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Economical Acquisition of Intersection Data to Facilitate CAV Operations Phase II – Implementation

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CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

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Economical Acquisition of Intersection Data to Facilitate CAV Operations: Phase II (Implementation)

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<tr><td colspan="3">16. Abstract
Cost-effective collection and distribution of intersection data are needed to facilitate traffic operations at intersections in the HDV era and particularly, in the prospective era of CAVs. Existing methods are time consuming and costly. Phase I of this research (executed under CCAT Project Nr. 71) developed a cost-effective intersection data collection and distribution device for this purpose. In Phase II of this research, the device prototype was bench tested in Lansing and field tested at Owosso. It was confirmed that the device successfully facilitates SPaT and MAP data collection and dissimulation to mobile devices. These deployments provided evidence that the device provides public agencies a way to drastically reduce the cost of data collection at their intersections. The technological innovation is that the device provided a much simpler and effective way to collect intersection data. Overall, the expectation is that reducing the costs of infrastructure data delivery will ultimately encourage more rapid deployment of infrastructure data sources. That, in turn, is expected to encourage the entire connected intelligent transportation ecosystem to advance when the potential benefits of the system become more widely available. It is anticipated that could be the start of a rapidly expanding deployment on a much larger scale.</td></tr>
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LIST OF ACRONYMS

ATSC	Actuated Traffic Signal Controller
CAD	Computer-Aided Design
CAV	Connected and Autonomous Vehicle
CRC	Cyclic Redundancy Check
HDV	Human Driven Vehicle
IDE	Integrated Development Environment
ITS	Intelligent Transportation Systems
MAP	Intersection Map
MDOT	Michigan Department of Transportation
NATS	Neural Autonomic Transport System
NCTIP	National Transportation Communications for ITS Protocol
PCB	Printed Circuit Board
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
TSC	Traffic Signal Controller
TSCBM	Traffic Signal Controller Broadcast Messages
UART	Universal Asynchronous Receiver-Transmitter
UDP	User Datagram Protocol
UHD	User Handheld Device
USB	Universal Serial Bus

CHAPTER 1 INTRODUCTION

1.1 Study Background and Problem Statement

Roadway agencies seek cost-effective ways to obtain and distribute traffic data, and thereby, to facilitate operations decisions. This includes a need to make Signal Phase and Timing (SPaT) and Intersection Map (MAP) data more useful to mobile and other devices and connectivity infrastructure. Unfortunately, existing data collection and delivery methods are time consuming and costly. Therefore, to facilitate traffic operations in the current era of human-driven vehicles (HDVs) and the prospective era of connected autonomous vehicles (CAVs), this research developed, in its earlier phase, a device to acquire, process, and disseminate SPaT data from Traffic Signal Controller (TSC) cabinets in a manner that ensures system integrity and yet fosters accessibility of timing information for traffic data end-users.

1.2 A Synopsis of the Previous Study (Phase I)

In Phase 1 of this study (Gowda et al., 2023), the research team developed a device, referred to as a "Data Diode," consisting of two interconnected microcontrollers operating through simplex communication (one-directional data flow). The device connects the TSC cabinet and the end-user's device (such as a user-held device (UHD)), thus facilitating the extraction and processing of SPaT data. The process begins with one microcontroller establishing a connection with the TSC's Ethernet port. Then, utilizing the Simple Network Management Protocol (SNMP) interface, the device securely acquires the SPaT data which then undergoes Cyclic Redundancy Check (CRC) encoding to ensure integrity protection and subsequently transmitted through a unidirectional UART interface to the second microcontroller. SNMP commands cannot be passed back to the signal controller from the Internet, thus, it is not possible to use the interface as an attack surface.

The second microcontroller interfaces with a 4G Cell Modem to transmit the processed SPaT data to the NATS open-source messaging system, incorporating a unique identifier specific to each TSC. A battery of such TSC-Diode systems collects the data from various intersections, and the collected data are routed through their respective channels within the NATS system, thereby facilitating efficient organization and streamlined access.

A backend script acquires GPS coordinates from the UHD, establishing the nearest signalized road intersection. Leveraging this information, the script retrieves relevant SPaT data from the database associated with the corresponding TSC. The user is granted access to this data through a user-friendly web app on the user's UHD. The app dynamically presents real-time information about the traffic signal status and the precise timings of signal phase transitions for the lane of interest.

Overall, the integration of this technology into human-driven or connected autonomous vehicle driver assistance systems can help smoothen arterial traffic flow and transform urban mobility.

The development and implementation of the data diode system represent a significant step forward in enhancing traffic management and control systems. Through the seamless integration of hardware and software components, this research project successfully created a robust and reliable solution that addresses the challenges of secure data transmission from traffic signal controllers.

1.3 Study Objectives

This project explores innovative and cost-effective methodologies for collecting intersection data, a goal that is strategically aligned with the evolving landscape of traffic operations and general quest to prepare road infrastructure in the imminent era of CAVs (Othman, 2021; Saeed et al., 2021). The ultimate objective is to make intersection data more widely accessible to end users in a way that is economically viable.

1.4 Study Framework

To achieve the stated objective, the study framework was designed to consist of development and deployment of a cutting-edge, low-cost data diode solution. This involves partitioning the existing system to facilitate SPaT and MAP data distribution via a simple connection to the traffic signal controller, and then using edge devices to create digests of that data for more efficient delivery to the end users including mobile objects. Figure 1.1 presents the physical view diagram for the entire process.

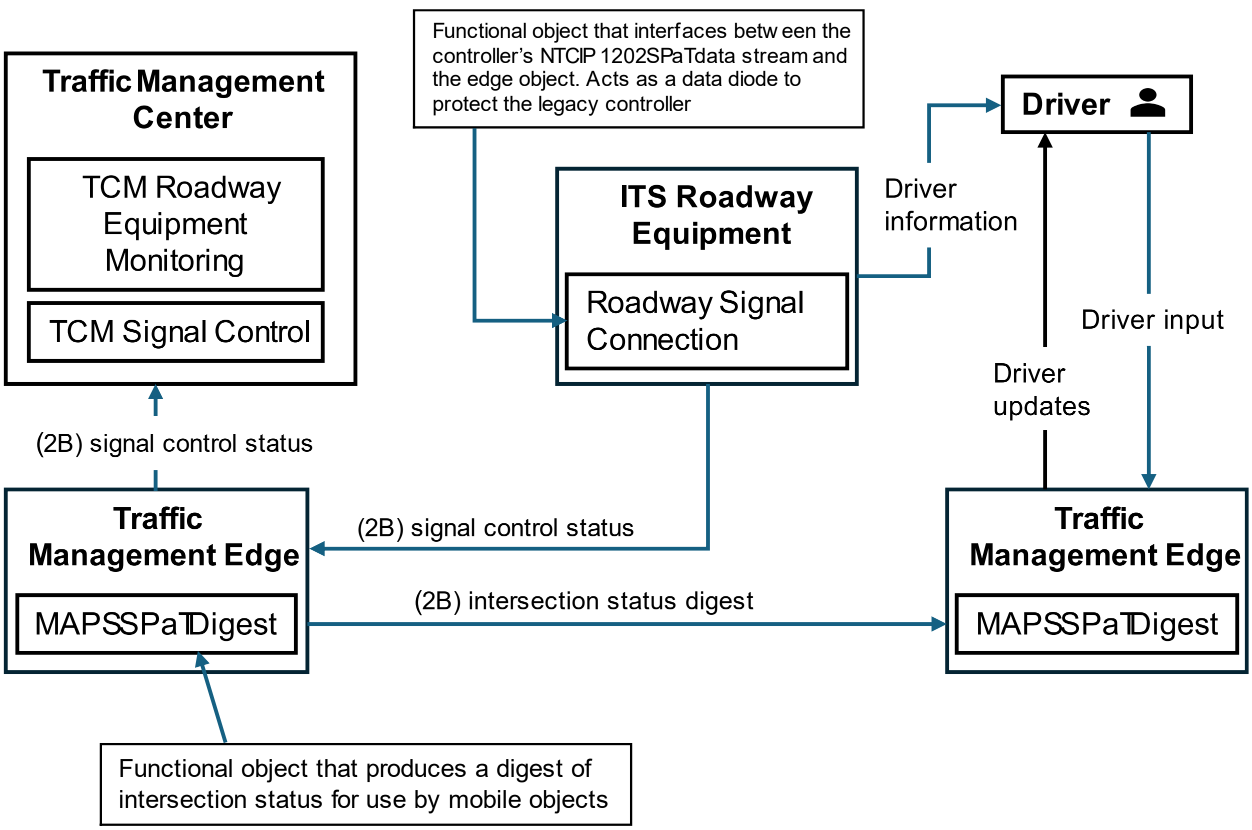

Figure 1.1 Physical view diagram for partitioning the system to distribute SPaT and MAP data, as conducted in Phase I of the study

The physical object on this physical view diagram – ITS Roadway Equipment – served as an opportunity to create a high-integrity data diode. The unidirectional diode was developed to be capable of delivering the state data stream from a legacy traffic signal controller to the edge object using Internet protocols over the wide-area network where the digest will be maintained. This was done while protecting the legacy controller from any harm that may come from the Internet. This opportunity served as the motivation for creating a low-cost, high-integrity device.

