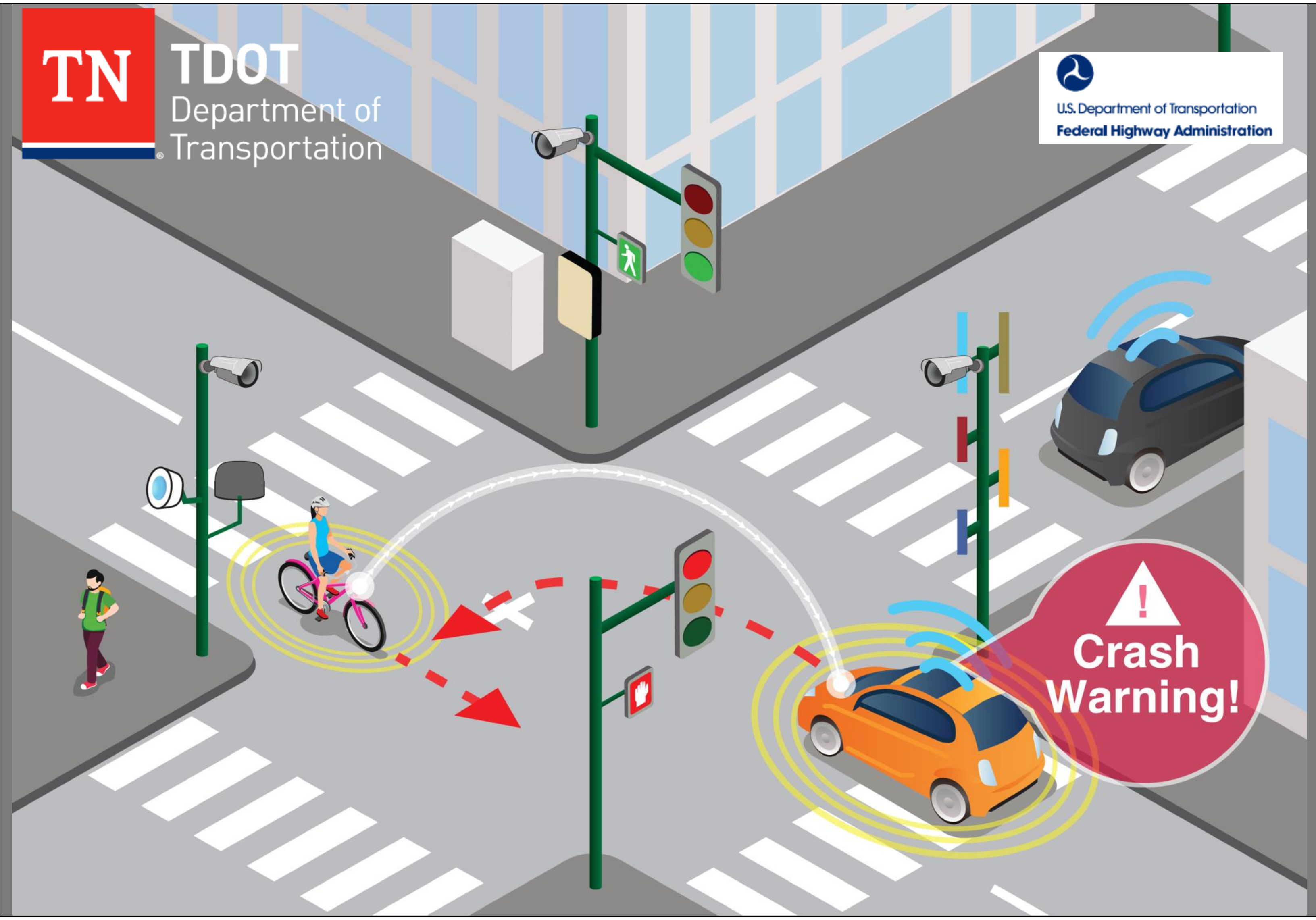

Feasibility of Real-Time Infrastructure-Driven Intervention for Improving Pedestrian Safety

Research Final Report from The University of Tennessee at Chattanooga | Dr. Mina Sartipi| September 30, 2023

Sponsored by Tennessee Department of Transportation Long Range Planning
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THE UNIVERSITY OF TENNESSEE CHATTANOOGA

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16. Abstract

The long-term objective of our research is to improve VRU safety in all neighborhoods in an inclusive and equitable way. For this project, we leverage the existing infrastructure in Chattanooga, TN (MLK Smart Corridor) to explore various wireless communication technologies for generating critical traffic notifications for both connected and nonconnected VRUs and vehicles in real time. More specifically, we implemented Software-Defined Radio (SDR)-based technologies on UTC campus and then evaluated them at two intersections within the Chattanooga Smart City testbed, Houston and Douglas. We employed two laptops and two SDRs to transmit and receive the signals. The receiver assumes the role of a pedestrian traversing the intersection with a laptop, SDR and an external GPS. Data collection is conducted for both LTE and BLE at each intersection. Our experiments and analysis effectively characterize the latency and reliability profiles of LTE and BLE in an urban environment through hexagonal binning visualizations and quantitative performance metrics. This furnishes critical insights into the real-world capabilities of these salient IoT protocols.

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4. Executive Summary

Key Findings

- The performance of the communication system is heavily impacted by several factors such as wireless communication technologies, modulation type, bandwidth, antennas, local environment (topography, vegetation, weather, temperature, humidity, etc.), environmental electromagnetic noise, transmission power and receiver sensitivity and others.

- The literature review discusses the challenges of transportation in urban areas and the need for Intelligent Transportation Systems (ITS) to enhance safety. It focuses on Vehicle-to-Pedestrian (V2P) communication, which involves the exchange of information between vehicles and pedestrians. The review also highlights the different categories of Vulnerable Road Users (VRUs) and their unique characteristics and challenges. Various devices, such as smartphones, connected helmets, and wearable devices, are mentioned as tools for VRUs to enhance their safety through communication with other road users. The review also discusses the importance of wireless technology in facilitating communication in ITS and the role of Cooperative Intelligent Transport System communication (ITS-C) in improving road safety. The choice between direct and indirect communication architectures for V2P systems is explored, along with the role of wireless technology in enabling real-time information exchange. The review also mentions the allocation of bandwidth for vehicular communication and the use of Cellular Vehicle-to-Everything C-V2X technology in autonomous driving and intelligent transportation systems. Overall, the review emphasizes the importance of V2P communication systems in enhancing road safety and the potential benefits of implementing these systems.

- We delve into the performance assessment of key wireless technologies, including LTE, and Bluetooth Low Energy (BLE) with a particular focus on gathering performance statistics and evaluating their applicability in ensuring safety and mitigating collision avoidance in Vehicle-to-Pedestrian (V2P) communications. To achieve our objectives, we have developed a cost-effective Software-Defined Radio (SDR) based testbed. Our primary emphasis lies in assessing the quality of service (QoS) and robustness of such a system to determine its suitability for supporting road safety applications and enhancing cooperative awareness in smart cities.

- The report discusses the importance of examining intersection safety and conducting studies on V2X and communication technologies for VRU safety. The focus is on analyzing LTE and BLE wireless technologies at intersections in the Chattanooga Smart City testbed. LTE C-V2X is found to have superior reliability compared to BLE, with lower latency and higher packet delivery ratio. The height of the eNodeB and placement of the Universal Software Radio Peripheral (USRP) at the intersections impact performance, highlighting the importance of antenna elevation for better connectivity. The experiments provide insights for optimal base station placement to enhance C-V2X performance and the efficacy of hexagonal binning in representing spatial disparities in LTE/BLE performance.

Key Recommendations

- Utilizing Software-Defined Radio (SDR) offers a streamlined approach to wireless technology evaluation, enabling cost-effective performance assessment of LTE, and BLE transceivers. SDR's software-based parameters simplify implementation, facilitating rapid prototyping and experimentation in real-world scenarios, ultimately enhancing V2P communications and smart city safety.

- For future work, we recommend focusing solely on C-V2X and evaluating both LTE and 5G cellular-based implementations as well as PC5-based direct communication in real-world environments across diverse geographical areas, weather conditions, and obstacle densities.

- We recommend developing a C-V2X enabled VRU collision alert system that leverages bidirectional communication between pedestrian user devices and interconnected roadside infrastructure to deliver real-time hazard warnings and improve situational awareness. This system would integrate proactive hazard detection via vehicle connectivity with reactive localized warnings based on roadside sensors to provide comprehensive protection for pedestrians and cyclists at high-risk intersections.
- Another recommendation is to develop applications for both VRUs and vehicles to enable bidirectional communication and information exchange through C-V2X connectivity. The VRU application would provide collision warnings and situational awareness insights to pedestrians and cyclists by leveraging data from nearby connected vehicles and infrastructure. Conversely, a vehicle application could receive VRU location alerts to boost driver awareness and safety. Rigorous real-world testing across various environments and user cases will be imperative to validate performance and optimize these connected applications to maximize transportation safety improvements.
- We recommend that TDOT further research delivering warning messages to VRUs via personal devices like smartphones, tags, and helmets. Field studies should evaluate real-world behavior after receiving alerts, compare device effectiveness, study optimal warning modalities and frequency, and examine technical connectivity challenges.

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7. Glossary of Key Terms and Acronyms

VRU– Vulnerable Road Users
UTC– University of Tennessee at Chattanooga
BLE - Bluetooth Low Energy
3GPP- Third Generation Partnership Project
BSM – Basic Safety Message
CSMA-CD - Carrier Sense Multiple Access with Collision Detection
CV – Connected Vehicle
C-V2X - Cellular Vehicle-to-Everything
DSRC - Dedicated Short-Range Communication
SDR - Software-Defined Radio
FCC – Federal Communication Commission
I2V- infrastructure to vehicle
IEEE - Institute of Electrical and Electronics Engineers
IPU - Information Processing Units
ITS - Intelligent Transportation System
ITS-C - Intelligent Transportation System Communication
LED - Light-Emitting Diode
LTE – Long-Term Evolution
NLOS - Non-Line-of-Sight
OBU – On Board Unit
OTA - Over-The-Air
PER - Packet Error Rate
PDR - Packet Delivery Rate
PVMS - Portable Variable Message Signs
RDS - Radar Detection System
RSU – Roadside Unit
SPaT - Signal Phasing and Timing
V2I - Vehicle to Intersection
V2N - Vehicle to Network
V2P - Vehicle to Pedestrian
V2V - Vehicle to Vehicle
V2X - Vehicle to Everything
WAVE - Wireless Access in Vehicular Environments
NTIA- National Telecommunications and Information Administration
USRP- Universal Software Radio Peripheral

Chapter 1 Introduction

1.1 Problem Description

With the rapid advancement of intelligent transportation systems (ITS) and communication technologies, there is a growing focus on creating an infrastructure-driven, human-involved system to facilitate seamless and cooperative driving experiences for hybrid road users. For instance, pedestrians, who are among the most VRUs, currently receive only passive protection due to the lack of real-time interaction between existing onboard and infrastructure-based sensing systems and non-connected road users. Despite the presence of reliable sensing technology and robust computational capabilities, effectively integrating, managing, securing, and disseminating critical traffic information to all road users, particularly those not connected to the network, remains a pressing challenge. Thanks to advanced traffic detection sensors and cutting-edge processing algorithms, this valuable information encompasses various aspects such as road conditions (e.g., closures, obstacles, construction), weather conditions (e.g., environmental factors, severe weather), traffic warnings (e.g., pedestrians crossing incorrectly, distracted driving), and traffic alerts (e.g., near misses, wrong-way driving, regional emergencies). While this information is readily available at the infrastructure or operational level in real-time, a clear means, platform, or interface for integrating and swiftly sharing this information with minimal delay among all road users is currently lacking. In essence, pedestrian safety can be significantly enhanced through proactive measures taken by pedestrians and vehicles alike, and the initial step towards achieving this is by providing pedestrians and drivers with real-time traffic information to enhance pedestrian safety and mitigate the risk of potential accidents. As an example, Figure 1.1 shows a scenario where the vehicle will have a conflict with the cyclist based on the infrastructure's observation of location and speed of all objects as well as their predicted trajectory. The goal of this project is exploring the best practices to communicate this warning to all road users. Wireless communication technologies (LTE and Bluetooth) were tested to measure latency and reliability of these technologies. Furthermore, an extensive literature review was conducted to understand the existing VRU devices that can be used to ensure the warning message is communicated without distracting road users.

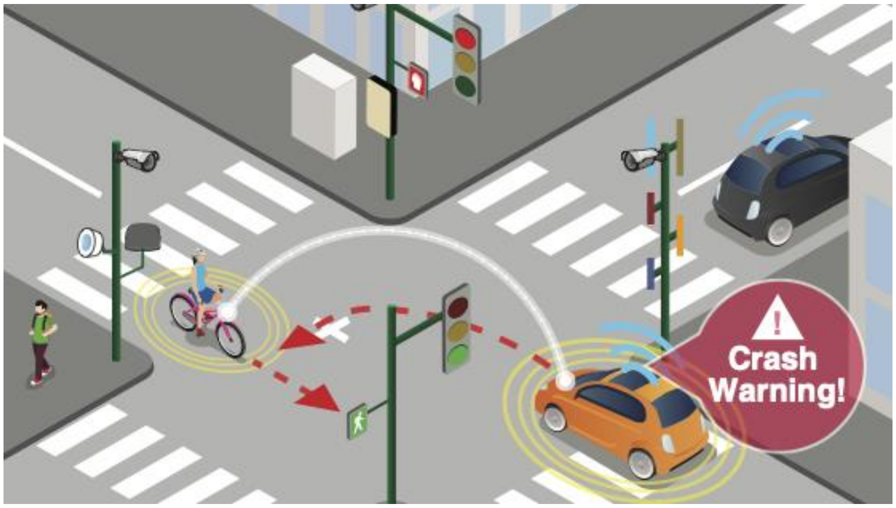

Figure 1.1: A Potential Conflict Being Observed by the Infrastructure

1.2 Purpose of the Work

For this project, we leverage the existing infrastructure in Chattanooga, TN (MLK Smart Corridor) and generate critical traffic notifications using our existing computer vision and risk assessment models to improve VRU safety in all neighborhoods in an inclusive and equitable way. This project focuses on communicating that traffic alert back to VRUs in almost real-time. The following tasks were completed in this project:

- Performed a comprehensive literature survey on the existing work on communicating information to non-connected road users.
- Explored communication options for non-connected vehicles and VRUs.
- Determined the use-case-specific feasibility based on communications delay/latency to VRUs.
- Demonstrated several use-case on the MLK Smart Corridor.
- Included equity and inclusion as an important factor in the design of the solution and ensure the potential solutions can be utilized by underserved communities.

1.3 Approach

> - ***Task 1:*** *A set of scenarios is developed based on connected infrastructure use-cases for VRU safety.*
> - ***Task 2:*** *Each scenario is performed for each communication method on the MLK Smart Corridor.*
> - ***Task 3:*** *Data is collected and then analyzed based on the performance metrics and use-case requirements. While this study is limited and more data collection and analysis are needed, we have summarized our findings that show the feasibility of different wireless communication technologies for real-time communication.*

Currently, the primary emphasis in VRU safety applications is on alerting the driver and relies heavily on the vehicle's environmental perception. This approach, however, leaves VRUs at risk and disconnected. By integrating VRUs through connected devices, overall situational awareness can be enhanced for all individuals using the road. Nevertheless, challenges persist for non-connected VRUs. Hence, it is imperative to establish a uniform and inclusive mechanism for detecting and disseminating safety-related information to all road users. A solution rooted in infrastructure is essential to ensure continuous pedestrian safety for both connected and non-connected road users. In this project, our focal point revolves around assessing communication methods for delivering safety alerts to both connected and non-connected VRUs. Our approach can be divided to the following tasks:

Task 1: A set of scenarios is developed based on connected infrastructure use-cases for VRU safety. **Task 2:** Each scenario is performed for each communication method on the MLK Smart Corridor. **Task 3:** Data is collected and then analyzed based on the performance metrics and use-case requirements. While this study is limited and more data collection and analysis is needed, we have summarized our findings that show the feasibility of different wireless communication technologies for real-time communication.

The effectiveness of pedestrian safety applications hinges on the successful and rapid delivery of information to VRUs. Several factors contribute to the overall performance, including range, positioning accuracy, scalability, latency, message size, security, and privacy. These attributes serve as performance benchmarks during the evaluation process. However, external elements like weather conditions and obstacles can also impact performance. Scenarios accounting for these variables are developed for infrastructure-based VRU systems. VRU safety application use-cases can be categorized into two distinct groups: awareness and collision avoidance. Collision avoidance applications have significantly more demanding performance requirements compared to awareness applications. Awareness applications aim to provide VRUs with proactive situational information, while collision avoidance applications must deliver time-critical data to ensure the safety of road users.

Two intersections along the MLK Smart Corridor were chosen that have different characteristics in terms of traffic volume and signal phases. Pedestrians walked across all crosswalks under different obstruction scenarios that are explained later in Chapter 4. Data is collected using BLE and LTE and metrics are collected at both the transmitter and receiver. These metrics include latency, packet loss, range, and throughput. Evaluation criteria for each communication technology is developed to consider environmental effects on performance. Additionally, deployment and operations criteria, as well as maintenance and cost are needed to be considered in future studies to fully evaluate the feasibility of a VRU system.

