Avoid" or other channel-sharing solutions, which led them to modify available 802.11ac devices to operate in the DSRC band. This limitation may impact the accuracy of test results when compared to actual coexistence scenarios. As a result, the report suggests future research and testing aimed to improve characterization, including detailed performance evaluation of DSRC radios with improved receivers and access to a broader range of 802.11ac settings for deeper analysis. Further testing with various 802.11ac traffic patterns and realistic DSRC link RSS values representative of required performance capabilities is also essential to enhance understanding of cross-channel interference dynamics.

CHAPTER 3. IN-LAB EQUIPMENT

1x Field Fox Real-Time Spectrum Analyzer

1x Denso Hercules Dual-Mode DSRC/C-V2X OBU

1x Cohda Wireless DSRC OBU

1x Cohda Wireless DSRC RSU 1x Cohda Wireless C-V2X RSU

4x Danlaw CV2X RSU 1x Danlaw CV2X OBU

2x Kapsch CV2X OBU

2x Cohda CV2X OBU

1x RSU Antenna from Danlaw CV2X OBU

1x Cohda Wireless RSU Antenna

1x Mobile Mark OBU Antenna (DSRC)

1x Mobile Mark Shark Fin OBU Antenna (CV2X)

1x Software Defined Radio (USRP B210 with GPS Disciplined Oscillator)

25x OwlBox Kit with (Low-Cost U-NII-4 Interferers)

25x OwlBox Kit with (Low-Cost U-NII-5 Interferers)

1x Wi-Fi 6e (European Union Device)

1x Synology Router (Wi-Fi 5 new 5.9GHz channels)

LOW-COST OLDER U-NII-4 INTERFERERS

Our approach uses low-cost older IEEE 802.11a chipsets available on the aftermarket to act as U-NII-4 devices. However, to enable the older chipsets to broadcast in the 5.9GHz band, our existing FCC license enables us to use modified Linux kernels. We also created custom user-space applications in Python to operate the older chipsets in the 5.9GHz band. The computing platform is based on the Raspberry Pi Compute Module 4. As pictured in Figure 2, these devices were previously characterized and open-sourced in [11], what we refer to as: OwlBoxes. They are comprised of several components, the main component being a Compute Module 4, which is a small computer similar to any other Raspberry Pi unit, however it is specifically designed for use in embedded systems. A carrier board allows for the Compute Module 4 to be placed in allowing extra expansion using a M.2 adapter allowing for a second Wi-Fi card (the older IEEE 802.11a chipsets) to be connected to the board, allowing the OwlBox to both connect to a network and output signals on a specified 5.9GHz channel and bandwidth programmatically from local host. To the M.2 adapter either a Wi-Fi 5 card (AR5BHB116) is connected as to check both frequencies from either end surrounding the 5.9GHz frequency spectrum, connected to the either Wi-Fi cards is a pair of 5.9Ghz antennae. All of these components together make up the 25 OwlBoxes which serve as our U-NII-4 transmitters in this study. Each OwlBox is flashed with a custom version we created of the Raspberry Pi OS, allowing for all configurations to be done within this software.

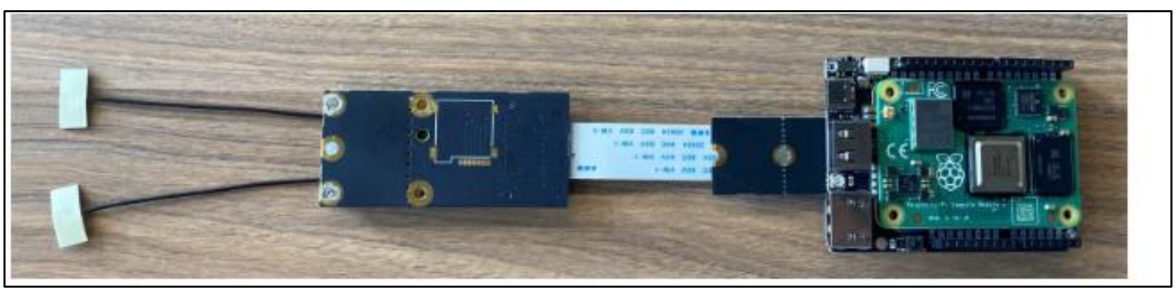


Figure 2. Photo. The OwlBox open-source project used as U-NII-4 interferer.

LOW-COST U-NII-5 INTERFERERS

Twenty-five OwlBoxes served as low-cost U-NII-5 interferers. There is a substantial guard band above C-V2X spectrum and Wi-Fi 6e North American spectrum. Wi-Fi 6e North American spectrum is very high (Channel 33 is the lowest U-NII-5 20MHz channel with center frequency at 6.135GHz), see Figure 3. This is not the case for Wi-Fi 6e devices that operate in the European Union, which utilize the lowest channels in the U-NII-5 band. Hence, to see how C-V2X *could* be affected by Wi-Fi 6e spectrum if the North American regulatory environment allowed to U-NII-5 Channel 1 at 20MHz centered at 5.955GHz, an EU Wi-Fi 6e router was configured to manage devices on Channel 1, and the client OwlBox devices with a Wi-Fi 6e chipset also joined that channel.

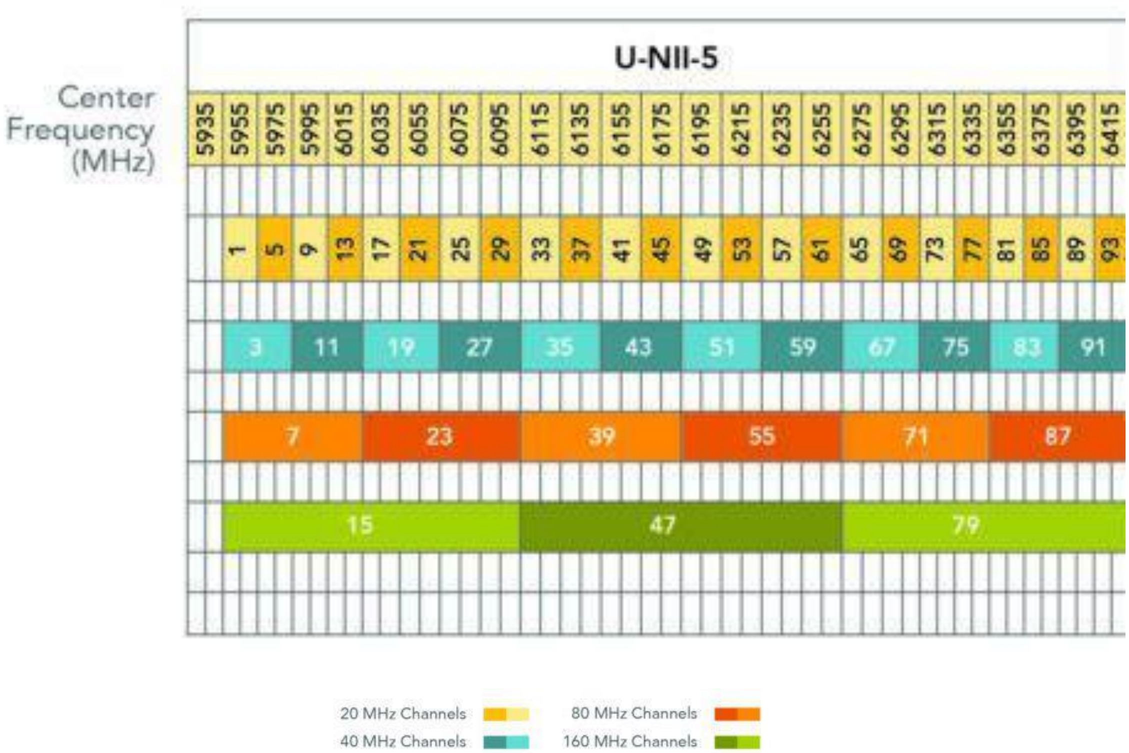


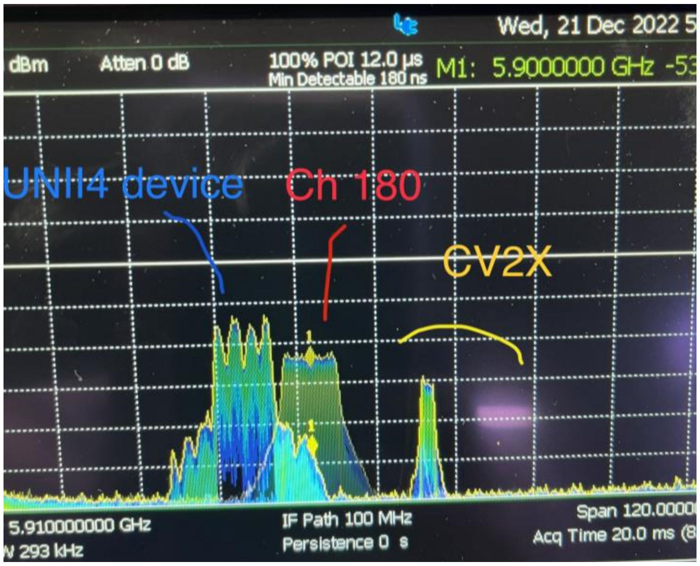
Figure 3. Plot. U-NII-5 Unlicensed band channelization for Wi-Fi 6e.
Source: https://www.litepoint.com/blog/wi-fi-6e-standard-and-channels/

