JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Traffic Management Geocast Study with Connected Vehicles on Indiana Highways

Zhitong He, Abin Mathew, Abhijeet Ingale,
Jue Zhou, Feng Li, Yaobin Chen

SPR-4743 • Report Number: FHWA/IN/JTRP-2024/19 • DOI: 10.5703/1288284317753

RECOMMENDED CITATION

He, Z., Mathew, A., Ingale, A., Zhou, J., Li, F., & Chen, Y. (2024). *Traffic management geocast study with connected vehicles on Indiana highways* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2024/19). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317753

AUTHORS

Zhitong He
Graduate Researcher
Elmore Family School of Electrical and Computer Engineering
Purdue University

Abin Mathew
Graduate Researcher
Elmore Family School of Electrical and Computer Engineering
Purdue University

Abhijeet Ingale
Graduate Researcher
Purdue Polytechnic Institute
Purdue University

Jue Zhou, PhD
Research Associate
Elmore Family School of Electrical and Computer Engineering
Purdue University

Feng Li, PhD
Professor of Computer and Information Technology
Purdue Polytechnic Institute
Purdue University

Yaobin Chen, PhD
Professor of Electrical and Computer Engineering
Director of Transportation & Autonomous Systems Institute
Elmore Family School of Electrical and Computer Engineering
Purdue University
(765) 495-7816
chen62@purdue.edu
Corresponding Author

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

ACKNOWLEDGMENTS

This work was supported by the Joint Transportation Research Program (JTRP), administered by the Indiana Department of Transportation (INDOT) and Purdue University. The authors would like to thank all members of the INDOT Study Advisory Committee (SAC), including Tim Wells, project advisor (PA), Jim Sturdevant, the business owner (BO), Ed Cox, Tim Overman, Nathan Sturdevant and Hilary Lowther for their guidance, advice, and technical support throughout the project period. Special thanks go to Dr. Darcy Bullock, Director of JTRP, and his staff at Purdue University for their administrative support and service.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2024/19	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Traffic Management Geocast Study with Connected Vehicles on Indiana Highways		**5. Report Date** March 2024
		6. Performing Organization Code
7. Author(s) Zhitong He, Abin Mathew, Abhijeet Ingale, Jue Zhou, Feng Li, and Yaobin Chen		**8. Performing Organization Report No.** FHWA/IN/JTRP-2024/19
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.**
		11. Contract or Grant No. SPR-4743
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

Vehicular communication allows vehicles to interact with road users, roadside infrastructure, and cloud-connected devices. It holds a crucial position in modern transportation systems, impacting both fundamental and advanced aspects and enhancing traffic safety and efficiency. C-V2X is a wireless communication technology that uses cellular networks to enable communication between vehicles and infrastructure. C-V2X can be used for applications such as collision avoidance, traffic management, and remote vehicle diagnostics.

This project conducted a feasibility study on the current position of C-V2X in the industry and developed a prototype, RampCast, to fundamentally understand the current C-V2X implementations as part of the 3GPP Release 14. A comprehensive review on the state-of-the-art CV2X technologies and various demonstration projects were carried out by the automotive industry, cellular wireless chips/systems companies, and federal/states DOTs in the U.S. and Europe. A geocast-based prototype system, named RampCast, was built using a software-defined radio approach. The RampCast algorithms focused on the geocasting and were developed for improving message prioritization and retransmission. The field tests that were conducted in a campus parking lot and on the test track revealed sub-100 ms latency and a range of up to 2,500 ft for C-V2X, which emphasized its effectiveness in transmitting critical messages and traffic guidance. Further extensions for the prototype include incorporating multiple units, expanding message types (e.g., points of interest and location-specific adverts), optimizing the prototype's GUI for diverse scenarios, and conducting long-term data analysis for better message flow optimization.

17. Key Words C-V2X, connected vehicle, geocast	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 26	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

Vehicular communication allows vehicles to interact with road users, roadside infrastructure, and cloud-connected devices. It holds a crucial position in modern transportation systems, impacting both fundamental and advanced aspects, most notably enhancing traffic safety and efficiency. Wireless communication technologies like Dedicated Short-Range Communication (DSRC), Cellular Vehicle-to-Everything (C-V2X), and Wi-Fi enable this form of communication. C-V2X is a wireless communication technology that uses cellular networks to enable communication between vehicles and infrastructure. C-V2X can be used for applications such as collision avoidance, traffic management, and remote vehicle diagnostics. C-V2X operates in two modes: (1) Direct Communication (PC5) and (2) Network Communication (LTE).

The Transportation and Autonomous Systems Institute (TASI) of the Purdue School of Engineering and Technology at Indiana University-Purdue University Indianapolis (IUPUI) and the Traffic Management Center of INDOT have worked together to conduct a feasibility study on the current position of C-V2X in the industry and develop a prototype, RampCast, to fundamentally understand the current C-V2X implementations as part of the 3GPP Release 14. The core functionality of the prototype system would be to create and set up the short-range PC5 interface defined by the C-V2X standard to understand the message transmission capabilities of the system.

Findings

The research team conducted a feasibility study detailing and analyzing various C-V2X implementations and demos across the US and EU. The results suggest that C-V2X communication has the potential to make substantial contributions to the overall modern transportation system by providing efficient solutions for traffic management and control. The prevalence of this use case underscores the importance of C-V2X technology in shaping the future of transportation and its role in creating safer and more efficient roadways.

Following the feasibility study, the team designed a prototype system called RampCast that includes hardware and software components with multiple algorithms for the geocasting use case. The RampCast scenario consists of two main actors in the system. One actor is the Road Side Unit, which is present at the entry of a ramp to an interstate. The other actor is the Onboard Unit, which is present inside the vehicles entering the ramp. The hardware is built using a Software-defined Radio (SDR) and a computing unit.

The RampCast software framework uses a generalized messaging pattern based on the concept of publisher-subscriber architecture. To adapt the framework to the use case for V2X communication, several geocasting algorithms were envisioned. The major goals were to analyze the impact of message priority and message retransmission on the delivery of messages from the Traffic Management Center to the target road vehicles.

The RampCast system uses geofencing algorithms that perform location-based message filtering on both the Road Side Unit and the Onboard Unit. The prioritization and message retransmission during the transport of messages from RSU to OBU were researched and optimized to manage congestion and packet loss.

Implementation

The prototype system was tested for key performance indicators including latency, packet reception ratio, and packet inter-reception rate. Field tests conducted in a campus parking lot and on the test track revealed sub-100 ms latency and a range of up to 2,500 ft for C-V2X, emphasizing its effectiveness in transmitting critical messages and traffic guidance.

Further extensions for the prototype include incorporating multiple units, expanding message types (e.g., points of interest, location-specific adverts), optimizing the prototype's GUI for diverse scenarios, and conducting long-term data analysis for better message flow optimization.

CONTENTS

1. INTRODUCTION 1

2. CURRENT AND PREVIOUS C-V2X ACTIVITIES IN THE US AND EU 1
   2.1 Demonstration Projects. 2
   2.2 Pilot Projects 3
   2.3 Analysis and Investigation of the Current C-V2X Activities and Future Trend 5

3. RAMPCAST PROTOTYPE SYSTEM 6
   3.1 RampCast Hardware Components. 6
   3.2 RampCast Software Stack. 6
   3.3 Graphical User Interface. 7

4. GEOCASTING ALGORITHMS FOR RAMPCAST 8
   4.1 Data Source. 9
   4.2 Geolocation-Based Message Delivery Algorithm 9

5. TESTING 14
   5.1 Campus Parking Lot Test 14
   5.2 Testing on the Test Track 15

6. CONCLUSION 17

REFERENCES 18

LIST OF TABLES

Table 3.1 Hardware used in the Rampcast system design 7

Table 5.1 Communication METRIC in static-vehicle test using omnidirectional antennas 16

Table 5.2 Communication METRIC in static-vehicle test using directional antennas 16

Table 5.3 Communication METRIC in dynamic-vehicle test with and without directional antennas 16

Table 5.4 Experimental testing results in static-vehicle test in test track 17

LIST OF FIGURES

Figure 2.1 Pedestrian scenario from Honda and Verizon's collaboration: field test in Mcity 2

Figure 2.2 Pedestrian scenario from Honda and Verizon's collaboration: animated illustration 2

Figure 2.3 Pedestrian scenario from Honda and Verizon's collaboration: pedestrian warning shown on the dashboard 3

Figure 2.4 Use case of signal phase shown from 5GAA demonstration 3

Figure 2.5 Use case of pedestrian crossing shown from 5GAA demonstration 4

Figure 2.6 C-V2X application in roadside worker protection by Qualcomm, Commsignia, and Audi 4

Figure 2.7 The warning displayed on the dashboard of the Audi Q8 reads, "Drive carefully!" 4

Figure 2.8 C-V2X helps intelligent tunnel with traffic monitoring in Spain 5

Figure 2.9 Monitoring tub at the end of the tunnel management team 5

Figure 2.10 Proportion of different use cases 6

Figure 3.1 SDR units 7

Figure 3.2 The architecture of the designed Rampcast system 7

Figure 3.3 RampCast virtual GUI 8

Figure 3.4 RampCast GUI shown in a driving scenario using a tablet 8

Figure 4.1 Picture of the West St. ramp 9

Figure 4.2 511 API message structure 10

Figure 4.3 511 traffic events in Indianapolis 10

Figure 4.4 Distribution of top eight events by priority level based on 511 traffic events in Indianapolis 11

Figure 4.5 Heatmap shows the frequency of crash events during different time slots in a week 11

Figure 4.6 Heatmap for crash events from the last 6 months that show similar patterns 11

Figure 4.7 Map illustrating crash hotspots, with red areas indicating locations prone to crash events 12

Figure 4.8 The message transmission logic using the MQTT protocol 12

Figure 4.9 RabbitMQ MQTT broker dashboard 12

Figure 4.10 Message framework flowchart 13

Figure 4.11 Priority queue representation 13

Figure 4.12 Pie chart depiction of message filtering by deading direction 14

Figure 5.1 Two SDR units are positioned at the two ends of the hallway in SL building 15

Figure 5.2 Campus surface parking lot 15

Figure 5.3 Testing vehicle with antennas on top of the front windshield 15

Figure 5.4 RSU with antennas mounted on top of a stand pole 16

Figure 5.5 Bird's eye view of the test track 16

Figure 5.6 Capture of the communication test with static vehicle 16

Figure 5.7 Packet reception rate during the dynamic vehicle testing 17

Figure 5.8 Packet inter-reception during the dynamic vehicle testing 17

1. INTRODUCTION

Vehicular communication allows vehicles to interact with road users, roadside infrastructure, and cloud-connected devices. It holds a crucial position in modern transportation systems, impacting both fundamental and advanced aspects, notably enhancing traffic safety and efficiency. Wireless communication technologies like Dedicated Short-Range Communication (DSRC), Cellular Vehicle-to-Everything (C-V2X), and Wi-Fi enable this form of communication.

