

# INTELLIGENT TRAFFIC MONITORING AND CONTROL SYSTEM

By

Nabil Al Nahin Ch

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APPROVED:

Dr. Dejan Raskovic, Committee Chair

Dr. Denise Thorsen, Committee Member

Dr. Michael Hatfield, Committee Member

Dr. Charles E. Mayer, Chair

*Department of Electrical and Computer Engineering*

Dr. Bill Schnabel, Dean

*College of Engineering and Mines*

Dr. Michael Castellini, *Dean of the Graduate School*

## **Abstract**

This thesis presents an intelligent system for monitoring and controlling traffic by sensing vehicles' attributes and using communication between vehicles and roadside infrastructures. The goal of this system is to improve the safety of the commuters and help the drivers in making better decisions by providing them with additional information about the traffic conditions. A prototype system consisting of a roadside unit (RSU) and an on-board unit (OBU) was developed to test the functionalities of the proposed system. The RSU consists of sensors for detecting vehicles and estimating their attributes and a radio for communicating with the OBU. The OBU also has a radio for communication purpose. Afterward, a vehicle was used to test the functionalities of the system and the communication between OBU and RSU was evaluated by emulating the presence of a vehicle.

A protocol for exchanging messages between the RSU and the OBU was developed to support effective communication. The efficiency of the communication process was further improved by varying the transmission range of different messages. A format for the message was proposed to convey all the necessary information efficiently. The process of collecting vehicle data, processing them and extracting useful information from the data was discussed here along with some limitations of the proposed system.



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## **Chapter 1 Introduction**

The number of vehicles on the road is increasing at an alarming rate and the conventional transportation systems are being stretched to their limits. This is affecting the safety of the commuters while the loss in productivity due to traffic congestion is hurting the economy. According to the World Health Organization (WHO), the number of traffic-related deaths worldwide was 1.35 million in 2018 [1]. Traffic congestion cost the United States \$87 billion in lost productivity in 2018, according to the INRIX Global Traffic Scorecard [2]. Smart traffic monitoring and controlling system can play an important role in making the existing transportation system more efficient. According to National Highway Traffic Safety Administration (NHTSA), as much as 80 percent of accidents where the driver is not impaired, can be prevented by enabling Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) based safety applications [3]. The United States Department of Transportation (USDOT) has laid out a strategic plan to outline goals of an Intelligent Transportation System (ITS) program and provided a framework for steps of conducting research, development and implementation [4].

### **1.1 Intelligent Transportation Systems**

An Intelligent Transportation System (ITS) is an integration of advanced communications technologies, vehicles, and transportation infrastructures that aims to improve safety, mobility, and productivity. ITS has already been applied in various capacities in different areas across the globe and it is having a significant impact on the transport network of those areas. In the United States, applications of ITS include electronic toll collection, traffic cameras, signal coordination, transit priority, ramp meters, and traveler information systems [5]. The United States Department of Transportation (DOT) estimates total nationwide benefits of over \$3.2 billion per year due to the implementation of these applications [6]. DOT plans to continue researching and keep integrating these ITS technologies into vehicle and infrastructure. All agencies within DOT, including Federal Highway Administration (FHWA), National Highway Traffic Safety Administration (NHTSA), Federal Motor Carrier Safety Administration (FMCSA),

Federal Railroad Administration (FRA), and Federal Transit Administration (FTA) are involved in the research of connected vehicles [7]. The European Union (EU) is also working on coherent and properly coordinated ITS applications across Europe. The European Commission (EC) is aiming for smooth ITS advancements by working with member states, industry and public authorities. EC is also setting the groundwork for deploying Cooperative-ITS (C-ITS), which focuses on connecting vehicles, infrastructures and commuters with one another [8]. In the city of Glasgow, ITS is used to provide information to the daily commuters about public transports, timings, the density of passengers and seat availability, the current location of buses, next stoppage and estimated arrival time [9]. It is clear that ITS will play an important role in shaping the future of transportation systems and consequently, a lot of research is being conducted in this area. A report published by IBM estimated that as much as \$30 trillion will be spent on transportation infrastructure in two decades from the year 2009 [10].

## **1.2 Contribution of Thesis**

The major contributions of this thesis are:

1. Development of a prototype system for traffic monitoring and control to allow research on vehicle data collection and processing, and communication between vehicles and infrastructures.
2. Detecting vehicles and estimating vehicle attributes by the implementation of sensor synergy techniques.
3. Development of a system that can accept sensors with different interfaces (SPI, UART, I2C, and analog).
4. Development of a system capable of tracking vehicles entering and leaving an intersection from different directions.
5. Implementation of wireless communication between a vehicle and road infrastructures and among different infrastructures of an intersection.

6. Development of a system to identify potentially dangerous situations and broadcast warning messages to the vehicles.
7. Further development of a system to detect the need for calibration by comparing the data collected by the roadside unit with the data received from vehicles.

### **1.3 System Overview**

The purpose of this thesis is to propose a smart traffic system, capable of monitoring the traffic conditions of an intersection, using different sensors and vehicle to infrastructure (V2I) communication and providing vehicles with relevant information and warning messages. A prototype system was developed to collect data about vehicles using different sensors. Afterward, the system analyzed the data to determine relevant attributes of the vehicle and to identify potentially dangerous situations. Then, the system communicates applicable information about vehicles and traffic conditions among the vehicles and the infrastructures. The system can also warn drivers about less than ideal driving conditions or any possibly hazardous situations. Each vehicle in the intersection is equipped with a unique temporary identification number (ID), which is a combination of a random number generated by a vehicle and a number sent to the vehicle from the infrastructure unit. This ID is used to monitor the traffic condition of the intersection by tracking which way the vehicle entered and exited the intersection.

### **1.4 Thesis Organization**

Chapter 2 presents an overview of the Intelligent Transportation System (ITS) and explains some aspects related to it. It also provides a brief description of different vehicle detection and classification methods and Vehicle to Everything (V2X) communication.

Chapter 3 describes the system architecture, different units of the system and their components and functionalities. It also presents the procedure for the exchange of messages between vehicles and infrastructures.

Chapter 4 discusses the hardware implementation of the RSU and OBU for the prototype system where different sensors are integrated with the microcontroller. It also describes the integration of the transceiver in the RSU and OBU of the system.

Chapter 5 discusses data collection and data processing techniques used for determining relevant vehicle attributes. It also presents the results obtained of collected data from a vehicle and discusses the accuracy of the system.

Chapter 6 provides a brief conclusion of the proposed system and discusses steps for further improvement of the system. This chapter also discusses some ideas to add more functionalities to the system.

## Chapter 2 Literature Review

The conventional transportation systems are getting smarter with time, in order to incorporate the rapidly increasing number of vehicles on the road. With the advancement in wireless communication and big data analysis, more and more Intelligent Transportation System (ITS) applications are being deployed to tackle traffic congestion. We are continuously being presented with innovative ideas to make the transportation system safer and more efficient. For example, Ford is exploring the prospect of removing traffic lights altogether and letting vehicles pass through intersections at speed prescribed by the Intersection Priority Management (IMP) system [11]. Technology entrepreneur Elon Musk founded The Boring Company to test the use of tunnels in large cities to reduce traffic congestion [12].

### 2.1 ITS Technologies

As more and more ITS applications are introduced, the need for supporting technologies and standards are becoming significant. Dedicated Short-Range Communications (DSRC) are wireless technologies designed for Vehicle to Everything (V2X) communications. DSRC consists of allocated channels for wireless communications and a set of standards and protocols [13]. The United States Federal Communications Commission (FCC) and European Telecommunications Standards Institute (ETSI) allocated 75 MHz and 30 MHz of spectrum in the 5.9 GHz band to be used by ITS [14] [15]. DSRC standards and protocols are significantly different in the United States, Europe, and Japan and as a result, they are not compatible.

The IEEE 802.11p standard was approved to support DSRC for ITS [16]. It is an amendment to the IEEE 802.11 for adding wireless communication in vehicular environments. This amendment allows data exchange without waiting for association and authentication procedures. This allows for communication between vehicles and infrastructures within a shorter time interval. Higher network layers provide association and authentication functionalities.

Cellular Vehicle to Everything (C-V2X) has recently emerged as a competitor of DSRC and rapid advancement in cellular communication technologies means it could be the future of V2X communications. Both DSRC and C-V2X have some unique advantages over one another. Unlike DSRC, C-V2X is yet to be used for ITS applications. The 2017 Cadillac CTS sedan is the first mass-produced vehicle to use DSRC for including vehicle-to-vehicle (V2V) capabilities [17]. Trade association Global Automakers also voiced their support for DSRC. However, the advantages of longer range, lower latency, and compatibility with existing cellular infrastructure make C-V2X an important part of the future of ITS [18]. A new chipset 9150 C-V2X was recently released by Qualcomm which can be used in infrastructures and vehicles for C-V2X communication [19]. Ford announced that C-V2X technology will be available to all new vehicles starting in 2022 [20].

## **2.2 Vehicle to Everything Communication**

Vehicle to Everything (V2X) communication is the exchange of information between vehicle and any other entity that may affect the transportation system. The goals of V2X are the safety of commuters and traffic efficiency. Depending on the technology used, V2X can either be WLAN based (IEEE 802.11p) or cellular based (LTE/5G). V2X may include vehicle to vehicle (V2V), vehicle to infrastructure (V2I), vehicle to pedestrian (V2P) or other types of communications.

### **2.2.1 Vehicle to Infrastructure Communication**

Vehicle to Infrastructure (V2I) technologies collect data from vehicles about traffic and send information about safety, mobility, and environment from infrastructure to the vehicles through wireless communication. V2I technologies can be used for traffic monitoring, smart signals, electronic toll collection, traffic-related warnings, and smart parking.

### **2.2.2 Vehicle to Vehicle Communication**

Vehicle to Vehicle (V2V) communication allows vehicles to wirelessly exchange information with the primary goal of ensuring the safety of the commuters. V2V devices can be either OEM (original equipment manufacturer) devices or aftermarket devices that aim to add more functionalities to the vehicle. V2V communications allow vehicles to know about other vehicles in their vicinity. Research and Development teams are working on improving forward collision warning, blind spot or lane change warning, emergency vehicle warning, do-not-pass warning, vehicle-based road condition warning and control loss warning using V2V technologies [21].

### **2.2.3 Vehicle to Pedestrian Communication**

Pedestrians are among the most vulnerable road users in traffic accidents [22]. Vehicle to Pedestrian (V2P) communication can play an important role in making the roads safer for pedestrians. A lot of researchers are working on road safety applications using V2P technologies [23] [24] [25]. Especially with the recent improvement in cellular technologies, cellular vehicle to everything (C-V2X) communication has become an important area of ITS. Unlike DSRC, C-V2X makes V2P communication easier to implement because most of the pedestrians already use cellular devices. Prototype V2P applications for pedestrians or bicycles using terminals like smartphones, walking sticks and bicycle lights demonstrate safer transportation for all commuters [26].

## **2.3 Traffic Surveillance Technologies**

An important role of infrastructures in ITS is to gather traffic information from vehicles and driving environment. There are a lot of different technologies used for traffic surveillance. Among intrusive technologies for traffic surveillance, inductive loop, pneumatic tube, and piezoelectric sensor are most commonly used. Magnetometer, microwave radar, infrared-based system, ultrasonic sensors, and video image processing are some of the common non-intrusive traffic monitoring technologies. All these

technologies have their advantages and disadvantages and they can be used to gather different types of traffic data. Table 1 presents a comparison of the capabilities of different surveillance technologies [27].

**Table 1: Traffic surveillance technologies capabilities comparison**

Technology	Capabilities				
	Presence	Occupancy	Vehicle Count	Measuring Speed	Vehicle Classification
<b>Inductive Loop</b>	Yes	Yes	Yes	Yes	Yes
<b>Pneumatic Tube</b>	No	No	Yes	Yes	Yes
<b>Piezoelectric Sensor</b>	No	No	Yes	Yes	Yes
<b>Magnetometer</b>	Yes	Yes	Yes	Yes	Yes
<b>Microwave Radar</b>	Yes	Yes	Yes	Yes	Yes
<b>Infrared (active)</b>	No	No	Yes	Yes	Yes
<b>Infrared (passive)</b>	Yes	Yes	Yes	Yes	Yes
<b>Ultrasonic Sensor</b>	Yes	No	Yes	No	No
<b>Video Image Processing</b>	Yes	Yes	Yes	Yes	Yes

### 2.3.1 Inductive Loop

An inductive loop is the most commonly used vehicle detection technology for traffic surveillance. In this system, a signal of frequency between 10 and 200 kHz is sent through a wire loop and the change in inductance is detected in the presence of a vehicle. The speed can also be estimated using a pair of inductive loops [28]. Using a higher sampling rate, classification of a vehicle is also possible using an inductive loop. Because of its high accuracy in vehicle detection, it is considered the standard of the industry. The biggest disadvantage of the inductive loop is its high installation and maintenance cost. As the wire loop needs to be embedded under the pavement, traffic needs to be stopped during its installation or maintenance. This technology is also susceptible to stress and temperature, and high repair cost means a broken detector is very rarely replaced [29].

