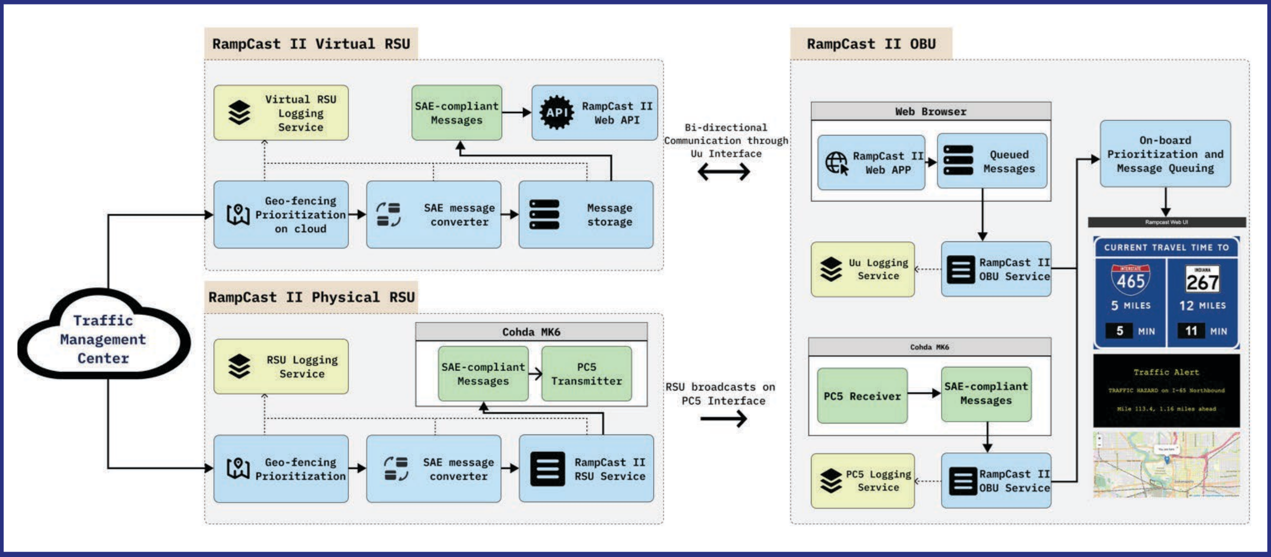
JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION AND PURDUE UNIVERSITY

RampCast Phase II: Connected Vehicles Traffic Management Application on Indiana Highways



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16. Abstract

This project advances connected vehicle applications by developing and testing an enhanced RampCast system, a comprehensive traffic management system using C-V2X technology for Indiana highways. The system features a dual-mode architecture integrating both short-range (PC5) and long-range cellular (Uu) Cellular Vehicle-to-Everything (C-V2X) communication pathways, utilizing commercial-grade Cohda MK6 hardware and adhering to SAE J2735 standards to ensure interoperability. A key innovation is the integration of an AI-based prioritization framework, which leverages a large language model to enhance the contextual relevance of traffic messages. This AI system introduces two intelligent agents: one to dynamically estimate the appropriate display distance for an event based on its severity, and another to prioritize the order of messages based on urgency and potential driver impact. Field tests conducted on I-65 and I-70 in Indianapolis validated the system's hybrid design. Results confirmed that the PC5 link provides very low latency (around 25 ms), ideal for time-critical alerts, while the Uu link ensures highly reliable coverage in complex environments, albeit with higher latency (around 45 ms). The AI framework was successfully shown to reorder and present messages based on real-time context, improving the clarity and usefulness of information provided to the driver. These findings support a hybrid C-V2X architecture as a robust model for future smart highway deployments.

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EXECUTIVE SUMMARY

Introduction

The rapid evolution of connected vehicle technologies has created a diverse landscape where modern, connected vehicles must coexist with legacy vehicles. This disparity presents a significant challenge for traffic management systems which need to ensure seamless and effective communication across all platforms to enhance roadway safety and efficiency. Building on the foundation of the RampCast Phase I project, the Phase II project addresses this challenge by developing an advanced, multimodal traffic management solution. The project's core objective is to create an AI-enhanced system capable of delivering real-time, geolocation-based traffic alerts.

Researchers from the Elmore Family School of Electrical and Computer Engineering and the School of Applied and Creative Computing at Purdue University, in collaboration with the Traffic Management Center of the Indiana Department of Transportation (INDOT), have developed a dual-pathway Cellular Vehicle-to-Everything (C-V2X) architecture that integrates both the direct, low-latency PC5 interface for vehicles with dedicated Onboard Units (OBUs) and the reliable, long-range cellular Uu interface for the broader ecosystem of connected vehicles. The enhanced RampCast system leverages commercial C-V2X hardware and implements advanced artificial intelligence (AI) models to intelligently prioritize traffic management messages based on real-time geolocation and contextual factors.

Findings

The project team successfully designed, implemented, and tested the RampCast prototype, a hybrid traffic management system utilizing commercial Cohda MK6 C-V2X hardware for its physical Roadside Unit (RSU) and a cloud-based virtual RSU for cellular communication. To ensure interoperability with the wider V2X ecosystem, the system's architecture standardizes all traffic data into SAE J2735-compliant Traveler Information Messages (TIM) and Road Safety Messages (RSM).

To enhance message relevance and responsiveness, an AI-based geofencing prioritization system was developed and integrated into the RampCast prototype. This system consists of two intelligent modules: the Event Display Distance Estimation agent, which determines how far in advance each message should be shown, and the Event Prioritization agent, which ranks messages based on event severity, location, and expected driver action. These modules are powered by a large language model and operate without altering the core RSU-OBU message flow. The AI system builds directly on the RampCast architecture and significantly improves the clarity and usefulness of displayed messages by aligning them with real-time driving context.

Extensive field tests on sections of Interstate 65 (I-65) and Interstate 70 (I-70) in Indianapolis validated the performance of the dual-pathway system. The findings confirmed a clear performance trade-off:

- The **PC5 link (short-range)** delivered messages with very low and stable latency (averaging 20–30 ms), but its reliability was susceptible to physical obstructions like overpasses, which caused signal degradation.
- The **Uu link (long-range)** provided highly reliable message delivery, demonstrating its strength in overcoming line-of-sight issues, though with a higher average latency of around 45 ms.

Both communication modes performed well within the 100 ms latency threshold required for safety applications. The results strongly indicate that a hybrid architecture combining the low-latency advantage of PC5 with the broad reliability of Uu offers the most robust and effective solution for advanced traffic management systems.

Implementation

The enhanced RampCast prototype system was tested for key performance indicators including latency and packet reception ratio. Extensive field testing, from controlled environments to interstate ramps, specifically the I-65 and I-70 ramps on West Street in Indianapolis, validated the system's design. The RampCast freeway application will be deployed and demonstrated under the SPR-5018 project.

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1. INTRODUCTION

The dynamic landscape of vehicular communication and the rapid evolution of connected vehicle technologies such as Cellular Vehicle-to-Everything (C-V2X; 5GAA, n.d.) have introduced new complexities and opportunities that necessitate advanced research and development. With a growing number of vehicles equipped with varying levels of connectivity, there is a critical need to bridge the gap between state-of-the-art capabilities and the legacy systems still prevalent on the road. This disparity poses significant challenges for traffic management systems, which must cater to a diverse technological landscape and ensure seamless communication across different platforms.

Building upon the foundational work of the RampCast Phase I project (He et al., 2024), which demonstrated the potential of geocast applications for traffic management on Indiana highways, Phase II aims to address these evolving challenges. The Phase II project focuses on enhancing and integrating new technologies into a comprehensive traffic management solution. The major requirement is to advance connectivity and communication paradigms to create a multimodal, artificial intelligence (AI)-enhanced system capable of real-time, geolocation-based traffic management that serves the entire vehicular ecosystem effectively. This research seeks to answer critical questions regarding the integration of real-time traffic data with advanced AI models, the implications of emerging C-V2X technologies on existing infrastructure, and the best practices for developing robust Vehicle-to-Everything (V2X) applications.

The enhanced RampCast framework leverages real-time 511 traffic data from Indiana highways (Indiana Department of Transportation [INDOT], n.d.), utilizes Codha MK6 C-V2X units, and implements AI models to prioritize traffic management messages based on geo-location and other contextual factors. Key innovations include an integrated short-range (PC5) and long-range (Uu) C-V2X message transmission system, the development of geofencing and AI-based message prioritization algorithms, the implementation of standardized SAE messaging sets for interoperability, and a robust architecture designed for scalability and adaptation to future advancements in transportation networks.

This report presents a comprehensive technical overview of the RampCast II project. It will detail the system architecture and implementation, explain the messaging and prioritization algorithms, present the results from extensive system testing in real-world environments, and conclude with the key findings and implications for future V2X deployments. The following sections will provide an in-depth examination of the system's design, performance, and its potential to serve as a scalable model for the smart highways of tomorrow.

2. RAMPCAST ARCHITECTURE AND IMPLEMENTATION

The RampCast II system was developed to meet several key requirements for an advanced traffic management application. The primary need was to deliver reliable, location-aware traffic messages to vehicles from a central Traffic Management Center (TMC). The system needed to support a diverse vehicle fleet, composed of dedicated C-V2X Onboard Units (OBUs) using the PC5 link and Uu link-based OBUs. This required an architecture that could integrate multiple communication methods.

Furthermore, the system had to be capable of processing and prioritizing a high volume of messages to ensure that the most critical information is presented to the driver in a timely manner. To fulfill these requirements, a modular and scalable architecture was designed. This architecture separates concerns between roadside infrastructure, cloud services, and in-vehicle units, allowing for flexible deployment and future expansion.

2.1 System Design

The overall architecture of the RampCast II system (Figure 2.1) was composed of three main parts: a TMC, a Roadside Unit (RSU) component, and an OBU component. The RSU component was further divided into a physical RSU for direct short-range communication and a virtual RSU hosted on a cloud server for cellular-based long-range communication. This dual-RSU approach provides multiple pathways for message delivery and allows for performance comparisons to be made between the communication links.

Traffic messages originate from the TMC and are sent to both the physical and virtual RSUs. Each RSU processes these messages, applying geofencing and prioritization logic before converting them into the standardized SAE J2735 and J2945 formats (SAE International, 2006, 2016). The physical RSU broadcasts these messages over the PC5 interface, while the virtual RSU makes them available via a web Application Programming Interface (API) over the Uu interface. In the vehicle, the OBU is equipped to receive messages from both interfaces, manage them in a local queue, and display them to the driver through a graphical user interface.

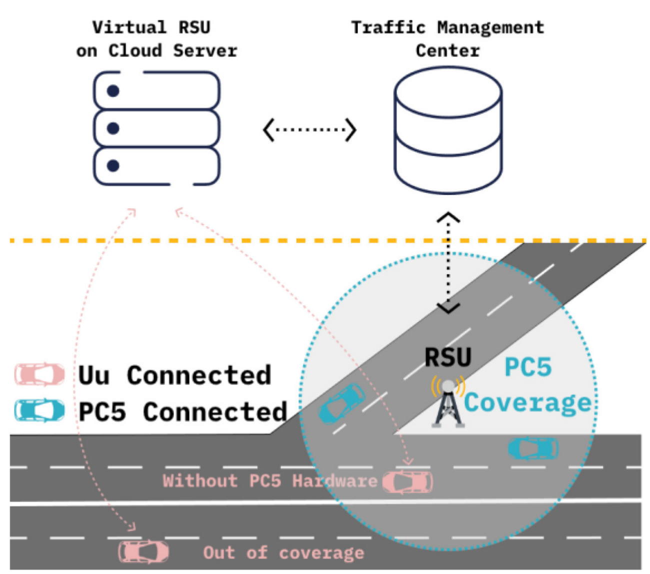

Figure 2.1 RampCast System Framework.