The categorization of vehicular communication includes various types: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), Vehicle-to-Network (V2N), Vehicle-to-Cloud (V2C), and the comprehensive Vehicle-to-Everything (V2X) (Papadimitratos et al., 2009). V2V communication enables vehicles to interact, facilitating exchanges like sharing data for enhanced highway cruise control. V2I communication involves vehicles connecting with roadside infrastructure such as traffic lights and toll booths. V2P communication revolves around information exchange between vehicles and pedestrians. V2N and V2C establish connections between vehicles and the network or cloud server for online information exchange or substantial data processing. Finally, V2X communication encompasses all these forms of interaction, representing a comprehensive communication framework.

Examples of commonly seen vehicular communication include the following.

1. *Collision avoidance:* V2V communication can detect potential collisions between vehicles, alerting drivers to take preventive measures.
2. *Traffic management:* V2I communication gathers real-time traffic data for effective traffic flow management and congestion reduction.
3. *Emergency services:* V2X communication serves to notify emergency services in the event of accidents or emergencies.
4. *Navigation:* V2X communication provides the road users with real-time information on road conditions and route options, including optimal trajectories calculated at the cloud side for autonomous vehicles.

C-V2X is a wireless communication technology that uses cellular networks to enable communication between vehicles and infrastructure. C-V2X can be used for applications such as collision avoidance, traffic management, and remote vehicle diagnostics. C-V2X operates in two modes: Direct Communication (PC5) and Network Communication (LTE).

The C-V2X mainly has the following features that are superior to the traditional DSRC method (Nguyen et al., 2017).

1. *Extended range:* C-V2X can leverage the coverage of cellular networks, which can extend its range beyond the limited range of DSRC.
2. *High bandwidth:* C-V2X has a higher bandwidth than DSRC, which can support more data- intensive applications such as video streaming and remote diagnostics.
3. *Easy deployment:* C-V2X can be deployed using existing cellular infrastructure, which can simplify deployment and reduce costs.

C-V2X offers a broader range of applications compared to DSRC due to its extended range and higher bandwidth. For instance, it enables remote vehicle diagnostics, allowing vehicles to communicate with service centers and provide real-time maintenance information. Moreover, C-V2X supports video streaming, offering drivers immediate updates on road conditions and alternative routes. This underscores substantial efforts by both industry and government in its development and adoption (Lucero, 2016).

As a testament to this advancement, the Public Safety and Homeland Security Bureau, the Office of Engineering and Technology, and the Wireless Telecommunications Bureau of the Federal Communications Commission (FCC) collectively approved a request by automotive and equipment manufacturers, alongside state departments of transportation. This joint request sought a nationwide waiver of specific FCC rules to facilitate the implementation of cellular-vehicle-to-everything (C-V2X) technology within the 5.895-5.925 GHz band (Federal Communications Commission, 2023).

The rest of the report has the following structure: Section 2 will delve into various C-V2X implementations and use cases within the US and European Union. Section 3 introduces the RampCast prototype system, detailing the chosen hardware and the architecture of the designed software. In Section 4, we'll illustrate the Geocasting Algorithms, encompassing geolocation-based message delivery algorithms and preprocessing methods for real traffic data. In Section 5, we'll present the designed field tests focusing on C-V2X communication implementation and the corresponding results. Finally, the project's findings are concluded in Section 6.

2. CURRENT AND PREVIOUS C-V2X ACTIVITIES IN THE US AND EU

This section will explore and discuss two types of C-V2X implementation: demonstration projects and pilot projects. Demonstration projects serve as public trials aimed at showcasing proven technology. They play a crucial role in accelerating technology adoption by highlighting its value and potentially showcasing optimal practices. These projects are particularly beneficial for introducing unfamiliar users to the technology. On the other hand, pilot projects focus on validating the technology's value and reducing uncertainties. They aim to identify and establish best practices in implementing and operating the technology, contributing to its successful deployment.

2.1 Demonstration Projects

2.1.1 Honda and Verizon's Collaboration

Through the collaboration of Honda and Verizon with the University of Michigan's Mcity, a test bed dedicated to connected and autonomous vehicles, research has been conducted to explore the capabilities of new connected safety technology utilizing 5G and mobile edge computing (MEC). The focus of this research is to establish fast and reliable communication among road infrastructure, vehicles, and pedestrians, with the ultimate goal of minimizing collisions and saving lives (Honda, 2021). The study delved into three safety scenarios, including pedestrian scenarios (as depicted in Figures 2.1, 2.2, and 2.3), emergency vehicle warning scenarios, and red light runner scenario. These scenarios exemplify the potential of 5G and MEC in facilitating prompt communication of critical safety messages between vehicles and infrastructure, thereby reducing the necessity for intricate computing systems onboard each connected vehicle.

The pedestrian scenario will be elaborated with some detailed illustration while the other two scenarios will be introduced briefly to indicate the basic functionality. In the pedestrian scenario, as depicted in Figures 2.1 and 2.2, a pedestrian is crossing a street at an intersection. However, an approaching driver is unable to see the pedestrian due to a building obstructing the view. To address this safety concern, smart cameras positioned in the intersection capture and relay information to MEC through the 5G network. Leveraging Verizon's MEC and V2X software platforms, the system detects both pedestrians and vehicles, accurately determining the precise location of road users with the assistance of Verizon's Hyper Precise Location services. In response to this information, a visual warning message (as illustrated in Figure 2.3) is promptly transmitted to alert the driver about the potential danger, enhancing overall safety at the intersection.

In the emergency vehicle warning scenario, a driver faces the challenge of being unable to see an approaching emergency vehicle and is further impeded by the high volume of in-vehicle audio, preventing the

Figure 2.1 Pedestrian scenario from Honda and Verizon's collaboration: field test in Mcity.

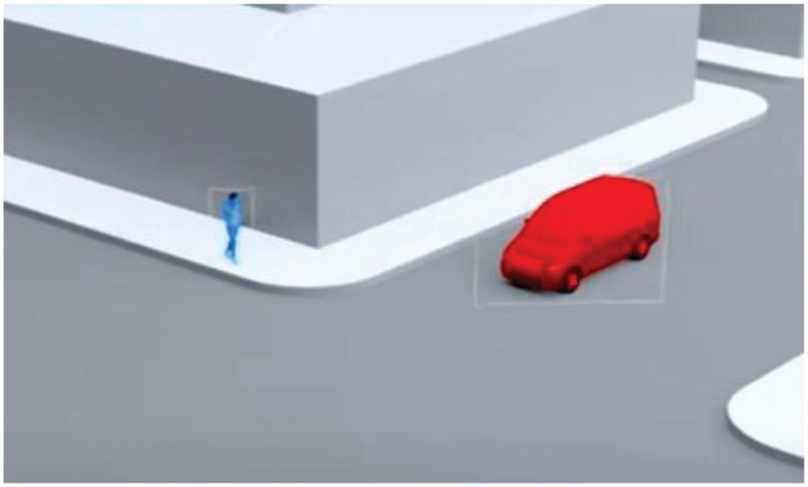


Figure 2.2 Pedestrian scenario from Honda and Verizon's collaboration: animated illustration.

detection of the emergency siren. To address this critical situation, Verizon's MEC and V2X software platforms receive a safety message transmitted by the emergency vehicle. Subsequently, a warning message is dispatched to nearby vehicles through the V2X system.

In the red-light runner scenario, data from smart cameras is utilized by MEC and V2X software to identify a vehicle that disregards a red light. Upon detection of this red-light violation, the system promptly generates a visual warning message for other vehicles approaching the intersection. This warning message serves as a real-time alert, notifying nearby vehicles about the presence of a red-light runner, thereby promoting heightened awareness and contributing to the overall safety of the intersection.

2.1.2 The First European C-V2X Demonstration

In 2018, the 5G Automotive Association (5GAA) collaborated with BMW Group, Ford Motor Company, Groupe PSA, and Qualcomm Technologies, Inc. to present the inaugural European demonstration of Cellular Vehicle-to-Everything direct communication interoperability across multiple automotive manufacturers (5GAA, 2018). This demonstration showcased the live implementation of C-V2X direct communication technology, fostering interoperability among passenger cars, motorcycles, and roadside infrastructure.

Figure 2.3 Pedestrian scenario from Honda and Verizon's collaboration: pedestrian warning shown on the dashboard.

The demonstration highlighted the tangible benefits of C-V2X in enhancing road safety and traffic efficiency. Specifically, it showcased the application of C-V2X for V2V collision avoidance and V2I connectivity to traffic signals and Traffic Management Centers (TMC).

The six demonstrated scenarios included the following.