CHAPTER 4. IN-LAB METHODOLOGY AND IN-LAB RESULTS

RESEARCH OBJECTIVES

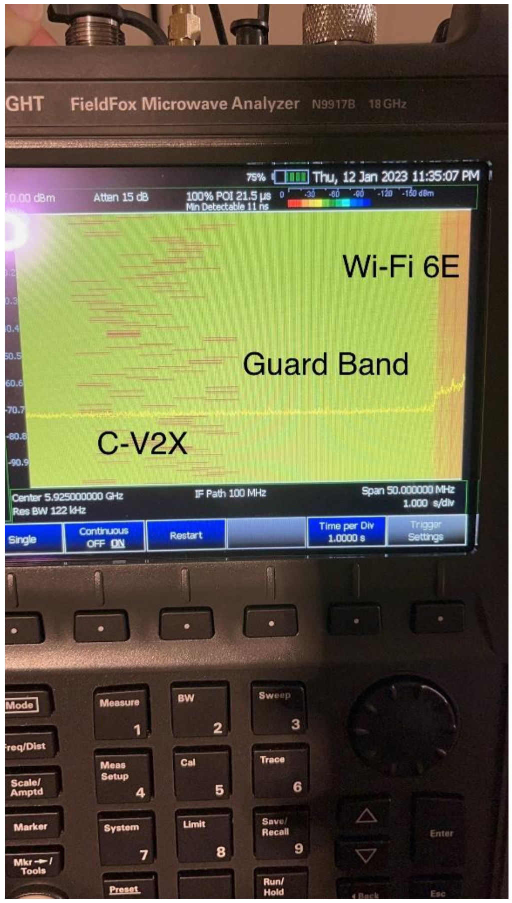
The goal of the in-lab study was to observe the effects of low-cost older Wi-Fi devices on the 10MHz IEEE 802.11p Channel 180 currently in use in the United States, and the effects of low-cost Wi-Fi 6e devices on the 20MHz 3GPP Rel 14 LTE-V2X Channel 183 currently in use in the United States. While a limited number of expensive U-NII-4 Wi-Fi routers are available to purchase, one challenge is that there are not enough low-cost *older* client consumer devices that feature RF component degradation.

As shown in the figure below, U-NII-4 low-cost older devices will interfere as the number of devices go up. While it is impossible to predict the amount of interference for every scenario, it is possible to see the overall effects of **worst-case** through substantial in-lab tests to focus purely on the radio performance without the effects of movement or attenuation due to large separation distances.



See youtube video: https://youtube.com/shorts/7-ciSWqTsUQ?feature=share

U-NII-5 low-cost devices in the United States will not interfere. As shown in the figure below, U-NII-5 low-cost devices will not interfere as the number of interferes goes up.



See youtube video: https://youtube.com/shorts/nGAlW86UIZw?feature=share

U-NII-4 Wi-Fi Traffic Generation

Our interfering devices (the OwlBoxes described previously) are centrally controlled by a local host. From the configuration tool we developed for this work we were able to - in real time - change the center frequency of the interferes and the bandwidth. We were also able to change the traffic generation behavior of the interferes according to two profiles. The first profile provides for us a worst-case interference scenario for a Wi-Fi network in which every interfering device is transmitting the exact same payload at the fastest broadcast rate possible, what we refer to as

FULL-RATE. Under the FULL-RATE profile each interferer transmits 78 bytes at a rate of 2000Hz.

The second profile provides for us a more realistic behavior of network traffic in a Wi-Fi network for random data of random payload sizes and random time delay between payload generations. We adopted network traffic models following the Wi-Fi IEEE 802.11ax evaluation methodology for File Transfer Protocol (FTP), Video Conferencing (VIDEOCONF), and Web browsing (WEB) [12]. The interferer network generation type is randomly assigned following a uniform distribution. The actual payload size in bytes and delay between payload generations follow the probability distributions in Table 1.

Table 1. Network Traffic Profiles Used by The U-NII-4 Devices

Profile	Packet Size (bytes)	Time Difference (ms)
FULL-RATE	78	.5
FTP	**LogNormal**(μ=3.9,*sigma*=.155)	**exp**(*mu*=164.48)
VIDEOCONF	*Choice of 1500 (full-frame) or less than 1500* **binomial**(*p*=.721) where *p* is probability of full-frame If not full-frame: **weibull**(*A*=769.82,*B*=1.51)	**exp**(*mu*=6.65)
WEB	*Choice of 1500 (full-frame), 576 (mid-frame) or neither* **multinomial**(*p*1=.3836,*p*2=.5458,*p*3=.0706) where *p*1 is probability of full-frame *p*2 is probability of mid-frame *p*3 is probability of neither If neither: **gamma**(*shape*=2.13,*scale*=304.27)	**exp**(*mu*=26.65)

IEEE 802.11p Devices

We use a commercially available RSU and a commercially available OBU made by the same vendor. Using the built in packet generation tools we are able to vary the broadcast rate from 1HZ to 1000Hz, and the packet size depending on the direction of the information flow RSU-to-

OBU or OBU-to-RSU. All IEEE 802.11p packets were broadcast at the highest allowed transmit power.

RSU-to-OBU: The RSU transmits a 468-byte payload to the OBU (the OBU is not transmitting). The payload is determined by the average of typical deployment MAP, Signal Phase and Timing (SPAT), Traveler Information Message (TIM), and Signal Status Message (SSM) sizes, which are 778,389,381,326 bytes, respectively.

OBU-to-RSU: The OBU transmits a 362-byte payload to the RSU (the RSU is not transmitting). The payload is determined by the average of typical deployment Basic Safety Message (BSM) and Signal Request Message (SRM) sizes, which are 464,261 bytes, respectively.

ACPR Measurements

We first measure the Adjacent Channel Power Ratio (ACPR) to measure interference in the lower adjacent channel to channel 180. We also assessed the ACPR experienced with various available RSU antennas and OBU antennas commonly used in deployments in the United States. The formula for ACPR being:

$$\text{ACPR} = \frac{\text{power in adjacent channel}}{\text{rms power in the main channel}}$$

where rms is the root mean square power. Our units for ACPR were provided by a wideband portable spectrum analyzer in the form of dBc and dBm. Decibels relative to carrier (dBc) is the power ratio of a signal to a carrier signal, expressed in decibels, this is a measure of the strength of an instantaneous signal at radio frequency. The formula for dBc is:

$$x(dBc) = 20log_{10}\frac{P_i}{P_c}$$

where Pi is the input signal power, and Pc is the carrier signal power.

When dBc is positive this means that the non-carrier signal strength is greater than the carrier signal strength, thus when it is negative the non-carrier strength is less than the carrier signal strength.

Decibel milliWatt (dBm) is 1 milliWatt (mW) of power into a terminating load, such as an antenna or power meter, or how much power an antenna or amplifier can produce, with the formula:

$$dBm = 10log_{10}(mW)$$

A strong signal for dBm typically ranges from -70 dBm or higher and a weak signal is -100 dBm or lower. One note to understand is that for every 3dB increase that equates to a doubling of the RF power.

