Collision Avoidance System at Intersections

FINAL REPORT - FHWA-OK-09-06

ODOT SPR ITEM NUMBER 2216

By

Fadi Basma
Research Assistant

Hazem H. Refai
Associate Professor

Electrical and Computer Engineering Department
The University of Oklahoma
Tulsa, Oklahoma 74135

Technical Advisors:
Harold Smart, Traffic Engineering Division Head

December 2009

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT=S CATALOG NO.
FHWA-OK-09-06		

4. TITLE AND SUBTITLE	5. REPORT DATE
Collision Avoidance System at Intersections	December 2009
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Fadi Basma and Hazem H. Refai	8. PERFORMING ORGANIZATION REPORT
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Oklahoma 4502 E. 41st Street Tulsa, Oklahoma 74135	10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. ODOT SPR Item Number 2216
12. SPONSORING AGENCY NAME AND ADDRESS Oklahoma Department of Transportation Planning and Research Division 200 N.E. 21st Street, Room 3A7 Oklahoma City, OK 73105	13. TYPE OF REPORT AND PERIOD COVERED Final Report From February 2008 – To October 2009 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Oklahoma Department of Transportation
Planning and Research Division
200 N.E. 21st Street, Room 3A7
Oklahoma City, Oklahoma 73105

16 . ABSTRACT

The number of collisions at urban and rural intersections has been on the rise in spite of technological innovations and advancements for vehicle safety. It has been reported that nearly a third of all reported crashes occur in such areas. Consequently, there is a need for a reliable-real time warning system that can alert drivers of a potential collision. Most collision avoidance systems currently being researched are based on road-vehicle or inter-vehicle communication. Such systems are vehicle dependent, thus limiting its applicability to vehicles that are equipped with the proper technologies.

In this project, an intersection collision warning (ICW) system based solely on infrastructure communication was developed and tested. ICW utilizes wireless sensor networks (WSN) for detecting and transferring warning information to drivers to prevent accidents. The system is deployed into intersection roadways and supports real time prevention by monitoring approaching traffic and providing a warning system to motorists when there is a high probability of collision.

The ICW system has been tested at the University of Oklahoma Tulsa campus. For the purpose of evaluation, different collision scenarios have been emulated in a lab setup while the system performance and detection accuracy are evaluated. Results confirm the ability of the system to provide a warning signal in high probability collision situations.

17. KEY WORDS	18. DISTRIBUTION STATEMENT		
Auto, Collision, Intersection, Collision avoidance	No restrictions. This publication is available from the Planning & Research Div., Oklahoma DOT.		
19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 114	22. PRICE N/A

SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
LENGTH				
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
TEMPERATURE (exact)				
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
AREA				
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
VOLUME				
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

Table of Contents

LIST OF FIGURES

LIST OF TABLES

Abstract

The number of collisions at urban and rural intersections has been on the rise in spite of technological innovations and advancements for vehicle safety. It has been reported that nearly a third of all reported crashes occur in such areas. Consequently, there is a need for a reliable-real time warning system that can alert drivers of a potential collision. Most collision avoidance systems currently being researched are based on road-vehicle or inter-vehicle communication. Such systems are vehicle dependent, thus limiting its applicability to vehicles that are equipped with the proper technologies.

In this project, an intersection collision warning (ICW) system based solely on infrastructure communication was developed and tested. ICW utilizes wireless sensor networks (WSN) for detecting and transferring warning information to drivers to prevent accidents. The system is deployed into intersection roadways and supports real time prevention by monitoring approaching traffic and providing a warning system to motorists when there is a high probability of collision.

The ICW system has been tested at the University of Oklahoma Tulsa campus. For the purpose of evaluation, different collision scenarios have been emulated in a lab setup while the system performance and detection accuracy are evaluated. Results confirm the ability of the system to provide a warning signal in high probability collision situations.

1 Introduction

Each year there have been over 40,000 fatalities and 2,788,000 non-fatal injuries due to traffic accidents in the United States [1]. In addition, it is predicted that hospital bills, damaged properties and additional accident-related costs will add up to approximately one to three percent of the world's gross domestic product [2][3]. Accordingly, developing a collision warning system that is capable of preventing accidents regardless of unexpected conditions is of great importance.

Although there have been a number of technological innovations in vehicle safety, the number of accidents continues to rise. This is especially true for intersection accidents. It has been reported that nearly 30% of the reported accidents in the United States are due to intersection collision [4] [5]. Most of these accidents take place at rural intersection areas equipped with traffic signals or stop signs. As a result, it is recommended that an intersection collision warning system be implemented as a part of vehicle safety systems, thus reducing the number of accidents. To be most effective, such a system should have the capability of supporting real time systems that can warn potential drivers of an impending collision. It also should be adaptable to different types of intersections.

This report presents an intersection warning system framework ICW that utilizes the concept of Wireless Sensor Network (WSN) to perform even driven operations. The system is composed of sensor network nodes linked to a central base station in which sensor nodes continuously monitor traffic behavior. After information has been collected by the nodes, it is sent to the base station to be processed. Once there, a collision avoidance prediction algorithm can be used to warn a driver of collision probability.

1.1 System overview

The foremost functionality of ICW is to prevent collision rural intersections. The system is based solely on infrastructure communication and is deployed into roadways around the intersection. The system supports real time prevention by monitoring approaching traffic and warning a motorist if collision probability is high. ICW utilizes telematics and wireless sensor networks (WSN) to detect and transfer information to prevent accidents. Figure 1 depicts a high-level overview of the entire system.

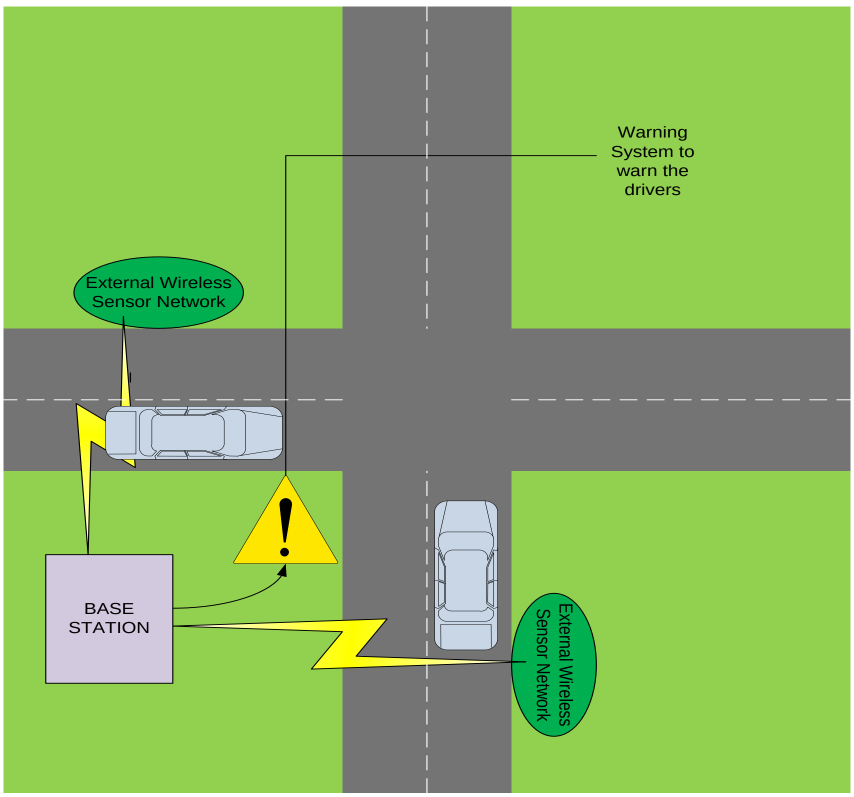


Figure 1: Overview of ICW

The system is comprised of the following:

1. External sensor nodes: collect vehicle information passing through the sensor.

2. Base Station (BS): located on the junction of each intersection to analyze data; receives collected information from external sensor nodes wirelessly.
3. Warning system: embedded on both mainline and minor road junctions to activate a warning signal after BS has analyzed data and determined the possibility of a collision.

1.2 Organization

The balance of this report is organized as follows. Chapter 2 will discuss the available technologies for intersection collision avoidance and their disadvantages. Current research will be presented as well. Chapter 3 will discuss the presented intersection collision avoidance. To provide a logical explanation of the algorithms used, system requirements are listed. The chapter also lists the chosen system components and gives logical analysis for each choice. Afterwards, a detailed hardware description is presented. Finally, the chapter ends with the system wireless communication design. Chapter 4 represents the processing aspect of the system. All the software algorithms that are used are discussed and presented. Chapter 5 will present simulated test results that was conducted in a lab sitting and provide appropriate discussion for each test.

2 Background

2.1 Background of intersection Traffic control devices

Intersection traffic control devices are comprised of signs, signals, roundabouts or pavement markings that can be placed alongside the intersection. They are used to move vehicles and pedestrians safely and efficiently, consequently preventing collisions by providing the “right-of-way” principle assignment. The Federal Highway Administration periodically publishes recommendations on how to setup specific control devices in its manual on Uniform Traffic Control Devices (MUTCD) [6], thus ensuring safety by standardizing operations. The most extensively used devices for current traffic control include traffic signals, stop signs and roundabouts. These are explained in this section.

2.1.1 Traffic Signals

Traffic signals are used to assign right-of-way for drivers with the use of signal lights (Red - Amber - Green). The universal standard for this three-light set is red on top, amber in the middle, and green on the bottom. However, widely accepted road rules may differ throughout the world, depending on how the traffic lights are interpreted. For example, in most countries green means go and amber means prepare to stop, while red means stop. Conversely, Canada and New Zealand consider amber red, which interpreted as stop to their citizens.

Traffic signals are typically used at busy intersections to evenly distribute the time delay between different directions at the intersection. The purpose is to ensure smoothness in the traffic flow. Previously, the timing delay for light color change was fixed; however, newer signals utilize vehicle detection for light color change.

2.1.2 Stop signs

In addition to traffic signals, stop signs are also used to control driver behavior. Stop signs are usually installed at road junctions and instruct drivers to stop, check the road and proceed if the road is clear. The standard stop sign has a specified size of 75 cm (30 in) across opposite flat sides of the red octagonal field, with a 20 mm (¾ in) white border [7]. Stop signs are mostly used for low to medium levels of traffic [8]. They are usually best suited for rural highway intersections. If the traffic volume for a four-way intersection is approximately equal in all directions, a four-way stop sign can also be used.

2.1.3 Roundabouts

Roundabouts are another solution for intersection traffic. In the United States these are often referred to as a "rotary" or "traffic circle". A roundabout brings together conflicting traffic streams by allowing vehicles to safely merge and traverse the roundabout, and then exit in a desired direction. In essence, traffic enters a one-way stream around a central island. There are many types of roundabouts and usually depends on the intersection design. Roundabouts often provide a more safe type of traffic control when compared to other methods. They are recognized for having fewer delays, increased traffic circulation efficiency and enhanced community aesthetics.

2.1.4 Disadvantage and Limitation of Conventional Intersection Control Devices

2.1.4.1 Installation and Placement

Installing traffic control devices in unnecessary locations may lead to significant traffic flow to the increase of unwanted delays in an intersection. This might not only annoy drivers but would also increase fuel consumption. For example, a four way stop sign might be justified when the traffic volume on all four sides is equal; however, if not, unnecessary delays could occur. Moreover, the improper placement of a traffic control device may decrease the efficiency of the system. A driver may see the signal too late to safely react to the situation, which may lead to an increase in the number of accidents at the intersection. One such example is placing the device too closely around the bend of a sharp curve. Catastrophic results will occur when drivers fail to stop in time.

Sudden changes that could potentially happen along the intersection pose other safety issues. For example, emergency vehicles assisting with a disastrous situation would lead to an increase in traffic throughout the entire intersection. Conventional traffic control devices are superseded by police officers attempting to manage traffic flow.

2.1.4.2 Safety

The primary goal of all traffic control devices is to maintain the safety of the drivers advancing through the intersection. Conventional devices currently in use have significant shortcomings that hinder due to physical and electrical infrastructure requirements. This is especially true under certain conditions,

Traffic signal lights are one such example. When configuring a signal light an engineer must be careful with the timing of the amber (yellow) light. If the illuminated time is too short, drivers might have to slam on their brakes to avoid crossing the intersection when the light turns red. This could cause an increase in real-end collisions. On the other hand, if the time the amber (yellow) light is illuminated is too long, drivers might ignore it and continue through the intersection, which might result in intersection collisions.

Stop signs can be just as dangerous. They are easily susceptible to vandalism or weather conditions. If this occurs, a vehicle entering an intersection that is typically dangerous won't be warned to stop, thinking rather that it is safe to go through. This might result in collision.

2.1.4.3 Cost

The cost of a traffic control lighting system depends on the complexity of the intersection and the properties of the traffic using it. This is dependent not only on installation, but maintenance, as well. While the cost of a traffic control has traditionally been perceived as justified, in reality one traffic signal costs the range of $80,000 to $100,000 for installation only. Often the perpetual costs, such as electrical power consumption, are not considered [9].

2.2 Causes of Intersection-Related Collision

As mentioned earlier, intersection-related collisions constitute the majority of collisions. Consequently, knowing the source of collisions is of great importance. According to the INTERSAFE project [10], five scenarios represent between approximately 60% and 72% of injury accidents at intersections in France and Germany. These are further defined as belonging to two accidents types, namely turn across path and turn into/straight crossing path. Two groups, LAB and GIDAS provide the data for the study. Data from the LAB database classifies an accident as follows:

- A vehicle (case vehicle, CV) pulls into an intersection after ignoring a stop sign. This defines the situation.
- Another vehicle (principal other vehicle, POV) must compensate for the vehicle suddenly cutting across his path.

In the GIDAS database, each accident is viewed as a single accident type that includes both the movement of the CV and the movement of the POV. Figure 2 depicts these scenarios using the two-group representation.

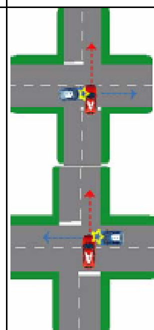
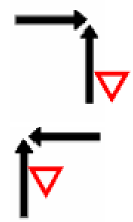
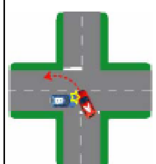
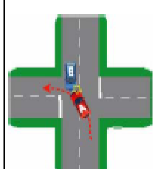
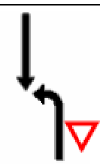
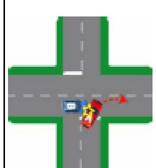
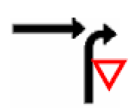
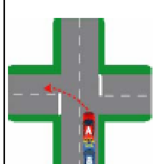
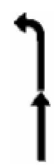
	general accident type	description	LAB pictograms (cv "A" in red, pov "B" in blue)	% of injury accidents	GIDAS pictograms	% of injury accidents	severe injuries +fatalities
a	turn into/straight crossing path	straight crossing path, opponent coming from the left or right		34%		33,3%	28,5%
b	turn into/ straight crossing path	left turn into path, opponent coming from the left		10,5%		13,5%	12,5%
c	turn across path	left turn across path, opponent oncoming (opposite direction)		10%		18,7%	16,6%
d	turn into/straight crossing path	right turn into path, opponent coming from the left		2%		4,1%	2,8%
e	turn across path	left turn across path, preceding opponent (same direction)		2%		2,2%	3,3%
			58,5% of all intersection-related accidents = 15.636 accidents in France		71,8% of all intersection-related accidents = 106.260 accidents in Germany		

Figure 2: Distribution of common accident situations [10]

The main causes in these scenarios are attributed to either driver failures or external contributing factors. Driver failures include those defined as human error, e.g. perception, comprehension, decision and action. Contributing factors on the other hand include those that complicate a situation, thus causing an accident, e.g. sight obstruction, vehicle type and climate factor. Table 1 summarizes the basic factors.

Table 1: Intersection-related collision source description

Driver Failure	**Perception:** due to inattention or other reasons the situation is not perceived at all or there is a delay in correctly perceiving **Comprehension:** evaluation and interpretation of a situation perceived was not adequate to the circumstances **Decision:** strategy to cope with a specific perceived and evaluated situation comes too late **Action:** a completely inadequate action was performed, e.g. accelerating instead of decelerating
Contributing Factors	**Sight Obstruction:** external e.g. walls, internal e.g. A-pillar **Vehicle Type:** Depends on classification of cars, the more momentum a vehicle has, the more harder for it to slow down and insufficient observance) **Climate Factor:** Icy and wet weather conditions increase the friction in the road making it hard for a vehicle to stop

2.3 Advantages of Using Intersection Collision Warning System

The purpose of the research is to improve the performance of conventional intersection traffic devices. The research focuses on implementing a dynamic system that can adapt to conditions. The reason for such a device is to ensure the safety of drivers coming toward an intersection. The benefits of such a system can be summarized as follows:

- Using a decentralized system that can be used in dense traffic
- Utilizing telematics for sensing and reporting
- Enabling drivers to be aware of their environment, even if line of sight is not present
- Implementing a low cost device that can be adapted to any intersection
- Developing a collision warning system that captures driver attention
- Providing a system that is easily installed and maintained.
- Using a system that can be easily configured for other functions, such as vehicle count, thus providing an input for traffic analysis systems

2.4 Literature Review

There has been increased interest from the United States (US) Department of Transportation to develop and implement an efficient traffic control device. This has in turn resulted in an increase in research focused on and defined as vehicle-to-vehicle communication (v2v), vehicle to road communication (v2r) and road to road communication (r2r). The v2v can be categorized into 3 classes based on the technology used: 1) radar based [11][12], 2) camera based [13][14] and 3) radio based system [15]. Radar-based and camera-based technologies are used to avert collisions in the same lane as a result of line of sight limitation. Radio-based technologies have a broader use for collisions independent of either line of sight or passing lanes.

V2r applications focus primarily on an intersection warning system, whether it is embedded inside the vehicle or externally. Most v2r use DGPS technology to support a base station installed at a junction, thus facilitating required vehicle information to the prediction [16][17]. Alternative implementations are possible. For example in [18] a unique RFID is embedded in each vehicle for differentiation purposes. The system makes use of WSN in the road to supply the BS with information necessary for prediction.

R2r communication, on the other hand, is totally independent of the vehicles. Sensing functionality is the focus of such a system. The control device has the ability to fetch information about a vehicle in real-time scenario. A variety of such approaches have been made. One uses WSN technologies that adopt magnetic sensors [19]. Another uses a radar as a sensing functionality [20]. Vision methods can also be employed [21].

Three important intersection collision avoidance programs are currently being conducted in the US and are funded by Intelligent Transportation System (ITS). These are lead by University of California (UC Berkeley), the University of Minnesota (UMN) and Virginia Polytechnic Institute/Virginia Tech Transportation Institute (VTTI). The UC Berkeley program is known as the Partners for Advanced Transit and Highways (PATH), and it supports about 65 projects related to transportation safety research. One of their innovative research endeavors focuses on a warning system placed at a signaled intersection to warn drivers from a possible collision. This system employs a group of loop detection sensors and radars that communicate wirelessly with the traffic light system to warn drivers [22]. UMN research is similar to the PATH project. Intelligent Vehicles Laboratory and Policy & Planning for ITS are two of their foremost projects. The UMN Intelligent Vehicles lab is the first to focus on developing and testing innovative technologies that reduce driver error by integrating sensor networks, vehicle control systems, navigation systems, and specially designed human interface components.

The Planning for ITS program is designed to equip transportation and infrastructure professionals with the technological tools to address congestion and other system challenges in the coming years. The focus is on collisions that occur at an unsignalized intersection [23]. VTTI projects are equally as important. They focus on collisions due to traffic signal and stop sign violations. VTTI is the largest research center at the university, containing nine center groups dealing with different types of transportation issues.

One drawback to the aforementioned research projects is that all are vehicle dependent, i.e. the vehicle is equipped with either sensors or a warning system. The shortcoming of this approach is that the system would require equipment be installed in each vehicle. While not expensive, the implementation would be lengthy. Some researchers have therefore abandoned the vehicle equipment approach [25][26]. Instead, their systems are now mainly comprised of wireless road sensors that transmit traffic flow information to a base station. The BS will generate a predictive analysis calculating whether a collision might take place, and then send a warning signal from an embedded mechanism in the road if there is a possibility of an accident. Another drawback to PATH and VTTI projects is their message routing implementation. For example, PATH employs Time Division Multiple Access, where as VTTI employs wireless mesh networks. Both technologies achieve high message latency that is not tolerable for intersection collision avoidance systems.

In addition to intersection collision avoidance research, a commercially available product has been developed by Sensys Network Inc. IT is comprised of repeaters, access points and wireless sensors, and in addition to vehicle count and stop bar detection, it can predict a vehicle's trajectory [27]. The product uses a Time Division Multiple Access (TDMA) technique to enable sensor nodes to communicate with a base station. The major drawback for such a product is its latency time, as each node must wait approximately 125 ms to communicate with the base station if its time slot has already passed. This is unacceptable for an intersection warning system, as it should be time-latency sensitive; the less the delay, the better system will operate.

3 Intersection Collision warning system

3.1 System Basic Requirements

The purpose of every collision warning system is to alert drivers about the existence of unexpected or unseen vehicles. In producing an effective product, the system should provide a reliable real time warning system that is not only capable of warning the driver, but also gives the driver time to react, as well. In doing so, the system should pass through several phases. These are shown in the Figure 3.

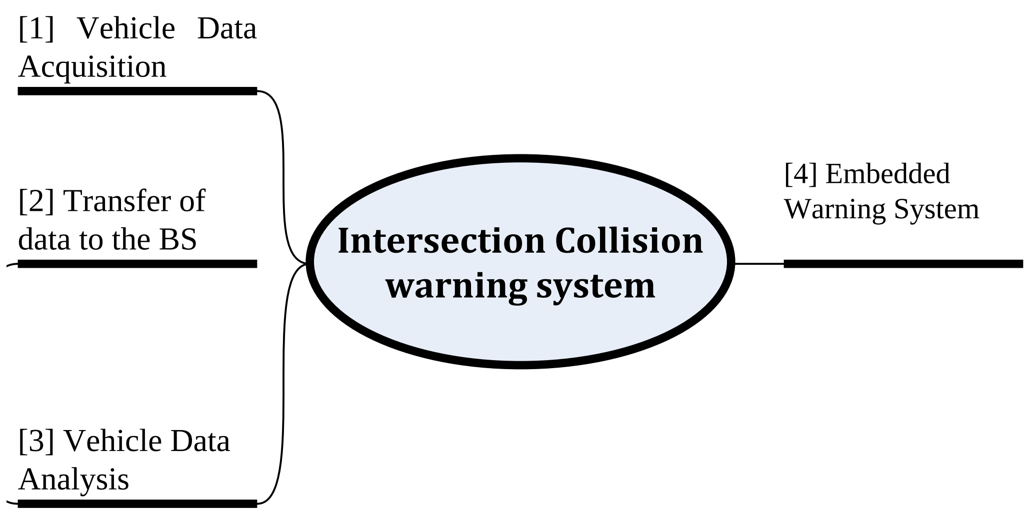


Figure 3: Intersection collision warning system phases

In the first phase, the system must detect vehicles approaching the intersection and capture all data needed for collision prediction in real time. The sensing functionality used should have the ability to differentiate between signals coming from the vehicle and extraneous noise. During the second phase, acquired telematic data is transmitted to the base station. The use of a transceiver is required. After the BS receives the data, it is placed into input queues for analysis. If the analysis in the third phase results in a high probability of collision, a warning system is activated to alert drivers of possible collision.