1. Emergency electronic brake light.
2. Intersection collision warning.
3. Across traffic turn collision risk warning.
4. Slow vehicle warning and stationary vehicle warning.
5. Signal phase and timing/signal violation warning (as depicted in Figure 2.4).
6. Vulnerable road user (pedestrian) warning (as illustrated in Figure 2.5).

These demonstrations provided a comprehensive exhibition of the diverse applications and capabilities of C-V2X technology in promoting safer and more efficient interactions between vehicles and their surroundings.

2.2 Pilot Projects

2.2.1 C-V2X Application in Roadside Worker Protection

In another collaborative effort involving Qualcomm, Commsignia, and Audi, the focus was on enhancing roadside worker safety through the application of

Figure 2.4 Use case of signal phase shown from 5GAA demonstration.

Figure 2.5 Use case of pedestrian crossing shown from 5GAA demonstration.

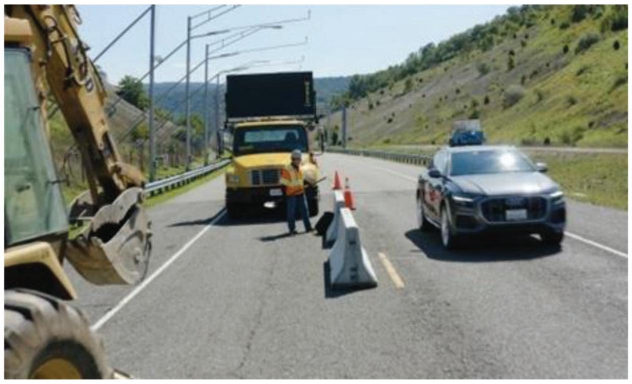


Figure 2.6 C-V2X application in roadside worker protection by Qualcomm, Commsignia, and Audi.

Figure 2.7 The warning displayed on the dashboard of the Audi Q8 reads, "Drive carefully!"

C-V2X technology. In a year-long pilot project conducted in Virginia in 2020, Qualcomm, Audi, and the state's Department of Transportation (VDOT) joined forces to address the safety of roadside workers when vehicles approached, as depicted in Figures 2.6 and 2.7 (Audi of America, Inc., 2020; Qualcomm, 2020).

During this initiative, the teams in Virginia developed C-V2X and Vehicle-to-Pedestrian (V2P) hardware and software. This technology enabled communication between an Audi Q8 test vehicle and roadside workers, who routinely face perilous situations in close proximity to fast-moving highway traffic. The road workers wore safety vests equipped with C-V2X technology, while the Audi Q8 was outfitted with Qualcomm's C-V2X-based hardware platform to transmit warnings to approaching drivers. Utilizing direct V2V or C-V2X communication, the Audi Q8 could receive safety messages on the dashboard every 100 milliseconds, contributing to heightened driver awareness and, ultimately, the safety of roadside workers.

2.2.2 Intelligent Tunnel Supported by C-V2X Technology

Telefonica, in collaboration with project partners including Nokia, Ineco, Stellantis, CTAG, and SICE, achieved a significant milestone by connecting the Cereixal tunnel (as depicted in Figure 2.8) to vehicles, marking it as the first smart tunnel in Spain (Sharma, 2021). This innovative infrastructure enables the tunnel to communicate essential information to drivers, including updates on weather conditions at the exit, ongoing road works, alerts about slow-moving vehicles, potential congestion, accidents, road obstacles, the presence of pedestrians, approaching vehicles, and instances of sudden braking during their passage. Furthermore, the system provides warnings about the entry of emergency vehicles.

The collected information is then transmitted to a dedicated monitoring tool, allowing infrastructure managers to access a comprehensive view of the data gathered by IoT sensors, as illustrated in Figure 2.9. This capability enables managers to analyze the

Figure 2.8 C-V2X helps intelligent tunnel with traffic monitoring in Spain.

Figure 2.9 Monitoring tub at the end of the tunnel management team.

information and issue alerts and warnings to vehicles passing through the tunnel when necessary, enhancing overall safety and efficiency.

2.3 Analysis and Investigation of the Current C-V2X Activities and Future Trend

From the analysis of eleven demonstration or pilot projects conducted in the US and Europe, the pie chart in Figure 2.10 reveals that the traffic management or control use case holds the largest share at 34.78% among all the presented projects. This highlights the prominence of C-V2X in offering effective and valuable information to various stakeholders, including vehicle drivers and the traffic monitoring and management teams, such as traffic management centers.

The diverse applications of C-V2X showcased in these projects demonstrate its capability to enhance traffic safety and efficiency, both in urban and highway scenarios. The results suggest that C-V2X communication has the potential to make substantial contributions to the overall modern transportation system by providing efficient solutions for traffic management and control. The prevalence of this use case underscores the importance of C-V2X technology in shaping the future of transportation and its role in creating safer and more efficient roadways.

The merits of C-V2X technology are substantiated through its deployment and widespread adoption. In terms of range and coverage, C-V2X capitalizes on the extensive coverage of cellular networks, facilitating long-range communication capabilities that surpass those of DSRC. This extended range proves particularly advantageous in highway scenarios and rural areas with lower infrastructure density.

In matters of scalability, C-V2X's operation within the existing cellular ecosystem allows for easier and more efficient deployment and scaling compared to DSRC, which demands dedicated infrastructure deployment. Regarding operation bandwidth, C-V2X stands out by supporting large data transfer volumes, enabling applications such as real-time video streaming,

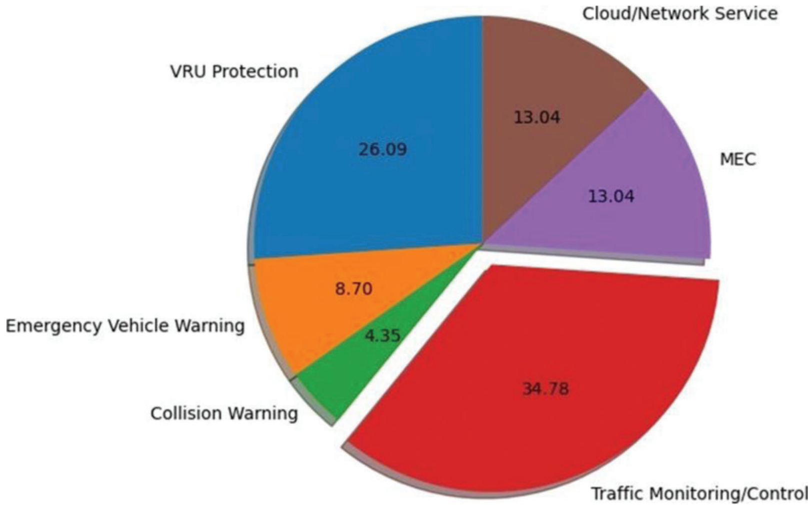


Figure 2.10 Proportion of different use cases.

high-definition maps, and over-the-air software updates.

An additional crucial feature is coexistence, as C-V2X seamlessly integrates with other cellular technologies, optimizing radio spectrum use and minimizing interference. As C-V2X technology continues its rapid development with increasing commitment, the existing applications are poised for further deployment, ensuring greater benefits and reliability in the future. The ongoing evolution of C-V2X promises a robust and versatile technology that will play a pivotal role in enhancing communication and safety within the transportation landscape.

3. RAMPCAST PROTOTYPE SYSTEM

As part of the feasibility investigation, a prototype system, RampCast, has been developed and tested to fundamentally understand the current C-V2X implementations as part of the 3GPP Release 14. The core functionality of the prototype system would be to create and set up the short-range PC5 interface defined by the C-V2X standard to understand the message transmission capabilities of the system.

Multiple implementations for C-V2X systems (Eckermann & Wietfeld, 2021; Nikaein et al., 2014) were analyzed and the decision to develop with a software defined radio was chosen as it provides the flexibility to operate open-source code and understand the different modules of the V2X communication stack. It was also proved to be a cost-effective method as the number of commercial C-V2X equipment manufacturers was limited and thereby cost-prohibitive when procuring in small quantities.

3.1 RampCast Hardware Components

The RampCast hardware primarily consists of the B210 SDR boards from USRP (Figure 3.1). These are general-purpose SDRs whose radio properties such as the transmitting and receiving frequencies can be modified as per the user requirement. For the Ramp Cast prototype, the frequency set is 5.9 GHz which is the approved frequency for C-V2X.

An Intel Core i5 laptop is used to interface with the SDR units and additional power backup using batteries is also used for outdoor scenarios. There are two types of antennae used with the SDR systems, omnidirectional, and directional. While omnidirectional antennas receive signals equally from all directions, the directional antennas pull in signals better from one direction. For the RampCast Scenario, the Onboard Unit uses the omnidirectional antenna, and the RSU is tested with both omnidirectional as well as directional antennas. A Samsung Tablet is used as the display unit for the In-vehicle OBU. The complete hardware list is tabulated in Table 3.1.

3.2 RampCast Software Stack

Building on top of the hardware is the RampCast Software stack. The software interface used for the SDRs is the Sidelink Interface (Geppert, 2023). This open-source software is built on top of the popular framework SRSRAN (SRSRAN, 2023). SRSRAN is an open-source radio implementation suite built using C++. The Sidelink software sets up a 3GPP Release 14 based PC5 interface between the SDR units. Each of these units is assigned a virtual address (IP address) which would be then used by the messaging framework.

The RampCast messaging framework is a custom-built framework that handles the transmission of C-V2X messages from the Traffic Management Center to the Road User Vehicle. It uses a publisher/subscriber architecture to manage the different users in the system. The main users of the system are the Roadside Unit (RSU) and the Onboard Unit (OBU). Alongside the messaging framework, the other components present in the software stack are the GPS module and the Metrics module. The OBU contains a GPS module to calculate

TABLE 3.1
Hardware used in the Rampcast system design

Sr. No	Hardware	Description	Quantity
1	YAG12-5900 Directional Yagi Antenna	5.9 GHz Antenna	2
2	USRP B210 SDR Board	Software Defined Radio	2
3	Ubuntu Laptop	CPU: Intel Core i5 RAM: 8 GB	2
4	GPSDO	GPS Unit for SDR	2
5	Portable Battery Backup	Power Supply Unit for SDR	2
6	Tablet	Samsung S7 tablet	1

Figure 3.1 SDR units.