IEEE 802.11p Packet Reception Rate Measurements

We report packet reception rates (PRR) under various numbers of U-NII-4 interferers and profiles. PRR is simply defined as:

$$\text{PRR} = \frac{\text{Number of packets received}}{\text{Number of packets transmitted}}$$

Results

Our in-lab results report the ACPR measurements for various deployment antennas under various U-NII-4 traffic profiles, we then report the PRR for commercial IEEE 802.11p devices. The U-NII-4 adjacent channel interferer settings and the settings of the IEEE 802.11p devices are provided in Table 2.

Table 2 U-NII-4 Device Settings

Parameter	Value
U-NII-4 Center Frequency	5.885GHz (Wi-Fi 5 Ch. 177)
U-NII-4 Bandwidth	20MHz
IEEE 802.11p Center Frequency	5.9GHz (ITS Ch. 180)
IEEE 802.11p Bandwidth	10MHz
IEEE 802.11p Data Rate	6Mbps
IEEE 802.11p Tx Power	RSU: 23dBm, OBU: 23dBm
IEEE 802.11p Broadcast Rate	1/10/100/1000Hz

ACPR Results

We first captured baseline dBc and dBm values when no U-NII-4 interferer is operating. Next, we started one interferer and recorded the change in dBc and dBm. We then proceeded to increase the number of interferers to 5, then 10, then 15, then 20 and then finally 25 recording the change in dBc and dBm each time. We also measured the results according to different network generation profiles, including FULL-RATE in Table 3 and typical network traffic rates in Table 4.

Table 3 U-NII-4 ACPR for FULL-RATE Network Traffic (dBc/dBm)

Num. of Interferers	OBUAnt1	OBUAnt2	RSUAnt1	RSUAnt2
0	-2.98/-61.54	-2.85/-60.73	-3.08/-60.88	-2.97/-60.78
1	-18.55/-41.84	-16.3/-44.23	-16.5/-44.44	-17.36/-43.23
5	-16.59/-43.86	-14.38/-46.38	-11.78/-48.94	-13.05/-47.7
10	-19.63/-40.67	-16.09/-44.55	-12.34/-48.39	-13.05/-47.7
15	-19.06/-41.39	-17.17/-43.39	-18.35/-42.12	-17.65/-42.92
20	-18.51/-42.1	-18.25/-42.36	-22.37/-37.84	-22.37/-37.82
25	-13.91/-46.73	-11.32/-49.27	-23.88/-36.04	-25.17/-34.5

Table 4 U-NII-4 ACPR for Typical Network Traffic (dBc/dBm)

Num. of Interferers	OBUAnt1	OBUAnt2	RSUAnt1	RSUAnt2
0	-2.78/-58.60	-2.90/-58.45	-3.03/-58.54	-2.93/-58.60
1	-8.69/-52.40	-4.44/-56.77	-12.04/-48.94	-15.61/-45.48
5	-20.49/-39.82	-21.51/-38.90	-20.05/-40.59	-15.57-45.18
10	-19.11/-41.16	-23.37/-36.66	-19.55/-40.74	-16.57/-43.92
15	-21.08/-38.91	-23.15/-36.95	-23.34/-36.39	-19.91/-40.42
20	-19.78/-40.57	-22.32/-36.99	-24.38/-34.94	-26.79/-32.16
25	-18.98/-41.43	-15.87/-44.43	-24.78/-34.16	-26.02/-33.05

The main takeaways from these ACPR tables are:

- Not all 5.9GHz antennas will respond to the Out of Band Emission (OOBE) the same. RSU antennas typically have higher gain and fewer nulls in their antenna patterns, and thus the likelihood of absorbing interference from U-NII-4 devices is higher.
- Increasing the number of interferers will decrease the ACPR around -20dBc to -25dBc (i.e., increases the power leakage into Ch. 180 by almost x2.5 per 25 interferers).
- The difference in ACPR between typical interference (more randomized network traffic) and worst-case interference (constant fixed network traffic) can range from: .5dB to 9dB (almost 3x the power)

IEEE 802.11p PRR Results amid U-NII-4 Interference

The results of the effect of real low-cost and aged U-NII-4 Wi-Fi device operations on Ch. 180 messages are shown in the two plots of Figure 4. The main takeaways from these PRR plots are:

- Under WLAN traffic interferences, the SPATs, MAPs, TIMs, and SSMs, are more likely to make it to the OBU than the OBU messages (BSMs, SRMs). OBU messages are less likely to make it to the RSU even in typical network traffic interference.
- OBU to RSU messages will always perform poorly, regardless of the type of WLAN interference (whether worst case or with typical WLAN traffic profiles (FTP, WEB, VIDEOCONFERENCE)
- 1000pps is an unnecessary test because the experiments hit the devices limit to process the messages.

These results were accepted for publication to TRB 2024.

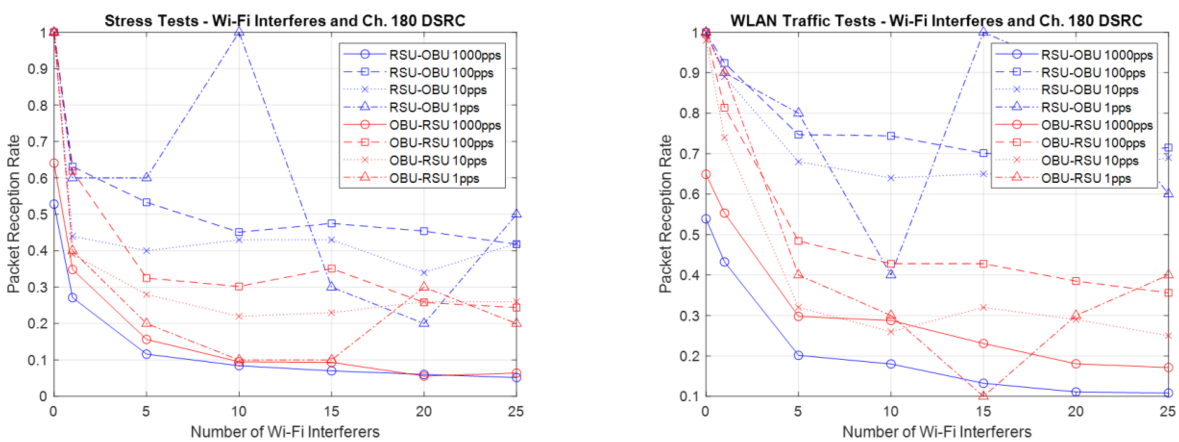


Figure 4. Plots. PRR of commercial IEEE 802.11p OBU/RSU links amid U-NII-4 interference. The left plot shows the results for Stress Testing (i.e., FULL-RATE). The plot on the right shows the results for WLAN Traffic (i.e., FTP/VIDEOCONF/WEB). (pps = packets per second)

Where Figure 4 presents the effects against different dummy data rates, we also provide Figure 5 to show the effects of U-NII-4 OOBE on DSRC devices that are communicating actual V2X messages, the OBUs in the plot on the left and OBU in the plot on the right are transmitting BSMs at a rate of 10Hz, and the RSU in the plot on the right is transmitting SPAT at 10Hz and MAP at 1Hz. The Packet Error Rate between OBUs increases as the number of interferers increases, and the number of BSMs received by an RSU decreases as the number of interferers increases.