3.1.1 Vehicle Data Collection

ICW systems should be capable of acquiring dependable telematics data from vehicles that pass through different sides of the intersection. This has to be done in a timely fashion to allow for additional data analysis and the activation of a warning system if the probability of collision is high. Data fed to the system are represented as follows:

- Location of each vehicle
- Speed of each vehicle
- Time acquiring the data
- Direction of the vehicle

3.1.2 Vehicle Position-Time Prediction

In order to potentially prevent collisions, the system must have an accurate time prediction algorithm for a certain input position. In other words, the system must predict the time by which the car is going to reach the point of collision.

3.1.3 Accuracy

To get a better position-time estimation of vehicles passing by the intersection, the information being processed should be accurate and within range of acceptance. This will ensure effective prediction analysis and fewer false warnings.

3.1.4 Coverage Area

Coverage areas can be represented by either distance or time. The coverage of the system, or in other words the range by which the system should start collecting data, must take into account important variables. These are represented as follows:

- Normal deceleration period while reaching the intersection
- Deceleration period needed to come to full stop (pressing hard on the brakes)
- Reaction period of the driver
- Processing period of the system

3.1.5 Arbitrary Approaches

Vehicles usually approach an intersection arbitrarily. Consequently, random approaches should not affect the system. As soon as a vehicle advances through the intersection, the system should be able to detect its presence and send the information back for analysis.

3.1.6 Real time

Safety is the focus of the system; therefore, it is essential to obtain data in a timely manner. The moment a vehicle reaches the coverage area, data has to be collected and sent to the BS immediately for analysis. This will ensure the driver has time to react before the collision occurs.

3.1.7 Cost Effective

The purpose of the ICW is to implement a system that is not only effective and efficient, but also one that is affordable in both prediction time and cost. If a system is to be implemented at the intersection, certain costs should be considered:

- System components
- Installation
- Distribution
- Maintenance and calibration
- Development

3.2 System Component

3.2.1 Sensors

ICW should be able detect the presence of a moving vehicle through the intersection. In doing so, the system requires a sensing functionality that is able to detect the presence of a vehicle and convert its location to traffic parameters. This functionality must have the ability to fetch all data needed in this phase.

In determining the best product for the system, a consideration of a comparison of different sensors made by the Vehicle Detector Clearing House Corporation [29] was conducted. Figure 4 characterizes sensor technologies and their capabilities. Output data for each available sensor along with its lane coverage, communication bandwidth and the purchase cost is listed.

Traffic output data (typical), communications bandwidth, and cost of commercially available sensors (Klein, 2001).

Sensor Technology	Output Data: Count	Output Data: Presence	Output Data: Speed	Output Data: Occupancy	Output Data: Classification	Multiple Lane, Multiple Detection Zone Data	Communication Bandwidth	Sensor Purchase Cost[a] (each in 1999 U.S. $)
Inductive loop	✓	✓	✓[b]	✓	✓[c]		Low to moderate	Low[i] ($500 to $800)
Magnetometer (Two-axis fluxgate)	✓	✓	✓[b]	✓			Low	Moderate[i] ($900 to $6,300)
Magnetic (Induction coil)	✓	✓[d]	✓[b]	✓			Low	Low to moderate[i] ($385 to $2,000)
Microwave radar	✓	✓[e]	✓	✓[e]	✓[e]	✓[e]	Moderate	Low to moderate ($700 to $3,300)
Active infrared	✓	✓	✓[f]	✓	✓	✓	Low to moderate	Moderate to high ($6,500 to $14,000)
Passive infrared	✓	✓	✓[f]	✓			Low to moderate	Low to moderate ($700 to $1,200)
Ultrasonic	✓	✓		✓			Low	Low to moderate (Pulse model: $600 to $1,900)
Acoustic array	✓	✓	✓	✓		✓[g]	Low to moderate	Moderate ($3,100 to $8,100)
Video image processor	✓	✓	✓	✓	✓	✓	Low to high[h]	Moderate to high ($5,000 to $26,000)

[a] Installation, maintenance, and repair costs must also be included to arrive at the true cost of a sensor solution as discussed in the text.
[b] Speed can be measured by using two sensors a known distance apart or estimated from one sensor and the effective detection zone and vehicle lengths.
[c] With specialized electronics unit containing embedded firmware that classifies vehicles.
[d] With special sensor layouts and signal processing software.
[e] With microwave radar sensors that transmit the proper waveform and have appropriate signal processing.
[f] With multi-detection zone passive or active mode infrared sensors.
[g] With models that contain appropriate beamforming and signal processing.
[h] Depends on whether higher-bandwidth raw data, lower-bandwidth processed data, or video imagery is transmitted to the traffic management center.
[i] Includes underground sensor and local detector or receiver electronics. Electronics options are available to receive multiple sensor, multiple lane data.

Figure 4: Sensor comparison [29]

Picking a suitable sensor for the system should be dependent upon basic requirements aforementioned. Classification capability is not be of huge importance, as this feature is not addressed in this report.

Lower priced sensors within our expenditure limits provide only inductive loops, magnetometer and magnetic sensors. Others that are higher priced provide additional noise filter that is beneficial for vehicle detection and tracking. A major disadvantage, however, is poor performance during inclement weather conditions. Inductive loops are not reliable. On the other hand, wire loops are subject to stress of traffic and temperature.

A study by the University of Berkeley demonstrates the accuracy of magnetic sensors in detecting, classifying and calculating the speed of the vehicles [30]. It shows a vehicle detection rate of100 percent and more than 90 percent for speed calculation.

Consequently, magnetic sensors are the logical choice for the system. In addition to their high accuracy rate, these sensors are insensitive to inclement weather conditions, e.g. snow, rain and fog, and are easily deployed and maintained.

An important consideration to be noted is the addition of the power efficiency issue to the basic system requirement. This is highly important due to the fact that magnetic sensors are to be deployed under the road where a power source is not provided. An expected long life and minimum cost maintenance should be expected, as customer satisfaction will be directly related. A study on energy consumption appears in later in this chapter.

3.2.1.1 Magnetic Sensor technology

Magnetic sensors are passive devices that detect changes in the earth's magnetic field. After detection they convert a highly localized disruption to a differential voltage output. When a vehicle passes by a sensor, the field alteration caused by different parts of the vehicle is recorded. Figure 5 shows changes in the output of the magnetic sensor when a vehicle travels over it.

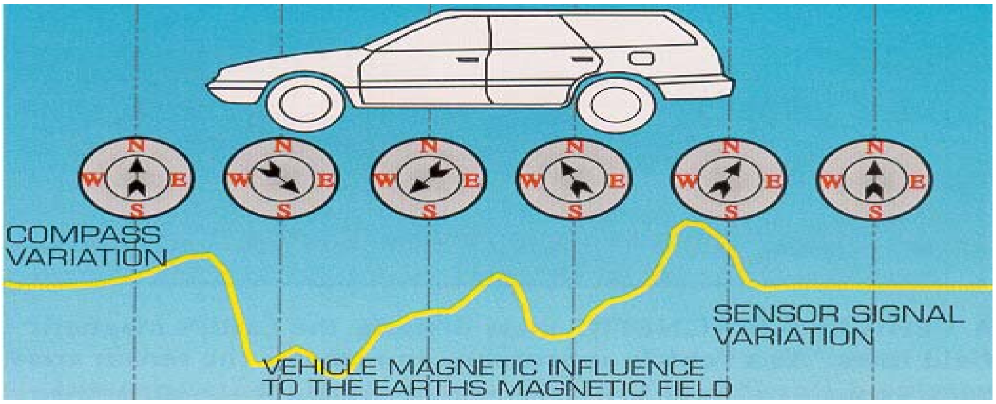


Figure 5: Magnetic anomaly in the Earth's magnetic field induced by magnetic dipoles in a ferrous metal vehicle [29]

3.2.1.2 Honeywell HMC1021Z

Honeywell is widely recognized as a leading manufacturer of magnetic sensors; the company is well known for their reliable products and excellence. The HMC1021Z sensor has been chosen for this research from their wide variety of product selection. The sensor is a one-axis surface mount that utilizes Honeywell's Anisotropic Magneto resistive technology. It is cost effective and was designed for low field magnetic sensing from tens of micro-gauss to six gauss [31].

A simple vehicle detection system was implemented by University of Oklahoma [32] and used in the current system investigation. In addition to the magnetic sensor, an AD623 amplifier and LM393 comparator chips were used to output a high (1) for vehicle presence and low (0) otherwise. Figure 6 illustrates the basic concept, and Figure 7 shows a capture of voltage output on the AD623 when a car travels above the sensor. Additional information regarding the sensor implementation can be found at [31].

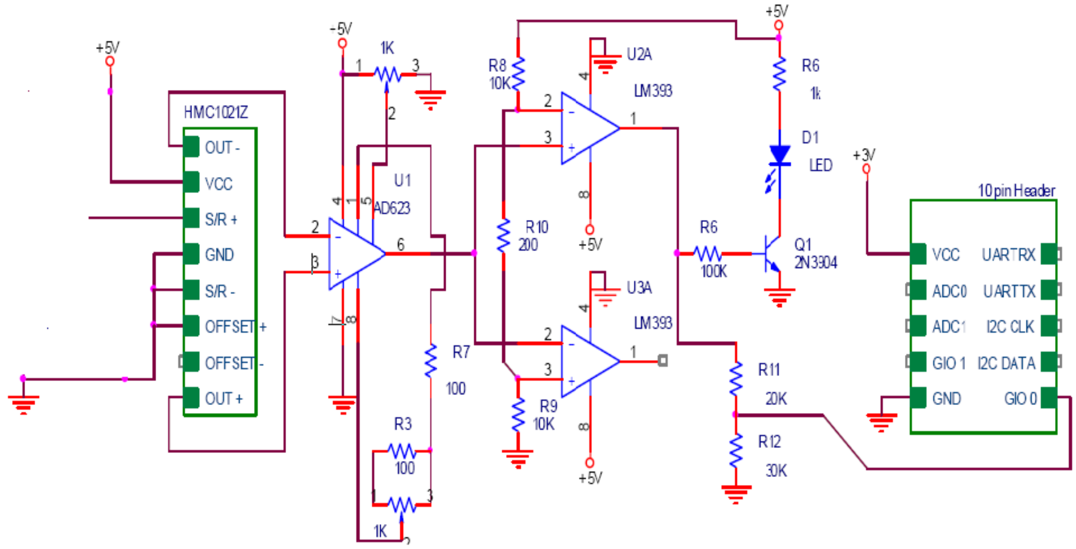


Figure 6: Vehicle detection sensor schematic [31]

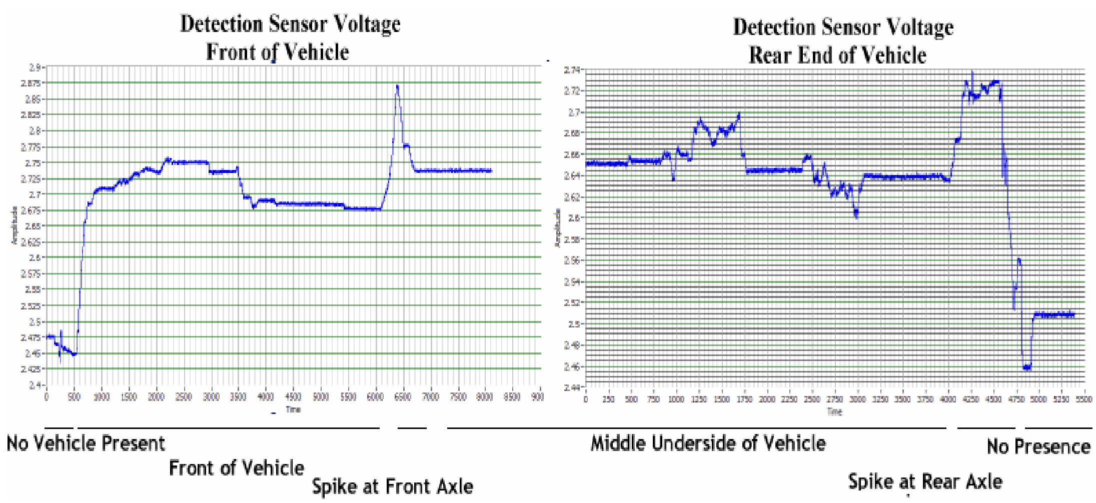


Figure 7: Measured sensor voltage from vehicle disturbance [31]

3.2.2 Transceiver

As illustrated in Figure 3, detecting an approaching vehicle is merely the first phase of three for the system structure. The second is to transmit data from the sensor to the BS in order for required analysis. To accomplish this wirelessly, a transceiver must be interfaced (hard wired) with the magnetic sensor, thus, when vehicles approach the intersection, the sensor will detect changes in the earth's magnetic field and the transceiver linked to the sensor should immediately transfer the telematic data wirelessly to the BS. Details about the system structure are discussed later in this chapter.

The choice for an ICW transceiver should be based on the consideration of imperative parameters; most important are unit range, power consumption, interface, temperature and price. While the detection signal and time synchronization parameters will be sent in the wireless domain; the throughput does not constitute high importance due to the small size of the data packet. Table 2 summarizes the capabilities of popular transceivers considered for the system. As shown, only the Radiotronix Wi.232DTS fulfilled all requirements. The remainder are either too costly or require an unnecessarily high output power.

Table 2: Candidate transceivers

	Radiotronix Wi.232DTS [33]	AeroComm, AC4790-200[34]	Z-Accel 2.4 GHz ZigBee [35]	UHF902-928 [36]
Price (a piece)	20$	63.85$	99$	55$
Frequency	902 - 928 MHz	902 - 928 MHz	2400 - 2483.5 MHz	902 - 928 MHz
Range	1 mile	Up to 4 miles	1 mile	1.5 miles
Output Power	Up to 25 mW	Up to 200 mW	27 mW (lowest)	Up to 1 W
Needs Antenna	Yes	No	Yes	Yes
Programmability	Yes	Yes	Yes	Yes
Interface	SCI	SCI	SCI	SCI
Throughput	Up to 152.32	76.8 kbps	250 Kbps	57.6 Kbps

	kbps			
Temperature	-40° to +85°C	-40° to +80°C	-40° to +85°C	-40° to +85°C
Sleep mode	Yes	NO	Yes	NO
Encryption	No	Yes, 56-bit DES	NO	NO

3.2.2.1 Radiotronix Wi.232DTS

Radiotronix Wi.232DTS is a low power, embedded radio transceiver in an FCC modular-approved solution and is part of the Wireless Serial Engine (WiSE) Modules. It is a combination of digital spread spectrum (DTS) and protocol controller. Figure 8 shows the structure of a WiSE module.

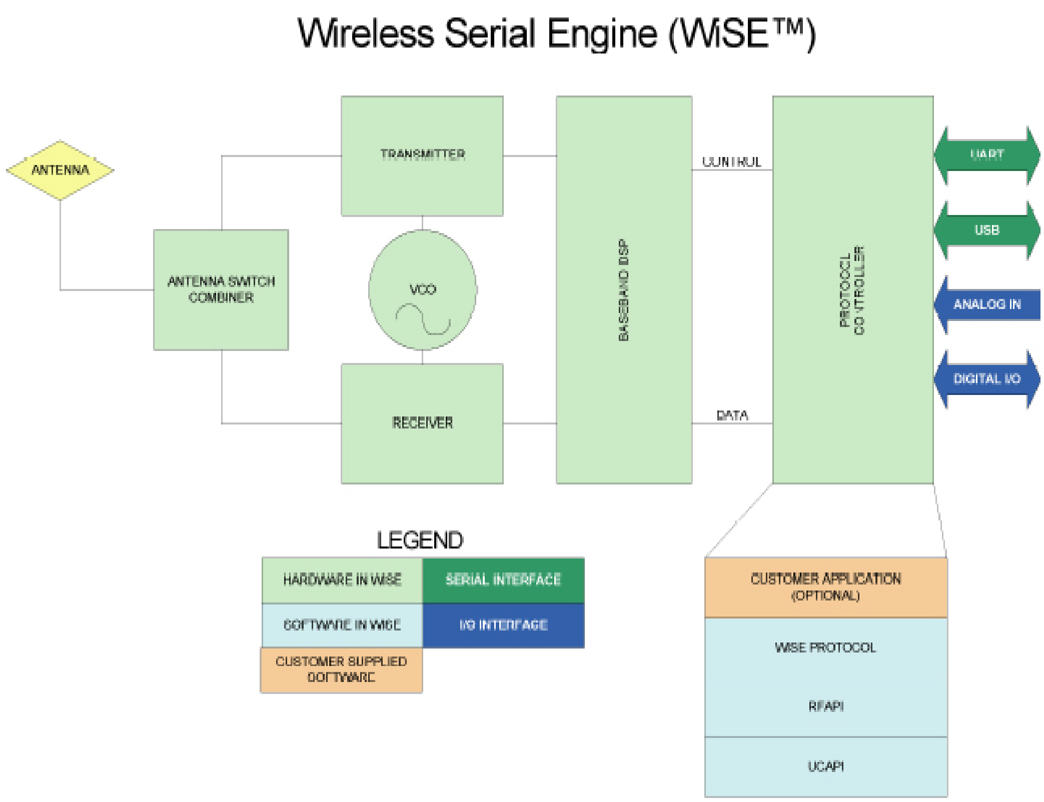


Figure 8: WiSE block diagram [33]

One of outstanding features of Wi.232DTS is its support for the universal asynchronous receiver/transmitter (UART) protocols, which ensures ease of access to data module registers. Wi.232DTS supports four power modes—DTS low/ high and Low power low/high; this feature gives the system the necessary feasibility to select optimal power options. Sleep mode is an important feature, as well; it is essential for power control, which is highlighted later in this report. Basic module features are listed in Table 3 below.

Table 3: Feature summary for WI.232DTS module

Feature	Description
Interface	True UART to antenna solution
Error checking	16-bit CRC error checking
Data rate	100kbit/ sec maximum effective RF data rate
# of channels	32 channels in DTS mode, 84 channels in LP mode, North American Version
Size	Small size- .8” x .935” x .08”
Low Power Options	Low power Standby and Sleep modes
Protocol Layers	PHY and MAC layer protocol built in
MAC	CSMA medium access control
Network Group	0-127 Networks
Network Mode	Normal and Slave
Link Budget	115dB link budget in DTS mode
Power modes	4 modes allow user to optimize power/ range
Configuration	Command mode for volatile and non-volatile configuration

3.2.3 Microcontroller

A major component requirement for the system is a processing functionality capable of performing data analysis in a reliable, energy-efficient and real-time manner. Essential functionalities for the processer include the ability to:

- Transfer data from the magnetic sensor to the transceiver and eventually to BS

- Perform time synchronization for better collision detection
- Perform collision detection logic when data is available from all sensors

The system does not require a high computational processor to perform the functions listed above. Hence, a low-cost versatile microcontroller is suitable for the project, as it performs the all requirements in an efficient and effective way. Component features necessary for the system are listed in the following table.

Table 4: Expected microcontroller features

Issue	Feature
Energy Efficiency	Low power consumption
	Sleep mode functionality
	Sleep mode Interrupt driven
Sensor Interface	Digital I/O inputs
Transceiver Interface	UART serial communication
Speed	Fast sleep wake up
Temperature Change	Reliable Oscillator

Microchip is a well-known manufacturer of Programmable Intelligent Computer (PIC) microcontrollers [37]. The company produces a wide variety of PIC technologies, ranging from 12- to 16-bit flash microcontrollers. The PIC is a powerful, completely featured processor with internal RAM, EEROM FLASH memory and a broad range of peripherals. The microcontrollers are small and can easily be programmed to accomplish a number of tasks. High-level programming, e.g. C language, can be accomplished, as can lower level, such as Basic or Assembly. The Microchip microcontroller comes with a free MPLAB integrated design environment, which is comprised of an assembler, linker, integrated C, software simulator, and debugger.

PIC24FJ128GA010 was chosen from the broad range of PIC products because of its higher computational performance. This model can support up to a 16 MIPS (million instructions per second) Operation at 32 Mhz, thus ensuring superior system utilization. The PIC uses a 16-bit data and 24-bit address path to register access. In addition to these core features, it has a built in 8 Mhz internal oscillator able to amplify to 32 Mhz using its Phase Lock Loop (PLL) frequency multiplier functionality. For low-power use, a 31 Khz oscillator is integrated in the PIC. This is extremely important in applications required to maintain minimal power usage. Usability of external oscillators is feasible in the PIC24FJ128GA010, as it utilizes two crystal and two external clock modes. Serial communication can be accomplished using the fully equipped, two independent Universal asynchronous receiver/transmitter (UART) and two independent Serial Peripheral Interface (SPI) modules in the PIC. This microcontroller supports parallel communication, as well. Likewise, it supports a Parallel Master Port (PMP) module used to communicate with devices that support parallel communication. Additionally, the PIC implements a full-featured clock and calendar with alarm functions in its hardware. This particular module is optimized for low-power operation. It uses an integrated, low-power oscillator for clock synchronization, and sleep mode with fast wake up time is also applicable. The unit consumes current as low as 120µA while in sleep mode and can increase to120µs to wake up.

A summary of these important features are listed in the table below.

Table 5: PIC24FJ128GA010 features [37]

Parameter Name	Value
Architecture	16-bit
CPU Speed (MIPS)	16
Memory Type	Flash
Program Memory (KB)	128
RAM Bytes	8,192
Temperature Range C	-40 to 85
Operating Voltage Range (V)	2 to 3.6
I/O Pins	85
Pin Count	100
System Management Features	BOR
Internal Oscillator	8 MHz, 32 kHz
nanoWatt Features	Fast Wake/Fast Control
Digital Communication Peripherals	2-UART, 2-SPI, 2-I2C
Analog Peripherals	1-A/D 16x10-bit @ 500(ksps)
Comparators	2
CAN (#, type)	0 None
Capture/Compare/PWM Peripherals	5/5
16-bit PWM resolutions	16
Timers	5 x 16-bit
Interrupt Driven	43
Hardware RTCC	Yes
Parallel Port	PMP

3.2.4 Warning System

To inform the drivers about a possible collision, a suitable and reliable external warning system should be implemented. However, capturing the driver's attention is a complex job because it relates to his/her psychological behavior. Humans tend to adapt and quite down statistical regularities [38]. One idea is to place Lighting LEDs as the visual stimulus [32], but if the LEDs are going to be attached to the road, they would be too small to capture driver's attention. However, using a large screen with regular background color change deployed beside the road would be enough to get driver's attention.

For testing, ICW employs 3V Tianma TM162JCAWG1 LCD that is mounted on the microcontroller testing board. The TM162JCAWG1 is an LCD dot matrix module that consists of an LCD panel and controller/driver circuits. The display is capable of displaying two lines of sixteen 5 by 8 dot matrix characters. An example of a warning signal displayed by the LCD is shown in Figure 9.

Figure 9: Warning signal displayed by TM162JCAWG1 LCD

3.3 System Description

ICW is a wireless collision avoidance system that implements road-to-road communications to warn drivers of a possible collision. Figure 10 depicts a two-way stop on an intersection. As shown, the system is comprised of the three main components for vehicle detection: nodes, a Base Station and a Warning System. For improved system exploitation, vehicle detection nodes are deployed in each road lane—four in all. When the nodes detect a moving vehicle, they send information wirelessly to the BS where it is processed and analyzed. If the telematic data predicts a possible collision, the BS warns the driver via a warning system installed at each side of the intersection. Depending on the format of the intersection, the BS can communicate with the warning system either wirelessly or via a wired cable.