This approach can ensure secure retrieval of traffic controller timing data while effectively addressing the demands of data acquisition particularly in the context of CAV operations. To achieve this, the project restricts the dataflow to unidirectionality—a core cybersecurity tenet that underpins the proposed data diode framework. The unidirectionality of the data ensures that sensitive information remains protected against unauthorized access, thereby mitigating potential vulnerabilities and enhancing the overall integrity of the data acquisition process. The device designed to facilitate such unidirectional data transfer is termed the **Data Diode**.

The pivotal contribution of the data diode lies in its ability to enable the seamless and secure transmission of traffic controller timing data at high speed to mobile devices, ensuring that drivers and passengers are equipped with real-time insights. By integrating this unidirectional movement mechanism, the project not only safeguards the integrity of the data but also upholds the security of the traffic controllers themselves.

1.5 The Study Team

The study team consisted of representatives from three key stakeholders: **government** (Michigan DOT, City of Owosso), **industry** (T-Mobile, The Transformation Network, Inc., CubeFog, Mark Goodfriend Inc.), and **academia** (Purdue University, Virginia Tech). These participants worked together to design the study product (that is, the data diode device) in Phase I and to carry out the pilot deployments of the device (in the current phase (Phase II).

1.6 Organization of this Report

The report first presents the study background and motivation, the study objectives and scope, and the study team. This is followed by Chapter 2 which describes the work done in Phase I (the overall approach, system architecture, components of the code, and the device development). In Chapter 3, the report provides details and results of the field deployment and testing processes, and Chapter 4 offers some concluding remarks including the practical usefulness of the device developed in this project, and avenues for prospective deployment and further device development. Chapter 5 summarizes the levels of established USDOT performance indicators achieved in this study. Chapter 6 presents the study outputs, outcomes, and impacts.

CHAPTER 2 APPROACH, SYSTEM ARCHITECTURE, AND DEVICE DEVELOPMENT

2.1 General Study Approach

The MAP message and the National Transportation Communications for ITS (Intelligent Transportation Systems) Protocol (NTCIP) 1202v2 Traffic Signal Controller Broadcast Messages (TSCBM) are key aspects of the intersection data acquisition and processing activities of this research project. The MAP message serves as a comprehensive repository of key information on an intersection's configuration and regulatory characteristics. It includes details such as lane-level road geometry, permitted turning maneuvers at stop lines, and other regulatory data specific to an intersection or associated roadway segment. This multifaceted message structure effectively conveys diverse road geometries, with particular emphasis on its "intersections" structure, which is important in this context. The NTCIP 1202v2 Traffic Signal Controller Broadcast Messages (TSCBM) are systematically disseminated by Traffic Signal Controllers (TSCs) and encapsulate the Signal Phase and Timing (SPaT) information (which is a cornerstone element for understanding current and future movements orchestrated by one or more signal controllers). Beyond SPaT, these messages also furnish insights into lane or intersection regulations that may be fluctuating with the time of day, such as designating a lane to one direction in peak traffic hours. Appendix A.1 of the Phase I report provides a link to the standard NTCIP Object Definitions for Actuated Traffic Signal Controller (ATSC) Units.

The combination of these messages facilitates a comprehensive and granular understanding of an intersection's dynamics. The MAP message, with its lane-level geometry details and turning maneuvers, provides a spatial blueprint of the intersection's layout and operational rules. On the other hand, the TSCBM, with its SPaT information and regulatory data, captures the temporal variations of traffic movements and regulation shifts.

Together, these messages synergistically contribute to the project's overarching goal of enhancing intersection data accessibility, accuracy, and security. By harnessing the power of the MAP and TSCBM messages, the developed device is intended to provide drivers with real-time information about traffic light status, ensuring safer and more informed commuting experiences. This integration of complex data structures not only fosters improved decision-making for drivers but also sets the stage for optimized traffic management in the context of CAV systems. This capability has wide applications in urban traffic engineering including dynamic urban traffic rerouting (Zhao et al., 2017; Aleksandr, 2018; Du et al., 2023) and scalable traffic signal control (Ha et al., 2022; Bao et al., 2023).

An individual signalized intersection consists of fundamental components (Urbanik et al., 2015): a controller, a cabinet, displays (or indications), and typically, detection mechanisms. These are illustrated earlier in Figure 2.1 (Chapter 2 of this report), and Figure 2.2 presents the component users interactions.

When approaching the intersection, mobile end users, including vehicles, pedestrians, and two-wheelers play a pivotal role in this ecosystem by transmitting messages to the controller as and when needed (for example, as they approach the intersection). Such communication forms the backbone of the ecosystem. Subsequently, the controller harnesses the input received from these ecosystem participants to orchestrate changes in signal controls and subsequent user displays for the benefit (safety, mobility, or mobility reliability) of the participants. These alterations in displays are predicated on the signal timing parameters defined by practitioners, thereby adhering to established guidelines.

The controller's role in allocating time to different users hinges on an interplay between the ecosystem participant detection mechanisms and signal timing parameters, often reflected through the controller settings (which are managed by traffic signal practitioners). This interdependence dictates the pace and synchronization of traffic flow, optimizing efficiency and safety within the intersection ecosystem. The symbiotic interplay among the intersection hardware, controller, and participants, and practitioner-defined settings fosters seamless management of traffic flow, optimizing travel efficiency and safety for all road users.

Traffic signal control cabinets located at road intersections house the vital control hardware and software needed for traffic signal operations. These cabinets also serve as repositories of critical data which are pivotal for informed analysis and decision-making towards signal operations optimization. As discussed in earlier sections of this report, the data acquisition process must not take place at the expense of the cabinet data security. When TSC housed in these cabinets interfaces directly with microcontrollers that engage in broader communication with external entities—wherein data are both collected and processed—an inherent security risk emerges. This exposure could potentially render the TSC vulnerable to exploitation by malicious actors, endangering the real-world management of vehicle traffic and thereby posing severe threats.

Figure 2.3 presents a prototypical cabinet and its internal components. This illustration provides insight into the physical structure and arrangement of these critical elements that collectively govern the functionality and orchestration of a signalized intersection. The data diode concept represents a comprehensive exploration into the realm of secure and efficient extraction of high-speed SPaT data from such TSCs. Leveraging cost-effective components such as 32-bit microcontrollers, compatible 4G cell modems, and advanced 4G Ultra-Wide Band Antennas. The current project seeks to establish a robust solution that maintains affordability while safeguarding the data transfer efficiency, and its reliability and security.

To address such cybersecurity concerns, the current project used a twin-microcontroller approach. The first microcontroller, housed in the cabinet, interfaces directly with the TSC. Its primary role is to extract intersection data that are then transmitted through a single-directional simplex communication cable to a second microcontroller. This second microcontroller serves as the intermediary that relays the data to a remote server using a cell modem. Then, comprehensive analytics can be carried out at the remote server. The key innovation of this approach lies in the physical isolation of the first microcontroller from external communication networks. By severing any direct physical links between the microcontroller and external entities, the security of data extraction is established. By such isolation, potential vulnerabilities are avoided, enabling a secure environment for data collection.