2.2 Hardware Components

The hardware for the RampCast II system was selected to support both development and real-world testing on Indiana highways. The setup includes core communication units for both PC5 and Uu links, computing devices to run the custom software, and supporting equipment for power and mounting in field environments. For the PC5 link, production-grade Cohda MK6 (Cohda Wireless, n.d.) units were chosen. These devices are designed specifically for V2X applications and integrate C-V2X PC5 communication in the 5.9 GHz band with a high-precision GPS module. These Global Positioning System (GPS) data were used for geofencing needs on the computing unit of the OBU. A detailed list of all components is provided in Table 2.1.

2.3 Software Framework

The software for RampCast II was built using a set of services and modules, with Python (n.d.) as the primary programming language. The framework is designed to be modular, allowing different components to be developed and tested independently. It handles message acquisition, processing, prioritization, transmission, and logging. The complete component diagram is shown in Figure 2.2.

2.3.1 Short-Range (PC5) Channel Implementation

The software for the direct, short-range PC5 channel was deployed on the physical RSU and the OBU's main computing device.

- **Physical RSU:** The RSU computer runs a service that ingests traffic messages from the TMC API. A geofencing and prioritization module filters and ranks the messages. A message converter then translates the data into formats compliant with the SAE V2X message set dictionary. To transmit, the main RampCast RSU service sends the final messages to the Cohda MK6's ACME (Application-to-Core Messaging-Entity) toolkit using the User Datagram Protocol (UDP) protocol. The ACME tool then interfaces with the internal Qualcomm chipset to broadcast the messages over the PC5 sidelink. A logging service records all sent messages and system metrics.
- **OBU:** On the receiving end, the OBU's Cohda MK6 unit listens for incoming PC5 broadcasts. The internal ACME toolkit

TABLE 2.1
List of Hardware Components.

Sr. No	Hardware	Description	Quantity
1	Cohda MK6 C-V2X Radios	C-V2X communication units with Qualcomm SA515 chipset for PC5 link	2
2	Intel Core i7 Laptop	Computing device running Ubuntu for Rampcast software services	2
3	Android Smartphone (*Android*, n.d.)	Commercial device for Uu link connectivity and running the web-based GUI	1
4	C-V2X/GPS Antennas	Roof-mounted antennas for signal reception	2
5	Portable Power Station	For powering the laptop and Cohda devices (RSU and OBU side)	2
6	Tripod, 12 ft	For mounting RSU C-V2X and GPS antenna	1

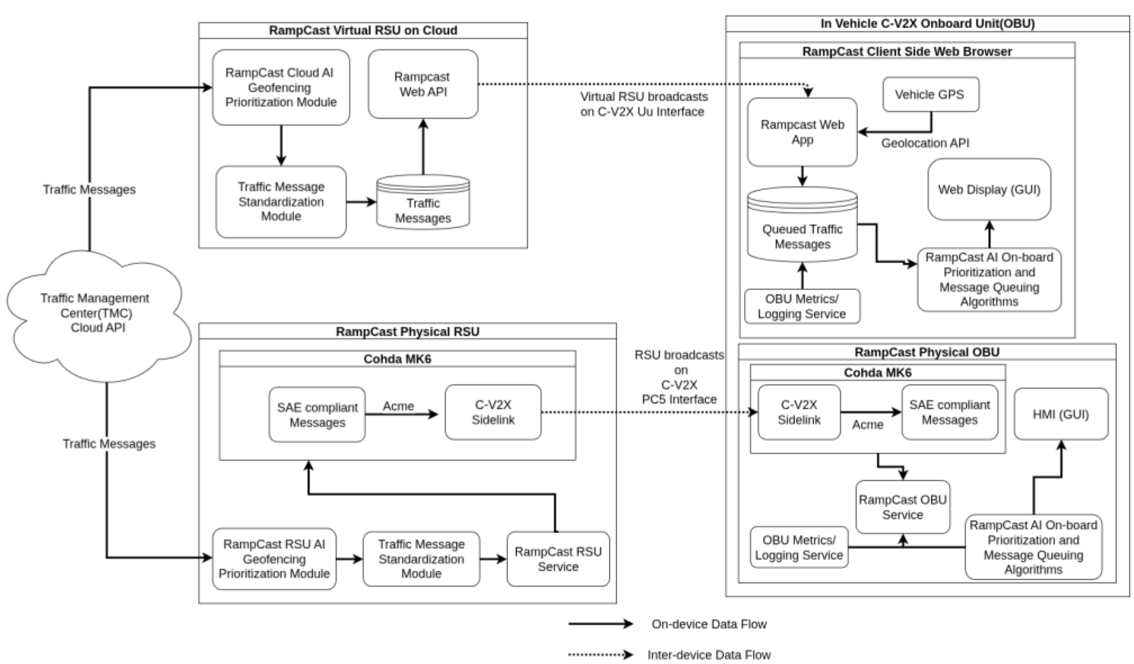

Figure 2.2 System Component Diagram.

receives these messages from the chipset and forwards them over UDP to the RampCast OBU service running on the laptop. The service decodes the received SAE messages and passes them to an onboard prioritization and message queuing algorithm. This algorithm manages how and when messages are displayed. A logging service records all received messages and GUI events.

2.3.2 Long-Range (Uu) Channel Implementation

The software for the long-range cellular Uu channel used a client-server model with a virtual RSU in the cloud and a web application in the vehicle. In this virtual RSU model, the server handles more of the processing logic to compensate for the limited processing capabilities in the OBU's web browser.

- **Virtual RSU:** Hosted on a Purdue cloud server, the virtual RSU performs similar functions to the physical one. It pulls messages from the TMC, applies geofencing and AI-based prioritization, and converts them to SAE formats. The processed messages are stored and made accessible through a RampCast Web API.
- **OBU Uu:** This is a web application that runs in the browser of the OBU's Android smartphone. The application communicates with the virtual RSU's Web API to receive traffic messages. It uses the browser's Geolocation API (Mozilla, n.d.) to send the vehicle's current position to the virtual RSU for geofencing. Incoming messages are placed into a queue for display on the Graphical User Interface (GUI).

2.3.3 Graphical User Interface

A GUI was used in the vehicle to present traffic information to the driver. The interface was designed to be clear and easy to understand at a glance. It is composed of two main elements:

- **Travel Time (TT) Board:** This panel displays the estimated travel times to upcoming major interchanges, giving the driver predictive information.

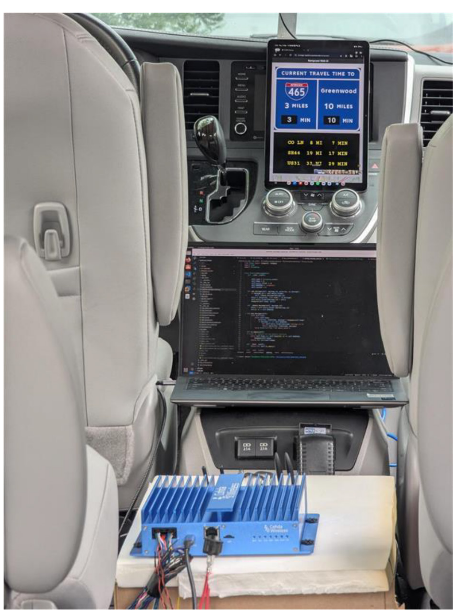

Figure 2.3 RampCast GUI Shown in a Driving Scenario Using a Tablet.

- **Dynamic Message Sign (DMS) Board:** This panel displays active traffic alerts. Messages are color-coded based on the event type (e.g., red for crashes, orange for construction) and show the location of the event. Custom AI prioritized messages are also integrated here with the regular traffic messages from Indiana highways

Figure 2.3 shows the GUI using an Android tablet in the vehicle driving scenario. The real-time Time Travel Information and the relevant crash information are presented.

3. RAMPCAST GEOFENCING AND MESSAGE TRANSMISSION TOOLKIT

A key requirement of the RampCast II project is the use of commercial messaging standards to ensure interoperability and compatibility with the wider V2X ecosystem. Therefore, the system relies on a set of algorithms and a standardized messaging toolkit to process and deliver traffic information. These components ensure that messages are relevant, timely, and can be understood by any compliant V2X system. The core functions include standardizing incoming data into a common format and filtering messages based on a vehicle's specific location and direction of travel.

3.1 Traffic Message Standardization

To ensure seamless data exchange between multivendor V2X systems, adherence to a common message set standard is essential. This practice maintains interoperability and prevents proprietary communication silos where a vehicle from one OEM cannot decode messages from another. SAE International has created standards for this purpose. The RampCast system follows the SAE J2735 and J2945 standards, which define the "dictionary" for V2X communications.

From the available message types defined in the standards, the Traveler Information Message (TIM) and the Road Safety Message (RSM) were selected for use in RampCast. The data fields within these two message types were a close match for the information provided by the INDOT 511 traffic data feed, which is the source of the system's alerts. This alignment made the process of converting the INDOT data into a standardized V2X format more direct. A Python-based translation toolkit was developed to handle this conversion. This translator tool extracted relevant fields from the incoming traffic data and performed all necessary data processing. This included modifying properties into specific formats required by the SAE standard, such as converting a Coordinated Universal Time (UTC) timestamp into separate month-of-year and day-number fields. After processing, the module encoded the data into the final SAE-compliant TIM or RSM messages before transmission. Figure 3.1 and Figure 3.2 display the reference data structure of the final message.

3.2 Geofencing Algorithms

To prevent information overload and ensure drivers only receive alerts relevant to their immediate route, a geofencing module was implemented. This module filters messages

```
{
  "MessageFrame": {
    "messageId": "27",
    "value": {
      "RoadSideAlert": {
        "commonContainer": {
          "eventPoint": {
            "eventPosition": {
              "lat": 51.509865,
              "long": -0.118092,
              "elevation": 100
            },
            "eventSource": "rsu",
            "eventConfidence": 80,
            "eventRadius": 50,
            "eventDescription": "Road hazard ahead",
            "startTime": "2025-07-30T12:00:00Z",
            "endTime": "2025-07-30T13:00:00Z",
            "causeCode": 1,
            "subCauseCode": 1,
            "affectedVehicles": [
              "all-vehicles",
              "cars-and-light-vehicles"
            ]
          },
          "regionInfo": {
            "regionPoint": {
              "lat": 51.509865,
              "long": -0.118092
            }
          }
        },
        "content": {
          "messageContainer": {
            "priority": "high-priority",
            "advisory": "Construction work ahead"
          }
        }
      }
    }
  }
}
```


Figure 3.1 SAE RSM Message Structure.


```
{
  "MessageFrame": {
    "messageId": "27",
    "value": {
      "TravelerInformation": {
        "payload": {
          "dataFrames": [
            {
              "frameType": "advisory",
              "msgId": "TIM",
              "msgCnt": 1,
              "packetID": "abcd1234efgh5678",
              "dataParameters": {
                "sspTimRights": 0,
                "frameType": "advisory",
                "startYear": 2025,
                "startTime": 480,
                "durationTime": 60,
                "priority": 5
              },
              "content": {
                "signText": "Road closed ahead",
                "data": [
                  {
                    "contentType": "text",
                    "data": "Detour via Main St."
                  }
                ]
              },
              "regions": [
                {
                  "regionId": 1,
                  "area": {
                    "shapePointSet": {
                      "anchor": {
                        "lat": 51.509865,
                        "long": -0.118092
                      },
                      "laneWidth": 300,
                      "directionality": "forward"
  }
}
```


Figure 3.2 SAE TIM Message Structure.

from the Traffic Management Center to provide vehicles with location- and direction-aware alerts.