### 2.3.2 Pneumatic Tube

This vehicle detection technique uses a long rubber tube, installed across the road on the pavement. When wheels of a vehicle pass over the tube, the air pressure inside the tube activates an air switch which triggers an electrical signal. It can be used for counting vehicles and classifying them based

on the number of axles. The simple hardware configuration of the system means the cost of installation and maintenance is relatively low. The drawback of this system is frequent maintenance required because of inevitable wear of the tube. The pneumatic tube technology is usually used for short-term traffic monitoring.

### **2.3.3 Piezoelectric Sensor**

A piezoelectric sensor is embedded under the pavement of the road and when a vehicle passes over the sensor, the change in applied force generates a voltage. This generated voltage is proportional to the weight of the vehicle. The voltage is generated only if the applied force is changing and so any stationary vehicle cannot be detected using this technology [30]. This traffic monitoring system is mostly used when the weight of the vehicle needs to be measured as well. It has similar drawbacks to those of inductive loop. Since the sensor is embedded under the pavement, the installation and maintenance are very expensive and causes traffic disruption.

### **2.3.4 Magnetometer**

A magnetometer measures Earth's magnetic field at a certain area. Using magnetometers, vehicles can be detected by measuring the change in Earth's magnetic field caused by the metallic components of the vehicles. Using two magnetometers, the speed of the vehicle can be estimated. A lot of different methods are proposed for the classification of vehicles using magnetometers [31] [32] [29]. Some researchers discuss using the angle between two axes of the Earth's magnetic field for detecting vehicles instead of using the magnitude of the magnetic field [31]. Using a gradient tree boosting algorithm XGBoost, the accuracy of vehicle classification of 80.55% can be achieved [32]. The advantages of using magnetometers for traffic surveillance include low cost of installation and the ability to detect speed and classify vehicles using simple calculations.

### **2.3.5 Microwave Radar**

Radar (Radio Detection and Ranging) is a system that detects objects and determines the direction, speed, and distance of them by using radio waves. The radar transmits a constant frequency signal and when an object passes the detection zone, a shift in the frequency of the reflected signal is induced. From this frequency shift, vehicles can be detected, and the speed of the moving vehicles can be estimated.

### **2.3.6 Infrared-based System**

Infrared (IR) based traffic surveillance system detects radiation ranging from 100 to 105 GHz to determine the presence of a vehicle [27]. Two types of infrared-based systems, called active IR and passive IR are used for traffic monitoring. Light-emitting diodes or laser diodes are used to emit low-energy radiation in an active IR system. To detect a vehicle, the time difference between transmitting and receiving the reflected signal is measured. If the time difference is shorter than a predetermined threshold, a vehicle is detected. A passive IR system uses the radiation emitted from road surface and vehicles. By monitoring the change in the received IR radiation, vehicles are detected. This system can be used to estimate vehicle speed and length for classification. IR based system is computationally intensive and its performance is affected by the environment.

### **2.3.7 Ultrasonic Sensor**

The ultrasonic sensor sends sound pulses and receives the reflected pulses. The distance between the receiver and the object that reflected the sound pulses is measured according to the sound wave travel time. If the measured distance is less than the distance measured to the background of the road, a vehicle is declared to be present. Disadvantages of this traffic surveillance technology are that they cannot be used for vehicle classification and that its performance is susceptible to temperature change and air turbulence. More advanced ultrasonic sensors can compensate for the temperature change, but they are more expensive.

### **2.3.8 LiDAR**

LiDAR (Light Detection and Ranging) is a reliable technology for remote sensing that uses pulsed laser light to measure distances. It measures the time difference and wavelengths of the reflected pulses of light to make three-dimensional representation of the target. Because of its high cost, this technology is more commonly used to detect vehicles for autonomous driving rather than traffic surveillance [33] [34].

### **2.3.9 Video Image Processing**

A Video Image Processing (VIP) system is one of the most sophisticated traffic surveillance systems. It uses one or several video cameras to capture images of a vehicle, digitize and process the images, and analyze the images to gather traffic data. Detection of a vehicle is done by comparing successive video frames. Three different types of VIP systems are used for traffic monitoring. Tripline system detects vehicles by monitoring changes in pixels in the detection zone. The speed is estimated by measuring the time taken for a vehicle to travel a detection region of known length. Closed-loop tracking system keeps track of vehicles by confirming several detections of the same vehicle along the road. Data association tracking system recognizes and tracks vehicles by finding unique linked areas of pixels and tracking them through successive frames. VIP systems can achieve up to 99% accuracy in terms of detecting vehicles and estimating their speed [35]. Drawbacks of this system include performance affected by non-ideal weather, high installation, maintenance and equipment cost, and compute-intensive data processing.

## **2.4 Existing Intelligent Traffic Monitoring Systems**

The concept of a traffic monitoring and control system is not new but recent advancements in V2X communication and ITS technologies are reinventing smart traffic monitoring system. With the introduction of smart vehicles and infrastructures and the ability to connect them all together, this is introducing many new possibilities.

### **2.4.1 Waycare**

Waycare is helping cities to monitor and control their traffic by using historic and real-time data. The goal of Waycare is to build an operating system for smart cities that can use the enormous amount of data coming from connected vehicles and infrastructures to improve the safety and efficiency of the transportation system [36] [37]. In 2017, the Waycare system was deployed in Las Vegas and it helped to reduce the number of primary crashes along the Interstate 15 (I-15) by 17 percent [38]. Waycare provides four solutions for traffic monitoring and control, traffic management operations, law enforcement and emergency services, roadway and safety service patrol, and traffic engineering. The Traffic Management Platform uses traffic data and AI (Artificial Intelligence) for smart traffic control, safety operations and advanced data visualization. Data gathered from different sources are processed through a GIS-based (Geographic Information System) interface and potentially dangerous roads are identified using the AI-driven event identification algorithm [39]. Law enforcement agencies are given on-board proactive solutions to improve communications and mitigation process. The solution can be accessed from the browser and the system can help the law enforcement agencies by providing the verified location and CCTV (Closed Circuit Television) footage of the incident [39]. The Roadway and Safety Service Patrol is another solution of Waycare, dedicated to improving traffic safety and incident reporting. The solution alerts service patrol drivers of relevant incidents and allows digital reporting of the incident. Traffic Engineering Solution enables automated reporting and easy data exporting capabilities for easy data access. Waycare uses historical data and real-time data from infrastructures, connected vehicles, and smartphone applications. Infrastructures like inductive loop traffic detectors, road cameras, warning signs, and microwave vehicles detectors are useful for traffic monitoring data. Data can also be collected from the on-board unit (OBU) of private vehicles and public transports. Other applications can also provide localized data about navigation, weather, events, construction, road closures, and road accidents. The implementation process of the Waycare system does not require any change in existing infrastructures.

Initially, the sources of internal and external data are assessed, and historical and real-time data are collected from these sources. After that, the platform is customized according to the needs of the city and training data is used to validate its functionalities.

#### **2.4.2 Pelco Traffic Monitoring**

Pelco, a security and surveillance technologies company, offer solutions for traffic monitoring to improve the safety of the commuters [40]. According to a study by the National Highway Traffic Safety Administration (NHTSA), 36 percent of all crashes are intersection related [41]. Pelco helps traffic officials with the solution for traffic management at intersections that focuses on the safety of commuters. The system allows traffic management officials to quickly access and respond to traffic incidents by providing real-time alerts. It provides tools to help officials in gathering information of an incident and filing report. Pelco traffic monitoring system also detects traffic flow and the gathered data can be used for designing a safer and more efficient transportation system for the city.

#### **2.4.3 Logipix**

The Logipix traffic surveillance system helps manage traffic flow and maintain the security of the commuters by detecting traffic violations, recording relevant footages and creating violation packages. It is deployed in Cairo and 70 intersections are equipped with the system [42]. Beside traffic counting, Logipix detects speeding, stop line violation, wrong way traffic violation, red light violation and one-way traffic violation at an intersection. After detecting a traffic violation, the system records footage of the violation, identifies license plate and collects vehicle and owner information [42]. Vehicle database and software for license plate recognition are integrated into the system. Lastly, a detailed violation package is created that includes 5 corresponding pictures of the violation and the license plate. The system works independently at an intersection, which is equipped with high-resolution cameras. IR flashes are also integrated with the cameras for capturing detailed images at night. Traffic lights controllers are connected

to the system, thus the states of them can be visualized on the captured images. Besides monitoring the traffic, Logipix is also used for city surveillance in important areas.

## Chapter 3 Proposed System

This chapter presents the general architecture of the proposed traffic monitoring and control system. This chapter also describes the functionality of different units of the system and a communication protocol between them.

### 3.1 System Architecture

The system consists of a number of RSUs (Roadside Units) and OBUs (On-board Units). Figure 1 shows the general architecture of the proposed system.

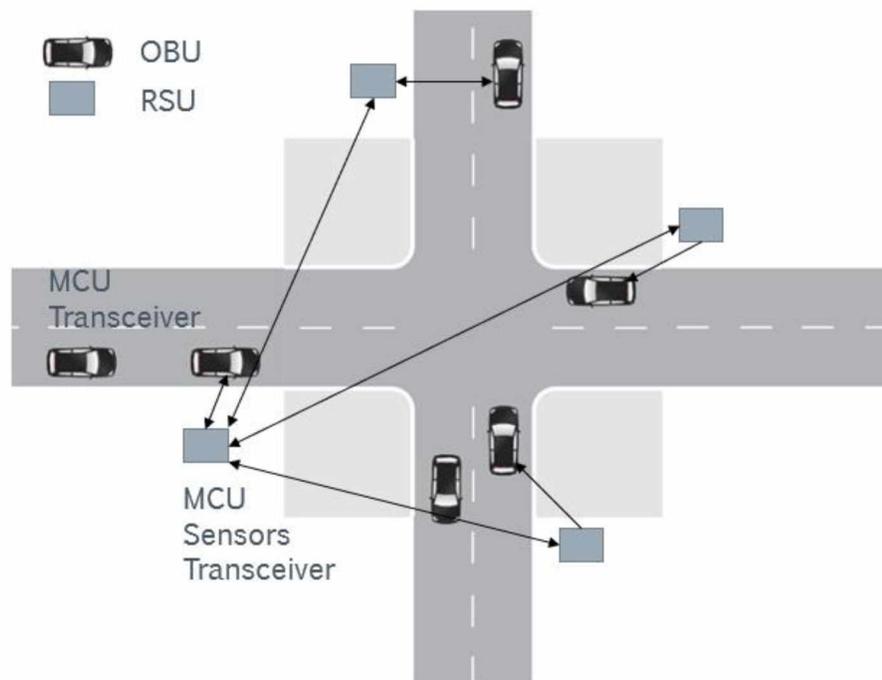
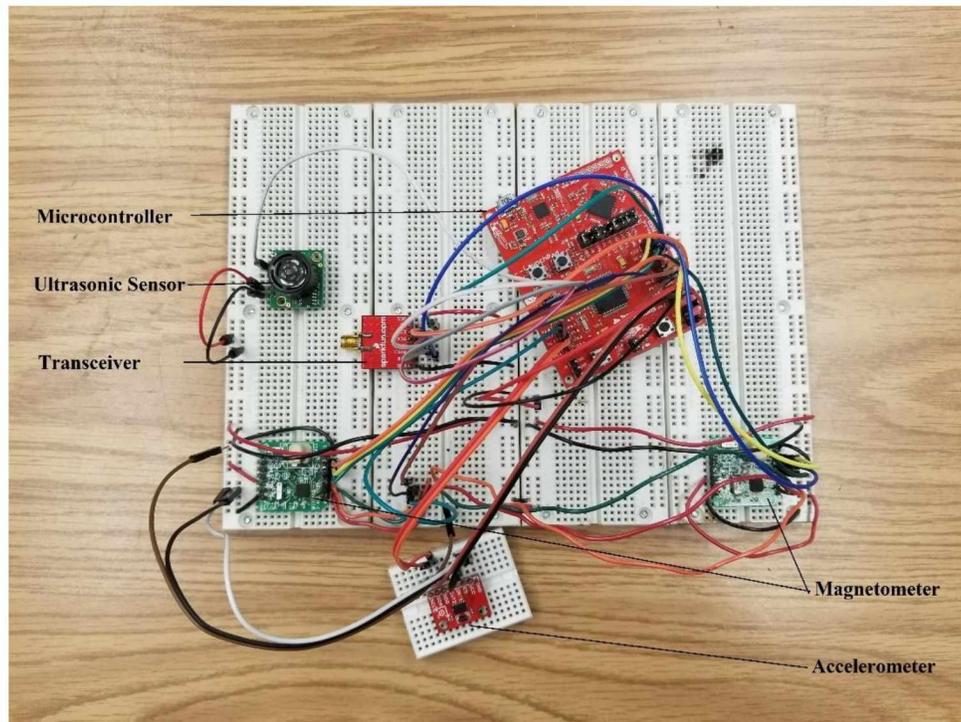


Figure 1: System Architecture of Intelligent Traffic Monitoring and Control System

#### 3.1.1 Roadside Unit

RSUs (Roadside Units) are placed on the side of each road, 200 meters away from the intersection and they consist of different sensors, a microcontroller, and a transceiver. Figure 2 shows the RSU built for the prototype system. Different types of sensors can be used to detect vehicles and gather relevant

information about vehicles and the environment. Magnetometers and ultrasonic sensors were used in the prototype system to detect vehicles, estimate speed and length of the vehicles and detect the lane the vehicles are on. Other sensors can also be added to the system to gather additional information like weight and height of the vehicles, road condition, and visibility conditions.