SPaT data are wirelessly transmitted by the cell modem interfacing the second microcontroller to a NATS Server where the data are categorized based on sender identification embedded by the second microcontroller. NATS, known for its lightweight and open-source architecture, seamlessly supports distributed systems while adhering to the core tenets of performance, scalability, and ease of use. Also, NATS simplifies the process of integrating additional TSC-diode units into the broader system. As new TSC-diode units are introduced, NATS effortlessly handles the integration of their data streams, ensuring smooth communication and coordination within the larger network. This streamlined scalability enables the system to grow in response to evolving traffic demands and changing intersection configurations without causing complications or disruptions.

Figure 2.1 Typical Signalized Intersection Components (Urbanik et al., 2015)

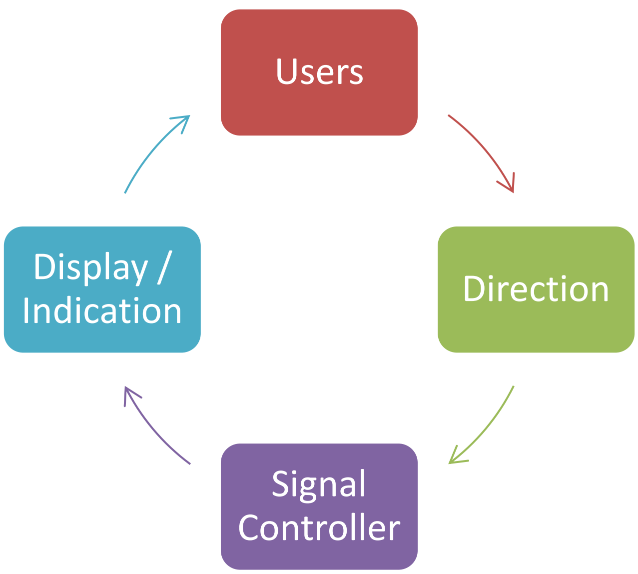

Figure 2.2 Generic Signalized Intersection Interaction (anon)

(image sources: www.pnj.com/story/news/local/pensacola/beaches/2018/02/21/new-solution-pensacola-beach-traffic-engineers-can-now-remotely-control-traffic-lights/354506002/; and www.kdmsteel.com/traffic-cabinet)

Figure 2.3 Typical TSC Cabinet

The intended product of this project represents a practical application that can enhance the convenience or experience of the end user. Leveraging the location information derived from a road user's mobile device, the system identifies the nearest intersection using the stored MAP data. By accessing the corresponding SPaT information, the system promptly communicates the traffic light status to the road user's or end user's handheld device. This real-time dissemination provides users with critical information, fostering a safer and more efficient commuting experience. In subsequent sections of this report, we provide comprehensive details of the project, spanning its constituent hardware and software elements to the workflow setup and operational methodologies. Ultimately, the project seeks to redefine the landscape of intersection data acquisition and security in the context of urban traffic operations. This, hopefully, will set a precedent for efficient, secure, and user-centric urban transportation systems in the current era of human driven vehicles as well as the emerging future era of connected and autonomous vehicles.

2.2 System Architecture

The end-to-end architecture of the system comprises four distinct components, each tailored to specific functionalities. The details, provided in the Phase I report (Gowda et al., 2023), are:

- Controller side of the data-diode
- World side of the data-diode
- Server/edge side of the system
- Mobile app side of the system

By decomposing the system into these discrete components, the complex processes of data acquisition, transmission, processing, and display are streamlined. Each component plays a designated role, enabling efficient communication, parsing, and analysis of the intersection data. This modular structure not only enhances the system's robustness and efficiency but also facilitates easy maintenance, scalability, and future enhancements. The preceding sections outlined the diverse components in conjunction with their interconnections that constitute the Data Diode system. Figure 2.4 presents this comprehensive architecture (synergistic integration of the components). Furthermore, Figure 2.4 presents the practical manifestation of the system and indicates a real-life demonstration. Notably, the initial rendition of the data diode, Version 1.0, is presented in Figure 2.4.

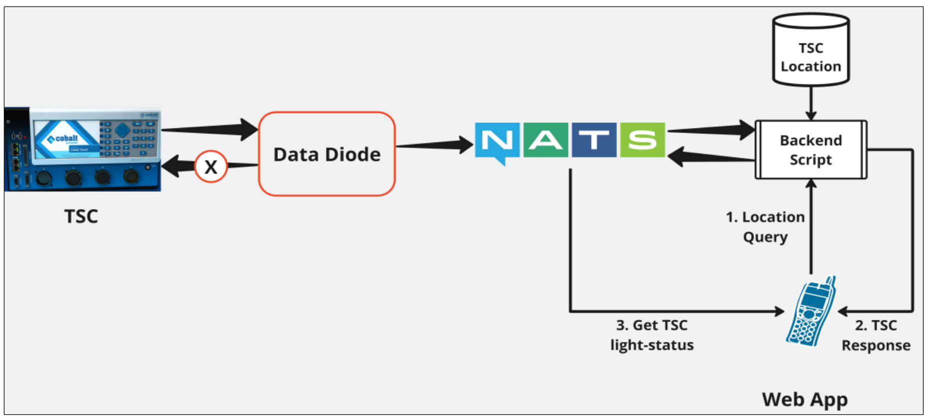

Figure 2.4 System Workflow (Gowda et al., 2023)

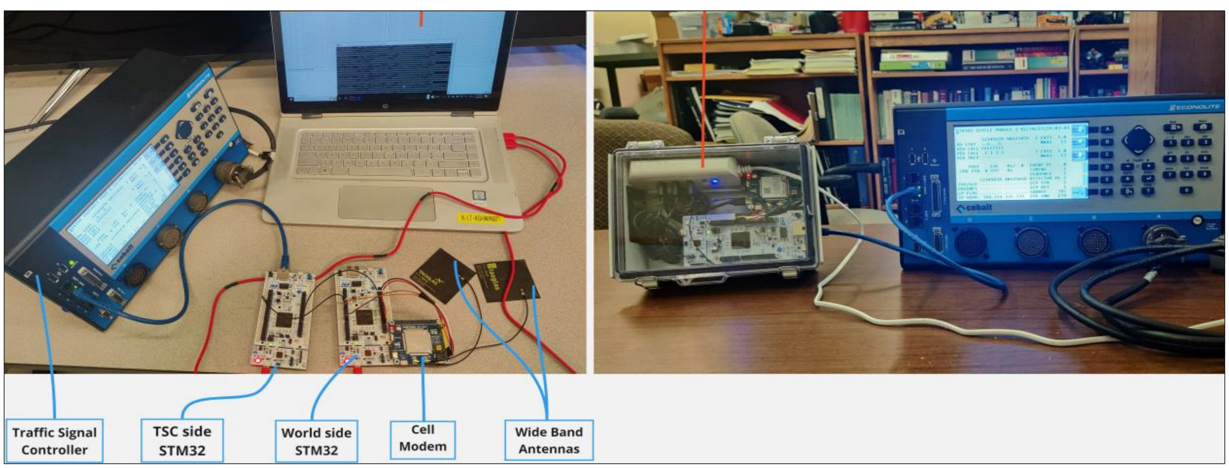

Figure 2.5 Data Diode Practical Representation (Gowda et al., 2023)

2.3 Components of the Code

The comprehensive suite of software and design resources used in this research project encompasses a range of essential components, each serving a distinct purpose within the system architecture. The tools and scripts, and their respective functionalities, are listed as follows:

- STM32 Arduino IDE Programs
- NATS Python Script
- Svelte Mobile App Code
- Python Program for MAP Conversion
- KiCad Files for PCB Layout (Version 2.0)
- CAD Files for Enclosure (Version 2.0)
- Auxiliary Tools to simulate TSC behavior in scenarios where direct access to a TSC might be impractical, and to facilitate quantification of system latency for comprehensive performance evaluation.