The algorithm used the OBU's GPS readings to calculate the vehicle's current direction of travel. It then compared this information to the region of interest defined in each traffic message. If the vehicle is not heading towards the area covered by the message, the message is discarded. The radius for this filtering is a configurable value. This logic was implemented differently depending on the communication channel being used, a decision based on the computational capabilities of the OBU in each scenario. The processing load was placed where it could be handled most effectively:

- **Short-Range (PC5):** For vehicles equipped with a dedicated OBU and a powerful local computing device, the geofencing logic is processed directly on the OBU. The device uses the GPS data from the connected Cohda MK6 unit to perform the calculations locally.
- **Long-Range (Uu):** For vehicles using the cellular-based web application on a smartphone, which has more limited processing resources, the geofencing calculations are offloaded. The mobile browser uses its GeoLocation API to send the vehicle's GPS data to the virtual RSU on the Purdue cloud server, which then performs the filtering and only sends back relevant messages.

4. AI-BASED MESSAGE PRIORITIZATION

Traditional digital signboards used in transportation systems typically rely on rule-based strategies to determine which messages are displayed to drivers. While these signs provide valuable traffic updates, they are often spaced far apart and cannot always be installed at locations where drivers most need context-specific guidance. As a result, critical alerts may be missed—particularly near complex interchanges, ramps, or incident zones—limiting drivers' ability to make timely and informed decisions.

To address this limitation, the integration of physical and virtual RSUs with OBUs presents a more flexible and granular solution. This configuration supports the targeted transmission of traffic messages based on real-time vehicle geolocation, thereby enhancing the relevance and actionability of information delivered to drivers.

In the current RampCast prototype, messages transmitted by the RSU continue to follow a rule-based prioritization mechanism. However, dynamically tailoring these messages to each driver's precise location and decision-making context is difficult to achieve through static rules alone. To complement this existing framework, we introduced an AI-based geofencing system designed to improve message responsiveness and contextual accuracy.

This pilot implementation employed two AI agents, both powered by Google's (n.d.) Gemini large language model (LLM). These agents operated sequentially within a unified AI decision framework to determine which messages should be delivered and from which locations. Together, they enabled a dynamic and adaptive messaging pipeline that aligns with drivers' real-time positional and route-specific contexts (Bommasani et al., 2021).

The AI framework was developed directly on top of the existing RampCast RSU-OBU architecture, ensuring seamless integration with the communication and broadcast infrastructure established in RampCast II. The following subsections describe the design, functionality, and implementation of each AI agent and outline opportunities for further refinement.

4.1 Addressing Limitations in Traditional RSU-Based Systems

Traditional rule-based RSU messaging systems exhibit two primary limitations that reduce their effectiveness in high-speed or high-risk driving environments: fixed event display boundaries and the absence of event prioritization. The AI-based geofencing prioritization system developed in this project directly addressed both challenges through a modular, agent-driven design.

4.1.1 Fixed Display Boundaries

One key limitation in existing rule-based systems is the use of a rigid 1-mi display window. Events are only presented to drivers once they fall within this fixed geographic range. For instance, if a major crash occurs at mile marker (MM) 114.1, it becomes visible only after the vehicle passes the RSU at MM 114.0—leaving less than 0.1 mi of reaction time, which is inadequate at interstate travel speeds.

To address this, an Event Display Distance Estimation (EDDE) Agent, powered by a reasoning-capable LLM, was developed. This agent analyzed each event and determined how far in advance it should be displayed to oncoming vehicles. Factors such as event severity, expected driver response time, and local lane configuration were considered to assign a custom display distance, extending up to 3 mi.

In the crash example noted above, the system could initiate message display as early as MM 111.1, allowing sufficient time for the driver to reduce speed, change lanes, or take an alternate route. This approach replaced fixed-range messaging with flexible, context-aware display logic tailored to individual events.

4.1.2 Lack of Event Prioritization

In traditional systems, all traffic events within a given 1-mi segment are treated equally, and messages are ordered strictly based on proximity to the RSU or vehicle, in the direction of travel. This can result in counterintuitive and potentially hazardous sequencing. For example, if a small piece of debris is located at MM 114.4, and a crash causing a full lane blockage occurs at MM 114.7, the system would display the debris alert first—simply because it is nearer. Such ordering fails to account for severity, urgency, or the potential impact on driver decisions.

To resolve this, the system introduced an Event Prioritization (EP) Agent, which ranks all visible events based on their relevance and urgency. Powered by an LLM, this agent evaluated each event by considering its type, severity, potential to disrupt traffic flow, and distance from the vehicle. In the scenario above, the crash with the full-lane blockage would be prioritized and displayed before the debris warning, ensuring that drivers receive the most critical information first. This dynamic ranking significantly improved both driver safety and the clarity of decision-making in real-time driving contexts.

4.2 Pilot System Overview

The pilot version of the AI-based geofencing prioritization algorithm was implemented as a modular, extensible system that integrated seamlessly with the physical RSU-OBU architecture developed in the RampCast II project. The system architecture, illustrated in Figure 4.1, outlines the interaction between the core AI components responsible for refining message display strategies in real time.

At the center of the framework is the AI Decision Engine, built on Google's Gemini LLM. This engine drives the two sequential AI agents: EDDE Agent and EP Agent (N. Liu et al., 2023). These agents process incoming traffic event data to determine which messages should be transmitted to drivers and how far in advance they should be displayed (Park et al., 2023).

Processing begins with the EDDE Agent, which evaluates each event based on multiple contextual factors—including event severity, location classification (e.g., through-road vs. exit ramp), and the type of driver response it may require (e.g., lane change or route diversion). The output is a dynamic display radius, extending up to 3 mi, that defines the geofenced region where the message should appear.

Once display distances are assigned, the system performs an Event List Update, mapping each event to a set of mile marker–specific message fields based on its estimated display radius. This step ensures that events are correctly injected into the appropriate downstream RSU broadcast posts, enabling timely delivery to vehicles in range.

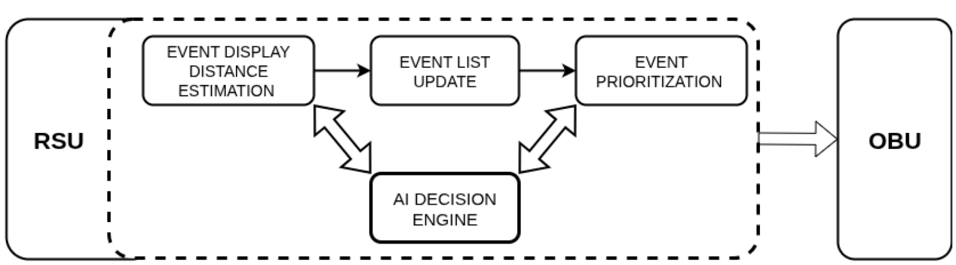

Figure 4.1 Architecture of the AI-Based Geofencing Prioritization Framework, Showing the Interaction Between the EDDE Agent, Event List Update, EP Agent, and the AI Decision Engine Within the RSU.

Following this, the EP Agent evaluates all events visible at a given RSU location and ranks them by relevance and urgency. The highest-priority events are then selected and converted into concise, structured messages conforming to the formatting specifications required by the OBU display system.

4.3 AI-Based Geofencing Framework

This subsection provides a detailed overview of the components within the AI-based geofencing framework.

4.3.1 Event Display Distance Estimation Agent

The first step in the AI framework involves processing all traffic events intended for transmission and determining how far in advance each event should be displayed to allow drivers sufficient time to respond appropriately. The AI pipeline is designed to operate nonintrusively, ensuring that it does not disrupt the normal flow of messages from the RSU to the OBU. When not active, the system continues to operate using the RSU's default output as input to the pipeline.

The EDDE Agent groups multiple events and sends them to the AI Decision Engine along with sufficient metadata to allow distance estimation. Each event is represented in a format compatible with the RSU system, including the following key fields:

- **Event ID**: A unique alphanumeric identifier.
- **Event Type**: Descriptions such as CRASH PI, CRASH PD, STALLED VEHICLE, MAINTENANCE, CONSTRUCTION, or MEDICAL EMERGENCY.
- **Event Severity**: Indicators of impact on traffic flow, such as No lanes blocked, One lane blocked, or All lanes blocked.

This information is directly extracted from the RSU's standard event feed.

In addition to this data, the EDDE Agent sends a prompt to the AI Decision Engine requesting it to act as a traffic analysis expert (P. Liu et al., 2023). The AI is instructed to determine, for each event, the appropriate display distance—ranging from 0.25–3.0 mi—based on the event's type and severity. Less critical events may require minimal display range, while high-impact incidents should be displayed well in advance. The expected output format from the AI Decision Engine is:

"display distance for <id>: <number> miles".

To reduce query overhead, events are grouped before submission. Once processed, the AI Decision Engine returns a list of event IDs with their respective display distances. As shown in Figure 4.2, the model successfully assigns longer display ranges to more severe events (e.g., ID 310640 – 3.0 miles) and shorter ranges to lower-impact cases (e.g., ID 312257_S – 1.0 mile). Notably, both examples involve STALLED VEHICLE events but differ in severity—demonstrating the model's ability to account for both event type and impact level in its decision-making process.

4.3.2 Event List Update

In the EDDE process, each event is evaluated independently, without consideration for the positions of other nearby events. However, for practical implementation at each RSU mile marker post, it is essential to determine which events must be broadcast from which RSU locations based on both distance and direction.

The RSU messages contain precise mile marker information for each event. Once the EDDE step assigns display distances, it becomes clear that several events need to be displayed not only at the RSU post nearest to their location but also at additional RSUs located up to 3 mi upstream or downstream, depending on travel direction.