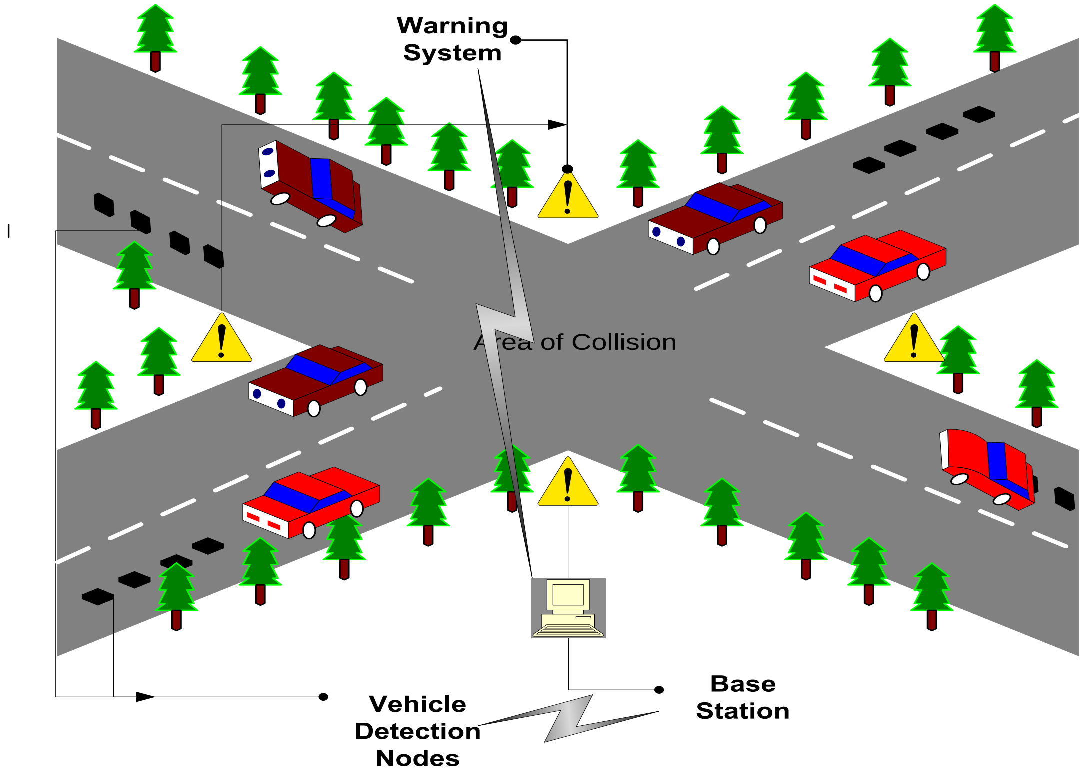


Figure 10: ICW design description

3.3.1 Vehicle Detection Nodes

3.3.1.1 Hardware Decomposition

As discussed earlier, the foremost functionality of a vehicle detection node is to sense vehicle presence and send information to the base station. Each node is comprised of the following:

- Batteries
- Honeywell magnetic sensor
- Wi.232DTS radio transceiver
- PIC Microcontroller

Because nodes are deployed roadside where no power source is present, batteries offer a simple solution. A voltage divider is added to the circuit to supply other components with power.

In short, when a vehicle passes through the intersection, the magnetic sensor detects fluctuation in the earth’s magnetic field. The analog signal is transformed to a digital via a LM393 comparator embedded in the sensor design. The signal is then passed to the microcontroller through one of the I/O ports. Afterwards, the CPU customizes the data and sends it through the Serial Communication Interface (SCI) so it can be sent wirelessly by the radio transceiver. SCI uses UART protocol as its serial transmission protocol. Figure 11 shows the node’s hardware decomposition.

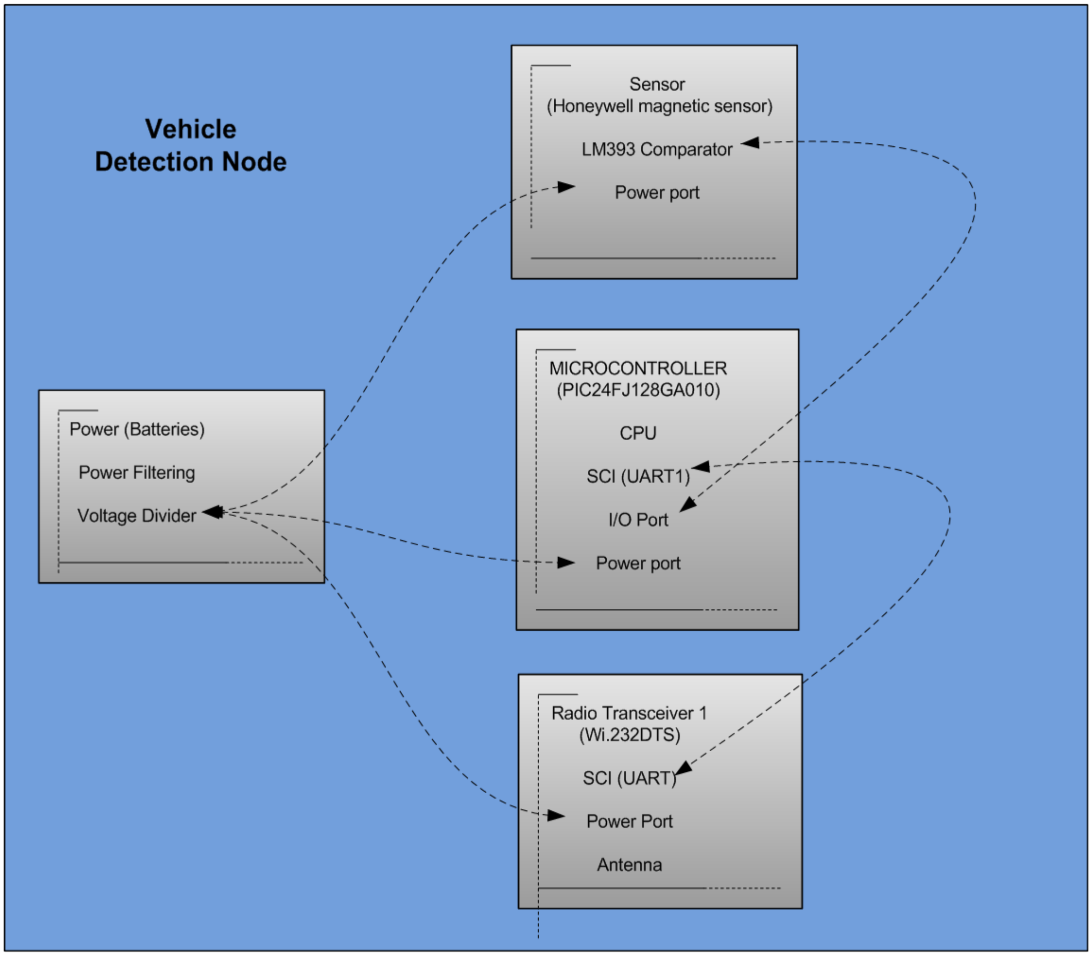


Figure 11: Vehicle detection node decomposition

3.3.1.2 Layout

Detection node placement is critical for identifying the presence of vehicles passing through the intersection. An important criterion for the Honeywell magnetic sensor is that it be mounted on the road surface. One option is to place the sensor at the center of the road. Although this leads to superior detection accuracy, there is the possibility that a vehicle damages it. Wireless range can also be a problem, due to the interference caused by the passing vehicle on the sensor. To accommodate these issues, sensors are placed on the side of the road rather than in the center.

The distance between detection nodes and the intersection is also critical. The system must ensure that the warning system on the LCD is promptly displaced to warn the drivers in time for them to respond. However, determining the appropriate warning distance for the driver is foremost. Accordingly, a two dimensional motion model is considered:

$$D_{Stop} = \frac{vi^2}{2a} + (t_{driver} + t_{mac\,hine} + t_{processing} + t_{wait}) * vi$$

Where

- t_{driver} driver brake response time
- $t_{mac\,hine}$ braking system in addition to the warning system response time
- $t_{processing}$ microcontroller Collision prediction processing time
- t_{wait} Maximum time the system has to wait to get information from the other sensor group to perform collision prediction.
- vi initial velocity of the vehicle
- a deceleration of the vehicle

As previously discussed in chapter 1, there are many sources for accidents in the intersection. Consequently, to determine the values of the above parameters is considered a real challenge. However, INTERSAFE project [10] has come up with reasonable values that are based on accident analysis. The values are summarized in Table 6

Table 6: Stopping distance value range [10]

	Min	Max	Average
t_{driver}	0.8 sec	2 sec	0.95 sec
$t_{machine}$	0.3 sec	0.5 sec	0.4 sec
a	0.31 g = 3.038 m/s^2	0.7 g = 6.86 m/s^2	4.9490 m/s^2

$t_{processing}$ is absent from the table above because of its relation to the microcontroller processing power and the algorithm complexity. Therefore, microcontroller and algorithms have differences in their timing processing speeds.

In the worst-case scenario, the system must use the maximum values stated above. However, this renders the system vulnerable to inaccurate collision detection, due to the fact that a driver will pass the sensors before the start of a deceleration phase. This might result in predication bias. The deceleration phase is defined by the time a driver starts decelerating. Hence, a suitable approach would be to take the average of the parameters in Table 6. Considering this, we can assume the following:

- Speed limit as an initial velocity of 40 mph with 10 mph added to obtain a design speed.
- $t_{processing}$ value of 0.158 seconds to process data [32].
- t_{wait} value of 1 sec is assumed as a maximum waiting time.

The above equation would lead to an approximate warning distance of 105 meters. Consequently, the last deployed detection node should be placed 85 meters far from the intersection.

To calculate the total distance between the first sensor and the intersection, the system must consider the spacing of the detection nodes. Two important criterions regarding nodes spacing should be considered:

- not too small: to give chance for speed calculation to take place
- not too big: to keep the detection nodes within an acceptable intersection range

The most suitable approximation is to use a shade over a car length as the separation distance. The average length of a car is about 4 meters [39]. For worst case scenarios 5 meters is used instead. With 4 detection nodes mounted on the road, the total distance between the first deployed detection node and the intersection end is $5 * 4 + 105 = 125$ meters.

3.3.2 Base Station

3.3.2.1 Hardware Decomposition

The base station processes data received from the vehicle detection nodes and is comprised of the following components:

- Batteries
- Two Wi.232DTS radio transceiver (each supports different radio channel)
- PIC Microcontroller

It is important to note that the BS supports two Wi.232DTS transceivers. Transceiver 1 is used to communicate with the detection node, while Transceiver 2 is used to communicate with the warning system. Although both transceivers are the same model, they operate on different channels.

Either AC or solar power can provide power for the node. As in the detection node, SCI (UART) is the communication interface between the transceivers and the microcontroller. When the BS becomes operational, the PIC waits for customized data from the vehicle detection nodes. When data is received through the first radio transceiver from all the sensor nodes, the CPU begins processing data necessary for collision prediction. If the probability of collision is high a wireless signal is sent to the warning system through the second transceiver. Figure 12 shows the base station hardware decomposition.

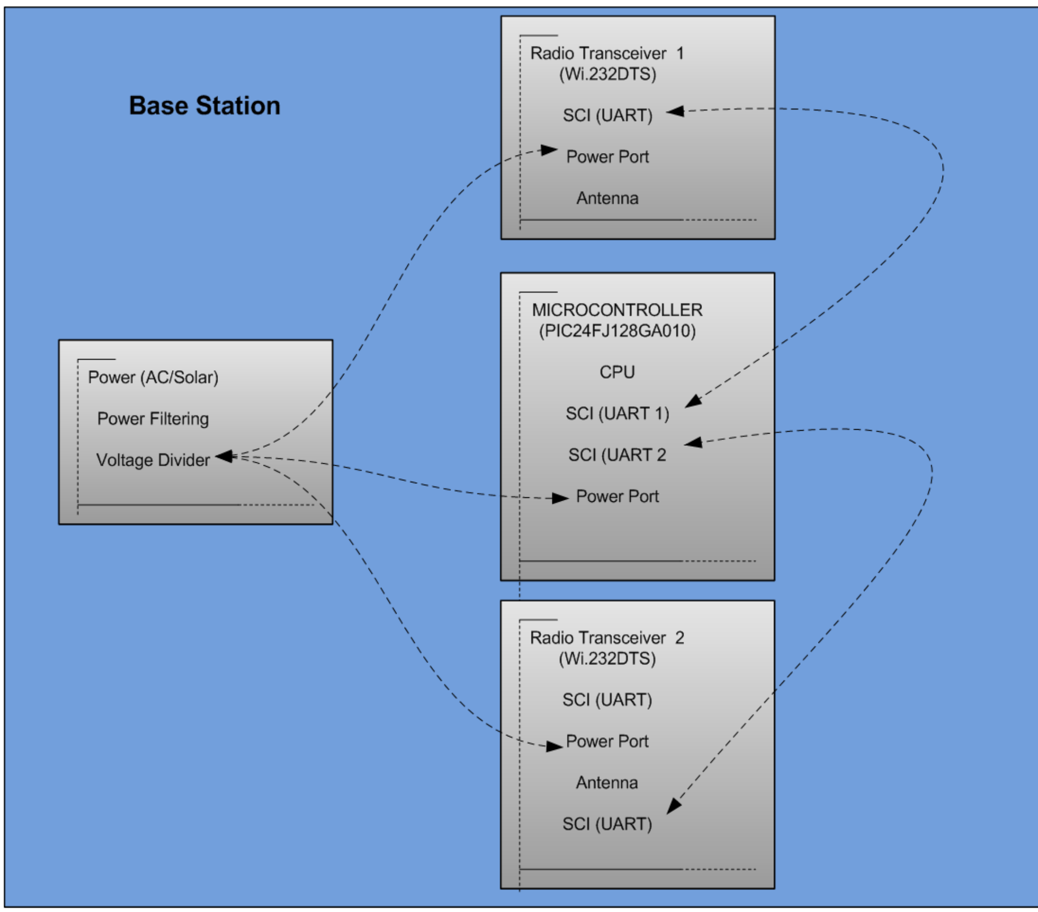


Figure 12: Base station decomposition

3.3.2.2 Layout

The position of the base station is dependent upon the layout of the vehicle detection nodes. The deployed nodes must be within the nearest range from the base station, which is typically best if cornered at the side of the intersection. An important consideration is that all nodes at an intersection are serviced by only one base station.

3.3.3 Warning System

3.3.3.1 Hardware Decomposition

The last phase in the system is providing reliable warning to drivers about a possible collision prior to their reaching a dangerous location. The basic decomposition of the warning system is summarized as follows:

- Batteries (car batteries)
- Wi.232DTS radio transceiver
- PIC Microcontroller
- Tianma TM162JCAWG1 LCD

In order to avoid interference with vehicle detection nodes, a Wi.232DTS radio transceiver that employs a frequency band similar to the second radio transceiver is installed in the base station. The transceiver communicates with the microcontroller through SCI (UART) protocol. A highly configurable 8-bit PMP is employed to communicate with the LCD. After the BS signal is deployed, a signal from the CPU is triggered to activate the LCD and display the warning message. Figure 13 shows the warning system hardware decomposition.

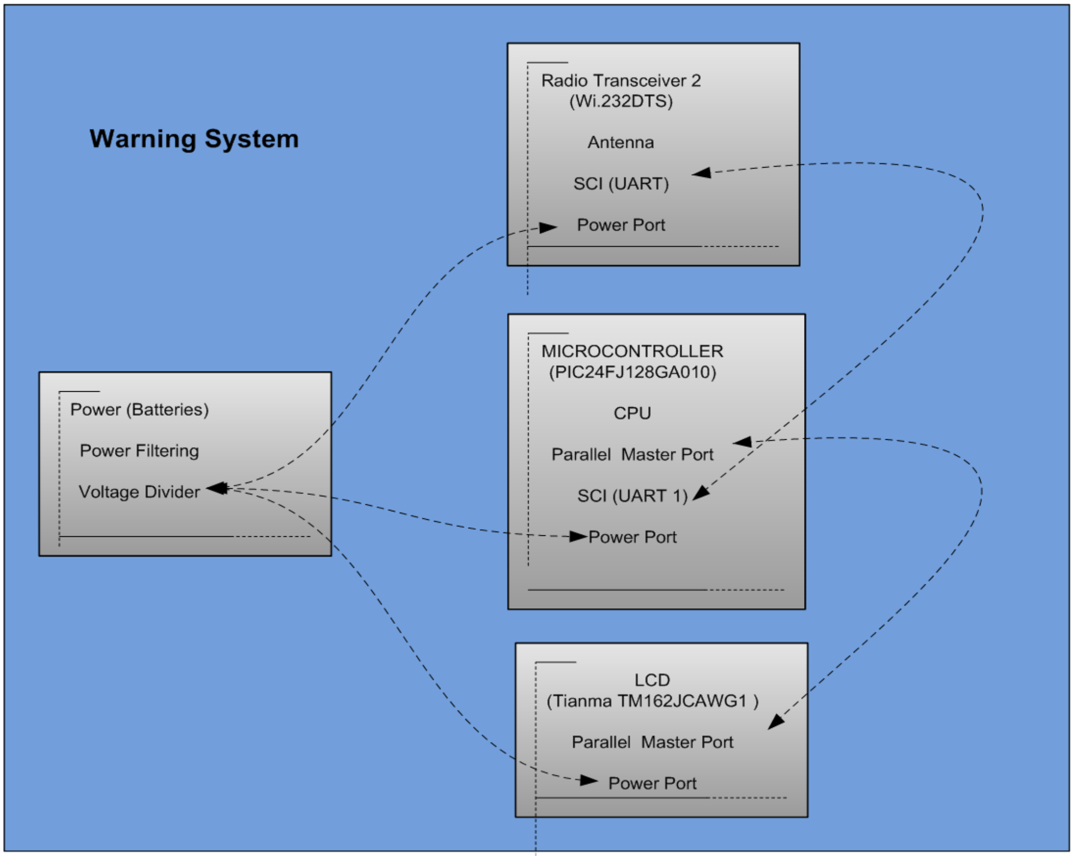


Figure 13: Warning system decomposition

3.3.3.2 Layout

In this layout, a driver must see the warning from the LCD, understand its meaning, and then actually perform the appropriate reaction. In addition, the device should allow time for system processing to take place. Consequently, the layout should be suitable enough to allow time for data processing and be close enough so that the driver can see the LCD screen. For the ICW system to be effective, LCD installation was set at a distance of 40 m from the intersection.

3.4 Wireless Communication

3.4.1 Modulation

Wi232DTS employs a Frequency-shift Keying (FSK) modulation method in which modulating the frequency of the carrier transmits digital signals. A higher bandwidth is achieved by using a Digital Transmission System (DTS). This modulation technique utilizes the digital spread spectrum provision employed by the Federal Communication Commission (FCC) part 15 rules.

3.4.2 Bandwidth

Wi232DTS requires the system to use at least 500 KHz of bandwidth to achieve a high power transmission. In DTS mode, the system uses 600 KHz of bandwidth, which can operate on 32 different channels and operate to 100 Kbps in channel throughput.

3.4.3 Interference

Wi.232DTS uses a public 902-928 MHz transmission; therefore, interfering with other devices is imminent. Devices that would likely interfere with the module are ones implemented through the IEEE 802.15.4 standard. Examples of protocols that apply to this standard include ZigBee, WirelessHART, and MiWi.

3.4.4 Range

The range of the Wi232DTS is dependent on the transmission power used. Wi232DTS employs eight operational power modes: High Low Power (LP), Mid-High LP, Mid-Low LP, Low DTS, High DTS, Mid-High DTS, Mid-Low DTS, and Low LP. To determine the range of the transmission, a link budget analysis of the wireless link is needed. This is calculated by adding the chosen transmit power, the antenna gains and the receiver sensitivity [33], as shown in the following equation:

$$LB = Ptx + Gtxa - SENSrx + Grxa$$

Maximum values chosen for the Wi232DTS transceiver are characterized by the following:

- Transmit power: 11dBm
- Antenna gains for each of the transmitter and the receiver: 3db
- Receiver sensitivity: -100dBm

A maximum link budget of approximately 117dB is capitulated, yielding more than enough to achieve a range of 403 meters. However, as highlighted in the previous section, the outermost deployed node is approximately 150m apart from the intersection. Thus, the system has a maximum range of 150 m, which is acceptable in transceiver design.

3.4.5 MAC

Non-persistent Carrier-sense multiple access (CSMA) is implemented in Wi.232DTS. This random access technique listens to the channel before transmitting a message and waits if another Wi.232DTS is already transmitting. After time expires the algorithm is repeated until the channel is free. Figure 14 shows a flow chart of the implemented algorithm.

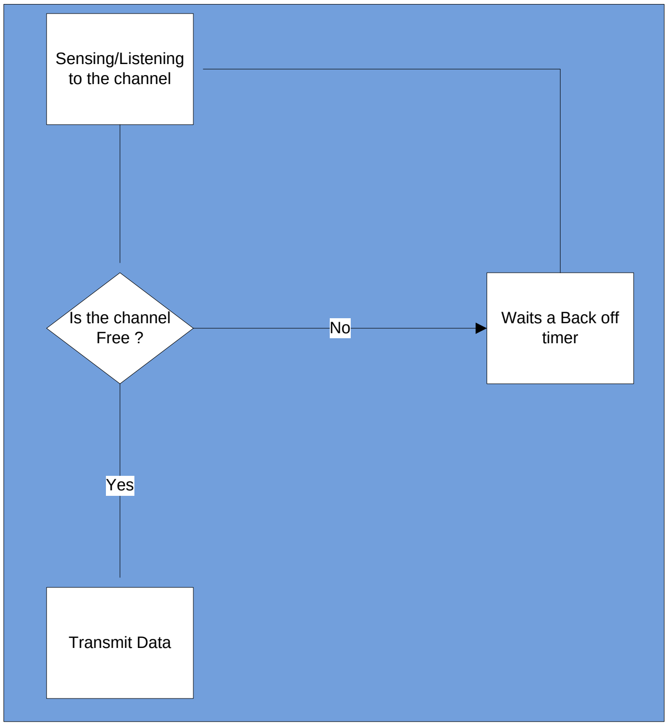


Figure 14: Non-persistent CSMA

3.4.6 Network Capacity

Due to its integrated MAC layer, the Wi.232DTS module can emulate a wired connection, thus enabling rapid deployment that can support an unlimited number of connections.

3.4.7 Error Detection

When using wireless channels transmission errors are expected. The source can subsist from either a wireless transmission medium (i.e. interference) or noise caused by the receiver itself. In order for the latter to occur, a 16-bit Cyclic Redundancy Check (CRC) error checking is used. More information on CRC can be found in [40].

It should be noted that CRC is an error-detection code not a correction scheme. If errors have been detected a retransmission of the message is require

4 System Processing

4.1 Oscillator Select

Selecting a suitable Oscillator is the first step to processing. In doing so, two important criteria's should be considered: its frequency and the accuracy tolerated. Frequency relates to the power of operation of the system, i.e. the power of the processor and the speed afforded the job. Accuracy refers to the degree of tolerance the processor can handle while temperature change is present. To get accurate data the stability of the oscillator should be between -2% and +2%. This is important for the system proposed in this report, as it will be deployed outside, where change of temperature is imminent.