The entirety of these resources, collectively contributing to the success of the project, is housed within the GitHub repository accessible at https://github.com/oats-center/data-diode. Within this repository, stakeholders can access, examine, and engage with the various tools and components integral to the Data Diode project. These resources collectively underpin the functional capabilities of the Data Diode project. The repository's accessibility ensures that stakeholders and enthusiasts can readily explore, understand, and harness the capabilities of the product of this research. For an in-depth exposition on the specifics of each resource, their roles, and their interplay within the project, the reader is referred to Chapter 5 of the Phase I report.

2.4 Device Development

This included the following aspects: the controller side of the Data Diode, the world side of the Data Diode, TSC simulator and server/edge side of the system, web app side of the system, setting up python server to listen to modem data in UDP version of the code, running the server on Amazon EC2 Instance, and developing the Grafana dashboard, diode component enclosures. Each aspect is discussed below.

2.4.1 The Controller side of the Diode

The TSC side of the Data Diode is effectively realized through the execution of four distinct sub-tasks which are comprehensively discussed in a previous chapter of this report. The subsequent sub-sections address four sub-tasks: (a) Programming the TSC, (b) Programming the STM32 microcontroller to receive SNMP data from the TSC via the Ethernet port, (c) Encoding data using a Base64 encoder, including the received SPaT data and a CRC value, and (d) Transmitting the encoded data over the Tx port of a simplex UART connection

2.4.2 The World side of the Diode

The World side of the Data Diode is realized by executing 3 sub tasks as mentioned in an earlier chapter of this report. Each of these 3 sub tasks is explained in the following sub sections: (a) Programming an STM32 microcontroller to receive encoded SPaT data from the controller side of the STM32 through the Rx port of a simplex UART connection, and (b) Interfacing the STM32 on the World side with a 4G LTE-compatible cell modem, (c) Publishing the encoded SPaT data to a remote NATS server using the Modem Client, with the data destined to the NATS subject specific to ”UNIQUE ID” (d) LED Indications for data diode operation and cellular modem status, and (e) Optimizing serial buffer size for efficient serial communication.

2.4.3 TSC Simulator and Server/Edge Side of the System

This consisted of (a) Establishing a NATS server configured to continuously listen for data from all TSC-Diode systems, (b) Simulating messages on NATS server, (c) Decoding the base64-encoded data and parsing the fields of the NTCIP 1202v2 TSCBM SPaT data, (d) Associating the UNIQUE ID with the corresponding intersection and re-publishing the parsed data to the relevant intersection subject, (e) Responding to the app’s queries by providing information about the nearest intersection name and ID, current traffic light status, and permitted maneuvers in the app’s queried location.

2.4.4 Web App Side of the System

The Svelte tool was used for building a simple web application. Svelte is a modern web application framework that offers a unique approach to building user interfaces. Unlike other frameworks where the user interface components are interpreted at runtime, Svelte takes a different approach by compiling components into efficient JavaScript modules during build time. This compilation process optimizes the performance of the application and eliminates much of the overhead that traditional user interface frameworks introduce. Since Svelte compiles components into efficient JavaScript code, there is significantly less runtime overhead compared to other frameworks. This leads to faster load times and smoother user experiences, as unnecessary abstractions and runtime computations are minimized. Its compilation process results in smaller bundle sizes for your application. The generated JavaScript modules are tailored to the specific features used in your components, reducing the need for shipping unused code to the client’s browser. It provides a rich library of components that one could use as a foundation for building one’s app. These components cover various aspects of UI, including forms, navigation, layout, and more. Additional information could be obtained at https://kit.svelte.dev/

This aspect involved: (a) Designing a user-friendly mobile application capable of capturing the user’s GPS location; (b) Querying the server for the nearest intersection number based on the user’s GPS coordinates; (c) Subscribing to the NATS topic specific to the intersection number to retrieve the parsed SPaT message; and (d) calculating and displaying latency information through a dedicated script.

2.4.5 Setting up Python Server to Listen to Modem Data in UDP version of the code

The initial version of the code did not include integration with the NATS messaging system. Instead, it focused on a straightforward UDP packet transmission to a remote server. In this version, the data from the Data Diode system was sent over a UDP connection to a designated server without the additional functionality and features provided by the NATS protocol. In this version, the data packet was constructed by directly appending the UNIQUE ID to the SPaT data, without any CRC or base64 encoding applied. Consequently, the total size of the data packet in this configuration was determined by the sum of the size of the SPaT data and an additional 12 bytes for the UNIQUE ID. This original implementation aimed to establish a basic data transmission mechanism for the current project’s requirements. In this regard, ”receive data.py” in the git repository realizes a python program that connects to a public IP, binds to a UDP socket and continuously listens to the incoming traffic. The code can be run the while the user intends to operate the Data Diode to receive the TSC SPaT messages. Then, data logging on to a text file, was carried out.

2.4.6 Running the server on Amazon EC2 Instance, and developing the Grafana Dashboard
A Grafana dashboard was developed to visualize the traffic light status at an intersection. Grafana is a versatile open-source analytics and interactive visualization web application that enables the creation of informative charts, graphs, and alerts when connected to compatible data sources. To construct this traffic light visualization, the team used the ”Traffic Lights” plugin available in Grafana. This plugin facilitates the design of a simple layout representing a four-lane intersection.

2.4.7 Diode Component Enclosures
Two enclosures were designed to house the two STM32 boards and the cell modem, each undergoing iterative improvements for optimal functionality and aesthetics. The first version, labeled as version 1.0, utilized a waterproof box from Polycase, specifically the WQ-48 Hinged Grey Waterproof Box with a transparent lid. The dimensions of this box were 8.24 x 6.29 x 3.93 inches. The choice of this box was based on factors such as its size, transparent lid, and compatibility with the diode layout. More details about this box can be found on the Polycase website https: //www.polycase.com/wq-48. The transparent lid of the box was particularly essential as it allowed the LED status indicators on the world side STM32 board to be visible from the outside. This way, observers could monitor the transmission status without needing to open the enclosure. A custom mounting plate was crafted using acrylic material with the assistance of the Purdue ECE mechanical shop. This mounting plate was affixed to the bottom of the box, and it featured strategically positioned holes, screws, and nuts to securely hold both STM32 boards and the cell modem in place.

The assembly process began by mounting the TSC side nucleo board onto the plate. Subsequently, the World side STM32 board was stacked on top of the TSC sideboard, with insulation material in between to prevent any electrical interference or contact issues. The Cell Modem was fixed to the plate in the space beside the stacked boards. This arrangement ensured that the LEDs on the World sideboard and the cell modem were directly visible through the transparent lid, offering a convenient means of monitoring the data transmission status.

To facilitate the connection between the TSC side nucleo board and the external network (Econolite or PC), a 1-inch hole was drilled in the enclosure in front of the ethernet port of the TSC side nucleo board. This aperture allowed for the easy insertion of an Ethernet cable for network connectivity.

A separate 5V USB hub was incorporated inside the enclosure to individually power both nucleo boards and the cell modem. This hub was also contained within the enclosure to maintain a clean and organized setup. The USB power cable from the hub was routed through another hole in the enclosure, effectively creating a plug-and-play system. This enclosure design and assembly process ensured the robustness of the system while allowing for easy monitoring, maintenance, and power management. The arrangement of components, transparent lid, and well-thought-out cable management contributed to the overall functionality and visual appeal of the enclosure. The version 1.0 enclosure is shown in Figure 2.6.

