GEORGIA DOT RESEARCH PROJECT 13-02

Final Report

IMPROVING TRANSPORTATION SAFETY FOR SUSTAINABLE ENVIRONMENTS USING VEHICULAR NETWORKING TECHNOLOGY

Georgia Department of Transportation

Office of Performance-based Management and Research
600 West Peachtree St. NW | Atlanta, GA 30308

1.Report No.: FHWA-GA-17-1302	2. Government Accession No.: N/A	3. Recipient's Catalog No.: N/A

4. Title and Subtitle: Improving Transportation Safety for Sustainable Environments Using Vehicular Networking Technology	5. Report Date: September 2016 6. Performing Organization Code: N/A
7. Author(s): Yusun Chang, Ph.D.; John A. Copeland, Ph.D.	8. Performing Organ. Report No.: 13-02
9. Performing Organization Name and Address: Kennesaw State University Southern Polytechnic College of Engineering and Engineering Technology 1100 S. Marietta Parkway, Marietta, GA. 30060	10. Work Unit No.: 11. Contract or Grant No.: PI# 0012666
12. Sponsoring Agency Name and Address: Georgia Department of Transportation Office of Performance-based Management and Research 600 West Peachtree St. NW Atlanta, GA, 30308	13. Type of Report and Period Covered: Final; March 2013 – September 2016 14. Sponsoring Agency Code: N/A

15. Supplementary Notes:

16. Abstract:
In this modern era, improving transportation safety became one of the most critical problems as the human, societal, environmental and economic losses from traffic accidents continue to grow rapidly in the recent years. A key initiative toward improving transportation safety is the introduction of Intelligent Transport System (ITS) whereby vital applications to spread safety messages on the road in real-time are being investigated to ensure road safety. This research provides novel and feasible solutions to disseminate these safety messages through connected Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications to improve the transportation safety. It also exploits the physical layer characteristics of the V2V safety messages in providing collision avoidance services through accurate detection of vehicles, pedestrians and other threats. In this research, novel algorithms and protocols enabling efficient and reliable communication between vehicles have been developed, tested and verified through real-world experiments in Georgia. The research findings and results presented in this report confirm the effectiveness of the proposed schemes in improving transportation safety, and reinforce the importance of the deployment of connected vehicle technologies for V2V and V2I communication in the state of Georgia.

17. Key Words: Vehicular Networks, Intelligent Transportation System, Connected Vehicle, Safety Message, Communication, Routing, Multi-Hop Broadcasting, Wireless, Transportation Safety, V2V, V2X, Road Side Unit, On-board Unit	18. Distribution Statement: No Restriction

19. Security Classification (of this report): Unclassified	20. Security classification (of this page): Unclassified	21. Number of Pages: 143	22. Price: Free

GDOT Research Project No. 13-02

Final Report

IMPROVING TRANSPORTATION SAFETY FOR SUSTAINABLE ENVIRONMENTS USING VEHICULAR NETWORKING TECHNOLOGY

Submitted by

Yusun Chang, Ph.D.
Associate Professor
Kennesaw State University
Electrical Engineering
Southern Polytechnic College of Engineering and Engineering Technology
1100 S. Marietta Parkway, Marietta, GA. 30060
Phone: (678) 915-7836, Email: yusun@kennesaw.edu

John. A. Copeland, Ph.D.
Professor
Georgia Institute of Technology
School of Electrical & Computer Engineering
Phone: (404) 894-5177, Email: jcopeland@ece.gatech.edu

Contract with

Georgia Department of Transportation

In cooperation with
U.S. Department of Transportation
Federal Highway Administration

September 2016

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Georgia Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation

ACKNOWLEDGMENT

The author would like to thank the Georgia Department of Transportation (GDOT) for its generous support. The work conducted in this report was sponsored by GDOT (Research Project 13-02). The author would like to acknowledge the Connected Vehicle Research Group for their invaluable input and support during this work.

EXECUTIVE SUMMARY

Over the past few years, the occurrence of enormous human, societal, environmental and economic losses due to traffic accidents has led to a search for highly innovative and practical solutions to improve safety on the roads. One such initiative is the introduction of Intelligent Transport System (ITS) area whereby a vital application is to ensure road safety by fast and reliable dissemination of safety/emergency messages. This research provides feasible solutions to disseminate these safety messages through connected Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications to improve transportation safety.

Through this research, a reliable platform/testbed has been developed. Novel algorithms have been designed, simulated, implemented and tested on Georgia highways as well as local roadways to verify the feasibility of the proposed methods. The research findings and results not only confirm the effectiveness of the proposed scheme in improving transportation safety but also reiterate the importance of the deployment of connected vehicle technologies for V2V and V2I communication in the state of Georgia. In addition, the proposed system also facilitates an efficient propagation and delivery of traffic-related information to the concerned authorities for real-time monitoring as well as for statistical analysis. Furthermore, many ITS applications for collision warning and avoidance can be also be readily incorporated into this system. As a result, this research provides a platform to dramatically reduce human causalities as well as lower the social, environmental and economical expenses.

TABLE OF CONTENTS

ACKNOWLEDGEMENT i

EXECUTIVE SUMMARY ii

TABLE OF CONTENTS iii

LIST OF FIGURES v

LIST OF TABLES viii

1. INTRODUCTION 1

2. LITERATURE REVIEW 5

    2.1. BACKGROUND 5

    2.2. PROBLEM 8

    2.3. RELATED WORKS 11

3. PROTOCOL DESCRIPTION 22

    3.1. MOTIVATION & CONTRIBUTION 22

    3.2. PROTOCOL DESIGN 23

    3.3. SUMMARY OF THE PROPOSED PROTOCOL DESIGN 29

    3.4. COMPARISON OF PROPOSED PROTOCOL WITH A TRADITIONAL MULTI-HOP ALGORITHM SB 32

4. THEORETICAL ANALYSIS 35

    4.1. THEORETICAL MODEL 35

    4.2. RESULTS & ANALYSIS 41

5. SIMULATION 52

6. EXPERIMENTATION 58

    6.1. EQUIPMENT & TEST-BED IMPLEMENTATION 58

6.2. PROGRAMMING GUIDE..59

6.3. FIELD TESTS IN STATIC AND DYNAMIC ENVIRONMENTS....................66

6.4. FIELD TEST RESULTS 68

7. DEMO..82

8. RECOMMENDATIONS..86

8.1.ANTENNA PLACEMENT 86

8.2.ROADSIDE UNIT PLACEMENT...87

8.3.MANUFACTURER 88

8.4.DEPLOYMENT REQUIREMENTS...89

8.5.DATA COLLECTION 91

8.6.COST 93

9. COLLISION AVOIDANCE..95

9.1.INTRODUCTION 95

9.2.DOPPLER DOMAIN ANALYSIS FOR COLLISION AVOIDANCE................96

9.3.RECEIVED SIGNAL STRENGTH BASED ON COLLISION AVOIDANCE 101

9.4.REDUCING FALSE ALARMS USING DOA 105

10. CONCLUSION..109

REFERENCES 110

APPENDICES 114

APPENDIX A: SAMPLE LOG DATA FROM AN OBU DURING A MULTI-HOP FIELD EXPERIMENTATION 114

APPENDIX B: AUTHOR’S RELATED PUBLICATIONS & POSTERS 125

LIST OF FIGURES

Figure 1 (A) V2V Communication, (B) V2I Communication......................................6

Figure 2 OFDM Sub-carrier Structure and IEEE 802.11p Frame 7

Figure 3 (A) Multi-hop V2P Communication, (B) Multi-hop V2V & V2I Communication 9

Figure 4 ESD Bitmap Construction 14

Figure 5 (A) Normal Rebroadcast Scenario, (B) ACK Decoupling and Recovery Process. 24

Figure 6 ACK Decoupling and Recovery Mechanism 27

Figure 7 Collision Resolution Mechanism (Not drawn to scale).................................28

Figure 8 Flow Chart Describing Key Design Steps at Each i-th Node.........................31

Figure 9 Timing Diagram – Normal Rebroadcast Scenario (Proposed Protocol vs. SB) 33

Figure 10 Timing Diagram – Collision Scenario (Proposed Protocol vs. SB)...............34

Figure 11 Highway Scenario 36

Figure 12 Average Per-Hop Rebroadcast Latency (Theoretical vs. Simulation Results) 42

Figure 13 Average Distance Progressed Per-Hop (Theoretical vs. Simulation) 44

Figure 14 Average Message Dissemination Speed (Theoretical vs. Simulation Results) 45

Figure 15 Effect of Changing Parameters on Per-Hop Delay 47

Figure 16 Effect of Changing *CWmax* Range on Per-Hop Delay 48

Figure 17 Effect of CWmax on Average Dissemination Speed 50

Figure 18 Effect of CW_{base} on Average Per-Hop Delay 53

Figure 19 Comparison of Per-Hop Delay (Proposed Protocol vs. SB) 55

Figure 20 Comparison of Max Throughput (Proposed Protocol vs. SB) 56

Figure 21 Snapshot of an Application being Developed in Eclipse IDE........................59

Figure 22 Eclipse Settings for Integrating Locomate in Eclipse Environment 60

Figure 23 List of Options for Parameter Setting in Multi-Hop EMD Application.........63

Figure 24 List of Options to Enable Different Printouts 64

Figure 25 Snapshot of a Particular Transmitted Packet..64

Figure 26 Snapshot of a Particular Received Packet 65

Figure 27 Single Hop: RSS vs. Distance 69

Figure 28 Indoor Experimentation: SNR vs. Distance 70

Figure 29 Indoor Experimentation: CWmax vs Distance...71

Figure 30 Indoor Experimentation: Per-hop Delay vs. Distance...................................72

Figure 31 Outdoor Static Experimentation: CW_{max} vs. Distance...................................74

Figure 32 Outdoor Static Experimentation: CW_{chosen} vs. Distance................................74

Figure 33 Outdoor Static Experimentation: Average Delay vs. Distance 75

Figure 34 Outdoor Multi-Hop Experimentation Topology 76

Figure 35 Outdoor Multi-Hop Experimentation: Average CW_{max} vs. Distance.............77

Figure 36 Per-Hop Delay for Outdoor Multi-Hop Experimentation 78

Figure 37 End-to-End Delay for Outdoor Multi-Hop Experimentation. 79

Figure 38 Distance Progressed by Various Safety Messages 80

Figure 39 MYSQL Database Containing Safety Messages Related Data 83

Figure 40 Live Map showing Multiple Emergency Events..84

Figure 41 Single Emergency Event 84

Figure 42 Attenuation due to Windshield Blockage..87

Figure 43 BSM Radar Map Development Simulation..92

Figure 44 Tracking Doppler Shift for Several Scenarios 98

Figure 45 Estimating Collision Likelihood from: A) Initial Detection Far-Away and B) At End of Decision Timer Duration 99

Figure 46 System Performance Under Multiple-Combinations 101

Figure 47 RSSI Trend between Two Cars for: Collision (Dashed, X's) and No-Collision (Solid, Circles) Outcomes in Three Pre-Crash Scenarios.............103

Figure 48 RSSI trends as recorded by Car A among multiple nodes for Rear End pre-crash scenario. If DOA is available, then RSSI values from Car C could be localized to the opposite lane to suppress a false-alarm and reduce prediction complexity among multiple nodes 106

Figure 49 RSSI Collision Prediction System...107

Figure 50 Performance Outcome for: A) LOS Rear End, and B) NLOS Straight Crossing Path (Intersection). 108

LIST OF TABLES

Table 1 BSM Data Fields 8

Table 2 Simulation Parameters...41

Table 3 D_i vs. SNR_i (GLIMPSE FROM THE DATA-SET).......................................46

Table 4 Simulation Parameters...52

Table 5 Data Gathered through the Reception of Safety Messages. 73

1. Introduction

According to US Department of Transportation (USDOT) statistics, the year 2011 alone recorded 5.3 million vehicular crashes resulting in 3.7 million property damage incidents, 2.2 million injuries, and 32,367 tragic fatalities [12] on top of an already massive $200 billion in societal damage annually [13]. This ever-increasing trend in societal, environmental and economic damages due to the enormous number of traffic accidents has resulted in the initiation of joint efforts by government, industry and academia to ensure road safety by exploiting innovative technologies. One such initiative is the introduction of Intelligent Transport System (ITS) [1], whereby one of the vital applications is to ensure road safety through efficient exchange of safety messages between the vehicles on the roads [2]. The Dedicated Short-Range Communications (DSRC) standards, developed for Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) communication, specify a dedicated channel for these time-sensitive safety messages [3]. This research project proposed a novel protocol that ensures fast and reliable dissemination of safety/emergency messages to the vehicles, infrastructure and pedestrians along the road. Such an exchange of messages will assist in preventing a significant proportion of crashes on the roadway, thereby reducing fatalities and injuries that occur each year.

Most existing research works exploit single-hop V2V or V2I communication. This kind of communication is easily established and provides many critical safety-related applications such as rear-end collision avoidance, head-on collision avoidance, and so on. However, several other applications require safety messages to be propagated well beyond the immediate transmission range to alert vehicles of hazardous driving situations. This communication is known as multi-hop vehicular communication. Through multi-hop vehicular communication, the vehicles further beyond the transmission range of the message-originating vehicle can be alerted well ahead of time about any potential collision or any other dangerous and unsafe conditions on the road. This proactive approach can help prevent a significant number of accidents. Fast and reliable multi-hop vehicular communication can also propagate traffic information to an infrastructure, which will then deliver the information to a central transportation management center for transportation analysis, operation and management.

However, disseminating safety messages efficiently to all the vehicles on the road using multi-hop communication is a challenging problem. Since no central administrator exists, propagation of messages through multi-hop becomes highly complex as multi-hop increases the chances of a message collision. This problem becomes severe in dense urban areas where a higher traffic volume results in excessive communication failures. These failures deteriorate the reliability of reception and overall message dissemination speed. It is therefore critical to develop innovative ideas for message routing in vehicular networks.

The major objectives of this research are to design, analyze, implement and test a safety/emergency message dissemination system using multi-hop vehicular communications for transportation and pedestrian safety. Some key features of this research include:

- Creating a reliable platform/test-bed to develop and experiment innovated networking technologies for V2V, V2I and V2P.
- Supporting ITS applications for collision warning and avoidance, traffic information propagation through vehicular communications.

- Performing statistical analysis of real-world data to optimize transportation traffic flows.
- Researching the impact and benefit of using new ITS technologies in sustainable environments to reduce air pollution and fuel consumption.

The benefits achieved through the successful completion of this research work are multi-fold. Firstly, the novel ideas established through this research have opened a new paradigm in transportation safety as human casualties, environmental and social expenses resulting from car accidents can be dramatically reduced. Secondly, by using state-of-the-art ITS technologies, the performance and management of transportation systems will be significantly improved. This research has also resulted in the successful development of a reliable test-bed at Georgia Institute of Technology and Kennesaw State University to aid in the implementation and experimentation of innovative V2V technologies and applications. The authors strongly believe that the research findings from this project will also contribute toward maintaining sustainable environments by reducing congestion and air pollution. Some of the key contributions of the research work are as follows:

1. A novel multi-hop algorithm to successfully disseminate the safety/emergency messages to vehicles, pedestrians and infrastructure
2. A state-of-the-art V2V multi-hop test-bed
3. Statistics and optimizations related to the safety/emergency message propagation process.
4. Recommendations for implementing V2V technology on Georgia highways.

The rest of the report is organized as follows: In Chapter 2, the background and related works are presented while Chapter 3 offers the protocol description. Chapter 4 presents the theoretical analysis and optimizations for the protocol, whereas simulation results are discussed in Chapter 5. Chapter 6, on the other hand, talks about the experimental setup, test-bed and results. In Chapter 7, a brief demo of the proposed protocol is shown. Chapter 8 offers some recommendations for implementing DSRC devices. In Chapter 9, a collision-avoidance scheme is described. Finally, the conclusion is presented toward the end.

2. Literature Review

As Dedicated Short-Range Communications (DSRC) standards become finalized, countries around the world are preparing to embrace the introduction of Intelligent Transportation System (ITS) protocols—collectively known as Vehicle-to-Everything (V2X)—to improve safety on the roads. In the United States, a combined effort from top American car manufacturers, the U.S. Department of Transportation (USDOT), state departments of transportation, and academia are working together toward effective integration of V2X protocols into the society. In fact, leading automobile manufacturing companies have already started producing vehicles equipped with DSRC devices to provide connectivity with other vehicles and infrastructure.

2.1. Background

All of the vehicles equipped with DSRC radios together would be able to form a Vehicular Ad-hoc Network (VANET). VANET—a specific type of mobile ad-hoc network (MANET)—is a group of vehicular nodes that spontaneously form a wireless network using 802.11p protocol for data exchange while moving on the road. Such networks have tremendous potential in enabling diverse applications related to traffic safety, traffic efficiency, and infotainment [25, 26 and 27].

In VANETs, communication can take place between the vehicular nodes as vehicle-to-vehicle (V2V) communication or between vehicles and infrastructure as vehicle-to-infrastructure (V2I) communication. An illustration of V2V and V2I communication is presented in Figure 1.

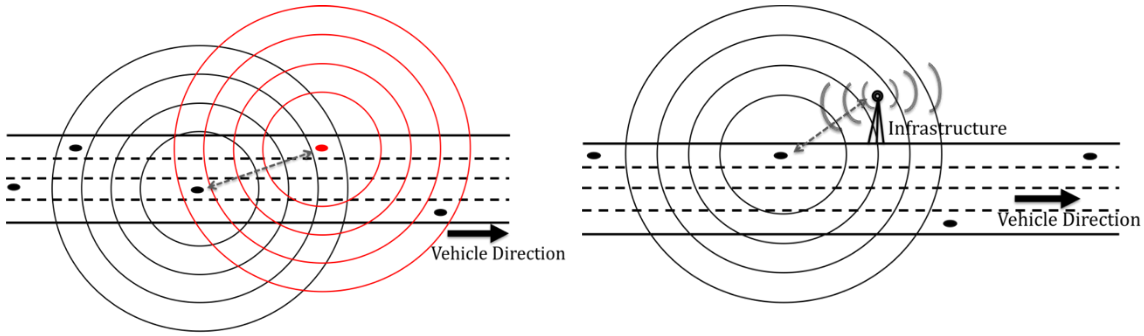


FIGURE 1

(A) V2V Communication, (B) V2I Communication

To improve the transportation safety, VANETs utilize the licensed ITS band of *5.9 GHz (5.85-5.925 GHz)* to exchange data between high-speed vehicles and between the vehicles and the roadside infrastructure. While safety is the main objective of this *75 MHz* freely available bandwidth, it also supports various other types of traffic and applications. Since this bandwidth is related to transportation safety, several standards specify the rules and regulations. Specifically, IEEE 802.11p and IEEE 1609 define rules of operation.

The IEEE 802.11p standard deals with the low-layer operations, such as medium access control (MAC) and physical (PHY) layers, while the IEEE 1609 standard regulates the operation of upper layers, such as network, security, and application layers. IEEE 802.11p is an enhancement of the generic IEEE 802.11 standard with an emphasis on providing special support for the communication between high-speed moving vehicles and road-side infrastructures.

The IEEE 1609 standards involve the following four components: IEEE 1609.1 for resource management, IEEE 1609.2 for security, IEEE 1609.3 for network and transport area services, and IEEE 1609.4 for multi-channel operation. The frequency spectrum consists of seven different channels where each channel has 10 MHz bandwidth. A channel specifically dedicated solely for safety purposes is known as a Control Channel (CCH). Six remaining channels, called Service Channels (SCH), are used for both safety and other applications, such as for infotainment and entertainment purposes. All V2X-enabled vehicles tune in to the CCH for *50* ms and then tune in to an SCH of choice for *50* ms. The cycle is continuously repeated.

The packets transmitted in V2X communication utilize Orthogonal Frequency Division Multiplexing (OFDM) that employs *48* sub-carriers to carry binary data through various modulation schemes. The IEEE 802.11p also outlines this OFDM frame structure with training symbols and guard intervals to precisely tune the received radio signal into the receiver of the V2X devices, as shown in Figure 2.