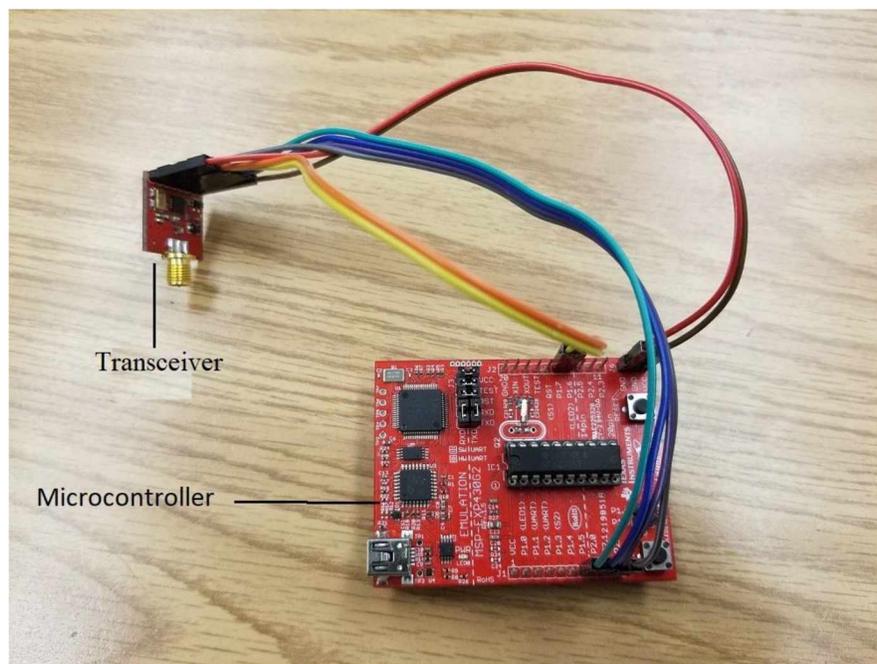
**Figure 2: Prototype Roadside Unit**

The transceiver of the RSU is used to communicate with other RSUs and vehicles. The transmission power of the transceiver is varied depending on the type of messages being transmitted. The sensors and the transceiver are connected to a microcontroller that collects data from sensors, processes them and prepares the message containing all the necessary information to be sent via the transceiver.

### **3.1.2 On-board Unit**

An OBU (On-board Unit) is placed in vehicles and it consists of a microcontroller, a transceiver, and different sensors. The sensors can detect road conditions and different attributes of the vehicle to be

sent to the RSU. For example, a GPS and accelerometers can be used to detect damaged road areas and their location [43] [44] [45]. That information can be transmitted to an RSU, which can warn other vehicles going in the same direction. A transceiver is used to communicate with the RSU. A microcontroller is used to process the data and the received message from an RSU to inform the drivers of relevant information. Figure 3 shows the prototype OBU used in the system. An OBU would be useful for vehicles that are incapable of communicating with infrastructures. Certain information like length or class of the vehicle can be set beforehand by the drivers to be transmitted to RSU even without using any sensors to determine them.



**Figure 3: Prototype On-board Unit**

### **3.2 Communication Protocol**

The exchange of messages between RSU and OBU will allow the system to monitor traffic and provide drivers with useful information about the traffic condition. The messages are categorized into four types and depending on the type of the message, the receiver can ignore or accept the message.

Different types of messages will also have different transmission power for controlling the transmission range, which will help reduce the probability of collision due to too many messages.

### **3.2.1 Types of Messages**

The types of messages and their functionalities are discussed below.

Type 0: This message will be sent from an RSU and will be received by an OBU. It will have a unidirectional range of 50 meters. RSU will send this message when a vehicle is detected.

Type 1: This message will be sent from an OBU to an RSU. It will have 50 meters range and it will be sent when a vehicle receives a type 0 message. There will be a random delay between 0 and 10 ms before sending this message. This delay will reduce the probability of collision if multiple vehicles are detected at the same time.

Type 2: This message will be broadcasted by an RSU and all other RSUs and OBUs of the intersection will receive this message. This message will have a range of 450 meters.

Type 3: This message will be sent by both RSUs and OBUs. The message sent by an OBU will have 50 meters range and the message sent by an RSU will have 450 meters range. Type 3 message will be used to track vehicles through the intersection.

### **3.2.2 Message Format**

The size of the message is 14 bytes and its contents can be divided into 5 sections. The format of the message will be the same for all types of messages sent from both RSU and OBU. Table 2 presents an overview of the format of the message.

**Table 2: Format of the Message**

Section		Contents	Size	
			Contents (Bits)	Section (Bytes)
Introduction		Intersection address	4	3
		Sender address	4	
		Road number	4	
		Total roads at the intersection	4	
		Message type	2	
		Reserved	6	
Information form RSU		Speed of Vehicle	8	3
		Lane the vehicle is on	3	
		Length of the vehicle	5	
		Class of the vehicle	3	
		Reserved	5	
Information from vehicle		Class of the vehicle	3	3
		Length of the vehicle	5	
		Weight of the vehicle	8	
		Reserved	8	
Warnings	From RSU	Speeding	1	2
		Damaged road	1	
		Icy road	1	
		Low visibility	1	
		Reserved	4	
	From OBU	Emergency vehicle	1	
		Damaged road	1	
		Reserved	6	
Temporary ID		From OBU	8	3
		From RSU	16	
<b>Total</b>				<b>14</b>

Introduction section of the message contains intersection address, sender address, road number, the total number of roads at the intersection and message type. All RSUs will have an intersection address, which will be transmitted to any vehicle entering the intersection, via type 0 message. Any message with a different intersection address will be ignored by an RSU and vehicles until the vehicle leaves the current intersection and enters another. Then the vehicle will receive a new intersection address from RSU. All

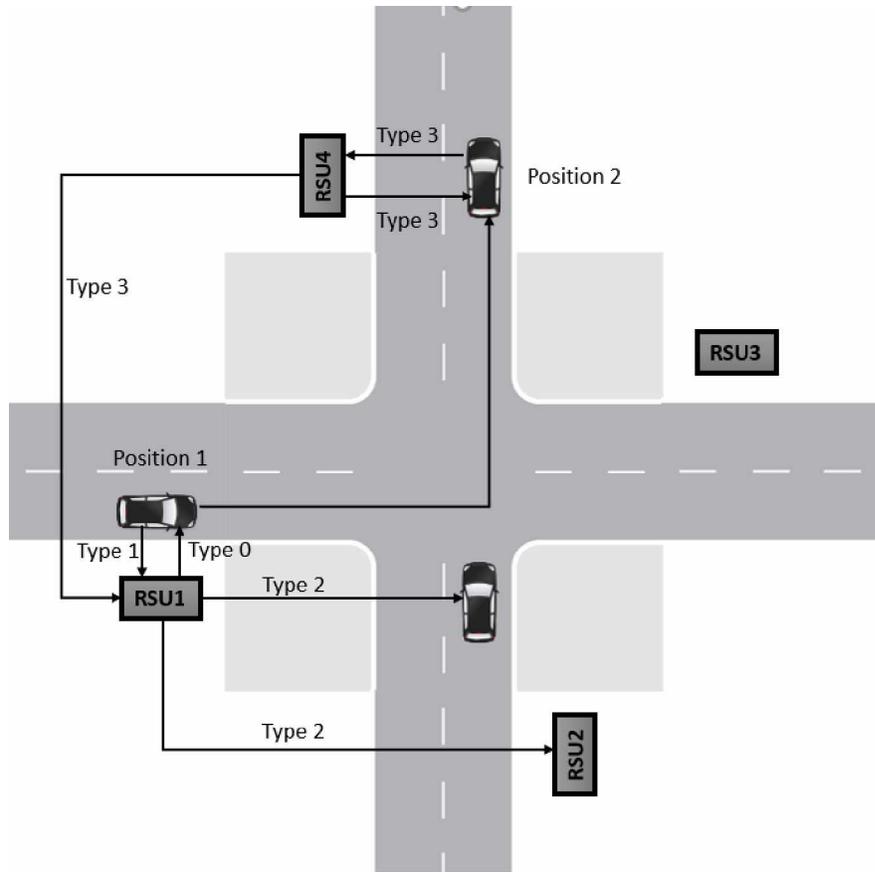
adjacent intersections of an intersection will have different addresses. The sender address will be the same for all vehicles and all RSUs of an intersection will have a unique sender address. Road number indicates which road the message is about. It may or may not be the same as the sender address depending on the situation. The information about the total number of roads at an intersection is useful for the vehicle to determine which road is represented by which number. For example, if a vehicle gets a message saying the road number is 3 and there are 4 roads at the intersection, that means the first road to the right is  $3+1=4$ , the second road to the right is  $3+2=5$ . Since 5 is greater than the total roads at the intersection, the actual number of that road will be  $5-4=1$ . The information about types of message will be used to interpret the message differently.

Information gathered using the sensors of the RSU, like the speed of the vehicle, lane the vehicle is on or class of the vehicle will be in the section called information from RSU. Any information that the vehicle can provide will be in the section called information from OBU. Information like length or class of the vehicle can be preset in the OBU as they will not change for that vehicle. These two sections will have some contents in common. For example, if the speed measured by the RSU is different from the speed sent by OBU, then the speed estimated by the RSU can be ignored and this information can be used to calibrate the RSU if needed. Each bit of the warning section will represent a specific warning. The first byte of this section is dedicated to warnings sent from RSU like vehicle exceeding the speed limit or low visibility condition. The second byte of the warning section is dedicated to warnings sent from the vehicle like an emergency vehicle or damaged road. Temp ID section will contain a unique, but non-identifiable ID for each vehicle entering the intersection and it will be used to track when and which road the vehicle takes to leave the intersection. The first byte of the ID will be generated randomly by the OBU and other 2 bytes will be provided by the RSU. This way, even if multiple vehicles are detected at the same time and receive the same type 0 message with the same ID from RSU, their final IDs will be probably different. Obviously, it is possible, but unlikely that two vehicles will receive an identical ID. Different vehicles approaching the

intersection from different roads can have same temporary ID because they will be separated by their road numbers.

### **3.2.3 Communication Between RSU and OBU**

In Figure 4, when a vehicle reaches position 1, it is detected by RSU1. RSU1 sends type 0 message to the vehicle and OBU receives intersection address, road number, information about the vehicle and traffic condition, warnings and a unique ID. After that, the OBU replies with a type 1 message that contains information about the vehicle which was preset in the OBU or gathered by the sensors in the vehicle. The message also contains warnings about dangerous situations detected by the OBU and a randomly generated ID. The ID provided by the RSU in type 0 message and ID provided by OBU in type 1 message will be combined to create the temp ID for that vehicle. If there were any warnings present in either of those messages, RSU1 will combine all the warnings and broadcast a type 2 message to all vehicles and RSUs. OBU will compare the intersection address of the type 2 message with the intersection address it received in the previous type 0 message to make sure any messages from RSUs of nearby intersections are ignored. All other RSUs will retransmit the message and all the vehicles in the intersection will get the information about the warnings and which road the warnings are about.