Directional context plays a key role in this process. For example, consider a CRASH event occurring on Interstate 65 (I-65) Northbound at MM 114 with a display distance of 3 mi. This event must be broadcast from RSUs located at MM 111, 112, and 113. Conversely, if the event occurred on the Southbound side, the appropriate RSU broadcast points would be at MM 115, 116, and 117.


```
Return only one line per event in this format:
display distance for <id>: <number> miles

ID: 310657 – CRASH PI – No lanes blocked
ID: 311109_S – CRASH PD – 1 lane blocked
ID: 311759_S – CRASH PD – 1 lane blocked
ID: 312077_S – STALLED VEHICLE – 1 lane blocked
ID: 310520 – MAINTENANCE – All lanes blocked
ID: 311108_N – CRASH PD – 1 lane blocked
ID: 311929_N – CRASH PI – 1 lane blocked
ID: 310519 – MAINTENANCE – No lanes blocked
ID: 311628_S – MEDICAL EMERGENCY – No lanes blocked
ID: 311746_S – TRAFFIC HAZARD – 1 lane blocked
ID: 311890_S – CRASH PD – 1 lane blocked
ID: 312255_N – TRAFFIC HAZARD – No lanes blocked
ID: 312258_N – TRAFFIC HAZARD – No lanes blocked
ID: 310693 – CONSTRUCTION – All lanes blocked
ID: 312259_S – STALLED VEHICLE – 1 lane blocked
ID: 310723 – MAINTENANCE – All lanes blocked
ID: 310640 – STALLED VEHICLE – All lanes blocked
ID: 312257_S – STALLED VEHICLE – 1 lane blocked
```

```
display distance for 310657: 0.5 miles
display distance for 311109_S: 1.5 miles
display distance for 311759_S: 1.0 miles
display distance for 312077_S: 1.5 miles
display distance for 310520: 3.0 miles
display distance for 311108_N: 1.0 miles
display distance for 311929_N: 0.75 miles
display distance for 310519: 0.25 miles
display distance for 311628_S: 0.5 miles
display distance for 311746_S: 1.0 miles
display distance for 311890_S: 1.25 miles
display distance for 312255_N: 0.5 miles
display distance for 312258_N: 0.25 miles
display distance for 310693: 3.0 miles
display distance for 312259_S: 1.5 miles
display distance for 310723: 2.5 miles
display distance for 310640: 3.0 miles
display distance for 312257_S: 1.0 miles
```

Figure 4.2 Output From the Event Display Distance Estimation Agent. Left: Input Events With Type and Severity; Right: AI-Assigned Display Distances Showing Longer Ranges for High-Impact Events.

```
DIRECTIONAL EVENT COUNT REPORT (MM 108-120)
================================================================================
Mile Marker  | Direction |  Before  |  After   |  Δ Change
--------------------------------------------------------------------------------
    109      |     N     |    1     |    2     |     1
    110      |     N     |    1     |    5     |     4
    111      |     N     |    1     |    11    |     10
    112      |     N     |    3     |    8     |     5
    112      |     S     |    0     |    8     |     8
    113      |     N     |    3     |    12    |     9
    113      |     S     |    3     |    4     |     1
    114      |     N     |    1     |    9     |     8
    114      |     S     |    1     |    8     |     7
    115      |     N     |    1     |    5     |     4
    115      |     S     |    0     |    2     |     2
================================================================================
N-BOUND POSTS:
Details: [(109, 1), (110, 4), (111, 10), (112, 5), (113, 9), (114, 8), (115, 4)]
--------------------------------------------------------------------------------
S-BOUND POSTS:
Details: [(112, 8), (113, 1), (114, 7), (115, 2)]
--------------------------------------------------------------------------------
```

Figure 4.3 Directional Event Count Report Across MM 109–115, Showing the Increase in Event Visibility Per RSU Before and After Applying the EDDE Step.

The Event List Update step is responsible for this directional allocation. As this task is deterministic and relies solely on positional metadata, it is implemented as a rule-based process and does not require assistance from the AI Decision Engine. The AI model is reserved for tasks requiring broader contextual reasoning; in contrast, the Event List Update operates efficiently through programmable logic.

Figure 4.3 illustrates the increase in the number of events transmitted from each RSU mile marker post in both directions, before and after applying the EDDE step, for a 6-mi segment of I-65. The “Before” column shows that only a small number of events were transmitted from each RSU, meaning that drivers would only become aware of many incidents once they were already nearby. The “Change” column reflects the growth in the number of events handled per RSU—at times, as many as ten additional messages. This expanded coverage provides drivers with earlier visibility into critical events, giving them more time to react safely.

4.3.3 Event Prioritization Agent

As noted previously, rule-based RSU systems determine message order based solely on event distance, displaying nearer events first regardless of their severity or potential impact. Without the EDDE step, this means that high-impact events may be displayed too late—only when the vehicle is already close—leaving drivers with little time to adjust their behavior. With EDDE increasing the number of visible events per RSU, effective prioritization becomes even more critical to prevent message overload and ensure the most urgent alerts are delivered first.

To address this, the EP Agent—like the EDDE Agent—queries the AI Decision Engine. Unlike EDDE, which evaluates events independently, EP processes the entire group of events assigned to a single RSU and requests the AI to rank them in order of relevance.

Once the event list for an RSU post is finalized via the Event List Update step, the EP Agent formulates a query containing all associated events. This query is sent to the AI Decision Engine with an instruction to treat the request as a traffic prioritization task (White et al., 2023). The AI is asked to order the messages from highest to lowest importance, considering factors such as:

- Event type
- Severity or lane impact
- Proximity to the RSU location

Events deemed more urgent or closer to the driver are assigned a lower priority rank number. The expected response format is:

“priority rank X for MM <mile>: <id>; <message>”

To keep input size efficient, the EP Agent sends only essential information—namely, the event ID, event type, and severity level—omitting unnecessary metadata. Once a response is received, the EP Agent reformats the AI output to match the RSU broadcast structure. The final output preserves compatibility with the OBU’s display logic, ensuring a seamless transition from AI output to in-vehicle display.

Figure 4.4 and Figure 4.5 demonstrate the result of this prioritization for RSU posts on I-65 in both northbound and southbound directions. For example, at MM 113 (northbound), the first prioritized message is a TRAFFIC HAZARD with no lane blockage—chosen for its proximity. However, the next two events, which are located outside the standard 1-mi range, are elevated in priority due to their high severity and full-lane impact. Without such prioritization, these critical alerts might appear later in the message cycle, potentially reducing driver response time. The AI prioritization enables safer, more informed routing decisions—for example, by giving the driver time to consider exiting the interstate if downstream blockages are detected in time.

```
Mile Marker 113
BEFORE PRIORITIZATION                                          || AFTER PRIORITIZATION
----------------------------------------------------------------------------------------------------------------------------
[P1] 310519 | MAINTENANCE | I-65 N Mile Marker 113.6 | No lanes blocke || [P3] 312258_N | TRAFFIC HAZARD | I-65 N Mile Marker 113.1 | No lanes b
[P3] 312255_N | TRAFFIC HAZARD | I-65 N Mile Marker 113.4 | No lanes b || [P4] 310693 | CONSTRUCTION | I-65 N Mile Marker 114.2 | All lanes bloc
[P5] 312258_N | TRAFFIC HAZARD | I-65 N Mile Marker 113.1 | No lanes b || [P4] 310723 | MAINTENANCE | I-65 N Mile Marker 115.2 | All lanes block

Mile Marker 114
BEFORE PRIORITIZATION                                          || AFTER PRIORITIZATION
----------------------------------------------------------------------------------------------------------------------------
[P4] 310693 | CONSTRUCTION | I-65 N Mile Marker 114.2 | All lanes bloc || [P1] 310693 | CONSTRUCTION | I-65 N Mile Marker 114.2 | All lanes bloc
                                                                       || [P3] 310640 | STALLED VEHICLE | I-65 N Mile Marker 116.6 | All lanes b
                                                                       || [P4] 310723 | MAINTENANCE | I-65 N Mile Marker 115.2 | All lanes block
```

Figure 4.4 Prioritization Example (Northbound I-65), Illustrating How the EP Agent Reorders MAINTENANCE, TRAFFIC HAZARD, and CONSTRUCTION Events Based on Their Urgency and Type.

```
Mile Marker 113
BEFORE PRIORITIZATION                                          || AFTER PRIORITIZATION
----------------------------------------------------------------------------------------------------------------------------
[P3] 311628_S | MEDICAL EMERGENCY | I-65 S Mile Marker 112.5 | No lane || [P1] 311890_S | CRASH PD | I-65 S Mile Marker 113.0 | 1 lane blocked
[P3] 311746_S | TRAFFIC HAZARD | I-65 S Mile Marker 112.8 | 1 lane blo || [P2] 311746_S | TRAFFIC HAZARD | I-65 S Mile Marker 112.8 | 1 lane blo
[P3] 311890_S | CRASH PD | I-65 S Mile Marker 113.0 | 1 lane blocked   || [P4] 311628_S | MEDICAL EMERGENCY | I-65 S Mile Marker 112.5 | No lane

Mile Marker 114
BEFORE PRIORITIZATION                                          || AFTER PRIORITIZATION
----------------------------------------------------------------------------------------------------------------------------
[P3] 312259_S | STALLED VEHICLE | I-65 S Mile Marker 113.1 | 1 lane bl || [P2] 312259_S | STALLED VEHICLE | I-65 S Mile Marker 113.1 | 1 lane bl
                                                                       || [P3] 311746_S | TRAFFIC HAZARD | I-65 S Mile Marker 112.8 | 1 lane blo
                                                                       || [P3] 311890_S | CRASH PD | I-65 S Mile Marker 113.0 | 1 lane blocked
```

Figure 4.5 Example of Prioritized Message Output Before and After Applying the Event Prioritization Agent at MM 113 and 114 (Southbound I-65). Messages Are Re-Ranked Based on Severity and Proximity.

4.4 Practical Performance Testing

To evaluate system performance, we deployed the pilot version of the AI pipeline within a virtual RSU environment to test its integration with the existing RampCast architecture. The demonstration simulates an OBU-equipped vehicle traveling northbound on I-65, with test outputs visualized for the stretch between MM 113 and 115.

To distinguish messages generated by the AI framework, the prefix "AI_" was used for all outputs produced by the EDDE and EP agents. The figures accompanying this section reflect the same prioritized message sequence shown earlier in the EP Agent example. In the visualization, red map pins denote the current location of the vehicle, while orange or yellow dots represent event locations.

The display sequence observed in the demonstration aligns with the priority ordering assigned by the AI Decision Engine. For instance, in addition to the top three prioritized messages displayed at RSU MM 113, the test also includes a TRAFFIC HAZARD event located at MM 113.4. Although this event does not involve lane blockage, it was still elevated in the display queue due to its close proximity to the driver's position.

Without AI-based prioritization, this proximity-based event would likely have been displayed second—immediately after the event at MM 113.1. However, with prioritization enabled, higher-severity events located farther ahead are surfaced first, improving the relevance and safety of the message sequence. This confirms the framework's ability to dynamically adjust messaging logic based on both severity and spatial context. In the example shown in Figure 4.6, the display order begins with a TRAFFIC HAZARD at MM 113.1, followed by a CONSTRUCTION event at MM 114.2 and a MAINTENANCE event at MM 115.2, before finally showing a TRAFFIC HAZARD at MM 113.4. Although the MM 113.4 event occurs earlier along the route, it is shown last because its impact is lower than the other events, all of which involve full-lane blockages. This demonstrates how severity can override proximity in the prioritization process.

A second example highlights how event priority can change between RSU posts as new events are introduced. At MM 113, the RSU prioritized a MAINTENANCE event at MM 115.2 immediately after a CONSTRUCTION event at MM 114.2. However, the RSU at MM 114 incorporated a newly visible event—a STALLED VEHICLE at MM 116.6—between those two entries.

Although the stalled vehicle is located farther ahead than the maintenance activity and has a similar impact, it received a higher priority ranking. This is because stalled vehicles represent unplanned disruptions, unlike maintenance work, which is typically scheduled with traffic mitigation measures in place. The AI Decision Engine was able to factor in this contextual distinction, recognizing the unusual and potentially more disruptive nature of the stalled vehicle event and adjusting the display sequence accordingly.