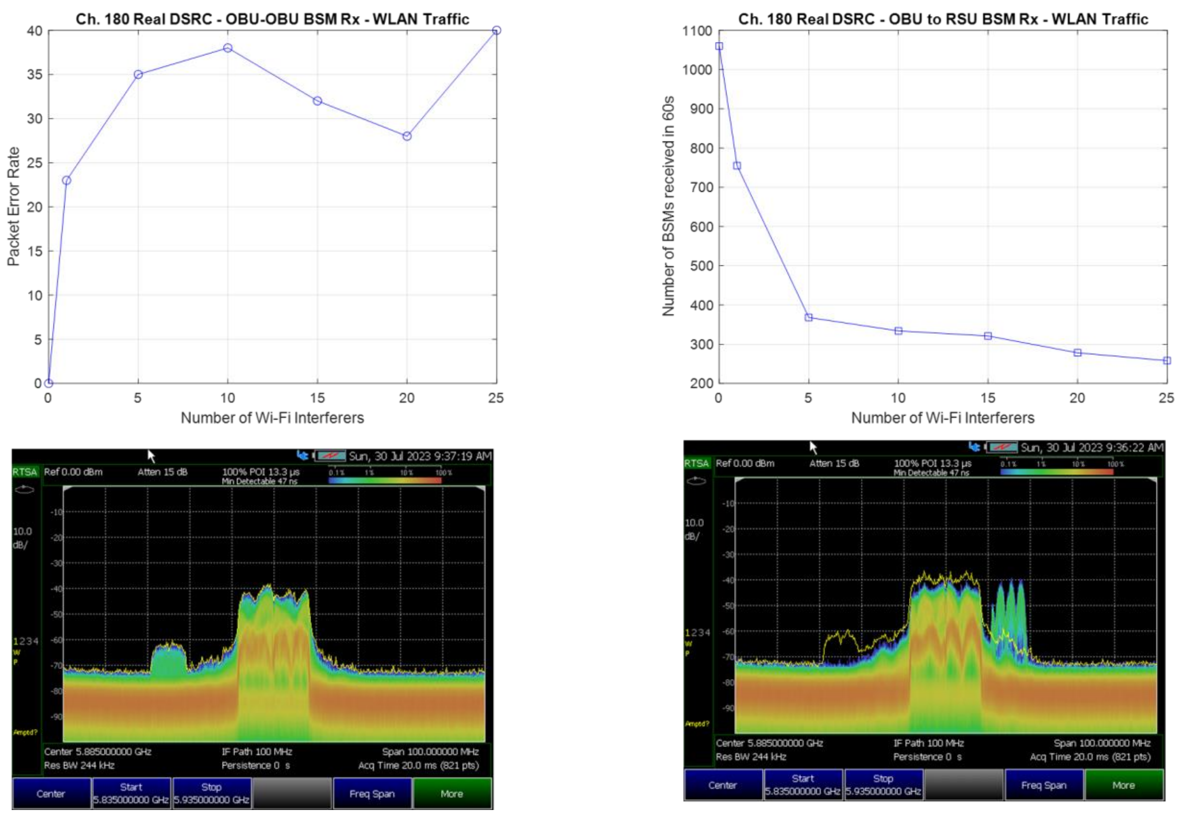


Figure 5. Plots. IEEE 802.11p with Real ITS Operations PRR Results amid U-NII-4 Interference.

Figure 6. Photo. Test set-up for DSRC U-NII-4 interference tests.

3GPP Rel 14 LTE-V2X Sidelink PRR Results amid U-NII-5 Interference

As expected, the U-NII-5 interferers did not impose any significant ACPR on the C-V2X spectrum. As seen in Figure 7, the guard band, even for Channel 1 usage in Wi-Fi 6e and low-cost newer hardware does not show significant interference. The ACPR measurements for low-cost newer Wi-Fi 6e devices are very low.

The Wi-Fi 6e devices feature a much tighter spectrum due to newer hardware. It is not known how over time Wi-Fi 6e devices will degrade as more low-cost Wi-Fi 6e devices enter the market. Furthermore, even if Wi-Fi 6e OOBE happens to jump the guard band, C-V2X features a channel hoping mechanism in its mode 4 operation, enabling it to move to the lower side of the

20MHz channel if it senses too much energy from in-band C-V2X devices, or a high ACPR from Wi-Fi 6e.

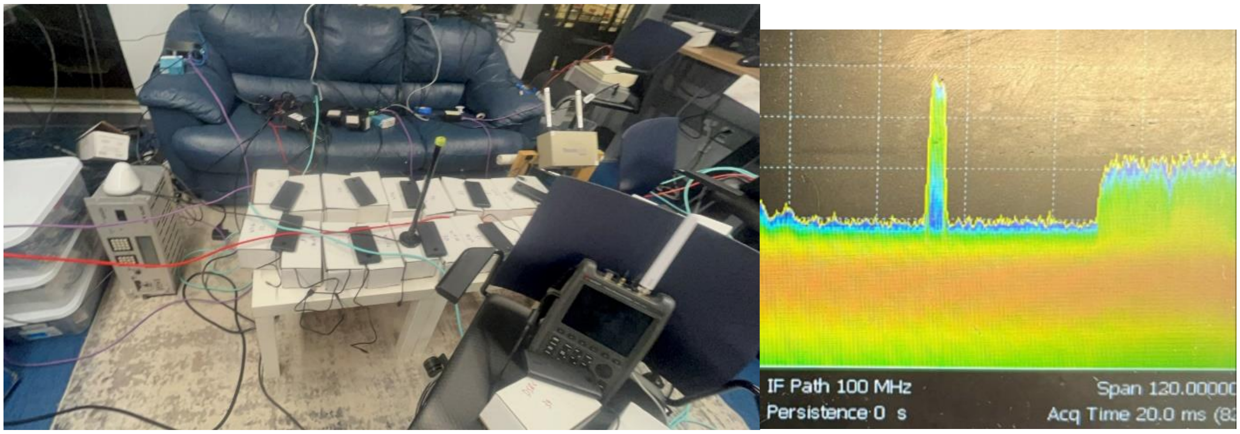


Figure 7. Photos. LTE-V2X 3GPP Rel 14 Sidelink with Real ITS Operations amid low-cost U-NII-5 operations show no significant interference.

3GPP Rel 14 LTE-V2X Sidelink Ch. 183 Results amid U-NII-4 Interference (Ch. 179)

With the sun setting of DSRC in channel 180 it is possible that one of three options could take place:

1. Ch. 180 becoming a guard band between U-NII-4 and C-V2X
2. U-NII-4 taking Ch. 180 which would allow for Ch. 179 operations at 20 MHz.
3. C-V2X taking Ch. 180 which would place it adjacent to U-NII-4 Ch. 180 at 20 MHz

Therefore, we sought to study the effects of U-NII-4 interference on C-V2X under Scenarios 2 and 3, since Scenario 1 did not show any negative effect on C-V2X operations. When attempting to do so, we observed the autonomous resource selection of C-V2X sensing the OOBE from U-NII-4 when a significant number of interferers were turned on, thus the C-V2X protocol moves to upper sub-channels of Ch. 183.

This resulted in no significant effect, even with a multitude of C-V2X transmitters broadcasting ITS messages at their full 10Hz rate. Some of the additional C-V2X devices are pictured in Figure 8.

Figure 8. Photo. LTE-V2X 3GPP Rel 14 Sidelink equipment acting as additional interferers at full-rate.

Channel Busy Ratio C-V2X Traffic Generator

Because it was not possible to force the C-V2X chipsets under study to stay close to the lower sub channels of channel 183 we implemented a channel busy ratio C-V2X traffic generator to force the C-V2X radios to use the lower sub channels of channel 183. This is pictured in Figure 9.