**Figure 4: Exchange of Different Types of Messages at an Intersection**

After sending the type 1 message, the OBU will start sending type 3 messages and it will ignore any type 0 messages until it gets a type 3 reply from an RSU. RSU1 will ignore the type 3 messages sent by the OBU if the message has the same road number as its own. The OBU will ignore any type 3 messages sent by any other vehicles by checking the sender address. The OBU will keep sending type 3 messages and keep listening for either type 2 or 3 messages from an RSU. When the vehicle reaches position 2, it will be inside the transmission range of RSU4. After receiving type 3 message from the vehicle, RSU4 will broadcast a type 3 message. RSU1 will receive the message and since the type 3 message was sent by an RSU and the message had the same road number as its own, RSU1 will record that the vehicle of that specific temp ID left the intersection through road 4. RSU2 and RSU3 will ignore this message since the road number of the message is different from theirs. OBU will receive the message and recognize that it

left the intersection. It will ignore all messages until it receives a type 0 message at the next intersection.

Figure 5 and Figure 6 shows the flowchart of the RSU and the OBU communication procedure.

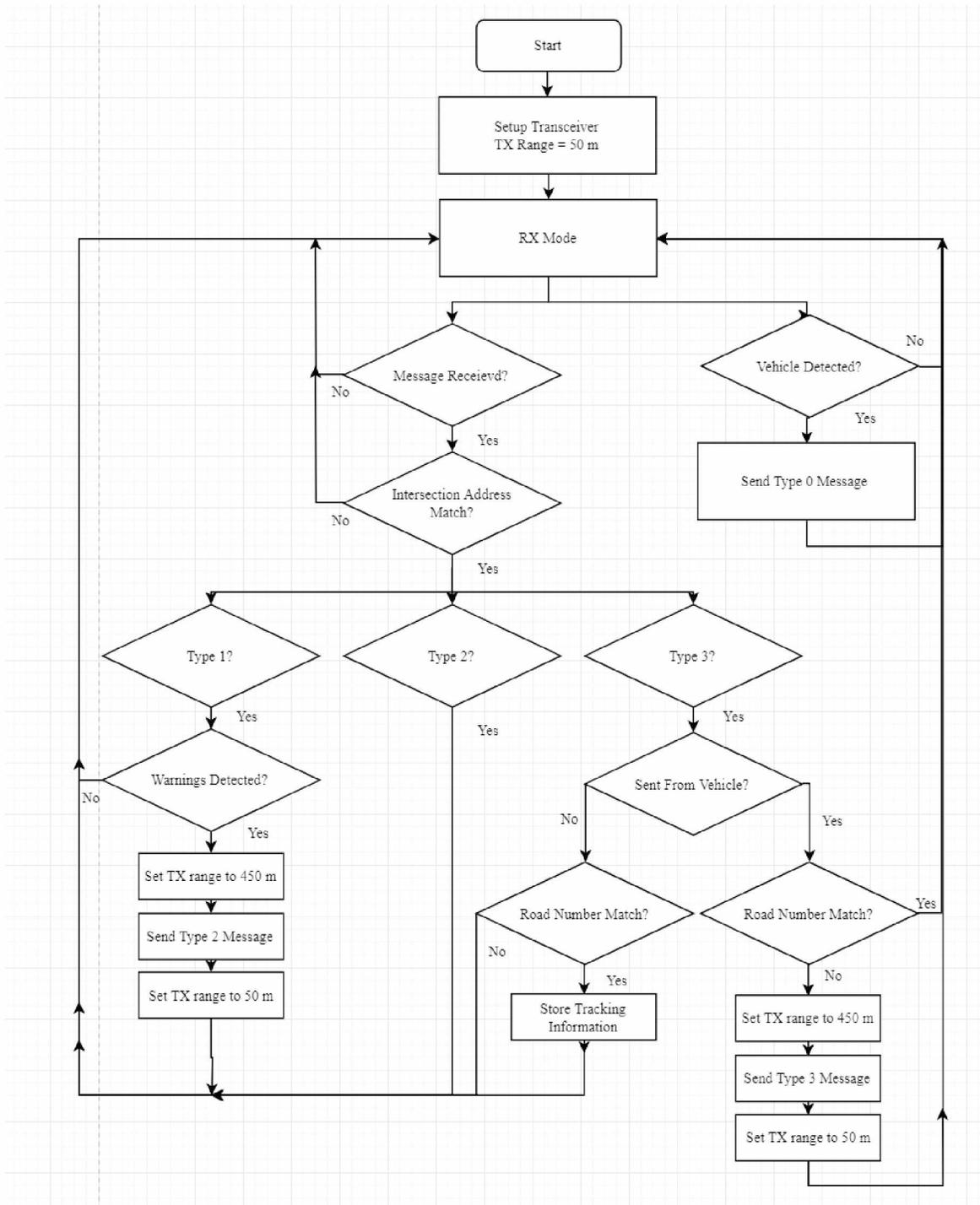
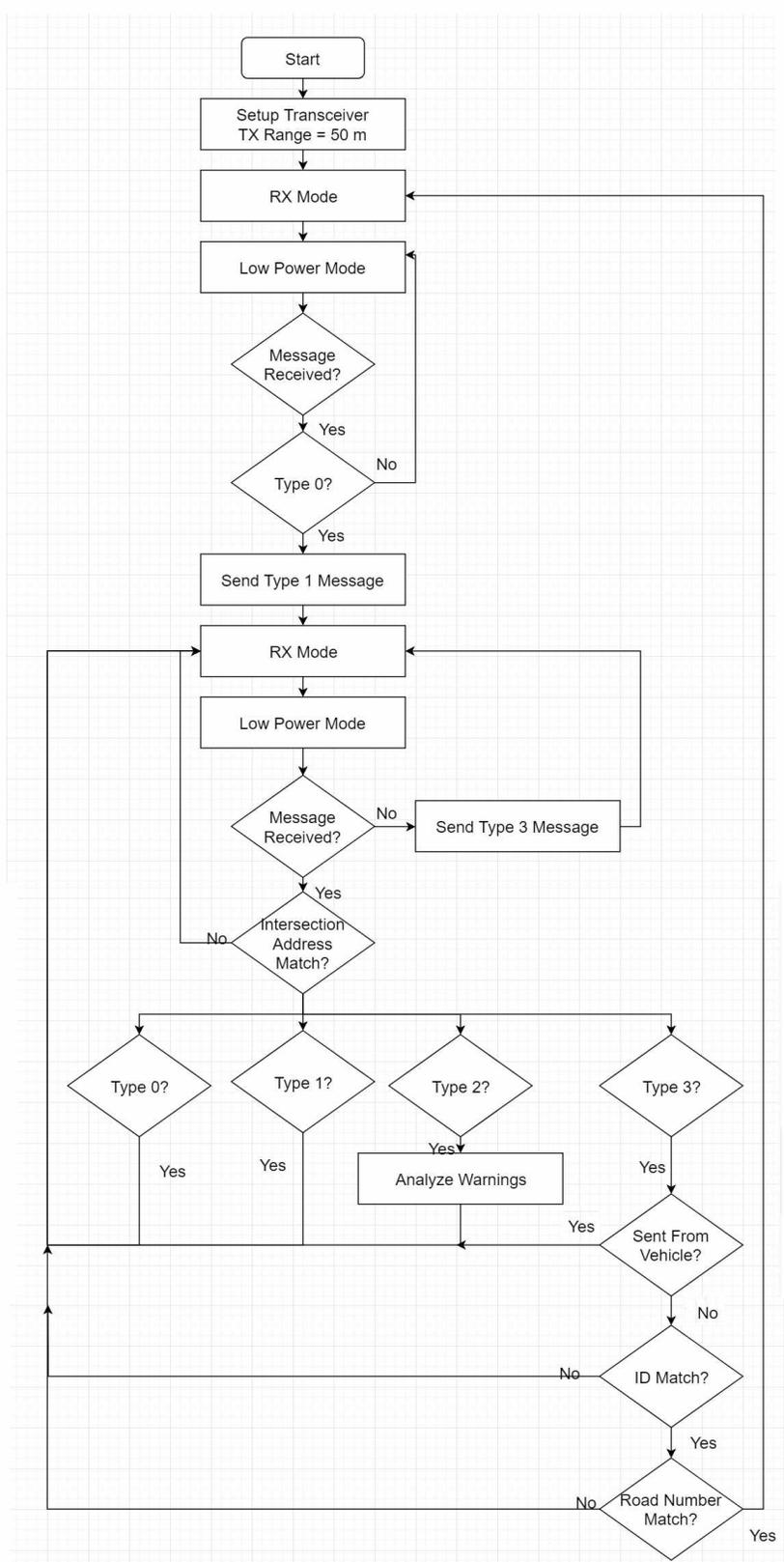


Figure 5: Flowchart of RSU Communication Procedure



**Figure 6: Flowchart of OBU Communication Procedure**

### **3.2.4 Advantages of Varying Transmission Range**

Reducing the transmission range for certain types of messages have two advantages. It ensures that the vehicle receives type 0 message only from the RSU that detected the vehicle and it also helps reduce the total number of messages transmitted in the system.

A vehicle receives all the necessary information about an intersection from the RSU that detects the vehicle while entering the intersection. From this message, the vehicle can identify the road number it is on and the road numbers of all other roads in that intersection. If a vehicle entering the intersection from another road receives this message, it will not be able to identify any of the roads at the intersection. To make sure that this message is not received by any vehicles entering the intersection from different roads, the transmission range of the message is reduced to 50 m.

Each vehicle entering the intersection will generate only one type 0, one type 1 and one type 2 message. However, each vehicle will transmit many type 3 messages and the number of type 3 message will depend on how long the vehicle takes to leave the intersection. So, most of the messages transmitted at an intersection will be type 3 messages. Since the RSUs will reply to any type 3 message received from a vehicle, the total number of transmitted messages can be significantly reduced by reducing the transmission range of this message. This will make sure only the RSU of the road that the vehicle uses to leave the intersection will receive the type 3 message.



## Chapter 4 Hardware Implementation

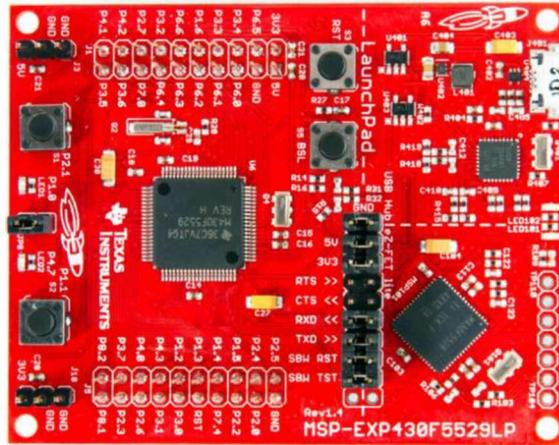
In this thesis, a prototype system was implemented to collect data using different sensors, to process the data to obtain information about the vehicle and to test communication between the roadside unit (RSU) and the on-board unit (OBU). An overview of the hardware integration is presented in this chapter.

### 4.1 Microcontroller Components

The RSU and OBU of the prototype system are based on MSP430 microcontrollers. The MSP430 is a family of ultra-low-power, 16-bit microcontrollers by Texas Instruments [46]. They are designed to be used for low cost and low power consumption embedded system, which makes them suitable for this prototype system. These mixed-signal microcontrollers feature a 16-bit RISC (reduced instruction set computer) type CPU and 16-bit registers. They also support timers, a real-time clock (RTC) module, analog to digital converters (ADC), digital to analog converter (DAC), universal serial communication interfaces (USCIs) and direct memory access (DMA).