This outcome demonstrates the system's ability to adapt prioritization logic dynamically, accounting not only for event severity and distance but also for the nature and expected variability of different event types (see Figure 4.7 for dynamic reordering across RSU locations).

Figure 4.6 Prioritized Message Sequence for Four Events, Illustrating How Severity Can Take Precedence Over Proximity When Determining Display Order.

5. RAMPCAST SYSTEM TESTING

Field testing of the RampCast II system was conducted to evaluate the performance of the C-V2X communication links in various environments. The primary goal was to test the C-V2X PC5 system and compare its performance against the C-V2X Uu link to understand the strengths and weaknesses of each pathway. Testing progressed from controlled, static environments to dynamic, real-world highway conditions.

5.1 Testing Methodology

The performance of the communication links was evaluated using two primary Key Performance Indicators (KPIs):

- **Packet Delivery Ratio (PDR):** This metric is the ratio of successfully received messages at the OBU to the total number of messages transmitted by the RSU. It measures the reliability of the link. The PDR visualizations in the test results is represented by dividing the test routes into 5-m segments and calculating the PDR within each segment to provide a holistic view of the performance through the entire route. The segments in black indicate a PDR of zero and the segments in color gradients from yellow to purple indicate increasing PDR brackets from 0 to 100.
- **Latency:** This is the one-way time difference between the RSU transmitting a message and the OBU receiving it. It measures the timeliness of the message delivery.

Additionally, to better understand the effects of prioritization of messages, a message transmission visualization was created. Here the RSU location was marked, with lines indicating the transmission path to the points where messages were successfully received by the OBU (green dots). Blue dots indicate the location where the message was ultimately displayed to the driver on the GUI. This visualization highlights the delay and distance traveled

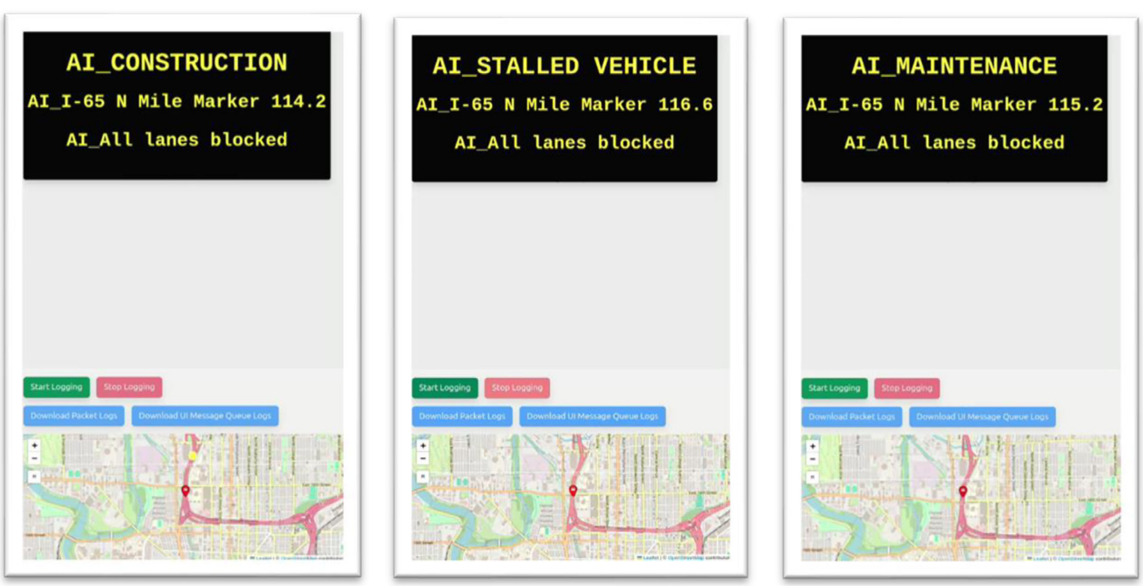

Figure 4.7 Dynamic Reordering of Events Between RSU Posts, Showing a Stalled Vehicle Elevated in Priority Over Planned Maintenance Despite Greater Distance.

Figure 5.1 OBU Installation.

Figure 5.2 RSU Installation.

between when a message is received and when it is presented, a factor influenced by vehicle speed and message queueing logic.

The test setup consisted of a test vehicle equipped with the OBU hardware and a stationary RSU. The OBU hardware was placed on the roof of the test vehicle, towards the front left side (Figure 5.1). The RSU was mounted on a 12-ft tripod to provide elevation for its antenna (Figure 5.2). For dynamic tests, the RSU was placed in a fixed location, and the OBU-equipped vehicle was driven along planned routes. These routes were selected to include varying traffic conditions, from busy roads to areas with light or no traffic, to observe the effects of a real-world environment on message transmission.

5.2 Preliminary Testing

The objective of this phase was to test the complete end-to-end system and verify all functionalities. Initial static tests were performed in a controlled environment (a parking lot) to establish baseline performance metrics for the PC5 interface. In this setup, a stationary OBU was positioned at various distances from the RSU, ranging from 200 to 800 m, with clear line-of-sight. The results showed a predictable performance degradation as distance increased (Table 5.1). The PDR was 98% at 200 m and dropped to 70% at 800 m. Latency remained low and stable across these distances, averaging between 16 ms and 28 ms.

TABLE 5.1
Preliminary Testing Summary.

Type of Test	Test Name	Variables	Runs	Location	Latency	Packet Delivery Rate	C-V2X Mode
Static	200M	10 Hz	5	Parking Lot	Avg: 16.19 ms Median: 16.25 ms	98.20%	PC5
Static	450M	5 Hz, Busy Traffic	5	Parking Lot	Avg: 24.09 ms Median: 24.69 ms	14.12%	PC5
		10 Hz, Busy Traffic	5	Parking Lot	Avg: 26.91 ms Median: 23.32 ms	30%	PC5
Static	800M	2 Hz	5	Parking Lot	Avg: 22.84 ms Median: 22.68 ms	80%	PC5
		10 Hz	5	Parking Lot	Avg: 28.12 ms Median: 24.30 ms	69.8%	PC5
		10 Hz, Busy Traffic	1	Parking Lot	Avg: 28.12 ms Median: 24.30 ms	3%	PC5
Dynamic	800M (straight line)	10 Hz, Busy Traffic	1	Street	Avg: 20.66 ms Median: 19.24 ms	53.30%	PC5
Dynamic	1KM Route. (0–450M)	10 Hz, Busy Traffic, LoS variation	1	Street	Avg: 19.88 ms Median: 20.09 ms	83%	PC5
Dynamic	1.25KM Loop (20–350M)	10 Hz, Busy Traffic, LoS variation	3	Street	Avg: 17.88 ms Median: 17.45 ms	49.50%	PC5

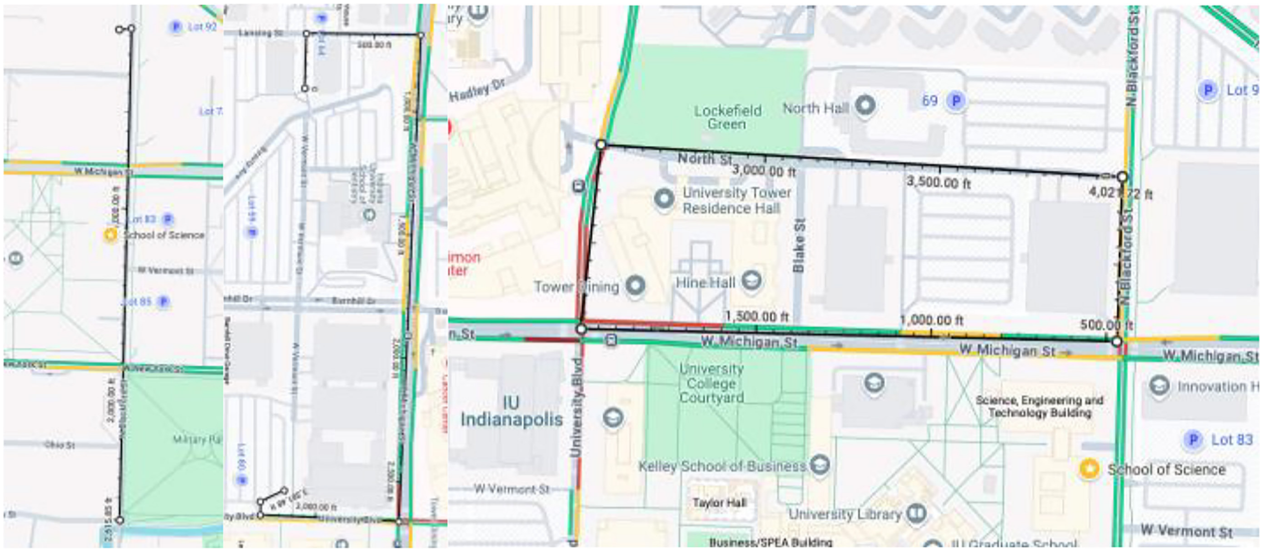

Figure 5.3 Testing Routes Selected on Campus. Map Data: ©2025 Google.

To evaluate the system in a more realistic environment, dynamic tests were then conducted on a 1250-m road loop near campus (Figure 5.3). This route featured a mixture of buildings and open areas, creating both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions. The RSU was placed in a central location, and the OBU-equipped vehicle drove the loop multiple times. In these tests, the PC5 interface continued to exhibit low and stable latency, averaging around 25 ms. However, the PDR was significantly affected by environmental factors. In NLoS conditions caused by buildings, the PDR dropped noticeably compared to the static tests. The Uu interface, tested along the same route, demonstrated a higher average latency of around 45 ms but maintained a consistent 100% PDR due to the robustness of the cellular network.

Figure 5.4 RSU Location.

5.3 Interstate Ramp Testing on I-65

This location presents a complex urban environment with significant infrastructure, including overpasses, and the potential for radio frequency interference. For this test, the RSU was positioned on its tripod near the I-65 ramps at West Street (Figure 5.4). The test vehicle was driven in a loop that covered both the entry and exit ramps for I-65 North (Figure 5.5).

The results for the PC5 link showed that when a connection was established, the latency was consistently low, typically observed within a range of 10–30 ms. However, coverage was not continuous throughout the entire route. Postprocessing analysis, visualized in Figure 5.6 and Figure 5.7, broke the driving path into 5-m segments to calculate performance. This revealed areas with a PDR of 0%, particularly on sections of the loop furthest from the RSU and where line-of-sight was obstructed by buildings or the highway overpass structure itself. For example, on one segment of the ramp, the PDR was measured at 66.7% with an average latency of 15.6 ms while the vehicle was traveling at 47.4 mph.

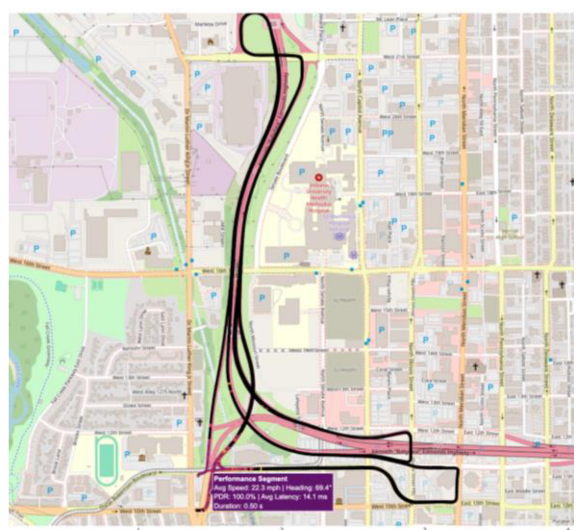

Figure 5.5 I-65 Ramp Test Driving Route.

