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Intelligent Blind Crossings for Suburban and Rural Intersections

Shahab Tayeb, PhD

CSUTC California State University Transportation Consortium

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16. Abstract

Blind intersections in suburban and rural areas pose significant safety challenges due to limited visibility and inadequate infrastructure. This project proposes an innovative solution leveraging the Internet of Vehicles (IoV) paradigm, utilizing connected and autonomous vehicles (CAVs) for seamless communication to enhance safety at these intersections. The research focuses on developing a specialized Road-Side Unit (RSU) system equipped with a Virtual Traffic Light Algorithm implemented on a Field-Programmable Gate Array (FPGA). Key stakeholders, including transportation authorities, vehicle manufacturers, and local communities, stand to benefit from this initiative. The RSU system acts as a critical infrastructure component, facilitating efficient intersection management and mitigating visibility challenges. Methodologies involve adapting the Virtual Traffic Light Algorithm, integrating it into the FPGA-based RSU system, and demonstrating RSU communication operability through software-defined radios. Additionally, a novel solar-powered system is designed for lightweight RSUs to enhance sustainability and energy efficiency. The project's findings indicate the feasibility and practicality of the proposed RSU solution in enhancing safety at blind intersections. Successful implementation of the Virtual Traffic Light Algorithm on the FPGA demonstrates its potential for real-world deployment. The operability demonstration of RSU communication validates the effectiveness of the proposed communication system. Overall, this research contributes to advancing safety measures in transportation infrastructure, with potential implications for future urban planning and policy development.

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Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2351

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Executive Summary

This project underscores the compromised safety at blind intersections, attributing it to factors such as limited visibility, high traffic speeds, inadequate infrastructure, and more notably absent infrastructural support such as stoplights. This safety challenge is particularly present in suburban and rural intersections, where traffic infrastructure development lags. In response to these concerns, the Internet of Vehicles (IoV) emerges as a pivotal solution, aiming to bolster safety through a network of connected and autonomous vehicles (CAVs) adept at seamless communication. This project advocates for a tailored approach to blind intersections in suburban and rural settings: a specialized Road-Side Unit (RSU) meticulously designed to alleviate visibility challenges inherent to such intersections.

The proposed solution involves the implementation of a RSU system leveraging Field-Programmable Gate Arrays (FPGAs). A distinctive algorithm, inspired by virtual traffic light methodologies, is integrated into the system to streamline intersection management. Key components of this solution comprise an FPGA housing the implementation of the algorithm, a communication module overseeing inter-vehicular communication, and a solar-powered energy system, supported by a simulation validating the operational efficacy of the proposed RSU. This comprehensive approach aims to enhance safety and address the unique challenges posed by blind intersections in suburban and rural intersections.

1. Introduction

The spectrum of vehicular autonomy is delineated across six intertwined levels, ranging from Level 0 to Level 5, as classified by the Society of Automotive Engineers (SAE) [1]. Each level corresponds to a specific degree of driving automation, with:

- Level 0 signifying 'No Driving Automation'
- Level 1 indicating 'Driver Assistance'
- Level 2 encompassing 'Partial Driving Automation'
- Level 3 involving 'Conditional Driving Automation'
- Level 4 denoting 'High Driving Automation'
- Level 5 representing the pinnacle of autonomy as 'Full Driving Automation'.

The realization of vehicular autonomy hinges on the integration of diverse sensors and connectivity. The underlying machine learning models play a pivotal role in vehicle control and fostering interactions with other Connected and Autonomous Vehicles (CAVs) and the road infrastructure. Leveraging data acquired by on-board sensors, these models make informed decisions. Notable on-board sensors include radio detection and ranging (radar), sound navigation and ranging (sonar), light detection and ranging (LiDAR), and cameras. Radar and sonar sensors utilize radio and sound waves respectively to detect objects and ascertain their distance, while camera and LiDAR sensors rely on a direct line of sight for visual detection and distance determination of objects.

1.1 The Internet of Vehicles

The Internet of Vehicles (IoV) constitutes a network of Connected and Autonomous Vehicles (CAVs) that engage in seamless communication with each other and with the road-side infrastructure. The envisioned functionality of the IoV is as follows: As vehicles traverse, they exchange pertinent information, including geographical location, speed, and intentions to change lanes. Strategically positioned road-side units govern specific areas within the network, and a central trust authority may also be present to oversee a broader jurisdiction. These units disseminate crucial information to vehicles, such as updates on traffic accidents and road conditions [2].

The central objective of the IoV is to enhance societal safety by curbing the influence of reckless drivers and minimizing decisions that jeopardize lives. This transformation envisions a safer transportation landscape where pedestrians can confidently cross streets, intersections adhere to established rules, and speed limits are consistently enforced. Additionally, the IoV has the potential to optimize routing, contributing to more efficient transportation in everyday life. Emergency vehicles such as ambulances and firetrucks stand to benefit from expedited navigation to their destinations (e.g., unimpeded by drivers who disregard their sirens) [3].

However, the successful implementation of the IoV necessitates meticulous consideration of resource constraints, including time and power. Efficient resource allocation is critical to prevent network congestion and maintain optimal functionality [6]. Furthermore, security emerges as a paramount concern due to the inherent vulnerability of the IoV to cyberattacks such as exploitation of the low-security in-vehicle Controller Area Network (CAN) bus, man-in-the-middle attacks, and replay attacks. The unmitigated consequences of such attacks, including injury and death for drivers and pedestrians, underscore the imperative of robust security mechanisms to safeguard the IoV's overarching safety objectives [4].

1.2 Vehicular Communications

Effective vehicular communication demands adherence to standards ensuring both safety compliance within a vast network of swiftly moving vehicles and operation within constraints of limited resources. Dedicated Short-Range Communication (DSRC) emerges as a wireless communication framework specifically tailored for automotive applications, encompassing vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) communication.

In the realm of wireless communication for Intelligent Transportation Systems (ITS), DSRC has secured frequency allocations of 5.850–5.925 GHz by the United States Federal Communications Commission (FCC) and 5.875–5.905 GHz by the European Union. This wireless communication paradigm is integrated into the IEEE 802.11 standard (Wi-Fi) under the Wireless Access in Vehicular Environments (WAVE) framework, specifically addressed by the 802.11p standard. Initially an extension of 802.11, 802.11p delineated the Physical Layer and the Data Link Layer without incorporating features such as exponential backoff or acknowledgements. Subsequently designated as IEEE standard 802.11-OCB (Outside the Context of a Basic Service Set), WAVE incorporates IEEE 1609 for security services (IEEE 1609.2), and multi-channel operation (IEEE 1609.4).

Vehicular networks must fulfill mobility requirements, including supporting speeds up to 200 km/hr, ensuring a wide communication range, and maintaining communication within a 100 ms timeframe [5]. V2I communication facilitates mobility management, wherein vehicles relay their position and trajectory to infrastructure for predictive analysis of future positions [7]. Another protocol contributing to vehicular network mobility is Mobile IPv6, defining a mechanism for mobile nodes to retain the same IP address during operations such as transitioning between links, managing node operations, and handling ICMP messages [9].