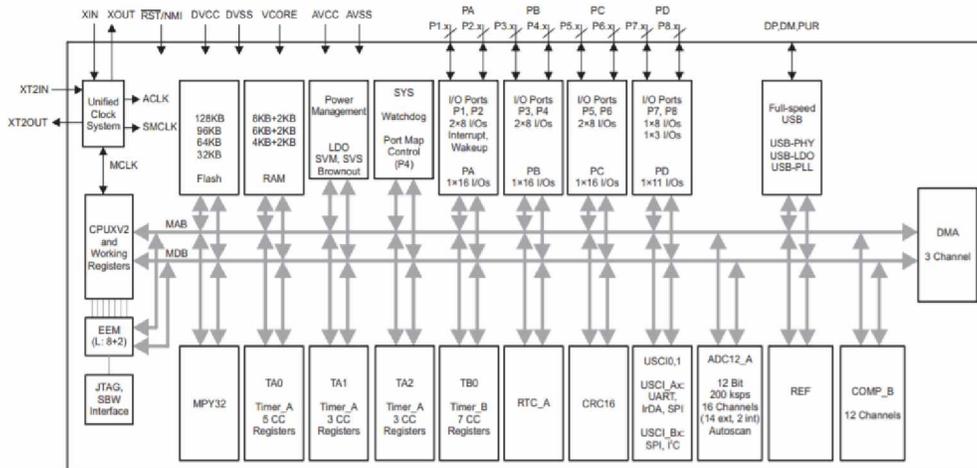
#### 4.1.1 Texas Instruments MSP-EXP430F5529LP

The MSP-EXP430F5529LP launchpad was used as the microcontroller for RSU [47]. Figure 7 shows the MSP-EXP430F5529LP launchpad breakout board. The microcontroller for RSU needs to support different types of sensors. The MSP-EXP430F5529LP launchpad supports different serial communication interfaces like SPI (serial peripheral interface), I2C (inter-integrated circuit) and UART (universal asynchronous receiver-transmitter). It has voltage regulators that can supply stable 3.3 V and 5 V voltage source. It is also equipped with user interfaces like switches and LEDs. The MSP-EXP430F5529LP launchpad satisfies all the requirements for the system and its relatively low cost, smaller size and low power consumption features make it a suitable choice for the microcontroller for the RSU.



**Figure 7: MSP-EXP430F5529LP Launchpad (Courtesy of Texas Instruments)**

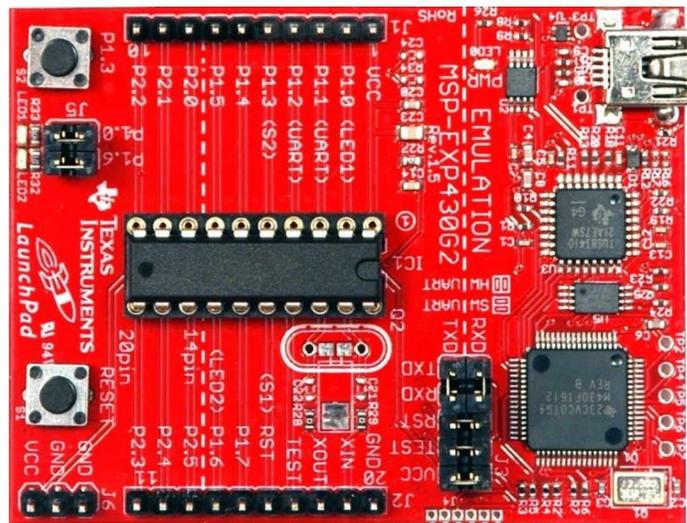
The MSP-EXP430F5529LP launchpad is based on the MSP430F5529 MCU (microcontroller unit) [48]. MSP430F5529 is a 16-bit microcontroller featuring integrated USB, 128 KB flash, 8 KB RAM, 12-bit/14 channel ADC with internal reference, 2 USCI (universal serial communication interfaces) modules to support SPI, I2C and UART serial communication protocols, 3.6 V to 1.8 V supply voltage and a 32-bit HW multiplier. The system clock supports up to 25 MHz frequency. It is very energy efficient because it consumes only 1.9  $\mu\text{A}$  in standby mode (low-power mode 3) and takes 3.5  $\mu\text{s}$  to wake up from standby mode. Figure 8 shows the functional block diagram of the MSP430F5529 MCU.



**Figure 8: MSP430F5529 Functional Block Diagram (Courtesy of Texas Instruments)**

#### 4.1.2 Texas Instruments MSP-EXP430G2553

The MSP-EXP430G2553 launchpad was used for the prototype OBU [49]. It is based on the MSP430G2553 MCU and it features simple user interfaces like LEDs and switches [50]. Figure 9 presents the MSP-EXP430G2553 launchpad breakout board and Figure 10 shows a functional block diagram of an MSP430G2553 MCU. This mixed-signal microcontroller also features 2 USCI modules to support SPI, I2C, IrDA and UART serial communication protocols, 1.8 V to 3.6 V operation, up to 16 MHz system clock, 16 KB of flash memory, 512 bytes of SRAM, 10-bit, 8-channel ADC, 8-channel comparator, 2 16-bit timers with 3 capture/compare registers, and 24 GPIOs (general purpose input output).



**Figure 9: MSP-EXP430G2553 Launchpad (Courtesy of Texas Instruments)**

The MSP430G2553 is energy efficient because it only consumes 0.5  $\mu\text{A}$  in standby mode and takes less than 1  $\mu\text{s}$  to wake up from standby mode. It is also inexpensive, small and can support different types of sensors, which make it suitable for OBU. The launchpad also supports a broad range of booster packs to add external LCD displays or sensor systems.

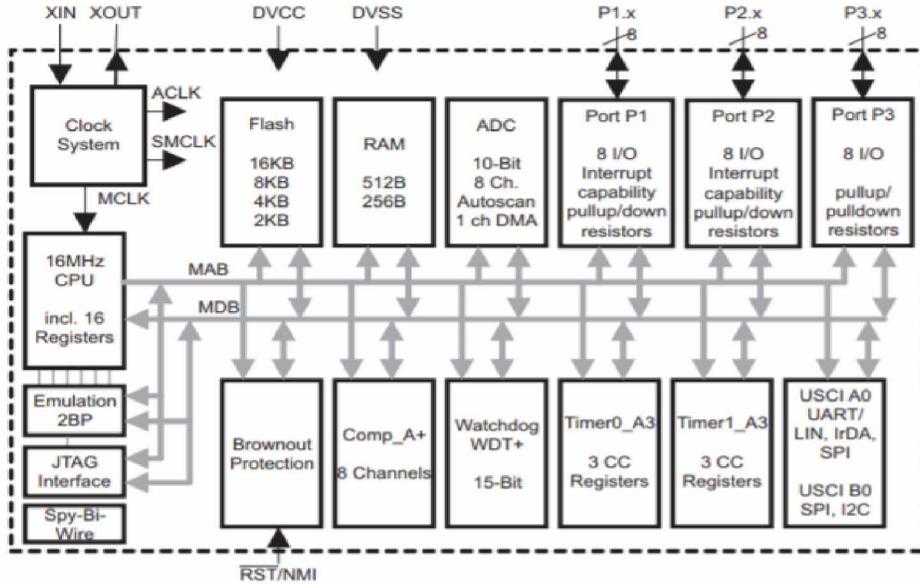


Figure 10: MSP430G2553 Functional Block Diagram (Courtesy of Texas Instruments)

## 4.2 Hardware Integration

### 4.2.1 MicroMag3 Integration

MicroMag3 is a 3-axis magnetic field sensing module, shown in Figure 11. It is a power efficient and small magnetic sensor that is used in prototype RSU for detecting vehicle and estimating speed, length and other attributes of the vehicle. It features a measurement range of  $\pm 1100 \mu\text{T}$ , resolution of  $0.015 \mu\text{T}$ , a sample rate of 2000 samples/second and draws less than  $500 \mu\text{A}$  current [51].

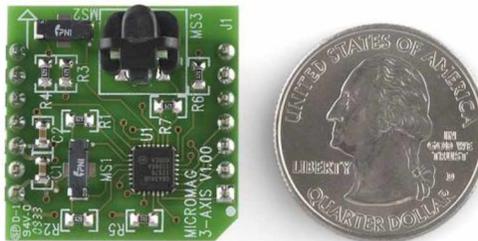
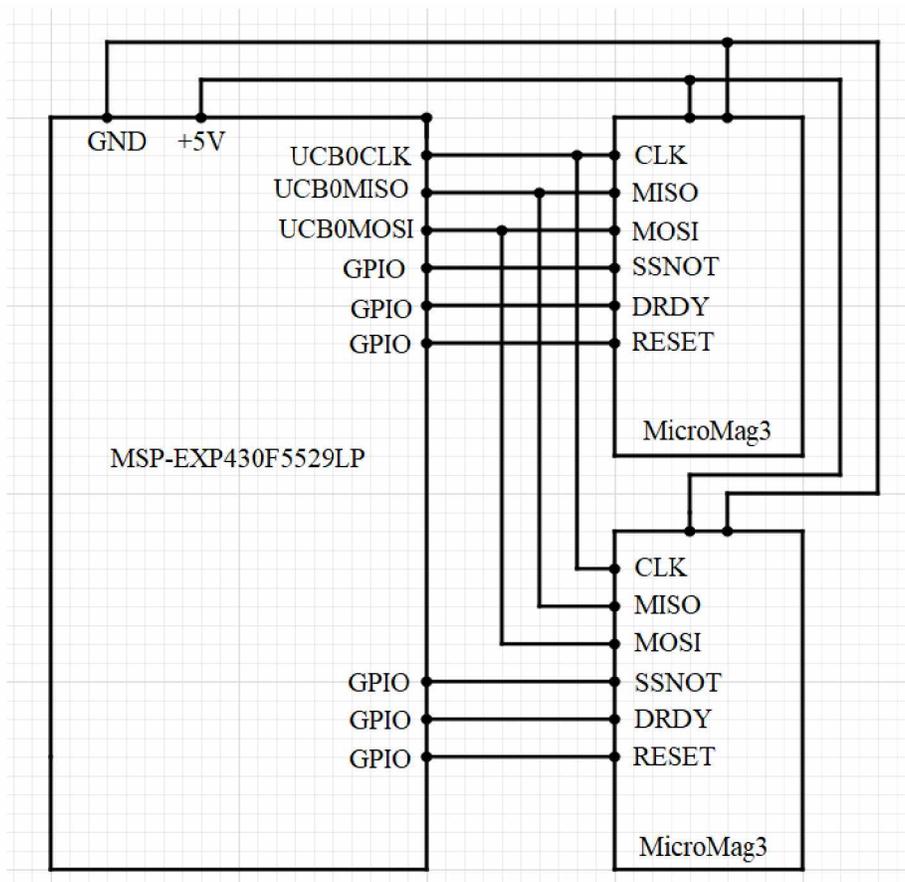


Figure 11: MicroMag3 Magnetic Field Sensing Module

MicroMag3 uses fully digital SPI (serial peripheral interface) protocol to exchange data. MicroMag3 can be easily integrated with MSP430F5529 using 4-wire SPI protocol where the microcontroller acts as an SPI master by controlling the clock for data exchange. The connections between the microcontroller and the sensor are CLK (serial clock), MISO (master in slave out), MOSI (master out slave in), SSNOT (slave select NOT), data ready (DRDY) and reset. CLK provides the serial clock from the SPI master, MISO is used to send data to the microcontroller from the sensor, MOSI is used to send commands to the sensor from the microcontroller, SSNOT is used to select between multiple SPI slaves and DRDY is used to check if new data is available from the sensor. USCI\_B0 module is used for the SPI communication and GPIO pins were used for SSNOT, DRDY and reset. Figure 12 shows the wire connections between the MSP430F5529 and the MicroMag3.



**Figure 12: SPI Connections Between MSP430F5529 and MicroMag3**

The microcontroller sends a command byte to the magnetometer, which sends back two bytes of data in response. The microcontroller also needs to send two dummy bytes in order to receive the data. The 2 least significant bits of the command byte determine which axis of the magnetic field is being measured. Table 3 presents the command byte for each axis of data. The PS0, PS1 and PS2 bits set the period being measured. MOT, ODIR and DHST bits are used for debugging and testing purposes.