Taking into account the principles of fairness and inclusivity, it is crucial that the available communication methods are accessible to underserved communities. One of the simplest and most evident ways to provide warnings to non-connected road users is through the utilization of infrastructure-based information delivery techniques, such as dynamic message signs, flashing traffic lights, and auditory alerts. These methods enable individuals to receive notifications without the need for them to possess any communication devices and represent the most practical approach in the near future. For instance, when a vehicle approaches an intersection and is detected in advance by infrastructure-based sensing systems, this information can be transmitted to the Rectangular Rapid-Flashing Beacon (RRFB) situated within the infrastructure. Subsequently, the RRFB can be activated to notify both distracted pedestrians and other vehicles. Additionally, VRU devices such as smartphones, helmets, tags, and wearables for communication can enhance safety of all road users. While infrastructure and VRU-based devices are valid and promising solutions, they are outside of the scope of our project, which is studying wireless communication technologies. The rest of this report will focus on the test scenarios and evaluation of the results. We want to emphasize that this was a 12-month project. As a result, we had limited time in collecting and analyzing data. Results reported here are based on our preliminary data collection. More data under wider scenarios will be needed for further exploration.

The proposed infrastructure-driven VRU systems are tested and demonstrated on the MLK Smart Corridor shown in Figure 1.2. Signalized intersections along the corridor are outfitted with a wide range of sensing and communications technologies. The findings from the field test have led to the formulation of appropriate responses and recommendations. Use-cases identified in the initial task are seamlessly incorporated into validation scenarios. These scenarios are showcased using the established interface to relay safety alerts to VRUs. To illustrate, pre-existing video analytics and perception software are employed to detect VRUs at risk. Once such VRUs are identified, the system initiates the dissemination of safety messages through the interface.

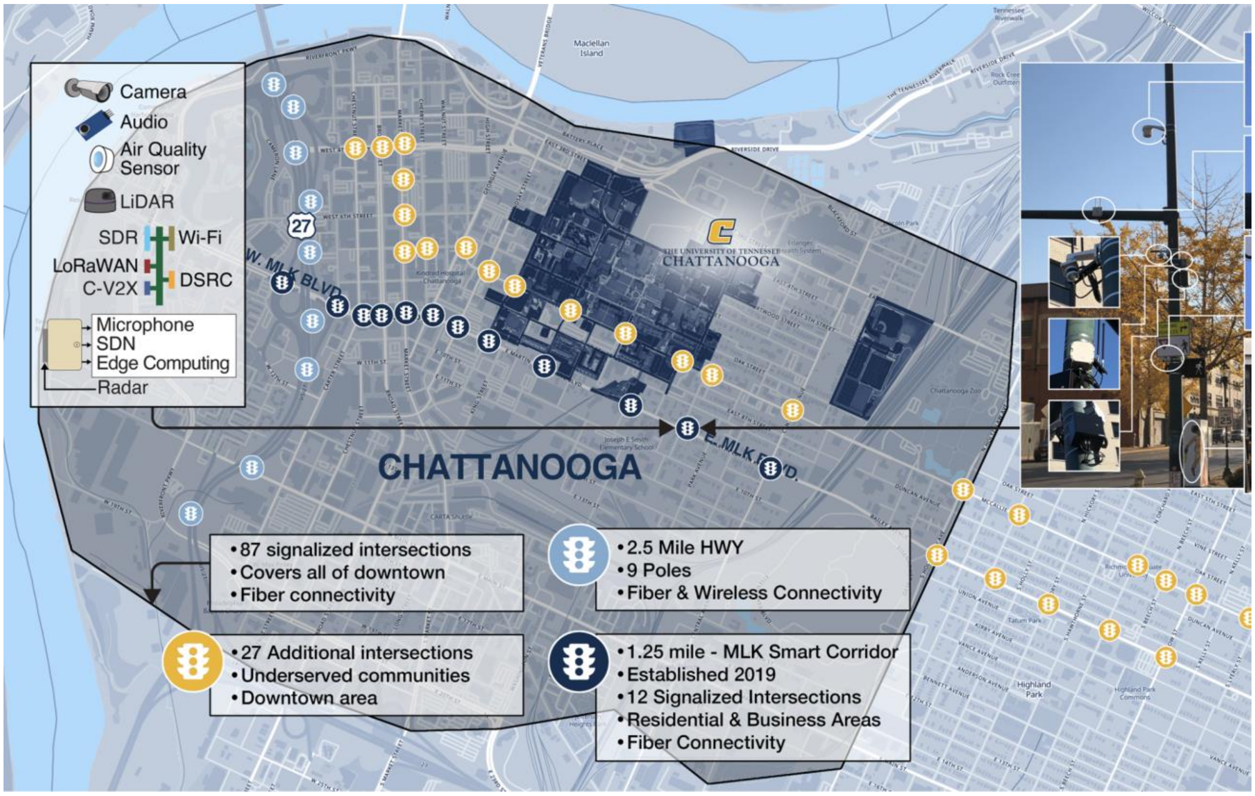

Figure 1.2: Current and Future Chattanooga Smart City Testbed

Chapter 2 Literature Review

2.1 Literature Review

Based on data from the World Bank, it has been observed that as of 2020, over 56% of the global population resides in urban regions [1]. The concentration of individuals in metropolitan areas gives rise to significant challenges in terms of transportation. According to the World Health Organization (WHO), there has been an uncontrolled rise in the volume of cars operating within major urban centers. This surge in vehicular activity poses a heightened risk of accidents, particularly for VRUs, such as pedestrians, cyclists, and motorcyclists, among other susceptible individuals. Intelligent Transportation Systems (ITS) have witnessed significant progress in enhancing the safety characteristics of vehicles and pedestrians. These safety elements contribute to enhancing the safety of both vehicle occupants and VRUs. Vehicle-to-Everything (V2X) communication is a safety feature that facilitates communication amongst different entities on the road in order to enhance cooperative safety. V2X encompasses the exchange of information across three key entities: Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), and Vehicle to Pedestrian (V2P). V2P refers to a comprehensive concept that involves the communication between vehicles and various forms of VRUs. By using V2P technology for VRUs, they can actively participate in ITS and facilitate the implementation of a range of safety and convenience applications inside the ITS framework [2].

VRUs encompass several categories, each with unique characteristics and challenges for V2P systems. These include distracted road users who are engaged in other activities while walking, special road users like the elderly and children who have low travel speeds and are at high risk, users of transport devices such as skates and scooters who lack external protection, animals that could be within the road driving zone, and road users with disabilities who navigate the road traffic ecosystem with assistive devices [3].

VRUs exhibit variations in their features, including factors such as speed, mobility, and travel habits. As an illustration, it may be seen that pedestrians generally exhibit a slower pace of movement in comparison to cyclists and individuals operating motorized two-wheel vehicles. Another illustration of this phenomenon is that powered two-wheel vehicles are required to come to a halt at intersections when the traffic light is displaying a red signal, whereas pedestrians are permitted to traverse the roadway for the same period of time. When developing a V2P system, it is imperative for system developers to take into account the diverse range of qualities in order to construct a V2P system that is efficient and effective. The aforementioned qualities can be effectively translated into suitable design criteria for the V2P system. Clearly stated standards can be crucial in effectively addressing the various issues associated with the incorporation of VRUs [2,3].

VRUs can enhance their safety using various devices that facilitate communication with other road users or infrastructure. These devices include smartphones, which are widely used for their cost-effectiveness and suitability for V2P communications due to their multiple sensors and intelligent capabilities [4,5,6,7]. Connected helmets [8] and tags, which can be attached to a VRU or their vehicle, are also used as they can send and receive safety-related messages and provide information about the VRU's location and movement. Wearable devices like smartwatches or fitness trackers are another type of VRU device. Equipped with sensors and communication capabilities, these wearable devices can send and receive safety-related messages and track the VRU's location and movement (See Fig. 2.1). All these devices can communicate with vehicles and infrastructure using technologies like Software-Defined Radio (SDR), enabling real-time monitoring and thereby improving overall road safety.

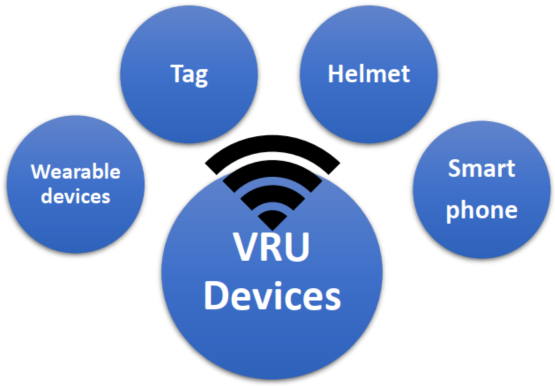

Figure 2.1: VRU Devices

There are two categories of VRUs and vehicles: connected and non-connected. The objective of a safety system is to ensure the protection of both types. To establish a safety system for VRUs, four main components are crucial: sensors, detection, classification, prediction, and conflict and risk assessment. These components work in unison to detect, classify, predict, and assess potential conflicts and risks for VRUs, thereby enhancing their safety. These components communicate with each other via a wireless system. Therefore, a comprehensive study on the performance of the communication system is essential. This ensures that the safety system for VRUs operates optimally, enhancing their protection on the road [9].

In the context of V2P communication systems, there are two primary types of communication architectures: direct and indirect. In direct communication architecture (See Figure 2.2 a), communication occurs directly between the vehicles or between vehicles and infrastructures. This method is more straightforward and faster as it eliminates the need for an intermediary. However, it requires both the vehicle device and the VRU device to be equipped with compatible communication technology. The devices must be capable of carrying out detection, tracking, trajectory prediction, and necessary action phases independently. In contrast, indirect communication (See Figure 2.2 b) involves some additional components like Road Side Units (RSU) or Information Processing Units (IPU). These units are responsible for carrying out the detection, tracking, and trajectory prediction phases. It determines the possibility of a crash based on the trajectory prediction and then notifies both the vehicle device and VRU device through infrastructure for necessary action, if required. The vehicle device and VRU device may then carry out the necessary action phase. While both methods have their advantages and disadvantages, the choice between direct and indirect communication would depend on factors such as infrastructure availability, technological compatibility, cost considerations, and safety requirements. It's crucial to note that regardless of the method chosen, the primary goal of V2P systems is to enhance road safety by preventing accidents involving vehicles and pedestrians [3,10,11].

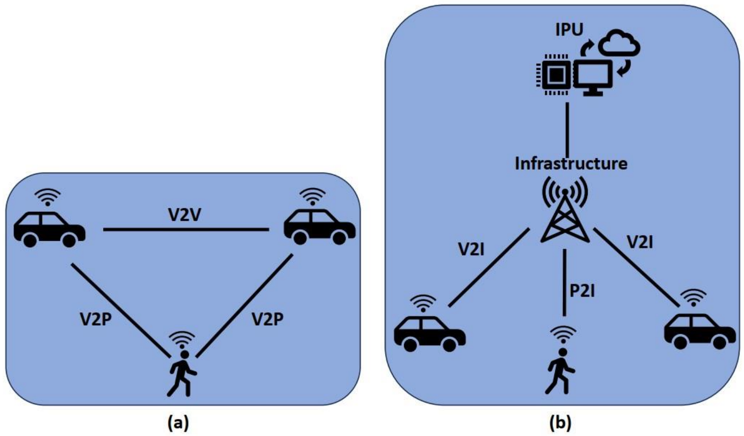

Figure 2.2: (a) Direct Communication (b) Indirect Communication

In both direct and indirect communication systems, wireless technology plays a pivotal role. In the realm of ITS, this technology facilitates the exchange of information in real-time, enhancing the efficiency and safety of transportation networks. A cooperative communication system is a pivotal technology within the ITS framework. The term "cooperative" denotes the synergy between vehicles and transportation infrastructure facilitated by wireless networks. Typically, Intelligent Transport System communication (ITS-C) encompasses four modes of communication: V2V, V2I, V2P, and Vehicle-to-Network (V2N). ITS-C employs a variety of sensors to assist drivers in particular scenarios, including the maintenance of appropriate speed, the maintenance of a safe distance from other vehicles, and a reduction of the risk of frontal collisions. The utilization of multifarious sensors facilitates the prompt and seamless transmission of data between vehicles and the transportation infrastructure [12]. The dataset encompasses real-time information on road conditions and real-time weather updates, thereby enhancing the benefits of ITS-C to a considerable extent. In addition, connected vehicles (CVs) are outfitted with advanced technology that allows them to establish connections with other vehicles, roadway infrastructure, pedestrians, cyclists, and various other devices through sophisticated wireless communication. This technology has the potential to enhance safety on the roads, increase travel efficiency, and promote energy conservation while minimizing vehicle emissions. Applications of CVs can boost throughput and mobility, and by eliminating human errors, they may also decrease the incidence of vehicle accidents. It is anticipated that CV technology will substantially enhance the safety and mobility of the transportation system while also reducing greenhouse gas emissions through the use of cutting-edge technologies and improved operational practices in transportation [10,11,12].

In recent years, researchers and scientists worldwide have dedicated substantial efforts to the standardization and allocation of bandwidth for vehicular communication. A significant breakthrough occurred in 1999 within the United States when a dedicated bandwidth was officially standardized for this purpose. This allocation consists of seven distinct channels, each spanning 10 MHz, effectively reserving a 5.9 GHz spectrum exclusively for Dedicated Short-Range Communication (DSRC). On the other hand, C-V2X, is a sophisticated wireless technology utilized in the context of autonomous driving and intelligent transportation systems (ITS) [13]. The implementation of this technology has resulted in an increased scope and improved capacity of autonomous cars to identify and address areas of limited visibility. From an economic standpoint, C-V2X presents a notably more cost-effective alternative to the standard sensors commonly utilized in autonomous vehicles. The economic efficiency of this technology makes it a viable option for broad-scale deployment [9]. device-to-device communication PC5-based C-V2X leverages Radio Frequency (RF) Sidelink (a direct device-to-device and device-to-network topology standardized by 3GPP) direct communication, enabling expedited connectivity for essential vehicular sensors. The sensor capabilities of autonomous vehicles can be significantly enhanced through C-V2X radio communications, broadening their scope to the network's coverage area. In 2020, 5G technology was commercialized worldwide, with Taiwan at the forefront. Telecommunication providers and governments alike are keen to assess its influence on everyday life, especially considering its low latency, high reliability, and considerable throughput [13].

C-V2X makes use of Third Generation Partnership Project (3GPP) technologies for signal transmission and reception, including Fourth Generation (4G) Long-Term Evolution (LTE) and Fifth Generation (5G) New Radio (NR) connection. It uses two complimentary transmission modes. The first mode includes direct interaction with nearby pedestrians, infrastructure, and automobiles. When operating in this mode, C-V2X is independent of cellular networks and uses a PC5 interface for communication. Cellular network connection is the secondary option, where

C-V2X uses established mobile networks to provide cars with data about nearby traffic and road conditions. It uses the Uu interface for communication in this mode. The LTE-Uu serves as the radio interface that establishes a connection between the User Equipments (UEs) and the eNodeBs. It is responsible for managing all signaling communications between the eNodeB and the Mobility Management Entity (MME), as well as overseeing the data traffic between the UE and the Serving Gateway (S-GW).

The adoption and integration of C-V2X technology would effectively address challenges related to human errors or road conditions leading to deadly accidents, as well as alleviate significant traffic congestion resulting from special events or accidents. Imminent advances include the forthcoming capability to identify dangers through C-V2X, V2V, and V2P before they escalate into threats, in addition to the ability to detect congestion via C-V2X, V2I, and V2N prior to their visual appearance. The realization of enhanced road safety and improved travel efficiency may be achieved via the collaborative endeavors of C-V2X [13].

C-V2X, known for its notable attributes of low latency and high dependability, facilitates communication such as V2V, V2P, V2I, and V2N, regardless of the availability of a cellular network. This technology plays a crucial role in tackling concerns pertaining to road safety and optimizing traffic flow. Furthermore, the C-V2X technology has the capability to overcome obstacles that obstruct the line of sight, commonly referred to as Non-Line-Of-Sight (NLOS) problems. This is achieved by leveraging the PC5 interface Sidelink communication or the cellular network, resulting in improved safety features [14]. C-V2X has the ability to integrate data obtained through cooperative perception, enhance the map with accurate road structural information, and distribute the localized High Definition (HD) map to cars according to their geographic positions. This technology enables the provision of sophisticated services, like blind-spot detection, long-range perception, remote driving, and platooning, among other capabilities. Through the enhancement of these services, C-V2X technology has the potential to greatly enhance road capacity, driver safety, and overall comfort.
Initial V2X technologies, exemplified by DSRC in the United States, find their foundations in the Institute of Electrical and Electronics Engineers (IEEE) 802.11p standard. This standard introduces the concept of Wireless Access in Vehicular Environments (WAVE) at both the physical and medium access control (MAC) layers. Despite DSRC's deployment in various countries for V2V, V2P, and V2I applications, it has not achieved large-scale commercialization despite nearly two decades of utilization [14,15].

DSRC presents several challenges, including inherent issues with its protocol algorithm known as Carrier Sense Multiple Access with Collision Detection (CSMA-CD). This algorithm is employed in direct V2V and V2I communications and is susceptible to challenges related to hidden nodes, data competition, and collisions. Additionally, DSRC's transmission distances are inherently limited, and it lacks the capability to seamlessly integrate with existing cellular networks. Consequently, the prevailing global trend in V2X development is shifting towards C-V2X, an advanced cellular technology that paves the way to 5G adoption while supporting features like seamless handover and roaming. This shift is underpinned by the preferences articulated by the National Highway Traffic Safety Administration (NHTSA) and the Federal Communications Commission (FCC) in the USA, both of which favor C-V2X over DSRC for ITS radio service [16].