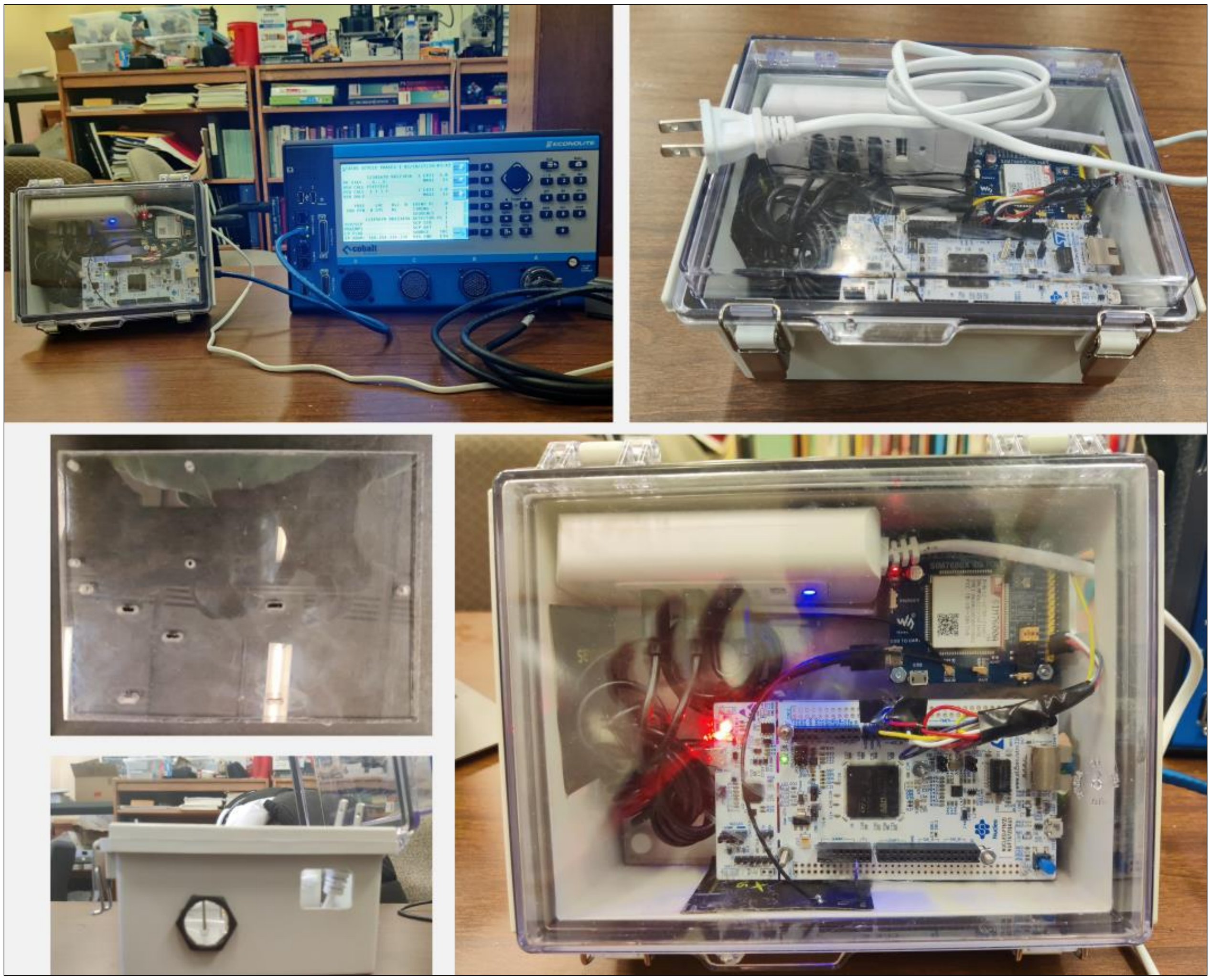

Figure 2.6 Diode Enclosure Version 1.0 (Gowda et al., 2023)

An alternative version, denoted as version 2.0, featured a more compact enclosure design that eliminated the need for wiring between components. This version embraced a miniature approach, with both STM32 boards and the cell modem mounted onto a single PCB plate. The KiCAD files required for fabricating the PCB can be accessed within the GitHub repository.

For this version, a 3D-printed enclosure was designed by the Virginia Tech members of the research team, namely, Professor Montasir Abbas and Mr. David Hong. The CAD files for this enclosure design are also available in the GitHub repository under the folder Diode Enclosure Version 2.0. Notably, the enclosure was tailored to accommodate the no-wire system, emphasizing a clean and organized setup. Unlike the previous version, the only cable involved in this configuration is the power cable connecting to the Green Terminal Blocks, responsible for supplying power to the PCB. This streamlined approach minimized clutter and enhanced the aesthetic appeal of the system. The dimensions of version 2.0 were considerably smaller than version 1.0, measuring 15cm x 14.5cm x 7cm. Additionally, the enclosure size could be further reduced by removing the programmer used to program the STM32 boards. In such cases, the boards could be programmed externally and connected to the PCB using wires. This is a feature of STM32 Nucleo boards.

A notable feature of this version are the jumper pins for the power supply arrangement. The JP3 jumper on both STM32 boards needed to be in the E5V position. It is important to emphasize that when the jumper is set to this position, the code cannot be uploaded to the boards using the USB interface. Code uploading requires switching the jumper to the U5V position. After uploading the code, it was noted that it is important for the jumper to be returned to the E5V position for normal operation. This is a common mistake made by programmers during debugging. The UART selection jumper on the cell modem must be in position A; this is meant to "access raspberry pi via USB to UART".

CHAPTER 3. FIELD TESTING AND DEPLOYMENT

3.1 Bench and Field Testing and Deployment

The first visit to the Michigan DOT Traffic Management Lab in Lansing took place on March 8, 2023, as part of pre-project activities (that is, before the official start date of Phase 2 of this project). At this event, the initial version of the system, version 1.0, was delivered by the Purdue research team. This marked the commencement of the bench testing phase. The diode system, equipped with version 1.0, performed successfully for an entire week. However, a sudden interruption occurred as the system unexpectedly ceased transmitting data to the NATS server. After thorough investigation, the root cause was identified: the modem had lost cellular signal. The situation was rectified by performing a system reset, which reinstated the broadcasting functionality. Following this incident, the diode continued to operate reliably, and its performance remained consistent even when the enclosure door was closed. It was revealed that certain networks, notably Verizon, were experiencing connectivity issues at that time.

The testing phase utilized a SIM card donated by Purdue Open Agricultural Technology and Systems (OATS) Center, courtesy of Professor Jim Krogmeier, and by T-Mobile, courtesy of Mr. Tim Johnson. Figure 3.1 presents photos of the components of the data diode enclosure version 2.0 and Figure 3.2 presents a photo of the device ready for installation in the controller.

Figure 3.1 Diode Enclosure Version 2.0 developed in Phase I of the study

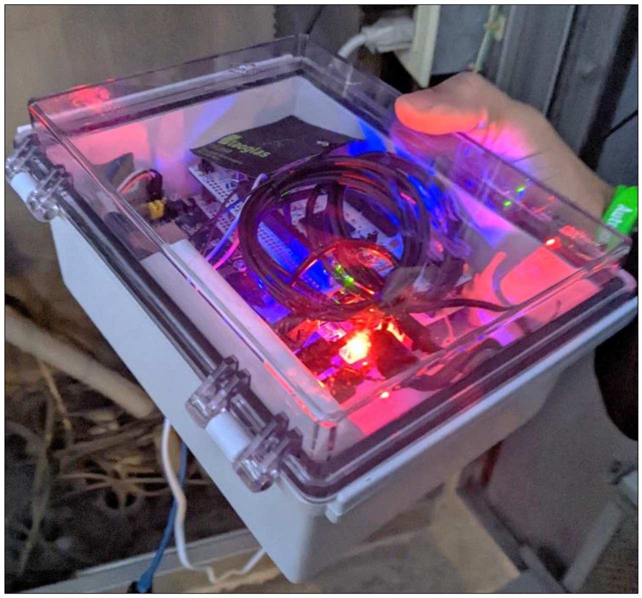

Figure 3.2 Installation-ready version of the device

The second visit to the Michigan DOT Traffic Management Lab in Lansing took place on August 7, 2023. During this visit, both versions of the diode system were set up in the Lansing signal shop and subsequently deployed at two MDOT-approved intersections (Figure 3.2) in Owosso.