The CCH is primarily used for the periodic exchange of a basic safety message (BSM) containing real-time information about the transmitting vehicle's speed, steering wheel angle, Global Positioning Coordinates (GPS) and so on [4]. Table 1 describes the structure of a BSM, which generally ranges in size from *100 bytes* to *800 bytes*. The BSMs are exchanged at a frequency of *10 Hz*, i.e. *10 messages/sec/node.*

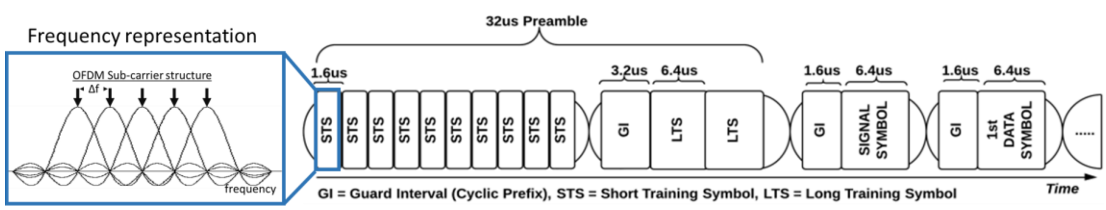


FIGURE 2

OFDM Sub-carrier Structure and IEEE 802.11p Frame

TABLE 1

BSM Data Fields

BSM Data Item	Type	Bytes	Part
Message ID	E	1	I
Message Count	E	1	I
Temporary ID	E	4	I
Time	E	2	I
Latitude	E	4	I
Longitude	E	4	I
Elevation	E	2	I
Positioning Accuracy	F	4	I
Transmission & Speed	F	2	I
Heading	E	2	I
Steering Wheel Angle	E	1	I
Accelerations	F	7	I
Brake System Status	F	2	I
Vehicle Size	F	3	I
Event Flags (opt)	E	2	II
Path History (opt)	F	Var.	II
Path Prediction (opt)	F	3	II
RTCM Package (opt)	F	Var.	II
Total Bytes		**44**	

Vehicles exchange BSMs to warn each other of an impending collision or a hazardous situation, and for preemptive safety measures. The operation of BSM exchange among vehicles is defined in the following standards: IEEE 1609 [5] and IEEE 802.11p [6]. Furthermore, the CCH is also used for WAVE Service Announcements (WSA) to announce the available services on the various SCH.

2.2. Problem

In VANETS, a lot of safety applications rely on sharing safety/emergency messages. This process of exchanging such messages is often referred to as Emergency Message Dissemination (EMD). Since the successful transmission of a safety message is often directed for all nodes in the target region well beyond the one-hop communication range of the source node, multi-hop communication is imminent. Figure 3 illustrates such critical multi-hop applications where safety messages are propagated along the road.

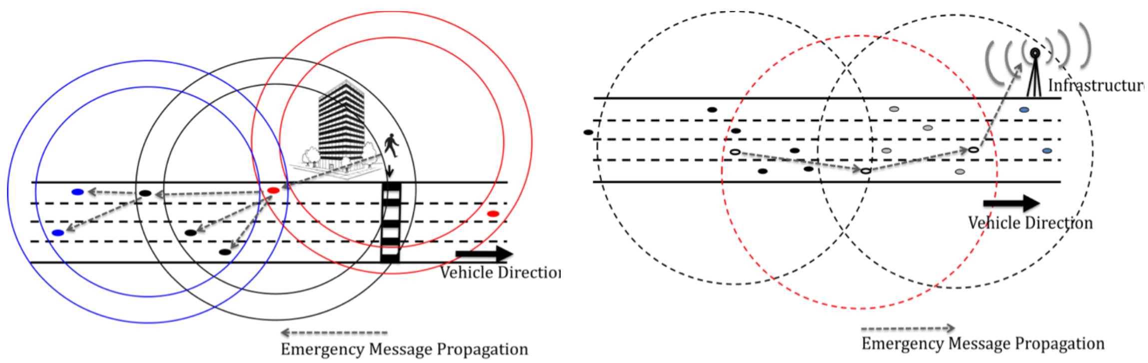


FIGURE 3

(A) Multi-hop V2P Communication, (B) Multi-hop V2V & V2I Communication

Among many interesting applications in transportation safety, EMD is especially essential when a driver in an emergency vehicle would want to warn all drivers in front of it so that a clear roadway is secured. Sometimes, the driver of a leading vehicle observing an obstacle or pedestrian in the middle of the road would want to transmit a notification message backward to warn the drivers of upcoming dangers. To better assist these critical applications of multi-hop safety message exchange, a DSRC Basic Safety Message (BSM) [1] is generally utilized to share traffic information such as the direction the vehicle is headed, its speed, the lane of traffic it is in, its GPS coordinates, a Time/Date stamp, the Original Sender ID, and the Retransmitted ID.

The DSRC standards have described a dedicated channel for the exchange of these time-sensitive safety messages [1]. For instance, an ambulance approaching a congested roadway needs to be able to notify the vehicles on the road of its location quickly so they can make space for the emergency vehicle. Currently, the US DOT has reviewed

Emergency Vehicle Preemption technologies deployed in several states that allow traffic lights to be adjusted to smooth the flow of traffic for ambulances to maneuver through RITA [2]. However, the concept of emergency vehicles being able to notify other vehicles will be more feasible once the DSRC radios are installed on the vehicles on a massive scale and all the required standards become finalized.

Considering the highly dynamic topology that VANETs could encounter, the common data transmission based on table routing and acknowledgments is highly inefficient and exhibits low throughput. Under normal networking connections, it would take a significant amount of time just to establish a stable connection among vehicles, build routing tables, and finish transmitting packets to their desired destinations. This entire process is highly infeasible for time critical safety message. While some non-emergency applications using DSRC radios may find this type of routing adequate, emergency message dissemination through Ad-hoc V2V connections in VANETs requires a more reactive packet delivery mechanism.

Hence, this problem of efficient routing and dissemination of safety/emergency messages in a VANET is indeed very challenging, and this research aims to address these challenges. To put it simply, the general way in which the emergency message can be propagated in the VANET is that the emergency message initiator broadcasts the message to everyone within its transmission range. Following this, one or more nodes within the transmission range are selected as forwarders, and they rebroadcast the safety message. This process is repeated until the safety message is disseminated in the entire VANET topology.

2.3. Related Works

There are several protocols that have been researched and developed to ensure fast and reliable dissemination of safety messages in a VANET environment. In this section, we present a discussion of some of the key protocols in the literature.

A. Urban Multi-Hop Broadcasting (UMB)

One of the original broadcasting schemes that were developed for VANETS is called Urban Multi-Hop Broadcasting (UMB)[5]. It is based on a sectional division of the road dependent on the distance from the original sender. The original sender will send out a Request to Broadcast (RTB) message. Each node within range will then self-calculate what section the node is in and begin sending out a jamming signal. A jamming signal for UMB is a continuous transmission with the furthest node having the longest jamming signal. In other words, the jamming signal is shorter as the nodes get closer to the original sender. If the closer nodes stop transmitting a jamming signal and the sender continues to overhear a jamming signal, then they will know that another node exists farther than the closer nodes. When the farthest node stops transmission of the jamming signal, it will send a Clear to Broadcast (CTB) packet to the original sender. This CTB packet will alert the original sender that it is ready to receive the data packet to be forwarded. Afterward, an acknowledgment (ACK) will be transmitted to end the process. UMB further discusses the separation of sections if two nodes collide on the CTB. This allows the sections to be shorter and therefore reduces the risk that two nodes are colliding when forwarding the message.

UMB inherently contains several pitfalls that need to be addressed and corrected.

The first pitfall is that the jamming signal prevents any other nodes within range to continue normal data exchange between each other as the channel will be flooded. Secondly, in a high traffic zone, the further separation of nodes may prove to be useless if two vehicles are side by side. This would mean that both vehicles are always going to be in the same section. Lastly, there are several other minute issues, such as the transmission delay and throughput that would be degraded due to the nature of the protocol. Hence, another protocol that was developed to try and correct some of these issues is called Smart Broadcast.

B. Smart Broadcast (SB)

Smart Broadcast (SB)[2] is an enhancement of UMB with a similar sectional divide. The main difference between UMB and SB is that SB assigns contention windows time slots based on which "sector" each node is in, as opposed to the UMB's jamming signal. SB is designed to use a random backoff timer based on the maximum contention window time slots available for each sector. The nodes calculate a set to choose a random waiting time by using equation (2.1) to calculate the maximum amount of slots. *Cw* is the duration of each contention window, and *r* is the sector that each node is located in. It is important to note that *r* = 1 represents the outermost sector.

$$W_r = \{(r-1)_{cw}, (r-1)_{cw+1}, \dots, r_{cw} - 1\}[2] \tag{2.1}$$

Additionally, SB has improved on the dynamics of the sectors by using additional sectors if traffic density is high. It is done with the periodic usage of heartbeat messages to gather information about traffic density; however, the main functionality of SB is similar to that of UMB. The sender uses an RTB message and will wait for a CTB message, at which point it will send out the data message to be forwarded. In the case of a CTB collision, the process begins again, and the sectors are further divided. SB also requires the transmission of an overheard message, ACK. A few noticeable downsides to SB is that it continues to use CTB/RTB messages, similar to UMB. Additionally, if two vehicles are in the same sector, their maximum set is identical. SB adds a random choice to reduce the possibility of collision; however, this is done from the same maximum set.

C. SNR based Linear Back-Off Protocol

One of the first pieces of literature to include SNR-based forwarder selection is called “A Simple SNR Based Linear Back-Off to Propagate Multi-hop Emergency Messages on the Distributed VANETs.”[9] The paper describes a timer backoff forwarder selection based on the SNR levels. From the literature, it is assumed, though not directly specified, that if the SNR level is lower, then it gets a lower backoff time and will forward the message first. Additionally, the paper discusses the removal of CTB/RTB packets. Furthermore, it also mentions that additional nodes waiting to rebroadcast would cancel the rebroadcast if the rebroadcast message is overheard. However, the paper does not give any indication of how a forwarder is selected or how long the backoff times would be for any of the nodes. Some inherent problems that were not covered are that SNR does not necessarily signify the furthest distance. Sometimes, a node reception can be blocked due to a larger vehicle being positioned between it and the sender. This would cause the SNR to drop significantly. This research does not discuss the possibility of collisions and how to resolve them, but it does provide insight into using a different standard beyond GPS. This is an important aspect when considering that a vehicle may encounter areas where GPS is not reachable, such as tunnels.

D. ROFF: RObust and Fast Forwarding in Vehicular Ad-Hoc Networks

One unique and more recent publication called "Robust and Fast Forwarding in Vehicular Ad-Hoc Networks" (ROFF)[16] discusses the usage of Empty Space Distribution (ESD) bitmapping to reduce the wasted wait time caused by empty spaces between one node and another contending to be a forwarder. The construction of the bitmap is based on continuous knowledge of the neighboring nodes inserted in a "neighbor table," called NBT[6]. NBT provides continuous monitoring of a node's local view to the other nodes. The NBT allows nodes to be set as Potential Forwarder Candidates (PFC)[6]. In ROFF, PFCs are advertised as an ESD bitmap.

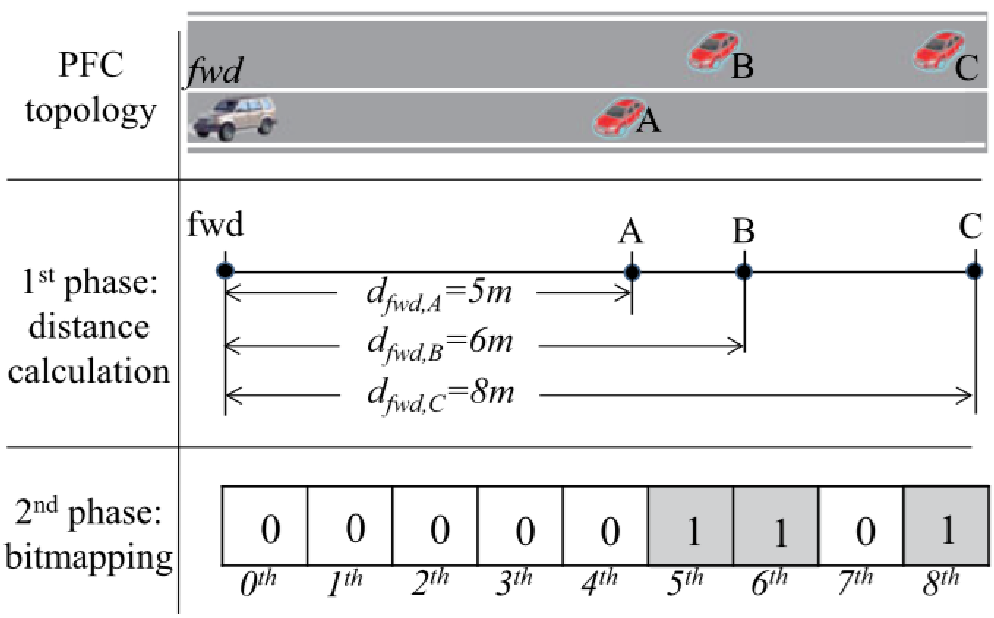


FIGURE 4

ESD Bitmap Construction.

The ESD bitmap construction process is illustrated in Figure 4[6]. The first phase considers distance in meters from the forwarding node (*fwd*), whereas the second phase is an actual bitmap divided into sectors with a bit set to 1 if the node is a PFC. The waiting time is found by using equation (2.2). To avoid transmission collisions caused by the short waiting time difference, *minDiff* is used, which denotes the minimum difference between the waiting times of two neighboring vehicles.

$$WT_{PFC(k)} = \sum_{i=2}^{k} minDiff_{PFC(i),PFC(i-1)} (k \geq 2) \tag{2.2}$$

ROFF is designed to reduce the waiting time wasted by vehicles that share no information with each other. One assumption ROFF uses is that the continuous reception of beacon messages can be used to build an ESD bitmap. Unfortunately, this does not always happen, and if additional beacon messages are sent, network traffic congestion may increase.

E. OppCast: Opportunistic Broadcast of Warning Messages in VANETs

OppCast[7] is a double-phased broadcasting protocol that attempts to resolve two main dilemmas. First, the fast forward dissemination is based on selecting the furthest forwarder in the "boundary range" (BR). This would allow further dissemination of the message. The literature does not cover the exact syntax as to how a forwarder is selected between other nodes next to it or how the actual message is transmitted.

The second phase, named "makeup-for-reliability," is based on a binary tree methodology of selecting other nodes within the one-hop range to provide the message to the nodes, which may have missed the opportunity to receive the message during forwarding. This is performed in parallel to the message transmission and, therefore, does not affect the message propagation speed. The main focus of performing the makeup-for-reliability phase is to improve the packet reception rate (PRR). This means that all nodes would be able to receive all messages. A few limitations to this would be the fact that the forwarder selection is seemingly distance-based, and the parallel makeup-for-reliability phase may cause unnecessary network traffic, causing possible collisions. However, it does provide a good approach to removing the hidden node terminal problem in VANETs.

F. Instant Broadcast (IB)

To compare the difference between handshaking protocols and non-handshaking protocols, the paper entitled "Handshaking vs. Instant Broadcast in VANET Safety Message Routing"[4] provides calculations and simulations of a modified version of Smart Broadcast that uses no handshaking mechanisms, such as RTC or CTB. Instant Broadcast uses a similar sectional divide of the road where vehicles pertaining to different sectors are given a different maximum slot time to choose from. The outermost sectors will provide the smallest amount of items in a set. This provides a higher probability of randomly choosing a smaller waiting period for rebroadcasting.

Instant broadcast uses equation (2.3) to calculate the delay used in comparing the simulated results of UMB, SB, and IB. Where X is the mean number of retransmission attempts. X is defined by equation (2.4). Let *Ps* be the probability of successfully transmitting a message and *Ptr* be the probability that transmission occurs between nodes[4].

$$E[D] = E[d]X \tag{2.3}$$

$$X = \sum_{n=0}^{W-1} \left(1 - P_s \cdot P_{tr}\right)^n P_s \cdot P_{tr} n \qquad (2.4)$$

The simulation was performed in Network Simulator, and the paper demonstrates a significant improvement by simply removing the handshaking mechanism. This paper demonstrates an improvement, but it is limited to distance-based forwarder selection. Furthermore, it does not cover the possibility that the original sender may not overhear the rebroadcasted message.

G. Routing in Sparse Vehicular Ad-Hoc Wireless Networks

To encourage research in the VANET community, literature such as "Routing in Sparse Vehicular Ad Hoc Wireless Networks"[17] was published to study past routing protocols using empirical traffic data collected on I-80 in California. The main focus of the publication is to calculate the time it would take to propagate a message to disconnected nodes called "re-healing time"[17]. Disconnected nodes are defined as nodes that are not within range due to the scarcity of traffic.

The average re-healing time is several seconds to a few minutes. This is an important discovery because new protocols would have to keep in mind a certain time to maintain data for forwarding. Other protocols may be able to use a multi-hop protocol to more quickly penetrate the environment, reducing the re-healing time. Unfortunately, without prior knowledge of nodes that are disconnected, there may be no other way but to define a certain time to keep data and retransmit when a disconnected node is detected.

H. Efficient Directional Broadcast

Efficient Directional Broadcast (EDB)[18] is an additional protocol that uses a distance-based broadcasting scheme, and it was published in the article, “A Distance-based Directional Broadcast Protocol for Urban Vehicular Ad Hoc Networks”[18]. It uses equation (2.5) to determine the waiting period.

$$W = \left(1 - \frac{d}{R}\right) maxWT \tag{2.5}$$

It is a linear based equation that divides the node distance by the maximum distance. D is the max range, whereas d is the node distance from the sender. This is multiplied by the maximum waiting period allowable to determine how long each node will take to rebroadcast.

The paper further describes the transmission of an ACK as a confirmation that a node will further the message. This is done to remove any other nodes in a range from contending to forward the message. Once this is done, the message will be forwarded, and the process will be repeated. Additionally, this process removed the need for handshaking by removing the need for RTB/CTB. Overall, the protocol improves on SB by removing the concept of sectors, but it does not allow room for mistakes in experimentation if the device range is not ideal. Furthermore, the additional ACK transmission reduces performance a little, but it increases reliability by reducing possible collisions; however, this does not mean ACK collisions are avoidable.

I. Weighted p-Persistence

In addition to distance-based forwarder selection, the literature discusses the use of probability-based algorithms to have forwarders selected based on the probability they are the most ideal. One of the most direct ways of doing this is by using the distance between a node and the transmitter. Weighted p-Persistence[19] does this using a very similar formula of distance divided by the total range. Based on this probability, the vehicles at the outermost distance will have a higher probability of being picked. The formula Weighted p-Persistence uses is equation (2.6), where *D* is the distance between node *i* and *j*, and R is the range.

$$P_{ij} = \frac{D_{ij}}{R} \tag{2.6}$$

This is one method for forwarding a message, and it shows that several distance-based protocols are similar in that the ratio of distance over the maximum range is used. Again, some limitations are that the range may change in live experimentation, and the potential for collision is increased as road traffic increases.

J. Optimized Adaptive Probabilistic Broadcast (OAPB)

Several other probability-based algorithms have been developed. An improved protocol of Weighted p-Persistence is called Optimized Adaptive Probabilistic Broadcast (OAPB)[20]. The aim of OAPB is to provide a more in-depth forwarding probability based on the surrounding node density. Based on equation (2.7), the protocol will use "HELLO" packets, or regular packets, to calculate the forwarding probability.

$$\overline{\emptyset} = \frac{P_0 + P_1 + P_2}{3} \tag{2.7}$$

P_0, P_1, P_2 represent one-hop, two-hop, and a combination of two-hop neighboring nodes through a one-hop neighbor. To further enhance and correct situations where vehicles have the same probability to be forwarders, the protocol provides a delay, which is calculated with equation (2.8). $\Delta(t)$ is the maximum wait time, and δ is a randomly generated variable in the order of milliseconds.

$$\Delta(t) = \Delta(t)_{max} \times \left(1 - \overline{\emptyset}\right) + \delta \tag{2.8}$$

OAPB is definitely an improvement over the Weighted p-Persistence because it gathers information about the surrounding environment, such as where nodes are in relation to each other. Additionally, it combines a probability-based algorithm with a delay-based algorithm to ensure fewer possibilities of collision. The pitfalls of the algorithm are that it is dependent on heartbeat messages to be transmitted periodically. Furthermore, it requires all surrounding nodes to maintain constant updates of their surrounding nodes and their probability factors. This could add significant overhead to the messages needed to be shared.