While both DSRC and C-V2X operate within the 5.9 GHz band and employ similar message sets for high-speed data exchange in connected vehicles, they diverge significantly in their underlying technological frameworks. DSRC relies on the wireless standard known as WAVE, whereas C-V2X leverages LTE and 5G. C-V2X holds several advantages over DSRC. C-V2X may offer more range than DSRC and improved performance with obstructions. It delivers messages more reliably than DSRC, even with constrained lines-of-sights and shorter range at intersections. C-V2X also has a higher data rate, lower latency, allows for multiple simultaneous transmissions, and is resistant to noise, interference, and jamming. Furthermore, cellular radio technology, which C-V2X is based on, is believed to have better growth potential for faster speeds and higher reliability [17,18,19].

Indeed, various other communication technologies have also been explored. Many researchers in the field of ITS have focused their studies on vehicular networking. This diversity in communication technologies enriches the field and opens up new possibilities for enhancing the safety of VRUs. A number of efforts [20,21,22] have been made to provide safety systems for VRUs utilizing Wi-Fi technology. These systems commonly utilize a smartphone as VRU device and provide a communication range of roughly 100-150 meters. While this range may be satisfactory for urban settings characterized by vehicle speeds typically not exceeding 50 km/h, it may be insufficient in suburban regions where speeds can reach up to 100 km/h. The reason for this phenomenon might be attributed to the limited timeframe that drivers have to respond to collision warnings. In addition, the need for association in Wi-Fi poses a significant obstacle in the context of vehicle mobility, as it might result in substantial delays in the transmission of safety signals. It is worth mentioning that Wi-Fi-based V2P systems can be deployed without the requirement of infrastructure support.

Anaya et al. [23] have spearheaded the development of a specialized V2P safety system tailored for cyclists, utilizing Bluetooth technology. This pioneering system utilizes iBeacon as a VRU device, enabling direct communication with vehicles. It is distinguished by its communication reach, extending up to 50 meters, which may suffice for specific pre-crash scenarios. Nevertheless, it's important to note that the restricted communication range inherent to Bluetooth technology may not comprehensively support V2P applications. This limitation, for example, may make it more suitable for urban environments characterized by lower travel speeds.

It is worth noting that the choice of communication techniques can vary depending on the safety systems and scenarios. Researchers may opt to use a single communication technique or a combination of several. For instance, in some scenarios, the communication between the vehicle and infrastructure might utilize C-V2X technology, while the final warning message sent to the pedestrian could be transmitted via Bluetooth technology. This multi-modal approach allows for greater flexibility and adaptability in different contexts.

The remainder of this report is dedicated to the exploration of communication systems and their implementation on the Chattanooga Smart City Testbed. The primary focus is evaluating the performance of V2P communication. This involves a thorough analysis of various communication technologies, their strengths, limitations, and suitability for different scenarios. The ultimate goal is to enhance the safety of VRUs in diverse environments.

Chapter 3 Methodology

The design of V2P/I2P systems has been influenced by the use of a variety of communication technologies. The selection of the communication technology can significantly impact certain attributes of the V2P systems. These attributes include the communication range, the type of V2P device used, and the need for infrastructure, among others. In this section, we will initially provide a brief overview of each communication technology and its specific characteristics. Following this, we delve into the performance evaluation of V2P communication. Finally, we explore the communication system established on our test bed and present the results derived from it.

3.1 Communication Technologies

A variety of communication technologies have been employed in the design of V2P systems. These technologies range from traditional methods like Wi-Fi and Bluetooth to more advanced solutions like C-V2X. The choice of technology often depends on the specific requirements of the system, such as range, speed, and infrastructure. Each technology has its strengths and limitations, making it more suitable for certain scenarios over others. The goal is always to enhance safety and efficiency in transportation systems.

3.1.1 Wi-Fi

Wi-Fi is a wireless networking protocol that enables devices such as computers, smartphones, and other equipment to connect to the Internet. It is based on the 802.11 IEEE network standard, and is the most frequently used means of communicating data wirelessly in a fixed location. In the context of V2X communication, Wi-Fi allows vehicles to wirelessly exchange information about their speed, location, and heading. This data is then used to alert drivers of potential dangers, helping to reduce accidents and traffic congestion. The technology behind V2V communication allows vehicles to broadcast and receive omni-directional messages (up to 10 times per second), creating a 360-degree "awareness" of other vehicles in proximity. These V2X communication messages have a range of more than 300 meters and can detect dangers obscured by traffic, terrain, or weather. In connected cars, Wi-Fi can be used to connect these systems using an automotive gateway. This enables vehicles to present mechanical health information to drivers and transmit valuable data to vehicle manufacturers using secure, two-way, over-the-air (OTA) communications and data transfers via Wi-Fi. Indeed, one of the advantages of Wi-Fi-based V2X/V2P systems is that they can be deployed without the need for extensive infrastructure. This makes them a flexible and cost-effective solution for enhancing road safety. However, it's important to note that while these systems can operate independently, their performance can be significantly improved with the support of well-placed infrastructure.

3.1.2 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a power-efficient wireless communication protocol designed for short-range communication between devices. It can scan for nearby peripheral devices, view their advertisement data, and establish connections. Once a connection is established, BLE allows for reading and writing characteristic and descriptor data, meaning that data can be exchanged between the devices. Furthermore, BLE allows users to subscribe to characteristics to enable notification or indication, setting up devices to receive updates whenever certain characteristics of the peripheral device change. These features make BLE an excellent choice for applications where low power consumption and short-range communication are essential [24,25]. BLE operates in the 2.4GHz ISM band. It is designed for ultra-low power applications and is an energy-efficient, short-range wireless connectivity technology. In the context of V2V and V2P communications, BLE has been demonstrated as a feasible alternative technology for data transfers. The Bluetooth 5.x core specifications enhance the trade-off between energy requirements, communication range, and flexibility. For instance, an android application called BLE-Horn uses BLE to realize bidirectional many-to-many communications. It also has advantages like lower battery consumption, low latency, low cost, and it is widely supported by smartphones. A concept smartphone app running on a pedestrian’s phone uses BLE messaging to communicate their location to a connected vehicle. This system is capable of differentiating between pedestrians, cyclists, and others based on their traveling speed and can continually evaluate their risk by monitoring their direction of travel.

3.1.3 802.11p (DSRC)

Dedicated Short-Range Communications (DSRC) is a wireless technology that facilitates direct communication between vehicles and other road users, as well as roadside infrastructure, without the need for additional infrastructure. Operating in the licensed 5.9 GHz band and based on the IEEE 802.11p standard, DSRC allows each vehicle to securely and anonymously broadcast its location, heading, and speed ten times per second.

The system architecture of DSRC, including its physical and Medium Access Control (MAC) layers, is defined by a series of standards from the Institute of Electrical and Electronics Engineers (IEEE) and the Society of Automotive Engineers (SAE) International. The IEEE 802.11p protocol simplifies authentication and data transmission processes, while the IEEE 1609/Wireless Access in Vehicular Environments (WAVE) standard outlines the network architecture and security protocols. Developers utilize the SAE J2735 standard to design the application layer of DSRC-based vehicular networks. At a European level, the European Telecommunications Standards Institute (ETSI) has defined Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs) to support the implementation and deployment of Cooperative Intelligent Transport Systems (C-ITS). These messages complement the standardized Basic Safety Messages (BSMs) used in the United States [26,27,28].

DSRC has a wide range of applications, including electronic toll collection, cooperative adaptive cruise control, intersection collision avoidance, approaching emergency vehicle warning, automatic vehicle safety inspection, transit or emergency vehicle signal priority, and electronic parking payments. However, it's important to note that while DSRC offers many advantages, it also has limitations such as a communication range limited to about 1000 meters and performance that can be affected by obstacles like buildings or other vehicles. Despite these challenges, DSRC continues to play a pivotal role in advancing connected vehicle technologies.

3.1.4 Cellular

In the near future, connected vehicles are set to become a common sight on our roads. Significant strides have been made in recent years towards equipping vehicles with connectivity features that enable them to exchange information with their surroundings, a concept known as V2X communication. This can involve communication between vehicles (V2V), roadside infrastructure (V2I), pedestrians (V2P), networks (V2N), and more. The advent of autonomous and connected vehicles promises to transform various facets of daily life, with a primary emphasis on improving road safety. Currently, it's estimated that a large majority (around 95%) of road traffic accidents in the EU are caused by human errors. Autonomous and connected vehicles have the potential to significantly improve road safety, enhance traffic efficiency, reduce fuel consumption, lower emissions of air pollutants, and optimize parking systems.

To aid the European Union (EU) and the European automotive industry in adopting autonomous and connected mobility, the European Commission launched the Cooperative, Connected and Automated Mobility (CCAM) initiative. This initiative acknowledges the numerous benefits offered by Cooperative Intelligent Transport Systems (C-ITS) and has led authorities worldwide to allocate dedicated spectrum for V2X technologies, particularly in the license-exempt 5.9 GHz band. For instance, the European Commission allocated the 5875-5905 MHz frequency band for safety-related ITS applications. Additionally, recommendations have been made for the extension of ITS spectrum in 5905-5925 MHz and the use of 5855-5875 MHz for non-safety ITS applications [29]. Similar spectrum allocation decisions have been made in other countries such as the United States, China, South Korea, and Australia. It's clear that C-ITS systems will play a crucial role in transforming road safety, transportation, vehicular communications, and autonomous driving.

Over the past decade, two distinct wireless communication technologies have emerged to facilitate direct data exchange in the 5.9 GHz band for V2V and V2I communication. The first is based on IEEE 802.11p, as explained in the preceding section. The second is C-V2X PC5 technology, also known as C-V2X Sidelink, which is cellular-based. While ITS-G5 and DSRC rely on 802.11p and employ Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) for medium access, C-V2X PC5 technology offers two operating modes: mode 3 and mode 4. Mode 3 enables direct message exchange among ITS stations, with the base station managing resource scheduling. In contrast, mode 4 allows ITS stations to autonomously schedule their resources using sensing-based semi-persistent scheduling (SPS). SPS enables each station to schedule its resource blocks strategically, minimizing the risk of collisions. However, in dense environments, resource scarcity may affect latency. Additionally, long-range communication technologies such as 4G and 5G, operating in licensed spectrum, further support the CCAM paradigm and enable communication with cloud services [30].

3.1.4.1 LTE-V2X

The initiation of the first phase of 3GPP Rel-14 in March 2017 signified the beginning of standards that facilitate V2V services and broaden V2X services via cellular infrastructure. As per the 3rd Generation Partnership Project (3GPP) Release 14, the C-V2X technology was primarily developed to address safety-related issues by utilizing cellular networks or Sidelink communication through the PC5 interface. To aid the deployment of C-V2X technology, a unique Long-Term Evolution Vehicle-to-Everything (LTE-V2X) band, specifically band 47, was introduced. This band operates within the unlicensed 5.9 GHz spectrum and provides variable bandwidths of 10 and 20 MHz. Moreover, this specific version introduced two new physical channels, namely the Physical Sidelink Shared Channel (PSSCH) for data transmission, and the PSCCH which provides the necessary control information for decoding the data channel at the physical access layer [11].

To expedite the development of LTE-V2X, C-V2X has incorporated both centralized scheduling mode (Mode 3) and decentralized scheduling mode (Mode 4) from LTE-Device-to-Device (D2D) communication. Mode 3 involves resource allocation management via cellular networks, while Mode 4 operates autonomously irrespective of cellular access. In this operational state, vehicles independently determine radio resources using a sensing-based, Semi-Persistent Scheduling (SPS) scheme, which is further enhanced by congestion control methods.

Subsequently, the second phase of 3GPP V2X, known as 3GPP Rel-15, was completed in June 2018. This phase implemented enhanced V2X services, which included platooning, extended sensor data exchange, advanced driver support, and remote driving capabilities. Platooning enables the formation of dynamic clusters of vehicles that move closely together, exchanging information to maintain safe distances. The concept of extended sensor capability involves sharing raw or processed sensor data among various entities such as vehicles, roadside units, pedestrian devices, and V2X application servers. This data sharing allows for an expansion of ambient awareness beyond the inherent capabilities of individual sensors, potentially achieved through live video exchange. The use of advanced driving features enables the implementation of semi-automated or fully-automated driving systems through the integration of perception data obtained from local sensors and the exchange of driving intents with neighboring vehicles. The use of remote driving technology allows remote operators of V2X applications to take control of vehicles, thereby achieving a variety of objectives such as assisting those with disabilities, navigating hazardous environments, or executing predetermined routes. The advancements in this field have established a secure and resilient ecosystem centered on LTE-V2X technology [31].

3.1.4.2 NR-V2X

The 5G NR (New Radio)-V2X, which forms the third phase of the 3GPP V2X framework, ensures backward compatibility with the upper layers of LTE-V2X. This compatibility guarantees that it can meet the strict low latency and high reliability requirements demanded by advanced V2X services. Within the V2N (Vehicle-to-Network) application category, 5G URLLC (Ultra-Reliable Low-Latency Communication) network slicing is utilized to provide advanced autonomous driving functions for L3 (Conditional Automation) and L4 (Highly Automation), complete with enhanced Quality of Service (QoS) profiles. The significant enhancements in Releases 16 and 17 are certain to play a critical role in expanding both the availability and the applicability of 5G NR in both industry and public services in the near future.

Certain advanced application scenarios require the periodic transmission of traffic. Therefore, in addition to the conventional broadcast method, 5G NR-V2X introduces two new communication types: unicast and groupcast. Similar to LTE-V2X, 5G NR-V2X defines two distinct Sidelink communication modes: Mode1 and Mode2. NR-V2X Mode 1 outlines mechanisms enabling direct vehicular communication while the cellular network's base station manages radio resource allocation through the Uu interface. Mode 2 supports direct vehicular communication via the PC5 interface in scenarios where cellular network coverage is unavailable. Notably, 3GPP Rel-16 was officially completed in July 2020, and the ongoing development of 3GPP NR Release 17 introduces a novel Sidelink communication relaying architecture tailored to support specific advanced V2X services [11].

One of the areas being explored for enhancement is NR multicast broadcast for infrastructure to vehicle (I2V) applications. This would allow for more efficient use of network resources when sending the same data to multiple devices, which is a common scenario in I2V communications. For example, a traffic alert could be sent to all vehicles in a certain area, such as the i-24 smart corridor in Nashville, where the information is sent to the RSU and transmitted to the vehicle (I2V), or sensor data could be shared between nearby vehicles to improve situational awareness and safety.

In the context of PC5-based C-V2X Mode4, the requirement for a cellular network is not essential. In order to facilitate the implementation of C-V2X V2I/V2V/V2P application scenarios, two distinct wireless devices, namely the Road Side Unit (RSU) and the On Board Unit (OBU), are often sufficient. These devices enable the implementation of several application scenarios within the framework of Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), and Vehicle-to-Pedestrian (V2P) communications. The aforementioned configuration facilitates streamlined and proficient communication, hence augmenting the overall safety of roadways and the control of traffic [32].

3.2 Performance Evaluation of V2P Communication

When evaluating the performance of wireless technologies, a key measure is reliability. This measure indicates the maximum acceptable failure rate in packet reception or Packet Delivery Rate (PDR) on the pedestrian side. Failures in packet reception can occur due to various factors such as packet collision and low Signal-to-Interference-plus-Noise Ratio (SINR) at the receiver. Packet Error Rate (PER) and PDR are metrics that correspond with reliability and specify the failure rate or success rate of packet reception. The PER can be examined over a variety of other parameters, such as pedestrian speed and distance. The effective communication range is another measure that demonstrates the relationship between the PER and reliability can be alternatively expressed in terms of PDR and communication range. The effective communication range expresses the maximum range of communication that provides a specified level of reliability. For safety applications, existing standards for minimum reliability and minimum communication range are restricting [26]. The PDR can be calculated by Eq. 1:

$$PDR = \frac{Ns}{Nt} * 100\% \tag{Eq.1}$$

Where Ns is the number of successfully delivered packets and Nt is the total number of packets sent.

End-to-End latency is a crucial performance metric, particularly for real-time applications. In wireless communication, latency is typically computed based on propagation delay, the time it takes for a signal to travel from the sender to the receiver, and serialization delay, the time required to put the packet onto the wire. In the context of communication systems, latency or delay is a significant factor, as it represents the duration it takes for a signal to be transmitted from a source to a destination. In Software-Defined Radio (SDR), latency calculation involves measuring the time taken for the signal to travel from the transmitter (Tx) to the receiver (Rx), considering elements such as processing time, modulation scheme, and channel conditions. Accurate latency calculation allows for optimization of the communication system for peak performance, ensuring efficient and timely transmission and reception of data. In this project, we employ Wireshark to record four time points: Tx (start), Tx (end), Rx (start), and Rx (end). Consequently, latency can be calculated using Eq. 2. This method provides an accurate measure of system latency, contributing to overall system performance optimization.

$$Latency = R_x(end) - T_x(start) \qquad \text{(Eq.2)}$$

These performance metrics are crucial for ensuring reliable and timely data transmission in V2P communications, thereby enhancing overall road safety and traffic management.

3.3 Software-defined radio (SDR)

SDR refers to a wireless device that commonly contains a programmable radio frequency (RF) front end integrated with a field-programmable gate array (FPGA) or a programmable system-on-chip (SoC) to execute digital operations. SDR hardware that is readily accessible in the commercial market possesses the capability to both broadcast and receive signals over a range of frequencies, enabling the implementation of several wireless protocols, including but not limited to: FM radio, 5G, LTE, and WLAN.