(M52 x King St.)
Roughly: 43°00'17.8"N 84°10'36.6"W
43.004956, -84.176830
&
(Washington x M21(Main))
Roughly: 42°59'51.0"N 84°10'14.4"W
42.997511, -84.170679

Figure 3.3 Coordinates of the intersection intended for the pilot deployment

3.2 Outcomes of the Bench and Field Tests

The installations at these intersections were aimed to assess the practical performance of the diode system under real-world conditions. The deployment was instrumental in evaluating the effectiveness of both version 1.0 and version 2.0 enclosures, as well as the overall functionality of the system. These visits underscored the significance of real-world testing and fine-tuning the system in response to unexpected challenges. It was further discovered that the mapping from lanes to signal group needed a revisiting. The insights gained from these experiences contributed to the refinement and optimization of the diode system, ultimately enhancing its reliability and suitability for deployment in traffic management scenarios. The deployment of the data diode system in the context of Michigan's traffic management yielded valuable insights and demonstrated the system's functionality in various scenarios. The diode system, consisting of STM32 Nucleo boards, cellular modems, and specialized software components, was rigorously tested and showcased its capabilities through field visits and bench testing.

During the initial phase of the project, the system was extensively tested to ensure its accurate functioning. A crucial aspect was the establishment of seamless communication between the diode, the NATS server, and the user interface application. The utilization of the NATS messaging system proved to be advantageous due to its subject-based addressing mechanism, which facilitated data flow and simplified the interaction between the various components. The system exhibited robust performance in practical operational scenarios, transmitting Signal Phase and Timing (SPaT) data from traffic controllers to the NATS server. The use of a data diode allowed the unidirectional flow of information, ensuring that critical infrastructure remained protected from potential external threats.

One of the key achievements of the project was the successful deployment of two diode systems in the city of Owosso, Michigan. These diodes were strategically positioned within traffic cabinets at two different intersections. The deployment process involved careful configuration, placement, and connectivity setup to enable smooth data transmission. Throughout the deployment phase, the diodes effectively transmitted SPaT data to the NATS server, contributing to real-time traffic analysis and decision-making.

Latency measurement emerged as a critical aspect of the system's performance evaluation. The latency measurement component was integrated into the diode system, allowing the calculation of uplink latency and end-to-end latency. The measurement revealed the average latency and its variance, providing crucial information for accurate prediction of future states of the traffic signal. This data allowed for a more informed understanding of traffic patterns and trends. The utilization of Svelte, a modern web application framework, facilitated the development of an intuitive user interface. The application enabled users to interact with the diode system, receive real-time traffic updates, and access SPaT data for different intersections. The app's accuracy was subject to the precision of GPS coordinates, and while the system provided valuable insights, it is important to account for the inherent limitations of GPS technology.

Furthermore, the integration of MAP data units and databases enhanced the system's capabilities. By mapping unique IDs to specific intersections, the system efficiently directed SPaT data to relevant subjects. This allows users to subscribe to intersections of interest and receive accurate, location-specific traffic information. NATS framework minimized the downlink latency of the system.

Through field visits and extensive bench testing, the data diode system demonstrated its reliability, adaptability, and potential to enhance traffic management practices. The successful deployment in Michigan showcased the system's seamless integration into existing traffic infrastructure and its capability to provide real-time, accurate traffic data.

3.3 Discussion

The overall Components of the system include 2 STM32 Nucleo-144 Boards, A cell modem, 2 Antennas, an Ethernet cable, 2 USB cables and 7 jumper wires. The estimated costs of the system components (not considering the cable cost) are presented in Table 3.1.

Table 3.1 Component costs

Component	Unit x Price	Total Cost in $
STM32	2x23	46
Cell Modem	1x71	71
Antennas	2x11	22
Polycase box	1x40	40
Mounting Plate	1x20	20
USB hub	1x10	10
PCB	1x10	10
3D Printing Box V2.0	1x20	20
Total (Verison 1.0)	-	209
Total (Version 2.0)	-	169

Version 2.0 of the system presents a cost-effective and streamlined solution compared to Version 1.0. In terms of initial costs, Version 2.0 is already more affordable than its predecessor. However, the cost advantages are expected to become even more significant when the system is scaled up and deployed on a larger scale, and scale economies kick in.

The reduced cost of Version 2.0 can be attributed to its efficient design and the elimination of certain components present in Version 1.0. The integration of the two STM32 boards and the cell modem onto a single PCB plate reduced the need for additional wiring and connectors, resulting in lower manufacturing and assembly costs. Additionally, the use of a 3D-printed enclosure for Version 2.0 simplified the manufacturing process and reduced material costs. One of the notable advantages of Version 2.0 is its compact design and minimalistic setup. The absence of wires and the USB hub in Version 2.0 contributes to a hassle-free deployment process. Without the need for additional components like USB hubs and separate power cables, the installation becomes more straightforward and less time-consuming. This feature becomes particularly advantageous when deploying the system across multiple intersections or locations, where simplicity and efficiency are crucial. Furthermore, the smaller footprint of Version 2.0's enclosure makes it easier to accommodate within traffic cabinets or other designated spaces. The reduced space requirement aligns well with the spatial constraints often encountered in such environments.

In conclusion, Version 2.0 offers a cost-effective, space-efficient, and simplified solution for data transmission in comparison to Version 1.0. As the system is scaled up for widespread deployment, scale economies and the efficiency of the design are expected to lead to even more significant cost reductions and smoother implementation processes.

In March 2023, as part of a pre-project activity, the Research Team visited Michigan DOT's Traffic Lab in Lansing, for a signal shop demonstration of the device developed in this study (Figure 3.3). Also, on May 16, 2023, research team member Manish Gowda presented work done in Phase 1 of the study at the Next-generation Transport Systems Conference (NGTS) (Figure 3.4). The presentation provided an insightful overview of the diode's functionality, integration, and potential applications in modern transport systems. In August 2023, the Research Team visited Michigan DOT's Traffic Lab in Lansing, for a signal shop demonstration of the device developed in this study (Figure 3.5). In September 2023, the Research Team visited the city of Owosso, Michigan, and worked with Michigan DOT engineers and Owosso-based industry stakeholders (Mr. Dave Acton of the Transformation Network), to install the developed device at one of the major intersections in Owosso (Figure 3.6). Figure 3.7 and Figure 3.8 presents an image of the research team's work activities at an intersection signal controller and in-vehicle monitoring of the deployed device at Owosso intersection, September 2023, as part of the test deployment exercise.

Figure 3.4 First Bench Test of the Data Diode at Michigan DOT's Traffic Lab in Lansing, March 2023 (persons in photo include Manish Gowda, Walt Fehr, Nathan Bouvy, and Samuel Labi)

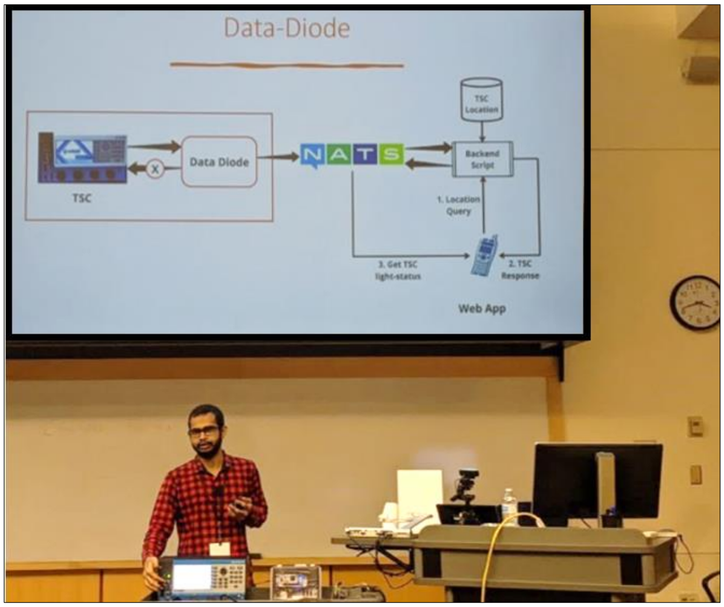

Figure 3.5 NGTS Conference Presentation of the developed Data Diode Device, by Manish Gowda, March 2023

Figure 3.6 Second Bench Test of the Data Diode at Michigan DOT's Traffic Lab in Lansing, August 2023