PIC24FJ128GA010 employs an 8 MHz RC internal oscillator that can tolerate 32 MHz by using PLL functionality. Such an oscillator provides high frequency, fast startup and low cost but experiences poor accuracy over temperature variation. With constant change in temperature, the accuracy of such a system is between -5% to +5 % [37], which is outside the required range. To solve this problem, rather than the RC oscillator, an 8 MHz external crystal resonator-based oscillator is chosen as the main clock source. Crystal oscillators are well known for their clean, reliable clock signals. Consequently, an extremely high initial accuracy that surpasses the RC oscillator is achieved

4.2 Interfacing

As shown in the system's functional decomposition, four types of interfacing are present:

- Asynchronous serial communication via RS232, which uses UART as the communication interface between transceiver 1 and the PIC

- USB OTG module between transceiver 2 and the PIC.
- Parallel communication via PMP between LC and the PIC
- Digital I/O port between the magnetic sensor and the PIC

4.2.1 Universal Asynchronous Receiver Transmitter

UART protocol is used primarily as a communication interface for serial communication. It is one of the oldest and simplest interfaces used in embedded-control.

4.2.1.1 Communication protocol

The most basic components for the UART interface include:

- Baud Rate Generator (BRG), i.e. the speed by which sampling the middle of a bit period takes place
- Transmit control (UxCTS) and Receive control (UxRTS), i.e. hardware flow control of the transmission with pins place at RF12 and RF13 respectively
- Transmit output buffer (UxTx), i.e. data output from the module in which the buffer is utilized through RF5 pin.
- Receive input buffer (UxRx), i.e. data input of the module placed at pin RF4.

In order to establish connection between the wireless transceiver and the microcontroller, a communication protocol should be established between the pins of the devices. Figure 15 depicts a simplified block diagram that describes the entire system interface.

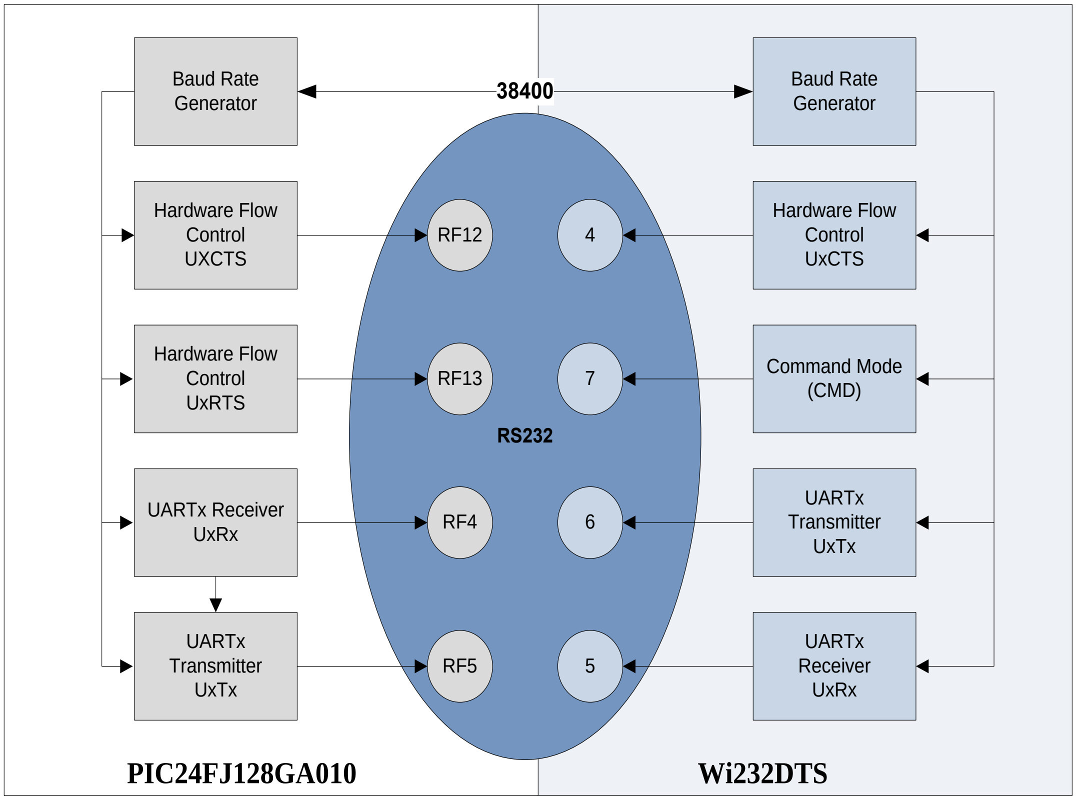


Figure 15: Simplified UART module interface between the microcontroller and the wireless transceiver

For better utilization of data flow, the I/O pins represented above are used as serial interface by way of an RS-232 chip. This chip provides serial communication interface through the use of RS-232 standard between the two ends.

4.2.1.2 Initialization

Before using a UART interface, timing parameters between the microcontroller and the wireless transceiver should be agreed upon. Afterwards, parameters must be set into their registers. The UART uses standard Non-Return-to-Zero (NRZ) format (one Start bit, eight or nine data bits and one or two Stop bits).

For the system represented herein, the device utilizes one stop bit, 8 data bits and no parity configuration. The stop bit alerts the receiver that a data word has been entirely received. If the receiver doesn't see the stop bit at the end of the data word, it will consider the data garbled and report back to the transmitter that a framing error has occurred. Eight data bits represent the size of the data word sent through the transmission medium. Parity bits are often used for error detection; however, they are used infrequently to maintain system simplicity.

Baud rate is the second UART configuration parameter, i.e. the speed by which data is sent. The higher the baud rate, the higher the data transmission speed. However, it should be noted that higher speed is at the expense of increased Bit error rate. While communicating, it is essential for the wireless transmitter and microcontroller to maintain the same baud. A baud rate of 38,400 was chosen for the proposed system due to the fact that it represents an optimal speed with an average error tolerance [41]. Additional information about UART operations can be found at [42].

Other important criterion should be considered, the first of which is enabling the interrupt and setting its priority in the system. This is explained in detail later.

PIC24FJ128GA010 employs a 16-bit register; therefore, to set the specified baud rate, the value must be transformed to a BRG number that represents the microcontroller 16-bit clock value. The equation below shows the calculation of the baud rate generator.

$$BRG = \frac{FCY}{(16 * Baud\ \ Rate\,)} - 1$$

For better understanding, the basic initialization of the UART is summarized as follows:

1. Set system clock to 8000000
2. Set FCY at SYSCLK/2
3. Set baud rate to 38400
4. Set baud rate generator to (FCY/16/BAUDRATE2)-1
5. Select one-stop bit and no parity configuration

6. Enable the UART module
7. Enable the transmit bit
8. Enable interrupt
9. Set interrupt priority to 6 (7 for BS)
10. Clear the receiver buffer

4.2.1.3 Transmitting and Receiving through UART

After the UART has been initialized, data can be either sent or received through the serial communication supported. For this purpose, two 16-bit registers UxTXREG and UxRXREG are used. U2TXREG is responsible for sending characters from the PIC to the transceiver and can only be used when the buffer responsible for the transmission is not full and the flag “clear to send” is raised. U2RXREG is responsible to receive characters from the opposite end. Algorithm 1 and algorithm 2 demonstrate UART transmit and reception.

Algorithm 1: Putting characters through UART (transmitting)

---

1. Set the character to be sent as T
2. Wait until the character is clear to send
3. Wait while transmitter buffer full
4. Set UxTXREG as T

Algorithm 2: Getting characters through UART (receiving)

1. Set the character to be received as R
2. Wait for a new character to arrive
3. Set R as UxRXREG

4.2.2 Parallel Master Port (PMP)

The use of PMP is necessary for LCD interfacing. This parallel port was created by the PIC24 family to automate and accelerate access to a large number of external parallel devices, one of which is LCD.

4.2.2.1 PMP interface

As mentioned earlier, most LCD's are designed to communicate through PMP modules. The PMP module implemented in the PIC is a parallel 8-bit bus used to communicate with parallel devices. The module is used as an interface to 11 I/O pins between the LCD and microcontroller. The 11 pins are represented as follows:

- Eight bidirectional data lines (pins PMD <7:0>)
- An enable strobe line (E) (pin PMRD)
- A Read/ Write selection line (R/W) (pin PMWR)
- An address line (RS) for the register selection (pin PMA0)

Figure 16 shows how the PMP module is implemented.

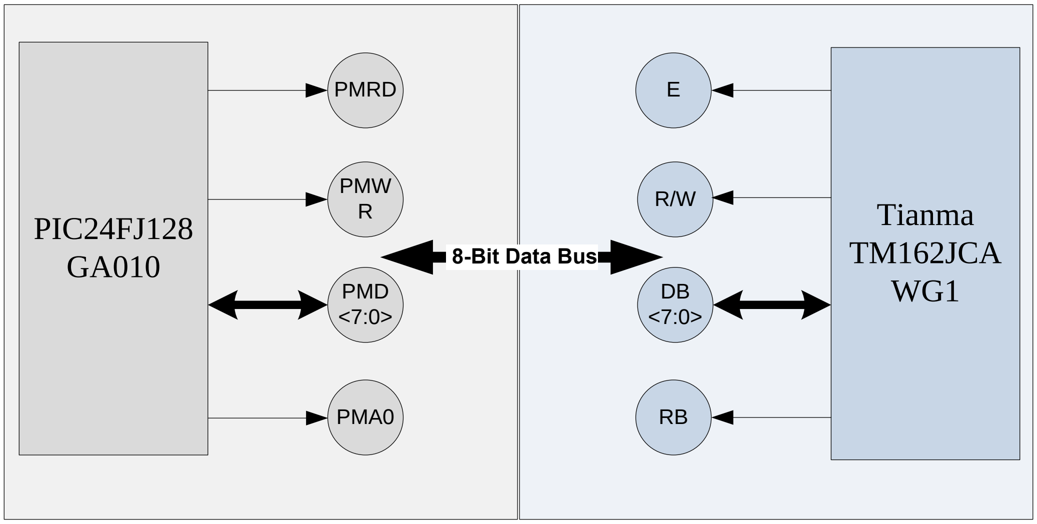


Figure 16: PMP module overview

4.2.2.2 Initialization

Unlike UART, the Reading/Writing selection line that uses the PMP module does not require timing parameters to synchronize. However, due to parallel peripherals varieties, the PMP module is more complex and involves more than one register. For the sake of simplicity and to specifically communicate with the LCD device, the PMP should be configured as follows:

- PMP register bit enabled
- Interface set to fully demultiplexed, i.e. separate data and address lines will be used
- Data lines to send specified messages required to appear on the screen, while address lines are used to control registers inside the LCD
- Write/Read Enable Strobe Port enabled and used to enable/set the pins needed for communication

- Master mode 1 is set with Read and Write signals on the same pin; to control the flow of information, a second control line is set to determine when a read or write action will take place.
- Enable the use of 8-bit, rather than 16-bit bus interface (The bus is used as a support for the length of the data sent through the transmission medium. and the choice is based on author's personal preferences.)
- Read/Write data set for long waits (LCD devices are usually extremely slow; therefore, longer waits are needed for communication.)
- Interrupts enabled with priority set to 7, i.e. highest (This will be discussed later in the chapter.)

4.2.2.3 Writing through the PMP module

The chosen LCD module (Tianma TM162JCAWG1) is HD44780 compatible. This means that the LCD controller contains two registers: one for sending data and the other for control. In order to use the fist register, data has to be sent in ASCII format. This is controlled by the PMDIN1 register in the microcontroller. The second register is controlled by PMADDR in the microcontroller. If the value of the control register is 1, the value used for PMDIN1 is used as display characters on the LCD. However, if the value is 0, the data sent through PMDIN1 is for instructions only. These represent explicit commands to the LCD to perform certain functionality, such as clear, display and go to next line. For more information about commands, refer to document [43].

Algorithm 3 shows how to write to the LCD.

Algorithm 3: Writing data to the LCD module

1. Set addr as the value of the control register
2. Set C as the value of data
3. Wait until LCD is not busy
4. Wait for availability of PMP module
5. Set PMADDR as addr
6. Set PMDIN1 as C

4.2.3 Digital I/O port

An I/O port is used as an interface between the magnetic sensor and the microcontroller. As stated earlier, the magnetic sensor uses a comparator to transform the analog signal to a digital one based on a given threshold. Hence, the interfacing process is straight-forward and simple to implement. Because the functionality of the magnetic sensor is merely to signal whether or not a vehicle has passed through the sensor field, the system needs only one digital input I/O port to fetch its signal. The chosen I/O port for the system is RD8. It is important to note that the system utilizes input capture interrupts to collect the signal. More about this will discussed later.

4.3 Interrupts

An "interrupt" is characterized as an internal or external event that requires quick attention from the CPU. The PIC24 architecture provides a rich interrupt system that can manage as many as 118 distinct sources of interrupts. Each source can have a unique piece of code, namely the Interrupt Service Routine (ISR). Three important things must be considered when activating an interrupt in a microcontroller:

1. Interrupts has to be enabled
2. For interrupt management, a priority must be set for each interrupt.
3. Interrupt flag cleared, in initialization and after use

Several types of interrupts will be used in the system:

- Timer1 interrupt: The timer module is a 16-bit timer and can either serve as a time counter for the Real-Time Clock or operate as a free-running interval timer/counter
- Timer 1 can operate in sleep mode conditions by utilizing the secondary oscillator. The most notable parameters in this module are its Period Register one (PR1) and TMR1 values. When Timer1 interrupt is enabled, the time period is loaded into the PR1 register. TMR1 is initially set to zero and continues to increase in increments until it reaches the PR1 value. The Timer1 interrupt occurs the instant the two values are equal.

- The Input Capture interrupt is defined when a change of state from 0 to 1 occurs at a specified I/O port, thus the interrupt routine is serviced. As mentioned earlier, the I/O port will provide the interface between the magnetic sensor and the detection node microcontroller. When a vehicle passes, a digital signal is transmitted through the port. If the signal is high, the interrupt is enabled, causing the system to detect to the approaching vehicle. Because the system is time sensitive, the priority of such an interrupt should be set to the maximum level, enabling the detection functionality in the detection nodes the highest priority among other interrupts.

- UART interrupts are used to inform the PIC about incoming data from the transceiver and are only used when there is incoming data from the UART.

4.3.1 Power Efficiency Methodology

Energy efficiency has been a significant issue in wireless sensor network [44]. The detection nodes deployed in an intersection are in an environment where no peripheral power is present. The nodes are installed under the road and makes replacing the power source in the system difficult. Therefore, the nodes must use a methodology that conserves energy and allows the system to operate for extensive periods without wired power sources. To achieve this, two methods have been chosen: selecting suitable transmission power and utilizing sleep mode functionality.

4.3.2 Wi232DTS Network Routing

As discussed earlier, the deployed vehicle detection nodes will communicate directly to the BS where no use of hopping methods or mesh network technique is needed. Consequently, the range of the system depends on the layout of the detection nodes. This would initially give transmit space for all possible communication, foremost the furthest node with the Base Station and the last with the vehicle.

It has been previously discussed that vehicle detection nodes will be deployed under the road to ensure reliable sensing, and sensors will be attached to the pavement at a low height. This system architecture causes high pass loss resulting in a diminished communication range. Consequently, using the transmitter in a low power mode is unacceptable. However, this issue may be resolved by using low power transmission to employ a multi hopping methodology to transfer the signal. This can be easily accomplished when each node continually shifts the data to the next nearest node until the message eventually reaches the base station. However, according to [45], the power consumption of a two or more hops network is much higher than a one hop system. Additionally, the transmission delay of the data would increase due to the hops the information must make to reach the Base Station. Consequently, a one hop network with feasible power transmission is the best solution.

4.3.3 Power consumption

ICW is still in prototype phase; therefore, studying the power consumption for such a system is difficult. The research would require bending the PIC, transceiver and magnetic sensor pins out of a socket, plugging in the modules, and then subsequently connecting a resistor to measure the current traveling through. Hence, it is suggested that the power consumption phase be implemented when the final sensing system is designed and ready for commercial use. For the sake of ease, an approximation of the power is calculated through data sheets provided with components used in the system. Table 7 shows the power and current consumption at 5v for the various system components.

When the PIC goes into sleep mode, the power consumption varies with temperature change. This is a result of variation in current. For example, at -40C, the PIC consumes approximately 0.0002watt, while at 85C it reaches 0.003075 watt. It is important to note that the values for power consumption presented for sleep mode in Table 7 include an additional peripheral, these being the modules that remain running when the PIC is in sleep mode. In the proposed system the peripherals include the RTCC, Timer1 and UART. In normal mode operation, the maximum power consumption for PIC is approximately 0.02 watt.

When Wi.232DTS is in sleep mode, the RF section is completely shut down and the protocol processor remains idle. During this operation the system consumes approximately 0.00014 watt (35 µA). However, when the system is awake and in its highest transmission mode it consumes approximately 0.2079watt (63 mA).

The Honeywell magnetic sensor must be active at all times in order for vehicle detection. The power consumption for this device is less than 0.005 watt (<1 mA). It has to be noted that the Honeywell magnetic sensor requires approximately 0.5mA to set or restore its sensor characteristics when influenced by a strong magnetic field. ICW utilizes the reset each time vehicle detection takes place.

Table 7: Current/Power consumption for system components

	Voltage	**Max Current (sleep Mode)**	**Max Power (sleep Mode)**	**Max Current (normal Op)**	**Max Power (normal mode)**
PIC24FJ128GA 010	5v	40-615 µA	0.0002-0.003075 watt	4 mA	0.02 watt
Wi.232DTS	3.3v	35 µA	0.00014 watt	63 mA	0.2079watt
Honeywell HMC1021Z	5v	-	-	<1 mA	0.005 watt
			Overall power (without the magnetic sensor reset operation)	Sleep Mode Op	0.00034-0.0032 watt
				Normal Mode Op	0.2329 watt

4.3.4 Sleep Mode

The wireless sensor network takes advantage of sleep mode functionality to conserve power, thus power consumption is reduced to a minimum when data processing is not needed. Placing the system in sleep mode will result in cutting off power to unnecessary node parts, achieving the lowest energy consumption for the system.

Two system components in ICW utilize the sleep functionality, namely the microcontroller and the transceiver. It is not possible for the magnetic sensor to go into sleep mode, as it is the source of detection. The digital signal taken from the comparator is therefore used to wake up the other system components.

Setting the PIC into sleep mode is straight-forward by changing the PWRSAV instruction to zero. Updating this value will automatically shutdown the oscillator clock. As discussed earlier in the section on interrupt, the interrupts are used to wake up the system.

In the previous section, it was mentioned that the Wi.232DTS radio transceiver is interfaced with PIC through UART protocols. In order to set the following transceiver to sleep mode, commands must be sent from the PIC to the radio via the selected interface. Therefore, the methodology is a bit more complicated. The user must first set the UART CMD pin to low, making sure that the UART data is routed to the command parser rather than the wireless interface. Afterwards, a 0x01 command is sent from the PIC through the UART to set the regSLPMODE (0x58) register in the transceiver. The same algorithm is used to wake the system; however, instead of setting the regSLPMODE (0x58) to 0x01, a command sequence of "0x0F, 0xFF, 0xFF" is sent to the same register. To verify whether or not the Wi.232DTS is up, the module will send an acknowledgement character (0x06) through the UART TxD pin to communicate to the PIC that it is awake. Figure 17 illustrates the logic behind the sleep mode functionality of the entire proposed system.

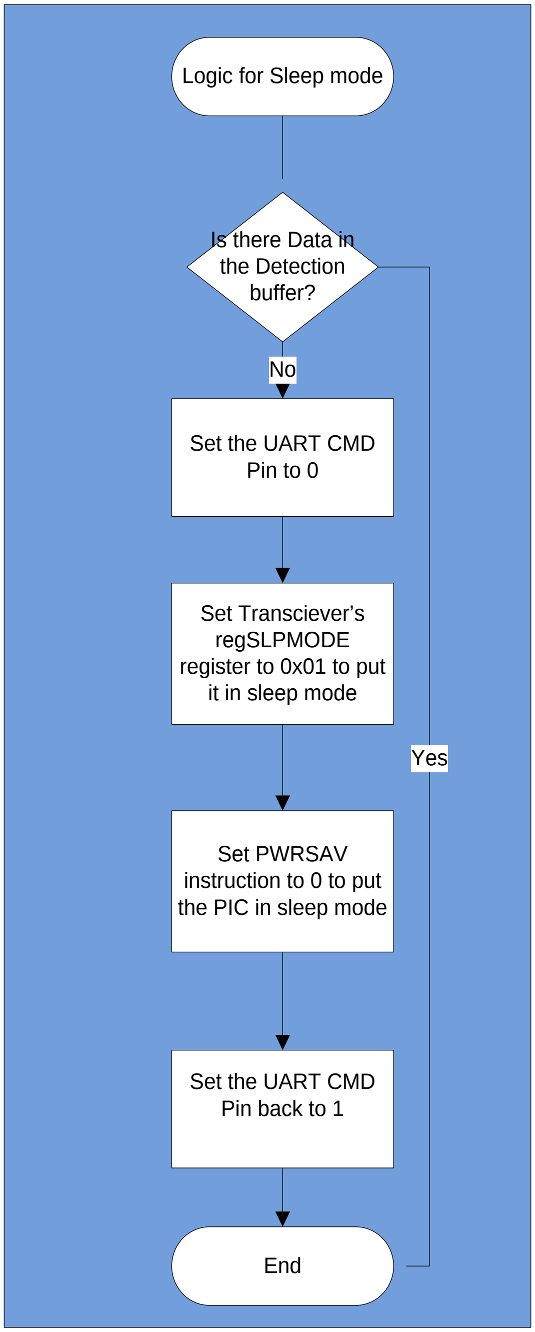


Figure 17: Detection node sleep mode logic

4.4 Vehicle Trajectory Prediction

In order to potentially prevent collisions, the system must have a reasonable time prediction algorithm that can estimate the trajectories of the cars while going through an intersection. To detect the time by which the car reaches an intersection, a function of velocities plus accelerations measurements should be available to the BS. However, those information are dependent of the driver's behavior, thus they are constantly changing.

To get enough measurements, the system employs four detection nodes that are embedded on the ground. The node's main functionality is to sense the car and afterwards send the time of detection to the base station. Consequently four time periods of the same car are taken based on a predefined distance. Using the following two dimensional motion model:

$$d = v_i * \Delta t + (\frac{1}{2} * a * \Delta t^2)$$

the time of arrival of the car to the intersection and time of its exit can be approximated. The algorithm is as follows:

Consider the following:

- t1 represents time captured by the first node
- t2 represents time captured by the second node
- t3 represents time captured by the second node
- t4 represents time captured by the second node
- d_{en} valued 125 m, represents the separated distance between the last node and the entrance of the intersection.
- d_{ex} valued 135 m, represents the separated distance between the last node and the exit of the intersection

Two accelerations (a_1 and a_2) and two velocities (Vi_1 and Vi_2) can be calculated in the following manner:

$$a_1 = \frac{2}{\Delta_1} * ((\Delta t_2 * \Delta x_1) - (\Delta t_1 * \Delta x_2))$$

$$a_2 = \frac{2}{\Delta_2} * ((\Delta t_3 * \Delta x_2) - (\Delta t_2 * \Delta x_3))$$

$$Vi_1 = \frac{1}{\Delta_1} * ((-\Delta t_2{}^2 * \Delta x_1) + (\Delta t_2{}^2 * \Delta x_1))$$

$$Vi_2 = \frac{1}{\Delta_2} * ((-\Delta t_3{}^2 * \Delta x_2) + (\Delta t_2{}^2 * \Delta x_3))$$

Where,

$$\Delta_1 = (\Delta t_1{}^2 * \Delta t_2) - (\Delta t_2{}^2 * \Delta t_1)$$

$$\Delta_2 = (\Delta t_2{}^2 * \Delta t_3) - (\Delta t_3{}^2 * \Delta t_2)$$

$$\Delta t_1 = t2 - t1$$

$$\Delta t_2 = t3 - t1$$

$$\Delta t_3 = t4 - t1$$

After acceleration and velocity values are calculated, time of intersection entrance of the car (ten) and its exit (tex) can be calculated by:

$$ten = v - \frac{\sqrt{v^2 \pm 2 * a * d_{en}}}{a}$$

$$tex = v - \frac{\sqrt{v^2 \pm 2 * a * d_{ex}}}{a}$$

Where,

$$v = \frac{Vi_1 + Vi_2}{2}$$

$$a = \frac{a_1 + a_2}{2}$$

Figure 18 depicts a detailed description of the algorithm describes above.