SDR hardware serves as an economical, real-time platform that wireless engineers can leverage for a multitude of wireless engineering tasks. These tasks include conducting over-the-air lab and field testing with live RF signals, rapidly prototyping custom radio functions, and gaining hands-on experience with wireless communications concepts and design skills. When used in conjunction with GNU radio for wireless design, simulation, and analysis, SDR enables researchers to understand the implementation of wireless transceiver hardware, configure SDR hardware with pre-set radio functions, transmit and receive signals that are standards-based and custom-generated, and test designs under real-world conditions, including interference. It also allows for real-time signal analysis and measurement, verification of implementation with radio-in-the-loop tests, transmission and capture of signals at sample rates up to 250 Msps for testing wideband wireless systems and performing spectrum monitoring, capture of wideband signals for training deep learning models for wireless applications, and prototyping, verification, and testing of practical wireless systems. This comprehensive platform provides a robust environment for learning, designing, and testing in the field of wireless communications. Furthermore, With the use of SDR, we have the capability to examine, modify, and experiment with every facet of the communication system.

In our study, we have chosen to utilize SDR due to its multitude of benefits, such as cost-effectiveness, compatibility with a broad spectrum of wireless technologies, and adaptability for real-time monitoring applications. Specifically, we have applied SDR technology in our testing procedures on Chattanooga's testbed. To enhance our use of SDR, we have incorporated GNU Radio into our framework. GNU Radio is a widely recognized open-source software development framework that provides essential signal processing capabilities for the implementation of software-defined radios. It stands out by offering a graphical design approach and supporting development in both Python and C++. With the backing of a robust open-source community, GNU Radio is widely used across government, commercial, and academic environments. It provides users with access to a wide range of existing projects dedicated to wireless communications research and the practical implementation of real-world radio systems. Fig.3.1 shows the testbed in a block diagram with more details on internal system setup.

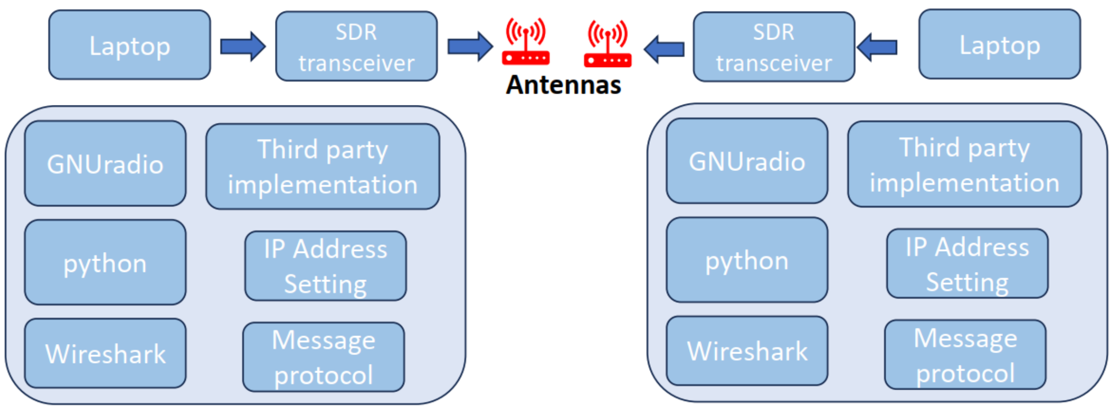

Figure 3.1: Testbed in a Block Diagram.

Due to the availability of a variety of third-party repositories for implementing wireless technologies, we have utilized several types of SDRs that are compatible with these repositories. This approach allows us to leverage the extensive capabilities of these SDRs and the wide range of wireless technologies supported by the third-party repositories, thereby enhancing the effectiveness and efficiency of our research and development efforts.

3.4 Field Tests and Data Collection Preparation

The importance of intersection safety studies cannot be overstated, as traffic intersections are hotspots for accidents that can result in injuries or fatalities. The U.S. Department of Transportation (USDOT) reports that over half of road accidents that lead to injuries or fatalities occur at or near traffic intersections [34]. This underscores the critical need for ongoing research and implementation of safety measures at these locations. In an effort to improve road safety, particularly for VRUs, we have identified four potential collision scenarios at intersections in urban areas [35]:

1. A vehicle is moving straight and a VRU crosses the street.

2. A vehicle is making a left turn and encounters a pedestrian in the crosswalk at a signaled intersection.
3. A vehicle is making a right turn and encounters a VRU at an intersection.
4. A vehicle is moving straight and a VRU is moving parallel to the vehicle.

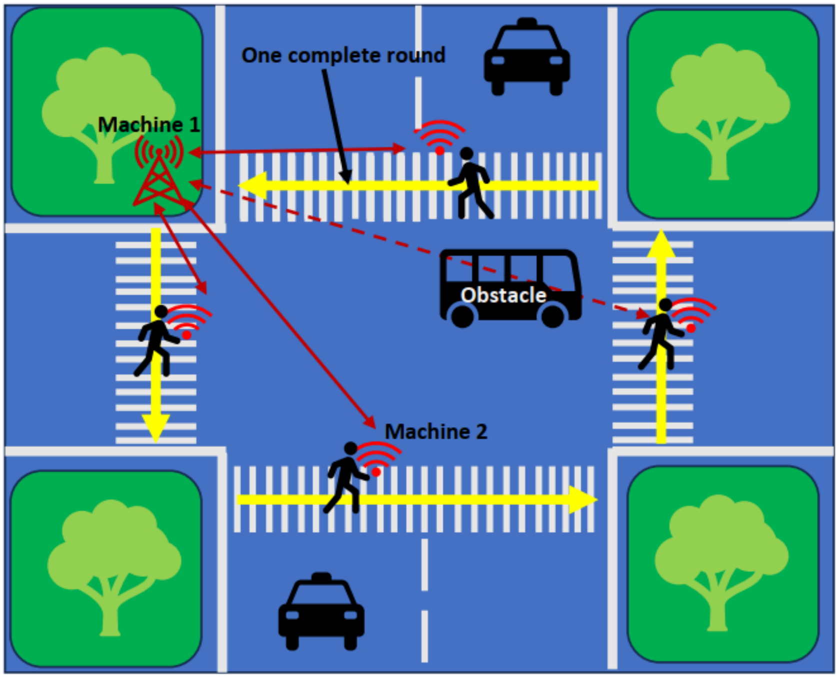

Figure 3.2: Experimental Environment

To analyze these scenarios, we have created an experimental environment, as shown in Figure 3.2. In this setup, a pedestrian walks around the intersection carrying a laptop equipped with a SDR and an external GPS to track their path. Note that the pedestrian is only crossing safely while the light is red and the indicator to cross the intersection is active. The equipment utilized for these experiments is depicted in Figure 3.3. As an initial step, we have carried out tests using a variety of SDRs. To scrutinize the functionality of the system, we have established a testbed both indoors and on the university campus. Figure 3.4 and 3.5 provide a visual representation of our experiment conducted on the University of Tennessee at Chattanooga (UTC) campus. This experiment served as a crucial preliminary step conducted before venturing into real city intersections.

We conducted this experiment at two locations within the Chattanooga Smart City corridor: the intersections of East MLK Blvd. with Douglas St. and with Houston St. (See Fig. 3.6). At each intersection, we set up an SDR and a laptop on one of the corners, as depicted in the block diagram in Figure 3.1.

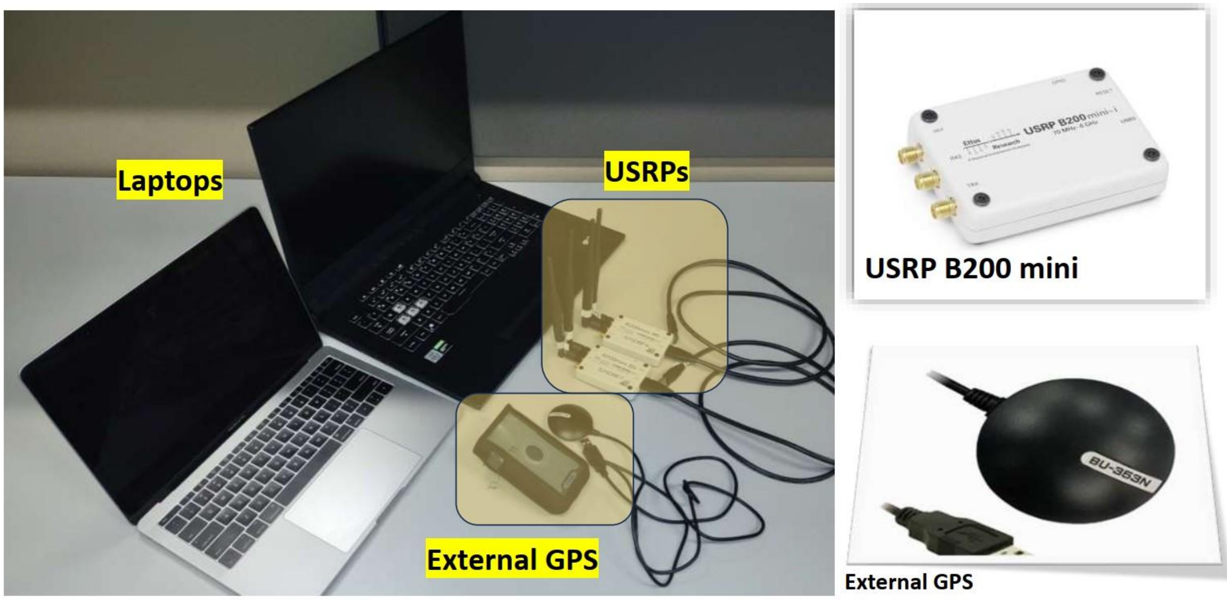

Figure 3.3: Equipment Used for the Field Test

To ensure the accuracy of our results, we conducted 15 rounds for each scenario at each intersection. We used Wireshark on both laptops to capture the transmitting and receiving packets, which allowed us to calculate the end-to-end latency. The use of an external GPS enabled us to create a high-level visualization using hexagons to display the latency for each round. This comprehensive approach allows us to thoroughly analyze the performance of wireless communication technology in potential collision scenarios at intersections, providing valuable insights that could contribute to enhancing road safety in urban areas.

Figure 3.4: Initial Testbed on University Campus

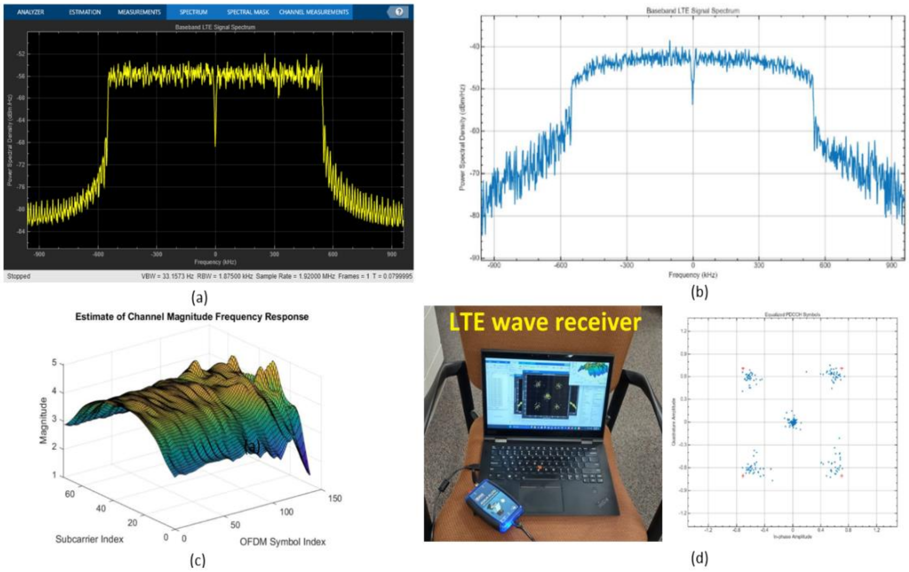

Figure 3.5: Initial LTE test on University Campus

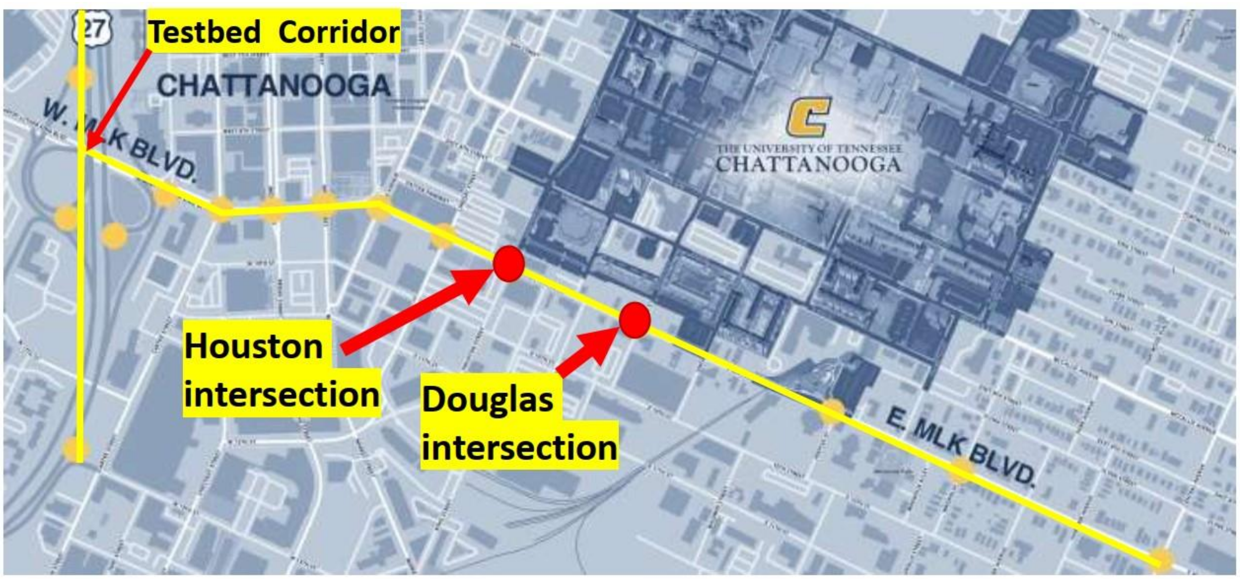

Figure 3.6: Testbed Corridor and Experimental Test Locations

3.4.1 LTE Communication Field Tests - Data Collection Methodology

To set up an end-to-end LTE mobile wireless network, we used srsRAN 4G [36] . srsRAN 4G is an open-source software radio suite developed by Software Radio Systems (SRS). It provides a comprehensive set of 4G LTE applications, including a full-stack SDR 4G UE application with prototype 5G features (srsUE), a full-stack SDR 4G eNodeB application (srsENB), and a lightweight

4G core network implementation with MME, HSS, and S/P-GW (srsEPC). The eNodeB, or Evolved Node B, is a key component of the E-UTRA network of LTE. It is essentially the hardware that communicates directly with mobile handsets and manages the radio resources for the cell. Unlike traditional Node B, which is controlled by a Radio Network Controller (RNC), eNodeB embeds its own control functionality, simplifying the architecture and allowing lower response times. The suite is designed to be installed on Ubuntu. In our experiment, we utilized two machines. On the first machine, we ran both the srsEPC and srsENB applications, each in a separate console session. This setup allowed us to simulate the network infrastructure. On the second machine, we ran the srsUE application, representing a device in the network. This configuration was crucial for testing and analyzing the performance of our system. The setup for the srsRAN 4G LTE experiment with USRPs is depicted in Figure 3.7. This figure illustrates how the USRPs and the srsRAN 4G LTE applications are configured and interact with each other in the experimental environment.

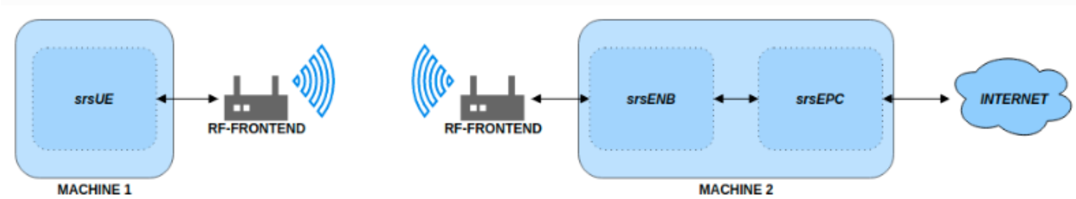

Figure 3.7: srsRAN 4G LTE set-up with USRPs

In our experiments, we have utilized PC5 communication, a subset of the 3GPP Release 14 specification that defines Cellular Vehicle-to-Everything (C-V2X) technology. Unlike traditional cellular communication, PC5 does not require the presence of a base station. Instead, it enables User Equipment (UE), such as mobile handsets, to directly communicate with another UE over the direct channel. This is particularly useful in scenarios where immediate, low-latency communication is essential, such as in vehicle-to-vehicle or vehicle-to-infrastructure interactions in intelligent transportation systems.

In the context of vehicular networks, PC5-based C-V2X uses an RF (Radio Frequency) Sidelink direct communication for low latency mission-critical vehicle sensor connectivity. Over the C-V2X radio communications, the autonomous driving vehicle's sensor ability can now be largely enhanced to the distances as far as the network covers.

For these experiments, we used the USRP B200mini, a compact and flexible Software-Defined Radio (SDR). It has a wide frequency range from 70 MHz to 6 GHz and is equipped with a user-programmable Xilinx Spartan-6 XC6SLX75 FPGA. The RF front end uses the Analog Devices AD9364 RFIC transceiver, providing 56 MHz of instantaneous bandwidth. The board is bus-powered by a high-speed USB 3.0 connection for streaming data to the host computer. However, the eNodeB can also be run on the low power Raspberry Pi-4 with a variety of SDR.