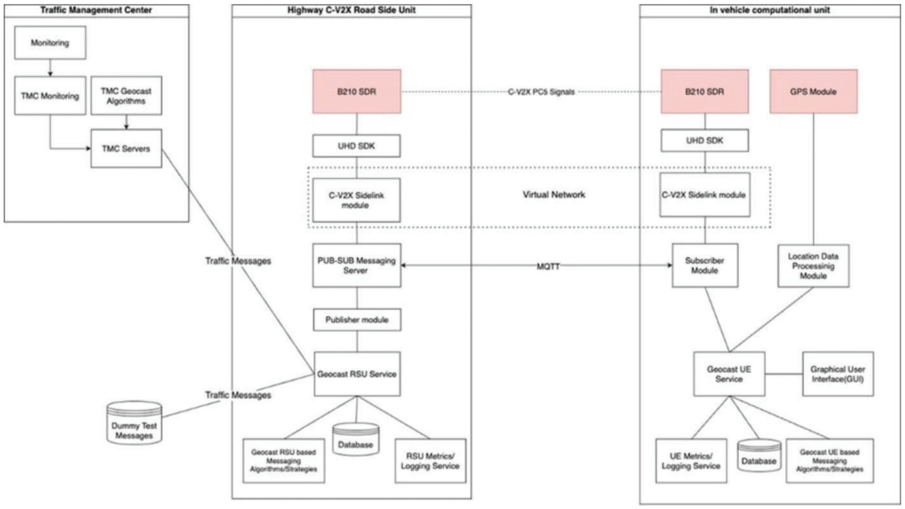


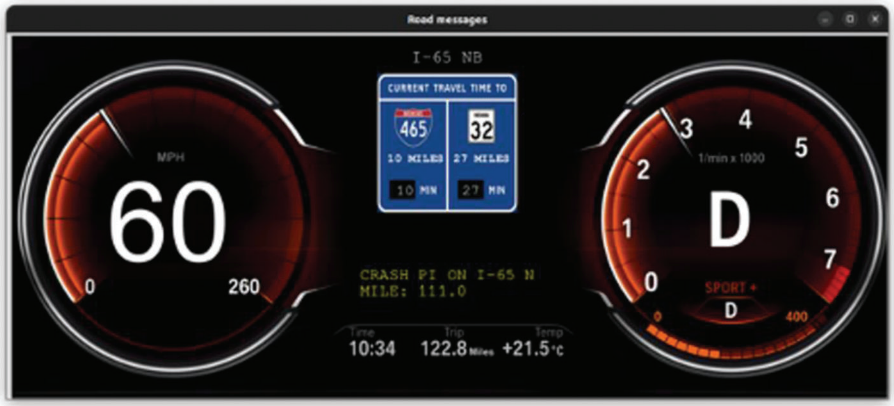
Figure 3.2 The architecture of the designed Rampcast system.

the positioning and heading of the vehicle. It is integrated with the messaging framework. The metrics module is present in both the RSU and the OBU. The complete component diagram for the RampCast prototype is provided in Figure 3.2.

Along with managing the transmission of traffic messages between the RSU and OBU, the messaging framework implements multiple algorithms dedicated to the RampCast Scenario. These algorithms make up the fundamental characteristics of the messaging flow originating from the TMC to the road users. The development of the algorithms is further detailed in Section 4.

3.3 Graphical User Interface

To view the traffic messages transmitted via C-V2X signals, a custom Graphical User Interface (GUI),



CRASH PI ON I-65 N
MILE: 111.0

Figure 3.3 RampCast virtual GUI.

Figure 3.4 RampCast GUI shown in a driving scenario using a tablet.

shown in Figure 3.3, has been developed. The central part of the GUI displays two key pieces of information. The top half shows the travel time information to the nearest highways and interstates. The bottom half displays relevant messages on that route such as crash messages.

The current implementation of the GUI would cycle between messages for each available route for the vehicle. A vehicle near a ramp would display messages relevant for each possible route whereas a vehicle who has entered a specific ramp would only see messages for that specific route. Figure 3.4 shows the GUI using an Android tablet in the vehicle driving scenario. The real-time travel time information and the relevant crash information are presented.

4. GEOCASTING ALGORITHMS FOR RAMPCAST

The RampCast framework uses a generalized messaging pattern based on the concept of publisher-subscriber architecture. To adapt the framework to the use case for V2X communication, several geocasting algorithms were envisioned. The major goals were to analyze the impact of message priority and message retransmission on the delivery of messages from the Traffic Management Center to the target road vehicles.

For the first phase of RampCast, the major geofencing scenario is the “ramp entry/exit” regarding the West St. ramp to get on I-65/I-70 (Figure 4.1). Here, there are multiple possible routes that the user can take.

1. Ramp to I-65 North
2. Ramp to I-65 South/I-70 East

For users taking either option, the messages shown on the OBU should be relevant to only that route. Furthermore, the messages broadcasted at the RSU on West St. need only to send messages that have relevance within a particular radius.

There are also three main parts where the vehicle would receive different information.

1. *Before ramp:* The vehicle reads messages for all possible routes available through the ramp.
2. *On ramp:* The vehicle reads messages only on the interstate that it is entering and discards other irrelevant messages.
3. *After ramp:* The vehicle reads messages for the interstate it is on and considers further messages along the route.

Figure 4.1 Picture of the West St. ramp.

Geofencing is a crucial aspect of the RampCast system that has been used to filter messages so that the target vehicles receive only those messages that are relevant to them (Hasenburg & Bermbach, 2020). The filtering logic is applied on the Roadside Unit (RSU) as well as the Onboard Unit (OBU).

Another area of focus is message retransmission. Retransmitting messages increases the rate of message delivery. Alongside the higher delivery rate, the priority of messages is also reflected in the retransmission rate. Generally, the approach is to have a higher transmission rate for messages with higher priority.

4.1 Data Source

The messages used in the RampCast scenario are primarily traffic messages and these are sourced from the 511 API (INDOT, n.d.). The traffic messages were pulled from the API using Python scripts and stored in JSON files and an SQL DB. These are preprocessed to filter out unnecessary fields and saved. A sample of the processed message is shown in Figure 4.2. Alongside the use of messages in the RampCast scenario, they were also used to conduct data analysis. Over 6 months of data was used to perform the analytics.

From the analytics performed, various insights were derived (Figures 4.3 and 4.4). The traffic messages consisted of multiple types of events with the major being *crash, construction, stalled vehicle,* and *maintenance* types. The *crash* and *construction* messages had more significance as their frequency was much higher than other types of events (Figure 4.4).

The crash events were then plotted against the time of day and day of the week to derive the following heatmap in Figure 4.5. The heatmap shows a larger frequency of crash events during the beginning and end of the working hours in a work week. This correlation could be used to adjust the frequency of message transmission for certain message types (Ardakani et al., 2023). The message delivery pipeline detailed in the next subsection can alter the message transmission frequency to reflect the priority of the messages.

Additionally, a comparison of monthly plots as shown in Figure 4.6 reveals consistent patterns, such as increased crash events on weekdays compared to weekends, suggesting there exist factors influencing traffic incidents during the workweek.

Figure 4.7 pinpoints crash hotspots in Indiana, particularly around Indianapolis. Red zones highlight areas where collisions are most frequent, often coinciding with major roadways and intersections. Intense coloring for these locations reflects their heightened risk, likely due to factors like higher speeds, multilane configurations, and increased traffic volume. Analyzing crash patterns (Thelin et al., 2020) in these areas is crucial, allowing for the assignment of higher priority values to messages, adjusted message retransmission frequencies, and advanced warnings to drivers during peak times, enhancing overall safety measures.

4.2 Geolocation-Based Message Delivery Algorithm

The core aspect of the publisher-subscriber messaging framework consists of multiple software components with the message broker being the major component. A message broker is an intermediary platform that manages the routing and delivery of messages from source to destination. Multiple messaging brokers were investigated before implementation to weigh their pros and cons. The key factors for the comparison were scalability, durability, protocol support, and ease of integration.

The protocol for messaging is also a key aspect of V2X communication as V2X messaging systems require low latency and low bandwidth overhead along with reliability. The MQTT open-source protocol supports these features and is purpose-built for IoT applications which makes it an ideal candidate for V2X scenarios (Figure 4.8).

```
{
  "priorityLevel": 8,
  "locationDetails": {
    "city": null,
    "county": [
      "Hendricks"
    ],
    "district": [
      "CRAWFORDSVILLE"
    ],
    "unit": [
      "Lizton Unit 3"
    ],
    "subdistrict": [
      "CLOVERDALE"
    ],
    "region": [
      "Central Indiana"
    ]
  },
  "geometry": "POINT (-86.36661935 39.84623039)",
  "endMileMarker": null,
  "positiveLaneBlockageType": "N/A",
  "eventType": "MEDICAL EMERGENCY",
  "eventStatus": "COMPLETED",
  "id": 83439,
  "additionalPublicAudio": null,
  "dateStart": 1684422170784,
  "dateEnd": 1684427515695,
  "negativeLaneBlockageType": "N/A",
  "additionalPublicText": null,
  "route": "I-74",
  "startMileMarker": 67.6,
  "dateUpdated": 1684427515676,
  "positiveLaneBlockage": {
    "entranceRampAffected": false,
    "exitRampAffected": false,
    "insideShoulderAffected": false,
    "outsideShoulderAffected": true,
    "lanesAffected": [],
    "allLanesAffected": true
  }
}
```

Figure 4.2 511 API message structure.