1.3 Vehicular Standards

The vehicular standards that were followed throughout this project include the following:

Autonomy:

- SAE J3016: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles
- DSRC/WAVE Communication Protocol:
    - IEEE 1609: Family of Standards for Wireless Access in Vehicular Environments (WAVE)
    - IEEE 802.11p: IEEE Standard for Information technology—Local and metropolitan area networksSolar Power System Standards:
    - IEEE 1013: Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems.
    - IEEE 1361: IEEE Guide for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems
    - IEEE 1562: IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems

Additional standards relevant to the field of IoV include the following:

- ETSI TR 102 893: Intelligent Transportation Systems; Security; Threat, Vulnerability, and Risk Analysis
- ETSI TS 102 941: Intelligent Transportation Systems; Security; Trust and Privacy Management
- ETSI TS 103 097: Intelligent Transportation Systems; Security; Security header and certificate formats
- USDOT Report FHWA-JPO-17-589: Dedicated Short-Range Communications Road-Side Unit Specifications

2. Methodology

The outlined methodology ensures a focused approach to developing a roadside unit prototype tailored to the unique challenges presented by blind intersections in suburban and rural areas featuring two-way stop signs. We propose to develop an FPGA-based system for Road-Side Unit (RSU) devices to oversee vehicle interactions at a rural blind intersection. This involves the following steps:

a. Determine Interaction Flowchart: Define the interaction algorithm that governs how vehicles will communicate and interact at the rural blind intersection.

b. Design Embedded System: Design the embedded system using Quartus Prime and Qsys, integrating the determined algorithm. Program the algorithm using NIOS II Software Build Tools for Eclipse.

c. Optimize System Power Consumption: Implement measures to optimize power consumption within the designed FPGA-based system, ensuring efficient energy utilization.

d. Create a Communication Module for the RSU Device: Establish a communication module to facilitate seamless communication among vehicles at the rural blind intersection.

e. System Integration: Develop and integrate the 802.11 interface for effective communication as well as conduct integration testing to ensure harmonious operation between the communication module and the FPGA-based system.

f. Optimize System Power Consumption: Employ strategies to minimize power consumption in the communication module as well as design and configure a power system tailored to the specific needs of the RSU device.

2.1 Intersection Selection Criteria

The study focuses specifically on blind intersections in suburban and rural areas characterized by two-way stop signs. Other intersection types, including those with three- or four-way stop signs, are excluded from consideration for the roadside unit prototype. This exclusion is based on the distinct traffic patterns associated with intersections featuring different stop sign configurations. The rationale behind excluding intersections with three- or four-way stop signs is rooted in the need for distinct logic in managing traffic flow. By concentrating solely on two-way stop sign scenarios, the study can develop a roadside unit prototype tailored to the specific challenges posed by blind intersections in suburban and rural areas. Geographical specificity is addressed through the selection of a blind intersection situated east of Fresno. This location provides a tangible case study for assessing the prototype's effectiveness in mitigating visibility challenges associated with rural blind intersections.

2.2 Characteristics of the Selected Intersection

The blind intersections under consideration involve a main road with faster traffic and no stop sign intersected by a side road [10]. The chosen prototype scenario aims to capture the dynamics of intersections where the side road joins the main road. Illustrative examples of such intersections are depicted in Figures 5 and 6, showcasing a rural intersection east of Fresno situated at coordinates (36°42'26.6" N, 119°15'32.1" W). The blind nature of these intersections arises from the topography, particularly the positioning of the side road at the summit of a hill, obstructing the line of sight from one side of the intersection to the other.

The selected intersection's characteristics and blind nature are visually validated through the inclusion of Figures 1 and 2 below, offering a concrete representation of the intersection's layout and potential visibility constraints. This visual verification serves to enhance the understanding of the chosen prototype scenario.

Figure 1. Example Rural North–South Intersection

Figure 2. Example East-West Rural Intersection

3. Experimentation

3.1 Experimentation Setup

The experimentation involved the utilization of the Quartus Prime Education Design Suite to design the RSU system for the Terasic DE2-115 board. Subsequently, the board is programmed to execute the necessary operations. The Software Build Tools for Eclipse, integrated into the Quartus Prime Suite, facilitate the development and programming processes, requiring proficiency in C programming. Programming the HackRF One for wireless communication involves the use of GNU Radio on the designated PC. This step ensures the correct configuration of the HackRF One to align with the IEEE 802.11p standard. The overall experimentation setup incorporates a seamless integration of hardware and software components, leveraging established tools for system design, programming, and wireless communication configuration. To execute 802.11 on the SDRs, the communication module relies on a GNU Radio project. This project is bifurcated into two distinct components: the transmitter and the receiver.

- The Terasic DE2-115 Development and Education Board serves as the primary component for processing information within the Road-Side Unit (RSU), featuring a Cyclone IV E processor.

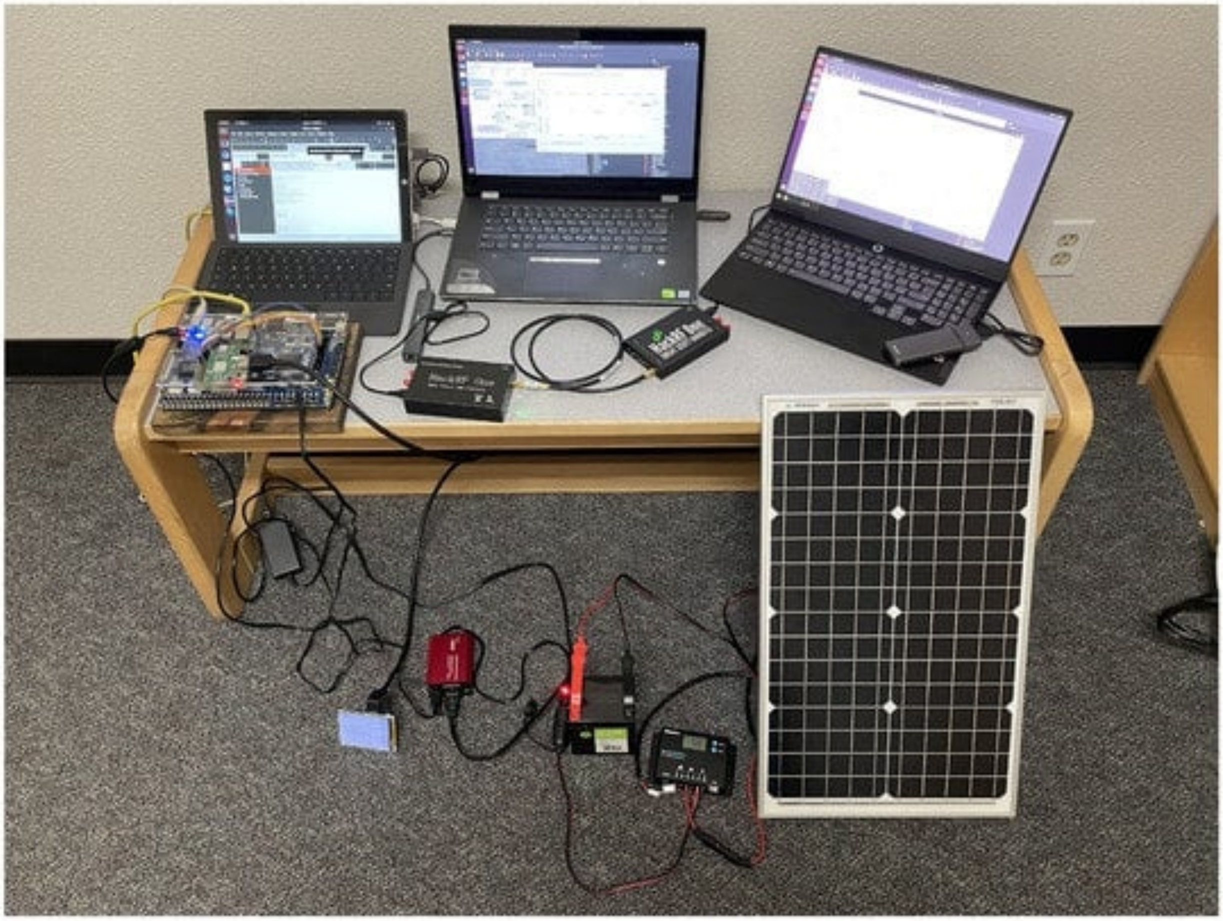
- The HackRF One is employed for wireless communication with vehicles. This software-defined radio can be programmatically configured to adhere to the IEEE 802.11p standard while meeting the DSRC/Wave standards.