Figure 3.7 Deployment of the Data Diode Device at an Owosso intersection, Sept. 2023

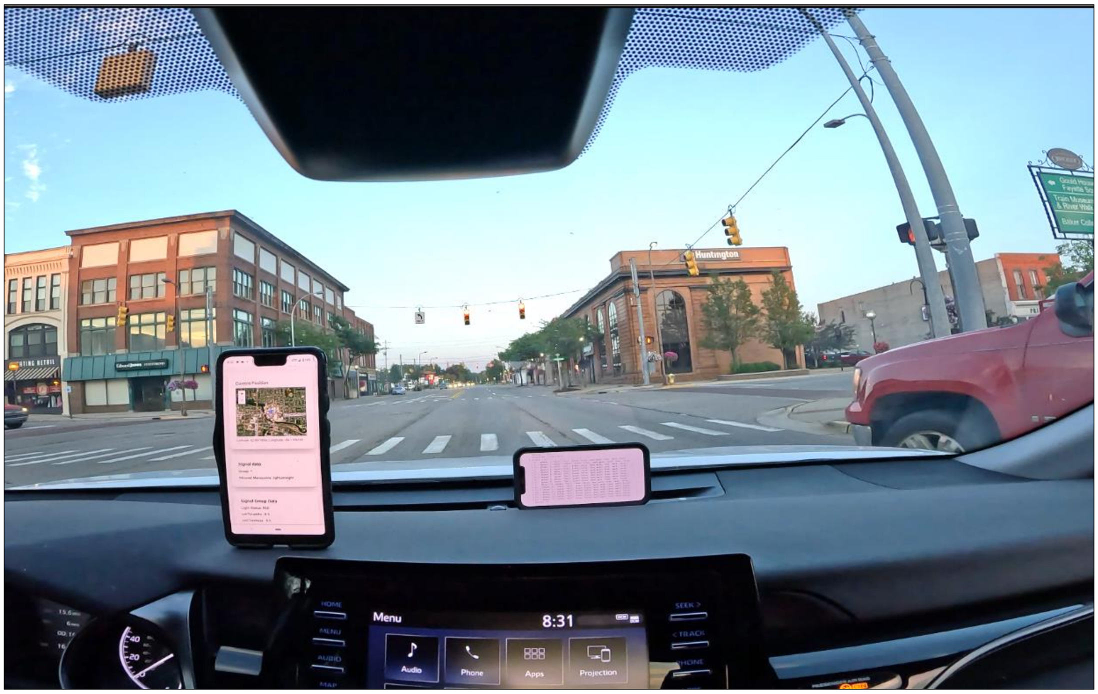

Figure 3.8 In-vehicle monitoring of the deployed device at Owosso intersection, Sept. 2023

CHAPTER 4. CONCLUDING REMARKS

4.1 Summary

Road agencies seek cost-effective ways to obtain and distribute traffic data to traffic control centers and specified authorized end users, and thereby, to facilitate efficient decision making on traffic signal operations. This includes a need to make Signal Phase and Timing (SPaT) and MAP data more useful to mobile and other devices and connectivity infrastructure. Unfortunately, existing data collection and delivery methods are time consuming and costly. Therefore, to facilitate traffic operations in the current era of human-driven vehicles (HDVs) and the prospective era of connected autonomous vehicles (CAVs), this research developed a device to acquire, process, and disseminate SPaT data from Traffic Signal Controller (TSC) cabinets in a manner that ensures system integrity and yet fosters accessibility of timing information for traffic data end-users.

The device, referred to as a "Data Diode," consists of two interconnected microcontrollers operating through simplex communication (one-directional data flow). The device connects the TSC cabinet and the end-user's device (such as a user-held device (UHD), thus facilitating the extraction and processing of SPaT data. The process begins with one microcontroller establishing a connection with the TSC's Ethernet port. Then, utilizing the Simple Network Management Protocol (SNMP) interface, the device securely acquires the SPaT data which then undergoes Cyclic Redundancy Check (CRC) encoding to ensure integrity protection and subsequently transmitted through a unidirectional UART interface to the second microcontroller. No SNMP commands can be passed back to the signal controller from the Internet. Thus, the interface cannot be used as an attack surface.

The second microcontroller interfaces with a 4G Cell Modem to transmit the processed SPaT data to the NATS open source messaging system, incorporating a unique identifier specific to each TSC. A battery of such TSC-Diode systems collects such data from various intersections, and the collected data are routed through their respective channels within the NATS system, thereby facilitating efficient organization and streamlined access.

A backend script acquires GPS coordinates from the UHD, pinpointing the nearest traffic intersection. Leveraging this information, the script retrieves relevant SPaT data from the database associated with the corresponding TSC. The user is granted access to this data through a user-friendly web app on their UHD. The app dynamically presents real-time information about the traffic signal status and precise timing of signal phase transitions for the lane of interest.

The device was bench tested at Michigan's DOT Traffic Signal Lab, and field tested at Owosso, Michigan. These tests were successful, indicating that the developed device works well as planned. Overall, the integration of this technology into human-driven or connected autonomous vehicle driver assistance systems can help smoothen arterial traffic flow and transform urban mobility.

4.2 Discussion on Practical Usefulness and Future Work

The development and implementation of the data diode system represent a significant step forward in enhancing traffic management and control systems. Through the seamless integration of hardware and software components, we have successfully created a robust and reliable solution that addresses the challenges of secure data transmission across traffic signal controllers.

CHAPTER 5 SYNOPSIS OF PERFORMANCE INDICATORS

5.1 USDOT Performance Indicators Part I

Three (3) transportation-related courses (two (2) at Purdue and one (1) at Virginia Tech) were offered annually during the study period that was taught by the PI and a teaching assistant who are associated with the research project. Three (2) graduate students participated in the research project during the study period: two (2) Purdue students and one (1) Virginia Tech students. Three (3) transportation-related advanced degree programs (one (1) MS program (Purdue) and two (2) doctoral programs (one each at Purdue and Virginia Tech) utilized the CCAT grant funds from this research project, during the study period to support the graduate students.

5.2 USDOT Performance Indicators Part II

Research Performance Indicators:1 conference presentation was produced from this project. The research from this advanced research project was disseminated to 23 people from industry, government, and academia, through the conference presentation.

Leadership Development Performance Indicators

This research project generated 3 academic engagements and five (5) industry engagements (The City of Owosso, The Transformation Network, Michigan DOT, Cubicon Inc., T-Mobile). The PIs held positions in 2 national organizations that address issues related to this research project.

Education and Workforce Development Performance Indicators

The methods, data and/or results from this study were incorporated in the class content of:

- **Virginia Tech:** The Fall 2023 version of the following courses in the undergraduate civil Engineering program: CEE 5694: Traffic Signal System Operations & Control
- **Purdue University:** The Fall 2023 and Fall 2024 versions of the following courses in the undergraduate civil engineering program: (a) CE 299 (Smart Mobility), an optional undergraduate-level course, and (b) CE 398 (Introduction to Civil Engineering Systems), a mandatory undergraduate course.

The students in these classes will soon be entering the workforce. Thereby, the research helped enlarge the pool of people trained to develop knowledge and utilize the technologies developed in this research, and prospectively, to put them to use when they enter the workforce.

Collaboration Performance Indicators

During this project, there was collaboration between the main institution (Purdue University) and other partners, as follows:

Five (5) industrial partners: The Michigan Department of Transportation, The City of Owosso, The Transformation Network, Cubicon Inc., and T-Mobile.

One (1) government agency (USDOT Volpe Center)

One (1) tertiary institution (Virginia DOT)

Two (2) academic institutions that provided matching funds.

The outputs, outcomes, and impacts are described in Chapter 8.

CHAPTER 6 STUDY OUTCOMES AND OUTPUTS

6.1 Outputs

Good and reliable data are central to any traffic management or operations effort. It has been demonstrated, through a field deployment in the city of Owosso, that the main study output (a novel data diode device), can contribute towards the efficiency and effectiveness of urban road transportation systems operations and management. The study processes and findings have been presented in a conference. Elements of the study will continue to be included in related graduate and undergraduate transportation engineering courses at Virginia Tech and Purdue University.