Considering the requirements and support for the MQTT protocol, the RabbitMQ (RabbitMQ, n.d.) message broker was chosen as the central component for message distribution (Figure 4.9).

The messaging broker lies on the RSU side and manages multiple queues carrying messages to the OBU. The detailed flow between the RSU and OBU is explained in the coming section.

4.2.1 RSU Side Geofencing and Message Prioritization

In the program residing at the Roadside Unit, the basic scenario begins with a traffic message from the TMC traveling to the RSU and then finally broadcasted to the OBU. This flow is depicted in the flowchart given in Figure 4.10. The RampCast program residing in the RSU fetches messages from the TMC through the 511 API. The RSU can also prefetch messages and keep them in local storage to reduce the number of requests to the TMC servers.

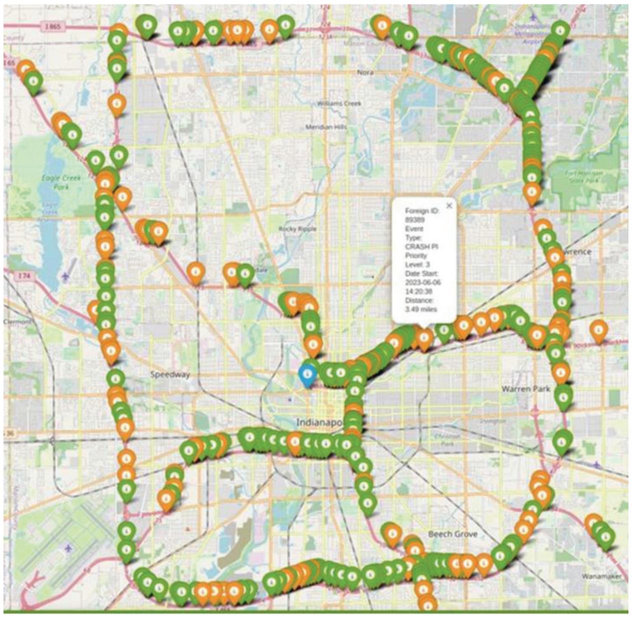


Figure 4.3 511 traffic events in Indianapolis.

The RSU program calculates the priority of the message using the existing priority from the message data as well as using an internal priority which is determined by the type of message and the number of times it has already been retransmitted.

The next step is to verify the validity of the message. This is performed by comparing the message start and end date which are present in the body of each message with the system date.

Once the message is checked for validity, the program decides if the message is relevant for the region of interest of the RSU. If it is outside the region of interest concerning the RSU, then the message is filtered out.

After the initial filtering logic, the RSU program sends the message to the message broker where it is passed onto the client priority queue. When each OBU of a vehicle gets in range of an RSU it will be given a client queue called UE (User Equipment) Queue. The queue is durable so that if the vehicle is out of range of the RSU and returns, it can still be able to receive the messages. The message broker would also handle the retransmission of the messages within the priority queue. A simple representation is provided in Figure 4.11.

4.2.2 OBU Side Geofencing and Message Prioritization

The client vehicle side or the OBU side program receives the message from the broker at RSU via C-V2X signals. It also implements a filtering mechanism within it before displaying the messages on the GUI. Initially, the OBU program obtains the GPS coordi-

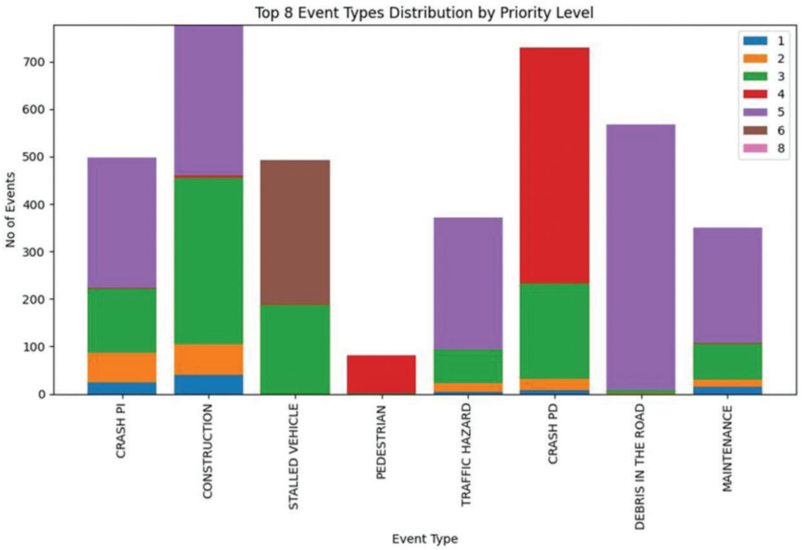


Figure 4.4 Distribution of top eight events by priority level based on 511 traffic events in Indianapolis.

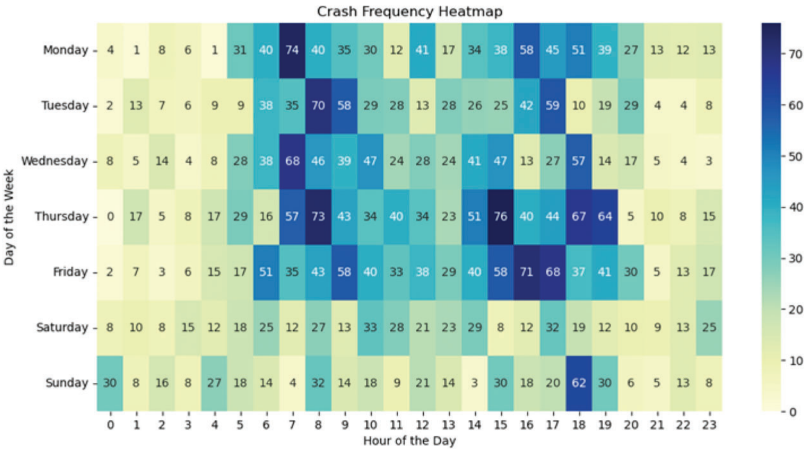


Figure 4.5 Heatmap shows the frequency of crash events during different time slots in a week.

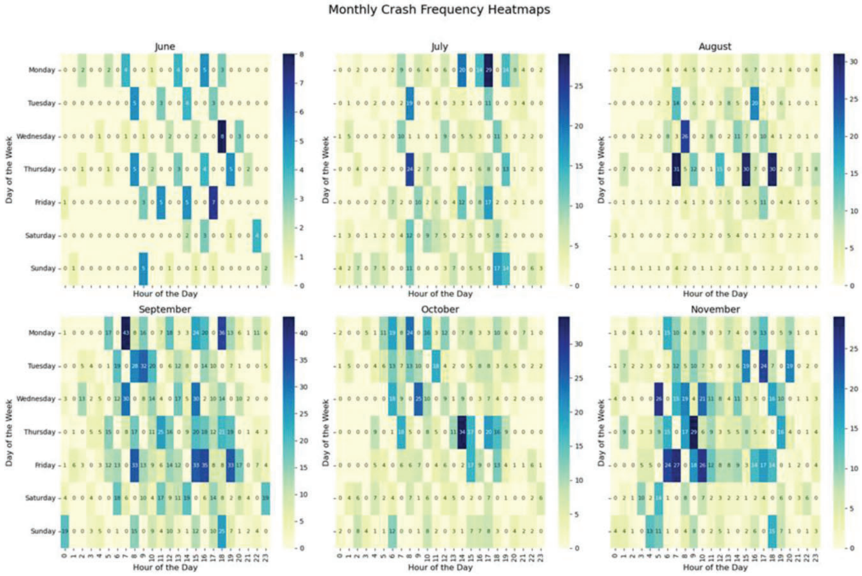


Figure 4.6 Heatmap for crash events from the last 6 months that show similar patterns.

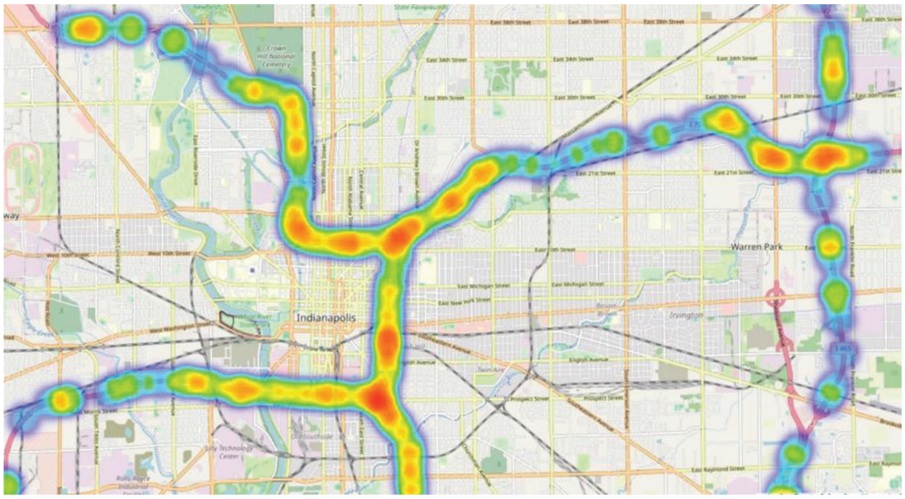


Figure 4.7 Map illustrating crash hotspots, with red areas indicating locations prone to crash events.