- Quartus Prime Education Design Suite: The experimentation necessitates a workstation equipped with the Quartus Prime Education Design Suite. This suite is utilized to design the system for the DE2-115 board and to program the board for the requisite operations. Notably, the Software Build Tools for Eclipse, employing C programming, are embedded within the Quartus Prime Suite.

- GNU Radio: The workstation is also employed to run GNU Radio, a crucial tool for programming the HackRF Ones to facilitate wireless communication.

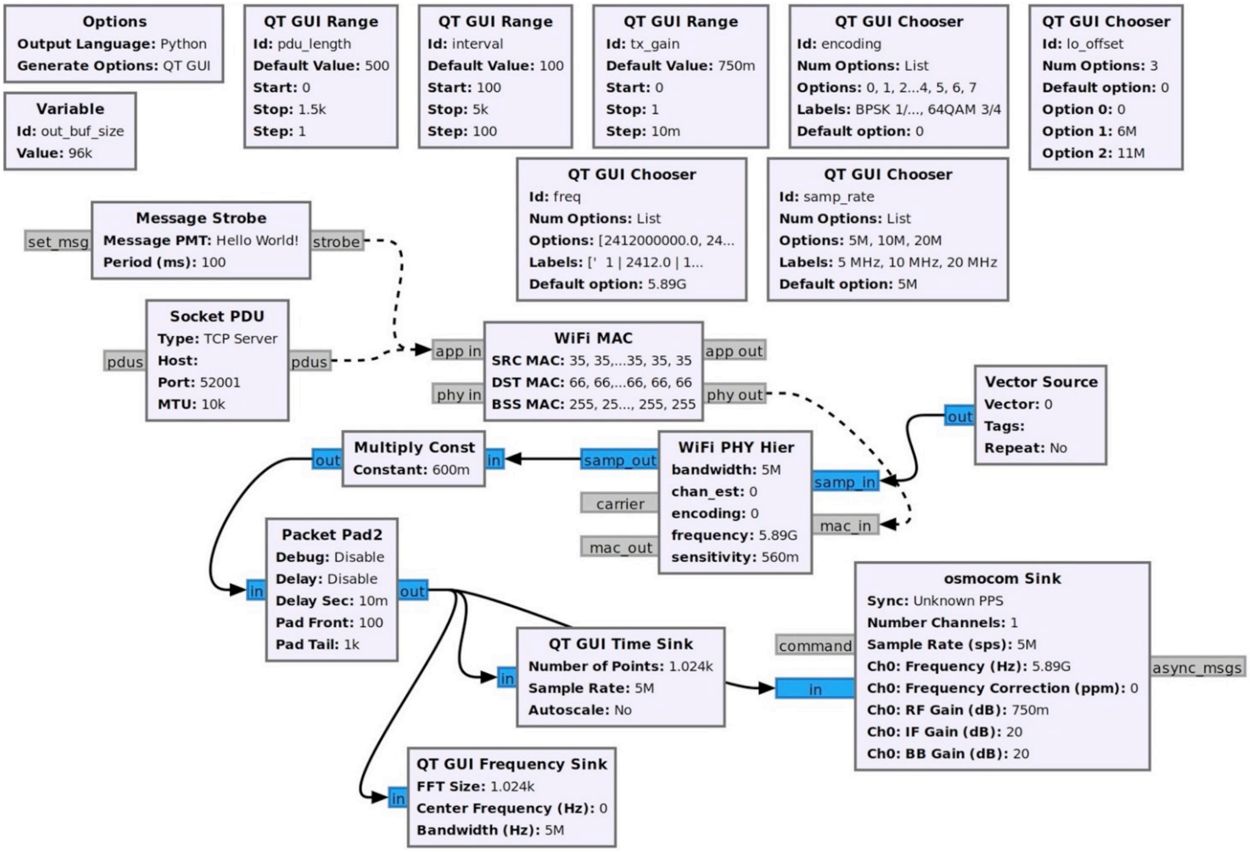
Figure 3 presents the system layout of the experimentation setup. The leftmost laptop controls the DE2-115 FPGA board, the middle laptop controls the transmitting HackRF One SDR, and the rightmost laptop controls the receiving HackRF One SDR.

Figure 3. System Layout



The communication module utilizes two software defined radios (SDRs), the previously mentioned HackRF Ones, that are connected by a coaxial cable. The cable is used for demonstration purposes: Transmitting a signal is practically the same, except it does not broadcast over open radio frequencies and does not potentially interfere with restricted frequencies. The communication module uses a GNU radio project to implement 802.11 on the SDRs. The project is separated into two parts: the transmitter, and the receiver. The GNU Radio flowchart for the transmitter is shown in Figure 4. The GNU Radio flowchart for the receiver is shown in Figure 5.

Figure 4. GNU Radio Transmitter Flowchart



Options
Output Language: Python
Generate Options: QT GUI

Variable
Id: out_buf_size
Value: 96k

QT GUI Range
Id: pdu_length
Default Value: 500
Start: 0
Stop: 1.5k
Step: 1

QT GUI Range
Id: interval
Default Value: 100
Start: 100
Stop: 5k
Step: 100

QT GUI Range
Id: tx_gain
Default Value: 750m
Start: 0
Stop: 1
Step: 10m

QT GUI Chooser
Id: encoding
Num Options: List
Options: 0, 1, 2...4, 5, 6, 7
Labels: BPSK 1/..., 64QAM 3/4
Default option: 0

QT GUI Chooser
Id: lo_offset
Num Options: 3
Default option: 0
Option 0: 0
Option 1: 6M
Option 2: 11M

QT GUI Chooser
Id: freq
Num Options: List
Options: [2412000000.0, 24...
Labels: [' 1 | 2412.0 | 1...
Default option: 5.89G

QT GUI Chooser
Id: samp_rate
Num Options: List
Options: 5M, 10M, 20M
Labels: 5 MHz, 10 MHz, 20 MHz
Default option: 5M

Message Strobe
Message PMT: Hello World!
Period (ms): 100

Socket PDU
Type: TCP Server
Host:
Port: 52001
MTU: 10k

WiFi MAC
SRC MAC: 35, 35,...35, 35, 35
DST MAC: 66, 66,...66, 66, 66
BSS MAC: 255, 25..., 255, 255

Vector Source
Vector: 0
Tags:
Repeat: No

Multiply Const
Constant: 600m

WiFi PHY Hier
bandwidth: 5M
chan_est: 0
encoding: 0
frequency: 5.89G
sensitivity: 560m