K. Autocast

An additional probability-based algorithm is called Autocast[21]. Similarly, Autocast, is based on the nodes in the vicinity. The probability is determined with equation (2.9), where Nh is the one-hop nodes within range.

$$P = \frac{2}{N^h \times 0.4} \tag{2.9}$$

One difference between Autocast and OAPB is that it does not make use of a delay for nodes with a similar rebroadcast probability. Therefore, the usage of periodic rebroadcasting is necessary to make sure messages are propagating correctly. This is something that would increase the network traffic and possibly cause an unnecessary broadcasting storm. “Broadcasting storm” is the term used for continuous broadcast message flooding[19].

There are many more protocols developed to help assist in the rapid dynamics of VANET, but they are not listed here due to space constraints. In summary, due to the speeds at which vehicles travel and properties of VANETs, network communication has to be quick and reliable.

3. Protocol Description

This chapter describes the key design principles of the proposed multi-hop broadcasting protocol [11], [30], [31]. The few main contributions of this algorithm, which will be explained further in this chapter, are to reduce the channel access time by removing the handshaking mechanisms (i.e., RTB/CTB) preceding the safety message transmission, to minimize the message propagation delay by either eliminating the ACK-ing process or at least decoupling the message propagation process from ACKs to the sender, and to quickly recover from collisions using a novel collision resolution mechanism.

3.1. Motivation and Contribution

When considering safety messages, reliability and speed are by far the most important parameters. They are especially essential considering the highly dynamic nature of the VANET environment. Therefore, the rapid propagation of safety messages in a reliable manner is one of the biggest challenges for a multi-hop algorithm. As common broadcasting schemes use geographical information (i.e. GPS coordinates) in the forwarder selection process [5], [2], [6], [7], [8], [18], they are not very reliable and accurate as they don't consider terrain interference, signal characteristics, GPS errors, malicious nodes injecting false GPS values and so on. To counter this, the proposed approach employs the use of SNR together with GPS coordinates in the forwarder selection process. Additionally, traditional VANET broadcasting algorithms, such as UMB [5] and SB [2], use handshaking mechanisms (RTB/CTB) before broadcasting the safety message and ACKs afterward. This sequential process introduces overheads and, thus, reduces the message dissemination speed. Therefore, the proposed algorithm removes the need for these costly handshaking mechanisms as well as decouples ACKs from the message dissemination process. The proposed protocol also suggests a novel and improved collision resolution mechanism.

3.2. Protocol Design

As discussed earlier, in the proposed multi-hop algorithm, the handshake process (exchange of RTB/CTB packets) prior to broadcasting the safety message is entirely removed. The original sender (safety message initiator) simply accesses the medium using the standard 802.11 CSMA/CA technique and broadcasts the entire safety message. Each neighboring node *i* in the vicinity of the sender (i.e. within the transmission range *R* of the sender) calculates its corresponding SNR value (SNR_i) as well as its Euclidean distance (D_i) from the sender by using the GPS coordinates. Each receiver then uses these calculations to compute their specific maximum contention window sizes (CW_{max}) according to the following formula:

$$CW_{max,i} = k\,\frac{D_{max}}{D_i}\,CW_{base}^{\frac{(SNR_i - SNR_{thresh})}{\alpha dB}} \tag{3.1}$$

In the equation (3.1), *k* is a scaling factor to contain CW_{max} values within a suitable range (the contention window range is typically *[0, 1023]* but could be optimized under different traffic conditions as explored later in the report), D_{max} (or *R*) is the maximum transmission range of the sender, SNR_{thresh} is the minimum SNR threshold value for reliable transmission, α is the exponential scaling factor to effectively accommodate the effect of SNR_i while determining CW_{max} , and CW_{base} is the contention window base value that can be optimized based on the density of the network.

After each node calculates its CW_{max}, it randomly chooses a time slot in the range *[0,* CW_{max}*]* and waits for that amount of slot times. This randomly selected time slot is also known as CW_{chosen}. The node that chooses the earliest time slot wins the contention and is chosen as the forwarder, hence rebroadcasting the safety message. All other contending nodes, after hearing this rebroadcast message, drop out of the rebroadcasting race. The rebroadcast message from the forwarder serves the purpose of an implicit acknowledgment back to the original sender from the forwarder since the broadcast is omnidirectional. This mechanism of forwarder selection and rebroadcasting the safety message (which also acts as an implicit ACK to the sender as described above) is portrayed by Figure 5(A).

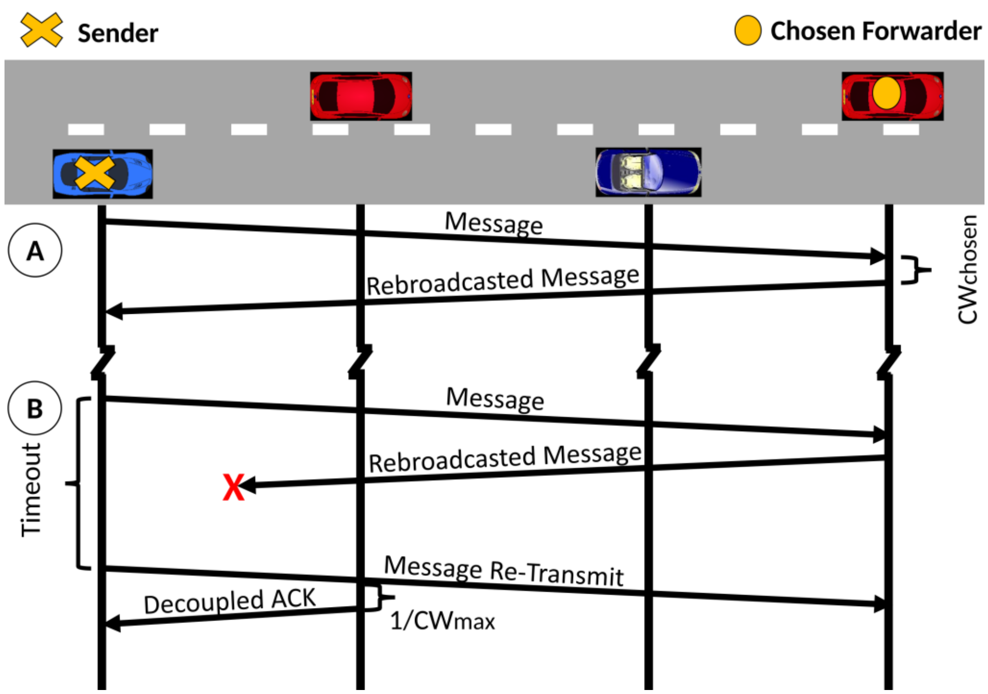


FIGURE 5

(A) Normal Rebroadcast Scenario, (B) ACK Decoupling and Recovery Process.

Note that nodes that are farther away from the sender (and thus have lower SNR_i) will have a smaller waiting time on average before retransmission, and therefore, they will more likely be chosen as forwarders. This unique approach of selecting forwarders based on nodes' *GPS* coordinates as well as *SNR* level helps counter the limitations of distance-based or SNR-based multi-hop broadcasting algorithms.

Algorithm 1

---

1. **Procedure** *Forwarder Selection (SNR(i), GPS coordinates)*
2. *Choose* α, *k*, CW_{base} *according to optimal parameter choice [Refer to:* ***Section 3.2(B)****]*
3. *Distance(i) = Calculate Distance (GPS coordinates);*
4. CW_{max} *= Calculate* CW_{max} (α, *k*, CW_{base}, *SNR(i), Distance(i));*
5. *Calculate Wait Time = Slot Period * Random Number [0,*CW_{max}*];*
6. **while** *(Wait Time != 0)*
7.   *Listen for Rebroadcast*;
8. **if** *(Rebroadcast Received = false)*
9.   *Rebroadcast Safety Message;*
10. **else** *Do Nothing;*
11. **End Procedure**

Algorithm 1 presents simple pseudocode portraying the process of forwarder selection and how the safety message rebroadcast occurs.

As the algorithm proposes the use of both SNR and GPS together in the forwarder selection process, the original sender is almost always able to overhear the rebroadcasted message from the forwarder, thus eliminating the need for a costly ACK-ing process; therefore, the safety message can progress without having to specifically wait for the successful reception of ACKs as opposed to traditional multi-hop protocols, such as SB

[2]. Eliminating the ACK dependency yields a significant improvement of the proposed protocol over SB in terms of performance.

However, under certain rare circumstances in which the sender might be unable to overhear the rebroadcast message due to the backward communication channel being lossy or the forwarder node moving out of the vicinity of the sender, as depicted in Figure 5(B), the following ACK Decoupling and Recovery Mechanism has been proposed: If the source does not receive the rebroadcasted message within a timeout period, it will once again broadcast the safety message. Upon getting the same message twice from the source, a node in the vicinity of both the source and the forwarder will send an explicit ACK to the original sender to cancel any further retransmissions from the source. However, this ACK-ing process is totally decoupled from and independent of the message propagation progress and, thus, will not contribute toward message propagation delay at all.

Although, the ACK-ing process does slightly increase the chances of collision in the vicinity of sender, these collisions can be drastically reduced by choosing the node closest to the sender for sending ACK as well as by limiting the power with which the ACK is transmitted. In order to find the node closest to the sender for an ACK transmission, the exact opposite of the contention process proposed by equation (3.1) can be used, which will provide more opportunity to a node with a strong SNR_i and shorter distance from the sender to send ACK.

Nevertheless, the best way to completely eliminate the need for ACKs is to select an $SNR_{threshold}$ with extra power budget (more than *3 dB*) so that the sender is always able to overhear the broadcasted messages from the forwarders, and the entire need for the ACK decoupling procedure is removed. Note that the additional power budget to add a few more *dB* in SNR will only slightly reduce the distance between the sender and the chosen forwarder, since the receiving power in typical mobile environments is inversely proportional to the *4th* power of distance.

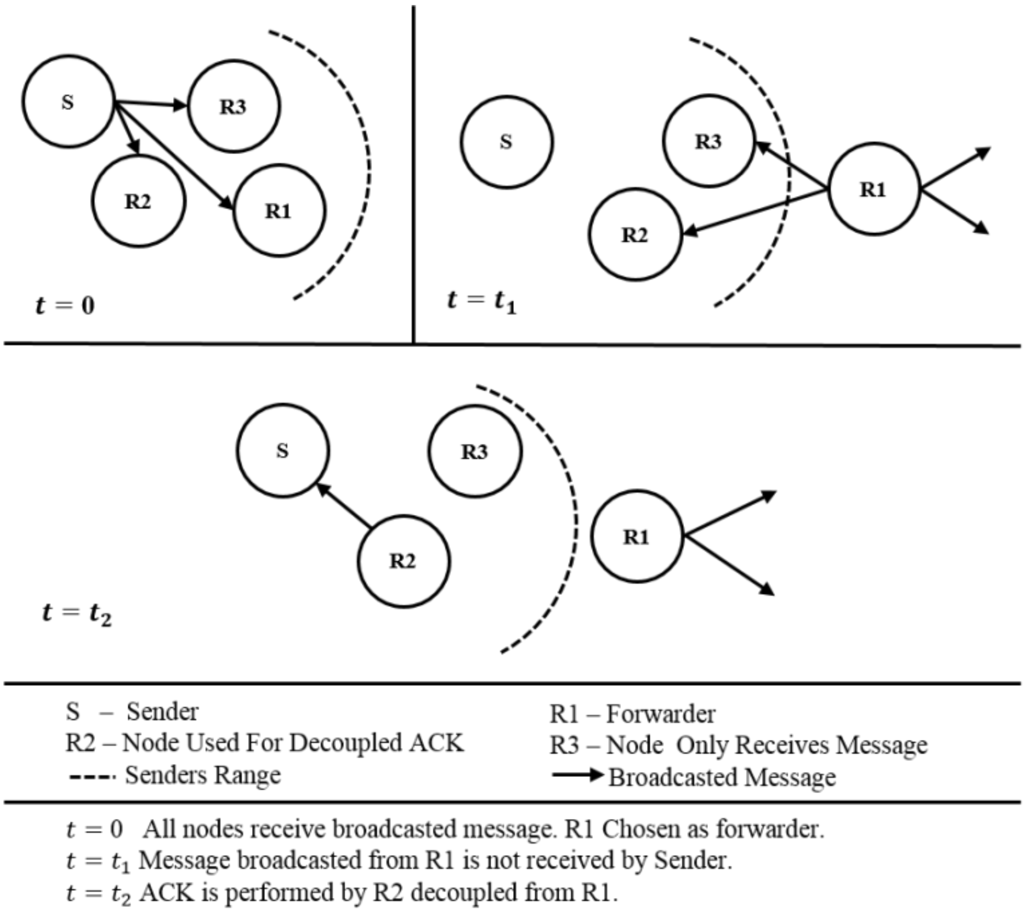


FIGURE 6

ACK Decoupling and Recovery Mechanism

Figure 6 is a graphical demonstration of *Receiver 2 (R2)* recovering the ACK while the message propagation process is continued in parallel by *Receiver 1 (R1)*. This ACK recovery process occurs after both of the following events: *1)* the forwarder *R1* rebroadcasts the safety message at t_1, and *2)* the sender *S* retransmits the message again at t_2 (which is the timeout period).

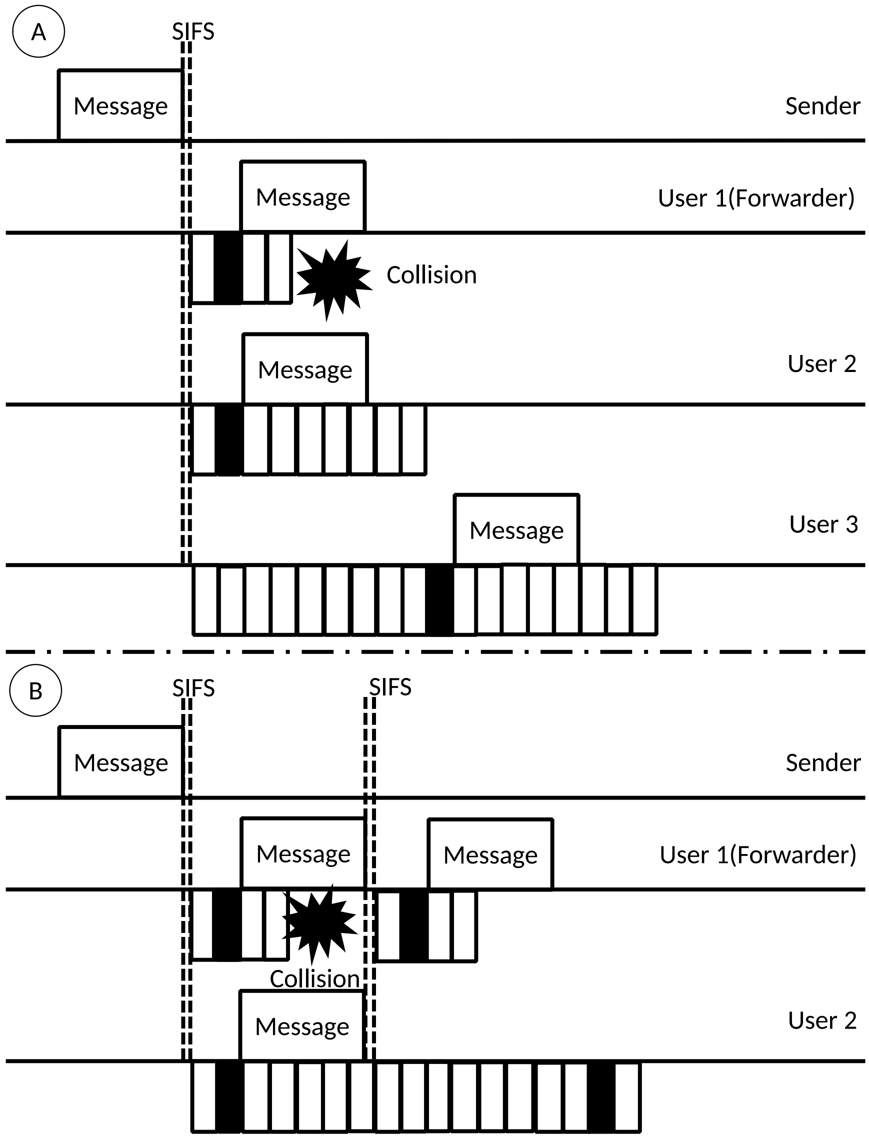


FIGURE 7

Collision Resolution Mechanism (Not drawn to scale)

In a typical VANET environment, even with a large number of broadcasting messages (usually 10/sec/node), only a few safety messages actually collide as safety messages are quite small in size and are randomly distributed over time. Once collision does occur, it can simply be resolved by the quicker of the following two mechanisms: 1) by selecting the next node (other than the two nodes that caused collision) which wins the contention as the forwarder as shown in Figure 7(A), or 2) by repeating the contention resolution procedure between the colliding nodes until the message is rebroadcasted as depicted in Figure 7(B). Note that, in this case, the nodes use the same CW_{max} calculated as before, but a new randomly selected time slot (CW_{chosen}) is used to rebroadcast. Out of the above two techniques, the one through which the forwarder is selected earliest is selected to resolve collisions.

To the best of our knowledge, this novel collision resolution mechanism, which tries to resolve the collisions in a VANET environment by selecting the quicker of the two aforementioned mechanisms, has been proposed for the first time. The improved collision resolution mechanism results in a significant reduction in the overall message propagation delay.

3.3. Summary of the Proposed Protocol Design

The following summary briefly outlines the steps of operation of the proposed algorithm:

1. *Source/Sender broadcasts a safety/emergency message without requiring any prior handshaking mechanisms.*
2. *All nodes within range receive the message, and a node is chosen as forwarder based on the contention resolution mechanism suggested by the proposed algorithm in Section 3.2.*
3. *The chosen forwarder node rebroadcasts the message further on.*
4. *If a collision occurs, the collision-resolution mechanism proposed in the previous section is applied.*
5. *If the source receives the rebroadcast message, then this serves the purpose of an*

acknowledgement (ACK).

6. *If the source doesn't receive the rebroadcast message from the forwarder, the source will rebroadcast the message once again after waiting for the timeout period.*
7. *Upon getting the same message from both the forwarder and the source node (after timeout occurs), a node in the vicinity of both the source and the forwarder will perform the ACK decoupling and recovery process (as explained in the previous section) and handle the transmission of ACK to respond to the original source/sender to cancel any further message retransmissions.*
8. *If the source does not receive a message back within the timeout period due to unavailability of nodes in the transmission range, repeat from step 1.*

Figure 8 shows a flow chart describing the design procedures executed at each *i-th* node. As can be noted, the proposed protocol is a distributed algorithm where all nodes cooperate to help in safety message dissemination in VANETs. Due to many advancements and novelties as described in Section 3.2, the proposed algorithm significantly improves the rate at which the message is propagated along the VANET as compared to the traditional protocols. The results achieved by analysis, simulation and experimentation demonstrate this improvement as explained in later chapters.