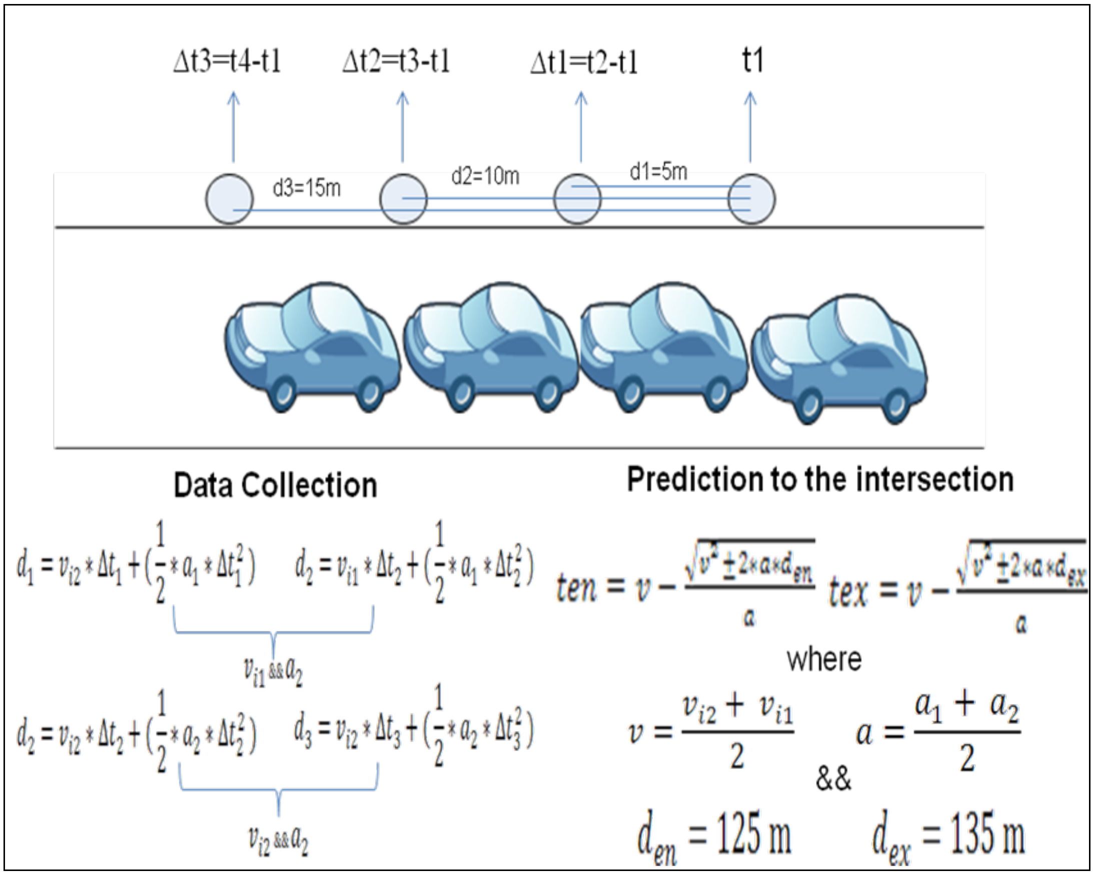


Figure 18: Detailed description of the system prediction algorithm

4.5 Time Synchronization

From the previous section, it can be concluded that ICW is a time dependent system. It uses time difference to calculate vehicle speed. Hence, implementing a reliable and accurate clock is imminent. To capture the vehicle's velocity at high speeds the system should be at least capable of supporting a millisecond time stamp.

4.5.1 Clock implementation

One method to employ a real-time clock is to use a PIC24 Timer1 fed by the secondary oscillator. The interrupt routine can then count seconds, minutes, days …etc. It has been well established that the timer is fed by the clock of the oscillator. It is not possible to use the selected 8 MHz primary oscillator because when in sleep mode the system's main clock is disabled. The sole option is to use the secondary oscillator. Because it is designed for low-frequency operation (32,768-Hz), this oscillator requires minimal power to operate. One disadvantage of such implementation, however, is that the PIC must wake up from sleep mode when an interrupt routine is executed. These results in the system alternating between sleep and wake up mode and is certainly not feasible in the system. Fortunately PIC24FJ128GA010 has a complete, built in Real-time Clock and Calendar (RTCC) module and has an integrated Alarm function that can generate interrupts. The module feeds automatically from the secondary oscillator; hence there is no need to wake up the system each time the clock is updated.

The time stamp for RTCC results in significant limitations for the module. The stamp diminishes only two seconds. A proposed solution uses PIC Timer1 listed above for a clock millisecond reference. This is feasible by disabling the Timer1 interrupt routine, which causes Timer1 to overflow when it reaches a period register value of one second. The value of Timer1 now indicates a millisecond time range. The figure below illustrates the algorithm for this basic concept.

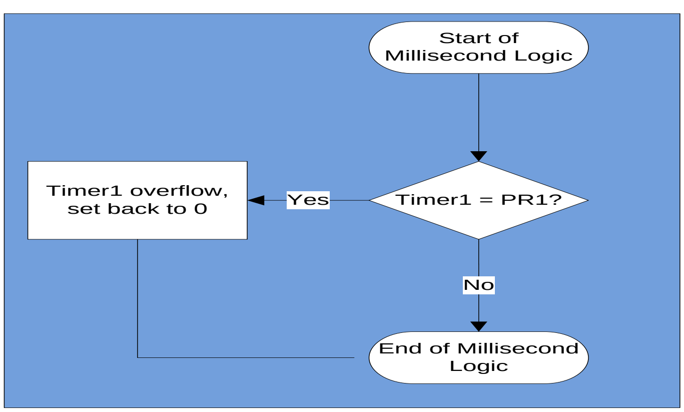


Figure 19: Logic to achieve a millisecond rang

To calculate the value of PR1, the following formula is used:

PR1= [Time (ms) / TCY (ms)] -1, where TCY=1/ (Oscillator clock) = 1/32.768 KHz.

So, for a Time =1000ms the PR1 value is 32767. Similarly, to calculate the value of Timer1 in milliseconds one must substitute the Timer1 value with PR1 and then calculate the time.

4.5.2 Time Synchronization

RTCC and Timer1 are used as a clock source. The margin of error and clock variation is approximately 2.64% per month. This figure might initially seem insignificant; however, for prolonged testing and implementation, the timing difference between the Base Station and the Vehicle detection node cannot be negligible. Thus there is a need for a synchronization algorithm.

The algorithm selected should have the capability to force the Vehicle Detection Node to follow the Base Station clock. Logically, it is feasible to implement an alarm system at the BS and then broadcast its clock to all detection nodes to achieve clock synchronization. However, this method cannot be implemented in the system due to the fact that the detection node transceivers are in sleep mode at this point in time. As mentioned before, when transceivers are in sleep mode, the RF functions are disabled. Consequently, the BS cannot communicate with the detection nodes unless the nodes initiate the communication.

A second solution suggests implementing the alarm system inside the detection nodes. The nodes will then wake themselves up and request clock synchronization from the BS. However, this requires a tremendous amount of effort, as evidence by the fact that the number of synchronization packets can advance to twelve on account of additional acknowledgment (ACK) packets.

To solve the problematic clock synchronization issue, an algorithm concept from Bluetooth technology [45] has been adopted. In Bluetooth, if a terminal is in standby and desires to synchronize to other terminals, it listens on different channels until it locks with the required device. This same concept is used in the proposed system, but rather than listening on different channels it listens on different time slots. The algorithm is explained as follows:

- Detection nodes and the BS agree on a predefined time frame.
- When the time frame is reached, both the detection nodes and the BS will be interrupted.
- The interrupt causes the BS to fetch its clock and then broadcast it. There is a possibility that the detection node and the BS won't wake up at the exact time as a result of clock margin error (2.64% per month). To solve this, BS continues to broadcast its clock on different time slots for a period of 2 seconds. Of note is that each broadcast differs from the other because a different clock is sent each time.
- Detection nodes will wake up for a maximum of 2 seconds and listen until they receive a broadcasted message. They save clock values and update their own clock accordingly. When the update is complete, each sends an acknowledgement and returns to sleep mode. If 2 seconds passes without the reception of broadcasted messages from the BS, a synchronization request will be sent to the BS. The nodes will wait for the clock values to be sent again by the BS. It will then save the values, update it clock and return to sleep mode.

- BS achieves its acknowledgements and then updates its database. If for some reason the BS doesn't receive an ACK from one of the detection nodes, it will wait for a synchronization request from the same node. When this is the case, it sends its clock to the specified node and waits for an ACK. If the same node is unresponsive to an ACK or doesn't send a synchronization request, it waits for a subsequently scheduled clock synchronization to occur. If the same node still does not respond, it will report it as "non functional."

4.5.2.1 Time Synchronization for Detection Nodes

For reliable synchronization, detection nodes for ICW employ two main algorithms for time synchronization: (1) listening and capturing and (2) wakeup and clock request. Listening and capturing is used as a primary method for synchronization, but if for some reason the detection nodes fail to synchronize with the BS, the wakeup and clock request function is activated to establish synchronization.

The built-in timer in the RTCC is used to wake up the detection nodes so as to update their clock with that of the Base Station clock. Setting the alarm depends on the time synchronization algorithm that has been employed. If the system has been able to listen and successfully capture the time within a two second margin from the BS, the alarm is set at either 4 a.m. or 4 p.m., depending on interruption time. However, if for some reason the detection node was not able to capture the BS clock, the system returns to sleep mode for an amount which is dependent on the node ID. For example if detection node "1" failed to capture the clock, it will sleep for one second. When the timer has been reached for one second, it will wake up and request a synchronization clock from the BS. In both algorithms, the clock update depends on two values, namely the BS clock and an offset. The offset is an approximated time for wireless transmission and processing. When the clock update is successful, the node must send an ACK to the BS for debugging purposes. If the node advances through the “Wakeup and Clock Request” a total of three times without BS response, the detection node will assume there is a problem with the BS.

Figure 20 shows the basic time synchronization logic for a detection node.

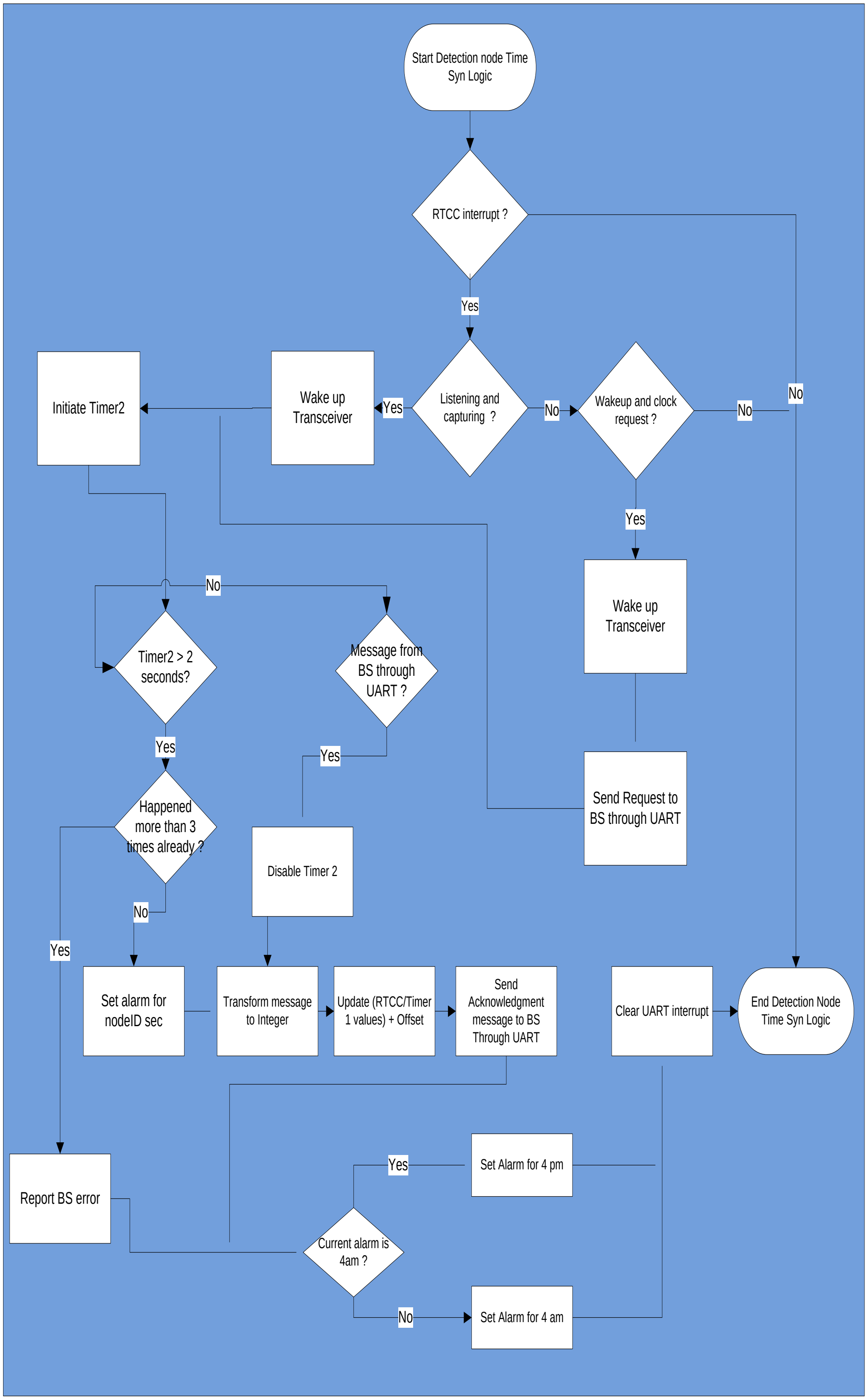


Figure 20: Basic logic for detection node

4.5.2.2 Time Synchronization for the Base Station:

Similar to the detection nodes, the BS employs two algorithms relative to the detection nodes: (1) regular clock broadcast and (2) clock value sent based on node request.

Regular clock broadcast begins when an alarm set via the RTCC is activated. Consequently, the BS broadcasts its clock for 2 seconds. It should be noted that the same alarm is employed on the detection nodes. In so doing, the BS should expect random ACKs from the nodes, which are used to inform the BS that the detection node has successfully updated its clock. Because the BS in unable to broadcast and receive at the same time, UART interrupt is enabled. This ensures that when the BS receives an ACK from the nodes it will save the node information and continue normal broadcasting. After the two-second margin has been reached, the BS confirms whether or not all ACKs have been received. If they have, the BS interprets that all the nodes have updated their clocks. Afterwards, the system updates its alarm mechanism, clears the RTCC interrupt and exit. However, if the BS failed to receive all ACKs within the two-second time margin, it verifies whether or not the specified nodes have failed to give an ACK at some point during the two alarm cycles. If it indeed experienced failure, the BS will report the specified nodes as dysfunctional. If not, it will save the information and await the second synchronization cycle.

A small chance exists that the detection nodes won't wake up in time to receive the clock update. As mentioned earlier, the nodes must request clock synchronization from the BS. When this occurs, the "clock value sent based on node request" algorithm will initiate. The BS simply receives the request, saves the node ID, sends the clock value and exits. However, the detection node must send ACK back in the same way it was previously executed.

Figure 21 shows the basic time synchronization logic for a BS.

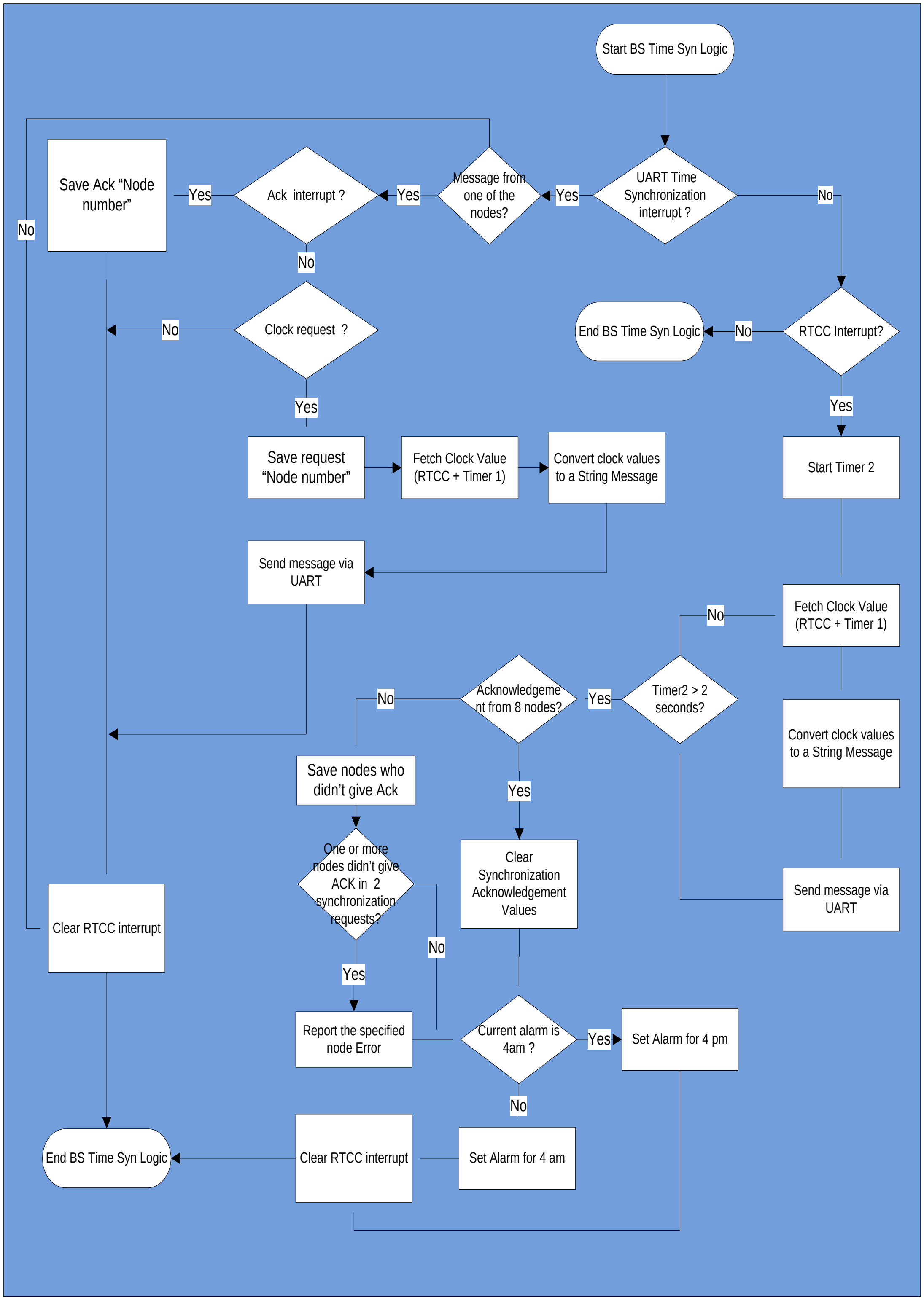


Figure 21: Time synchronizing logic for the Base Station

4.6 System Detection

ICW is an intersection collision system that exploits the use of WSN to track vehicles as well as detect possible collisions. The system must be capable of tracking all the vehicles coming through the intersection, immune to false node detection and finally it must be capable of recovering from packet loss. In doing so, the system must overcome couple of issues while detecting the vehicles. Table 8 shows the basic issues that the system might face and their corresponding suggested solutions.

Table 8: ICW solutions for detection issues

Issue	Solution
Multiple vehicle tracking	Buffers on both BS and detection nodes
Immune to false node detection	3 sec timer for all nodes on one lane employed at the BS
Packet loss	If no ACK has been received by the BS after 50 ms when a packet has been sent, resent the packet. Allow 4 tries

When a vehicle passes through one of the detection node, the communication between the BS and the detection nodes has to be matched.

On the detection node's side, when the detection takes place due to the magnetic sensor hocked to the detection nodes, it saves the time information in a buffer. If there was no information in the buffer before that detection, it sends the information to the BS with an identifier. However, if there were packets in the buffer that has still not been sent, it enters the buffer and waits its turn to be sent to the BS. When the packet is sent to the BS with its identifier, a timer is initiated that let the detection node to waits 50ms to gets an ACK from the BS. The detection node should expect the ACK to include the same identifier that has been sent with the packet. By the time the detection node gets the ACK for the specified packet; it sends the next packet in the buffer if it exits. However, if the detection node didn't get the ACK in the 50ms time margin due to packet loss, it will resend the same packet again. The same packet can be sent of a maximum of four times for a total of two seconds till the next packet waiting in the buffer gets the green light to be sent. So, if the two seconds has been over and the packet has still not got an ACK from the BS, the detection node will drop it and move for the next packet in the buffer if it exits.

Figure 22 depicts the vehicle detection logic of the detection nodes.