Our experiment using PC5 communication and USRP B200mini aligns with this approach as it bypasses the need for a cellular network. This comprehensive approach allows us to thoroughly analyze the performance of wireless communication technology in potential collision scenarios at intersections, providing valuable insights that could contribute to enhancing road safety in urban areas. Indeed, one of the advantages of using SDRs like the USRP B200mini is their low power consumption. They can be powered directly via a USB connection to a computer, eliminating the need for a separate power supply. This makes them not only energy-efficient, but also highly portable and convenient for a wide range of applications. The setup for the experiment at the Houston intersection is illustrated in Figure 3.8, while the setup at the Douglas intersection is depicted in Figure 3.9. These figures provide a visual representation of how we configured our equipment and carried out our tests at each location.

Figure 3.8: Houston Intersection Data Collection

Figure 3.9: Douglas Intersection Data Collection

3.4.2 BLE Communication Field Tests - Data Collection Methodology

Our software implementation for this experiment is based on the third-party library BTLE [37,38]. This library, available on GitHub, originally contained separate modules for receiving (RX) and transmitting (TX) data. These modules included a sniffer for Bluetooth Low Energy (BLE) and a module to create, modulate, and transmit BLE frames. However, we found that with our configuration for the SDR, the sniffer could not operate in real time. To address this issue and meet the Interframe Space (IFS) requirement, we made modifications to the original BTLE library to reduce the processing time.

The third-party library BTLE we used for our experiment boasts a number of features that provide full SDR flexibility. The Physical Layer (PHY) and upper layers are implemented in the C programming language, allowing for comprehensive control and customization. The software supports the BLE standard 1Mbps GFSK PHY. One of the key features of this software is its sniffer, which can parse and automatically track the channel hopping pattern. This capability is not limited to broadcasting channels or fixed channels, providing a broad scope for data collection and analysis.

In our experience, we utilized channel number 38 for the BLE experience with SDR. BLE operates on 40 channels, each 1MHz wide and numbered from 0 to 39, with a separation of 2MHz between each channel. Channels 37, 38, and 39 are exclusively used for transmitting advertisement packets, while the remaining channels facilitate data exchange during a connection.

During the BLE advertisement phase, a BLE Peripheral device sequentially transmits the same packet on all three advertising channels. This allows a central device scanning for other devices or beacons to listen to these channels for the advertising packets, thereby discovering nearby devices. The placement of channels 37, 38, and 39 across the 2.4GHz spectrum is strategic. Channels 37 and 39 are located at the extremes of the band, while channel 38 is positioned in the middle. This arrangement ensures that if one advertising channel encounters interference, the other channels are likely to remain unaffected due to their separation by several MHz of bandwidth. This is particularly beneficial as most devices that interfere with BLE operate on narrow bands. Channel 38 is specifically placed between Wi-Fi channels 1 and 6 to avoid Wi-Fi signals. The wide spacing of the advertisement channels enables BLE to effectively manage interference from various sources such as Wi-Fi, Classic Bluetooth, Microwaves, Baby Monitors, etc., ensuring successful advertisements.

When a BLE peripheral device is in advertising mode, it periodically sends out advertising packets on each of the advertising channels. The time interval between each set of packets consists of a fixed interval and a random delay. This interval is specified between the set of three packets, as three channels are typically used for this purpose. This strategy helps optimize the balance between power consumption and the likelihood of a central device discovering the peripheral device. The random delay helps to prevent multiple devices from continuously colliding if they happen to start their advertisements at the same time. In our experiment, we carefully considered the impact of both the fixed advertising interval and the random delay on the performance of the BLE device. The total delay, which is the sum of these two components, influences the rate at which the BLE device can transmit advertising packets, thereby affecting its responsiveness to connection requests. It's crucial to note that the choice of advertising interval can significantly affect the power consumption of the BLE device. A shorter interval results in more frequent advertising and consequently increased power consumption. On the other hand, a longer interval leads to less frequent advertising and reduced power consumption. Therefore, striking a balance between responsiveness and power efficiency in our BLE application was essential. In this experiment, we assumed a delay of 100 milliseconds between packets. This assumption was factored into our latency calculations to ensure accurate results.

For the hardware part of our experiment, we utilized HackRF (See Fig. 3.10), a SDR peripheral that can transmit or receive radio signals from 1 MHz to 6 GHz. HackRF is an open-source hardware platform that can be used as a USB peripheral or programmed for stand-alone operation.

Figure 3.10: HackRF SDR used for BLE experience

By combining the capabilities of the modified BTLE library with the HackRF hardware, we were able to effectively implement and test our system. This combination allowed us to create a robust and flexible platform for our experiments.

For the BLE sniffing in our experiment, we utilized a BTLE packet sniffer based on HACKRF. This sniffer supports all BTLE channels (0-39), including both ADV and DATA channels. The btle_tx and btle_rx modules can be used to send or sniff on any BTLE channel. We also added a Raw mode to both btle_tx and btle_rx. In this mode, after the access address is detected, the following raw 42 bytes (without descrambling or parsing) are printed out. This feature allows for additional experiments or communication between HACKRF boards.

To demonstrate the full real-time processing ability of our setup, we compared the HACKRF BTLE packet sniffer with smartRF protocol packet sniffer Texas Instrument (TI) packet sniffer under the fastest flow of continuous/non-gap BTLE packets sequence. Both sniffers captured the same number of packets and content, showcasing the efficiency and effectiveness of the BTLE packet sniffer system (See Fig. 3.11).

The setup for the experiment at the Douglas intersection is illustrated in Figure 3.12, while the setup at the Houston intersection is depicted in Figure 3.13.

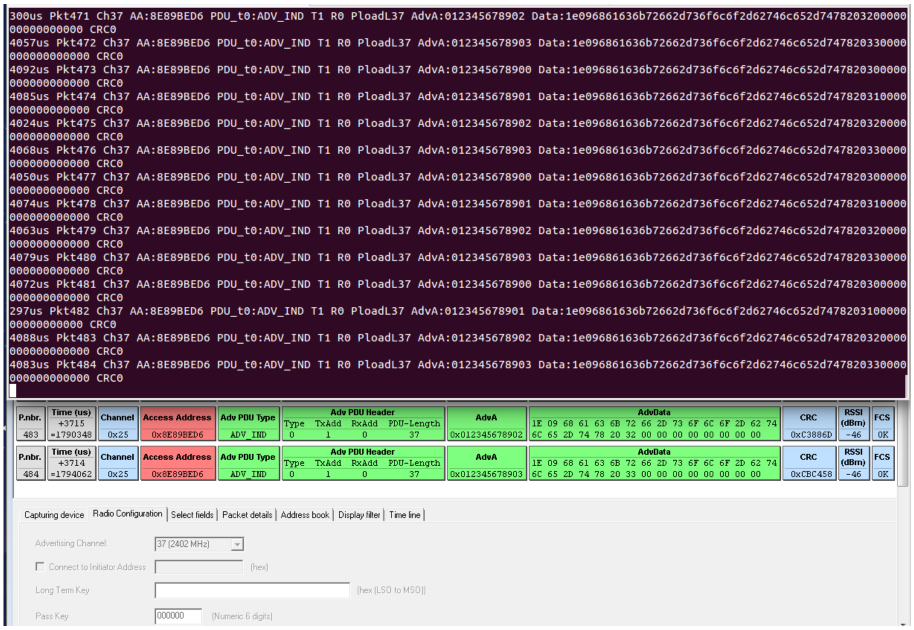

Figure 3.11: Comparison between TI packet sniffer and BTLE packet sniffer

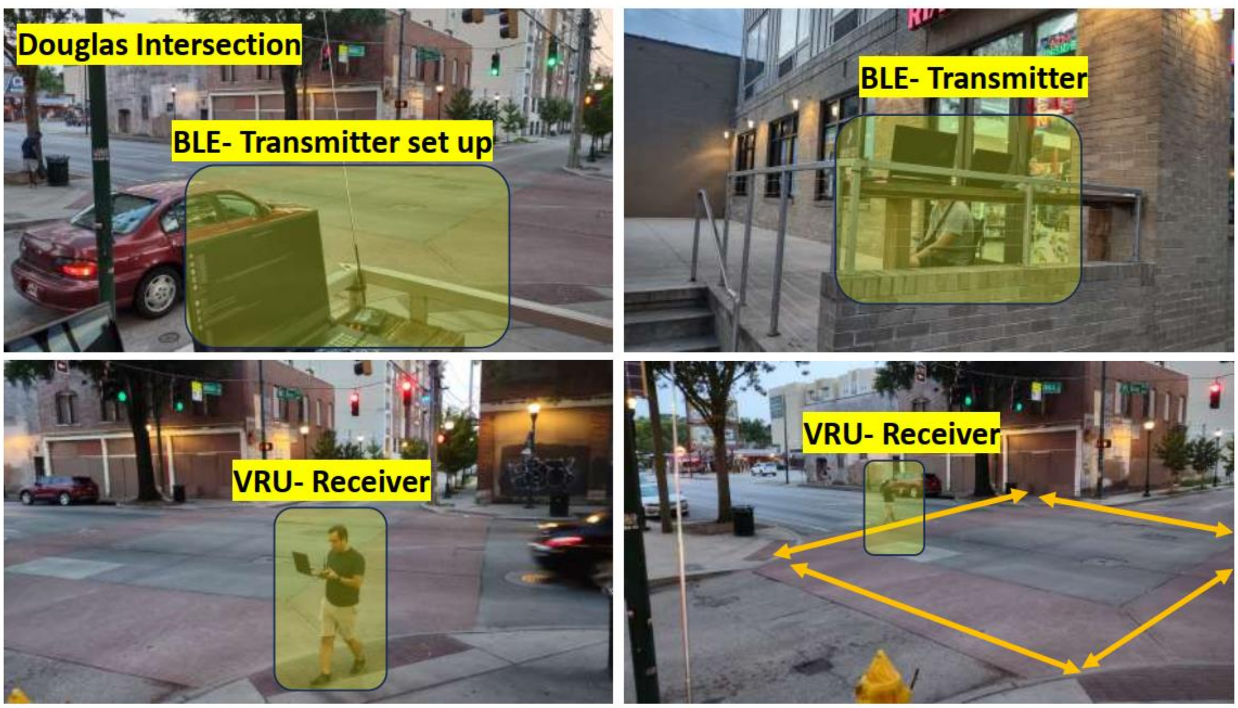

Figure 3.12: Douglas intersection BLE set up

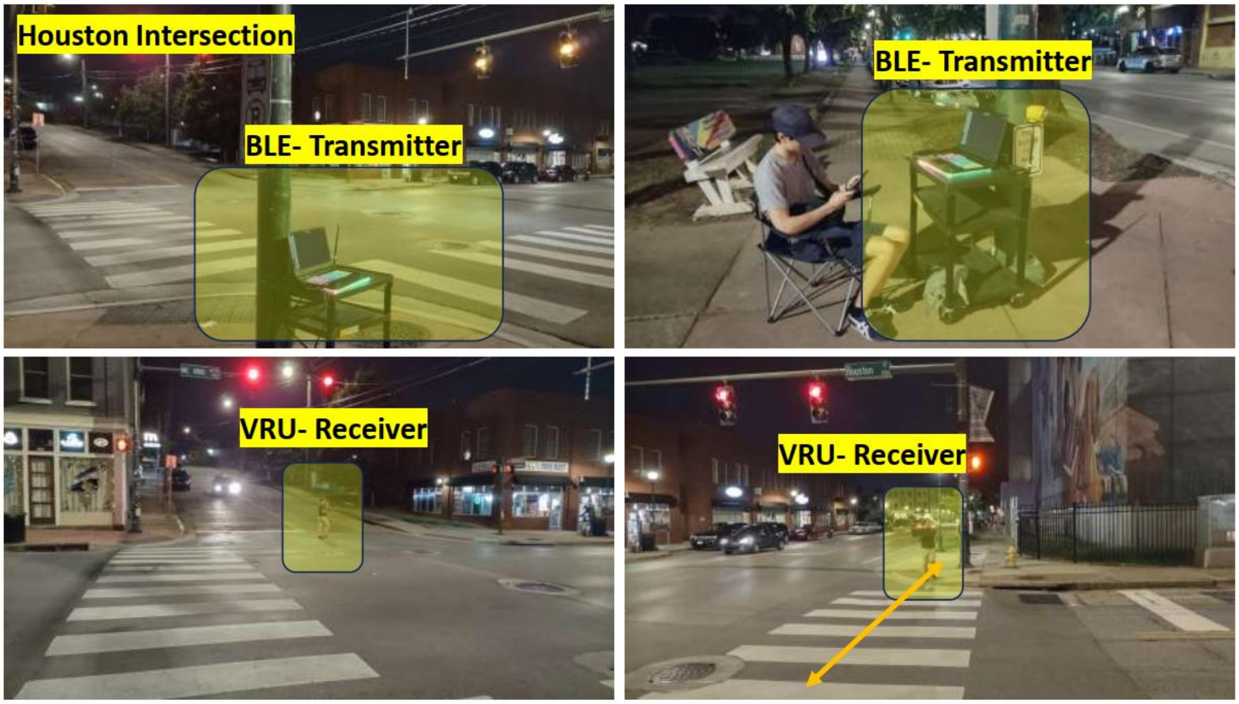

Figure 3.13: Houston intersection BLE set up

Upon conducting the experiments, we began the crucial phase of data processing and analysis. This involved gathering all the data generated from the experiments for preprocessing, which is the initial stage of preparing raw data for analysis by cleaning and transforming it. Following preprocessing, we proceeded to analyze the data. This step involved examining, cleaning, transforming, and modeling the data to discover useful information, draw conclusions, and support decision-making. Next, we visualized the data. Visualization is a critical step in understanding the patterns, trends, and insights within the data. It involves presenting the data in a graphical or pictorial format to provide a clear idea of what the information means by highlighting the relevant trends and outliers. Finally, we compared our findings.

Chapter 4 Results and Discussion

Pedestrian safety can be significantly enhanced through proactive measures taken by pedestrians and vehicles alike, and the initial step towards achieving this is by providing pedestrians and drivers with real-time traffic information to enhance pedestrian safety and mitigate the risk of potential accidents. Therefore, it is critical to determine the most effective technologies for communicating this information in a real-world setting.

4.1 LTE Field Test Results

In this experimental study, we conducted comprehensive testing of LTE and BLE protocols to compare their latency and reliability. Our experiments involved transmitting 84-byte LTE packets between SDRs while recording transmission and reception timestamps to quantify latency. We also calculated packet delivery ratios to evaluate reliability. To visualize the spatial distribution of latency, we employed hexagonal binning based on GPS coordinates. Figures 4.1-4.4 illustrate our results, with the color of each hexagon representing the average latency of packets logged within that area. This provides an intuitive map view of the latency characteristics across the intersections for both protocols. Table 4-1 offers a comprehensive summary of the data collected over 30 rounds of testing. It includes details such as the total number of packets per round, minimum and maximum latency, average latency, and delivery ratio. This table facilitates a quantitative comparison of timing and reliability performance between LTE and BLE.

The variability in LTE communication performance is influenced by factors such as geographical location and movement direction, which can be attributed to the existence of obstacles such as trees and buildings. In order to examine the specific influence of movement direction, our research was centered on the data obtained at crossings during non-peak hours following 6pm and under favorable weather conditions.

Figures 4.1 and 4.2 depict the latency outcomes of the Houston junction employing hexagonal binning, whereas Figures 4.3 and 4.4 present the outcomes for the Douglas intersection. The hexagons in the visualization correspond to different areas and are color-coded based on the average delay of the recorded packets within each region. This color-based representation offers a clear and straightforward depiction of the geographical distribution of latency.

As indicated in Table 4.1, a significant increase in delay was found in the areas located on the opposite side of crossings in relation to the LTE base station. This observation is consistent with the anticipated outcome, as an increased distance from the base station is known to result in diminished signal strength and increased delay. The delay observed at the Douglas junction exhibited an average value of 91 ms, so satisfying the 3rd Generation Partnership Project (3GPP) criterion of a latency threshold below 100 ms. The achieved packet delivery ratio of 89.67% demonstrates a close proximity to the targeted threshold of 90%, indicating a level of reliability in the communication process. On the other hand, the Houston junction demonstrated worse performance, characterized by an average delay of 379 ms and a diminished packet delivery ratio of 87.34%. After analyzing the base station placements depicted in Figures 3.12 and 3.13, it was seen that the Douglas base station was situated at an elevation of 8.2 feet, but the Houston base station was positioned at a height of about 2.5 feet above ground level. The observed disparity in performance may be reasonably accounted for by the difference in height, as elevation significantly influences the propagation characteristics.