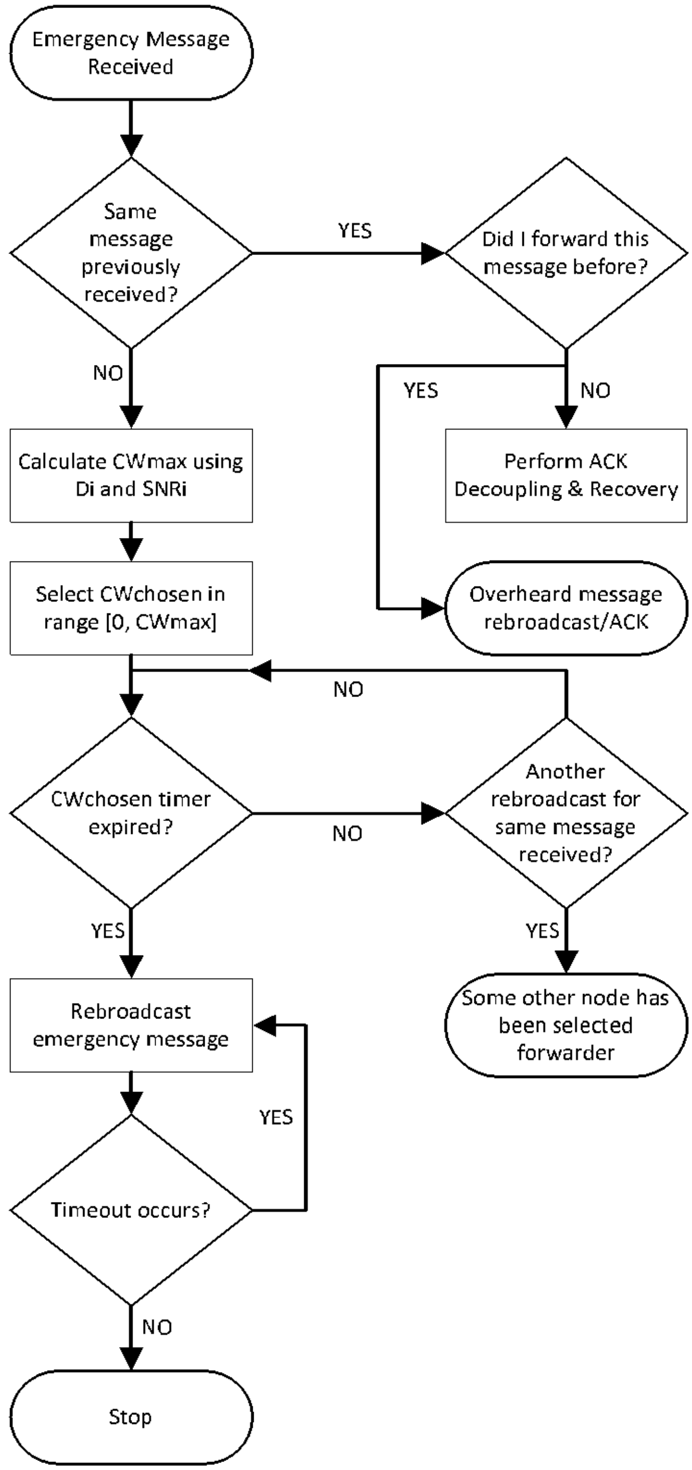


FIGURE 8

Flow Chart Describing Key Design Steps at Each i-th Node.

3.4. Comparison of Proposed Protocol with a Traditional Multihop Algorithm SB

In this section, we present a delay comparison of the proposed protocol to a handshaking protocol known as Smart Broadcast (SB) by the aid of timing diagrams.

In Figure 9, a detailed timing diagram is presented to illustrate message transmission and delay during a normal rebroadcast scenario in SB and the proposed protocol. In Figure 9(A), the sequence of packets being transmitted in SB is shown. Figure 10 depicts a scenario in which collision occurs while rebroadcasting the safety message in both SB and the proposed protocol. As shown in Figure 10(A), once a collision occurs in SB, the two nodes involved in collision remain in the contention phase, and the node with the next lowest minimum back off sends the CTB and is selected as a forwarder.

In the first mechanism, illustrated in Figure 10(B-1), the nodes involved in a collision once again back off for a random time slot (CW_{chosen}) in the range $[0, CW_{max}]$ to rebroadcast the message and repeat this cycle until the collision has been resolved. Figure 10(B-2) illustrates the second mechanism whereby a third node wins the contention and is selected as a forwarder before the two colliding nodes could recover from the collision.

It is quite obvious from Figure 9 and Figure 10 that the proposed algorithm significantly improves the rate at which the message is propagated along the VANET as compared to the traditional SB protocol. These results can be verified by the simulation results presented in Chapter 5.

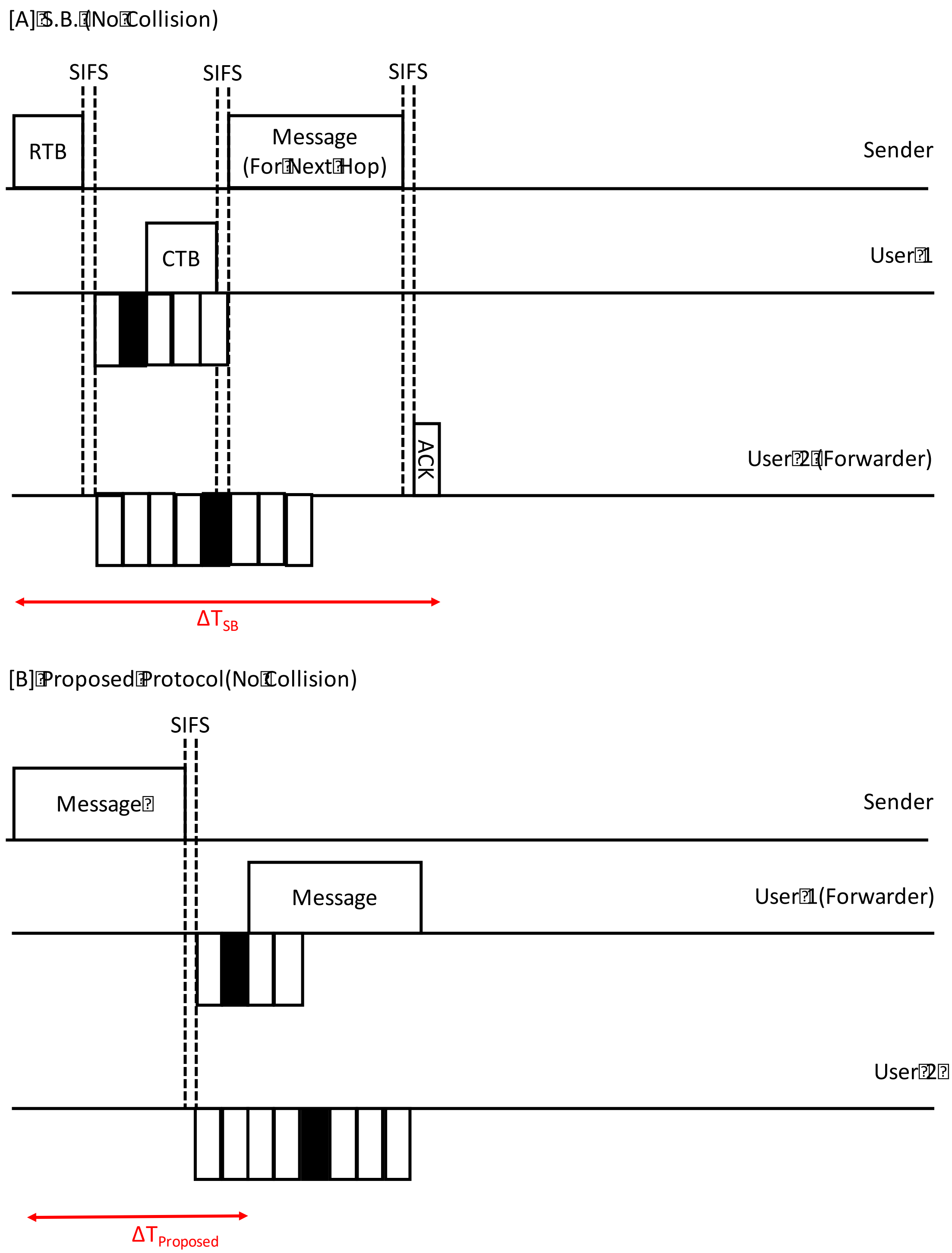


FIGURE 9

Timing Diagram – Normal Rebroadcast Scenario (Proposed Protocol vs. SB)

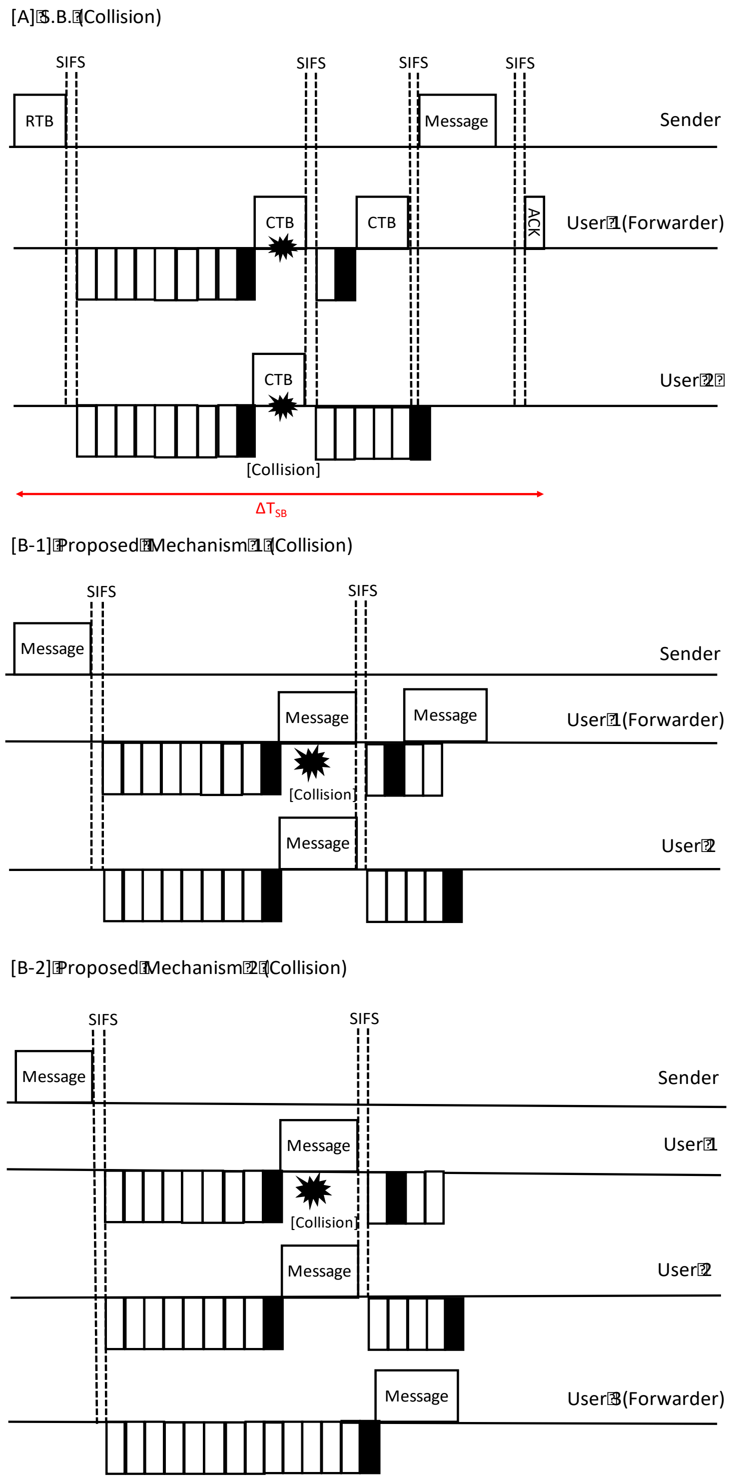


FIGURE 10

Timing Diagram – Collision Scenario (Proposed Protocol vs. SB)

4. Theoretical Analysis

In this chapter, the theoretical model of the protocol is presented and analyzed in order to establish and validate the effectiveness, robustness and reliability of the proposed scheme [30], [31]. In section 4.1, the theoretical model of the proposed protocol is described, along with the assumptions and hypothesis. Section 4.2 presents the results and analysis, while also suggesting optimal parameters to improve protocol efficiency.

4.1 Theoretical Model

In this section, the expressions that were constructed include per-hop rebroadcast latency (T_{HOP}), average distance progressed per-hop (D_F), average message dissemination speed (s) and average throughput. For the remainder of Chapter 4, a vehicle equipped with DSRC device (i.e. having V2V and V2I communication capability) will be referred to as a node.

A. Hypothesis and Assumptions

Before presenting the expressions constructed for theoretical analysis, this subsection lays down some basic hypotheses and assumptions. The highway scenario has been analyzed, whereby a safety message is disseminated along a rectangular strip of the road whereby the length of the strip represents the typical transmission range R of a vehicle. Typically, the nodes within this range from the sender will be able to hear the broadcast message, considering good channel conditions. Figure 11 depicts the highway scenario being modeled:

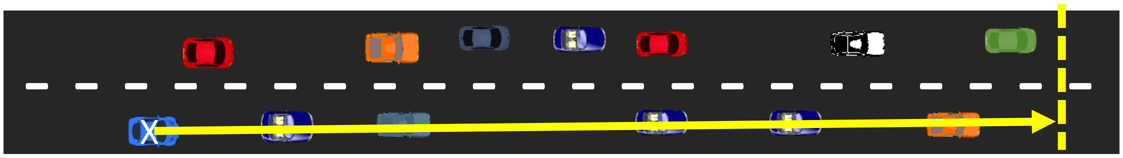


FIGURE 11

Highway Scenario

The distribution of nodes along the road strip follows a bi-dimensional Poisson process with the parameter λ nodes per strip. It is important to mention here that the nodes moving in the direction of the message propagation have a comparatively small *relative velocity* with respect to the message broadcaster (approximately less than 10s of mph) and, therefore, it will take at least a few seconds before any node within the range *R* of the broadcaster is able to leave the boundary. On the other hand, the time taken for message propagation and successful rebroadcasting (typically a few milliseconds) is negligible compared to this time. Hence, it is assumed that nodes don't leave the transmission range *R* of the broadcaster during the contention period.

After the sender broadcasts the safety message, each *i-th* node within the range *R* calculates its corresponding $CW_{max,i}$ value upon successfully receiving the message and chooses a random time slot ($CW_{chosen,i}$) in the range $[0, CW_{max,i}]$ as described in the previous chapter. It can be noted here that each node chooses its time slot independently of any other node. Let us denote N_X to be the total number of nodes that choose the *x-th* time slot to rebroadcast the message. Therefore, under the above assumptions, N_X are independent and identically distributed Poisson random variables with parameter $\hat{\lambda} = {}^{\lambda}/_{E\,[CW_{chosen}]}$ where $E\,[CW_{chosen}]$ is the expected number of time slots that a node will have to wait, on average, before it can rebroadcast the message. It can be calculated as

$$E[CWchosen] = \frac{\sum_{i=0}^{\lambda} E[CWchosen, i]}{\lambda} \approx \frac{\sum_{i=0}^{\lambda}(E[CWmax, i] / 2)}{\lambda} \quad (4.1)$$

As the message propagation time is almost negligible, and the nodes are within a relatively short distance of each other (less than *R*), the time slots for all the nodes are assumed to be synchronized. Therefore, at the *x-th* time slot, one of the events listed below occurs:

1. If $N_X = 0$: The channel remains Idle *(I)* as no node within the range *R* is able to win the contention to rebroadcast.
2. If $N_X = 1$: Only 1 node wins the contention in this time slot and, hence, rebroadcasts the message, resulting in a success *(S)*.
3. If $N_X > 1$: Multiple nodes try to rebroadcast in the same time slot, which results in a collision event *(C)*.

Hence, based on the independent and identically distributed Poisson random variable property of N_X, the above events occur with the following respective probabilities:

$$P_I: \; Pr(Nx = 0) = \frac{(\hat{\lambda})^0 e^{-\hat{\lambda}}}{0!} = e^{-\hat{\lambda}} \quad (4.2)$$

$$P_S: \; Pr(Nx = 1) = \frac{(\hat{\lambda})^1 e^{-\hat{\lambda}}}{1!} = \hat{\lambda} e^{-\hat{\lambda}} \quad (4.3)$$

$$P_C: \; Pr(Nx > 1) = 1 - P_I - P_S = 1 - e^{-\hat{\lambda}}(\hat{\lambda} + 1) \quad (4.4)$$

Where P_I is the probability of having an idle time slot, P_S is the probability of having a successful message rebroadcast in the time slot, while P_C is the probability of having a collision in the time slot.

B. Per-Hop Rebroadcast Latency (T_{HOP})

In this subsection, the mean per-hop delay (T_{HOP}) is calculated. In other words, T_{HOP} is the average time between a node receiving a safety message from the sender and rebroadcasting it to the next forwarder.

First, let us denote T_I to be the time taken for event *I*, T_S for the event *S* and T_C for event *C* respectively. T_I requires a single time slot. However, both T_S as well as T_C take message transmission/reception time (including message propagation delay), followed by SIFS.

Let us denote T_F to be the average time taken in case of a failure event (i.e., either the time slot is wasted *(I)* or a collision *(C)* occurs). Hence, T_F can be expressed as follows:

$$T_F = T_I \frac{P_I}{P_I + P_C} + T_C \frac{P_C}{P_I + P_C} \quad (4.5)$$

Therefore, the average number of occurrences of these failure events (N_F) before a subsequent success event (successful rebroadcasting) is given by the following expression:

$$N_F = \frac{1 - P_S}{P_S} \quad (4.6)$$

Additionally, let us denote T_Z to be the time spent when no forwarding node (exactly zero forwarders) is found within the range (*R*) of the sender. It can be calculated as

$$T_Z = P_Z \, . T_o \quad (4.7)$$

where T_o is the time-out value and P_Z is the probability of having no forwarding node within the range (R) and can be approximated as $e^{-\lambda}$ (Note: $\lambda = \hat{\lambda} \,.\, E[CW chosen]$). Finally, the expression for mean per-hop rebroadcast latency (T_{HOP}) is

$$T_{HOP} = N_F T_F + T_S + T_Z \tag{4.8}$$

C. Average Throughput

The average throughput can be defined as the total amount of useful data that can be successfully disseminated in the VANET per unit time. In our case, we can assume that a safety message (of a certain size) can be rebroadcasted in a mean per-hop rebroadcast time (T_{HOP}). The following expression gives the mean throughput:

$$Throughput = \frac{Average\ Message\ Size}{T_{HOP}} \tag{4.9}$$

D. Average Distance Progressed Per-Hop (D_{AVG})

In this subsection, the mean distance traversed during each successful message rebroadcast (D_{AVG}) is measured. As the node intensity in the road strip increases, there are more nodes per unit area resulting in increased chances of having some nodes closer to the border of the range (R) as compared to cases when the node intensity in the road strip is lower. Therefore, these furthest nodes within the transmission range (R) of the original sender would most likely be chosen as forwarders as their CW_{chosen} would likely be smaller due to the increased distance from the sender. If the exact geographical location of each node in the strip is known, the approximate distance between the sender and forwarder (D_F) can be constructed such that more weight is given to the farther nodes within range (R) during the forwarder selection process:

$$D_F = \sum_{i=1}^{total\ nodes} (W_i D_i) \tag{4.10}$$

where D_i is the distance between each *i-th* node and the original sender, W_i is the weight assigned to each *i-th* node based on its $CW_{max,i}$ (which is a function of the node's distance and *SNR* values). W_i can be calculated as follows:

$$W_i = \frac{1}{CWmax, i \, . \sum_{m=1}^{\lambda} \left(\frac{1}{CWmax, m} \right)} \tag{4.11}$$

Let us assume that the λ nodes are spatially placed along the road strip at a regular interval in such a manner that each node except the sender and the last node is equidistant from two other nodes and that the furthest node within the transmission range (*R*) is selected as the forwarding node. Hence, the average distance progressed per hop (D_{AVG}) can be given by

$$D_{AVG} = \frac{\lambda - 1}{\lambda} \, . R \tag{4.12}$$

E. Average Message Dissemination Speed (s)

Message dissemination speed (*s*) is defined as the average distance covered by the message per unit time. In other words, *s* can be defined as the ratio between average distance progressed per hop and average rebroadcast latency:

$$s = \frac{D_{AVG}}{T_{HOP}} \tag{4.13}$$

4.2 Results & Analysis

This section presents the validation of the theoretical model and suggests an optimal parameter choice to improve protocol efficiency. The simulation has been performed in NS-3, a discrete-event network simulator. The parameters used in the simulation are carefully chosen with minimal assumptions in order to get accurate results. Table 2 lists some of the parameters used for simulation.