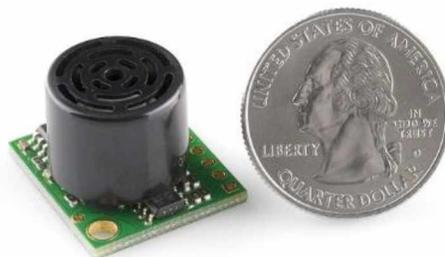
**Table 3: Command Byte for Measuring Each Axis of Magnetic Field**

Position	7	6	5	4	3	2	1	0
Bit	DHST	PS2	PS1	PS0	ODIR	MOT	AS1	AS0
X axis	0	0	0	0	0	0	0	1
Y axis	0	0	0	0	0	0	1	0
Z axis	0	0	0	0	0	0	1	1

#### 4.2.2 LV-MaxSonar-EZ1 Integration

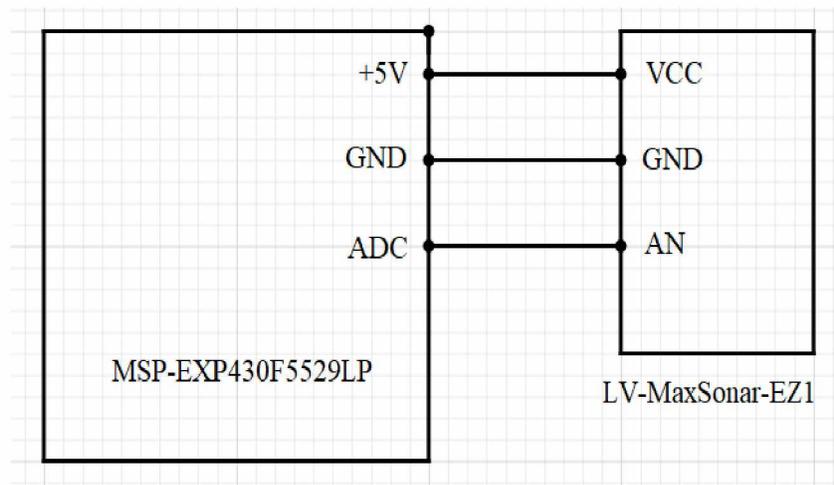
LV-MaxSonar-EZ1 is a 42 kHz ultrasonic sensor that features low (2 mA) supply current, 20 Hz data rate, RS232 serial output at 9600 bps, analog output at 10 mV/inch, and PWM output at 147  $\mu$ s/inch [52].

Figure 13 shows the ultrasonic sensor.



**Figure 13: LV-MaxSonar-EZ1 Ultrasonic Range Finder**

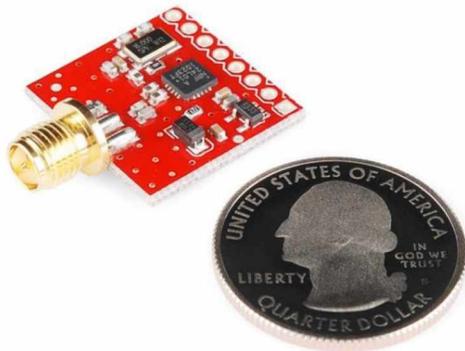
The ultrasonic sensor was used for a prototype RSU to estimate the distance of the vehicle from the surface of the road, which can be used to determine which lane the vehicle is on. ADC (analog to digital converter) was used to integrate the sensor with the microcontroller. Figure 14 shows the wire connections between the microcontroller and the ultrasonic sensor.



**Figure 14: Wire Connections Between MSP430F5529 and Ultrasonic Sensor**

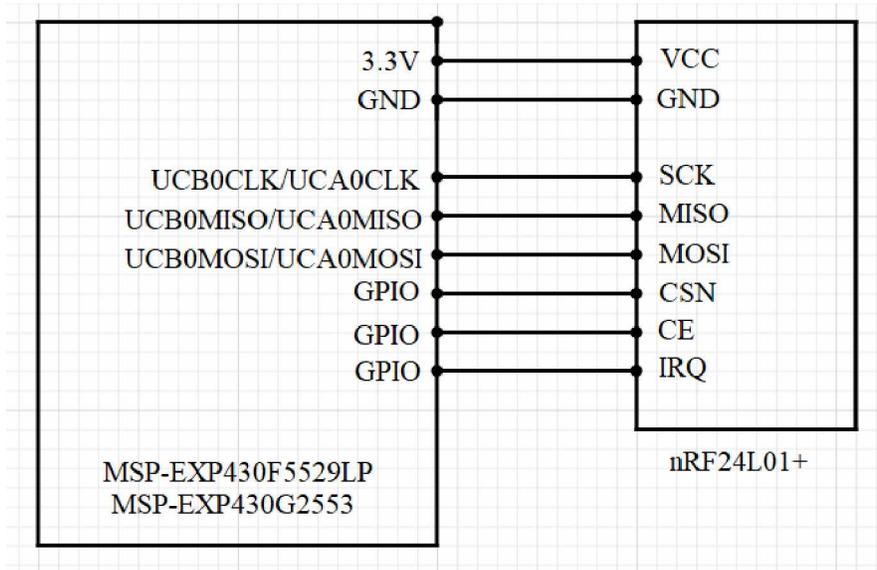
#### 4.2.3 nRF24L01+ Integration

For wireless communication between the RSU and OBU of the prototype system, nRF24L01+ transceiver breakout board was used. Figure 15 shows the nRF24L01+ transceiver breakout board.



**Figure 15: nRF24L01+ transceiver breakout board**

The transceiver operates on 3.3 V supply voltage and features 250 kbps to 2 Mbps data rate, up to 100 m range, auto acknowledgment and re-transmission, 6 data pipes for receiver, 32 bytes RX and TX FIFOs and 125 software selectable channels [53]. The transceiver is integrated with the microcontroller using a 4-wire SPI interface and the wire connections between the microcontroller and the transceiver is shown in Figure 16.



**Figure 16: Wire Connections Between the MCU and nRF24L01+**

USCI\_B0 module of MSP430G2553 was used to integrate the transceiver in the OBU and USCI\_A0 module of MSP430F5529 was used to integrate the transceiver in the RSU. In both cases, the connections between the microcontroller and the nRF24L01+ were the same. The connections were SCK, MOSI, MISO, CSN, CE, and IRQ. SCK pin provides the serial clock from the SPI master, MOSI and MISO pins transfer the data between the SPI master and slave, CSN pin selects among multiple SPI slaves, IRQ is an active low interrupt pin and CE pin selects between transmit, receive, standby and power-down mode. Table 4 shows different modes of operation determined by the CE pin state, the PWR\_UP register, and the PRIM\_RX register. The transceiver was configured to operate at 1 Mbps data rate and the auto-acknowledgment and re-transmission features were disabled.

**Table 4: Different Operation Modes of nRF24L01+**

<b>Mode</b>	<b>CE Pin</b>	<b>PWR_UP Register</b>	<b>PRIM_RX Register</b>
RX	1	1	1
TX	1	1	0
Standby 2	1	1	0
Standby 1	0	1	-
Power Down	-	0	-

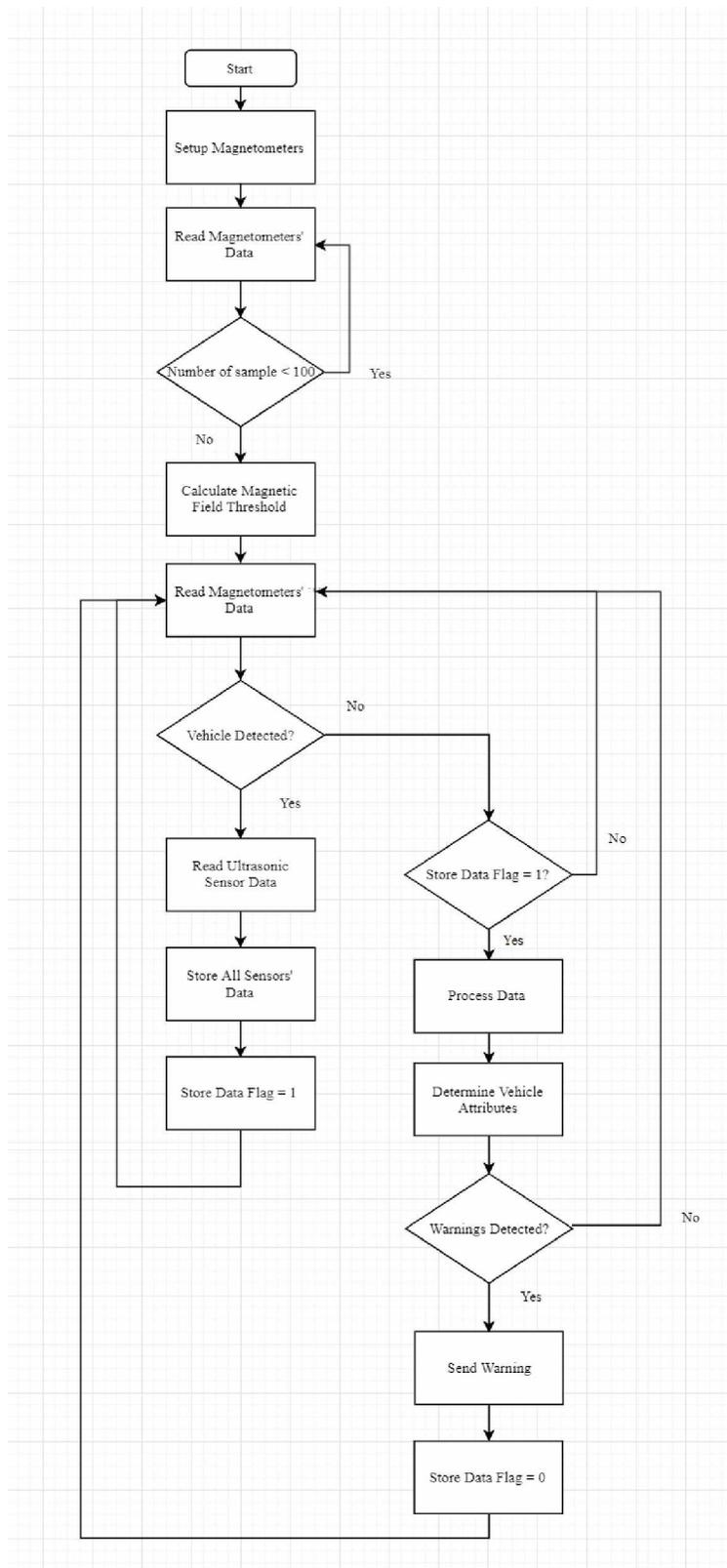


## Chapter 5 System Functionality Testing and Results

This chapter presents an overview of the functional testing of the prototype system and the corresponding results. The method of collecting data, processing them and acquiring vehicle attributes from the acquired data is discussed here. An example of the exchange of messages between RSU and OBU is also presented in this chapter.

### 5.1 Data Collection

The RSU collects data from two magnetometers and an ultrasonic sensor. The sampling rate of the magnetometers' data is 200 Hz and the sampling rate of the ultrasonic sensor is 20 Hz. Magnetometer provides magnetic field data along three axes and from that the magnitude of the field is calculated. After initializing the magnetometers, the RSU takes 100 readings in the first 0.5 seconds from each sensor. From those readings, the earth's magnetic field at that location is calculated. After that, the RSU continues reading data from both magnetometers and stores the 10 most recent samples. If the 10 most recent magnetic field samples of the first magnetometer differ from the previously calculated magnetic field of the earth, the RSU concurs that a vehicle is detected. After that, the RSU starts storing the data, including the previous 10 samples and starts reading and storing ultrasonic sensor data. When the 10 most recent samples of the magnetometer do not differ from the calculated magnetic field of the earth, the RSU concurs that the vehicle left the sensing range of the magnetometers. After that, the data is processed, and vehicle attributes are estimated. After exchanging the gathered information, RSU waits for the next vehicle to be detected. Figure 17 shows a flowchart of the data collection process.