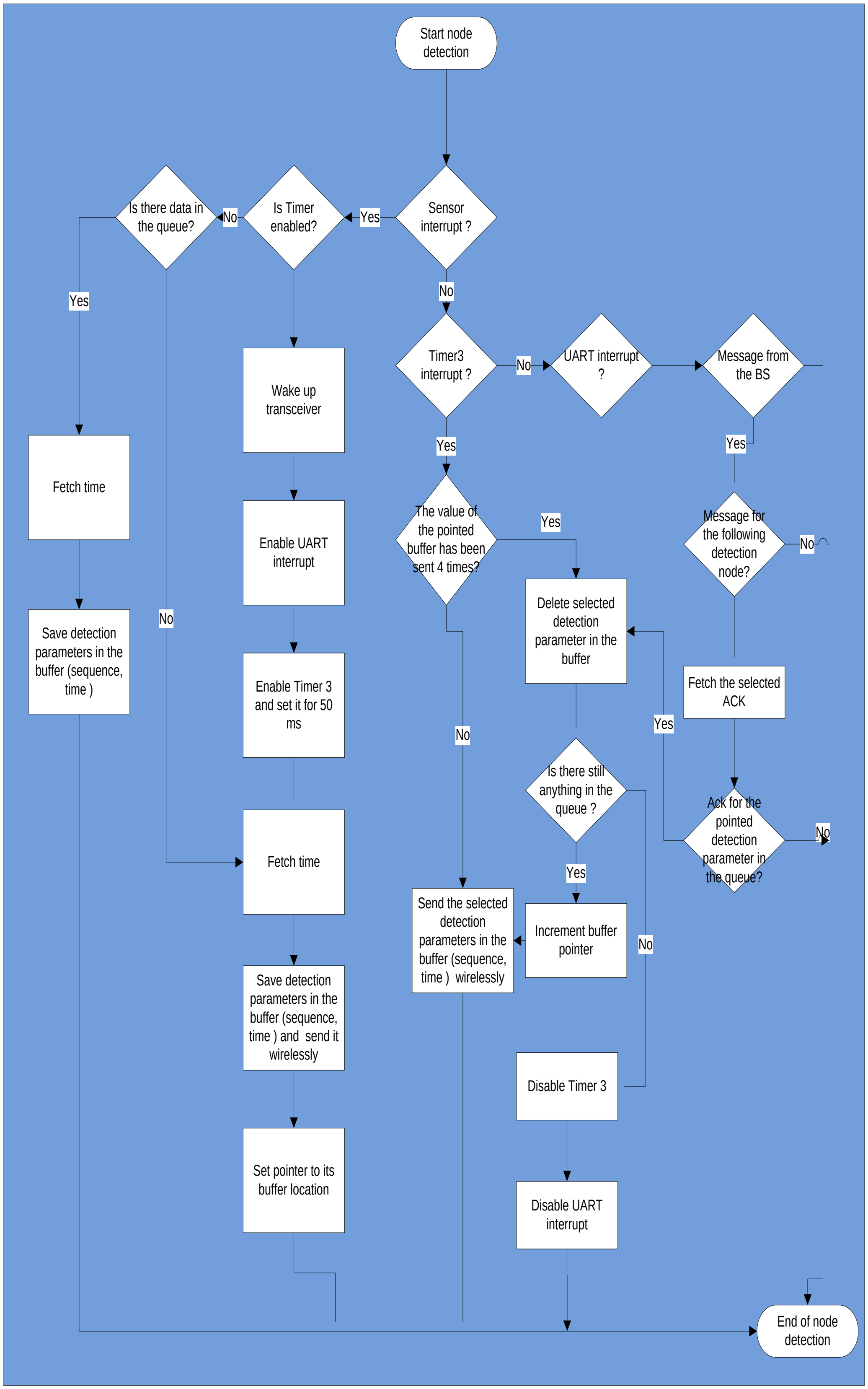


Figure 22: Detection node vehicle detection logic

With respect to the BS side, when detection takes place, the BS should expect a packet from the detection nodes with their ID in addition to the sequence of the packet. The sequence packet is only used for packet identification. The BS has to send ACK with the same identification ID as discussed earlier. At the BS, Detection node packets are separated into two groups, the main lane node group and the minor lane node group. For example, if the packet received was from node one in the main lane, the packet is saved in the main lane node group.

Buffers at the BS are more complex that the one's in the detection nodes. This is simply because for each vehicle passing through the intersection, a vehicle buffer group has to be created for it. For example if four vehicles are going through the minor lane at the three second margin, four vehicle buffers have to be created from the same group. The same concept goes for the main lane. This can be shown in Figure 23.

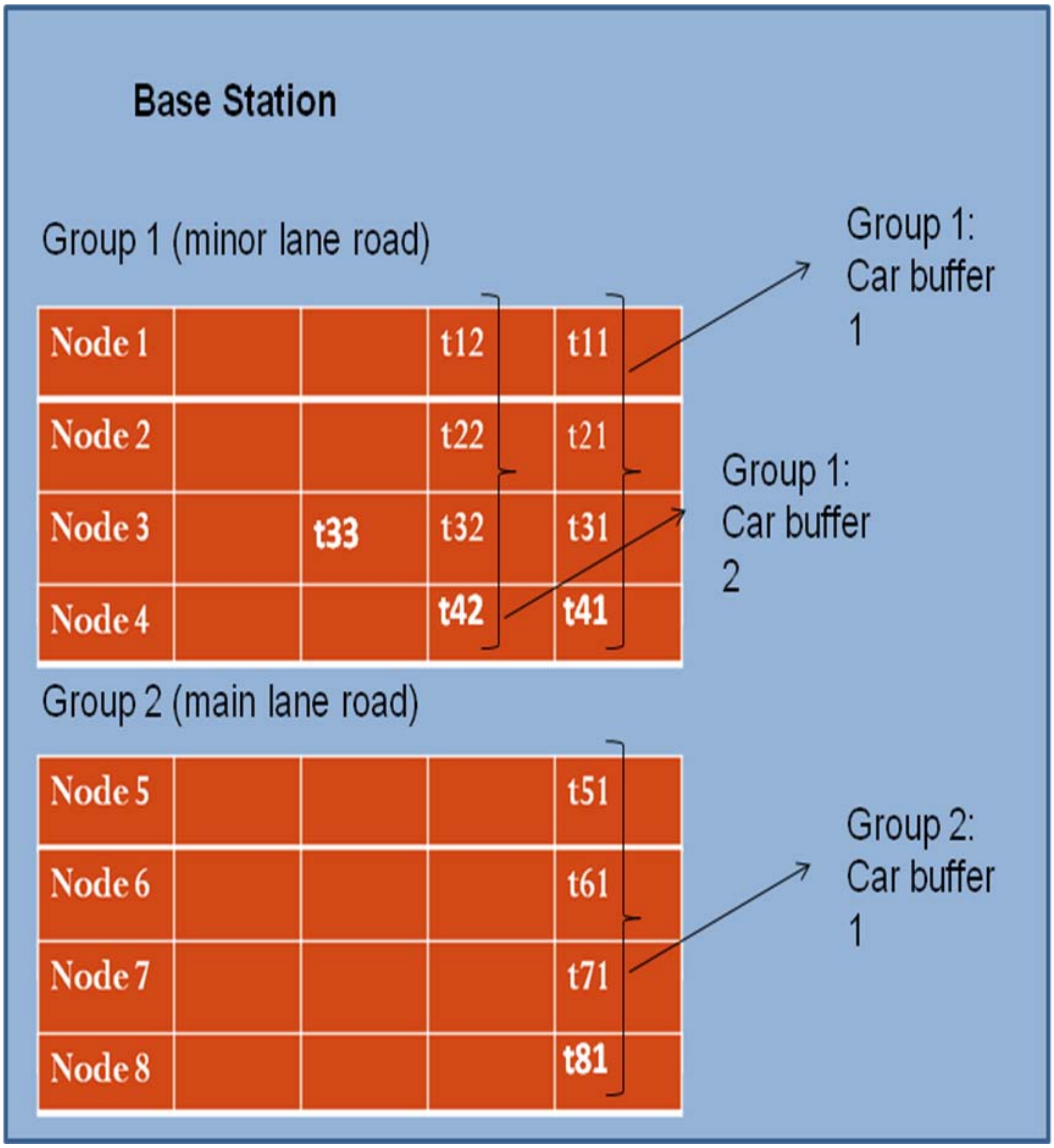


Figure 23: Example of BS group buffers representation in a three second margin

For each vehicle buffer in the group a timer is initiated for 3 seconds. The timer starts once the first packet of the vehicle buffer group has been received. The timer is used for two purposes, first to wait for the packets from the other vehicle buffer group, for example if all the packets from the main lane group are received for the same vehicle; they will have to wait for the packets of the other vehicle from the minor lane group nodes as well. The second purpose is to use it as a false trigger detection mechanism. If a packet is received, the BS should expect other packets from the same group nodes. If the other nodes from the same group didn't send any packets, the BS would assume that the first detection was triggered by mistake. In both scenarios, once the timer has reached without having all the info, the data will be dropped to move for other data for processing.

To achieve data fairness, the BS processes vehicle buffers according to the time they have been received. Once two complete vehicle buffers have been reached (one on each group) within the three second margin, the BS will start performing "intersection collision avoidance and warning system" analysis. More on this step will be explained in the latter section. However, no matter the result is, whether there is a collision or not, the system must still analyze the other vehicles values saved in the buffer within the three second range. In doing so, a recursive algorithm is applied where each buffer in one group is compared with another in the other group. The algorithm can be easily explained by the following example: If we look back at Figure 23, it can be seen that there are two vehicles in minor lane and one vehicle in the major lane. Consequently, the two vehicles in group one should be analyzed with the vehicle in group two. The analysis is done in the following matter: if we assume that t41 is less than t81, this means that the first vehicle coming from group one has come before the first vehicle coming from group two. So, after the collision analysis is made, there is no need for the data of vehicle one in group one, simply because it has been compared with a vehicle that came after it. After the values of vehicle one in group one (minor lane group) has been dropped, the vehicle buffer that represents vehicle one in group two (main lane group) is compared by vehicle two in group one. Now, if we assume that t41 is bigger than t81, the values of vehicle one in group two will be dropped after the collision analysis is made. However, there is no data in group two to be compared by group one. Thus, the vehicle buffers will be dropped once their time margin exceeds three seconds. It has to be noted that the algorithm is recursive, where all the buffers are going to be compared in the same manner. The overall BS detection logic is represented in Figure 24.

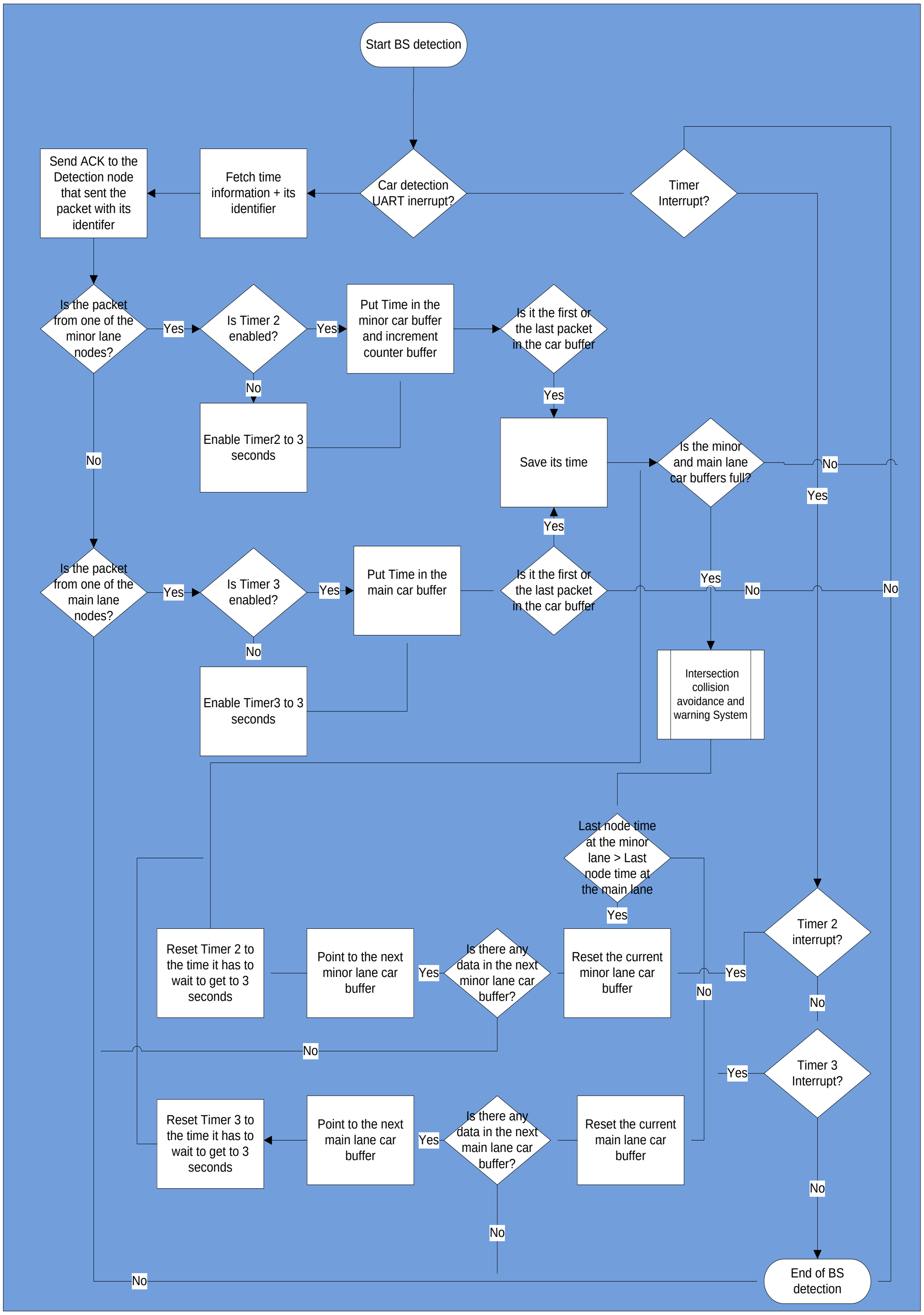


Figure 24: BS vehicle detection logic

4.7 Intersection Collision Avoidance and Warning System

Once two vehicles each on different lanes are going through the intersection and pass through all the sensor nodes, the system would have collected all the time data required for collision avoidance detection. Once the time data are complete, “Vehicle Trajectory prediction” logic discussed in previous section can be applied. After calculating the time of entrance and the time of exit of each vehicle, the BS can check whether there is any kind of overlap between the timing of the two cars. For example, Consider vehicle A and vehicle B passing through minor lane and main lane respectively as shown in Figure 25, At1 and Bt1 represent the entrance of the two vehicles and At2 and Bt2 represent their exit time. The only collision scenario that might occur is when one of the vehicles entrance time is less than the other’s exit time. If that happens, the warning system would be activated for five seconds through a wireless trigger by the BS. The logic is shown in Figure 26.

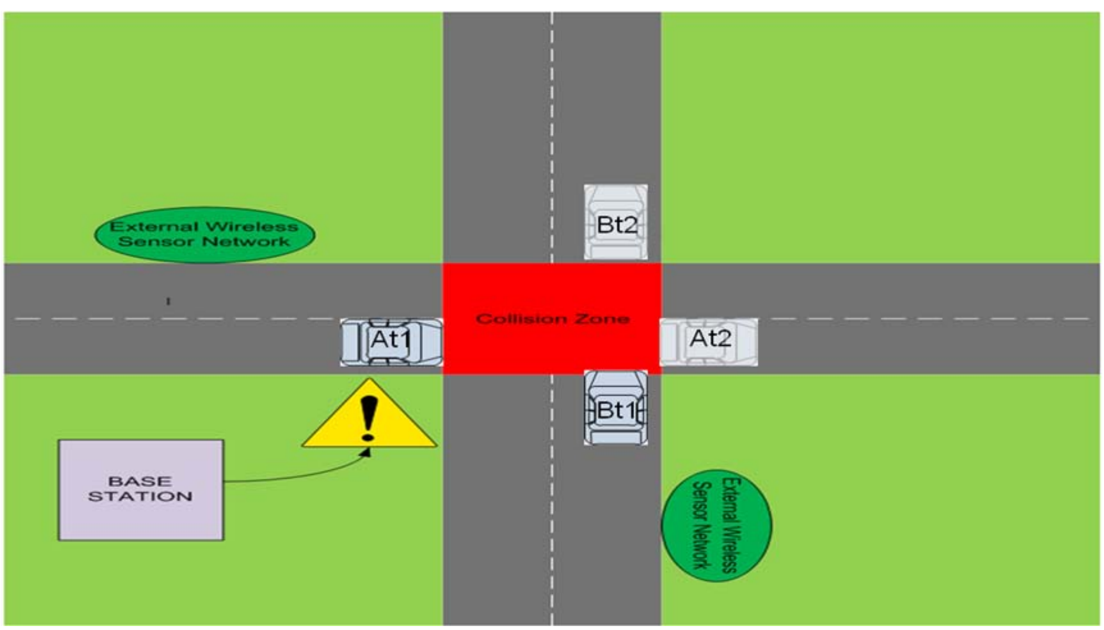


Figure 25: Representation of two vehicles entering and exiting the intersection

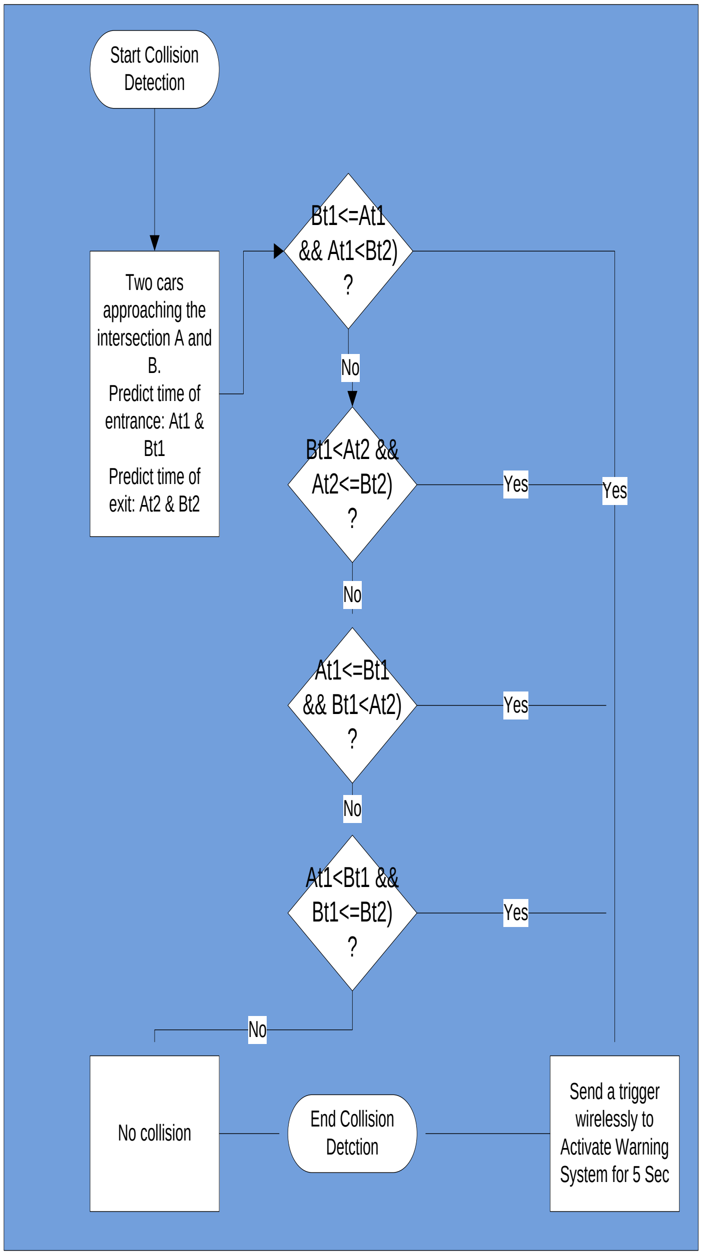


Figure 26: Intersection collision avoidance and warning System logic

4.8 Overall ICW System

Most of the logic of the system is based on the BS and the detection nodes. The system is sensitive towards time where the prediction algorithm is time dependent. So, the BS and the detection nodes have to be always time synchronized for accurate detection. The detection nodes are responsible of sending detection timing, and they should make sure that the time data have to be sent in sequence. The BS, on the other side, has to make sure that all the time data received by the detection nodes are processed. If the analysis of the time data resulted in predicted collision, the BS has to activate the warning signal through a wireless link. Figure 27 and Figure 28 depict the overall detection node and BS logic.

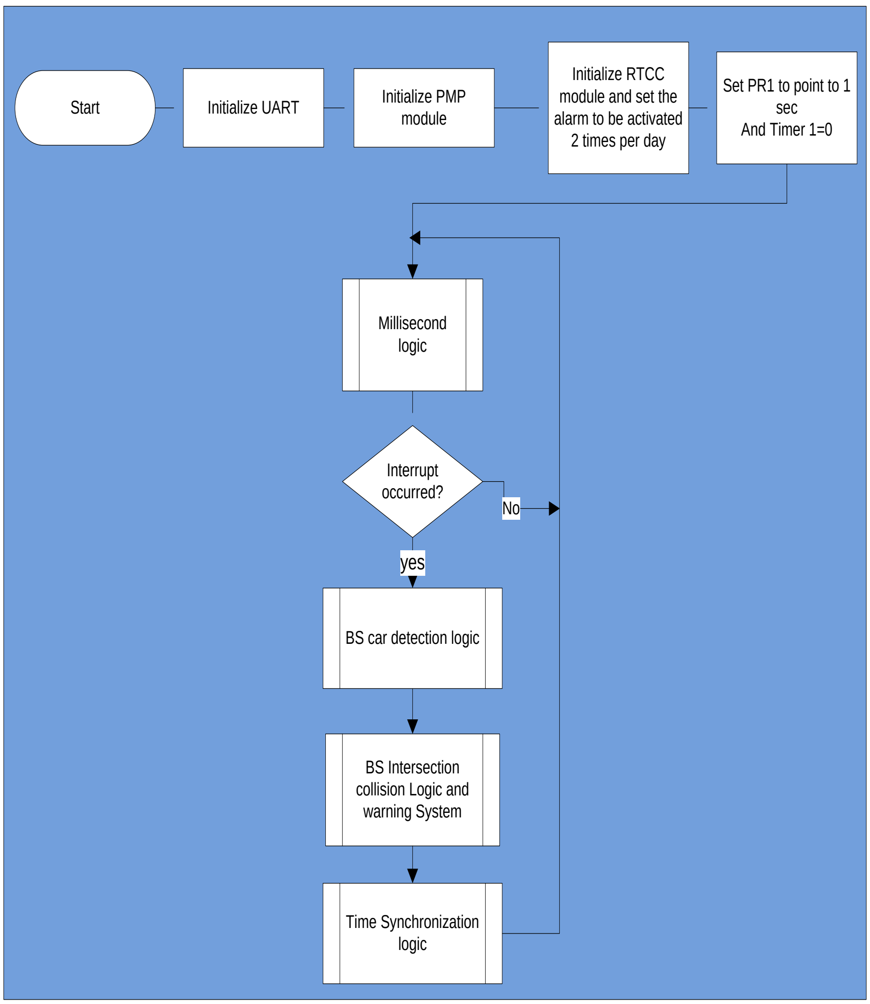


Figure 27: BS overall software logic

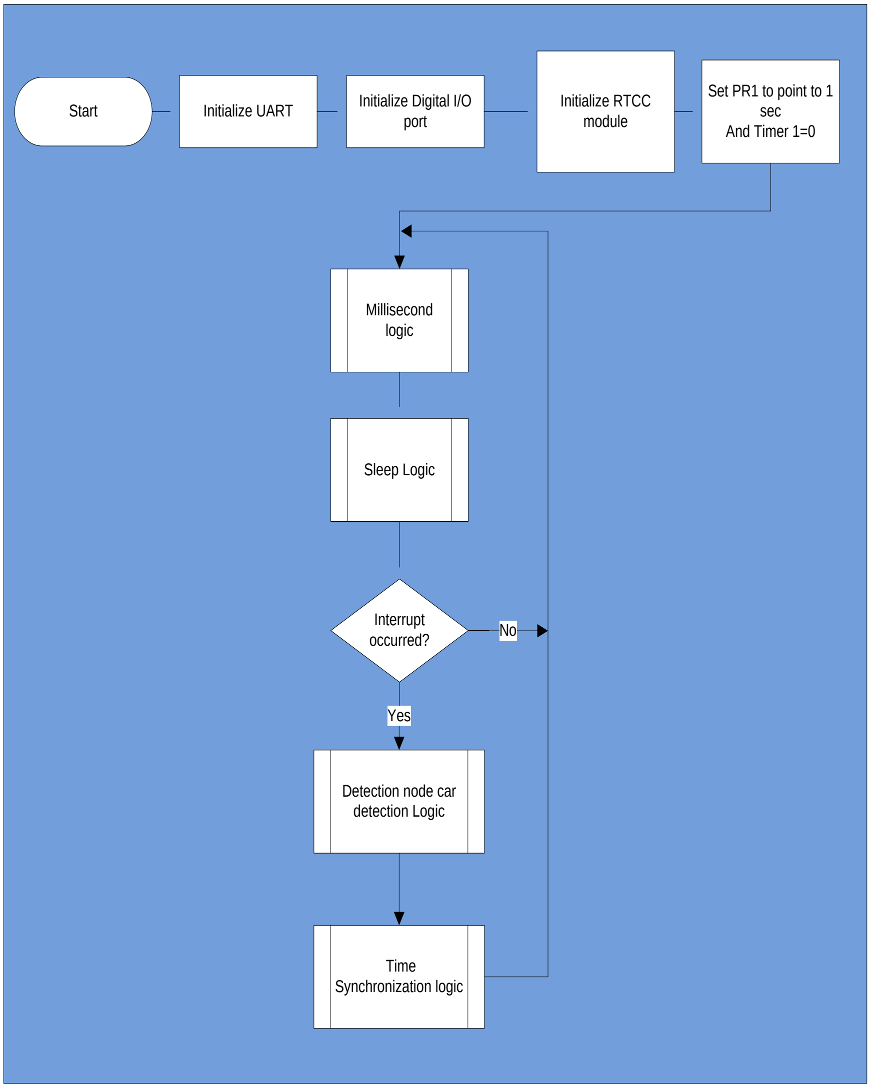


Figure 28: Detection node overall software logic

4.9 Packets Structure

For communication to take place packets have to be sent wirelessly through the wireless medium, the structure of the packets is important for two reasons, first to save transmission power, the less the size of the packets the less transmission is going to take place, hence less power. The second reason is transmission delay. If a node is transmitting a big packet, it will occupy the channel. This will prevent other transmission to take place; hence the packets coming from other nodes will be delayed.