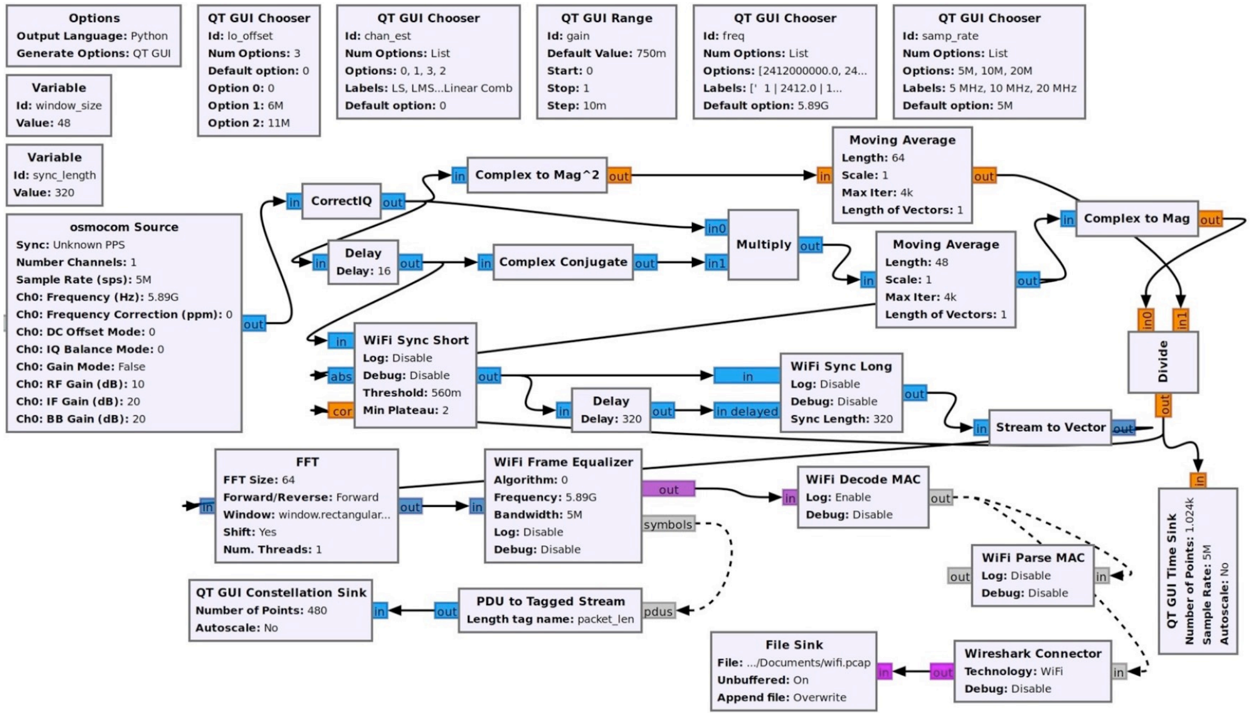
Packet Pad2
Debug: Disable
Delay: Disable
Delay Sec: 10m
Pad Front: 100
Pad Tail: 1k

QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 5M
Autoscale: No

osmocom Sink
Sync: Unknown PPS
Number Channels: 1
Sample Rate (sps): 5M
Ch0: Frequency (Hz): 5.89G
Ch0: Frequency Correction (ppm): 0
Ch0: RF Gain (dB): 750m
Ch0: IF Gain (dB): 20
Ch0: BB Gain (dB): 20

QT GUI Frequency Sink
FFT Size: 1.024k
Center Frequency (Hz): 0
Bandwidth (Hz): 5M

Figure 5. GNU Radio Receiver Flowchart



Options
Output Language: Python
Generate Options: QT GUI

Variable
Id: window_size
Value: 48

Variable
Id: sync_length
Value: 320

QT GUI Chooser
Id: lo_offset
Num Options: 3
Default option: 0
Option 0: 0
Option 1: 6M
Option 2: 11M

QT GUI Chooser
Id: chan_est
Num Options: List
Options: 0, 1, 3, 2
Labels: LS, LMS...Linear Comb
Default option: 0

QT GUI Range
Id: gain
Default Value: 750m
Start: 0
Stop: 1
Step: 10m

QT GUI Chooser
Id: freq
Num Options: List
Options: [2412000000.0, 24...
Labels: [' 1 | 2412.0 | 1...
Default option: 5.89G

QT GUI Chooser
Id: samp_rate
Num Options: List
Options: 5M, 10M, 20M
Labels: 5 MHz, 10 MHz, 20 MHz
Default option: 5M

osmocom Source
Sync: Unknown PPS
Number Channels: 1
Sample Rate (sps): 5M
Ch0: Frequency (Hz): 5.89G
Ch0: Frequency Correction (ppm): 0
Ch0: DC Offset Mode: 0
Ch0: IQ Balance Mode: 0
Ch0: Gain Mode: False
Ch0: RF Gain (dB): 10
Ch0: IF Gain (dB): 20
Ch0: BB Gain (dB): 20

CorrectIQ

Complex to Mag^2

Delay
Delay: 16

Complex Conjugate

Multiply

Moving Average
Length: 64
Scale: 1
Max Iter: 4k
Length of Vectors: 1

Moving Average
Length: 48
Scale: 1
Max Iter: 4k
Length of Vectors: 1

Complex to Mag

Divide

WiFi Sync Short
Log: Disable
Debug: Disable
Threshold: 560m
Min Plateau: 2

Delay
Delay: 320

WiFi Sync Long
Log: Disable
Debug: Disable
Sync Length: 320

Stream to Vector

FFT
FFT Size: 64
Forward/Reverse: Forward
Window: window.rectangular...
Shift: Yes
Num. Threads: 1

WiFi Frame Equalizer
Algorithm: 0
Frequency: 5.89G
Bandwidth: 5M
Log: Disable
Debug: Disable

WiFi Decode MAC
Log: Enable
Debug: Disable

WiFi Parse MAC
Log: Disable
Debug: Disable

QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 5M
Autoscale: No

QT GUI Constellation Sink
Number of Points: 480
Autoscale: No

PDU to Tagged Stream
Length tag name: packet_len

File Sink
File: .../Documents/wifi.pcap
Unbuffered: On
Append file: Overwrite

Wireshark Connector
Technology: WiFi
Debug: Disable

3.2 SAE J2735

In accordance with the stipulations set forth by the Society of Automotive Engineers (SAE) in document J2735, it is established that vehicles within a vehicular network disseminate crucial safety messages at a rapid rate, transmitting data ten times per second. These messages, vital for the simulation framework, are streamlined to encapsulate essential information comprising the vehicle's unique identification, as well as its precise spatial coordinates along the x and y axes.

Within this communication framework, the RSU assumes a pivotal role, orchestrating the flow of information by dispatching targeted unicast messages to individual vehicles within its vicinity. These unicast messages are meticulously crafted, containing pertinent details such as the vehicle's identification alongside distinct flags denoting the status of the traffic signal—whether it be signaling a green light, a red light, or soliciting information regarding the vehicle's intended direction.

In response to these tailored inquiries from the RSU, vehicles promptly relay their intentions via a unicast message. This transmission encompasses a binary representation signaling the vehicle's next maneuver, whether it be a straightforward progression (indicated by the binary code 11), a right turn (01), or a left turn (10). This exchange of data forms the cornerstone of an intricate vehicular communication system, facilitating efficient and safe navigation within dynamic traffic environments.

3.3 Simulation

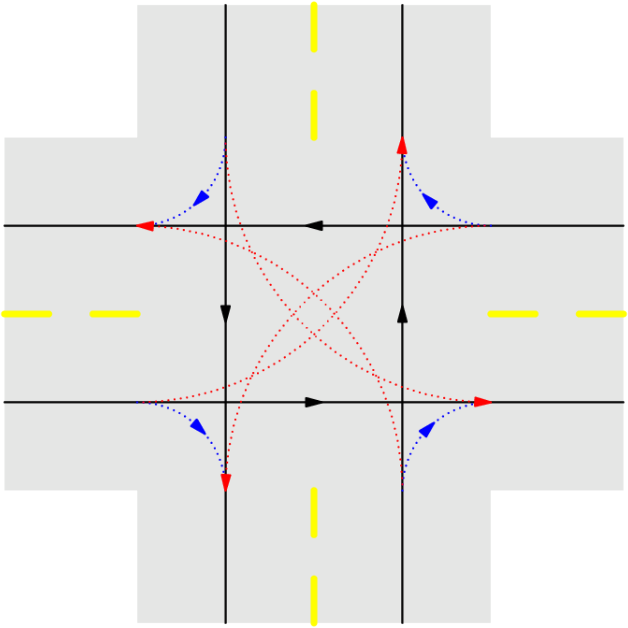
Within the realm of vehicular simulation, a microcosm was constructed to simulate real-world driving scenarios with precision. At the core of this simulation lay a dynamic representation of intersections, intricately mapped out as directed graphs, with each lane meticulously defined as edges within this graphical structure. This simulated environment was tailored to emulate the complex spatial relationships and traffic flow dynamics inherent to urban intersections.