**Figure 17: Flowchart of Data Collection Process of RSU**

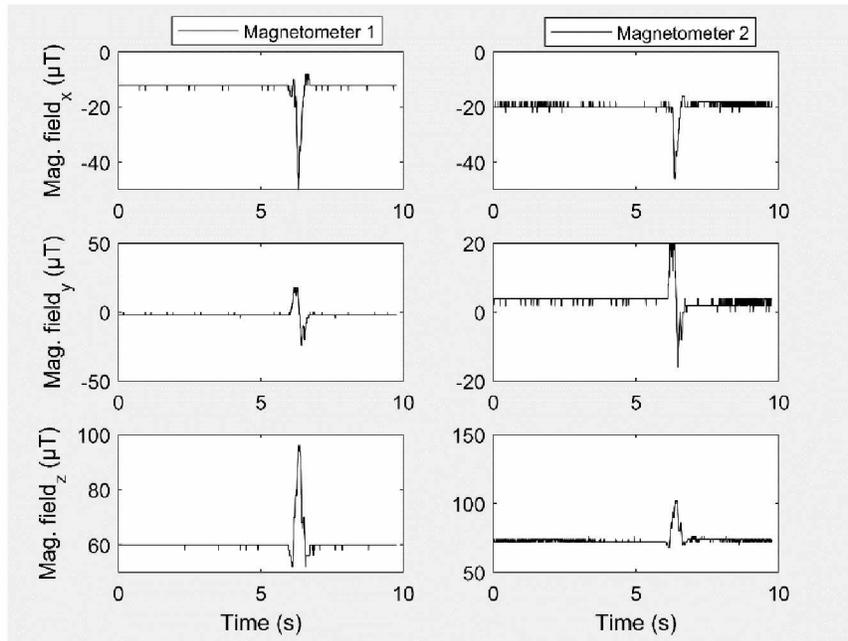
## 5.2 Data Processing

MicroMag3 sends 2 bytes of data for each axis of the measured magnetic field. The magnetic field along each axis is calculated using equation 1 and the magnitude of the magnetic field is calculated using equation 2. For data processing, only the magnitude of the magnetic field was stored instead of the magnetic field along each axis. This reduces the sampling rate because the calculations for measuring the magnitude of the magnetic field need to be done after each sample. This tradeoff was necessary as it allows the system to store 75% fewer data and still achieve a high enough sampling rate for estimating vehicle attributes.

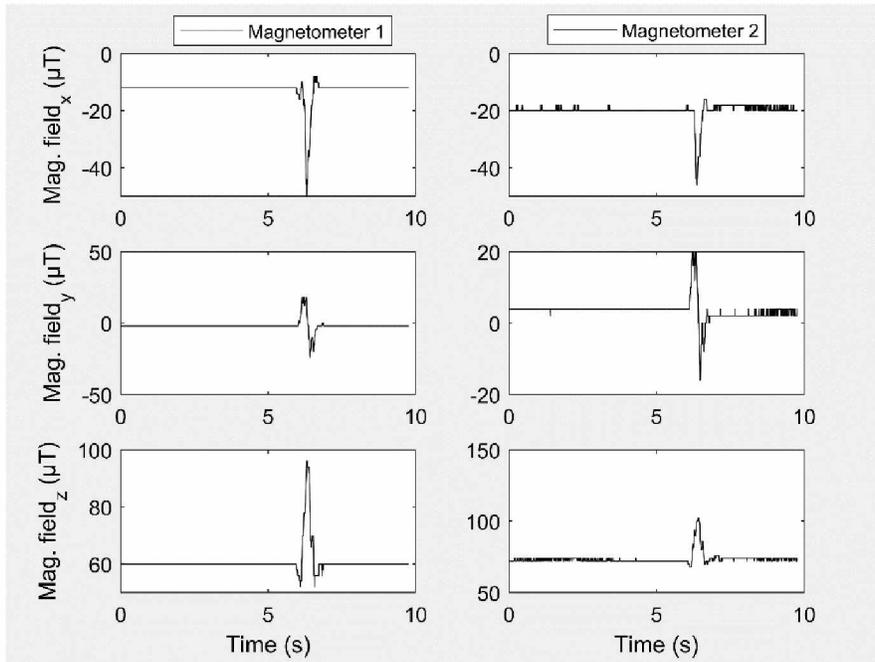
$$x_{MagField} = (MSB * 256) + LSB \quad (1)$$

$$MagField = \sqrt{x_{MagField}^2 + y_{MagField}^2 + z_{MagField}^2} \quad (2)$$

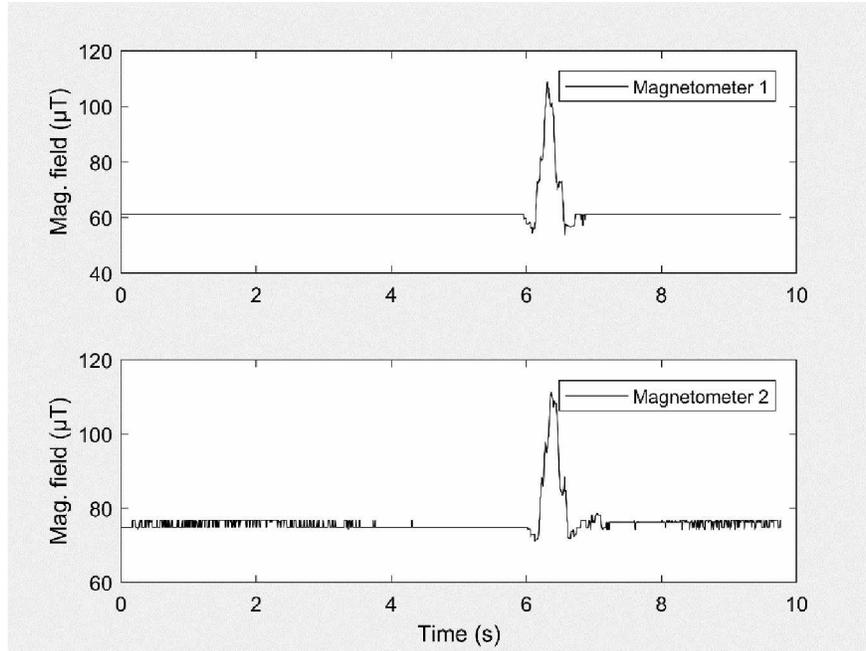
Figure 18 shows the change in the magnetic field, measured by two magnetometers along three axes when a vehicle is passing over them. The random spikes in the magnetometer data were removed by using a third-order one-dimensional median filter. This filter checks three consecutive samples and if the second sample is not the median, it is replaced by the median of those three samples. The filtered data is presented in Figure 19. Lastly, the magnitude of the magnetic field was calculated, which is presented in Figure 20. Different attributes of the vehicle were calculated using the processed data.



**Figure 18: Magnetic Field Data Along Three Axes**



**Figure 19: Resulted Signal After Using Median Filter**



**Figure 20: Change in the Magnitude of Magnetic Field Caused by the Vehicle**

### 5.3 Experiment Setup

The experiment setup is shown in Figure 21. For the test results presented in the next section, the magnetometers were placed 50 cm apart (2 m distance shown) and a car was driven over the sensors. The collected data was sent to a laptop from the microcontroller using UART. The speed of the car was observed by the driver and later it was compared to the speed estimated by the system. The experiment was repeated for different speeds and the results are discussed in the next section.

The performance of the setup can be improved by sampling data at a higher rate or by placing the magnetometers further apart. If the sampling rate is doubled to 400 Hz, similar error in estimating the lag in terms of the number of samples between two waveforms will result in half the error in estimated time difference. If the distance between two magnetometers is increased to 2 m, similar speed of a vehicle will result in 4 times the lag in terms of the number of samples between two waveforms and the error in estimated time difference will also be reduced by 4 times.



**Figure 21: Experiment Setup**

## **5.4 Results**

### **5.4.1 Vehicle Attributes Estimation**

The speed and the length of a vehicle can be calculated using the data collected from the magnetometer sensors. The speed of the vehicle can be estimated using equation 3, where  $d$  is the distance between two magnetometers and  $\Delta t$  is the travel time for the vehicle from sensor 1 to sensor 2 detection range.

$$v = \frac{d}{\Delta t} \quad (3)$$

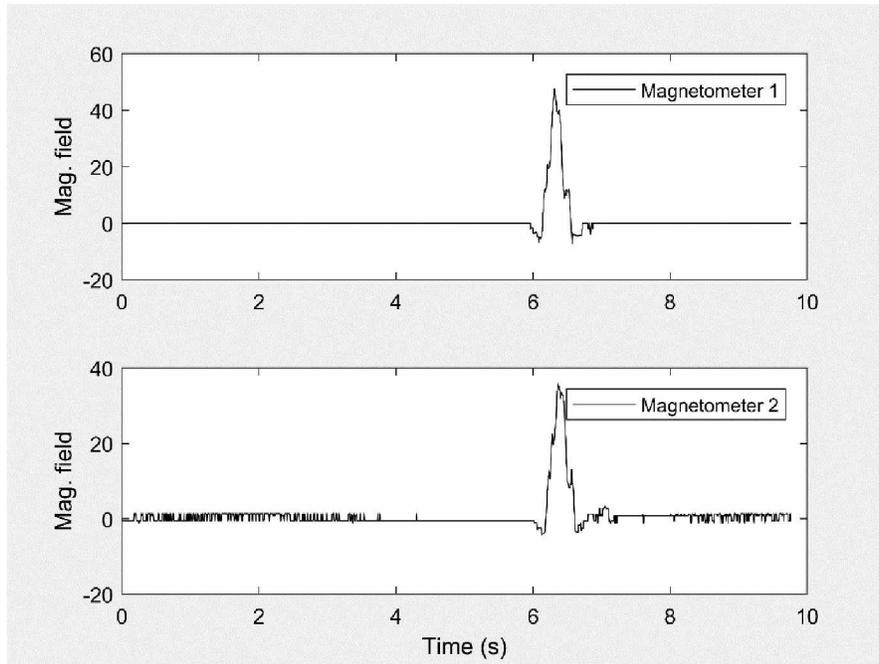
The distance between two magnetometers in the prototype RSU was 50 cm. The time difference between the two magnetometers detecting the vehicle can be calculated using the cross-correlation method or arrival time method.

In the cross-correlation method, one waveform is shifted both right and left to find at what lags the two waveforms become most similar to one another. This discrete cross-correlation method is presented in equation 4. Since we know that the second magnetometer detects the vehicle after the first magnetometer detects it, we can save roughly 50% of the computation for cross-correlation by shifting the second waveform only to the left instead. For the cross-correlation method, the earth's magnetic field without the presence of the vehicle needs to be removed from the waveforms. The resulting waveforms for one of the test runs are shown in Figure 22. Using equation 4, the lag for which the waveforms are most similar to one another was calculated to be 11 samples. At 200 Hz sampling rate, the time difference between the two waveforms was estimated to be 0.055 s. Then the speed of the vehicle was estimated to be 32.7 km/h using equation 3. The length of the vehicle was calculated to be 5.3 m by using equation 5 where  $v$  is the speed of the vehicle and  $t$  is the time for which the vehicle was in the detection range of the first magnetometer. The cross-correlation method is very compute-intensive which limits the functionality of the system (discussed in section 5.5 Time Constraints).

$$y[m] = \sum_{n=-\infty}^{+\infty} x_1[n] x_2[n - m] \quad (4)$$

$$l = v t \quad (5)$$

An alternative method of estimating the time difference between the two magnetometers detecting the vehicle is the arrival time method. In this method, the time difference between two waveforms is calculated by finding the difference between the time of arrival of the vehicle for both sensors. The time of arrival for each sensor is estimated by checking at what time the magnitude of the magnetic field is changed by 3  $\mu$ T for 10 consecutive samples. Using this method, the time difference between two waveforms was estimated to be 0.055 s. Then the speed of the vehicle was estimated to be 32.7 km/h using equation 3 and the length of the vehicle was estimated to be 5.3 m by using equation 5.



**Figure 22: Resulted Waveforms After Removing Earth's Magnetic Field**

The experiment was repeated for different speeds and the results are shown in Table 5. The estimated speed was compared with the speed observed by the driver.