TABLE 2

Simulation Parameters

Attribute	Value
Data rate	6 Mbps (OFDM)
Transmission range (R)	300 meters
Fading model	Nakagami fading model
Mobility model	Constant velocity mobility
Road dimensions	4 km long (2 lanes)
Node density	25 – 250 nodes
Time slot	40 µSec
SIFS	10 µSec
SNRthresh	8dB
Safety Message Size	50 bytes
Simulation Time (per run)	100 seconds

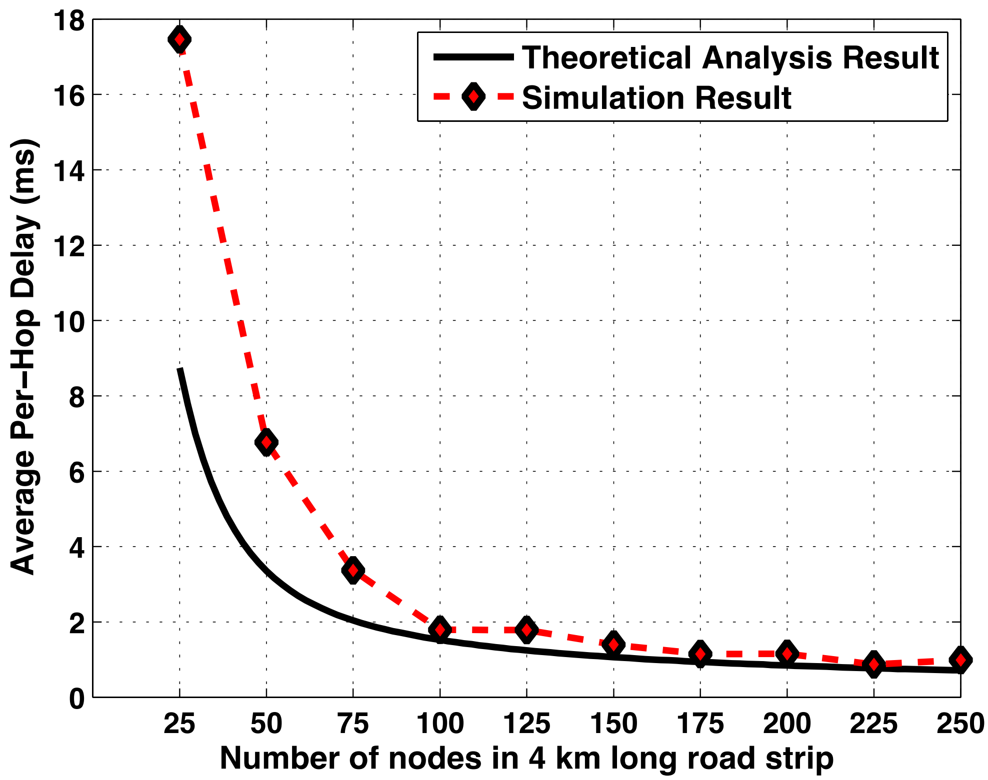


FIGURE 12

Average Per-Hop Rebroadcast Latency (Theoretical vs. Simulation Results)

A. Validation of Theoretical Analysis

In this subsection, the theoretical results are compared with simulation results to validate the mathematical expressions constructed in section 4.1. In order to closely align the simulation environment with the theoretical model, there are no background messages, other than the safety message itself, in the simulation setup.

A key performance metric used to evaluate the robustness and effectiveness of the proposed protocol is mean per-hop rebroadcast latency (i.e., the average duration it takes for the safety message to travel across one hop). Figure 12 shows the average per-hop rebroadcast delay versus the node intensity in a 4 km long road strip. As can be noted from the figure, under sparse traffic conditions (e.g., around 25 nodes), the average per-hop delay for both theoretical results as well as simulation results is much larger as compared to dense traffic conditions (>100 nodes). The reason is that when there are few nodes on the road strip, it is very probable that there is no node present within the transmission range (*R*) of the sender to rebroadcast the message, thus causing timeouts, which impact the delay values quite adversely. Another observation from Figure 12 is that simulation results generally depict higher delays as compared to theoretical results. This behavior can be attributed to the fact that simulation environments take into account many realistic limitations which the mathematical analysis tends to ignore, such as the signal fading model (Nakagami fading model), channel condition, medium characteristics and so on. These limiting factors have the negative effect of increasing the delay values of the simulations results. Moreover, under fairly dense traffic conditions (> 200 nodes), the delay decreases to a significantly lower value of less than 1 ms. This happens because, under such conditions, the chances of having a node closer to the boundary of the transmission range (with a small CW_{max} value) is quite likely, thus reducing the waiting time before a rebroadcast occurs.

Another interesting observation is that under very high traffic conditions (> 1000 nodes), the delay values start rising. This effect can be seen more clearly in Figure 16 and will be explained more toward the end of section 4.2. Overall, the results of theoretical analysis and simulation are conforming.

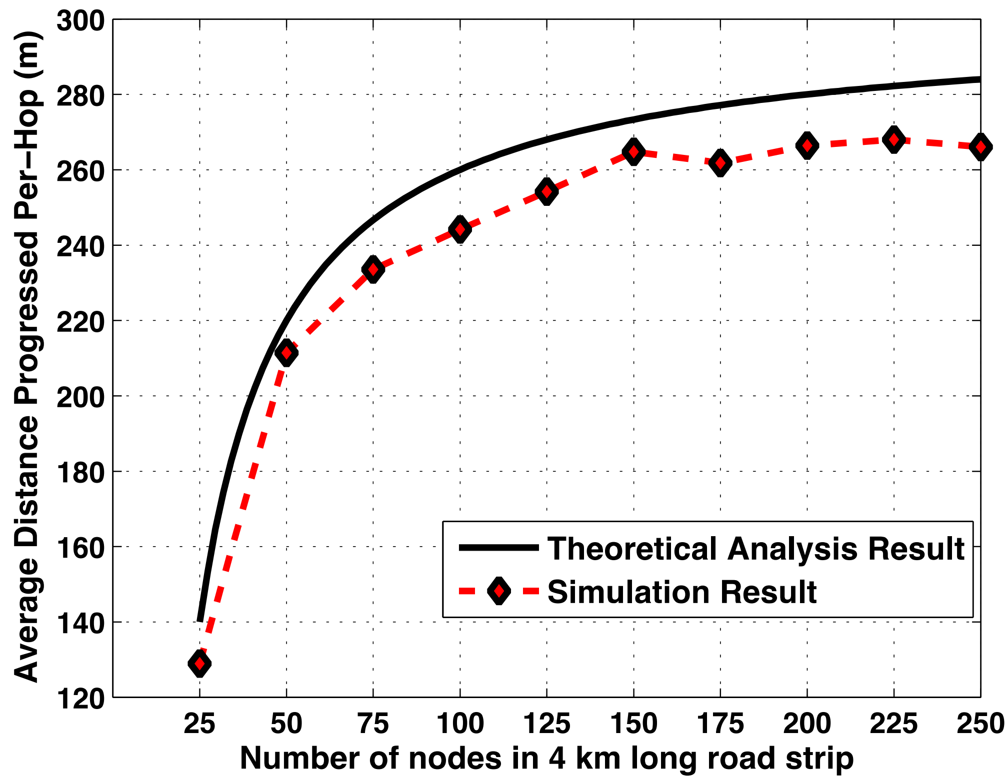


FIGURE 13

Average Distance Progressed Per-Hop (Theoretical vs. Simulation Results)

Figure 13 depicts the average distance covered by the safety message during a single successful broadcast (single-hop progress). It can be noticed from Figure 13 that as the number of nodes increase, the average distance covered by the message across a hop also increases. The reason for this increase is that with more nodes, the chances of having a node closer to the edge of the sender's transmission range *R* increases. Therefore, the forwarder selected to rebroadcast the safety message will likely be farther away from the sender. Thus, the message will travel a greater distance on average; however, as the node intensity increases further, the distance growth steadies toward the maximum transmission range (300m). Once again, the simulation and theoretical results match.

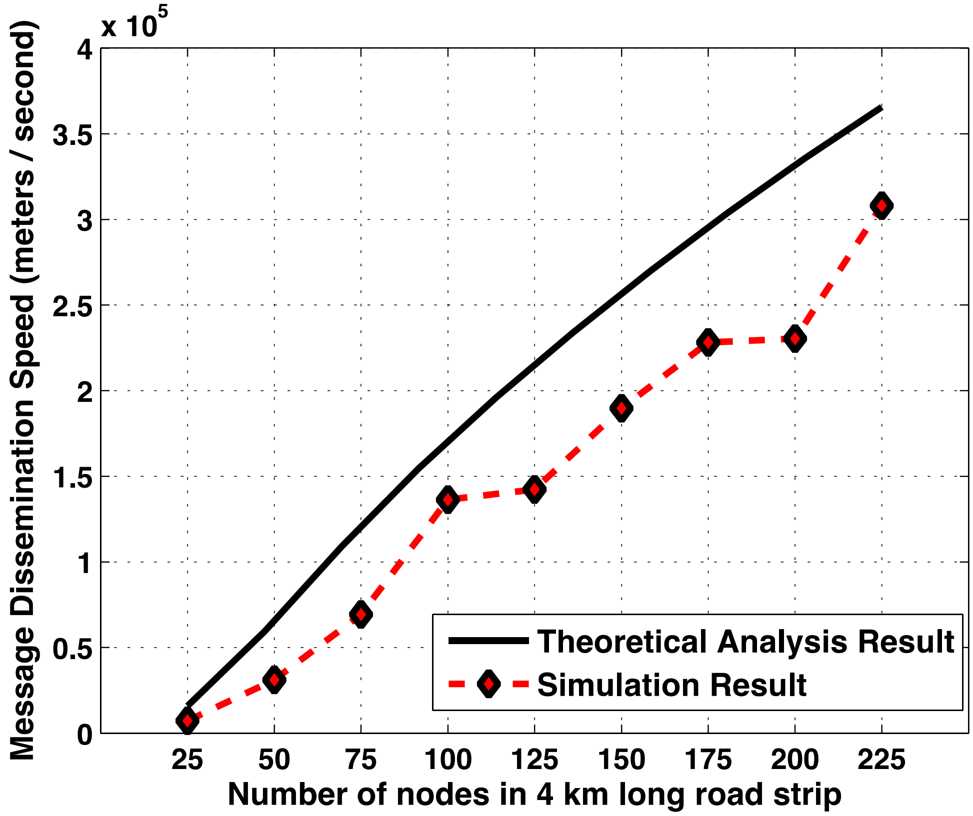


FIGURE 14

Average Message Dissemination Speed (Theoretical vs. Simulation Results)

Figure 14 shows the message dissemination speeds obtained by the theoretical and simulated results. As can be observed, the speed is generally increasing for both environments with an increase in node intensity. This upward trend occurs because as the number of nodes increase toward 225 nodes, the average per- hop delay decreases, whereas the distance progressed per-hop increases (as explained previously). Again the slight difference between the theoretical results and the simulated results is due to the lack of consideration of channel characteristics and other physical attributes in the theoretical model. However, both the curves are relatively matching with a similar trend.

B. Optimal Parameter Choice

This subsection determines the optimal choice of parameters to maximize the efficiency of the proposed protocol. Substituting the variables in equation (4.8) results in the following expression for average per-hop rebroadcast latency (T_{HOP}):

$$T_{HOP} = \frac{\sum_{i=0}^{\lambda} CW_{max,i}}{2\lambda^2}(T_I + T_C) + T_S + \frac{T_o}{e^{\lambda}} \tag{4.14}$$

where, $$CW_{max,i} = k\ \frac{D_{max}}{D_i}\ CW_{base}^{\frac{(SNR_i - SNR_{thresh})}{\alpha dB}}$$

It can be noted from equation (4.14) that the average per-hop latency (T_{HOP}) is mainly dependent upon two varying parameters, which are CW_{max} and λ, the number of nodes within the transmission range (R) of the sender that are contending to rebroadcast the safety message). Therefore, it is necessary to study the values of these parameters to minimize the T_{HOP}. It can be observed that CW_{max} can be optimized using k, α, and CW_{base}. To investigate the behavior of CW_{max}, repeated simulations (almost 100 runs) using the Nakagami propagation loss model were conducted to see how the SNR values at the receivers (SNR_i) vary as the distance from the sender (D_i) increases while keeping the transmission power constant. Table 3 offers a glimpse from the dataset of the relationship between SNR_i and D_i.

TABLE 3

D_i vs. SNR_i (GLIMPSE FROM THE DATA-SET)

D_i (meters)	SNR_i (dB)
10	35.95
50	23.25
100	17.48
150	15.48
200	14.20
250	13.06
300	11.00

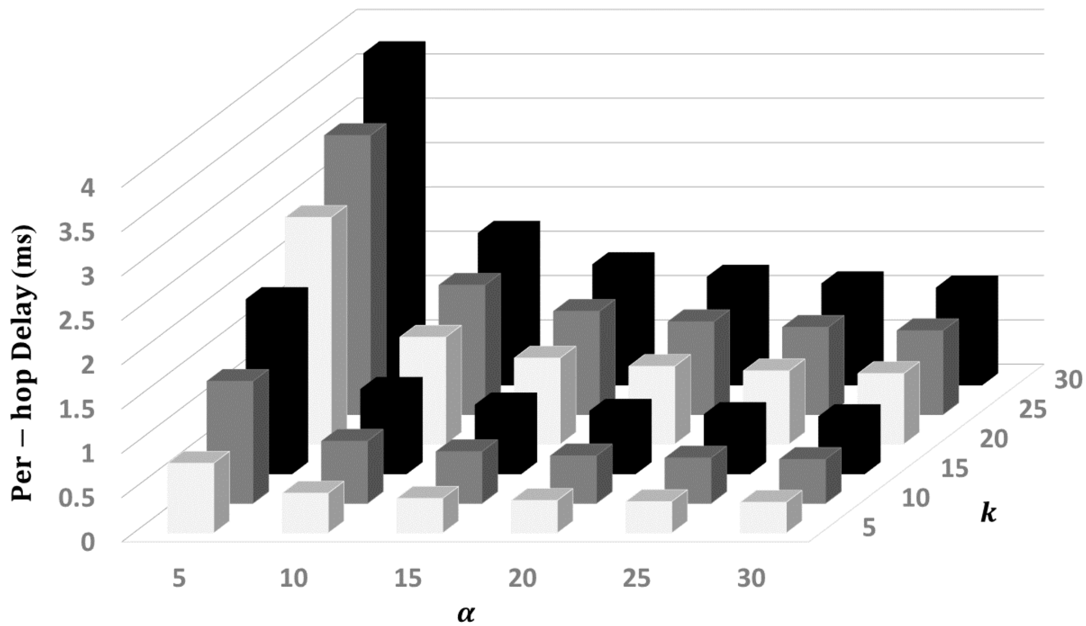


FIGURE 15

Effect of Changing Parameters on Per-Hop Delay

By using these (D_i, SNR_i) pairs, along with varying k, α, and CW_{base}, numerical analysis was carried out to determine the minimum value for mean per-hop delay (T_{HOP}). Figure 15 portrays a scenario in which the average per-hop delay (T_{HOP}) varies as a result of different combinations of k and α, while $CW_{base} = 2$ and $\lambda = 6$. Under such sparse traffic conditions, T_{HOP} decreases to less than 1 ms by choosing values of α >15 and k <20.

However, it is to be noted here that there is no unique range for α, k, and CW_{base} that would result in a minimum T_{HOP} under all traffic conditions and circumstances. For example, in cases of highly dense traffic conditions, smaller values of k and CW_{base} might result in more collisions as the CW_{max} range becomes significantly smaller, thus causing more delays due to message retransmission. On the other hand, very high values of k and CW_{base} would result in longer wait times before rebroadcasting as the CW_{max} range increases, hence increasing the delay. Therefore, figuring out a range of values of k, α, and

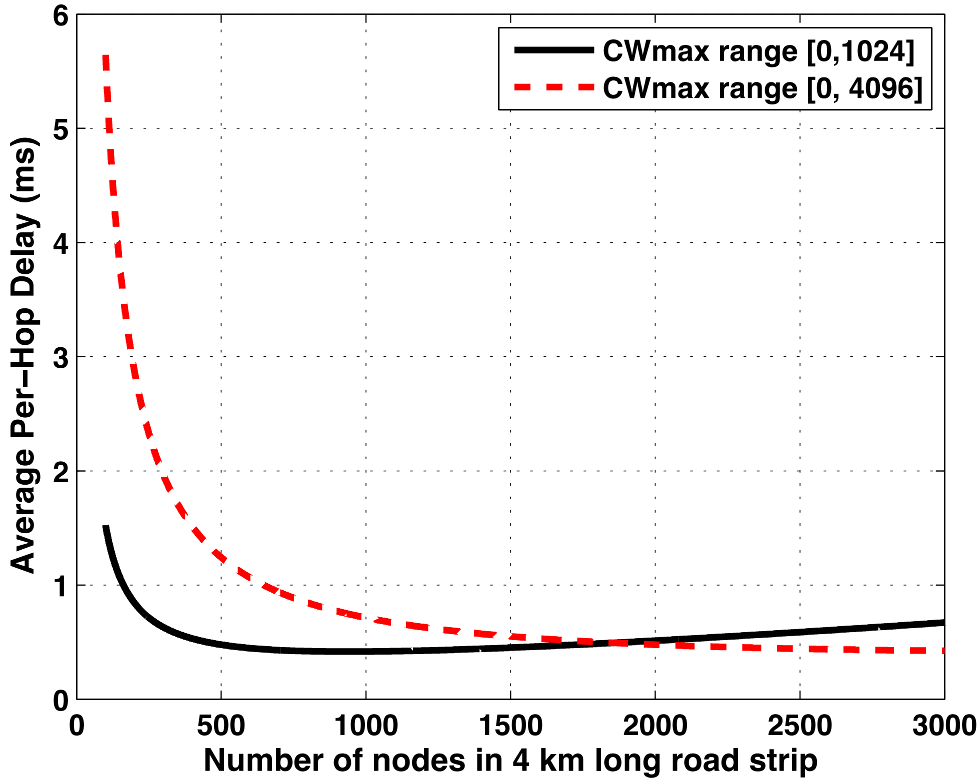


FIGURE 16

Effect of Changing CWmax Range on Per-Hop Delay

CW_{base} that take the prevailing traffic conditions into consideration would be more likely in incurring minimum delays.

For extremely congested scenarios (such as traffic rush hours in urban areas), it is suggested to use higher values for k (above 30), while lower values for α (less than 15). Under such conditions, CW_{base} size may also be increased to 3 or above to minimize message collisions. On the other hand, for light traffic conditions, choosing values of α >15 and k <20 will result in minimum T_{HOP}, as described earlier.

Figure 16 presents a comparison of the theoretical results of average per-hop delay (T_{HOP}) for a shorter CW_{max} range *[0, 1024]* versus a much longer range *[0, 4096]*. Figure 16 shows that when the CW_{max} range is increased under light traffic conditions (≈ 100 nodes in a 4 km long highway strip), there is a multifold increase in delay due to the likely occurrence of timeouts (timeout period is correlated to CW_{max}) which occur if no node is found within the transmission range (R) of the sender. Moreover, greater CW_{max} values mean forwarders have to wait much longer on average before rebroadcasting the message.

On the other hand, under heavy traffic conditions (> 2000 nodes), a larger CW_{max} range actually results in a better delay performance. This is due to the fact that under such dense traffic conditions, much fewer collisions will occur if a larger CW_{max} range is being used as opposed to a shorter CW_{max} range, resulting in lower delays. The sensitivity analysis of equation (4.8) shows that for lower node intensity, the timeout period (T_o) dictates the delay (T_{HOP}) values, whereas under higher node intensity, the number of collisions and time to recover from those collisions determine the T_{HOP} results.