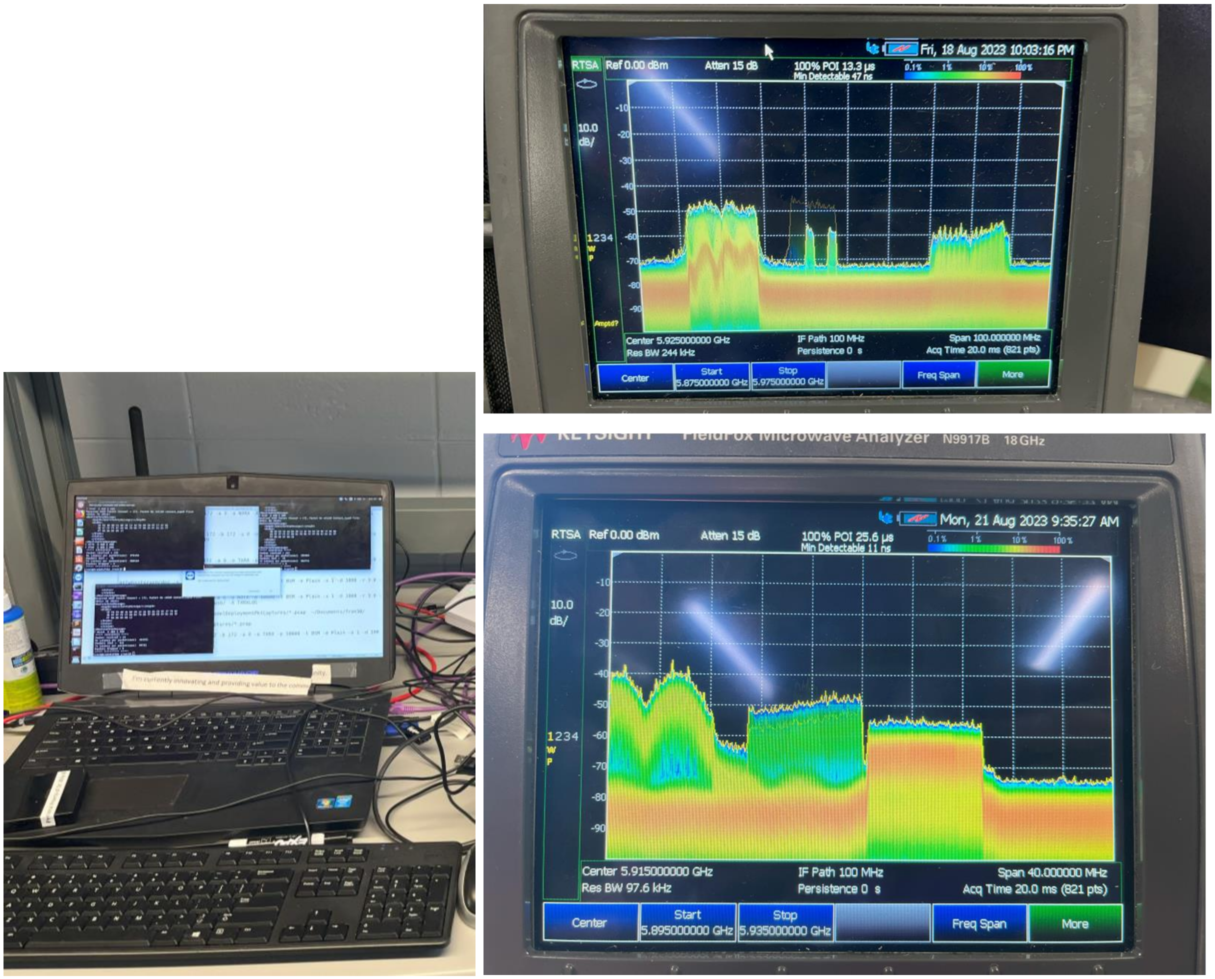


Figure 9. Photos. A software defined radio acting as a C-V2X traffic generator to force the C-V2X equipment to use the lower sub-channels of Ch. 183 so that the effects of U-NII-4 interference using Ch. 179 at 20MHz could be studied.

3GPP Rel 14 LTE-V2X Sidelink Ch. 183 Lower Sub-Channel Results amid U-NII-4 Interference (Ch. 179)

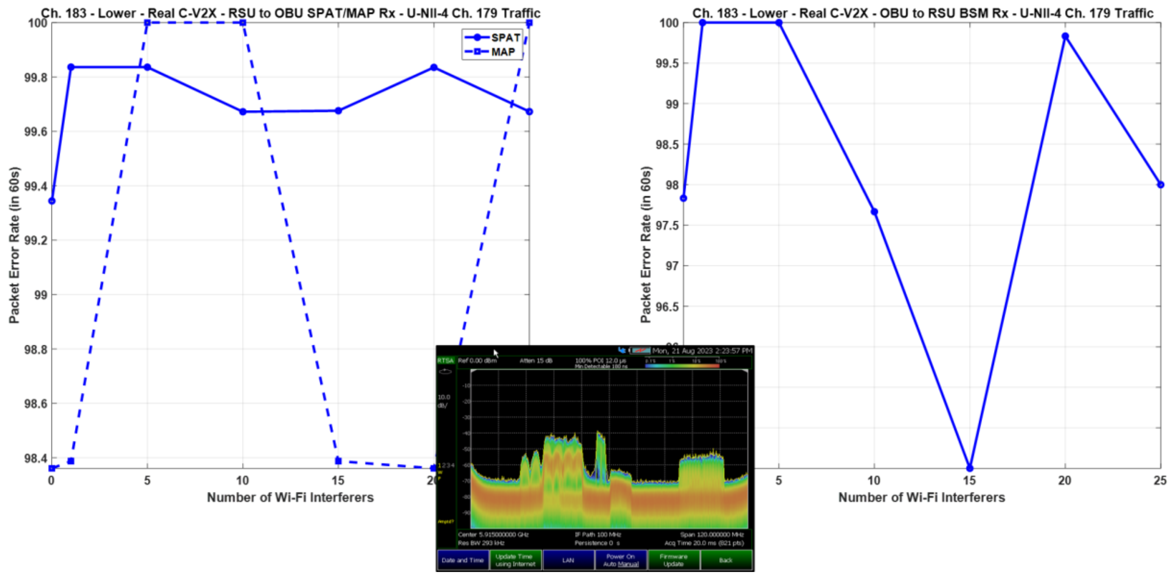


Figure 10. Graphs. Results of PRR on C-V2X V2I and I2V messages for real ITS traffic amid U-NII-4 interference Ch. 179 at 20 MHz. A C-V2X traffic generator was used to force the C-V2X devices under study to use the lower sub-channels of Ch. 183 closer to the U-NII-4 operations.

The results of the effects of U-NII-4 interference on C-V2X operations are not significant, as seen in Figure 10. Even under the same interference levels in lab as DSRC the CV2X modulation scheme appears to be resilient to this level of interference. However, the effects of interference when in a congested channels with other C-V2X operations in the lower sub-channels of Ch. 183 and with fading effects in the field would need to be further studied. The C-V2X field tests did not use the traffic generator due to power limitations.

CHAPTER 5. FIELD TEST EQUIPMENT

1x Field Fox Real-Time Spectrum Analyzer

1x Cohda Wireless DSRC OBU

1x Cohda Wireless DSRC RSU

1x Danlaw CV2X RSU

1x Kapsch CV2X OBU

25x OwlBox Kit with (Low-Cost U-NII-4 Interferers)

Wi-Fi 6e tests were not conducted in the field because they did not show interference effects in the lab-study. However, for testing C-V2X's resilience to U-NII-4 interferers, we performed a C-V2X field test under these assumptions, however, we were not able to see the effects at scale in-band with multiple C-V2X devices. The channel busy generator (CBG) was not used during the C-V2X field tests due to power constraints that the CBG required. Furthermore, the time of the field experiments was at night, and the research team was not able to properly ensure that research equipment theft would not have taken place.

DSRC Field Test Location

For the DSRC tests, the OwlBoxes were packaged in small boxes, and then placed at various locations near one side of an intersection on the side where the RSU was located. The OBU was installed in a vehicle with a magnet mount antenna. Figure 11 shows the location of the DSRC field tests on Memorial drive in Atlanta, GA. There were also five other RSUs deployed within range of the RSU at Grant which added to in-band interference.

Figure 11. Photos. DSRC Field Test Location: Grant and Memorial.

Source: [Google Maps]

C-V2X Field Test Location

For the C-V2X tests, the OwlBoxes were packaged in a small box, and then placed inside a larger inconspicuous cardboard box near one the side of intersection where the RSU is located. The OBU was installed in a vehicle with a magnet mount antenna. Figure 12 shows the location of the DSRC field tests on Buford Highway in Gwinnett County GA. There were also two other RSUs deployed within range of the RSU at Button which added to in-band interference.