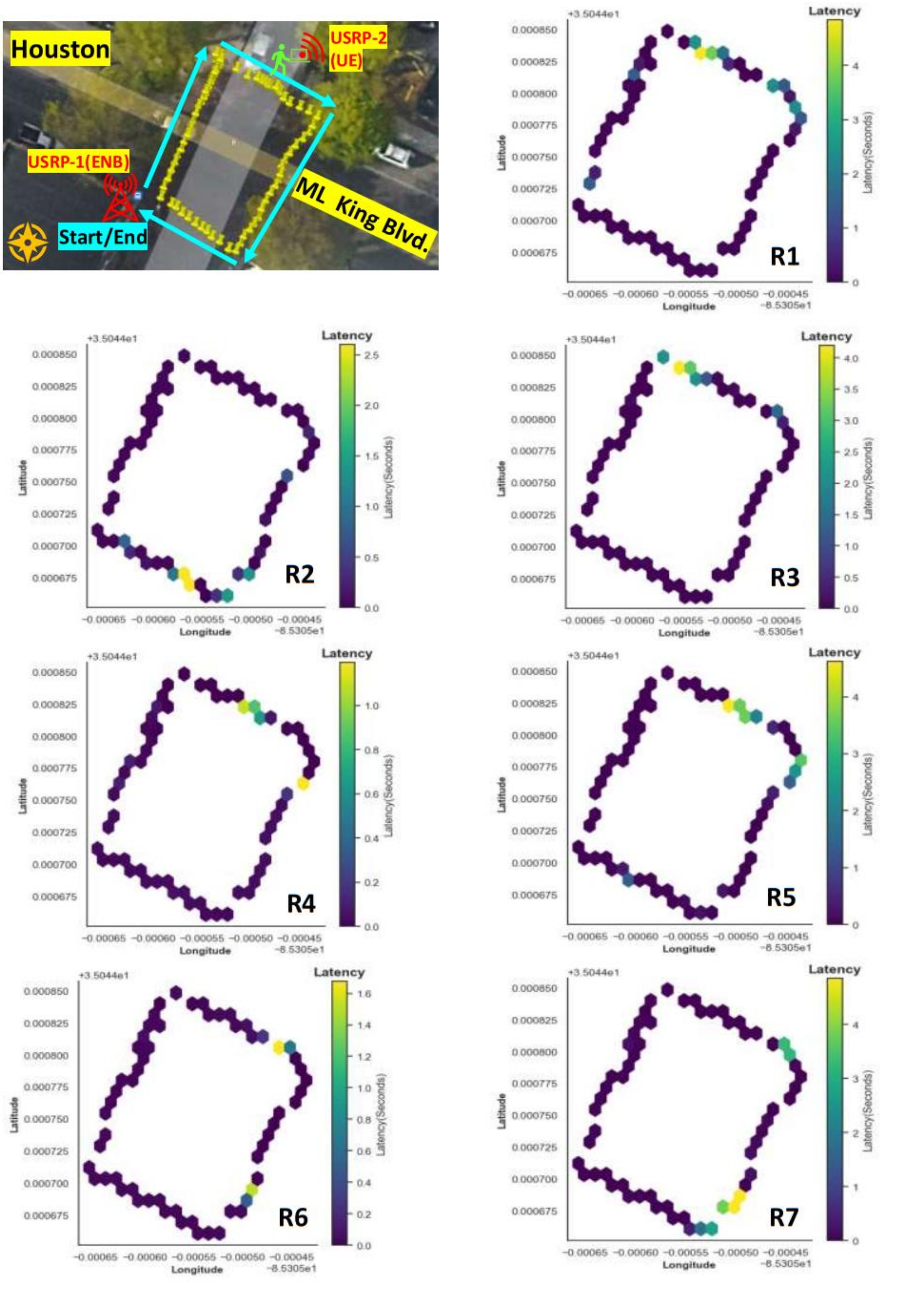

FIGURE 4.1: Hexagon binnings for Latency of LTE communication system at Houston intersection

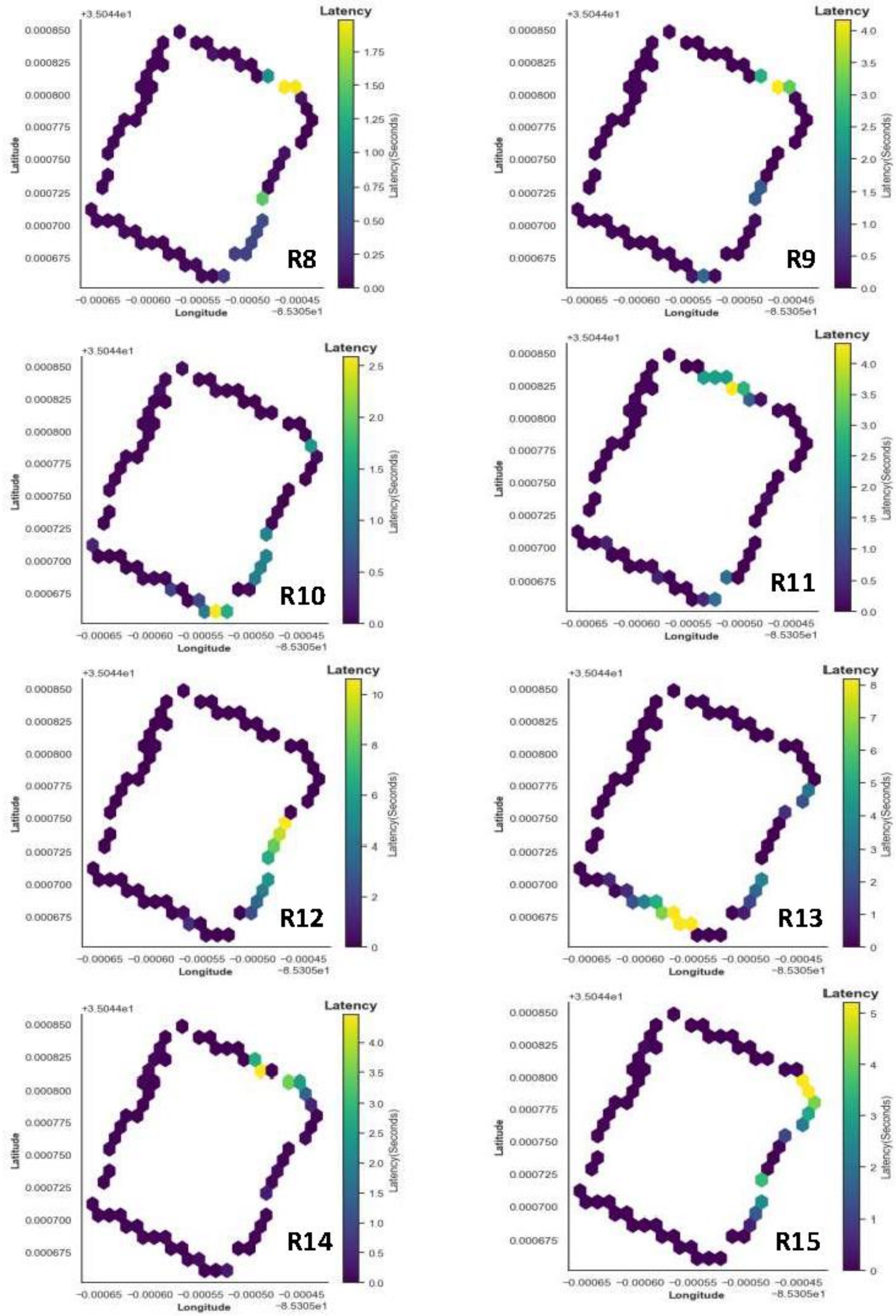

FIGURE 4.2: Continue of Hexagon binnings for latency of LTE communication system at Houston intersection

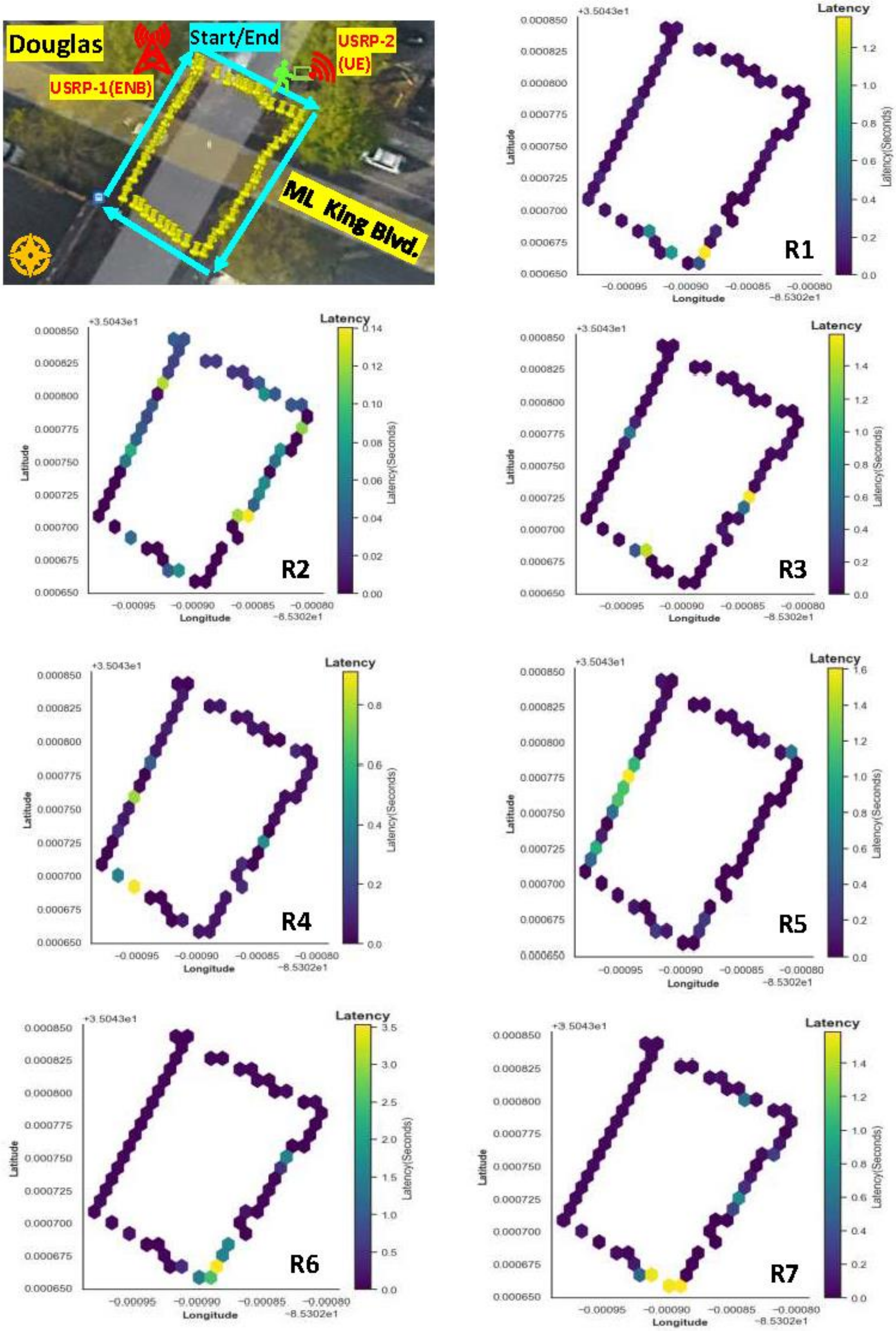

FIGURE 4.3: Hexagon binnings for Latency of LTE communication system at Douglas intersection

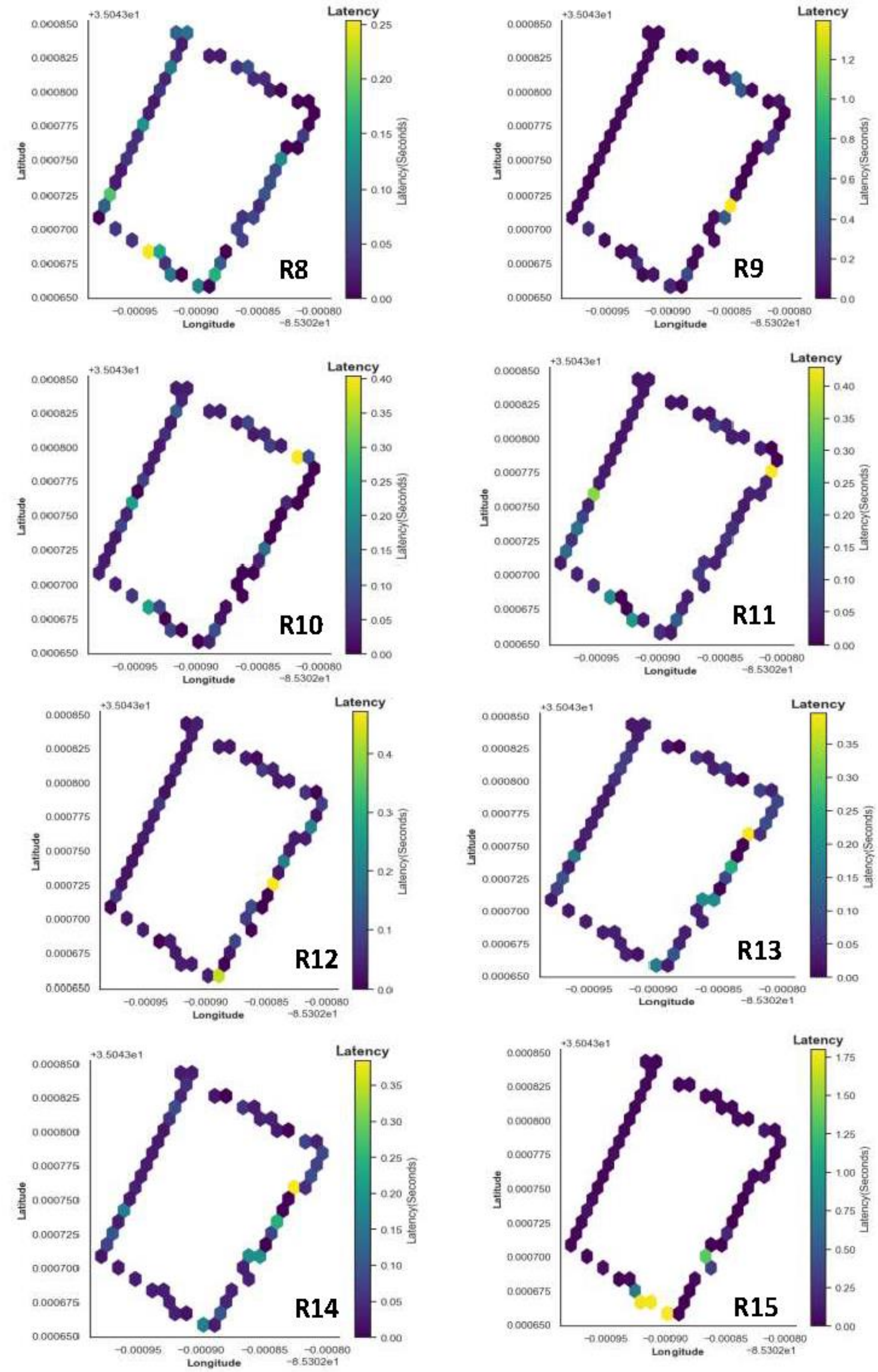

FIGURE 4.4: Continue of Hexagon binnings for latency of LTE communication system at Douglas intersection

TABLE 4-I
Summary of Data Collection. (H: Houston Intersection, D: Douglas Intersection)

Round No.	Inter-section	Total packet	Min latency (sec.)	Max latency (sec.)	Average latency (sec.)	PDR (%)	Failed package (%)
1	H	144	0.001	4.871	0.415	75	25
	D	95	0.0001	1.36	0.084	89	11
2	H	172	0.001	2.606	0.22	94.19	5.81
	D	156	0.0001	0.398	0.0349	83	17
3	H	108	0.001	4.227	0.311	93	7
	D	118	0.0001	1.594	0.0936	88	12
4	H	117	0.001	1.657	0.094	84	16
	D	138	0.0001	1.824	0.089	90	10
5	H	148	0.001	4.631	0.451	91	9
	D	134	0.0001	2.095	0.166	90	10
6	H	128	0.001	1.678	0.094	90	10
	D	104	0.0001	3.534	0.224	93	7
7	H	128	0.001	4.859	0.398	85	15
	D	113	0.0001	1.581	0.123	90	10
8	H	436	0.001	1.98	0.167	98	2
	D	97	0.0001	0.253	0.048	91	9
9	H	130	0.001	5.191	0.282	88	12
	D	106	0.0001	1.396	0.085	90	10
10	H	175	0.001	2.591	0.225	85	15
	D	81	0.0001	0.403	0.051	85	15
11	H	174	0.001	4.332	0.361	78	22
	D	120	0.0001	0.429	0.051	94	6
12	H	123	0.001	10.635	0.902	85	15
	D	101	0.0001	0.472	0.073	91	9
13	H	236	0.001	8.199	1.031	96	4
	D	85	0.0001	0.397	0.058	92	8
14	H	119	0.001	5.495	0.295	85	15
	D	98	0.0001	0.351	0.057	89	11
15	H	109	0.001	5.218	0.441	83	17
	D	82	0.0001	1.801	0.128	90	10
Average	**H**	**163.13**	**0.001**	**4.544**	**0.379**	**87.34**	**12.65**
	D	**108.53**	**0.0001**	**1.192**	**0.091**	**89.67**	**10.33**

4.2 BLE Field Test Results

In our experiment with BLE using a HackRF SDR, we transmitted packets on channel 38 during the advertising phase with a 100ms interval between packets to ensure successful transmission. After 16 rounds of testing, we analyzed the latency and packet delivery ratio (PDR). Figures 4.5-4.7 visualize the latency results for the Douglas intersection using hexagonal binning, while Figures 4.8-4.10 show the outcomes for Houston. The color-coded hexagons represent geographical areas, with the color indicating the average packet delay within that region. This provides an intuitive depiction of the spatial latency distribution. Figure 6 presents a bar chart comparing the average latency across the 16 rounds of testing for both intersections. The Houston intersection exhibited higher overall latency of 0.625 seconds and a lower PDR of 79%. In contrast, the Douglas intersection had a lower latency of 0.359 seconds and a higher PDR of 86%.