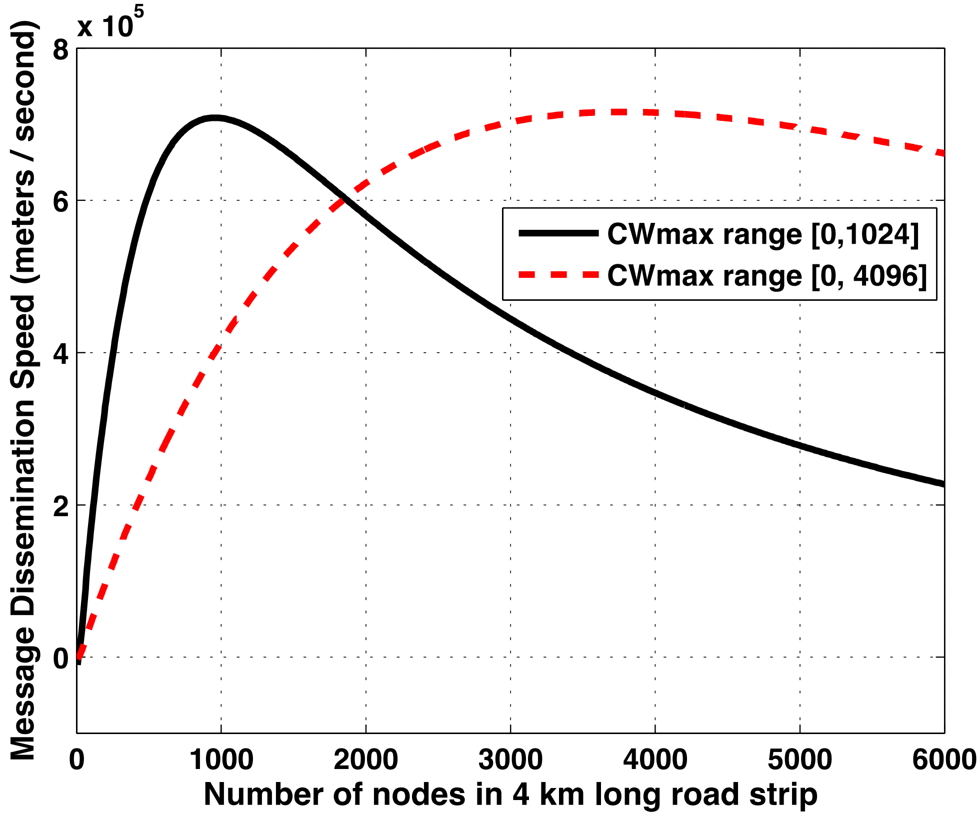


FIGURE 17

Effect of CWmax on Average Dissemination Speed

Figure 17 illustrates the comparison of the theoretical results of message dissemination speed between a smaller CW_{max} range *[0, 1024]* versus a larger range *[0, 4096]*. Note that for lower traffic intensity, the message propagation speed is higher with a smaller CW_{max} range as opposed to a larger CW_{max} range. This happens because, on average, smaller CW_{max} values result in shorter waiting times for forwarders before rebroadcasting the message, resulting in higher speeds. However, under higher traffic intensity (> 2000 nodes), the larger CW_{max} actually results in higher propagation speed as much fewer collisions occur if the larger CW_{max} range is being used. Nevertheless, an interesting observation from the figure is that as the number of nodes keeps on increasing, over the long run, the message dissemination speed ultimately drops, regardless of CW_{max} range, due to the increased occurrences of collisions. Therefore, in light of the observations from Figure 16 and Figure 17, under light traffic conditions (normal road scenario), lower CW_{max} ranges should be preferred throughout the network, whereas under high traffic conditions (such as during traffic congestion in multiple lane highways or during rush hours in urban areas), larger CW_{max} range should be used, as stated earlier. The optimal choice of parameters leads to a significant reduction in overall message propagation delays.

5. Simulation

In order to evaluate the efficiency of the proposed algorithm, the simulation is performed in NS-3, a discrete-event network simulator. This simulation environment facilitates conditions close to the VANET environment, such as Rayleigh fading model, the two-ray ground path loss model, the constant velocity mobility model and so on. Table 4 presents the parameters used in the simulation. The parameters chosen for simulation purposes are practical with minimal assumptions in order to get accurate results. The simulation is run in the presence of periodic beacon messages at 10 Hz with 400 byte-long payloads.

To see the performance of the proposed algorithm as compared to the traditional VANET broadcasting algorithms, the proposed protocol along with the Smart Broadcast (SB) protocol is implemented and evaluated under the same conditions.

TABLE 4

Simulation Parameters

Attribute	**Value**
Data rate	6 Mbps (OFDM)
Transmission range	300 meters
Fading model	Rayleigh fading model
Mobility model	Constant velocity mobility
Node density	5–25 nodes/km
Road dimensions	4 km * 30 m (2 lanes)
Vehicular Speed	70 mph
Time slot	20 µSec
SIFS	10 µSec
k, SNR_{thresh}	1, 8 dB
RTB, CTB, ACK	20, 14, 10 bytes
Emergency Message Size	100 bytes
Beacon Message Size	400 bytes
Beacon Generation Rate	1 Packet / node / sec
SB (# of Sectors)	10
Simulation Time (Per Run)	100 seconds

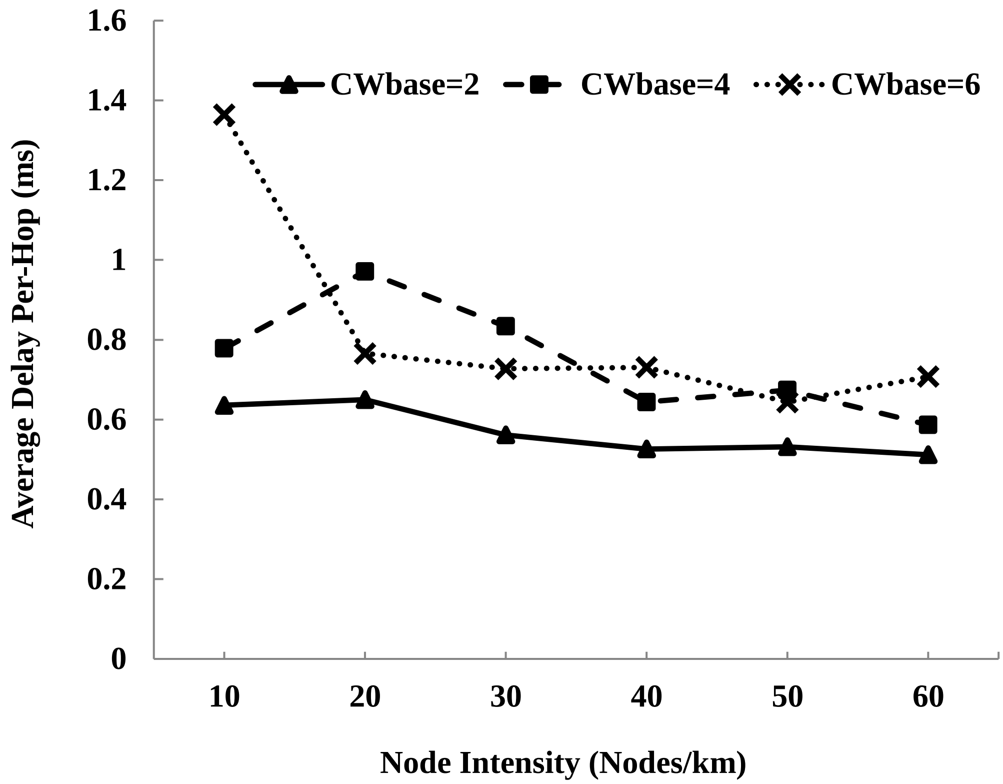


FIGURE 18

Effect of CW_{base} on Average Per-Hop Delay

In Figure 18, the average per-hop delay versus node density of the proposed protocol is displayed for different CW_{base} values of 2, 4 and 6. Note that for lower node intensity, the average per-hop delay is slightly higher for all CW_{base} values as compared to higher node intensity. Under sparse traffic conditions, such as 10 nodes/km, there is a high possibility that no node may fall within the 300-meter transmission range, and thus, the sender (message initiator) may have to wait for timeout value (which is greater than the maximum CW_{max}) before rebroadcasting the safety message. This increases the average delay values. However, toward the higher end of node intensity (more than 40 nodes/km), a slight increase in delay is observed. A possible explanation is that more nodes compete in contention for rebroadcasting the message, which increases the chances of collisions among nodes, thus increasing delays.

An interesting observation from Figure 18 is that the overall difference between the delay values of different CW_{max} values tends to narrow down as the node intensity increases. As the node intensity increases, more nodes are competing to rebroadcast the safety message and hence, under higher CW_{base} values, the nodes have less chance of collision due to more time slots available, which reduces mean per-hop delay. This, in turn, reduces the gap between low and high CW_{base} values.

Another important finding in Figure 18 is that under mild message generation rates of about 1 emergency message/node/sec, a lower CW_{base}, such as 2, tends to have a lower average delay. This is obvious as under conditions with less chance of collision; a low CW_{base} leads to lower CW_{max}, which implies that forwarders have to wait for a shorter amount of time before rebroadcasting. However, under higher collision conditions (i.e. a higher message generation rate), a larger CW_{base} might prove to be more effective as a longer range of time slots (due to the bigger *[0,* CW_{max}*] range*) reduces the chances of collision and, thus, reduces delays.

For the rest of the simulations, mild message generation rates are considered. Hence, the *optimal value of 2* has been chosen for CW_{base} for the remaining of simulation results.

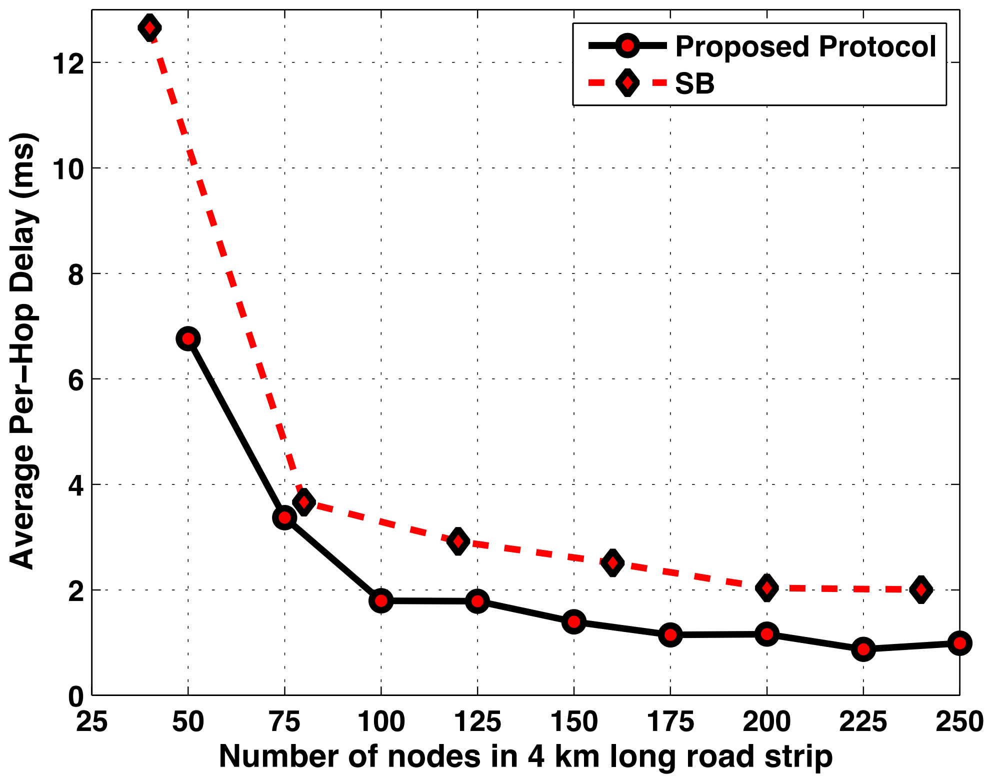


FIGURE 19

Comparison of Per-Hop Delay (Proposed Protocol vs. SB)

For an effective comparison of the proposed protocol against the SB protocol, two main performance metrics, per hop delay and throughput, are investigated. In Figure 19, the mean per hop delay for the proposed protocol versus SB is shown. The proposed algorithm performs up to 200% better than SB in terms of average per-hop delay. These results are expected from the two major design elements. First of all, while SB is highly dependent upon RTB/CTB for successful rebroadcasting, the proposed protocol broadcasts messages without prior handshaking mechanisms. Secondly, in SB, forwarders use ACKs before rebroadcasting the message, whereas the forwarder in the proposed algorithm uses the SNR and GPS to eliminate the ACK procedure or at least decouple it from the message propagation process.

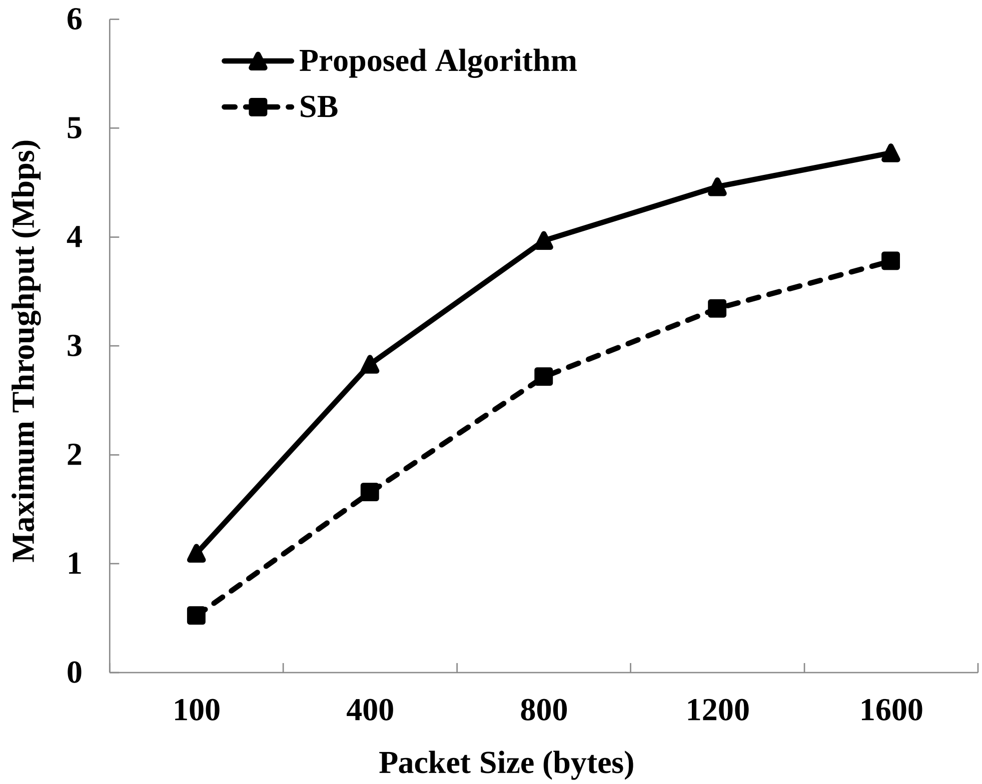


FIGURE 20

Comparison of Max Throughput (Proposed Protocol vs. SB)

In Figure 20, throughput is defined as the amount of useful information that can be exchanged between the nodes per unit time is portrayed. As shown in the plot, the proposed protocol achieves approximately twice the throughput compared to SB. In the SB protocol, a large amount of network resources is wasted in the mandatory exchange of RTB/CTB/ACK packets, which clearly is avoided by the proposed protocol, leading to an increased throughput. Secondly, in the proposed protocol, the mean per-hop delay is much smaller than SB, which also explains the throughput improvement. For all the variable payload sizes, the proposed algorithm consistently shows significant improvement over SB.

An interesting observation from Figure 20 is that as the safety message packet size increases, there is an improvement in the overall throughput. For the proposed algorithm, this improvement can be attributed to the fact that the time spent by the nodes in contention before rebroadcasting a message is almost the same regardless of whether it is a large or a small packet being rebroadcasted. Thus, for a larger packet, more data is transferred in similar latency, and thus, it results in a higher overall throughput. For SB, for each such successful packet rebroadcast, an RTB/CTB/ACK triplet must be exchanged along with the contention resolution.

6. Experimentation

In this chapter, the test-bed implementation, equipment, experimental platform, test scenarios and results of the field trials are discussed in an effort to validate the effectiveness of this protocol. The field trials were carried out to test the proposed scheme and algorithm in real life situations to validate its performance.

6.1. Equipment & Test-bed Implementation

The equipment used to establish V2V and V2I connectivity includes DSRC-equipped Arada Systems' LocoMate Classic On-Board Units (OBU) and the LocoMate Road-Side Units (RSU). Both the OBUs and RSUs operate at a frequency band of 5.9 GHz (5.85-5.925 GHz) and have a maximum power output of 23 dBm +/- 1dBm, which is equivalent to under 250 mW. The OBUs and RSUs also contain GPS modules with a claimed accuracy of less than 1 meter. However, during our experimental phase, the GPS error was discovered to be a bit larger, in the order of a few meters. Additionally, the OBUs are equipped with external USB Ports and Bluetooth and support a consistent 3 ms switch time at every 50 ms channel switching. The units fully support TCP/UDP, WAVE Short Messaging Protocol (WSMP), and WAVE Basic Service Set (WBSS). The main difference between the RSUs and OBUs is the antenna gain of 12 dBi in the RSUs and the weatherproofing capability of RSUs for outdoor conditions. The RSUs can be powered over Ethernet to remove the necessity of having a separate power line pulled to the device.

Through this project, we developed a test bed consisting of eight OBUs and 2 RSUs with the proposed multi-hop scheme implemented. The test bed can be used for safety-related as well as non-safety-related applications.

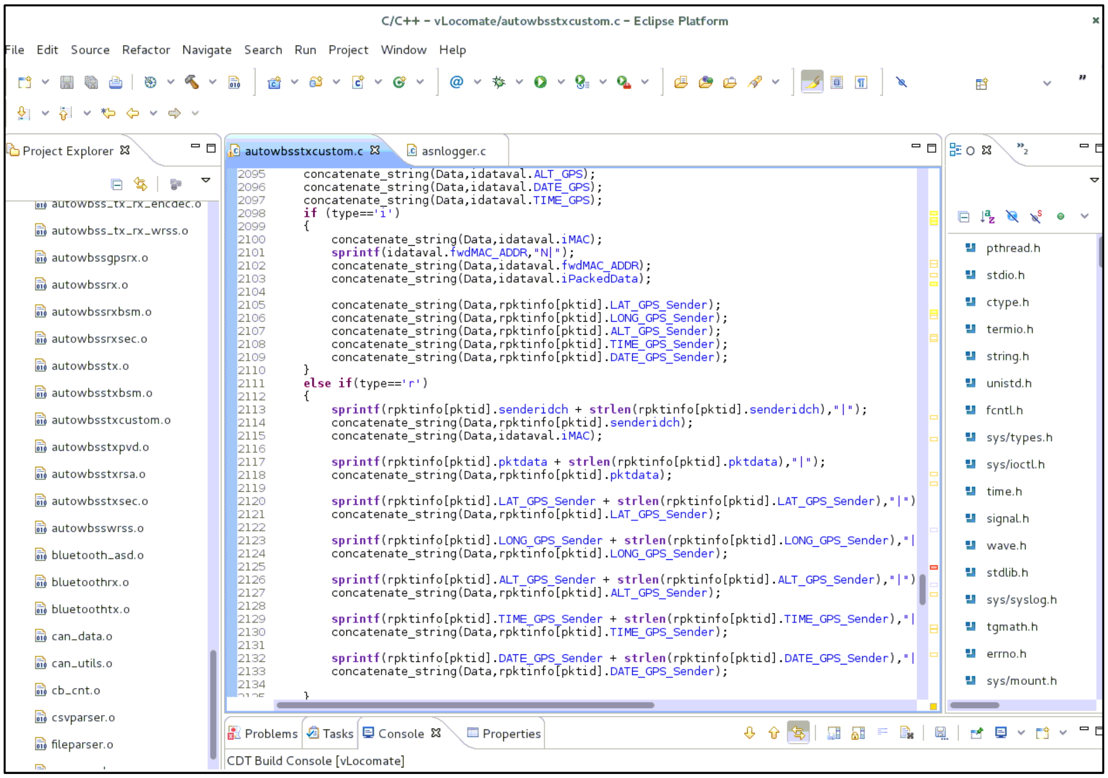


FIGURE 21

Snapshot of an Application being Developed in Eclipse IDE

6.2. Programming Guide

Arada Systems offers a built-in library called Locomate to support the creation and usage of numerous applications for safety, infotainment and entertainment purposes for V2X technology. The Locomate library provides support for both Windows and Linux/Unix-based operating systems. The applications are compiled using make files to generate the binary files, which are then uploaded to the OBU/RSU and executed. The Locomate library can be integrated with IDEs like Eclipse or NetBeans for an easier programming experience. Figure 21 portrays a snapshot of a Locomate application being programmed in the Eclipse environment.