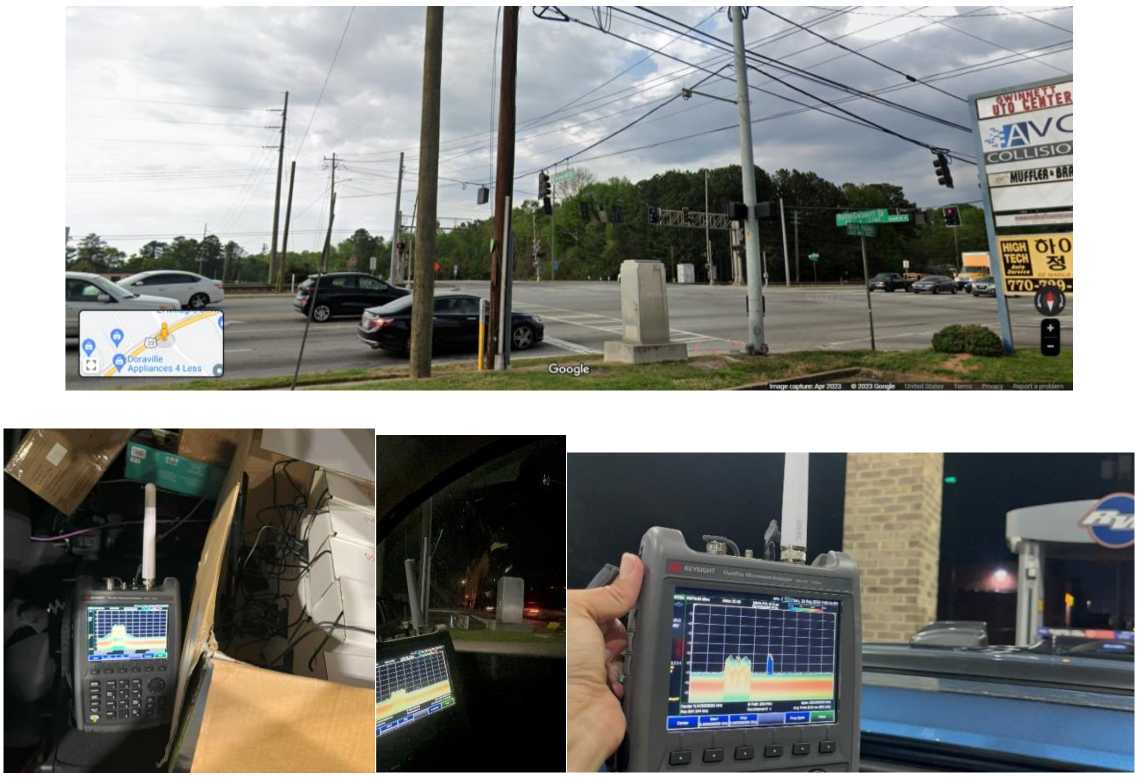


Figure 12. Photos. C-V2X Field Test Location: Button and Buford.

Source: Google Maps

CHAPTER 6. FIELD TESTS METHODOLOGY AND FIELD TESTS RESULTS

RESEARCH OBJECTIVES

The goal of the field tests was to observe the effects of U-NII-4 interference (Ch. 177 at 20MHz) on DSRC Ch. 180 devices in the field and U-NII-4 interference (Ch. 179 at 20MHz) on C-V2X Ch. 183 devices in the field.

DSRC FIELD-TEST METHODOLOGY

We drove east and west on Memorial drive with each east west pass pair increasing the number of U-NII-4 interferers. We varied the number of interferers from 0 to 25 in steps of 5. Post-processing of pcap logs from the RSU deployed at Grant and Memorial and the OBU was performed using MATLAB with custom analysis scripts.

C-V2X FIELD-TEST METHODOLOGY

We drove north and south on Buford highway with each north south pass pair decreasing the number of U-NII-4 interferers. We varied the number of interferers from 22 to 0 in various steps due to some of the devices failing to boot in the field. Post-processing of pcap logs from the RSU deployed at Button and Buford Highway and the OBU was performed using MATLAB with custom analysis scripts.