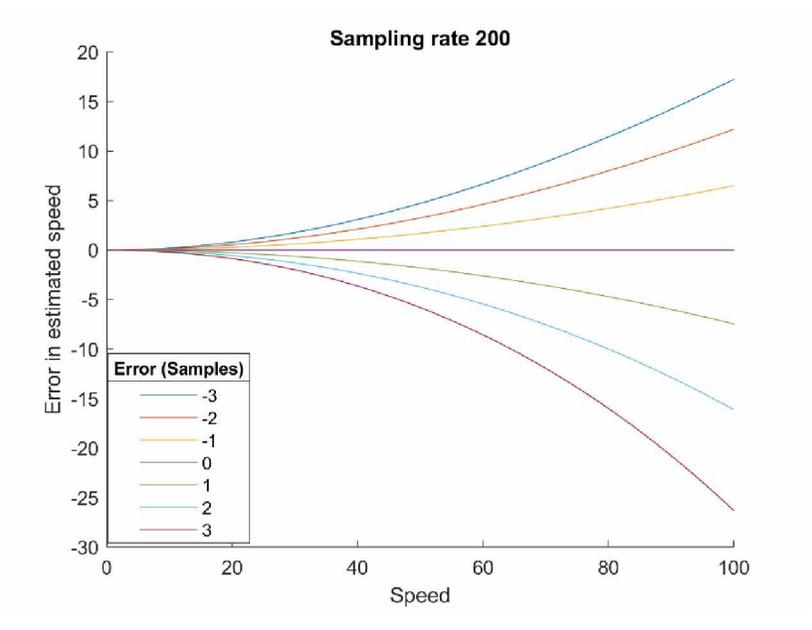
**Table 5: Comparison of Two Methods of Speed Estimation**

Speed of the Vehicle (km/h)		
Observed by the Driver	Estimated Using Time of Arrival Method	Estimated Using Cross-correlation Method
32.2	32.7	32.7
64.4	72	72
48.3	45	51.4
20	22.5	24

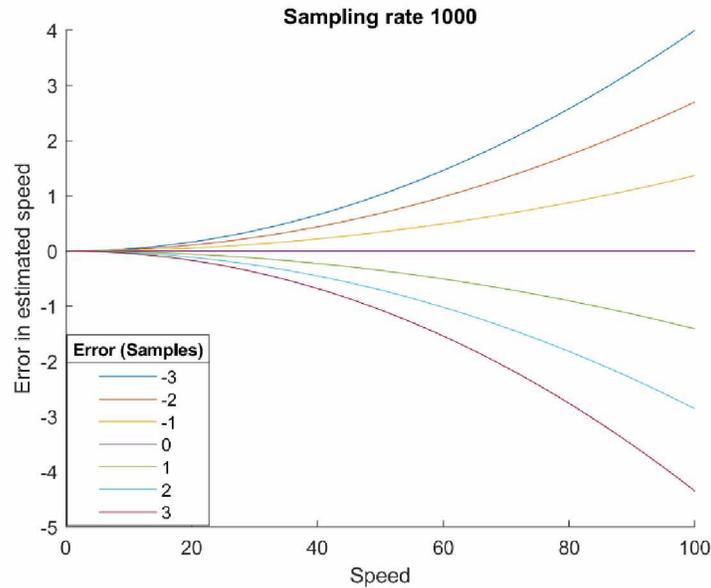
Error in estimated speed can be calculated using equation 6, where  $E_s$  is the error in estimated speed (in km/h),  $v$  is the actual speed (in km/h),  $d$  is the distance between two magnetometers (in m),  $f_s$  is the sampling rate and  $E_n$  is the error in terms of number of samples.

$$E_s = v - \frac{d * f_s * v * 3.6}{(d * f_s * 3.6) + (E_n * v)} \quad (6)$$

Figure 23 shows how the error in estimated speed changes depending on the actual speed. Error in estimated speed was plotted for different errors in estimated lag time in terms of number of samples. Figure 24 shows the improvement in the accuracy of the estimated speed when the sampling frequency is increased (discussed in 5.3 Experiment Setup). Distance between the magnetometers was 2 m for both figures and sampling rate was 1000 Hz for Figure 24 and 200 Hz for Figure 23.



**Figure 23: Error in estimated speed versus the actual speed (Sampling rate 200)**



**Figure 24: Error in estimated speed versus the actual speed (Sampling rate 1000)**

#### 5.4.2 Exchange of Messages

An example of the exchange of messages between different RSUs and OBU is presented in Figure 25. The detection of a vehicle by RSU1 was emulated by moving a magnet over the sensors, which resulted in the RSU1 sending a type 0 message to the OBU. This message was received by the vehicle, which is shown as the first message of Figure 25. The purpose of this experiment was to observe the exchange of messages between the RSU and the OBU. The vehicle attributes estimated here are not analyzed since they were examined in a separate experiment.

The message contains information about the intersection like the intersection address, road number, total number of roads in the intersection, sender address and information about the detected vehicle like speed, class, length, and weight of the vehicle. The section of the message reserved for the vehicle to send information to the RSU is left blank. The appropriate warning bits are also set. The speed limit of that road was set to 5 km/h. The estimated speed of the vehicle was 7 km/h and so the warning bit for speeding was set. The rest of the warning bits were set to demonstrate the functionality of the

system. The temporary ID sent for the vehicle was 0x002312. The first byte of the ID is 0 in this message because it will be a random number generated by the vehicle and sent to the RSU in the reply message. The last 2 bytes of the ID are set by the RSU. After receiving the message, the OBU replies with a type 1 message, which is shown as the second message of Figure 25. The message retains all the information received beforehand from the RSU. The message has a different sender address and it adds information about the vehicle which was preset in the OBU. The message also sets the appropriate warning bits for information detected by the vehicle. The ID of the vehicle sent in this message is 0x822312. The first byte of the ID is a random number generated by the OBU and last 2 bytes are retained from the message sent by the RSU. After receiving this message, RSU replies with a type 2 message as some of the warning bits were set. The message is received by the OBU and is shown as the third message in Figure 25. The message contains all the information from the last 2 messages. The fourth and fifth messages in Figure 25 are type 3 messages. The OBU keeps sending type 3 messages until it receives a type 3 message reply from an RSU. Here the OBU gets the reply from RSU3 which implies that the vehicle with temporary ID 0x822312 has left the intersection through road 3. After that, the OBU will stop sending type 3 message and wait to receive a type 0 message at the next intersection.

```

Intersection-0 Sender-RSU1   Road-1 TotalRoads-4 MsgType-0 Speed-07Kph Lane-2 Length-4m Cla
ss-2 Length-   Class-   Weight-   Warnings: Speeding-Y Water-N Ice-N LowVisibility-Y Emerg
encyVechiel-N DamagedRoad-N ID-0x002312Lf
LfCR
Intersection-0 Sender-Vehicle Road-1 TotalRoads-4 MsgType-1 Speed-07Kph Lane-2 Length-4m Cla
ss-2 Length-5m Class-2 Weight-2Tons Warnings: Speeding-Y Water-N Ice-N LowVisibility-Y Emerg
encyVechiel-N DamagedRoad-Y ID-0x822312Lf
LfCR
Intersection-0 Sender-RSU1   Road-1 TotalRoads-4 MsgType-2 Speed-07Kph Lane-2 Length-4m Cla
ss-2 Length-5m Class-2 Weight-2Tons Warnings: Speeding-Y Water-N Ice-N LowVisibility-Y Emerg
encyVechiel-N DamagedRoad-Y ID-0x822312Lf
LfCR
Intersection-0 Sender-Vehicle Road-1 TotalRoads-4 MsgType-3 Speed-07Kph Lane-2 Length-4m Cla
ss-2 Length-5m Class-2 Weight-2Tons Warnings: Speeding-Y Water-N Ice-N LowVisibility-Y Emerg
encyVechiel-N DamagedRoad-Y ID-0x822312Lf
LfCR
Intersection-0 Sender-RSU3   Road-1 TotalRoads-4 MsgType-3 Speed-07Kph Lane-2 Length-4m Cla
ss-2 Length-5m Class-2 Weight-2Tons Warnings: Speeding-Y Water-N Ice-N LowVisibility-Y Emerg
encyVechiel-N DamagedRoad-Y ID-0x822312Lf
LfCR

```

**Figure 25: Exchange of Messages Between RSU and OBU**

## 5.5 Time Constraints

The minimum distance required between two vehicles to be able to detect them depends on the speed of the vehicle and the time required to process the collected data and exchange messages among RSU and OBU. The time required to transmit a message depends on the length of the message and data transmission rate of the radio. It takes about 70  $\mu$ s to send a 14 bytes message with overheads using 2 Mbps data transmission rate. The maximum random delay before sending a type 1 message is 10 ms. The time required to process the collected data depends on the method of data processing, the amount of data needed to be processed and the clock speed of the microprocessor. The amount of data collected for processing depends on the sampling rate, length of the vehicle and speed of the vehicle. The number of samples that needs to be processed can be calculated using equation 7, where  $l$  is the length of the vehicle,  $f_s$  is the sampling frequency and  $v$  is the speed of the vehicle. Using equation 6, a 4.5 m vehicle moving at 10 km/h will need 648 samples to be processed at 200 Hz sampling rate and it takes 208.5 ms to process the data for cross-correlation method at 16 MHz clock speed. For the RSU to detect two consecutive vehicles successfully, the delay between them needs to be more than 218.71 ms, which can be calculated using equation 8. Here  $T_{tx}$  is the transmission time for three messages (type 0,1 and 2 messages need to be exchanged before detecting the next vehicle),  $T_r$  is the random delay before sending type 1 message and  $T_p$  is the processing time for the collected data. Equation 9 can be used to calculate the minimum distance required between two consecutive vehicles for the RSU to detect both vehicles. A vehicle moving at 120 km/h will need to be at least 7.3 m away from the vehicle in front, for the RSU to detect both vehicles.

$$D_a = \frac{2 * l * f_s}{v} \quad (7)$$

$$T_d = T_{tx} + T_r + T_p \quad (8)$$

$$d = v * T_d \quad (9)$$

This distance is too long for the system to perform as intended and it can be significantly shortened by reducing the processing time. If arrival time method is used instead of cross-correlation, the same amount of data takes 2.95 ms to process. Using equation 7, the minimum required delay between two vehicles to be detected becomes 13.16 ms. A vehicle moving at 120 km/h will now have to be at least 44 cm (using equation 8) away from the vehicle in front for the RSU to detect both vehicles. Table 6 presents a comparison of time constraints for cross-correlation and time of arrival methods.

**Table 6: Time Constraints for Two Methods of Speed Estimation**

Speed Estimation Method	Message Transmission Time	Maximum Random Delay	Processing Time	Total Time
Cross-correlation	210 $\mu$ s	10 ms	208.5 ms	218.71 ms
Time of Arrival			2.95 ms	13.16 ms

More testing needs to be done to evaluate the accuracy of these two methods of speed estimation. Also, it is important to note that the method that was used to determine the actual speed of the car (observation by the driver) was subjective. Table 5 shows that the two methods perform similarly. Cross-correlation method takes significantly more time to process the data than the time of arrival method. The processing time of the cross-correlation method will increase if the number of samples increases because of a slower speed of the vehicle, longer length of the vehicle or higher sampling rate. For the cross-correlation method, magnetometer data from both sensors need to be stored. For the time of arrival method, data from only one magnetometer needs to be stored for processing. So, the time of arrival methods requires less time for data processing and less memory to store data compared to the cross-correlation method.



## Chapter 6 Conclusion and Future Improvements

Intelligent traffic monitoring and control systems provide an alternative solution in cases where the conventional traffic management systems are pushed to their limit. With recent improvements of the vehicle-to-infrastructure and vehicle-to-vehicle communication, intelligent transportation systems are starting to have a significant impact on the transportation network worldwide. The proposed system can be an inexpensive solution for the vehicle to infrastructure communication for vehicles that lack this capability. The goal of the system is to improve the safety of the commuters and to make the transportation system more efficient by providing drivers with additional information about the traffic condition.

We tested the prototype system to detect the vehicle, estimate relevant attributes of the vehicle, detect potentially dangerous situations and communicate that information with the vehicle. Using the vehicle to infrastructure communication, we developed a method for tracking the vehicle through an intersection. This will help monitor the traffic condition and control traffic in a more efficient way.

We also presented an efficient message format and communication procedure to allow wireless communication between vehicles and infrastructures. The format of the message can be modified easily as more sensors are integrated with the system for collecting additional information.

Some limitations of the system and possible future improvements were also discussed here. The system was tested with only one type of vehicle and for a limited speed. For future improvements, the system needs to be tested on different types of vehicles and for different speeds. Integrating traffic displays in the system will allow the system to warn drivers even if the vehicle is not equipped with an OBU. The communication between the RSU and OBU was tested indoor by emulating the presence of a vehicle. More testing needs to be done to see how the system performs outdoor for radios with different

transmission range. By increasing the sampling rate, the required distance between two magnetometers can be reduced, which will improve the performance of the system.

The magnetometer sensors of the prototype system can be replaced with wireless sensors which will make the installation of the system a lot easier [54]. In addition, several different types of sensors can be added to the current system to collect additional information about the vehicle and driving condition. The system can integrate most of the currently available sensors on the market as it supports UART, I2C, SPI, and analog communication interfaces [55].

Moreover, the efficiency of the communication procedure can be improved by having different message length for different types of messages. The system should also be tested to check how the communication procedure performs at the presence of many vehicles. A simulation can be designed to see how the performance of the system varies with the different number of vehicles, message size, transmission range, and data transmission rate. Sending the relevant data from all the RSUs to a central control unit will also help us get an overview of the traffic condition of the whole area instead of just the intersections.

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