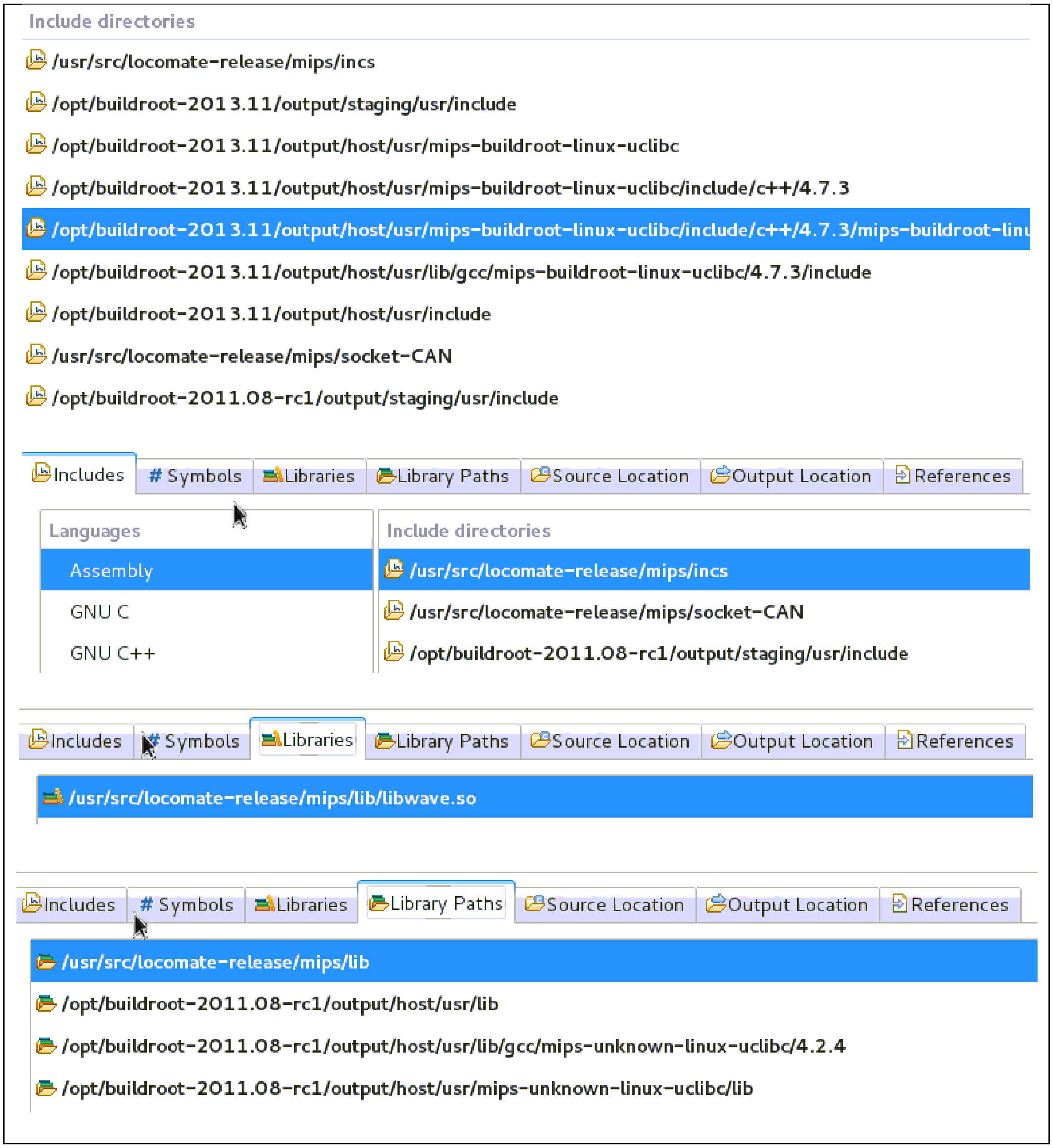


FIGURE 22

Eclipse Settings for Integrating Locomate in Eclipse Environment

Figure 22 illustrates a series of settings in the Eclipse environment to integrate Locomate project files in Eclipse. Starting a new workspace while importing the Locomate project is recommended.

Once the programming environment is set up, any custom application can be developed, allowing algorithms to be implemented and evaluated through practical experiments. For the remainder of this report, the custom application developed for carrying out field trials is referred to "Multi-hop EMD Application," where EMD stands for Emergency/Safety Message Dissemination.

The Arada Systems devices (OBU/RSU) can be remotely controlled and accessed through Telnet. Generally, the following steps should be performed in interacting with the devices and executing Multi-hop EMD Application:

1) Set up a static IP address on the computer to match the OBU/RSU's default gateway IP address. Commonly, it will be in the form "192.168.0.XXX," with the computer's gateway IP address set as "192.168.0.1" and subnet mask as "255.255.255.0," where XXX is a number other than that particular OBU/RSU's IP address.
2) Plug in the device (OBU/RSU) and connect it to the Ethernet port of the computer. If data logging is required, plug a flash drive into the USB port of the device before powering on the device.
3) Use either a Command Prompt Window for Windows or Terminal for Linux/Unix based OS to connect to the device using "telnet 192.168.0.XXX," where XXX is that particular device's allocated IP Address. The default IP address of the devices is 192.168.0.40.
4) Enter the username and password credentials for the Arada Systems DSRC devices (OBU/RSU) when prompted.

5) Once connected, the configurations can be read and modified using the "cli" command. To show configurations such as the device's IP address, type in "show configuration."

6) To run a particular custom application, simply go to the "var" folder where the binary file will be stored and can be executed. To open any custom application, follow these steps:

   a. Enter "cd /var"

   b. Type "./application_name." The custom application developed for this research project, "Multi-hop EMD Application," has been named "localtxcustom."

   c. Once the application has been opened, follow the prompt instructions which appear and are self-explanatory. For help "?" can be entered, and a list of items will appear, explaining the components and purpose of the application.

7) While the Multi-hop EMD Application is running, entering "x" transmits a single packet. Type "p" to enter a custom message. Type "i" to change the device's name. To transmit continuous packets, type "z."

   a. To have a delay between packets, type "y"; otherwise, type "n." If "y" is entered, enter the number of packets to be sent and press "Enter," followed by the time interval between packets in milliseconds.

   b. To end a continuous transfer, enter "z"; then type "n" and press "Enter."

```
?
 To send custom packet message press "p"
 To change if device is a forwarder or not press "f"
 To send a set number of packets press "q"
 To re-register provider press "h"
 To re-register user press "g"
 To change mac address or give custom Device ID press "i"
 To change CWbase "c"
 To change DMAX "d"
 To change SNR Threshold press "s"
 To change noise level "n"
 To change k value press "k"
 To change alpha value "a"
 To change tx power "t"
 To send singe packet press "x"
 To send two packet at 1 sec interval press "v"
 To send continuous packets (with interval) "z"
 To EnableDisable Log Press "o"
 To change log name press "j" (DOES NOT WORK)
 To Change Contention Slot Time press "u"
 To Change Data Rate press "y"
 To Change Display Screen Press "."

 you hit ?.
```

FIGURE 23

List of Options for Parameter Setting in Multi-Hop EMD Application

8) The application is designed in a manner such that parameters can be changed on the go as required during the field tests. Typing “?” lists all options. Figure 23 displays the list of different options that entering “?” generates.

```
. To show distance value press 1
 To show SNR value press 2
 To show CWMAX value press 3
 To show Chosen CW Slot value press 4
 To show Sender ID value press 5
 To show PacketID value press 6
 To show RSSI value press 7
 To show LAT,LONG,ALT value press 8
 To show Time value press 9
 To show Forwarder ID value press 10
 To show Transmitted Blob value press 11
 To show Received Blob value press 12
 To show TimeSent value press 13
 To show TimeReceived value press 14
 To show #Transmit value press 15
 To show #Received value press 16
 To show TypeOfTransmit value press 17
 To show More Detailed RX Information press 18
 To show Actual Message press 19
 To show MiscInfo press 20
 To Exit Enter 'q'

 Enter Option Number
```

FIGURE 24

List of Options to Enable Different Printouts

9) Enter "." to enable/disable different print outs of variables or data. Figure 24 presents the different options to enable/disable the console printout information.

Figure 25 presents a snapshot of a transmitted packet in Multi-hop EMD Application, while a received packet printout will be in the form shown in Figure 26.

```
 you hit ..
xTHE TRANSMIT PACKETID IS 13319
TRANSMIT DATA BLOB: 13319|33.963835|-84.007195|291.700000|210116|1453340044.800000|0C:E5:89:03:F0:ED|N|RANDOM|33.963835|-84.007195|291.70000
0|1453340044.800000|210116|
GOT TO BEG OF LOGSENDING TIME:  1:34:04 971613
Transmitted #1# Dropped #0# len #1300#

 Transmitted =  1 dropped = 0

 you hit x.
```

FIGURE 25

Snapshot of a Particular Transmitted Packet

```
RECEIVED TIMESTAMP:  1:40:22 467206
PACKETID: 29655
FORWARDER LAT: -5000
FORWARDER LONG: -5000
FORWARDER ALT: -5000
DATE FROM FORWARDER: -5000
TIME FROM FORWARDER: -5000
ORIGINAL SENDER ID: 0C:E5:89:03:F0:ED
FORWARDER ID: CB:FA:BA:21:7E:00
ACTUAL MESSAGE: RANDOM
ORIGINAL SENDER GPS_LAT: 33.963785
ORIGINAL SENDER GPS_LONG: -84.007159
ORIGINAL SENDER GPS_ALT: 285.400000
ORIGINAL SENDER GPS_TIME: 1453340422.400000
ORIGINAL SENDER GPS_DATE: 210116
Distance(Meters): 1000.000000
dBm: -66.000000
SNR: 29.000000
CWMax: 21.673809
Chosen CW Slot: 7
GOT TO BEG OF LOGRSSI: 68
TX Power: 14
MY ID: 0C:E5:89:03:F0:ED|
MY LAT: 33.963785|
MY LONG: -84.007159|
MY ALT: 285.400000|
MY GPS DATE: 210116|
MY GPS TIME: 1453340422.400000|
RECDATA BLOB: 29655|-5000|-5000|-5000|-5000|-5000|0C:E5:89:03:F0:ED|CB:FA:BA:21:7E:00|RANDOM|33.963785|-84.007159|285.400000|1453340422.4000
00|210116|
BLOB SIZE: 1300
END RECEIVE DATA
RET 1323
```

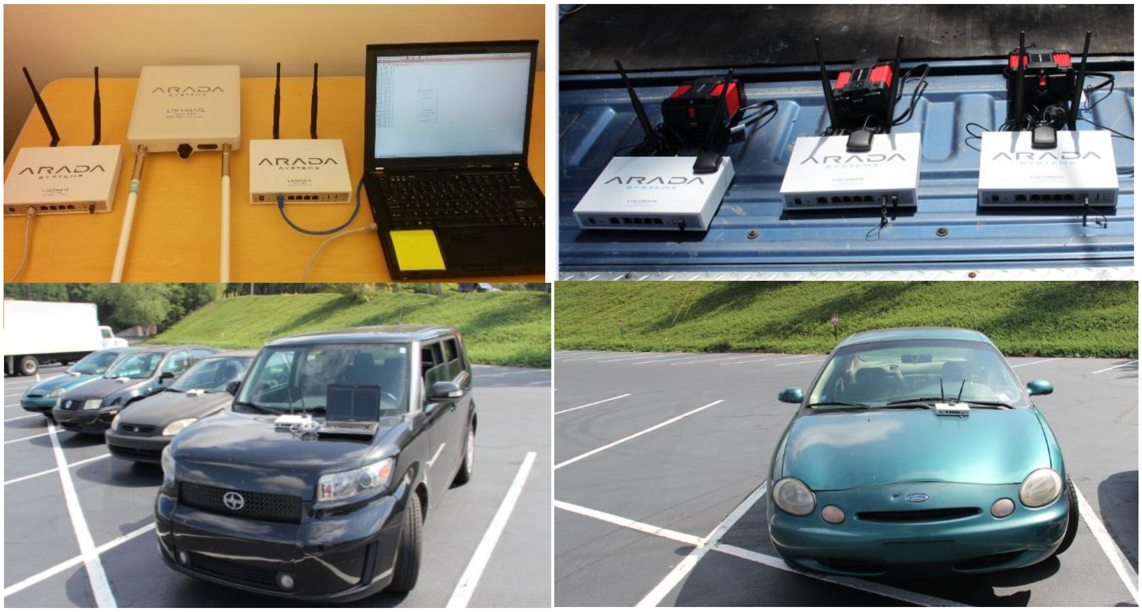
FIGURE 26

Snapshot of a Particular Received Packet

The Multi-hop EMD application captures logs which can be analyzed to gather results for testing the proposed protocol’s efficiency. Some of the logs gathered during the field trails are available in the Appendix, while others are available online. The field trials and their results are discussed in great detail in the following sections.

6.3. Field Tests in Static and Dynamic Environments

Single-Hop and Multi-Hop Experiments in Static Environment



Multi-Hop Field Test Experiments along I-75 Highway @ 60 mph

Single Hop Field Test Experiments along Northside Dr. in front of Georgia Dome

Multi-Hop Field Test Experiments in Local Roads at Lawrenceville

6.4. Field Test Results

A. RSSI and Transmission Range Measurements of an OBU

In the initial experimentation phase, a single hop V2V communication was established between two OBU devices. A stationary OBU would broadcast the safety messages, while the other mobile OBU, which was receiving the packets at different distances from the sender, was used to analyze the Received Signal Strength (RSS) information and transmission range of the devices.

Figure 27 portrays the RSS of the receiver OBU at different distances from the sender. Note that as the distance between the two OBU devices increases, the RSS decreases as expected. Hence, as the distance goes beyond 200 meters and approaches 300 meters (which is the approximate maximum transmission range of OBU), the RSS drops to a minimum of -90 dBm. Therefore, after approximately 250-300 meters, the signal strength is insufficient to transmit a packet accurately.

B. Indoor Experimentation

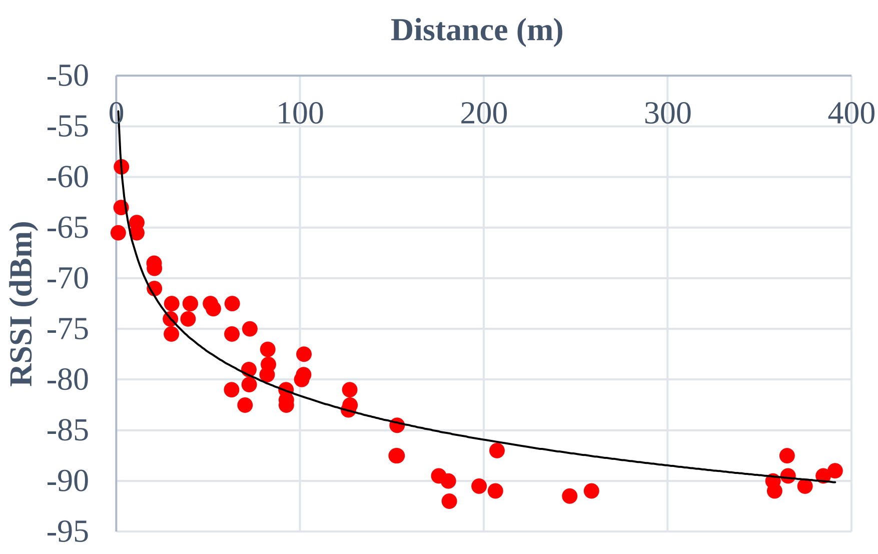


FIGURE 27

Single Hop: RSS vs. Distance

In this phase of experimentation, the proposed multi-hop algorithm was implemented on the Arada Systems DSRC devices (OBU/RSU) and evaluated under real-world indoor conditions. As the distance between the sender and the receiver increases, the *SNR* level of the received signal is drastically reduced due to the presence of multiple obstructions and walls in the indoor environment. This behavior is depicted in Figure 28. As can be noted from the figure, the SNR reduces to less than 8 dB after a distance of 15 meters, and therefore, the signal is considered too weak to be decoded properly. Hence, in indoor conditions, the transmission range of OBU/RSU is significantly reduced, and the packet loss rate increases sharply.

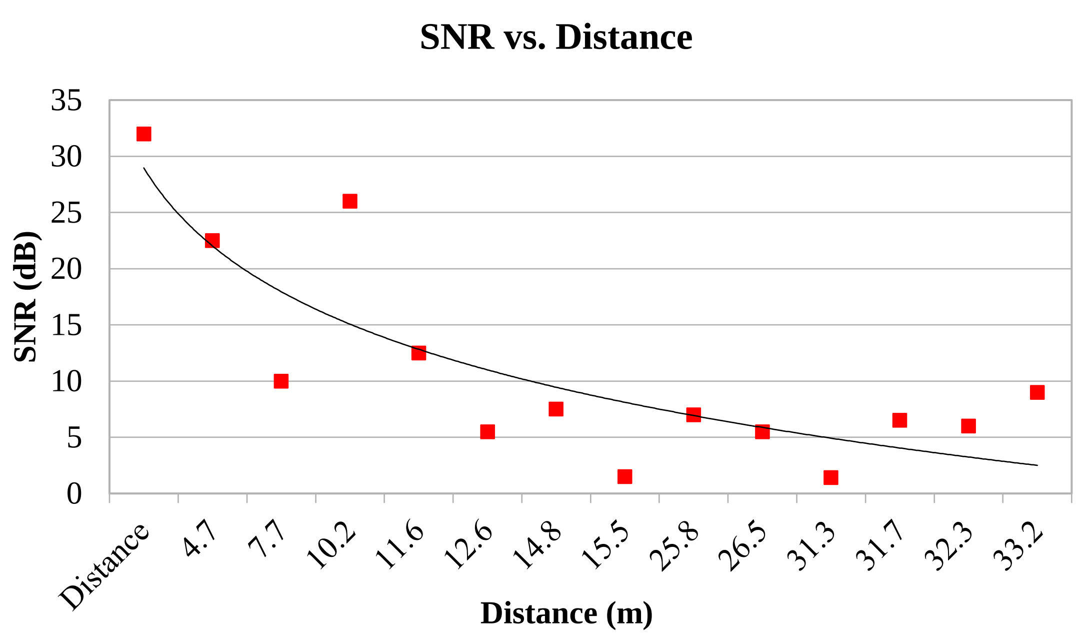


Figure 28

Indoor Experimentation: SNR vs. Distance

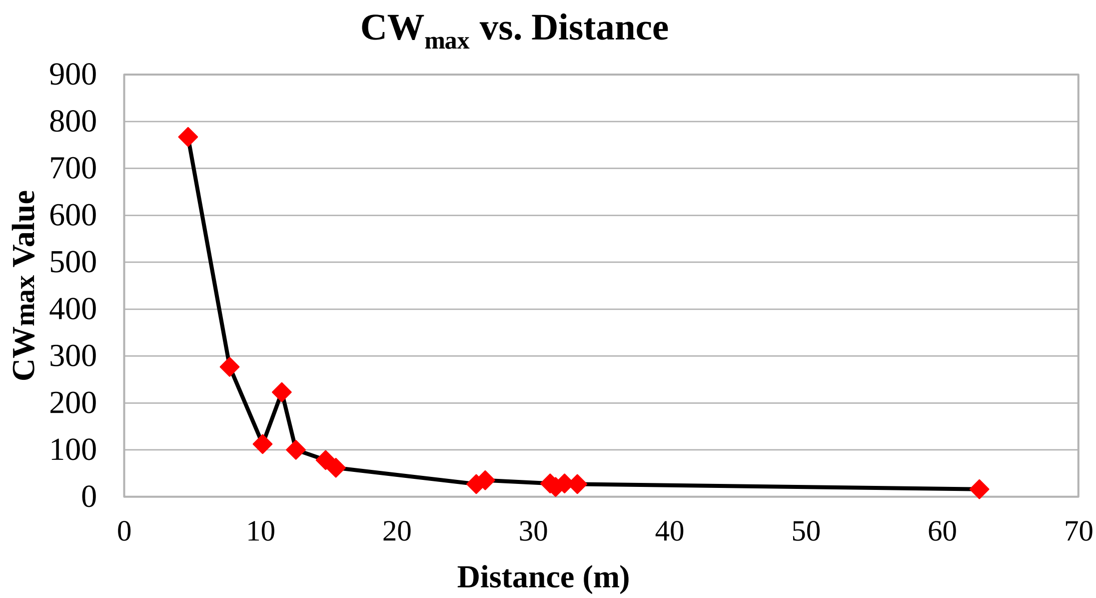


Figure 29

Indoor Experimentation: CWmax vs Distance

The CW_{max} exhibits a sharp drop as shown in Figure 29 due to the above mentioned sudden drop in SNR when the distance between the sender and the receiver increases in an indoor setting. Hence, the CW_{max} reduces to a bare minimum of < 50 slots as the distance between the sender and receiver increases beyond 15 meters. Therefore, a forwarding node (to rebroadcast the message) will be chosen very close to the original sender. This behavior is expected due to the fact that in an indoor environment, the effective transmission range of the sender is significantly reduced, so a forwarder very close to the sender has to be chosen.