Driving the simulation forward was the Intelligent Driver Model (IDM), a sophisticated algorithmic framework renowned for its ability to replicate authentic driving behaviors. Leveraging the IDM, the simulation accurately computed the positions of each virtual vehicle as they traversed their designated paths within the intersection graph, factoring in variables such as velocity, acceleration, and inter-vehicle spacing.

As these simulated vehicles navigated the virtual landscape, they actively communicated their real-time positions to a central RSU node. The RSU served as the nerve center of the simulation, orchestrating the exchange of critical information between vehicles and the simulation environment.

In response to these transmissions, the RSU played a pivotal role in managing the flow of information within the simulated domain (see Figure 6 for a complete set of the possible paths that are communicated via the RSU). Tailored messages were dispatched to individual vehicles, conveying vital instructions and updates regarding traffic conditions and signal status. This bidirectional communication framework fostered a dynamic feedback loop, enabling vehicles to adapt their behaviors in real-time based on the information received from the RSU, thus enhancing overall traffic efficiency and safety within the simulated environment.

Figure 6. Possible Paths Communicated to/from the RSU



Within the simulation framework presented in Figure 7, one can observe a scenario that showcases the traffic light algorithm in operation. In this scenario, there are two vehicles positioned on each side road, while one vehicle is situated on the main road. The main road consists of lanes designated as L1 and L2, which hold priority over the side road lanes denoted as L3 and L4.

As per the traffic light algorithm, the vehicle positioned on the main road (Vehicle 5) is granted the green light, allowing it to proceed through the intersection. Conversely, Vehicles 6 and 9, situated on the side roads, receive red lights and come to a complete stop, yielding to the vehicle with the right of way.

Furthermore, while Vehicles 7 and 8 are not leading vehicles within their respective lanes, they also come to a halt as the vehicles ahead of them have stopped in compliance with the traffic signal. This adherence to the traffic light algorithm ensures orderly and safe passage through the intersection, effectively managing the flow of traffic and prioritizing vehicles based on their designated lanes and positions within the simulated environment (see Figure 8).

Figure 7. Simulation Scenario

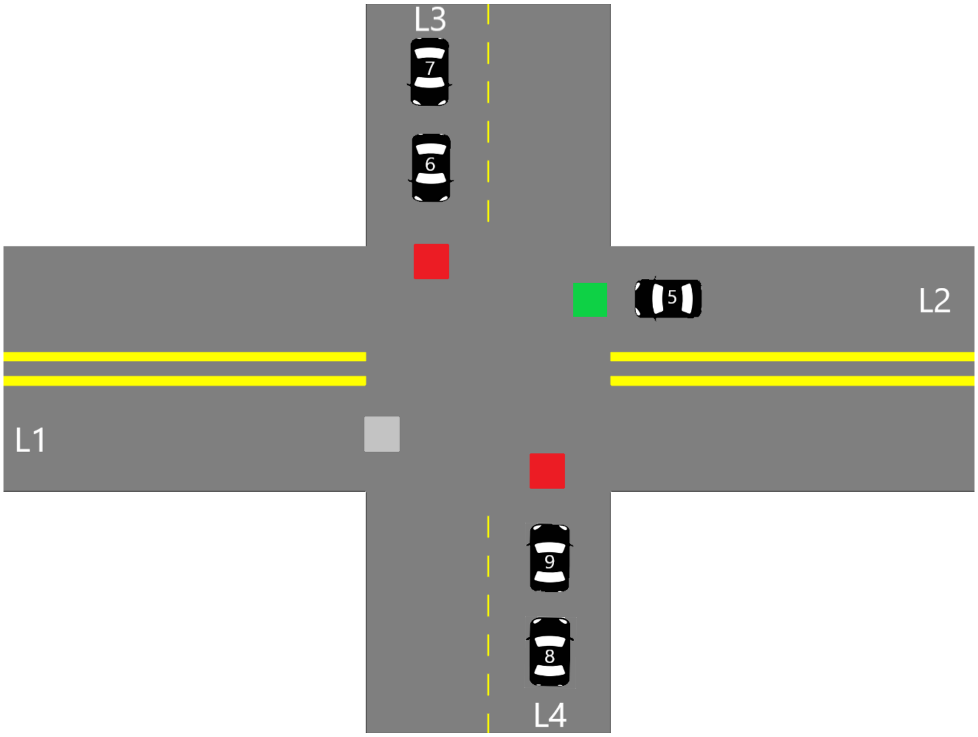
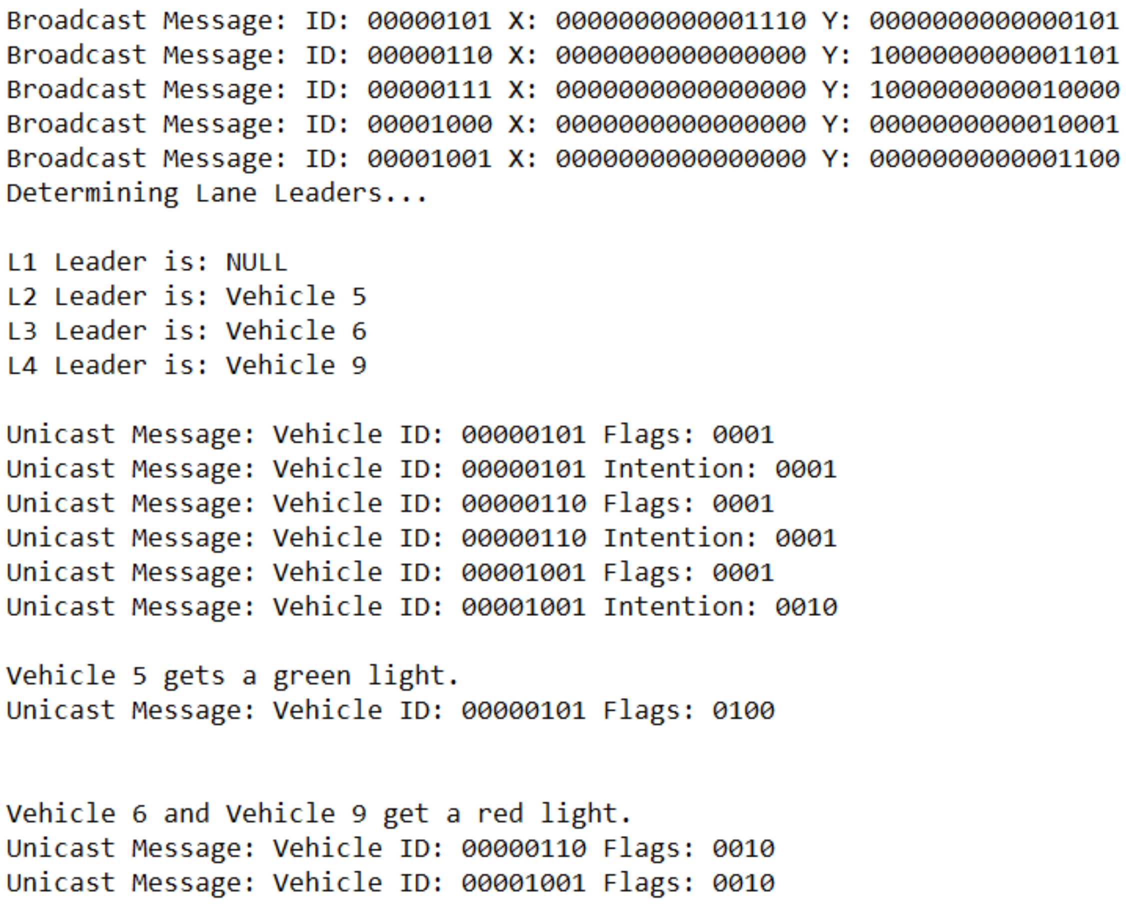