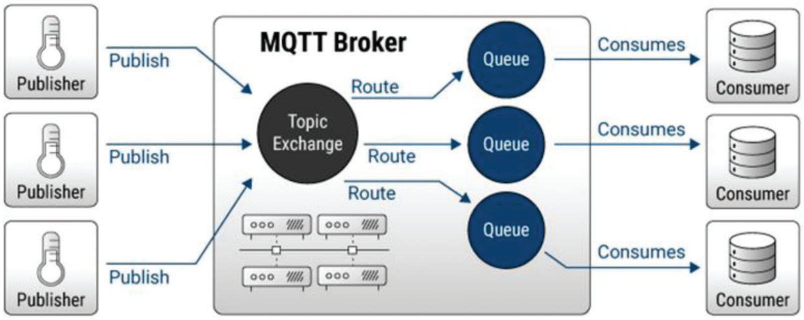
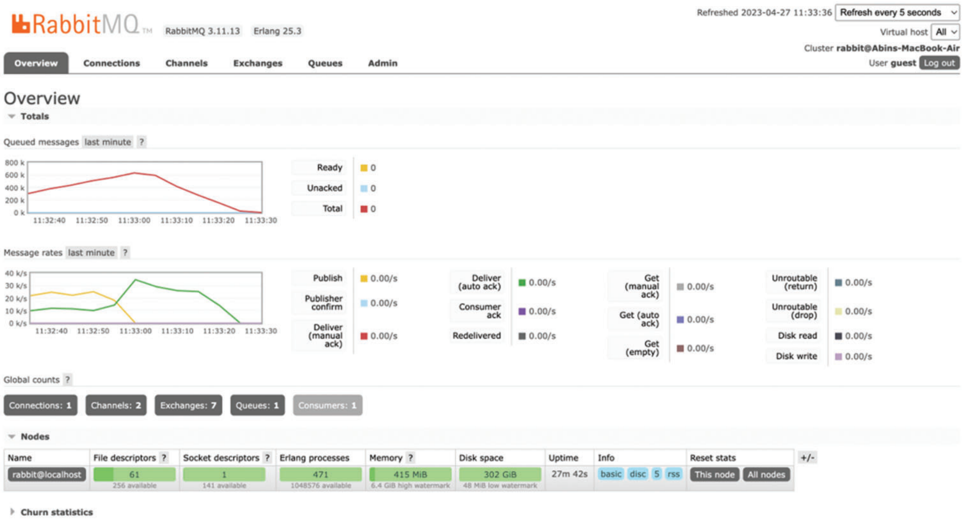


Figure 4.8 The message transmission logic using the MQTT protocol (Craggs, 2022).



Refreshed 2023-04-27 11:33:36 Refresh every 5 seconds
Virtual host All
Cluster rabbit@Abins-MacBook-Air
User guest

Overview

Totals

Queued messages last minute ?

Ready 🟨 0
Unacked 🟦 0
Total 🟥 0

Message rates last minute ?

Publish 🟨 0.00/s
Publisher confirm 🟦 0.00/s
Deliver (manual ack) 🟥 0.00/s
Deliver (auto ack) 🟩 0.00/s
Consumer ack 🟪 0.00/s
Redelivered ■ 0.00/s
Get (manual ack) ■ 0.00/s
Get (auto ack) 🟪 0.00/s
Get (empty) 🟫 0.00/s
Unroutable (return) ■ 0.00/s
Unroutable (drop) 🟨 0.00/s
Disk read ■ 0.00/s
Disk write 🟪 0.00/s

Global counts ?

Connections: 1
Channels: 2
Exchanges: 7
Queues: 1
Consumers: 1

Nodes

Name	File descriptors ?	Socket descriptors ?	Erlang processes	Memory ?	Disk space	Uptime	Info	Reset stats
rabbit@localhost	61 256 available	1 141 available	471 1048576 available	415 MiB 6.4 GiB high watermark	302 GiB 48 MiB low watermark	27m 42s	basic disc 5 rss	This node All nodes

Figure 4.9 RabbitMQ MQTT broker dashboard.

nates of the vehicle and calculates its heading. Following that, the on-board unit performs a check to see if the received message is within 330 degrees of its forward direction. If the region of interest of the message is outside the heading of the vehicle, the message is then ignored on the client side (Figure 4.12).

The vehicle-side program also continually adjusts the priority of messages within its received messages queue

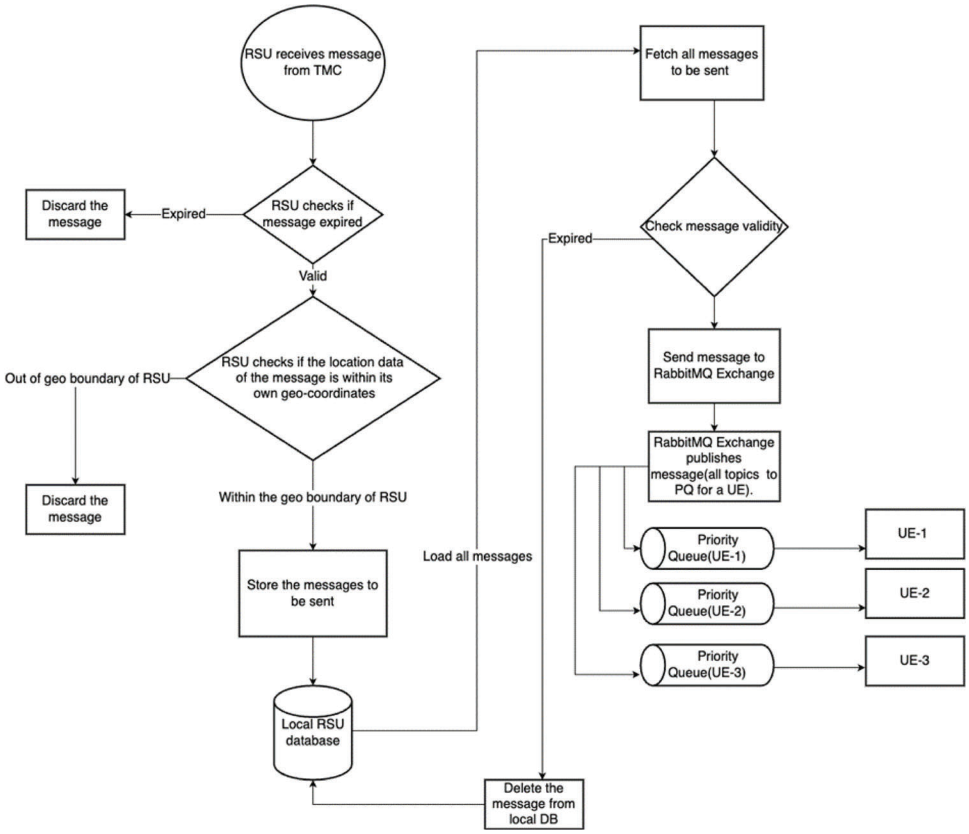


Figure 4.10 Message framework flowchart.

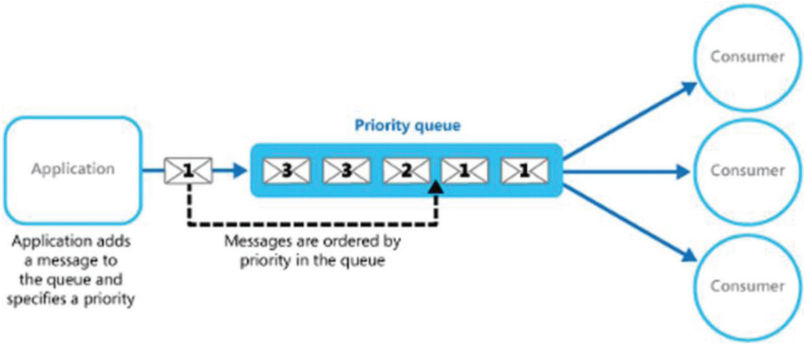


Figure 4.11 Priority queue representation (Gaston, 2016).

over time. This dynamic adjustment uses a Fading priority level logic which is explained as follows.

Upon the arrival of a new message from the RSU, the client reads a “repeat” value which is present in the body of the message. Subsequently, it establishes the initial priority of the message based on the original priority value and adds the message to the priority queue.

In each subsequent round, when no new message is received, and a message already present in the queue needs to be displayed again, the implementation follows a systematic process. It incrementally increases the priority value of messages in the queue by 2, thereby effectively lowering their priority and relocating them to the bottom of the priority queue. Simultaneously, the repeat value is decreased, and if it reaches 0 or less, the message is removed from the queue.

In the event of a new message with identical content arriving from the RSU, the implementation promptly resets the original priority value of the message. This way, critical and relevant messages stay high in the queue, while less critical messages fade in priority over time. This implementation optimizes message delivery by making the communication system more adaptive to repetitive messages.

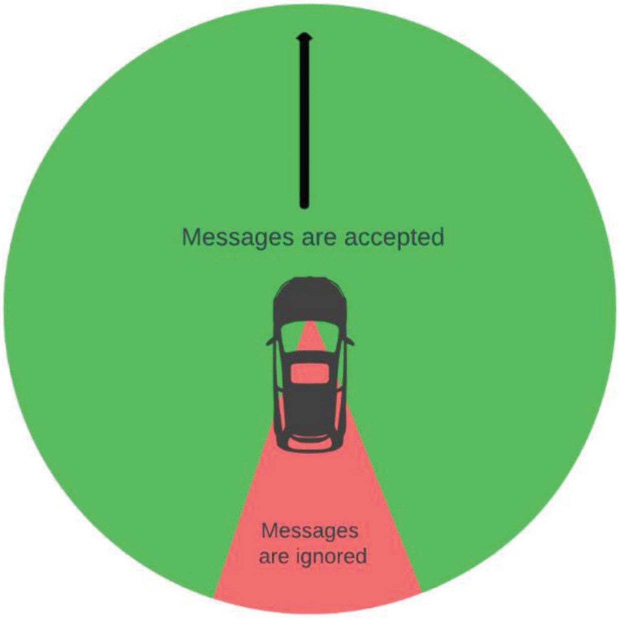


Figure 4.12 Pie chart depiction of message filtering by heading direction.