The higher than expected Bluetooth latency could be attributed to the Bluetooth version used and random delays in advertisement packets. Similar to our LTE findings, the Douglas intersection performed significantly better, likely due to the higher transmitter placement of 8.2 feet compared to just 2.5 feet in Houston. The increased height enabled broader propagation of the BLE signal, substantially improving the communication performance. Additionally, it was evident that the corners of each intersection farthest from the BLE transmitter faced the highest latency, as expected due to the increased distance and signal propagation loss.

Our BLE experiments and hexagonal binning visualizations revealed the impact of transmitter placement height and highlighted spatial variations in latency across different Chattanooga smart city intersections. These insights can guide optimal positioning for BLE deployments in urban areas

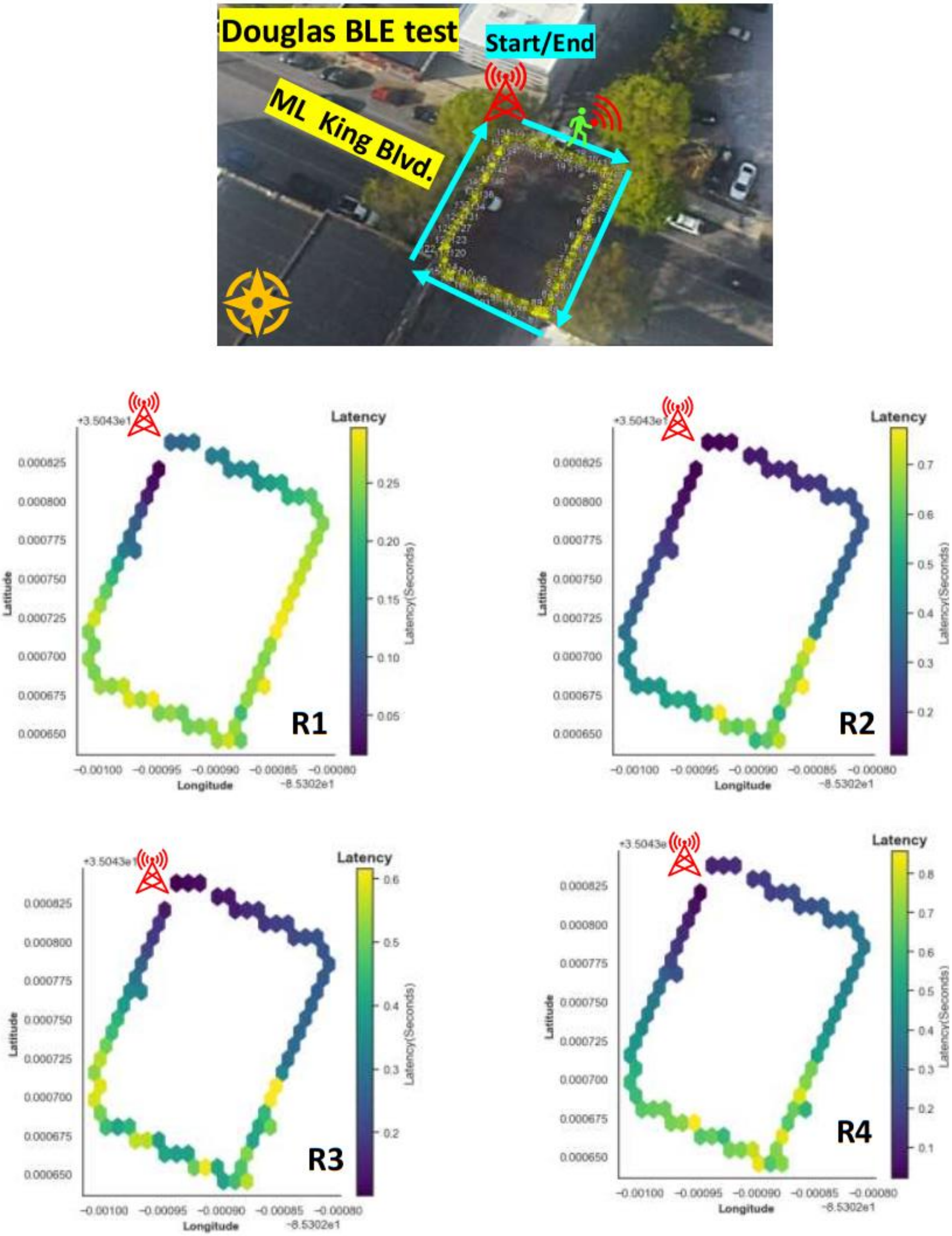

FIGURE 4.5: Hexagon binnings for latency of BLE communication system at Douglas intersection

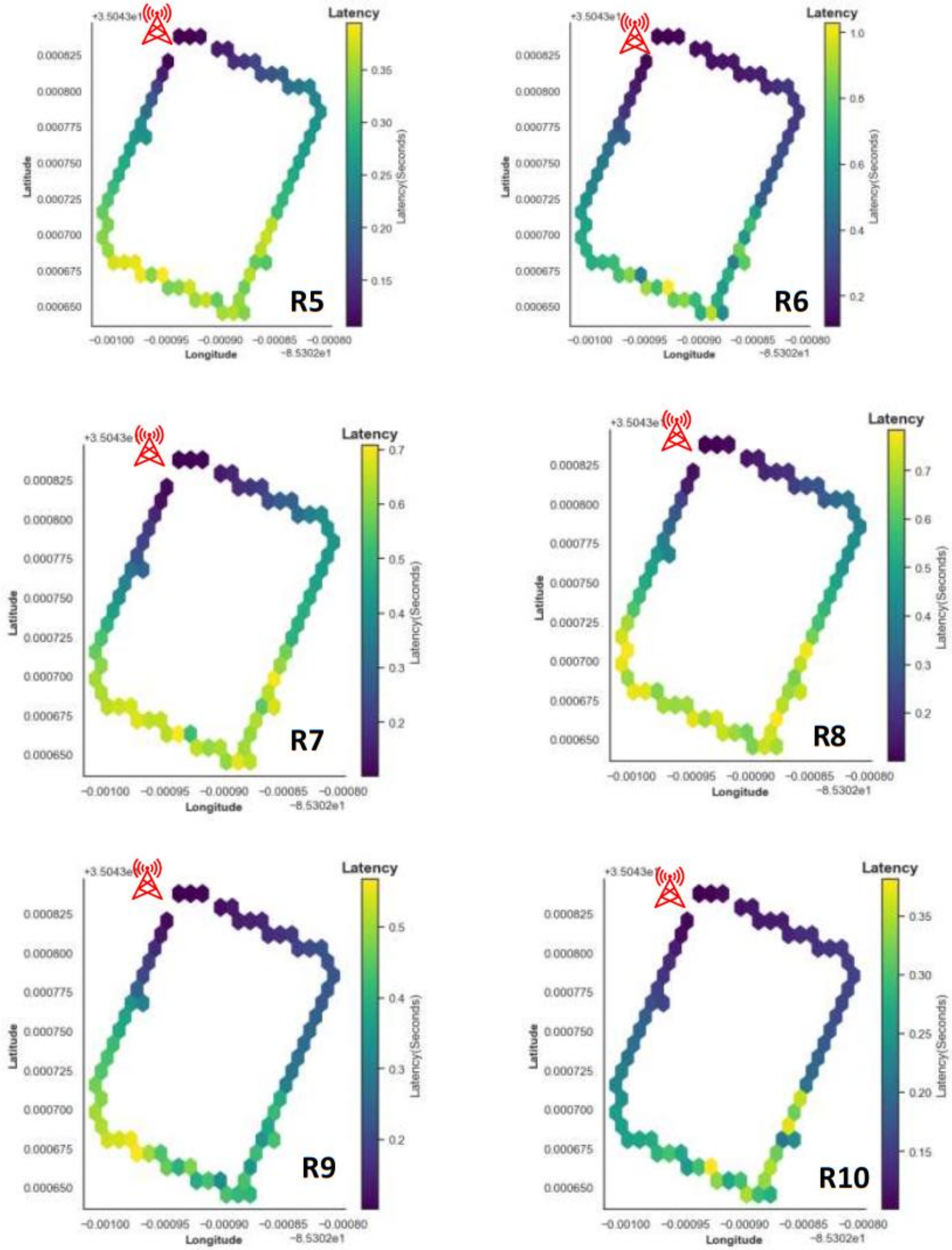

FIGURE 4.6: Continue of Hexagon binnings for latency of BLE communication system at Douglas intersection

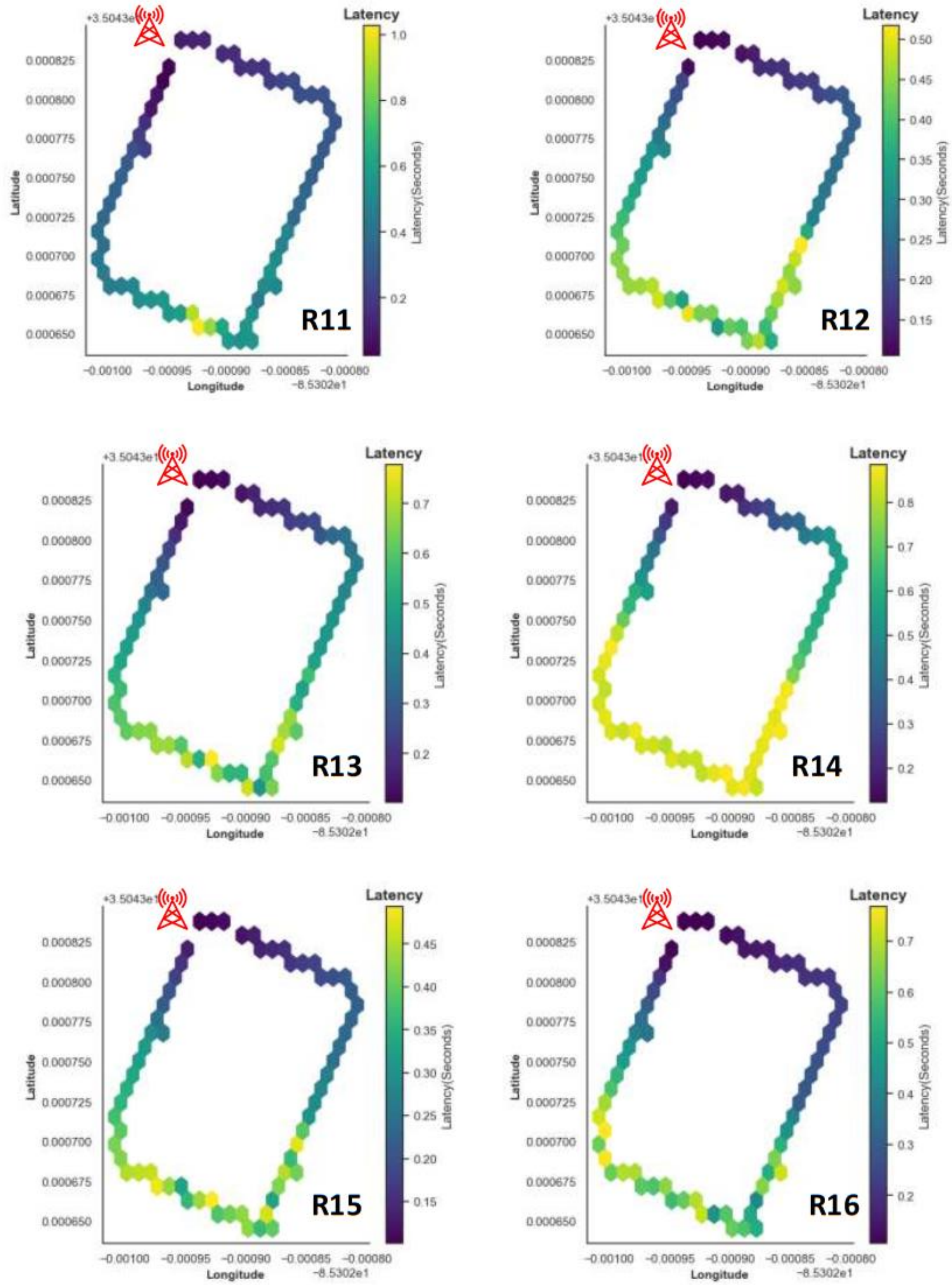

FIGURE 4.7: Continue of Hexagon binnings for latency of BLE communication system at Douglas intersection

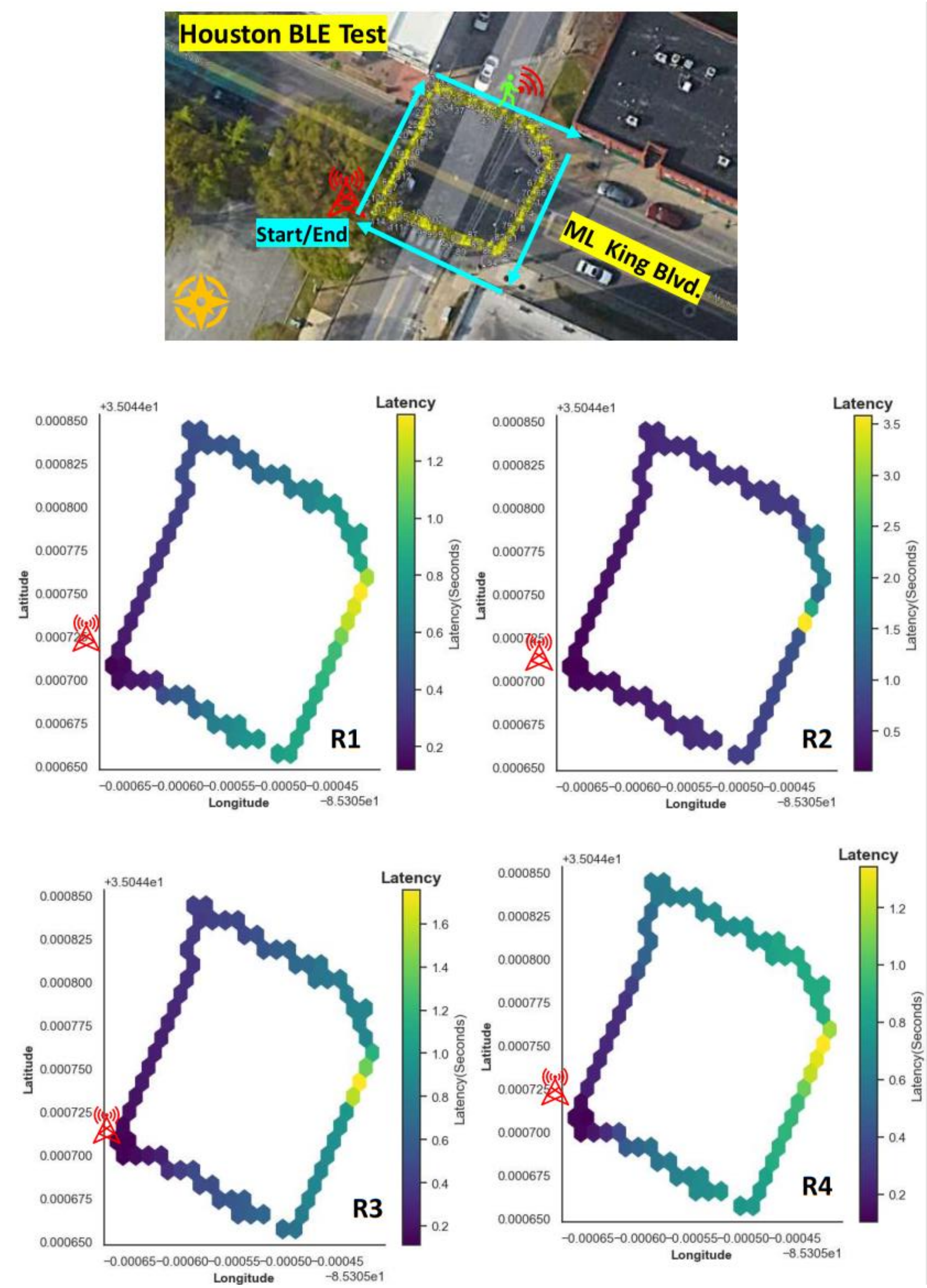

FIGURE 4.8: Hexagon binnings for latency of LTE communication system at Houston intersection