Structure of the packets employed by ICW depends on the purpose of the message. There are five different packet structures, three for the detection nodes and two for the BS. All the packets include a 10 bit header as well to a 2 bit value that resembles the purpose of the packet. The header is used by the receiver to recognize the beginning of the packet. The packets structures are as follows:

a- Detection node packets:

- Vehicle detection packet: this is used by the detection nodes to send the time detection information to the BS.16 bits is used to send the time information to the BS. Only seconds and milliseconds are included in the clock value. In addition to the time info, a 4 bit node ID and 3 bit sequence number are also employed. The first is used by the BS to differentiate between detection nodes while the last is used as a packet reference to be sent inside the acknowledgment packet by the BS.
- Time request packet: Whenever the “listening and capturing” method described in the time synchronization section fails, the detection node has to send a request to the BS to send its clock. Once the detection nodes receive the BS clock value it will update its clock accordingly. Additional 4 bit node ID is used as a tool for the BS to differentiate between the detection nodes.
- Detection node acknowledgment packet: 2 bits are used by the detection nodes to inform the BS that it has successfully updated its clock.

b- Base Station packets:

- Clock info packet: As described in the time synchronization section the BS has to broadcast its clock regularly to the detection nodes. So, there is no need to specify the packet destination (to which detection node to be sent). In addition to a 1 bit BS ID, a 22 bit clock value is added to the packet. Minuets, seconds and milliseconds are included in the clock value sent inside the packet.

- BS acknowledgment packet: 2 bits are used by the BS to inform the detection node that it has successfully received its vehicle detection packet. Consequently, the BS has to send the packet to a specified destination. A 4 bit detection node ID is used for such a purpose. Whenever, a detection node received an acknowledgment packet from the BS, it will check the detection node ID to its ID, if they match then the packet is for it, otherwise it will discard it.

Figure 29 shows the different ICW packet structures.

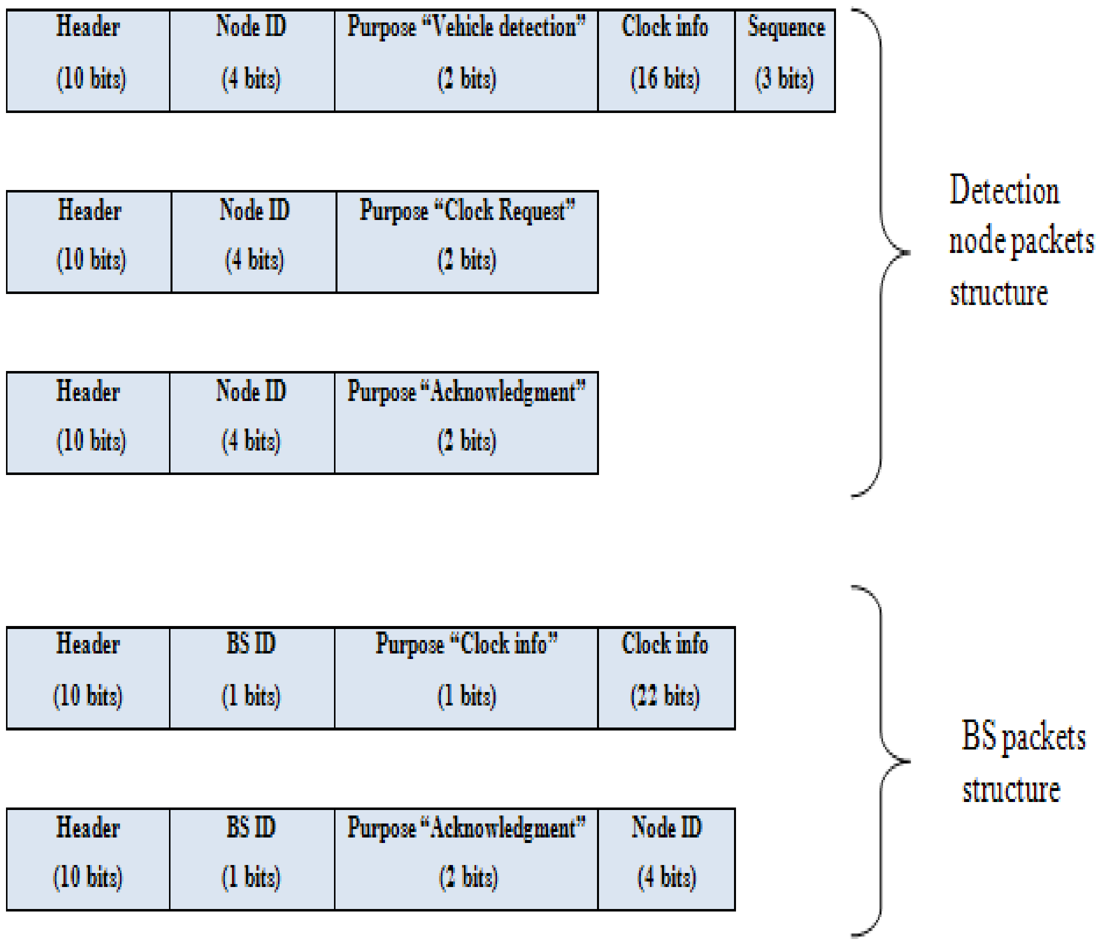


Figure 29: ICW Packets Structure

5 Simulation and Testing

In this chapter, important parameters that needed to be examined are presented. The accuracy of prediction using the 2nd order motion model is examined and compared to predictions derived from Kalman filters. The latency of the system is also examined to ensure the timely processing and transmission of warning signals. Finally, the overall system's performance, including vehicle detection, packet transmission, prediction processing, and transmission of a warning signal, is examined.

5.1 Kalman Filter Vs 2nd Order motion

The Kalman filter is one of the most widely-accepted position prediction algorithm used in navigation applications. To date, this application has been used extensively in many research studies [47]-[49]. Kalman filter is a recursive algorithm which uses previous noisy measurements combined with present measurement to estimate the future trajectory of a mobile object. The more measurements the Kalman filter uses, the better the estimation. In other words, the filter's prediction accuracy will be adversely affected if a low number of samples is used. As discussed earlier, ICW uses second dimensional motion equation to predict the time the vehicle will enter and exit the intersection. The following reasons are provided to justify the use of the 2^{nd} order motion model in our design. The complexity of the Kalman filter is much higher than the second dimension motion algorithm. A Kalman filter implementation can be found in [50]. Hence, Kalman filter requires more processing power, which needs faster processors with increased power consumption. Furthermore, the system is designed to provide only four position measurements, making Kalman filter performance comparable to that of the 2^{nd} order motion model.

To validate the second argument, a vehicle trajectory has been simulated. Position predictions using Kalman filter and 2nd order motion model are compared; Figure 30 and Figure 31 show the results of the trajectory accuracy simulations with and without position errors, respectively. The results shown in the Figures are the average of running the two simulations 100 times. In both simulations, a vehicle is approaching the intersection with a velocity of 45 mph and an acceleration of $1\ m/s^2$. In the simulation, the trajectory prediction starts after passing all four detection nodes. If the nodes are five meter apart and starting from zero as a reference, the vehicle must travel 20 meters in order for the prediction to start. However, in the first simulation (Figure 30) no errors are added, while in the second simulation (Figure 31), white Gaussian noise with a standard deviation of approximately 100 ms is added. It can be concluded that the accuracy of the Kalman and 2nd order model are about the same.

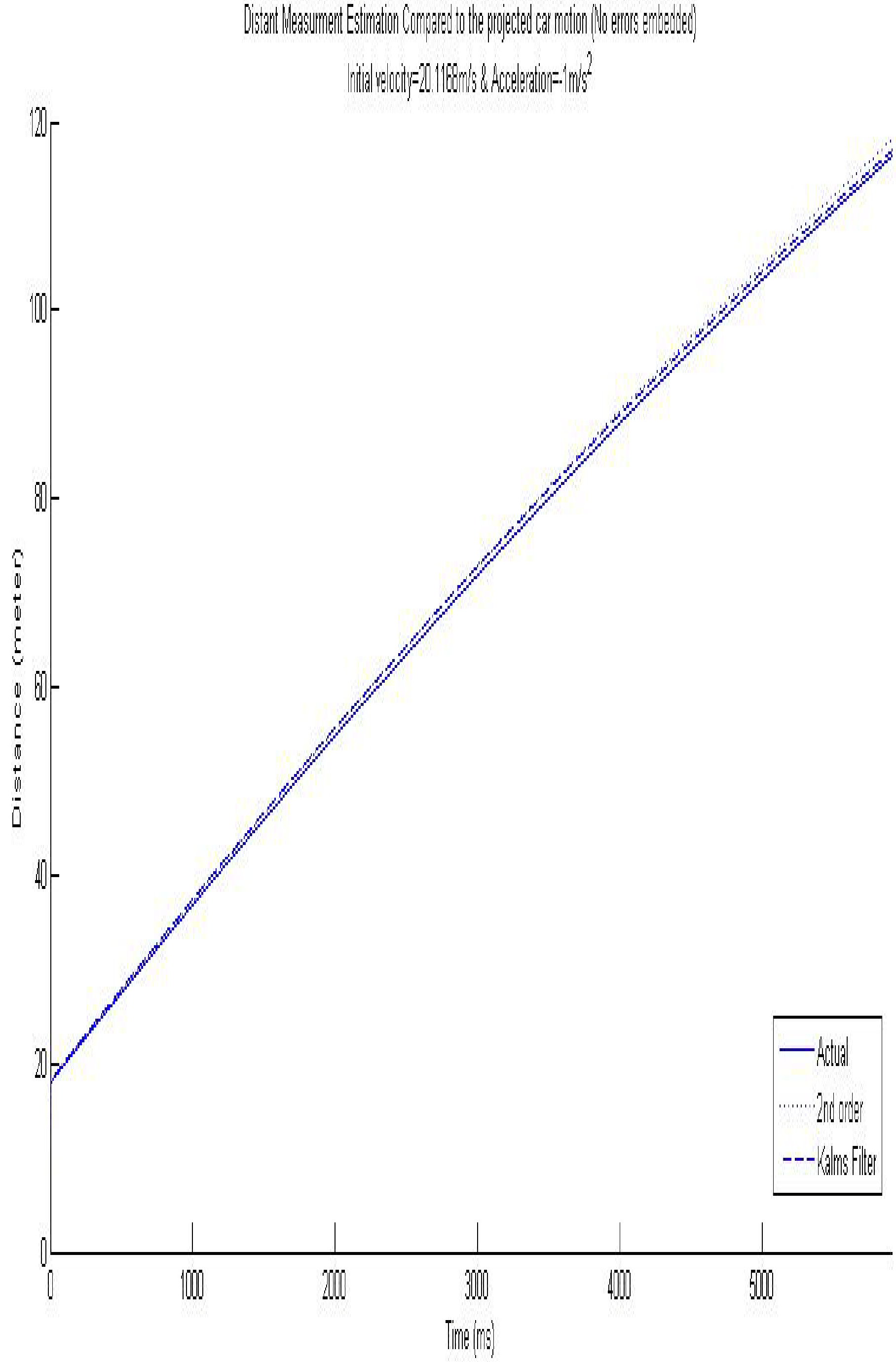


Figure 30: Predicted distance without errors (sampling rate=0.001, vi=20.1168 m/s, acceleration=-1m/s^2)

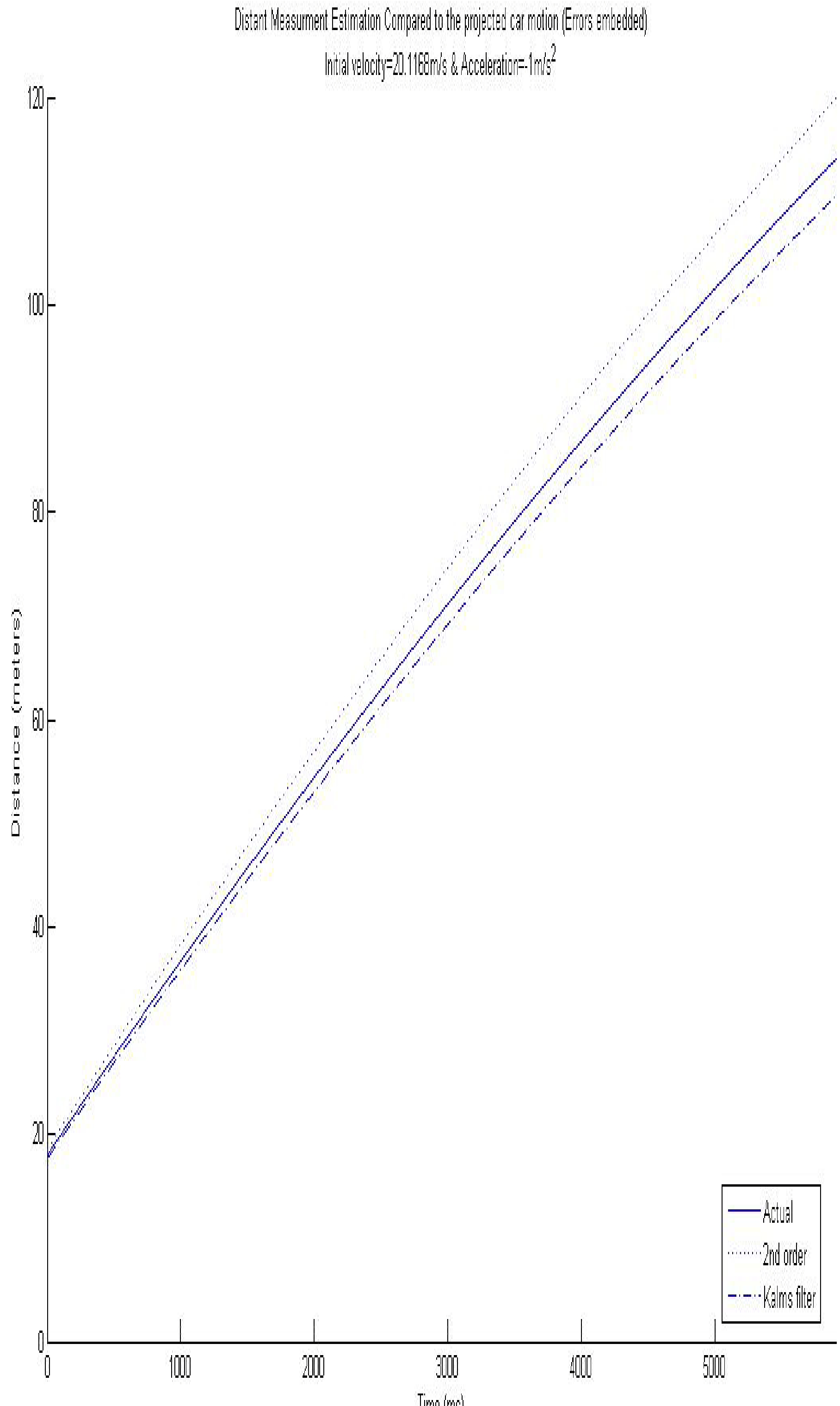


Figure 31: Predicted distance with errors (sampling rate=0.001, vi=20.1168 m/s, acceleration=-1m/s^2

5.2 Overall System Latency

5.2.1 Analysis and Results

The overall accuracy of early and effective warning of the ICW prior to imminent collision is the latency of the system, which includes system processing, transmission, and propagation times. The propagation time is calculated using the speed of light and signal travel distance between a system node and the base station. Using a maximum distance of 125 m, the time needed is approximately $4.17 * 10^{-7}$ seconds, which is considered negligible. The first tested latency is the transmission time. It refers to the time by which the packet of data traveled from the detection node to the BS. In order to test the transmission latency, the transceiver was placed on a loop mode. In other words, all packets transmitted will be received by the same transceiver. A timer is added to keep track of the time sent and received. With 100 tries, the maximum transmission latency was about 1.25ms. The resulted latency also takes into consideration the time by which the information is delivered into the microcontroller.

The final latency tested is the collision detection processing latency. For a real time collision avoidance system, the driver must have sufficient time to see the warning system and subsequently react, as well. Consequently, the processing time for collision should be as minimal as possible. This time reflects the "Vehicle Trajectory Prediction", "System Detection" and "Intersection Collision Avoidance and Warning System" methods discussed earlier in Chapter four. Through the use a timer, a trial testing comprised of 100 trials showed that by employing the selected microcontroller (PIC24FJ128GA010), a maximum of 100 ms is needed to estimate the time by which the each vehicle will enter and exit the intersection and, in addition, predict whether or not there is a collision. Table 9 presents the maximum latencies for the overall system.

Table 9: ICW system latency

System Description	Maximum Latency
Propagation Latency	Negligible
Transmission Latency	1.25 ms
Collision Detection Processing Latency	100 ms

5.3 Bit Error Rate Vs Distance

Bit error rate (BER) testing was performed to check the performance of the selected Wi.232DTS transceivers.

5.3.1 Testing Setup

Two Wi.232DTS radio transceivers were used for the testing. One was applied as base reference while the other was placed 110 m, 115 m, 120 m and 125 m away from the reference transceiver. The selected distances represent the distance detection nodes are away from the BS. The test was performed in windy conditions.

- Place/Date
  - Date: Monday, June 14th, 2009.
  - Place: University of Oklahoma, Tulsa. West Parking lot: Tulsa, OK.
- Requirements:
  - Two Wi.232DTS radio Transceivers
  - Batteries
  - Two Laptops with a Bit Error Rate Software

- Sonin 10300 Multi-Measure Combo PRO Professional Electronic Distance Measuring Tool w/Protective Pouch
- Honda Accord 2000 model.

➢ Setup 1
- Set the transmission power of the two transceivers to 10 dbm DTS.
- Place both transceivers on the ground with no vehicle interference.
- Assign one as a reference for measurement. Move the other horizontally 110 m away from the reference. The Sonin device is used for distance measurement. Transceiver placement is shown in Figure 32.
- At each location assign 1050 bits to be sent wirelessly through the transmitter. The packet should be in the following form: "…1010101010101…" Repeat the test 10 times. Check the received packets and calculate the Bit Error Rate for each test.
- Repeat the test, placing the second transceiver 115 m, 120 m 125 m, and then record the results.

➢ Setup 2
- Set the transmission power of the two transceivers to 15 dbm DTS.
- Place both transceivers on the ground with no vehicle interference.
- Assign one as a reference for measurement. Move the other horizontally 110 m away from the reference. The Sonin device is used for distance measurement. Transceivers placement is shown in Figure 32.
- At each location assign 1050 bits to be sent wirelessly through the transmitter. The packet should be in the following form:

"…1010101010101…" Repeat the test 10 times. Check the received packets and calculate the Bit Error Rate for each test.

- Repeat the test, placing the second transceiver 115 m, 120 m 125 m, and then record the results.

➢ Setup 3

- Set the transmission power of the two transceivers to 15 dbm DTS.
- Place both transceivers on the ground.
- Assign one as a reference for measurement and place the front axle of the Honda vehicle atop it. Move the other horizontally 110 m away from the reference. The Sonin device is used for distance measurement. Transceiver placement is shown in Figure 33.
- At each location assign 1050 bits to be sent wirelessly through the transmitter. The packet should be in the following form: "…1010101010101…" Repeat the test 10 times. Check the received packets and calculate the Bit Error Rate for each test.
- Repeat the test, placing the second transceiver 115 m, 120 m 125 m, and then record the results.

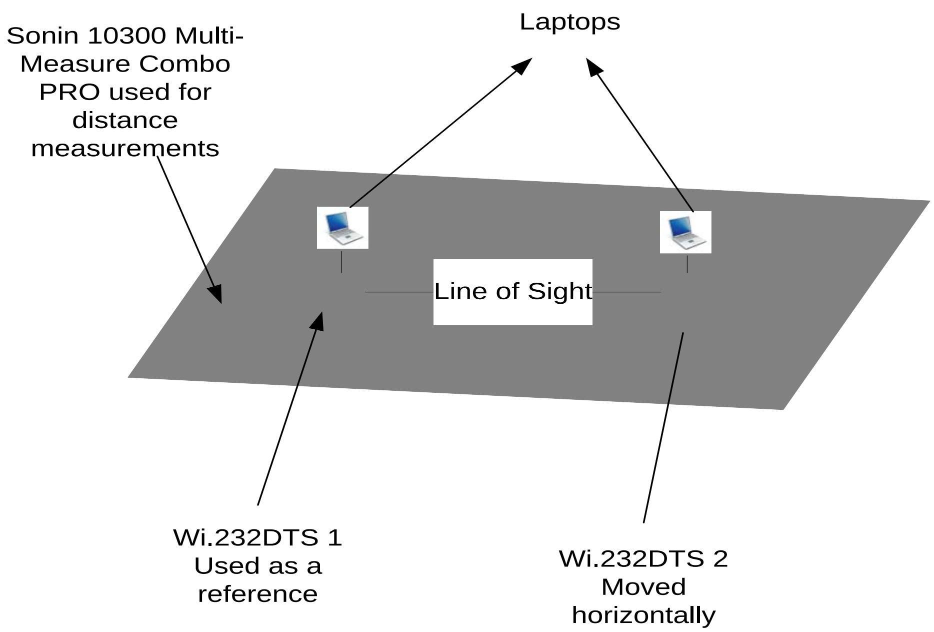


Figure 32: Transceivers placement for setup 1 and 2

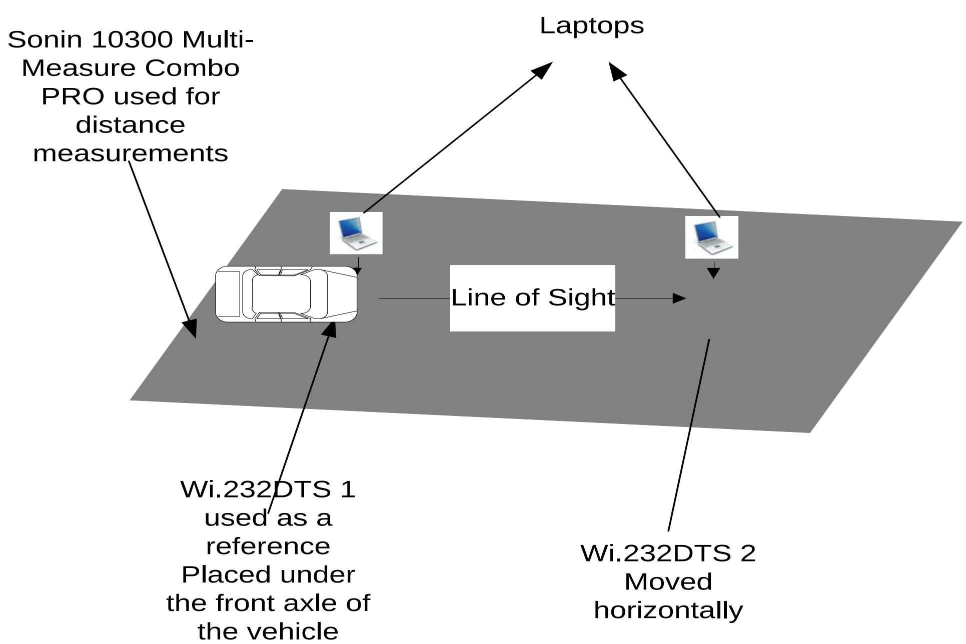


Figure 33: Transceivers placement for setup 3

5.3.2 Analysis and Results

BER determines whether or not the selected distance for the nodes is acceptable. Due to the importance of the message sent, the system cannot tolerate error. In wireless communication a BER of 10^{-3} is considered acceptable.