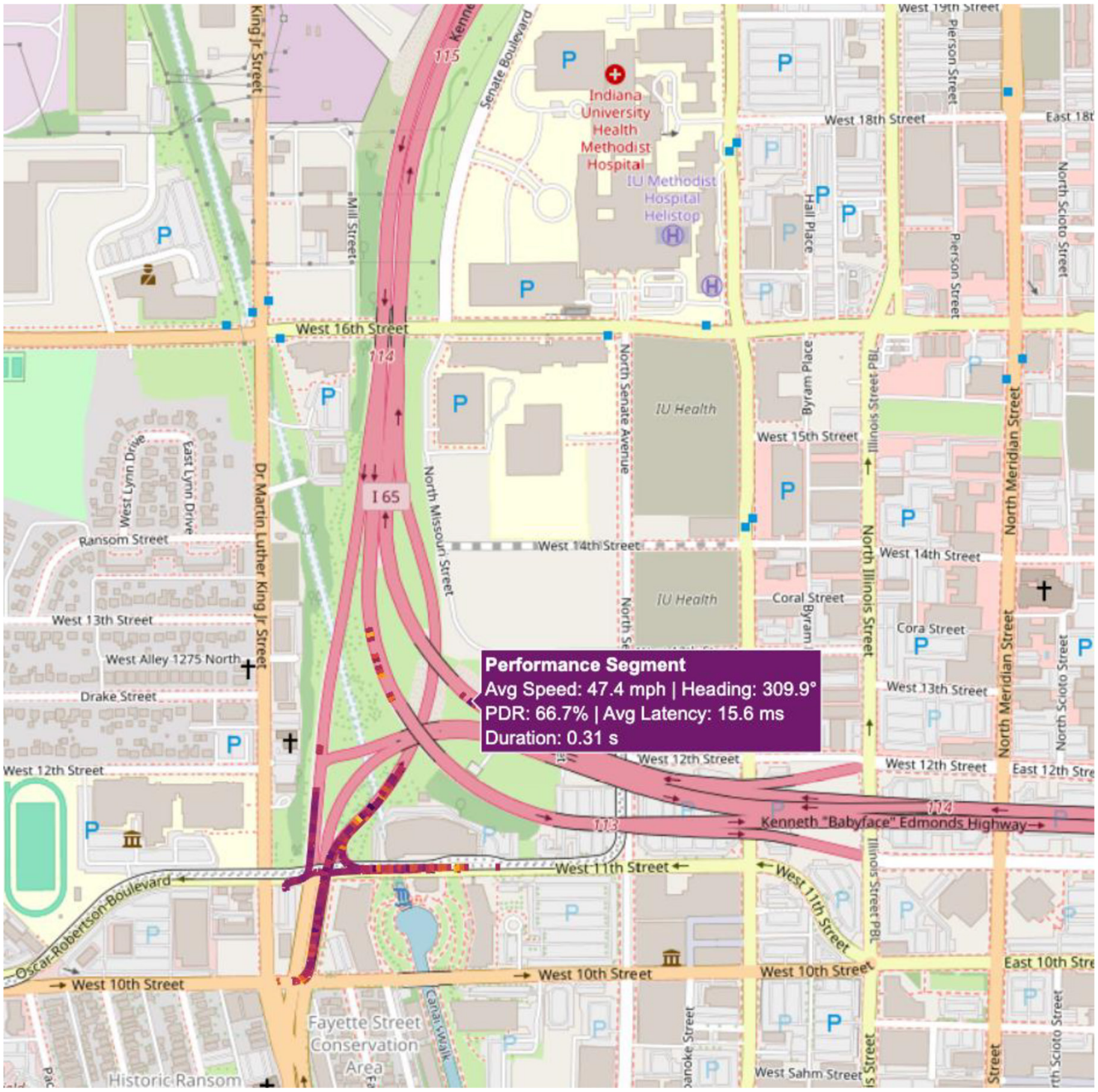

Figure 5.6 PDR Performance Segments Visualizing the Locations of Message Reception Near the I-65 North Ramp Via PC5 Interface. PDR Increases as the Gradient of Colored Segment Becomes Lighter.

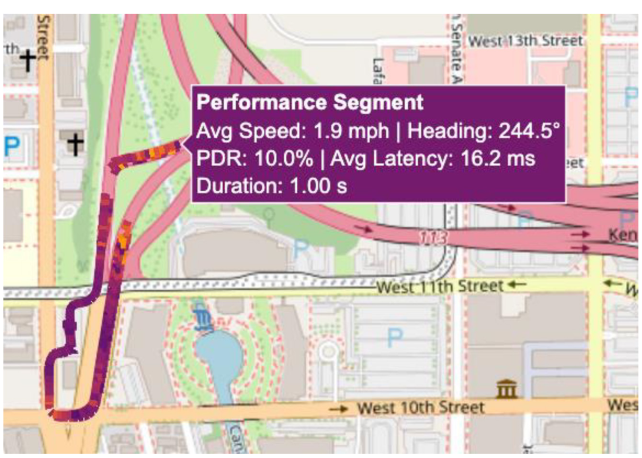

Figure 5.7 PDR performance Segments Visualizing the Locations of Message Reception Near the I-65 South Ramp Via PC5 Interface.

Further analysis, shown in Figure 5.8, Figure 5.9, and Figure 5.10, visualizes the entire message lifecycle, from message transmission on RSU until the display of the message on OBU side. The Uu link, tested simultaneously, provided 100% coverage (Figure 5.8) along the entire route, validating its role in filling the gaps left by the short-range PC5 link.

5.4 Interstate Ramp Testing on I-70

This test site, located near the Interstate 70 (I-70) and West Street interchange, featured a long driving route that included multiple ramps and surface streets, as shown in Figure 5.11 and Figure 5.12. The environment included significant line-of-sight obstructions from an interstate overpass and dense foliage.

The PC5 link performance was again characterized by very low latency. A median latency between 18 ms and 21 ms, with

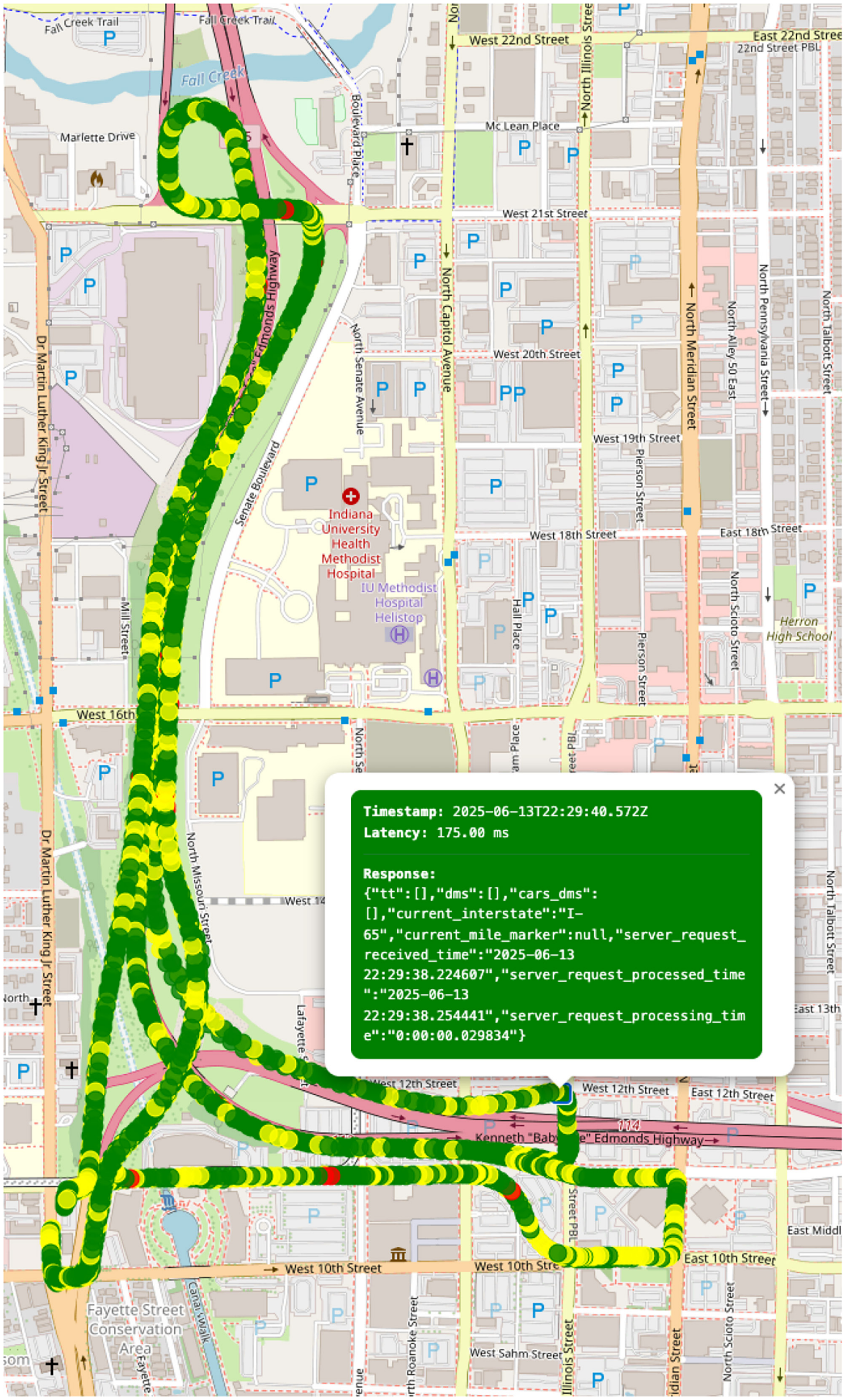

Figure 5.8 Visualizing the Latency on the Locations of Message Reception Via the Uu Interface. The Latency Increase as the Color Gradient Shifts From Red to Green.