DSRC FIELD-TEST RESULTS

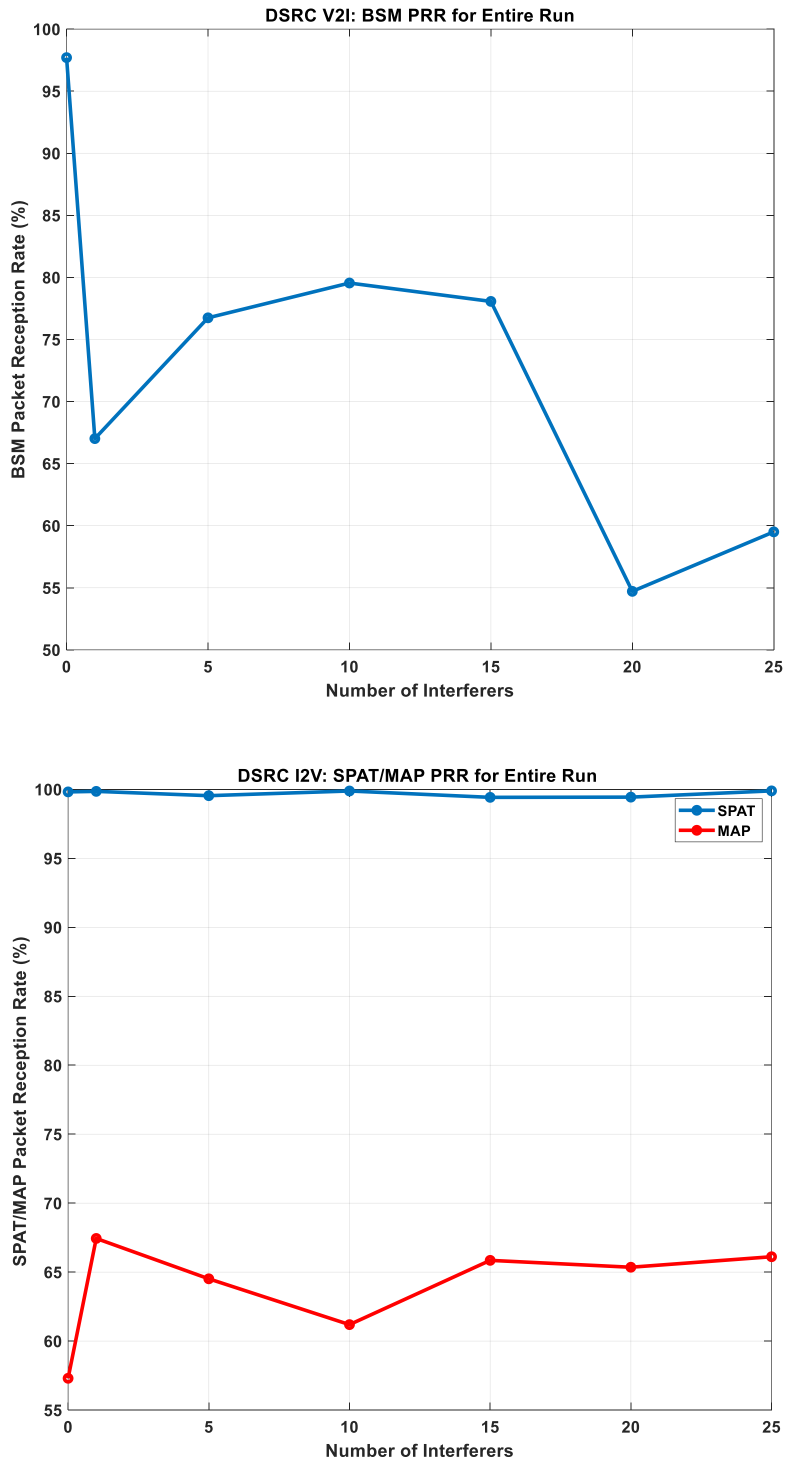


Figure 13. Graphs. DSRC PRR for Entire Run V2I and I2V

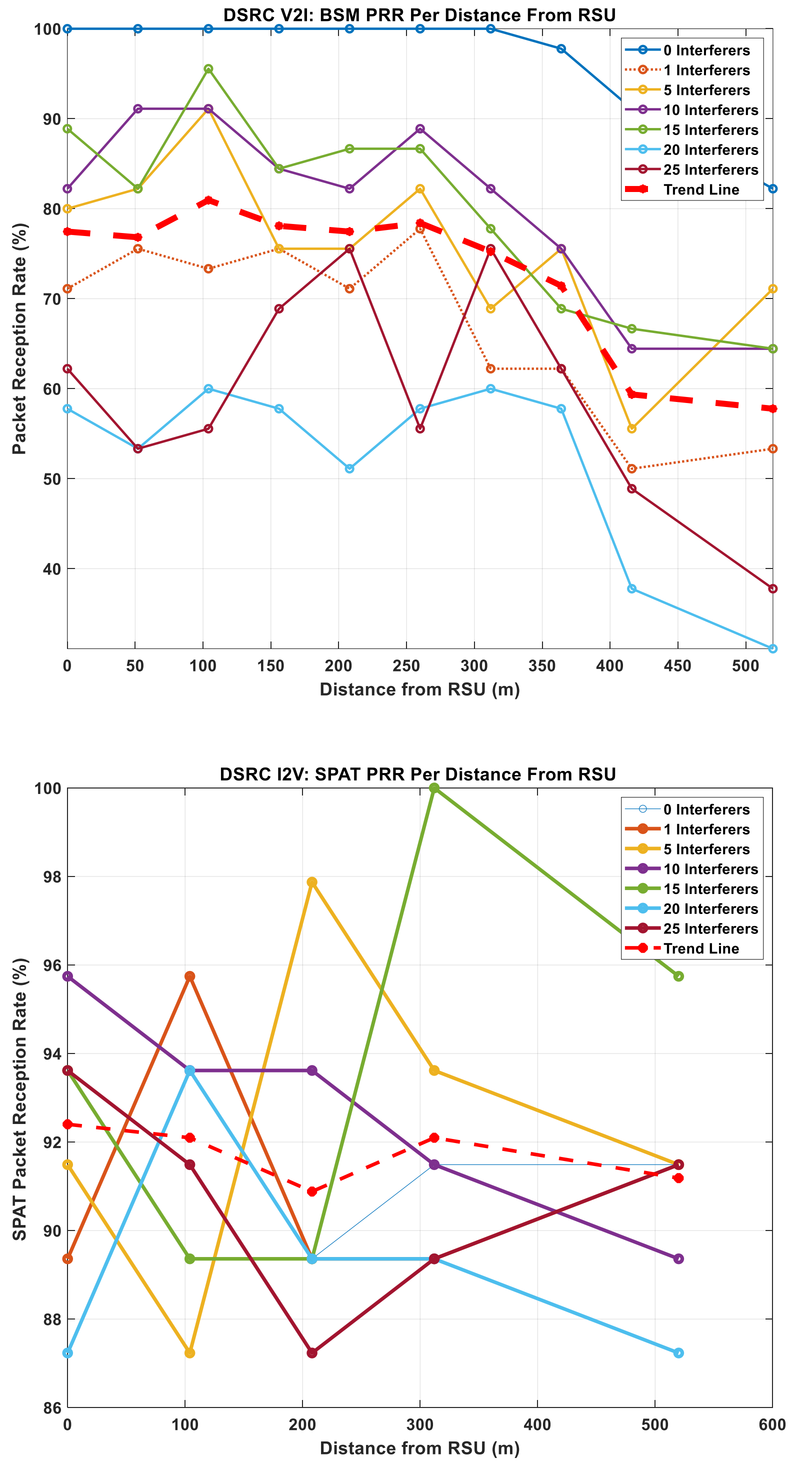


Figure 14. Graphs. DSRC PRR per distance from RSU for V2I and I2V

DSRC FIELD-TEST RESULTS DISCUSSION

Figure 13 displays the performance for the entire applicable testing range for both V2I and I2V links. As displayed in lab the DSRC protocol is susceptible to interference for V2I links. For I2V links the DSRC protocol is not susceptible to interference in a field environment.

Figure 14 displays the performance for different distances from the RSU for both V2I and I2V links. The field tests reveal that interferers positioned near intersections do not have harmful effect on DSRC I2V messages. However, interferers have a significant harmful effect on DSRC V2I which could affect car counting applications using CV equipment. More V2I packets are dropped sooner when interferers are near the intersection.