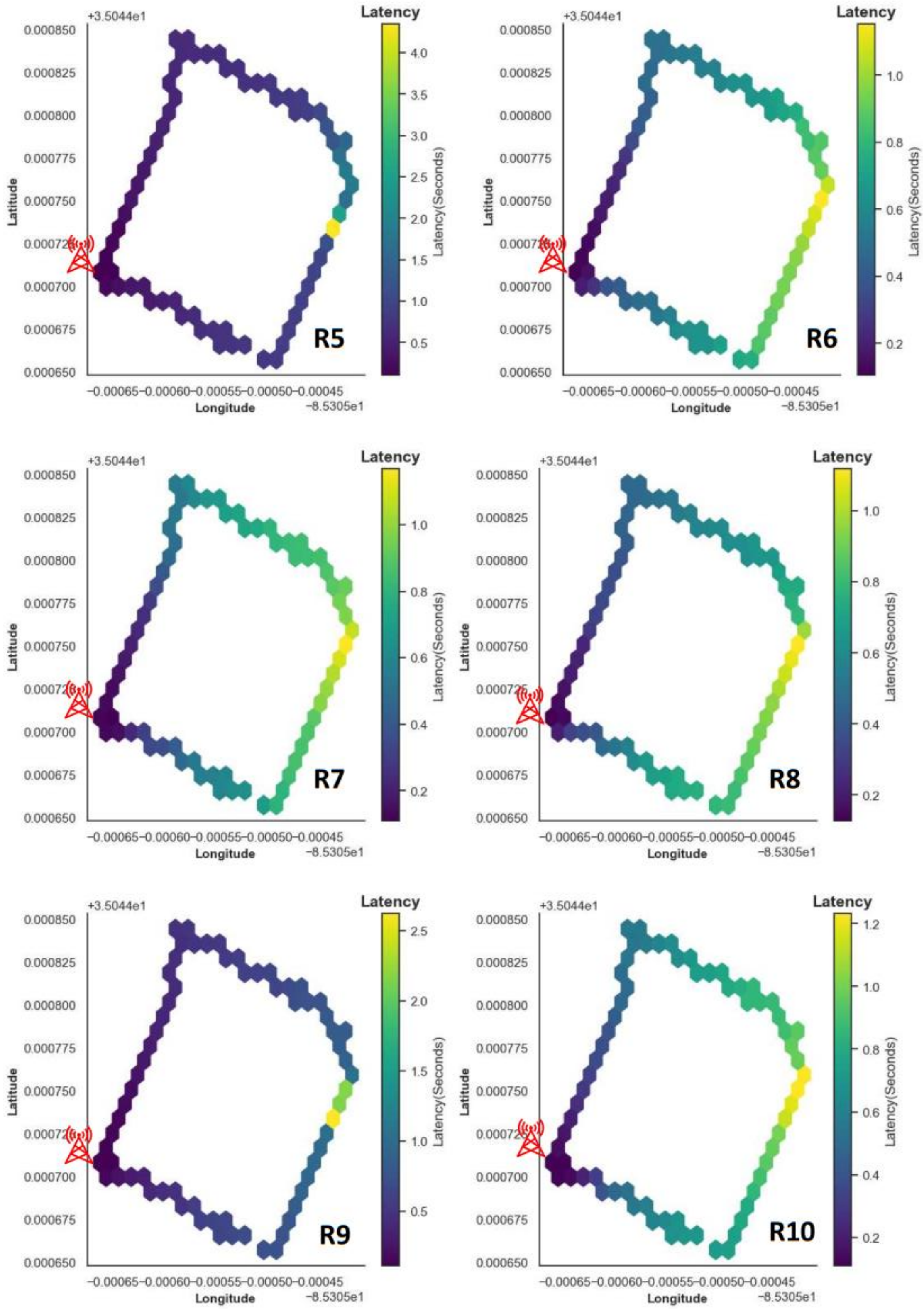

FIGURE 4.9: Continue of Hexagon binnings for latency of BLE communication system at Houston intersection

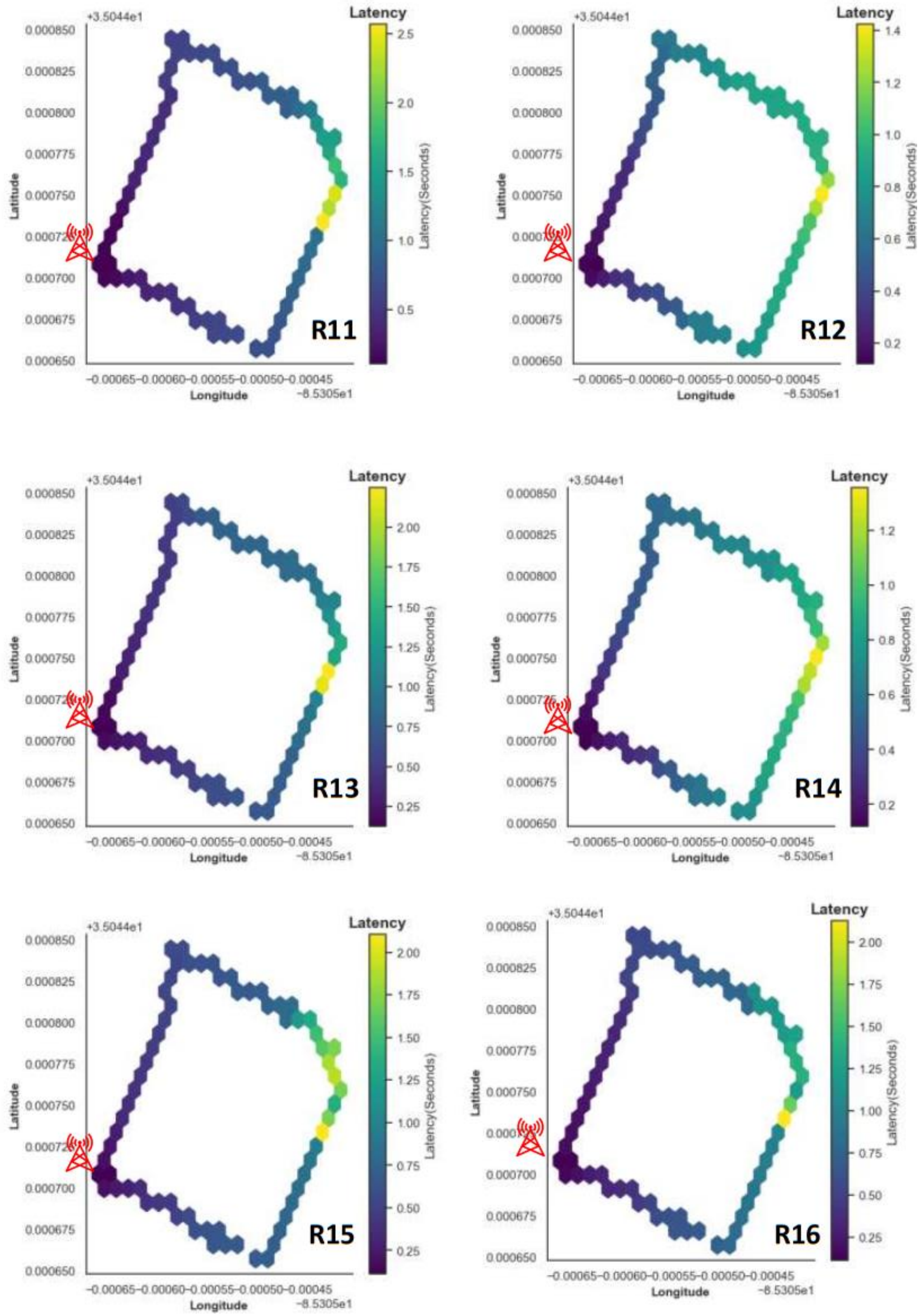

FIGURE 4.10: Continue of Hexagon binnings for latency of BLE communication system at Houston intersection

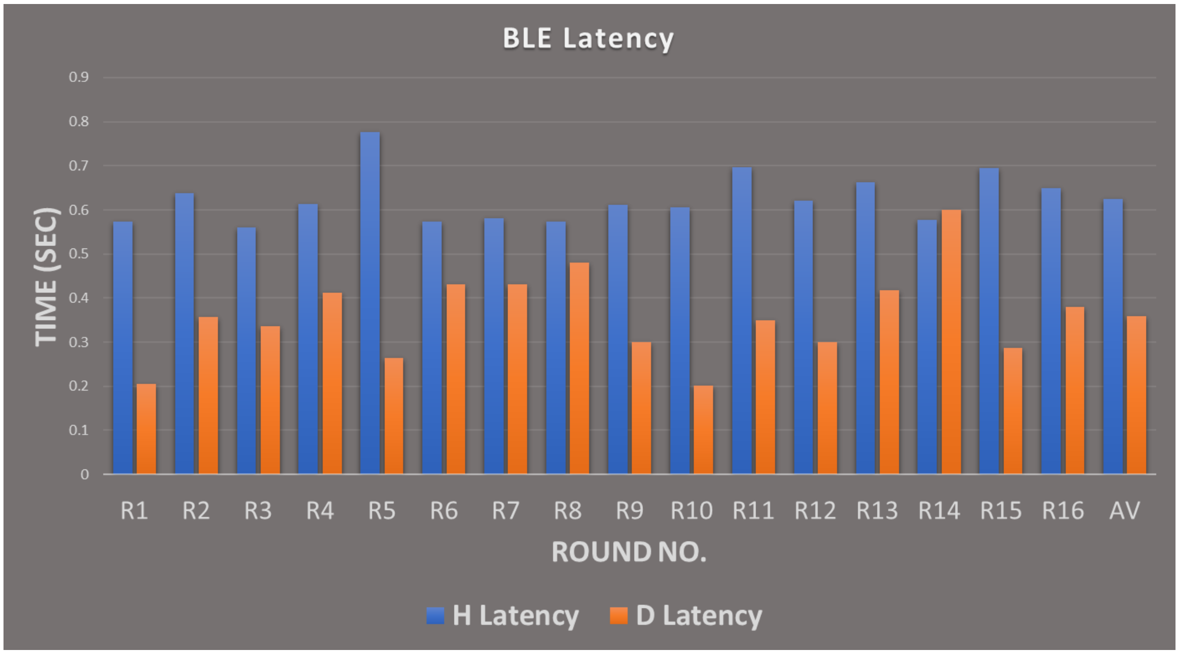

FIGURE 4.11: A Comparison Between Latency at Both Intersections

4.3 Overall Comparison

Table 4-2 and Figure 4.12 offer a direct comparison of the latency and PDR between LTE and BLE at the two intersections across 15 rounds for LTE and 16 rounds for BLE. As shown in the bar chart, LTE exhibited lower latency and higher packet delivery ratios compared to BLE, with the lowest latency observed for PC5-LTE at the Douglas intersection. This highlights the superior performance of LTE over BLE in terms of both speed and reliability in our urban testing environment. The comparison quantitatively demonstrates the advantages of using LTE technology for V2X communication applications that require ultra-low latency and highly reliable data transfer.

A limitation of this project was the lack of robust third-party repositories available for implementing PC5-based LTE communication using SDR, as this is an emerging area still under active development. Further research should focus on building out more comprehensive SDR-based LTE solutions to enable continued innovation and experimentation with PC5 and other leading-edge wireless protocols.

A key weakness of this project was the limited coverage provided by the SDR platforms used. SDRs can also face challenges such as: a lack of support for certain software such as GNU Radio; the absence of front-end filtering leaving them susceptible to interference; and performance constraints related to dynamic range, sensitivity, and bandwidth. Additionally, poor dynamic range in some SDR prototypes, difficulty writing supporting software for different platforms, and challenges interfacing analog and digital modules all present hurdles for implementation. For this research, the coverage limitations reduced the scale of testing, while the other SDR-related challenges highlighted the need for continued SDR development and more robust platforms to enable large-scale experimentation and deployment. Overcoming these limitations represents an important area for future work.

TABLE 4-2
Summary of data collection. (H: Houston intersection, D: Douglas intersection)

		BLE		LTE	
Round#	Inter.	Avrage Latency	Average PDR	Avrage Latency	Average PDR
R1	H	0.572908	75.23	0.415	75
	D	0.205793	83.27	0.084	89
R2	H	0.636941	70.11	0.22	94.19
	D	0.356273	85.88	0.0349	83
R3	H	0.55966	78.43	0.311	93
	D	0.335165	88.47	0.0936	88
R4	H	0.612278	80.12	0.094	84
	D	0.412895	71.55	0.089	90
R5	H	0.776697	82.94	0.451	91
	D	0.263915	89.77	0.166	90
R6	H	0.572743	77.92	0.094	90
	D	0.430989	88.18	0.224	93
R7	H	0.580163	79.14	0.398	85
	D	0.430807	70.12	0.123	90
R8	H	0.573718	83.12	0.167	98
	D	0.479478	83.91	0.048	91
R9	H	0.610407	84.12	0.282	88
	D	0.300083	93.63	0.085	90
R10	H	0.606019	81.55	0.225	85
	D	0.200448	90.03	0.051	85
R11	H	0.696526	79.42	0.361	78
	D	0.349906	91.56	0.051	94
R12	H	0.621567	85.23	0.902	85
	D	0.300273	96.66	0.073	91
R13	H	0.661994	79.19	1.031	96
	D	0.418485	80.76	0.058	92
R14	H	0.57758	77.1	0.295	85
	D	0.600774	80.65	0.057	89
R15	H	0.694261	79.69	0.441	83
	D	0.286041	90.21	0.128	90
R16	H	0.649808	80.8	--	--
	D	0.37883	87.02	--	--
Avrage	**H**	**0.6252**	**79.63**	**0.3790**	**87.34**
	D	**0.3594**	**85.73**	**0.0910**	**89.67**

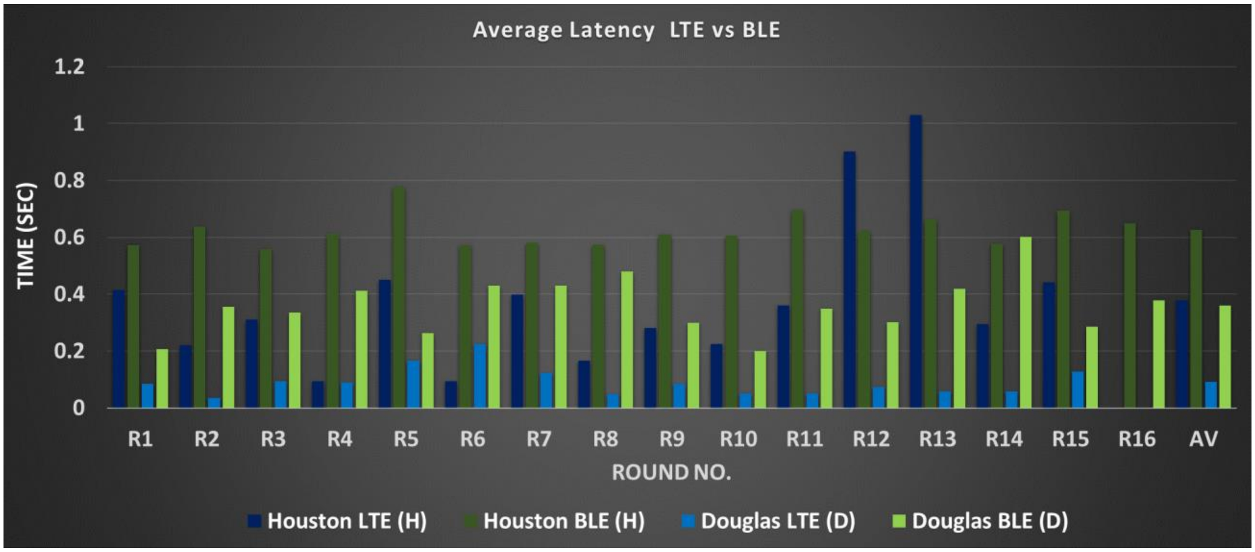

FIGURE 4.12: Overall comparison between latency for LTE and BLE at both intersections

Chapter 5 Conclusion

Examining intersection safety is imperative, as intersections constitute high-risk areas accounting for over 50% of injurious and fatal collisions on roadways. This alarming statistic from the USDOT underscores the exigency to augment protections for all road users at these junctions through studies that can inform efficacious interventions [39]. In this project, we conduct an exhaustive literature review of studies pertaining to V2X and communication technologies. We then scrutinize the technologies utilized for V2X communication for VRU safety. Based on prevalent collision scenarios, we focus our examination on intersections to analyze two wireless technologies: LTE and BLE.

Comparison constitutes an integral element of data analysis, as it enables apprehension of relationships and patterns within the data. By juxtaposing our findings with other studies or benchmarks, we can validate our results and derive more accurate conclusions. This comprehensive approach ensures exhaustive examination of all aspects of our experiment and elicits meaningful insights from our data.

Our evaluation has unveiled the significance of the positioning of base stations and has demonstrated the efficacy of hexagonal binning in visually representing spatial disparities in LTE performance within diverse urban junctions. The revelations offer valuable perspectives for ascertaining the most efficacious locations for base stations to augment the resilience of LTE networks and mitigate latency. Our experiments and analysis effectively characterize the latency and reliability profiles of LTE and BLE in an urban environment through hexagonal binning visualizations and quantitative performance metrics. This furnishes critical insights into the real-world capabilities of these salient Internet-of-Things (IoT) protocols.

Overall, C-V2X exhibited superior reliability in terms of lower latency and higher PDR when compared to the other technology examined, LTE. The average latency for LTE was approximately 91 milliseconds with about 90% packet delivery ratio, which is within the acceptable range specified in 3GPP TS 22.185 version 15.0.0 Release 15 part R-5.2.1-00. However, the results for the Houston intersection were slightly worse. Note that this could have resulted in part due to the height of the eNodeB at the Douglas intersection, which was 8.2 feet, while we placed the USRP on a small table with a height of just 2.5 feet at the Houston intersection.

The lower antenna height at Houston likely contributed to its slightly degraded performance relative to Douglas, as obstacles and interference have a greater impact on signal propagation closer to street level. This emphasizes the importance of elevating antennas above the clutter for better propagation characteristics and connectivity. Overall, our experiments characterize the real-world latency and reliability of LTE at urban intersections and provide insights to inform optimal base station placement for enhancing C-V2X performance.

Postface: Regulatory constraints play a significant role in the deployment of LTE and 5G cellular networks for V2X applications. The Federal Communications Commission (FCC) has allocated specific portions of the spectrum for different technologies, such as assigning the upper 30 MHz of the 5.9 GHz ITS band to C-V2X technology. However, before these technologies can be deployed, they need to receive regulatory approval. The FCC has been working for nearly two decades to develop a comprehensive national framework for ITS, manage finite spectrum resources, expand CV technology adoption and deployment, and position the United States to better compete in global markets. This includes managing interference with other devices and services operating in the same or adjacent bands. The FCC continues to work with USDOT and National Telecommunications and Information Administration (NTIA) to establish final rules for ITS. As these rules are still pending, there is some uncertainty in the industry about future regulatory requirements. These regulatory constraints need to be carefully considered when planning and deploying LTE and 5G cellular networks for V2X applications.

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