Figure 8. RSU Message Generation



```
Broadcast Message: ID: 00000101 X: 0000000000001110 Y: 0000000000000101
Broadcast Message: ID: 00000110 X: 0000000000000000 Y: 1000000000001101
Broadcast Message: ID: 00000111 X: 0000000000000000 Y: 1000000000010000
Broadcast Message: ID: 00001000 X: 0000000000000000 Y: 0000000000010001
Broadcast Message: ID: 00001001 X: 0000000000000000 Y: 0000000000001100
Determining Lane Leaders...

L1 Leader is: NULL
L2 Leader is: Vehicle 5
L3 Leader is: Vehicle 6
L4 Leader is: Vehicle 9

Unicast Message: Vehicle ID: 00000101 Flags: 0001
Unicast Message: Vehicle ID: 00000101 Intention: 0001
Unicast Message: Vehicle ID: 00000110 Flags: 0001
Unicast Message: Vehicle ID: 00000110 Intention: 0001
Unicast Message: Vehicle ID: 00001001 Flags: 0001
Unicast Message: Vehicle ID: 00001001 Intention: 0010

Vehicle 5 gets a green light.
Unicast Message: Vehicle ID: 00000101 Flags: 0100


Vehicle 6 and Vehicle 9 get a red light.
Unicast Message: Vehicle ID: 00000110 Flags: 0010
Unicast Message: Vehicle ID: 00001001 Flags: 0010
```

4. Findings

4.1 Results

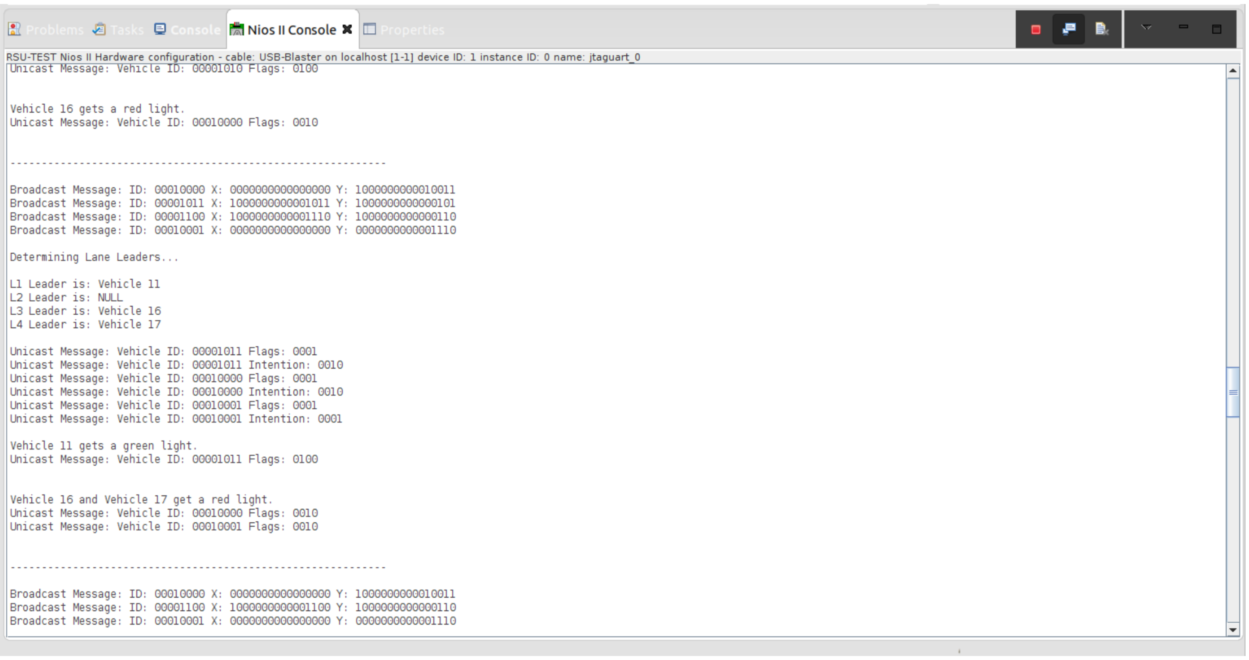
Various traffic scenarios were simulated and successfully facilitated by the RSU. Four such scenarios

are presented in Figures 9, 10, and 11. Indicated in Figure 9, there are four vehicles at the intersection that are broadcasting their positional information to the RSU: Vehicle 16, Vehicle 11, Vehicle 12, and Vehicle 17. Vehicles 11, 16, and 17 are determined to be the lane leaders for Lane 1, Lane 3, and Lane 4 respectively. The RSU then issues unicast messages to the lane leaders asking for their intention. Vehicle 11 responds with a unicast message indicating it intends to turn left, Vehicle 16 states its intention to turn left, and Vehicle 17 states it plans to turn right. Because Vehicle 11 is on the main road and there is no vehicle in Lane 2, it is issued a green light. Vehicles 16 and 17 are issued red lights to wait until the intersection is clear.

There are then three vehicles in the intersection that transmit broadcast messages to the RSU: Vehicle 12, Vehicle 16, and Vehicle 17 (refer to Figure 10). These three vehicles are determined to be the lane leaders for Lane 1, Lane 3, and Lane 4, respectively. The RSU issues unicast messages to these vehicles to determine their intentions. Vehicle 12 responds by stating it intends to turn right, Vehicle 16 relays that its intention is to turn left, and Vehicle 17 states it intends on turning right. Vehicle 12 is the only vehicle on the main road and is issued a green light by the RSU. Vehicles 16 and 17 must continue to wait until the intersection is clear. Vehicles 16 and 17 are then the only remaining cars in the intersection. They are identified as the lane leaders for Lane 3 and Lane 4, respectively. The RSU petitions the vehicles for their intentions, and they respond with unicast messages; Vehicle 16 states it wants to turn left and Vehicle 17 states it intends to turn right. Since the main road is empty, a tiebreaker is used by the RSU to determine which of the vehicles will go onto the main road. Vehicle 16 is selected and is issued a green light, and Vehicle 17 is issued a red light.

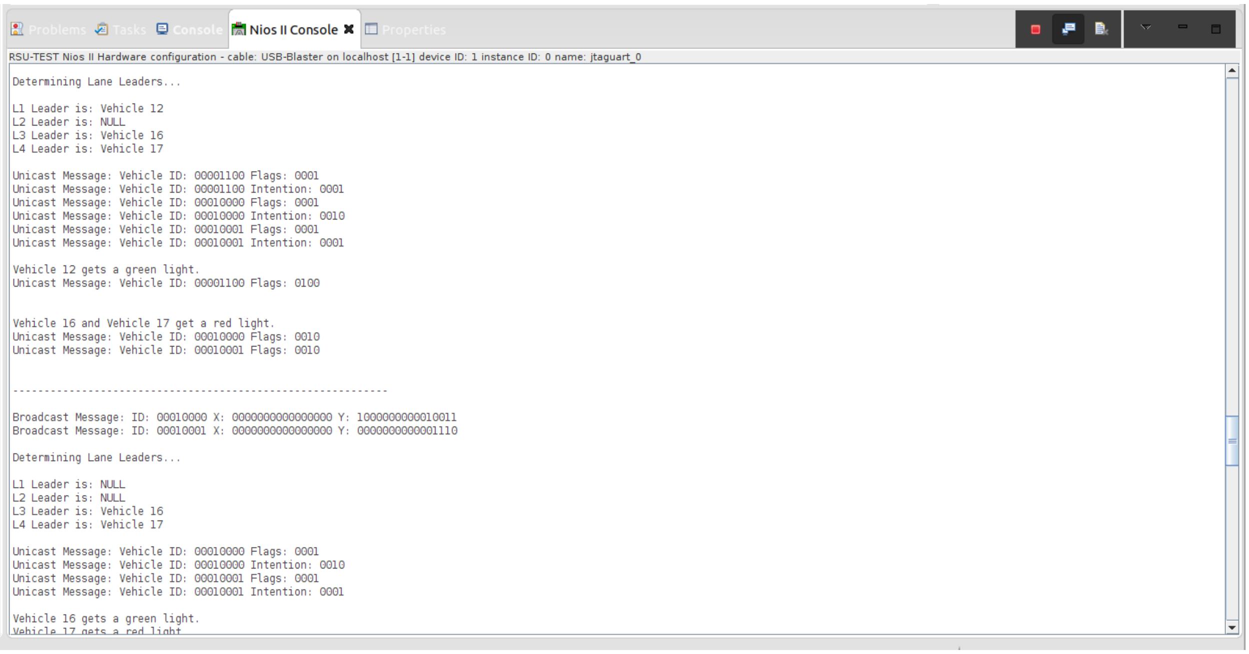
Figure 11 indicates that Vehicle 17 is the only remaining vehicle at the intersection. Using unicast messages, the RSU determines that Vehicle 17 intends on turning right and issues it a green light. The intersection is then empty. A visual realization of the communications shown in Figures 9–11 is presented in Figure 12.