C-V2X FIELD-TEST RESULTS

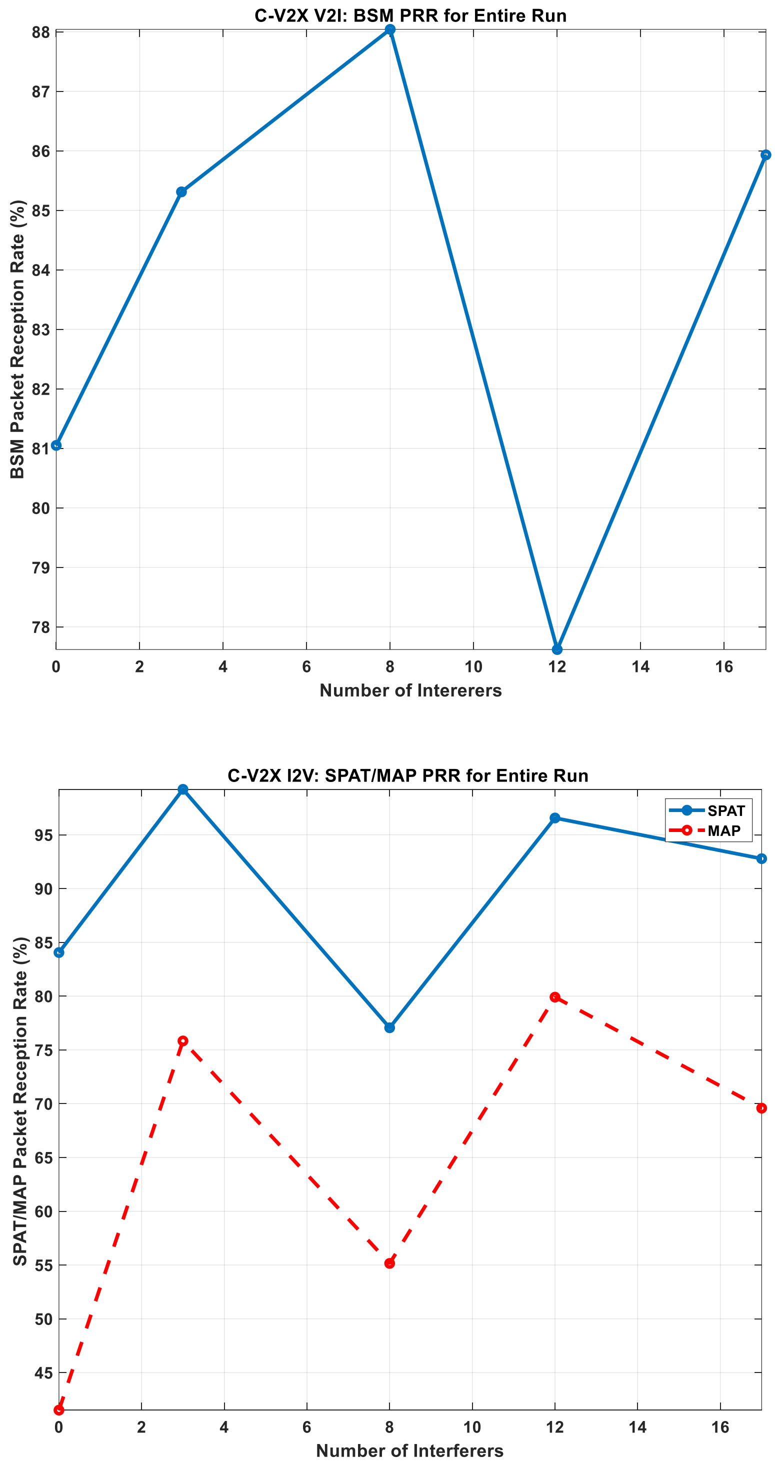


Figure 15. Graphs. C-V2X PRR for Entire Run V2I and I2V

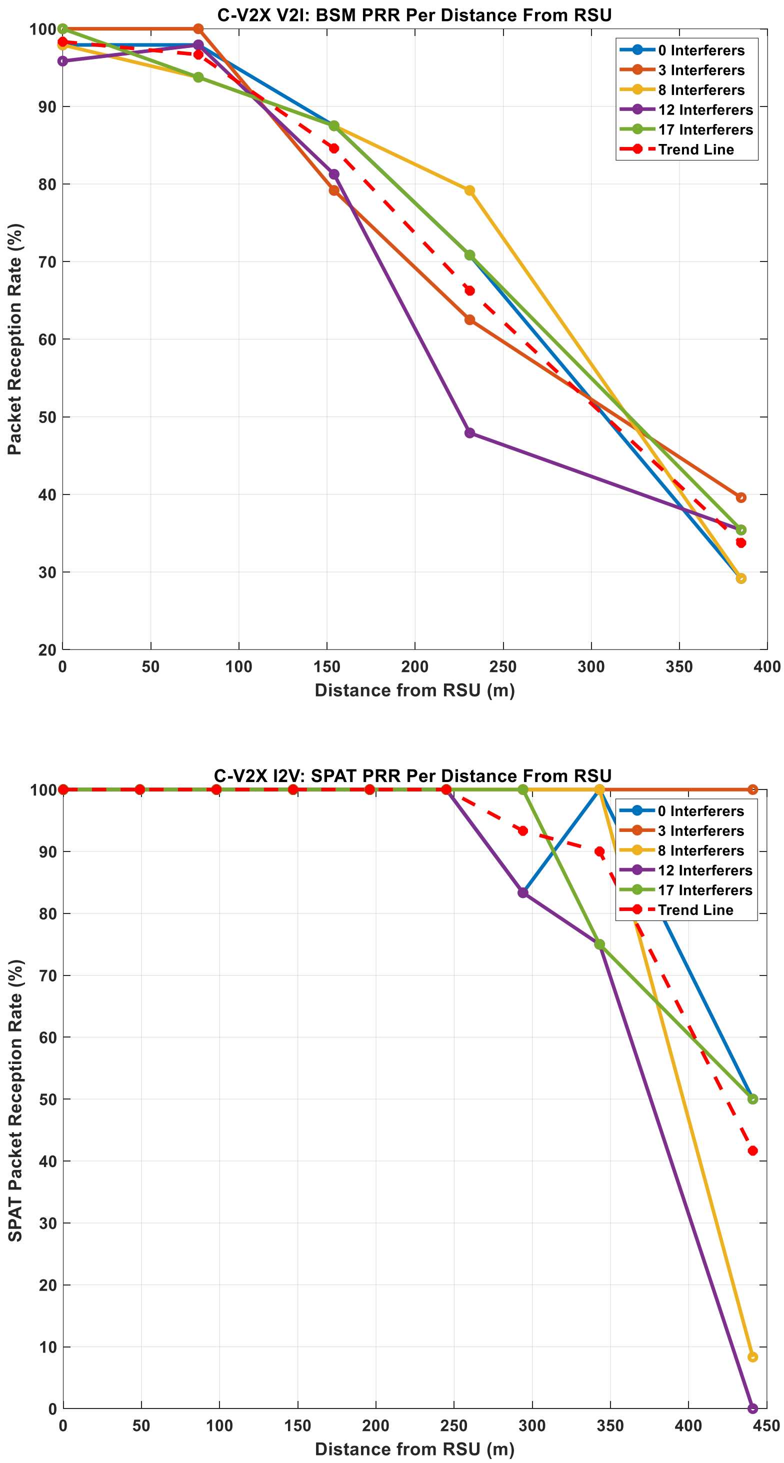


Figure 16. Graphs. C-V2X PRR per distance from RSU for V2I and I2V

C-V2X FIELD-TEST RESULTS DISCUSSION

Figure 15 displays the performance for the entire applicable testing range for both V2I and I2V links. As displayed in lab the C-V2X protocol is not susceptible to interference for V2I nor I2V links for a low number of C-V2X devices. This is because the C-V2X protocol will move towards higher sub-channels within Ch. 183 if U-NII-4 interference is sensed as a higher channel busy ratio. The lower MAP message count is due to MAPs further away being dropped and not a result of the interference.

Figure 16 displays the performance for different distances from the RSU for both V2I and I2V links. The field tests reveal that interferers positioned near intersections do not have a harmful effect on either C-V2X V2I or I2V messages. The interferer lines are simply following the trend of the 0 interferers line with some random probability of missing packets due to the distance the RSU is from the OBU at the time of message reception. Further studies would need to be conducted for a high density of C-V2X devices operating in the lower sub-channels of Ch. 183.

CHAPTER 7. CONCLUSION/RECOMMENDATIONS

QUANTIFYING THE COST TO GDOT TRAFFIC OPERATIONS DUE TO INTERFERENCE

- Preemption and Priority CV applications require: MAP, SRM,SSM. As long as 1 SRM makes it to the RSU, the controller can begin processing, as long as 1 corresponding SSM makes it to the OBU, the OBU can notify their driver.
    - In both C-V2X and DSRC, small messages like BSM and SRM are still being received over 400m away by the RSU.
- Red Light Warnings require SPAT, MAP for OBUs to calculate red light warning violations, no negative affect on this application.
- DSRC car counting applications at the RSU using CV could experience inaccuracies.
- TIMs would not be affected by interference.
- For U-NII-4 and U-NII-5 interference levels of 25 devices, there is currently no significant negative cost to GDOT CV operations.

MITIGATION RFFIGUREECOMMENDATIONS

- Most RSU antennas have a wide bandwidth.
  - Source RSU antennas that have tighter filtering on Channel 183 or Channel 180 only.
  - Retrofit in-line filters to RSU antennas that have tighter filtering on Channel 183 or Channel 180 only.
- Detect interference using a software defined radio and adjust RSU CV applications that rely on message availability accordingly.
- Request guard bands!

SUGGESTED CV EQUIPMENT INTERFERENCE AMENDMENTS TO GDOT VENDORS

- Chipsets of C-V2X devices should use upper sub-channels away from U-NII-4 Wi-Fi 5 interference.
  - This would have the trade-off of causing more congestion in Ch. 183. How much is undetermined.
- Require their devices reduce the effect of out of band emissions through better antennas.
  - Could make devices more expensive.
- Turn down the input gain to the RSUs / Allow operators to turn the input gain down.
  - This is not easily done from the user control.
  - Requires vendors to implement / make available this capability.
  - Potentially slight trade off of reception range for V2I.

KNOWN LIMITATIONS OF THE STUDY

- It is likely that newly manufactured U-NII-4 devices operating in 5.9GHz will likely have a tighter spectral mask due to better hardware.
    - This study focused on what degraded performance of U-NII-4 devices could possibly do to CV applications.
- Only 25 U-NII-4 interferers @ 20MHz
    - U-NII-4 devices in 5.9GHz spectrum can go up to 40MHz (more possibility of OOBE)
- U-NII-4 interference effects on C-V2X at scale is still unknown.
- U-NII-5 Wi-Fi 6e devices are newer, it is unknown how their performance will degrade over time.
- DSRC CV applications that require higher availability of V2I message reception (such as car counting / path prediction / eco-studies) are more susceptible to interference.
- Interference effects on OBU-to-OBU were not studied.

APPENDIX A. RESEARCH ARTIFACTS

All PCAP files can be made available upon request.

All multimedia can be made available upon request, however, a video playlist is made available here:

https://youtube.com/playlist?list=PLDJYX50qNaReGeHNr5ck9Q0KveY1tuQ9P&si=d6X3TPwE2VHhWBUY

All WLAN Interference source code is available here: https://github.com/Intelligent-Mobile-Device-Lab-at-KSU/owlbox_files

Control Server Code in Python can be made available upon request.

MATLAB post-processing scripts can be made available upon request.

Please contact: bkihei@kennesaw.edu

ACKNOWLEDGEMENTS

The success of this research would not have been possible without the support of several individuals. The study team would like to thank the Georgia Department of Transportation (GDOT) for their financial support and involvement during this research study. Specifically, we thank Alan Davis, GDOT State Engineer; Justin Hatch, Assistant State Engineer; Purser L with Southwest Research Institute for access to DSRC field equipment, and Bradley Bilsback, Research Engineer, for their direct involvement with the project. Additionally, the researchers wish to thank Ken Keena, Assistant Engineer from Gwinnett County DOT for supplying access to C-V2X field equipment. The PI would like to personally thank his Lord and Savior Jesus Christ for helping with the research, and his family and colleagues for their continued support!

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