8.1.1 Publications, conference papers, or presentations

Conference Presentations
Gowda, M., Fehr, W., Balmos, A., Ajagu, R., Abbas, M., Krogmeier, J., Labi, S. (2023). Secure Acquisition of Intersection Data for Connected Vehicle Operations, The Third Annual Next-Generation Transport Systems (NGTS–3) Conference May 16–18, 2023. West Lafayette, IN.

8.1.2. Other outputs
(a)At Purdue, the research product was used to:

- help teach relevant concepts in two (2) Purdue undergraduate-level courses: CE 299 (Smart Mobility) and CE 398 (Introduction to Civil Engineering Systems).
- support future research related to the subjects of UAV-CAV network, trajectory planning and operational monitoring for CAVs.

(b) Virginia Tech developed methods for vehicle-infrastructure integration in an educational setting. The components of this initiative included this CCAT project on the data diode development. The educational initiative included conceptual design of an intersection control system for connected vehicles, and the creation of illustrative concepts for a driver warning system in a microsimulation environment, designed for an interactive classroom setting.

(c) The synergy in the collaboration between Virginia Tech and Purdue's UTC research facilitated innovation in connected automated vehicle technology and development in educational systems. Virginia Tech assisted Purdue's data diode project team in the creation of MAP (intersection layout and geometry) units, which provided reference points for the tracking of the vehicle trajectory as connected vehicles move along a corridor.

(d) Virginia Tech's team also provided packaging solutions using 3D-designed (using SolidWorks) and printed hardware housing for the connected vehicle data diode system. This involvement also allowed Virginia Tech's team to help create one of the cutting-edge connected vehicle V2I communication systems and inspired the creation of a proposed small-scale intersection control system for educational purposes.

(e) The conceptual design of an educational intersection control system involved the use of Electronic Design Automation (EDA) software for designing the circuitry consisting of microcontrollers and microprocessors. This stage of the project is designed to discover the methods for showing the working mechanisms of a V2I system with a low budget for the classroom setup.

(f) At Virginia Tech, the research process and product were incorporated into coursework, as follows:

- Courses taught related to the project or where the project material was used in part of the course: CEE 5694: Traffic Signal System Operations & Control
- Three (3) short courses developed and delivered by CCAT PI's (Montasir Abbas and Walt Fehr) to audience sizes ranging from 7-10 students:
    - Cubicon Design Methodology Part 1
    - Cubicon Design Methodology Part 2
    - Cubicon Design Methodology Part 3

(g) Collaborations

U.S. DOT Volpe Center: Walt Fehr is the creator of the data diode concept. Walt and other Volpe Center staff's key role included that of Interactive Evaluator. Interactive Evaluation is a technology transfer process being developed by the U.S DOT's Volpe Center to investigate promising new technology and bring it into the transportation sector if it meets its claims. The process starts with the evaluator engaging with the technology developer as a subject matter expert to fully understand the technology and to develop specific metrics that will be used to confirm or refute the developer's claims – better, faster, cheaper, etc. When the developer then proceeds to a demonstration designed to showcase the technology's claims, the evaluator will assume the more traditional role of an evaluator to objectively measure the claims. The transportation community will then have a better understanding of the new technology and a measure of the potential benefit it might bring.

Michigan Department of Transportation (Lansing Signal Lab): The Michigan Department of Transportation (Lansing Signal Lab) bench agreed to test the developed device. Plans are underway to test the device (in Phase II of this CCAT project) at the MDOT Traffic Signal Lab in Lansing, and to field test it in Owosso, Michigan. The MDOT engineers involved in this effort and these plans include Mr. Nathan Bouvy, Scott Holzhei, Travis Phillips, Hilary Owen, Ryan Schian, Ross Venable, and James Kwapiszewski.

T-Mobile: Providing transport media for transportation infrastructure data are increasingly becoming an important service for the T-Mobile organization as the company strives to support connected intelligent transportation as part of the Internet of Things. The company expects to acquire wider knowledge of the needs of the transportation community by participating in this project. In turn, T-Mobile's expert suggestions and access to our data transport medium help strengthen the project goals. T-Mobile offered their extensive up-to-date wide area network service, for incorporation in the research. This will be particularly valuable in the follow-up testing and deployment phase where a focused performance evaluation of the developed device, in the context of its prospective role in infrastructure data distribution, will be carried out.

Transformation Network: David Acton is the President of The Transformation Network, Inc. (TTN). The Transformation Network's role was to provide technology and commercial development resources (including project management) to the deployment in Owosso, Michigan. Dave Acton is an internationally recognized subject matter expert in vehicle connectivity, Internet of Things (IoT) architecture design, and complex project deployment leadership.

Mayor Christopher Eveleth, City of Owosso, County of Shiawassee, MI: Owosso is a 15,000 person, four square mile, "micropolitan" city. The role of the City of Owosso is to be the project deployment location. Throughout its history, Owosso has been home to many inventors, industrialists, authors, politicians, and technology pioneers. A common thread in Owosso is that residents through the decades have acknowledged that geography is not the critical factor in determining success of various public initiatives. Rather, success is dependent on a community's ability to collaborate. Since 1836, Owosso has demonstrated that the city is able to align all necessary stakeholders quickly and decisively to achieve success. This project has further strengthened that tradition. In that spirit, Mayor Christopher Eveleth has agreed to provide access to the City of Owosso's traffic infrastructure in summer 2023 for testing the device.

Sandy Klausner (CubeFog Corporation): Sandy Klausner is the principal developer of the Cubicon Technology Suite. This phase of the project was unable to investigate two specific claims about Sandy Klausner's Cubicon technology. (1) that the Systems Engineering Language will help transportation practitioners better describe the desired system behaviors so that more efficient and economical implementations will result, and (2) that Cubicon technology will provide highly-efficient data distribution techniques that will synchronize the deterministic components of a distributed system using already-existing communication media. It is expected that this will be done in the next phase of the project (full deployment). The next phase will be conducted in part of the larger ad-hoc group's demonstration installation centered on the distribution of traffic signal state data and other infrastructure data for an entire community using already-existing wide area network communication. The installation and operation of the demonstration installation is expected to be significantly cheaper and faster to install and lower total cost-to-operate than similar installations that make use of short-range wireless communication without any sacrificed reduction in data integrity or delivery performance.

6.2 Outcomes

The success of this project could be attributed to the diversity of the research team. The team consisted of representatives from three key stakeholders of any transportation initiative: government (Michigan DOT, City of Owosso), industry (T-Mobile, The Transformation Network, Inc.) and academic (Purdue University, Virginia Tech). These participants worked together to design the study and to plan the prospective (Summer 2023) pilot deployment of the developed product. The expected outcomes of this project are the prospective changes that the economic acquisition of intersection data could bring to the road transportation system, or its regulatory, legislative, or policy framework. These are:

- City authorities and road public agencies are now provided the data diode device, a novel and cost-efficient way to drastically reduce the cost (while maximizing the effectiveness) of their data collection processes at their signalized intersections.

- Considering the effect of scale economies, expanded deployment will serve to further reduce the production costs of the data diode device.
- The research outcome is consistent with USDOT's strategic goals of innovation, cost-effectiveness, safety, and mobility. The device is novel in its functions. The project's explicit consideration of cost is rather unique because it addresses cost, an often-overlooked aspect of ITS deployments.

6.3 Impacts

A list of specific impacts from this research project, are as follows:

- The low costs of production, installation, and operations of the developed device will foster advancement of the connected intelligent transportation ecosystem when the potential benefits of the device become more widely recognized.
- The two Purdue graduate students and the Virginia Tech graduate student who worked on (and were funded by) this project will enter the workforce in 2024-2025 and are expected to help implement and/or improve the data diode device developed in this project.
- Students that took Virginia Tech's course CEE 5694 (Traffic Signal System Operations & Control) and those that participated in the 3 Cubicon workshops, will enter the workforce in 2024-2025 and are expected to help implement and/or improve the data diode device developed in this project.

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