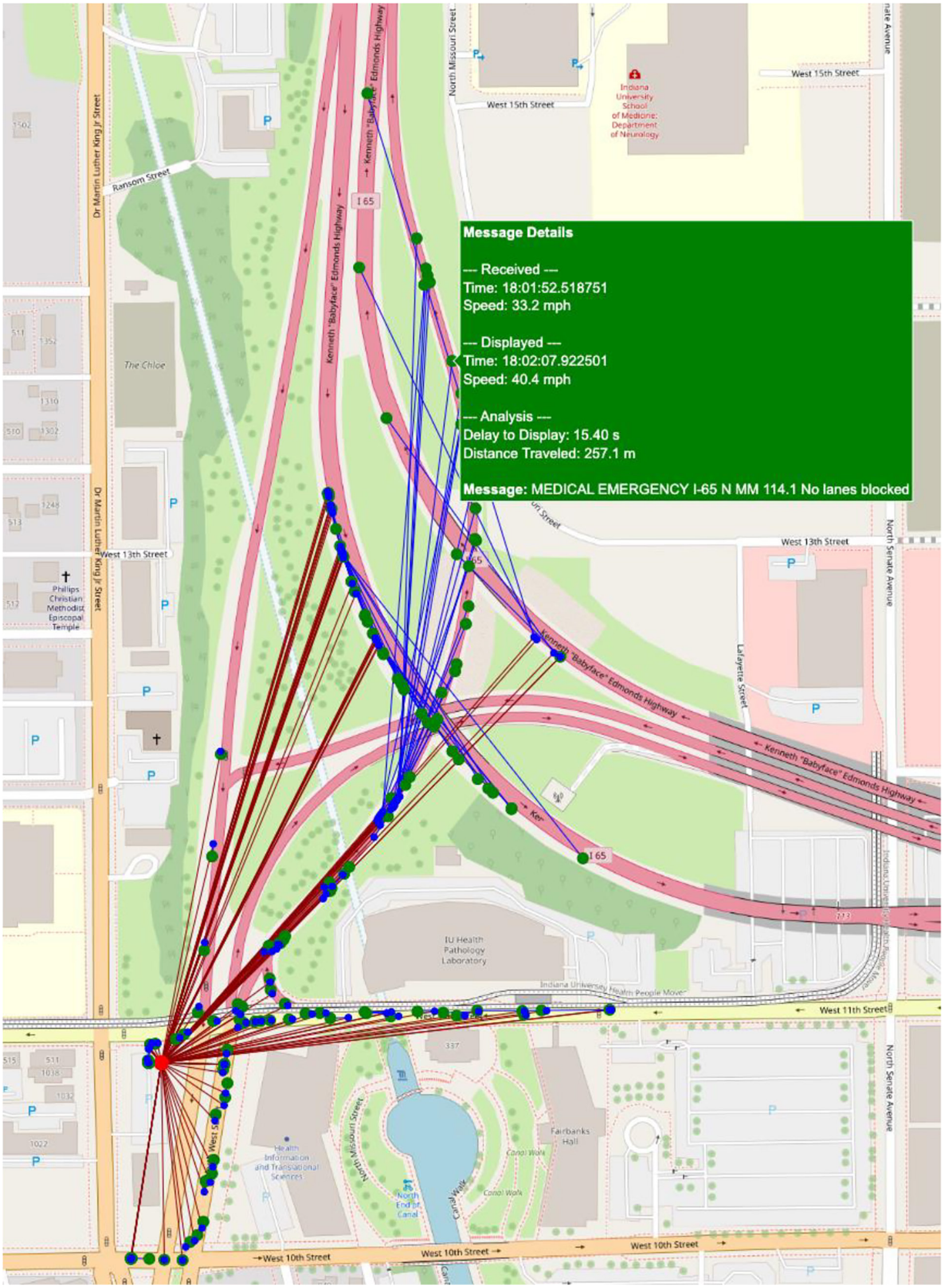

Figure 5.9 Visualization of Message Transmission, Reception, and Display on the I-65 North Ramp. The Red Lines Show the Message Path From the RSU to the Vehicle, While the Blue Lines Show the Distance the Vehicle Traveled Before the Alert Was Displayed on the GUI.

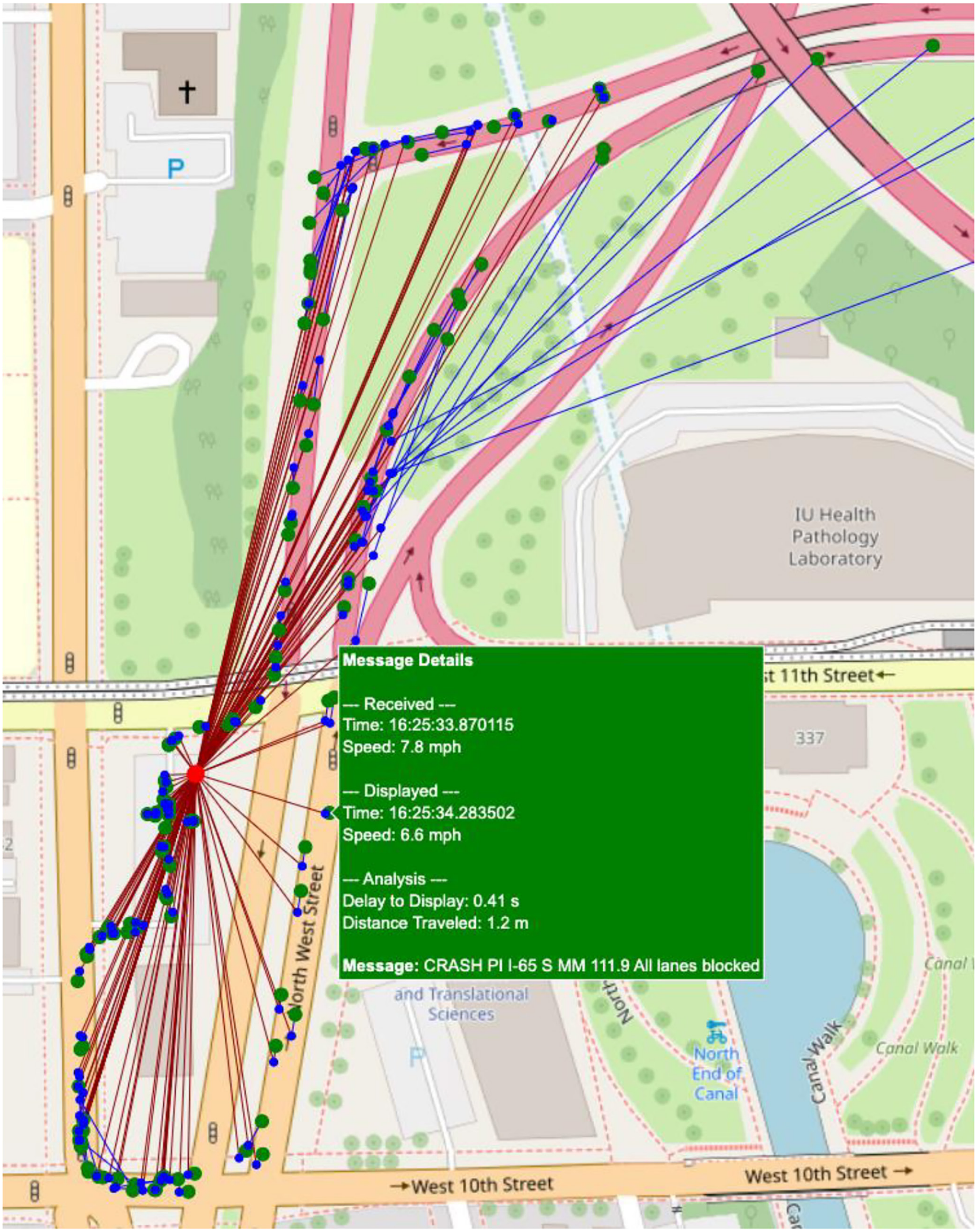

Figure 5.10 Visualization of Message Transmission, Reception, and Display on the I-65 South Ramp.

Figure 5.11 RSU Placement for I-70 Ramp Testing.

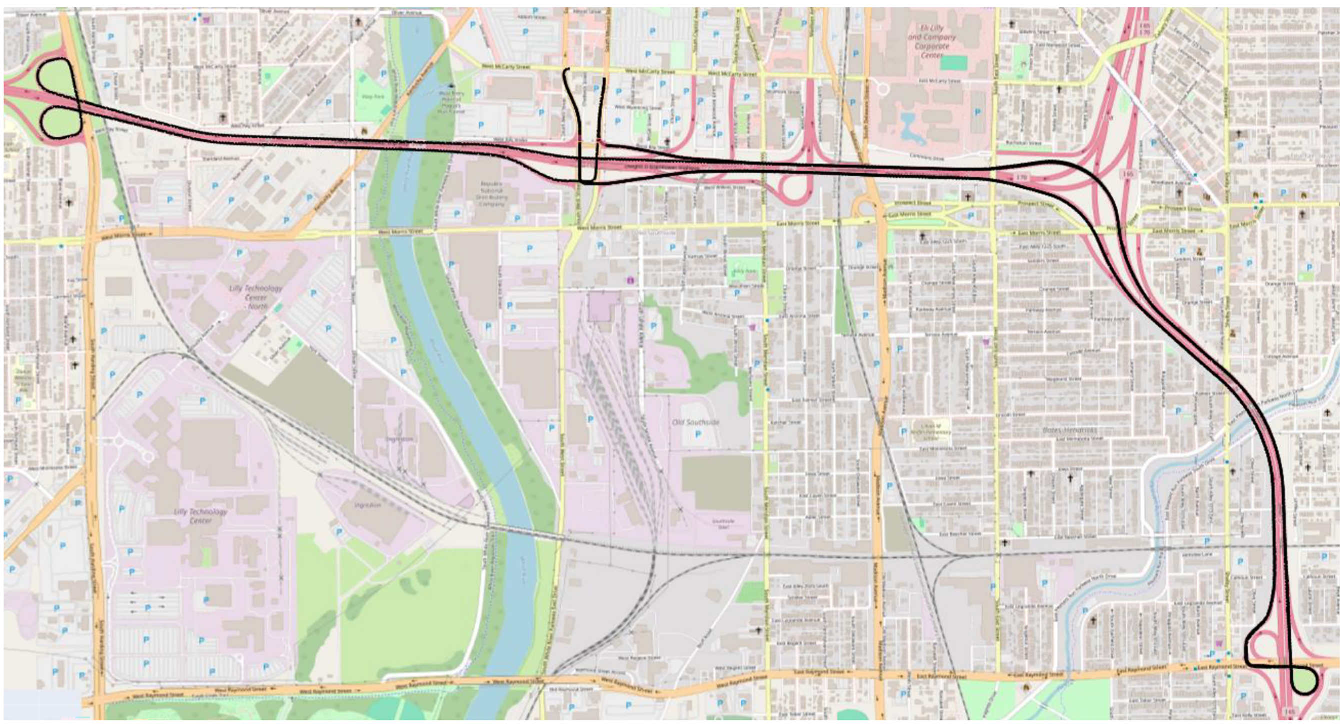

Figure 5.12 I-70 Ramp Test Driving Route.

average latencies consistently around 20 ms was observed. However, the PDR was heavily impacted by the environment (Figure 5.13 and Figure 5.14). As shown in the performance segment map (Figure 5.13), message reception was intermittent, particularly when the vehicle was directly under or occluded by the I-70 overpass. This confirms that physical obstructions are a primary limiting factor for PC5 reliability. In contrast, the cellular Uu link (Figure 5.15) provided consistent message delivery throughout the entire route, reinforcing its advantage for coverage in complex terrain.

5.5 Short-Range and Long-Range C-V2X Comparison

The comprehensive testing revealed a trade-off between the C-V2X PC5 and Uu communication interfaces.

- The **PC5 interface** provides deterministic, low-latency communication (around 25 ms), which is ideal for time-critical safety applications. However, its reliability (PDR) is susceptible to range and environmental obstructions, particularly in NLoS conditions.
- The **Uu interface** provides highly reliable, wide-area connectivity, achieving a near-perfect PDR even during high-speed travel.