5. TESTING

After designing the RampCast prototype system, some preliminary tests were conducted inside the lab (Figure 5.1). The preliminary testing phase encompassed a comprehensive assessment, involving a total of 30 tests which were performed in an indoor environment. Each test was conducted three times to average the KPIs of the system such as latency, packet reception ratio (PRR), and packet inter-reception rate (PIR).

Based on the evaluation metric from 3GPP Release 14 (Meredith, 2015), the definition for each KPI is as follows.

1. *Packet reception ratio:* For one Tx packet, the PRR is calculated by X/Y, where Y is the number of UE/vehicles that located in the range (a, b) from the TX, and X is the number of UE/vehicles with successful reception among Y.
2. *Packet inter-reception rate:* Time elapsed between two successive successful receptions of two different packets transmitted from node A to node B.
3. *Latency:* The difference between the time when RSU sends out the message and the time when the UE receives the information.

The primary tests at the initial stage were distance tests conducted at intervals of 1 meter, 5 meters, 20 meters, and 50 meters. Messaging capabilities tests which test data transmission capacities were performed at 900 Kb, 2,700 Kb, and 5,400 Kb message sizes. The testing scenario used socket transmission as well as a simple messaging broker implementation. The preliminary tests verified the basic communication functions between the SDR units.

The RampCast algorithms were polished through several iterations of development. After completing the algorithm development and the system design, field tests were conducted to test out further the communication functionality and the performance of the prototype and algorithms in the real-life scenario. In addition to the KPIs, some built-in metrics from the Sidelink project were utilized to measure and track the SDR communication signal. These metrics are valuable for assessing signal quality under varying conditions and enhancing performance.

The logged metrics include the following.

1. *RSRP:* Signal strength of received reference signals.
2. *PL:* Signal strength attenuation over distance.
3. *CFO:* Carrier frequency deviation monitoring.
4. *DL SNR:* Downlink signal quality.
5. *UL/DL bit rates:* Uplink and downlink data rates.
6. *Error metrics (BLER):* Data integrity assessment.
7. *RF parameters:* Relevant RF details (RF_O, RF_U, RF_L).

5.1 Campus Parking Lot Test

The campus parking lot test consists of two parts. One was under the condition of a static vehicle, mainly to explore the SDR communication performance within different ranges. Because of the limitation of the area, three ranges (100 ft, 200 ft, 300 ft) were selected. The other was dynamic vehicle testing, whose objective was to test out the success rate and the stability of the message delivery. The vehicle speed was within the speed limit (15 mph) of the parking lot.

For the testing in the campus surface parking area (Figure 5.2), the off-peak nighttime was selected to avoid traffic in the parking lot. The vehicle was equipped with the OBU, and the antennas were mounted on top of the testing vehicle as shown in Figure 5.3. The Yagi antennas were mounted on a stand pole at the height of 6 ft shown in Figure 5.4.

Omnidirectional and directional antennas were also selected respectively to compare the difference in connectivity performance. From the testing results shown in Table 5.1, the PRR decreased dramatically to 55.23% when the distance between the vehicle and the RSU was 300 ft. The latency for the three distances while using the omnidirectional antennas was around 30 ms. After substituting the omnidirectional antenna with the directional antennas, a higher value and more stable PRR was achieved, as is shown in Table 5.2. For all three distances, the PRR exceeded 98%. Table 5.3 also presented the KPIs when the vehicle was moving with a predefined 15 mph speed. The PRR while using the directional antenna was more than twice of the one achieved using the omnidirectional type. Meanwhile, the latency of the message transmission using directional antenna was 7.57 ms and was only 25.14% of that using the other. In general, directional antennas outperform the omnidirectional antennas both in the static and dynamic

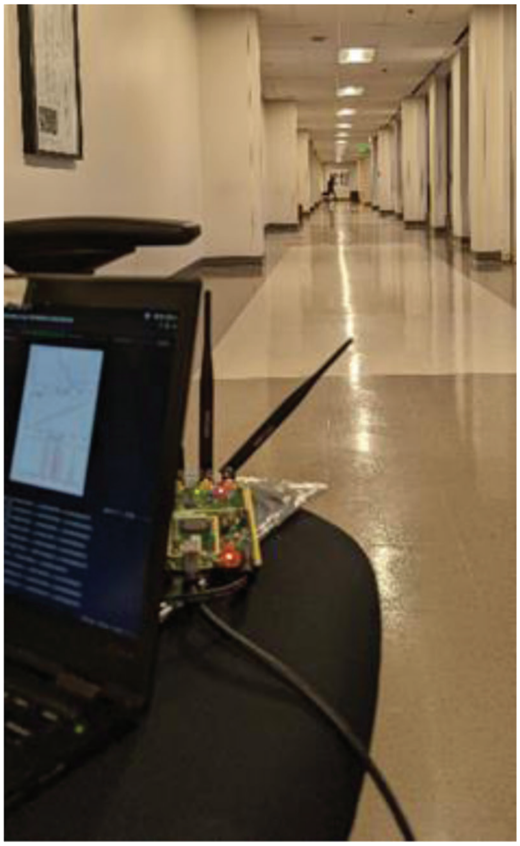


Figure 5.1 Two SDR units are positioned at the two ends of the hallway in SL building.

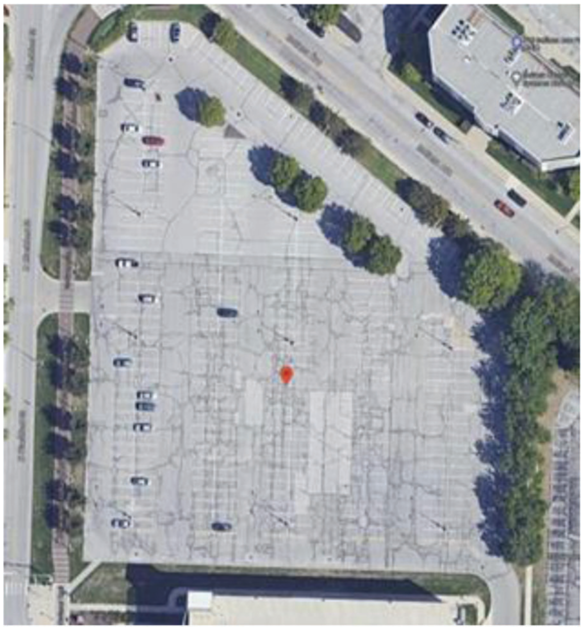


Figure 5.2 Campus surface parking lot.

tests, which shows the superiority of the directional antennas in the implementation of C-V2X communication.

Figure 5.3 Testing vehicle with antennas on top of the front windshield.

5.2 Testing on the Test Track

For the test track testing (Figure 5.5), a similar procedure was followed. Both static-vehicle and dynamic vehicle testing were investigated to explore the communication range and the communication stability (Figure 5.6). Because of the larger space and the increase of the vehicle speed limit, more ranges (600 ft, 900 ft, 1,200 ft, 2,500 ft) and higher speed (35 mph) were explored.

The overall testing results are positive and most of the testing shows a high value of the PRR even with 2,500 ft. As is presented in Table 5.4, the distance increased from 100 ft to 2,500 ft, while the PRR maintained a high value, all beyond 97%. The latency was lower than the value of 25 ms within the 1,200-ft distance. PIR showed a steady 0.2 s which also aligned with the defined message transmitting frequency (5 messages per second). Therefore, the fundamental functionality of the designed system was verified through static testing. Wi-Fi was utilized during the 2,500-ft test and that was the reason leading to 91.45-ms latency, which was comparatively higher than the other testing.

The dynamic vehicle testing was designed to test out the capability of the RampCast system in a more realistic urban scenario where the vehicle was moving at 35 mph. The corresponding plots for the PRR and PIR in the dynamic testing are shown in Figure 5.7 and Figure 5.8, respectively. As is illustrated by the two figures, a few messages were missing when about 70 messages (packets), 220 messages (packets), and 460 messages were sent out by the RSU, respectively. The missing message resulted in the drop of PRR and the increase of the PIR. Nevertheless, the result indicated that the SDR can also be applied to real-work scenario when a vehicle is approaching and leaving, where a PRR at 99.17% and 0.2 s PIR were achieved.

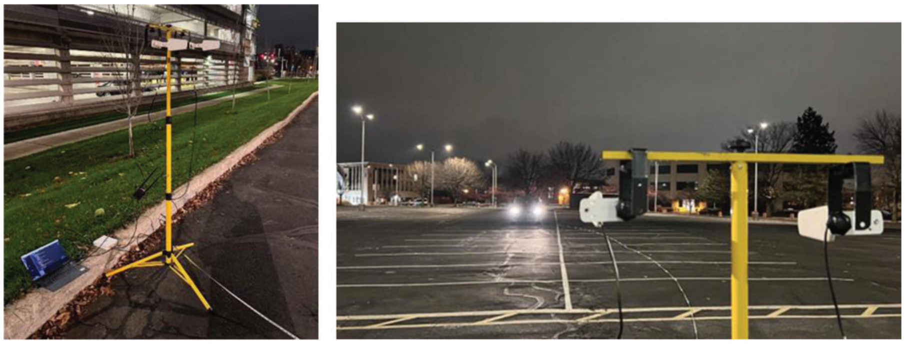


Figure 5.4 RSU with antennas mounted on top of a stand pole.

TABLE 5.1
Communication METRIC in static-vehicle test using omni-directional antennas

Distance	100 feet	200 feet	300 feet
No. of msg(s)/sec	5	5	5
PRR (%)	96.56	92.56	55.23
Latency (ms)	29.91	33.80	31.64
PIR (s)	N/A	N/A	N/A

TABLE 5.2
Communication METRIC in static-vehicle test using directional antennas

Distance	100 feet	200 feet	300 feet
No. of msg(s)/sec	5	5	5
PRR (%)	99.17	99.50	98.17
Latency (ms)	21.39	21.41	22.47
PIR (s)	0.20	0.20	0.20

Figure 5.5 Bird's eye view of the test track.