Figure 9. Successful Traffic Management of Four Vehicles at the Blind Intersection on Nios II Eclipse



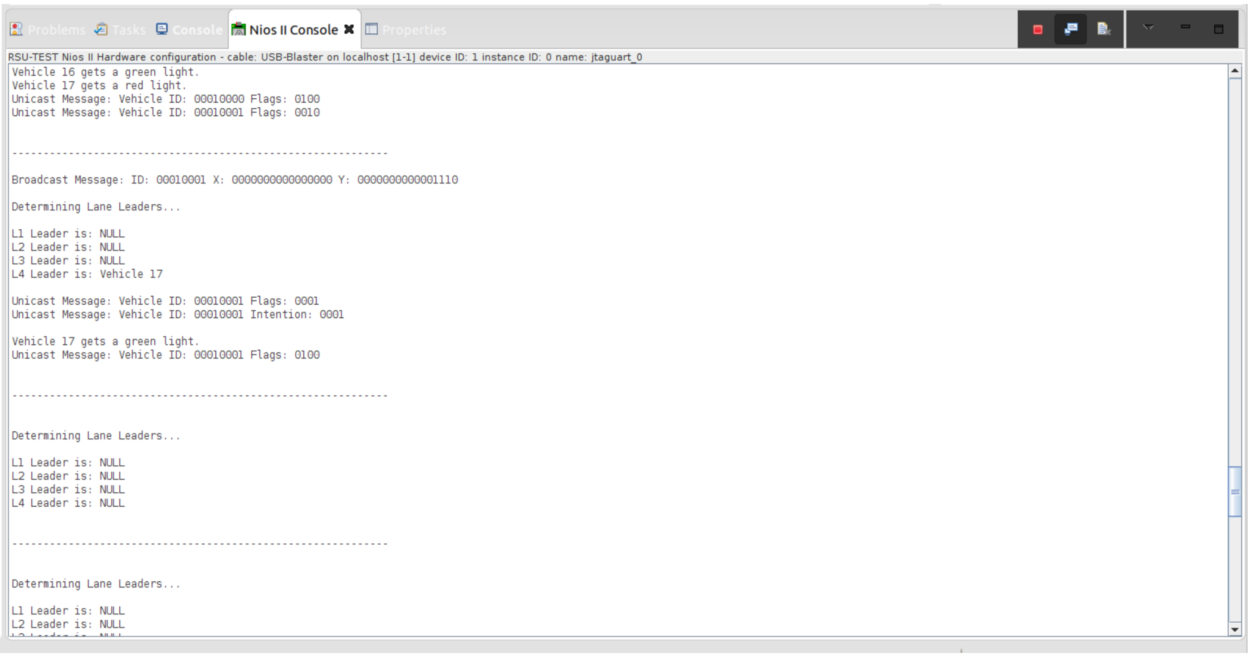
```
RSU-TEST Nios II Hardware configuration - cable: USB-Blaster on localhost [1-1] device ID: 1 instance ID: 0 name: jtaguart_0
Unicast Message: Vehicle ID: 00001010 Flags: 0100


Vehicle 16 gets a red light.
Unicast Message: Vehicle ID: 00010000 Flags: 0010


------------------------------------------------------------

Broadcast Message: ID: 00010000 X: 0000000000000000 Y: 1000000000010011
Broadcast Message: ID: 00001011 X: 1000000000001011 Y: 1000000000000101
Broadcast Message: ID: 00001100 X: 1000000000001110 Y: 1000000000000110
Broadcast Message: ID: 00010001 X: 0000000000000000 Y: 0000000000001110

Determining Lane Leaders...

L1 Leader is: Vehicle 11
L2 Leader is: NULL
L3 Leader is: Vehicle 16
L4 Leader is: Vehicle 17

Unicast Message: Vehicle ID: 00001011 Flags: 0001
Unicast Message: Vehicle ID: 00001011 Intention: 0010
Unicast Message: Vehicle ID: 00010000 Flags: 0001
Unicast Message: Vehicle ID: 00010000 Intention: 0010
Unicast Message: Vehicle ID: 00010001 Flags: 0001
Unicast Message: Vehicle ID: 00010001 Intention: 0001

Vehicle 11 gets a green light.
Unicast Message: Vehicle ID: 00001011 Flags: 0100


Vehicle 16 and Vehicle 17 get a red light.
Unicast Message: Vehicle ID: 00010000 Flags: 0010
Unicast Message: Vehicle ID: 00010001 Flags: 0010


------------------------------------------------------------

Broadcast Message: ID: 00010000 X: 0000000000000000 Y: 1000000000010011
Broadcast Message: ID: 00001100 X: 1000000000001100 Y: 1000000000000110
Broadcast Message: ID: 00010001 X: 0000000000000000 Y: 0000000000001110
```

Figure 10. Successful Traffic Management for Scenarios of Three Vehicles and Two Vehicles at the Blind Intersection



```
RSU-TEST Nios II Hardware configuration - cable: USB-Blaster on localhost [1-1] device ID: 1 instance ID: 0 name: jtaguart_0

Determining Lane Leaders...

L1 Leader is: Vehicle 12
L2 Leader is: NULL
L3 Leader is: Vehicle 16
L4 Leader is: Vehicle 17

Unicast Message: Vehicle ID: 00001100 Flags: 0001
Unicast Message: Vehicle ID: 00001100 Intention: 0001
Unicast Message: Vehicle ID: 00010000 Flags: 0001
Unicast Message: Vehicle ID: 00010000 Intention: 0010
Unicast Message: Vehicle ID: 00010001 Flags: 0001
Unicast Message: Vehicle ID: 00010001 Intention: 0001

Vehicle 12 gets a green light.
Unicast Message: Vehicle ID: 00001100 Flags: 0100


Vehicle 16 and Vehicle 17 get a red light.
Unicast Message: Vehicle ID: 00010000 Flags: 0010
Unicast Message: Vehicle ID: 00010001 Flags: 0010


------------------------------------------------------------

Broadcast Message: ID: 00010000 X: 0000000000000000 Y: 1000000000010011
Broadcast Message: ID: 00010001 X: 0000000000000000 Y: 0000000000001110

Determining Lane Leaders...

L1 Leader is: NULL
L2 Leader is: NULL
L3 Leader is: Vehicle 16
L4 Leader is: Vehicle 17

Unicast Message: Vehicle ID: 00010000 Flags: 0001
Unicast Message: Vehicle ID: 00010000 Intention: 0010
Unicast Message: Vehicle ID: 00010001 Flags: 0001
Unicast Message: Vehicle ID: 00010001 Intention: 0001

Vehicle 16 gets a green light.
Vehicle 17 gets a red light.
```