Figure 34 depicts the BER testing results. The first test was accomplished by setting the power of the transceivers to 10 dbm; nevertheless, the results show that with no vehicle interference on the selected detection nodes distance, the performance of the system was well below 10^{-3} . To improve the BER performance, transmission power was increased to 15dbm. It can be seen the performance was above average on all the selected distances with no vehicle interference. However, the vehicles are only detected when they are above the detection nodes. Consequently, a second test was conducted to test the effect of vehicle presence on the transceivers. As expected, vehicle interference will degrade the performance of the system. As seen in Figure 34, with transmission power of 15dbm added to vehicle interference, the BER increased by only a small margin, though it is still below applying 10 dbm as a transmission power.

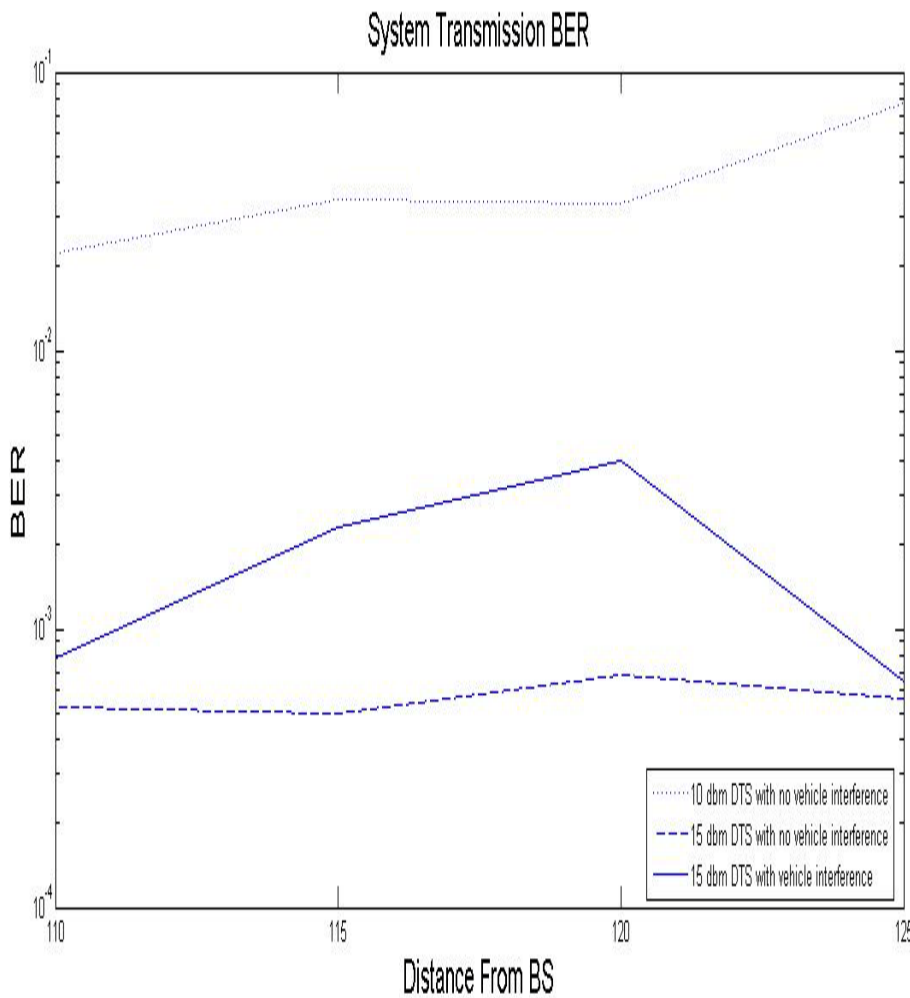


Figure 34: System transmission BER

5.4 System Collision detection performance

Due to safety concerns, testing of the ICW's collision detection performance is a complex task. However, simulation provides a good indication of the system behavior. Two simulations were made. In the first test, two colliding vehicles were simulated. This tested the system's ability to detect the collision. In the second test, the focus was to show the system's immunity to false detection. In this test, two vehicles advance through the intersection with no collision course. ICW must be able to recognize the vehicles and predict no collision behavior. Figure 35 depicts the overall testing setup.

5.4.1 Testing Setup

- Place/Date
  - Date: Monday, June 20th, 2009.
  - Place: University of Oklahoma, Tulsa. WECAD LAB: Tulsa, OK.
- Requirements:
  - Five Wi.232DTS radio Transceivers (w1,w2,w3,w4 & w5)
  - Six Explorer 16 Development Boards with PIC24FJ128GA010 as its primary microcontroller (e1, e2, e3, e4, e5 & e6).
  - Five 8 pin cross over cables
  - Bare Wires
- Setup 1 (Collision Detection)
  - Using cross over cables, connect each of the radio Transceivers to each of the Development Boards. Where w1 with e1 to become we1, w2 with E2 to become we2 ….. w5 with E5 to become we5.
  - Use we1- we4 as a detection node with we5 as a BS.
  - Using Digital I/O ports, connect the detection nodes with the remaining Explorer 16 Development e6 through two bare wires—one on the digital port, another on the ground.
  - Turn on the detection nodes and the BS. Manually activate the time synchronization algorithm by using one of the explorer board switches.
  - Use e6 to trigger the detection nodes as if detection has taken place. Each node is triggered twice: the first time to represent a car going through the minor lane; the second to represent a car advancing through the main lane.

The trigger timing should represent two cars going through minor and main lane, both with initial velocity 40 mph and -1 m/s^2 acceleration. For the two cars, the timing between the nodes should be as follows:

- we1 (node 1)→0
- we2 (node 2)→ 257 ms
- we3(node 3) →260 ms
- we4(node 4) → 264 ms

- When the trigger occurs on a detection node, it should send a time stamp and the node ID to we5 (BS) wirelessly through the transmitter. The BS should analyze the time stamps received wirelessly from the nodes and detect whether or not a collision will occur. However, for each detection node in the test, there will be two IDs. For example, the first trigger will be node 1, while the second will be node 5. In other words, each detection node represents two nodes: one in the minor lane and the other in the major lane.
- Check the LCD of the Explorer Board. If a warning message is sent, the system predicted collision; if not, there is no collision. In this case, a warning message should be displayed.
- Repeat the test 11 times.

➢ Setup 2 (Invulnerability to false detection)

- Using the cross over cables, connect each of the radio Transceivers to each of the Development Boards, where w1 with e1 becomes we1, w2 with E2 to become we2 ….. w5 with E5 to become we5.

- Use we1- we4 as a detection node, and we5 as a BS.
- Using Digital I/O ports, connect the detection nodes with the remaining Explorer 16 Development e6 through two bare wires: one on the digital port, another on the ground.
- Turn on the detection nodes and the BS. Manually activate the time synchronization algorithm by using one of the switches in the explorer boards.
- Use e6 to trigger the detection nodes as if detection has taken place. Each node is triggered twice: the first time to represent a car going through the minor lane, the other to represent a car going through the main lane. The trigger timing should represent two vehicles: one represents the trajectory of a vehicle passing through the minor lane at an initial velocity of 40 mph and -1 m/s^2 acceleration; the other represents a vehicle passing through the main lane at an initial velocity of 20 mph and -1 m/s^2 acceleration. The triggering timing is as follows:
    - Minor lane simulation (vehicle moving with initial velocity 40 mph and -1 m/s^2 acceleration)
        - we1 (node 1)→0
        - we2 (node 2)→ 257 ms
        - we3(node 3) →260 ms
        - we4(node 4) → 264 ms
    - Main lane simulation (vehicle moving with initial velocity 20 mph and -1 m/s^2 acceleration)

- we1 (node 1)→0
- we2 (node 2)→ 675 ms
- we3(node 3) →747 ms
- we4(node 4) → 848 ms

- When the trigger occurs on a detection node, the timestamp should be sent wirelessly with the node ID to we5 (BS) through the transmitter. The BS should analyze the time stamps received and detect whether or not a collision will occur. However, for each detection node test, there will be two IDs. For example, the first trigger will be node 1, while the second trigger will be node 5. In other words, each detection node represents two nodes: one in the minor lane and the other in the major lane.
- Check the LCD of the Explorer Board. A warning message signifies that the system predicted collision. With no vehicle interference, a warning message should not be displayed
- Repeat the test 11 times.

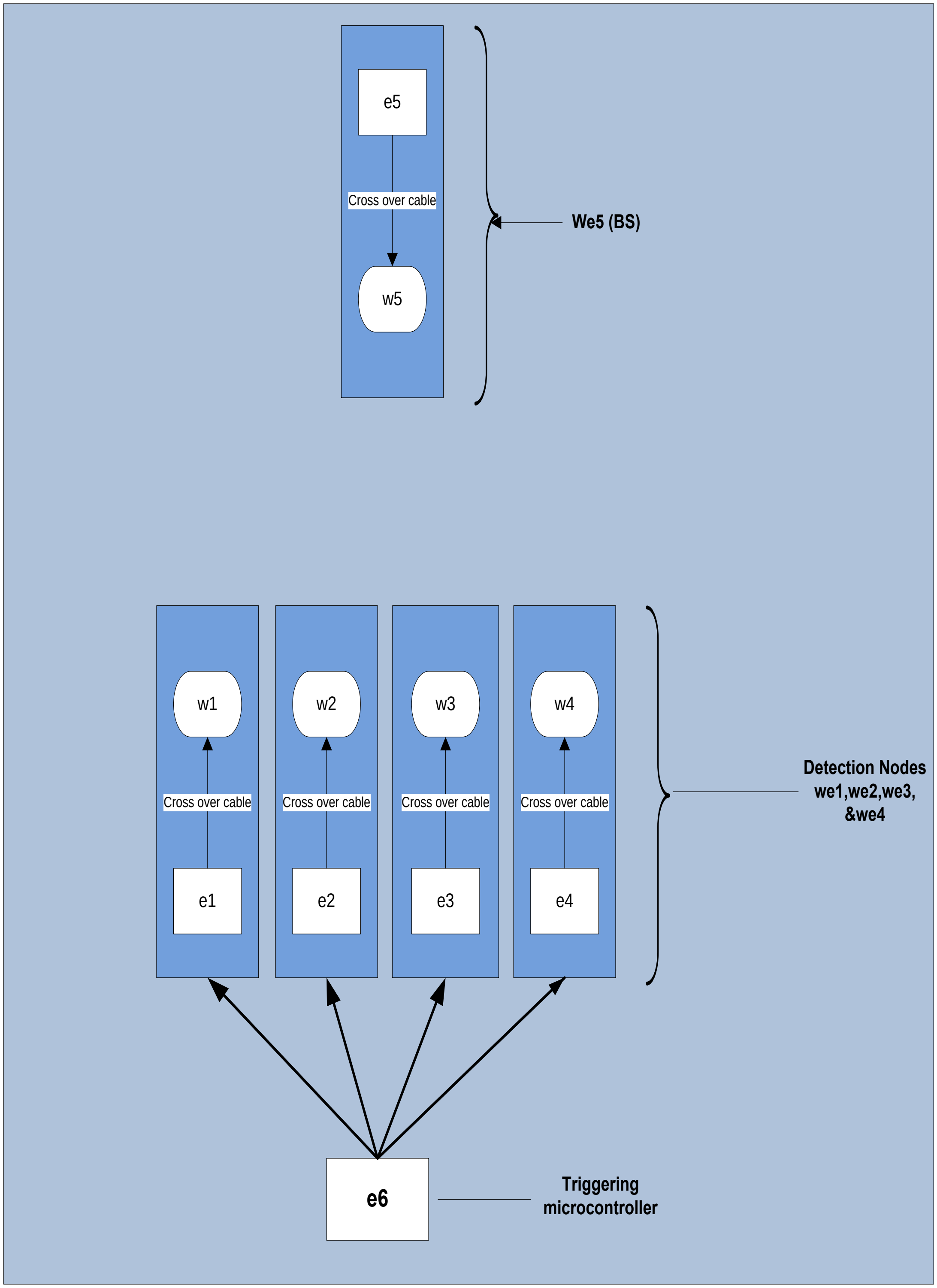


Figure 35: Collision detection testing Setup

5.4.2 Analysis and Results

Table 10 shows ICW effectiveness in the two scenarios presented. In the collision detection test, the system showed its capability to detect collisions and, accordingly, provide a warning. The system failed detection only once when a pointer was misplaced in the coding, causing misplacement of packets in the buffer of the BS. However, after this problem was fixed, consecutive testing for the same scenario resulted in successful functioning. In the false detection invulnerability test, the results showed the system immunity to false detection. In consecutive tests with detection, the system was able to comprehend that the two vehicles are safe to cross the intersection, and accordingly will not display a warning message.

Table 10: Collision detection testing results

Collision Detection Test				False Detection Invulnerability Test			
Trail	Test Results	Problems	Solution	Trail	Test Results	Problems	Solution
1	Failed	Buffer pointer was misplaced	Assigned the right pointer to buffer	1	Successful	n/a	n/a
2	Successful	n/a	n/a	2	Successful	n/a	n/a
3	Successful	n/a	n/a	3	Successful	n/a	n/a
4	Successful	n/a	n/a	4	Successful	n/a	n/a
5	Successful	n/a	n/a	5	Successful	n/a	n/a
6	Successful	n/a	n/a	6	Successful	n/a	n/a
7	Successful	n/a	n/a	7	Successful	n/a	n/a
8	Successful	n/a	n/a	8	Successful	n/a	n/a
9	Successful	n/a	n/a	9	Successful	n/a	n/a
10	Successful	n/a	n/a	10	Successful	n/a	n/a
11	Successful	n/a	n/a	11	Successful	n/a	n/a

6 REFERENCES

[1] Fatalities Analysis Reporting System - Encyclopedia, http://wwwfars.nhtsa.dot.gov/Main/index.aspx

[2] W. Jones, "Keeping Cars from Crashing," IEEE Spectrum, vol. 38, no 9, pp. 40-45, 2001.

[3] W. Jones, "Building Safer Cars," IEEE Spectrum, vol. 39, no. 1, pp. 82- 85, 2002

[4] J. Pierowicz, E. Jocoy, M. Lloyd, A. Bittner, and B. Pirson. "Intersection Collision Avoidance Using ITS Countermeasures." Technical Report DOT HS 809 171, NHTSA, U.S. DOT, September 2000. Final report.

[5] U.S. Department of Transportation – Federal Highway Administration and Institute of Transportation Engineers, Intersection Safety Briefing Sheets, USA, April 2004.

[6] Federal Highway Administration, http://mutcd.fhwa.dot.gov.

[7] Standard Highway Signs manual, 2004 Metric edition "http://mutcd.fhwa.dot.gov/SHSm/regulatory.pdf"

[8] US Department of Transportation. Manual on Uniform Traffic Control Devices, rev. 2Federal Highway Administration. 2007.

[9] Arizona Department of Transportation, "http://www.azdot.gov/Highways/traffic/Signal.asp#three"

[10] INTERSAFE, D40.4 Requirements for intersection safety applications, 28 Oct 2005.

[11] Giubbolini, L. (2000). "A multistatic microwave radar sensor for short range anticollision warning." Vehicular Technology, IEEE Transactions on 49(6): 2270-2275.

[12] Giancarlo, A., B. Alberto, et al. (2007). "Vehicle and Guard Rail Detection Using Radar and Vision Data Fusion." Intelligent Transportation Systems, IEEE Transactions on 8(1): 95-105.

[13] Dickmanns, E. D. (2002). The development of machine vision for road vehicles in the last decade. Intelligent Vehicle Symposium, 2002. IEEE.

[14] Wei-Chung, H., F. Li-Chen, et al. (2003). Vision based obstacle warning system for on-road driving. Intelligent Robots and Systems, 2003. (IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on.

[15] Gehrig, S. K. and F. J. Stein (2007). "Collision Avoidance for Vehicle-Following Systems." Intelligent Transportation Systems, IEEE Transactions on 8(2): 233-244.

[16] Jihua, H. and T. Han-Shue (2006). Design and implementation of a cooperative collision warning system. Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE.

[17] Shie-Yuan, W., C. Yow-Wei, et al. (2008). A Vehicle Collision Warning System Employing Vehicle-To-Infrastructure Communications. Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE.

[18] Kim, M., E. Lee, et al. (2006). Simulation of Intersection Collision Avoidance System in Wireless Sensor Networks. Geoscience and Remote Sensing Symposium, 2006. IGARSS 2006. IEEE International Conference on.

[19] Kyung Bok, S., Y. Jae Jun, et al. (2007). Collision Warning System on a Curved Road Using Wireless Sensor Networks. Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th.

[20] Menon, A., A. Gorjestani, et al. (2004). Roadside range sensors for intersection decision support. Intelligent Transportation Systems, 2004. Proceedings. The 7th International IEEE Conference on.

[21] Atev, S., O. Masoud, et al. (2005). A collision prediction system for traffic intersections. Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on.

[22] Ashkan Sharafsaleh, Ching-Yao Chan. "Experimental Evaluation of Commercially-off-the-Shelf Sensors for Intersection Decision Support Systems." Paper No. 1925. 12th World Congress on ITS, San Francisco. November 6-10, 2005.

[23] University of Minnesota Research: http://www.its.umn.edu/Research/

[24] Virginia Tech Transportation Institute: http://www.vtti.vt.edu/research.html

[25] King, T. I., W. J. Barnes, et al. (2007). A Wireless Sensor Network Architecture for Highway Intersection Collision Prevention. Intelligent Transportation Systems Conference, 2007. ITSC 2007. IEEE.

[26] Kyung Bok, S., Y. Jae Jun, et al. (2007). Collision Warning System on a Curved Road Using Wireless Sensor Networks. Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th.

[27] Sensys Networks, Inc., "The Sensys wireless vehicle detection system," System Overview, Berkley, CA, 2007.

[28] Road and Trail Intersection Safety "http://www.ptny.org/pdfs/greenways/road_trails/Road%20and%20Trail%20Intersectio %20Executive%20Summary.pdf "

[29] L. E. Mimbela, L. Klein. "A Summary of Vehicle Detection and Surveillance Technologies used in Intelligent Transportation Systems." Vehicle Detection Clearing House. August 31, 2007. http://www.nmsu.edu/~traffic/

[30] Traffic measurement and vehicle classification with a single magnetic sensor

[31] Application Note – AN218: Vehicle Detection Using AMR Sensors." Honeywell. Aug. 2005. http://www.ssec.honeywell.com/magnetic/datasheets/an218.pdf

[32] T. King, "A Warning System for Collision Avoidance at Highway Intersections", University of Oklahoma, Thesis. Electrical and Computer Engineering. 2006.

[33] Radiotronix, "Wi.232DTS-FCC-RA-R," radiotronix.com, Available: http://www.radiotronix.com/products/proddb.asp?ProdID=197

[34] AeroComm, "Product details: AC4790 900MHz peer-to-peer transceiver modules," aerocomm.com, Available: http://www.aerocomm.com/rf_transceiver_modules/ac4790_mesh-ready_transceiver.htm,

[35] Texas Instruments, "Z-Accel 2.4 GHz ZigBee Processor", Available: http://focus.ti.com/docs/prod/folders/print/cc2480a1.html

[36] JAVAD, "UHF902-928", Available: http://storage.javad.com/downloads/manuals/modems/UHF%20902_928.pdf

[37] PIC24FJ128GA010, "Product details: PIC24 16-bit Microcontroller Features," microchip.com, Available: http://www.microchip.com/wwwproducts/Devices.aspx?dDocName=en024805

[38] L. Itti, P. Baldi. "Bayesian Surprise Attracts Human Attention." Neural Information Processing Systems, 2005.

[39] "General Rules Techniques and Advice for All Drivers and Riders." 2004. highwaycode.gov.uk.

[40] Philip Koopman and Tridib Chakravarty *"Cyclic Redundancy Code (CRC) Polynomial Selection For Embedded Networks"*, The International Conference on Dependable Systems and Networks, DSN-2004

[41] Microchip, "Section 21. UART", available: http://ww1.microchip.com/downloads/en/DeviceDoc/61107D.pdf

[42] Serial and UART Tutorial, Available: http://www.freebsd.org/doc/en/articles/serial-uart/index.html

[43] Tianma TM162JCAWG1, Available: http://www.datasheetarchive.com/TM162JCAWG1-datasheet.html

[44] J. Polastre, R. Szewczyk, and D. E. Culler, "Telos: Enabling Ultra-Low Power Wireless Research," 4Th Intl. Conf. on Information Processing in Sensor Networks; Special track on Platform Tools and Design Methods for Network Embedded Sensors (IPSN '05/SPOTS)., 2005

[45] Bjornemo, E., M. Johansson, et al. (2007). Two Hops is One too Many in an Energy-Limited Wireless Sensor Network. Acoustics, Speech and Signal Processing, 2007. ICASSP 2007. IEEE International Conference on.

[46] Monson, Heidi (1999-12-14). "Bluetooth Technology and Implications". SysOpt.com.

[47] Messom, C. H., G. Sen Gupta, et al. (2003). Improving predictive control of a mobile robot: Application of image processing and Kalman filtering. Instrumentation and Measurement Technology Conference, 2003. IMTC '03. Proceedings of the 20th IEEE.

[48] Wang, L.-j., J.-k. Wang, et al. (2008). Location estimation of mobile user in wireless sensor network based on Unscented Kalman Filter. Microwave and Millimeter Wave Technology, 2008. ICMMT 2008. International Conference on.

[49] Yunpeng, Z., Z. Zhengjun, et al. (2008). An Extended Self-Adaptive Kalman Filtering Object Motion Prediction Model. Intelligent Information Hiding and Multimedia Signal Processing, 2008. IIHMSP '08 International Conference on.

[50] R. Brown, P. Hwang. Introduction to Random Signals and Applied Kalman Filtering, 2nd Ed. Wiley, New York. 1983. p. 230-236, 330-331.