TABLE 5.3
Communication METRIC in dynamic-vehicle test with and without directional antennas

Antenna Type	Directional	Omnidirectional
No. of msg(s)/sec	5	5
Vehicle speed (mph)	15	15
PRR (%)	82.67	31.60
Latency (ms)	7.57	30.11
PIR (s)	0.20	N/A

Figure 5.6 Capture of the communication test with static vehicle.

TABLE 5.4
Experimental testing results in static-vehicle test in test track

Distance	100 ft	200 ft	300 ft	600 ft	900 ft	1,200 ft	2,500 ft
No. of msg(s)/sec	5	5	5	5	5	5	5
PRR (%)	97.83	99.00	99.17	99.33	98.33	98.00	99.17
Latency (ms)	22.87	20.89	21.17	21.53	21.20	24.63	91.45
PIR (s)	0.20	0.20	0.20	0.20	0.20	0.20	0.20

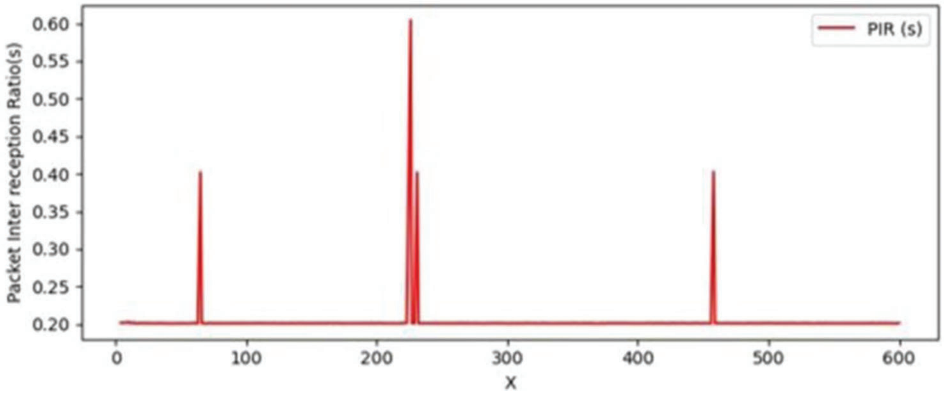


Figure 5.7 Packet reception rate during the dynamic vehicle testing.

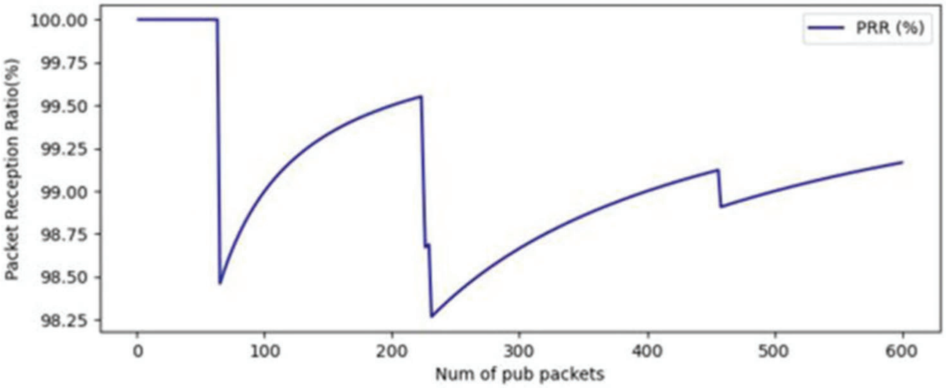


Figure 5.8 Packet inter-reception during the dynamic vehicle testing.

6. CONCLUSION

This study completed a comprehensive survey and review of state-of-the-art CV2X technologies and various demonstration projects by the automotive industry (OEM and suppliers), cellular wireless chips/systems companies, and federal/states DOTs in the U.S. and Europe.

After a year-long feasibility study examining the C-V2X implementations, a RampCast prototype system was developed using a software-defined radio approach. The prototype, built from the ground up, showcased low-latency communication between Roadside Units and On-Board Units, leveraging a publisher-subscriber architecture for transmitting traffic information sourced from INDOT's 511 API. Augmented by data-driven analysis, RampCast algorithms focusing on geocasting were developed for improving message prioritization and retransmission strategies. Field tests conducted in a campus parking lot and on the test track revealed sub-100 ms latency and a range of up to 2,500 ft for C-V2X, emphasizing its effectiveness in transmitting critical messages and traffic guidance.

Further extensions for the prototype include incorporating multiple units, expanding message types (e.g. points of interest, location-specific adverts), optimizing the prototype's GUI for diverse scenarios, and conducting long-term data analysis for better message flow optimization.

REFERENCES

5GAA. (2018, July 11). *5GAA, BMW Group, Ford and Groupe PSA exhibit first European demonstration of C-V2X direct communication interoperability between multiple automakers*. https://5gaa.org/5gaa-bmw-group-ford-and-groupe-psa-exhibit-first-european-demonstration-of-c-v2x-direct-communication-interoperability-between-multiple-automakers/

Ardakani, S. P., Liang, X., Mengistu, K. T., So, R. S., Wei, X., He, B., & Cheshmehzangi, A. (2023). Road car accident prediction using a machine-learning-enabled data analysis. *Sustainability*, *15*(7), 5939. https://doi.org/10.3390/su15075939

Audi of America, Inc. (2020). *Audi collaborates to deploy C-V2X communication technology on Virginia*. https://media.audiusa.com/assets/documents/original/7811-AudiQualcommVDOTCV2XDeploymentReleaseFINAL2.pdf

Craggs, I. (2022, June 29). *MQTT vs AMQP for IoT*. Hivemq.com. https://www.hivemq.com/article/mqtt-vs-amqp-for-iot/

Eckermann, F., & Wietfeld, C. (2021, April). SDR-based open-source C-V2X traffic generator for stress testing vehicular communication. *2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring)*. Institute of Electrical and Electronics Engineers. https://github.com/FabianEckermann/cv2x-traffic-generator

Federal Communications Commission. (2023, April 2). *Request for waiver of 5.9 GHz band rules to permit initial deployment of cellular vehicle-to everything technology* (ET Docket No. 19-138). https://docs.fcc.gov/public/attachments/DA-23-343A1.pdf

Gaston. (2016, October 11). *Improving throughput by using queue-based patterns*. MSDev.pro Blog. https://msdev.pro/2016/10/11/improving-throughput-by-using-queue-based-patterns/

Geppert, P. (2023). *Sidelink* [Data set]. GitHub. https://github.com/Paul-Geppert/sidelink

Hasenburg, J., & Bermbach, D. (2020). GeoBroker: A pub/sub broker considering geo-context information. *Software Impacts*, *6*, 100029.

Honda. (2021, April 8). *Through Mcity Consortium, Honda and Verizon test how 5G enhances safety for connected and autonomous vehicles*. https://hondanews.com/en-US/releases/release-32797eaea7316f1bed4bfcd279049a91-through-mcity-consortium-honda-and-verizon-test-how-5g-enhances-safety-for-connected-and-autonomous-vehicles

INDOT. (n.d.). *TrafficWise* [Website]. Indiana Department of Transportation. https://511in.org/@-103.07526,32.60853,7?show=incidents,normalCameras,stationsAlert,weatherWarningsAreaEvents,plowCameras,flooding

Lucero, S. (2016). *Cellular–vehicle to everything (C-V2X) connectivity*. IHS Technology, Internet Everything 3, 1–3. https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/ihs_technology_whitepaper_-_c-v2x_connectivity_-_june_2016.pdf

Meredith, J. M. (2015, June 22). *Study on LTE-based V2X services*. https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2934

Nguyen, T. V., Shailesh, P., Sudhir, B., Kapil, G., Jiang, L., Wu, Z., Malladi, D., & Li, J. (2017). A comparison of cellular vehicle-to-everything and dedicated short range communication. *2017 IEEE Vehicular Networking Conference (VNC)* (pp. 101–108). Institute of Electrical and Electronics Engineers.

Nikaein, N., Marina, M. K., Manickam, S., Dawson, A., Knopp, R., & Bonnet, C. (2014). OpenAirInterface: A flexible platform for 5G research. *ACM SIGCOMM Computer Communication Review*, *44*(5), 33–38. https://doi.org/10.1145/2677046.2677053

Papadimitratos, P., De La Fortelle, A., Evenssen, K., Brignolo, R., & Cosenza, S. (2009). Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation. *IEEE Communications Magazine*, *47*(11), 84–95.

Qualcomm. (2020, September 28). *C-V2X communication technology now deployed on Virginia roadways*. https://www.qualcomm.com/news/releases/2020/09/c-v2x-communication-technology-now-deployed-virginia-roadways

RabbitMQ. (n.d.). *MQTT plugin* [Data set]. https://www.rabbitmq.com/mqtt.html

Sharma, R. (2021, June 8). *Telefonica tests C-V2X at Cereixal Tunnel in Spain with 5G & IoT sensorisation*. TheFastMode. https://www.thefastmode.com/technology-solutions/19929-telefonica-tests-c-v2x-at-cereixal-tunnel-in-spain-with-5g-iot-sensorisation

SRSRAN. (2023). *Open source RAN* [Website]. https://www.srslte.com/

Thelin, R., Palmer, J., & Kalidindi, S. (2020). *Indiana crash facts 2020*. Indiana University Public Policy Institute and Indiana Criminal Justice Institute. https://www.in.gov/cji/research/files/TS-2020-Crash-Fact-Book_IU-PPI.pdf

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

He, Z., Mathew, A., Ingale, A., Zhou, J., Li, F., & Chen, Y. (2024). *Traffic management geocast study with connected vehicles on Indiana highways* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2024/19). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317753