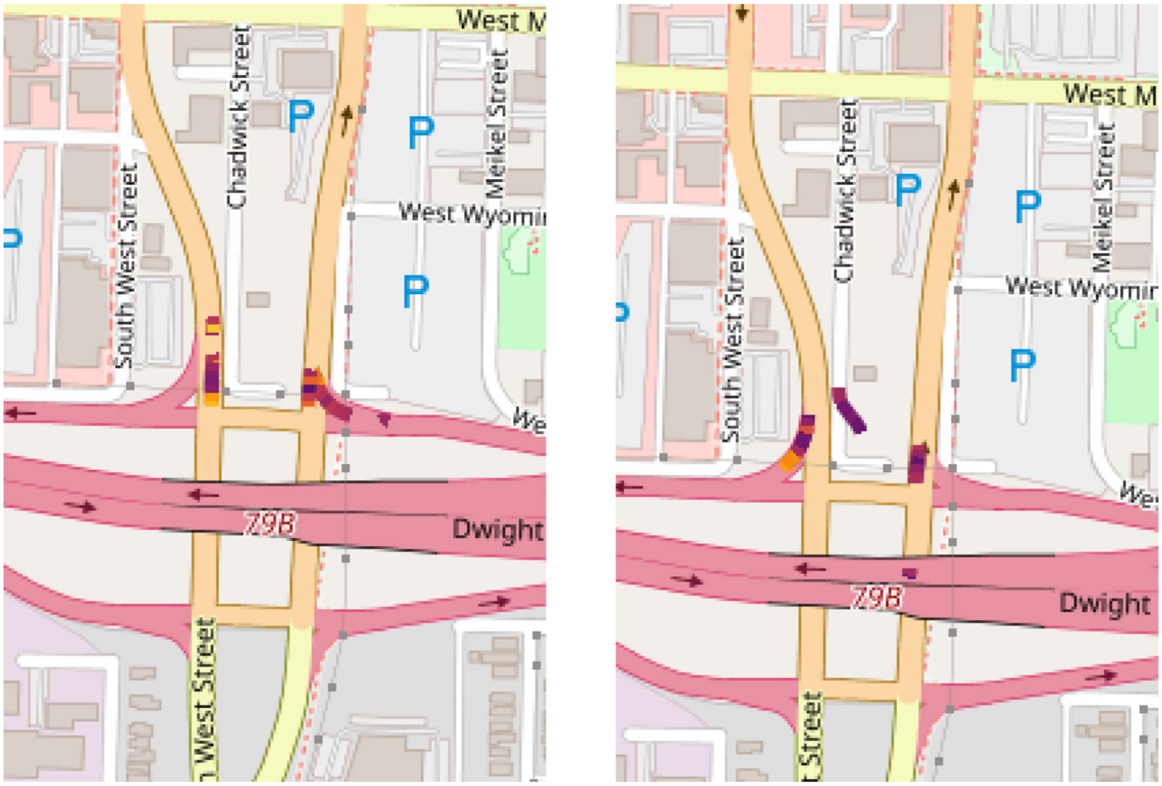

Figure 5.13 PDR Performance Segments Visualizing the Locations of Message Reception Near I-70 Eastbound (Left) and Westbound (Right) Ramps Via PC5 Interface.

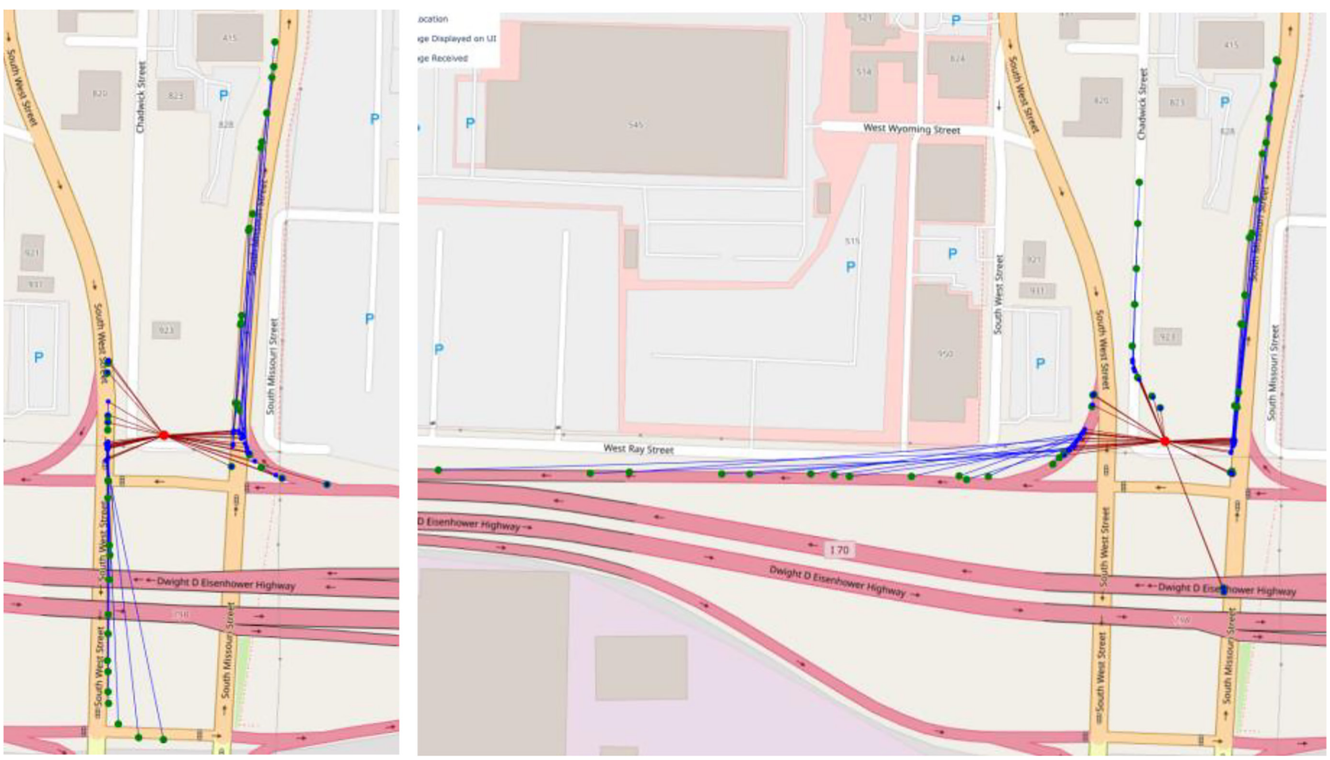

Figure 5.14 Visualization of Message Transmission, Reception, and Display on the I-70 Eastbound (Left) and Westbound (Right) Ramps.

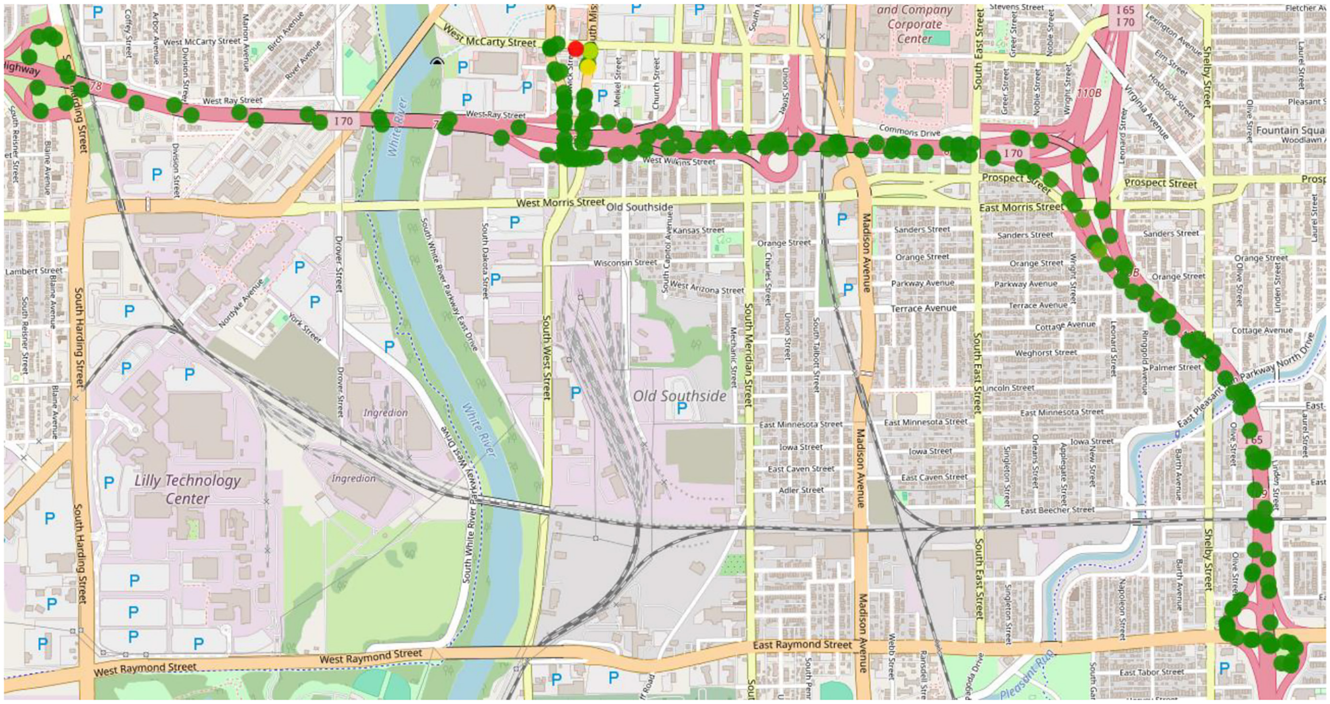

Figure 5.15 Latency Visualization of Locations With Message Reception on I-70 E and I-70 W Ramps Via the Uu Interface.

This reliability comes at the cost of higher and more variable latency (around 45 ms).

Despite their differences, both interfaces consistently delivered messages with latencies well below the 100-ms threshold often cited as the upper limit for transportation safety applications under 3rd Generation Partnership Project (3GPP) standards. These findings emphasize that neither interface is a standalone solution. Instead, their complementary features support the development of a hybrid system architecture, which can utilize the strengths of each mode to ensure reliable and timely message delivery across various operating environments.

6. CONCLUSION AND FUTURE WORK

The phase II of RampCast addressed the need to implement advanced traffic management solution using commercial C-V2X equipment and the latest 3GPP standards. This was achieved by implementing a flexible, dual-pathway architecture that supports both dedicated C-V2X hardware via the low-latency PC5 link and cellular-based devices via the reliable Uu link. A key component of the implementation was the adherence to SAE J2735/J2945 standards, ensuring all traffic messages are interoperable. The system's software framework features distinct processing logic for its physical and virtual RSUs, effectively managing traffic message translation and geofencing. Advanced AI based prioritization approaches were designed and implemented for the RSU and OBU systems. Extensive field testing, from controlled environments to interstate ramps, specifically the I-65 and I-70 ramps on West Street in Indianapolis, validated the system's design. The findings confirmed the expected trade-offs: the PC5 link provides stable low-latency performance ideal for immediate traffic alerts but can be affected by line-of-sight obstructions The Uu link can guarantee message delivery over a wider area at the cost of higher latency. Both modes can be integrated in a hybrid for deployments in traffic scenarios.

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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 docs.lib.purdue.edu/jtrp/.

Further information about JTRP and its current research program is available at engineering.purdue.edu/JTRP.

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