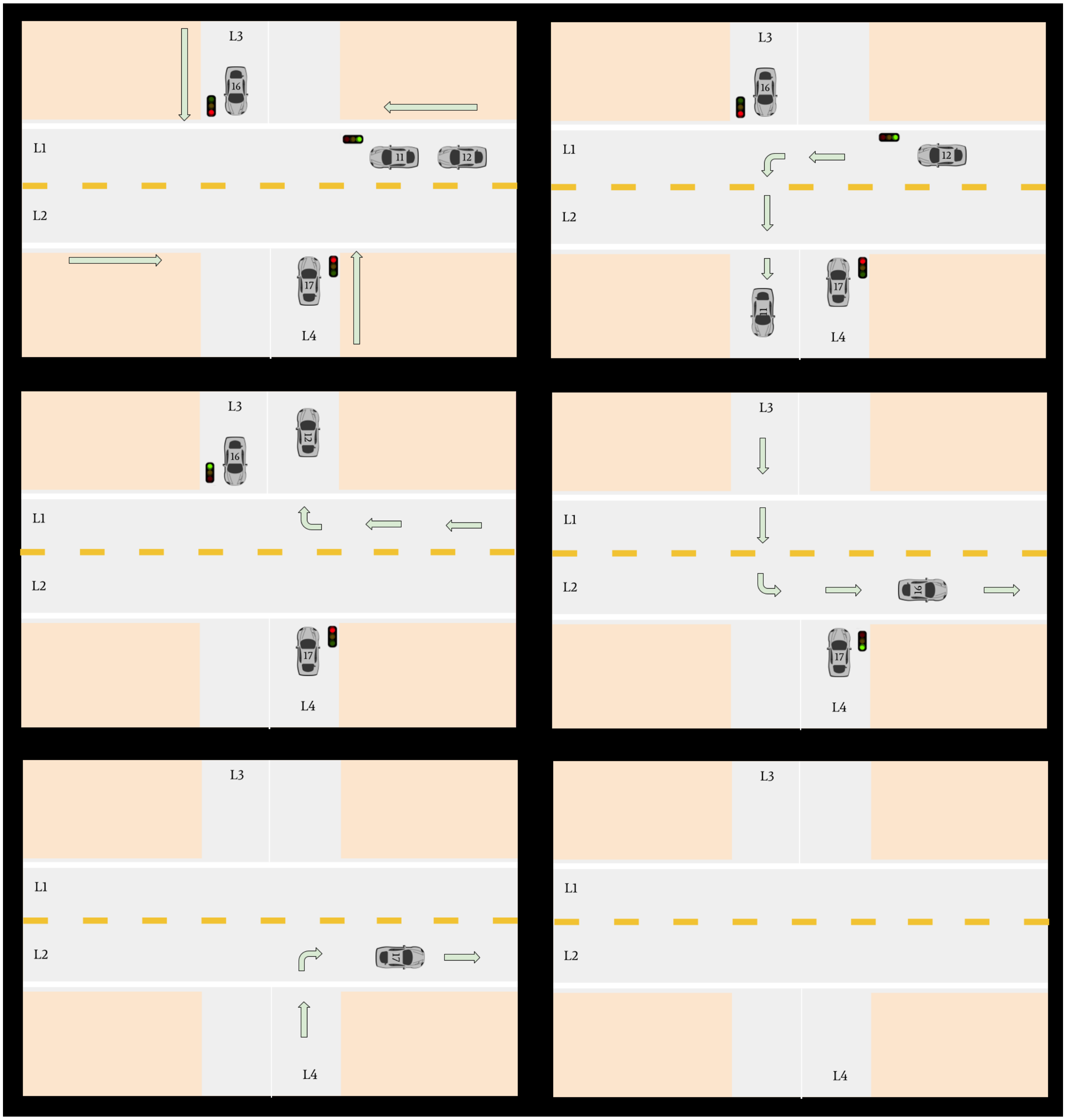
Figure 11. Successful Traffic Management of a Single Vehicle
at the Blind Intersection



RSU-TEST Nios II Hardware configuration - cable: USB-Blaster on localhost [1-1] device ID: 1 instance ID: 0 name: jtaguart_0

```
Vehicle 16 gets a green light.
Vehicle 17 gets a red light.
Unicast Message: Vehicle ID: 00010000 Flags: 0100
Unicast Message: Vehicle ID: 00010001 Flags: 0010


------------------------------------------------------------

Broadcast Message: ID: 00010001 X: 0000000000000000 Y: 0000000000001110

Determining Lane Leaders...

L1 Leader is: NULL
L2 Leader is: NULL
L3 Leader is: NULL
L4 Leader is: Vehicle 17

Unicast Message: Vehicle ID: 00010001 Flags: 0001
Unicast Message: Vehicle ID: 00010001 Intention: 0001

Vehicle 17 gets a green light.
Unicast Message: Vehicle ID: 00010001 Flags: 0100


------------------------------------------------------------


Determining Lane Leaders...

L1 Leader is: NULL
L2 Leader is: NULL
L3 Leader is: NULL
L4 Leader is: NULL


------------------------------------------------------------


Determining Lane Leaders...

L1 Leader is: NULL
L2 Leader is: NULL
```

Figure 12. Traffic Management Conducted by the RSU



4.2 Power Analysis

The battery size for the provided solar power system was 12 V and 5 Ah. The energy contained in this battery can be calculated as

$$(\text{Voltage}) \times (\text{Charge Capacity}) = (\text{Energy Capacity})$$

$$(12\ \text{V}) \times (5\ \text{Ah}) = 60\ \text{Wh}.$$

The power consumption of each device in the system was measured using a multimeter to determine current, voltage, and power. These results are documented in Table II. The total system power consumption based on these measurements was 11.85 W. Since the RSU will be operating continuously, the battery lifetime is given by

$$60\ \text{Wh} / 11.85\ \text{W} = 5.06\ \text{hrs}.$$

It is important to note that the recorded power data is for the prototype of the design, and it will change in an implementation using non-developmental equipment. The recommended system backup time for critical infrastructure is at least 10 days per the IEEE 1562 standard. A backup time of 5.06 hours is not acceptable for an RSU since it is critical infrastructure, but this can be corrected by purchasing larger batteries and solar panels. The correct sizing of the panels can be determined from the IEEE 1013 and 1562 standards that specify sizing guidelines for stand-alone photovoltaic systems.

5. Summary & Conclusions

To summarize, this research project makes the following contributions to the existing body of knowledge:

- Adaptation of a Virtual Traffic Light Algorithm: The project modifies a virtual traffic light algorithm to delegate substantial computational tasks to a roadside unit, enhancing efficiency and effectiveness.

- Implementation of the Algorithm on an FPGA Development Board: The adapted algorithm is successfully implemented on a Field-Programmable Gate Array (FPGA) development board, showcasing the feasibility and practicality of the proposed approach.

- Operability Demonstration of Roadside Unit Communication: The project demonstrates the functionality of roadside unit communication through the utilization of software-defined radios. This demonstration serves to validate the efficacy of the communication system.

- Design and Implementation of a Solar-Powered System: A novel solar-powered system, specifically designed for lightweight roadside units, is prototyped. This system operates off the grid, contributing to sustainability and energy efficiency in roadside unit power management.

- Further research should be conducted to determine the system's validity outside of a simulated environment.

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About the Author

Shahab Tayeb, PhD

Dr. Shahab Tayeb is a faculty member with the Department of Electrical and Computer Engineering in the Lyles College of Engineering at California State University, Fresno. Dr. Tayeb's research expertise and interests include network security and privacy, particularly in the context of the Internet of Vehicles. His research incorporates machine learning techniques and data analytics approaches to tackle the detection of zero-day attacks. Through funding from the Fresno State Transportation Institute, his research team has been working on the security of the network backbone for Connected and Autonomous Vehicles over the past five years. He has also been the recipient of several scholarships and national awards, including a US Congressional Commendation for STEM mentorship.

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