For these experiments, the configuration was set up as follows: Packet size = 1300 Bytes, Transmission Power = 14, Rate = 6Mbps, GPS polling frequency = Every .2 seconds, and Time Slot period = 25 us.

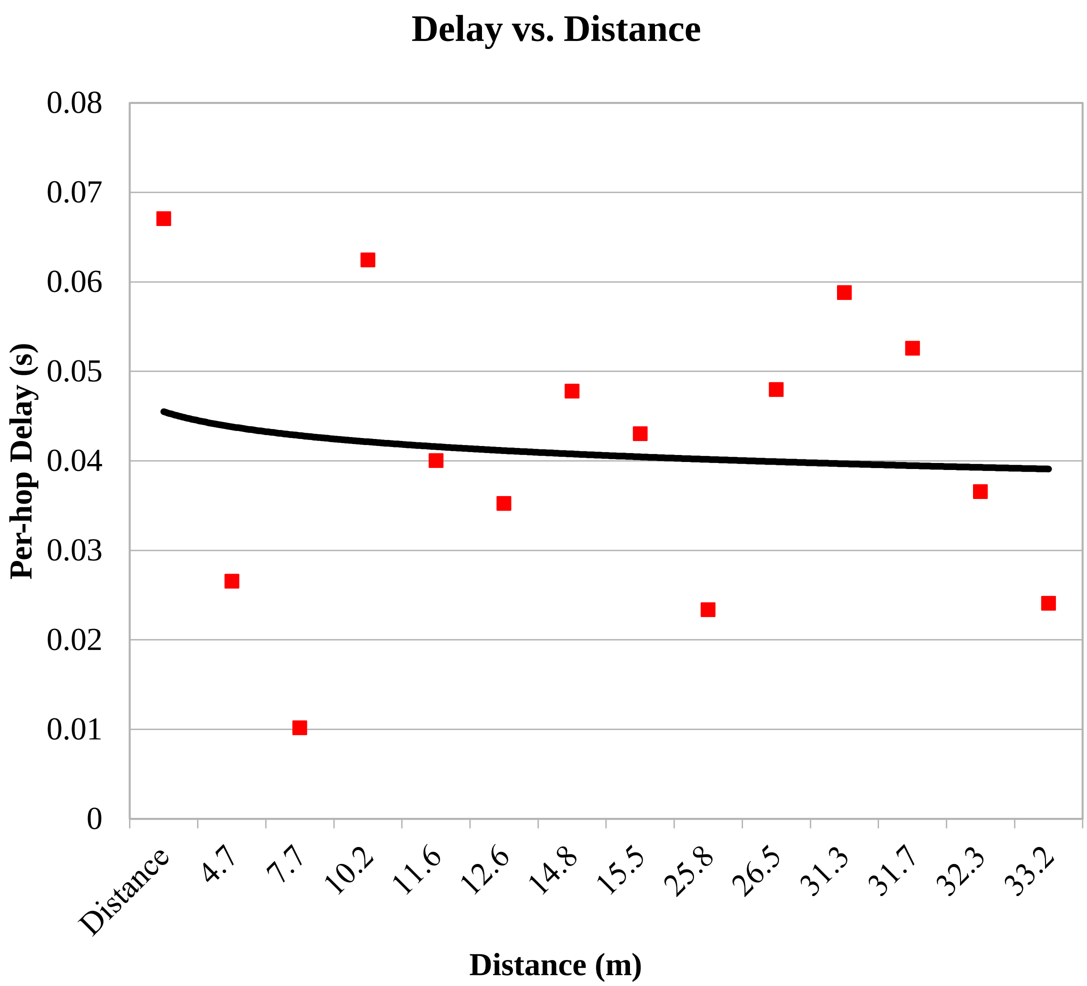


Figure 30

Indoor Experimentation: Per-hop Delay vs. Distance

Figure 30 presents the per-hop delay results for the indoor environment as the distance between the sender and forwarder varies. It can be noted that the delay values are high (around 40 ms). This occurs because for indoor environments, there are a lot of packet losses that cause timeouts, resulting in higher delays. Furthermore, as the effective transmission range of the sender in the indoor scenario is quite small, the waiting times for the forwarding nodes before rebroadcasting is significantly high (as dictated by the algorithm). One observation from Figure 30 is the lack of any particular trend in the delay results (data points scattered everywhere). This can be attributed to irregularities in the indoor environments in terms of packet loss, multiple obstructions, walls, and so on.

C. Outdoor Experimentation in Static Environment

In the third phase, the outdoor field tests were conducted in a static environment at Lawrenceville, Georgia. The objective of this experiment was to evaluate the forwarder selection process based on the receiver's SNR level and distance from the sender.

For this experiment, vehicle 1 (sender) broadcasts the safety message, while vehicles 2, 3 and 4, which are at a distance of 40 meters, 75 meters and 160 meters from the sender, receive the safety message and contend to be the next forwarder. Table 5 shows some of the values of different parameters collected by each vehicle while receiving safety messages. Note that the farther the vehicle is from the sender and the lower its SNR value,

TABLE 5

Data Gathered through the Reception of Safety Messages

Vehicle #	***Distance (m)***	***SNR (dB)***	CW_{max}	CW_{chosen}
2	40	19.5	458	121
	40.6	14.5	130	148
	40.3	14	116	83
	39.8	19	406	133
	39.4	14.5	134	104
	40.1	15.5	169	47
3	76.259	12	37	31
	75.238	11.5	33	27
	75.61	11.5	33	9
	75.729	11	29	18
	75.52	14	62	21
	75.694	13	48	34
4	163.549	13	22	3
	162	12	18	13
	164.199	13.5	25	12
	163.38	11	14	0
	163.45	13	22	14
	163	14	29	17

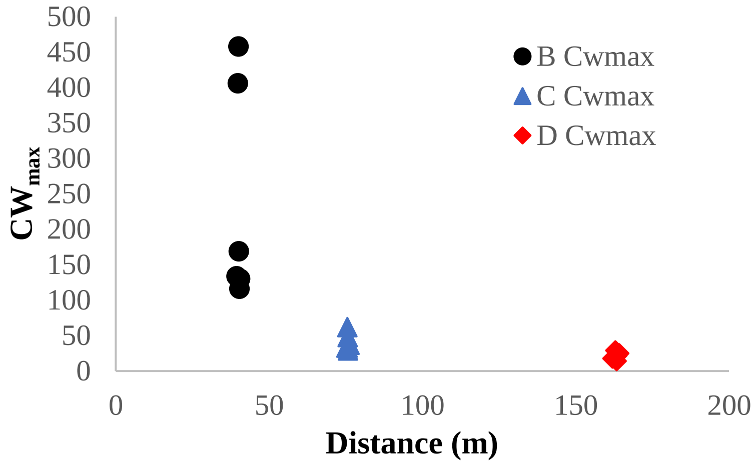


Figure 31

Outdoor Static Experimentation: CW_{max} vs. Distance

the shorter its waiting time will be before rebroadcasting the message; thus, such a vehicle will have a higher probability of being chosen as the forwarder.

In the plots in Figure 31 and Figure 32, the proposed protocol's forwarder selection process is evaluated. Figure 31 shows the CW_{max} values that were calculated by each vehicle (within the transmission range, R, of the sender) when they receive the safety messages. Figure 32, on the other hand, depicts the variation in CW_{chosen} versus distance.

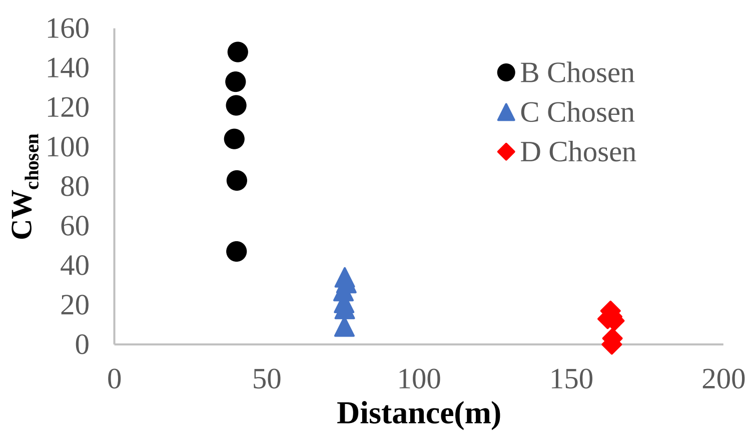


Figure 32

Outdoor Static Experimentation: CW_{chosen} vs. Distance

It can be noted from Figure 31 and Figure 32 that the vehicles that are farther away from the sender (but within *R*) generally have a lower CW_{max} as well as CW_{chosen}, and hence, there will be a lower waiting time before rebroadcasting the message. Such vehicles have a higher probability of being chosen as a message forwarder. The algorithm results were consistent with expectation.

Figure 33 presents the average delay it takes for a safety message to progress a certain distance. Note that the delay reduces until reaching a distance of about 300 meters and starts increasing afterwards. This can be attributed to the fact that until about 300 meters (which is the typical transmission range of an OBU), the waiting time of a forwarder before rebroadcasting the message is reduced as the distance increases, resulting in lower delays. On the other hand, above 300 meters, there is a high probability of more than one hop communication being required, which multiplies the delay. The average delay was

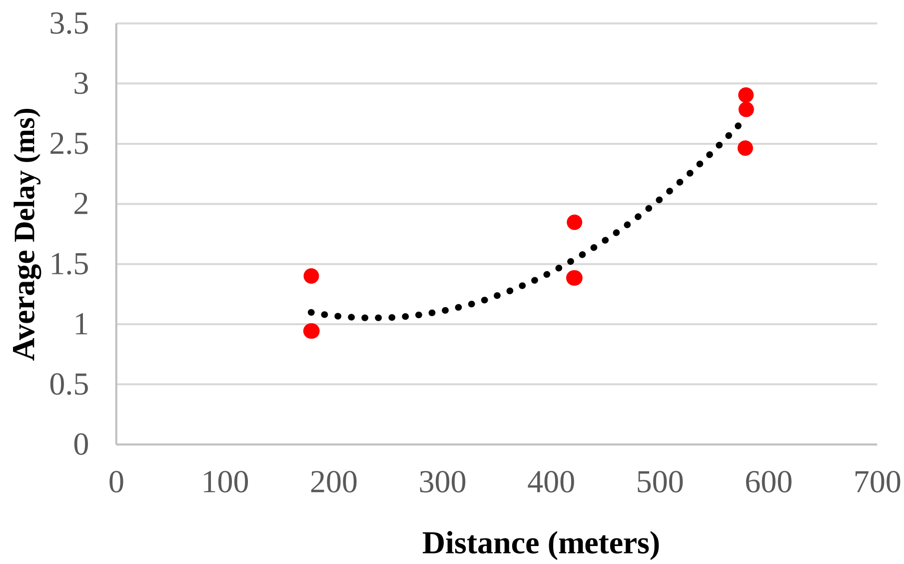


Figure 33

Outdoor Static Experimentation: Average Delay vs. Distance

measured to be 1.93 ms. It is to be noted that these delay values are significantly lower than indoor delay, due to having nodes present near the boundary of the transmission range of the sender and having less packet drop (thus fewer timeouts).

D. Outdoor Multi-Hop Experimentation in Dynamic Environment

In the final stage of experimentation, field trials of the proposed multi-hop algorithm were carried out using a fleet of moving vehicles. A convoy of six to seven vehicles equipped with OBUs were used to deliver the safety message in a Multi-hop manner to the RSU that was installed on the roadside. Figure 34 shows the formation of vehicles for the experiment.

Field experiments were carried out under different traffic scenarios, such as a highway scenario along I-75 as well as under a local road scenario in Lawrenceville. The multi-hop algorithm behaved as expected, and several interesting findings were discovered from the experimentation.

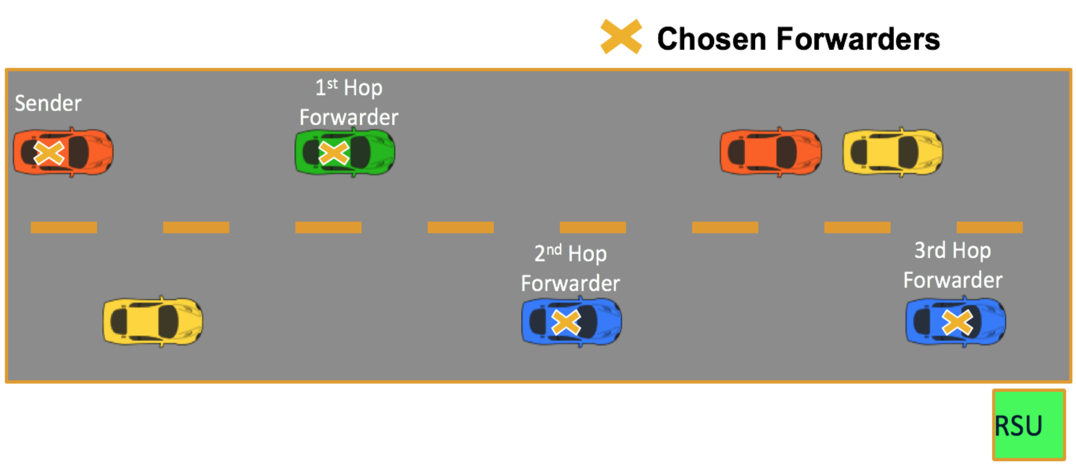


Figure 34

Outdoor Multi-Hop Experimentation Topology

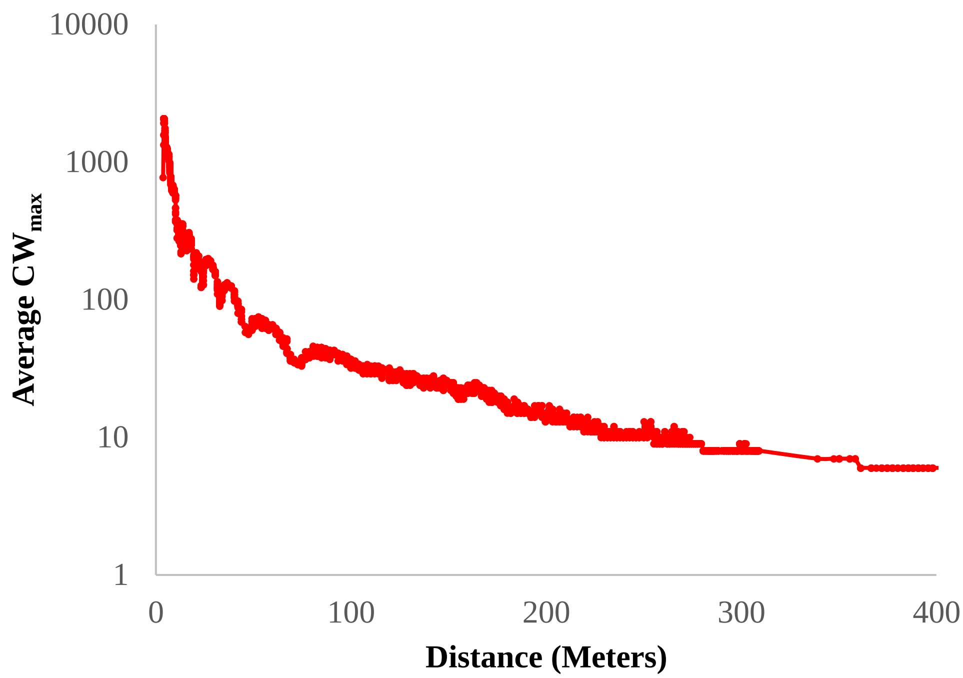


Figure 35

Outdoor Multi-Hop Experimentation: Average CW_{max} versus Distance

First, the proposed forwarder selection process was studied under the previously mentioned experimental settings. Figure 35 depicts the average CW_{max} values that are calculated by each vehicle (within the transmission range, R, of the sender) when they receive the safety messages. Note that the CW_{max} range in this case is almost between [0, 1023]. This range can be adjusted using parameters such as CW_{base}, k, α. Note that the vehicles farther away from the sender (but within R) have a higher probability of being chosen as a message forwarder as they have a lower CW_{max}. An interesting observation from the field trials is that the transmission range of OBU goes well beyond 300 meters in case of availability of line of sight.

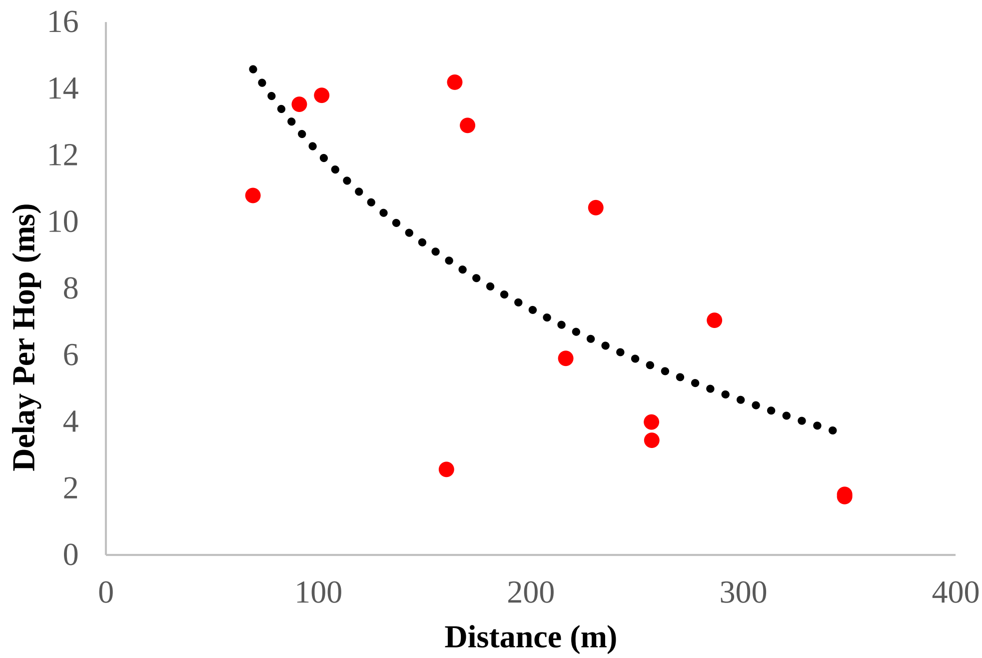


Figure 36

Per-Hop Delay for Outdoor Multi-Hop Experimentation

One of the crucial parameters to evaluate the performance of the proposed multi-hop algorithm is a per-hop delay, i.e., the average time it takes the safety message to progress one hop. Figure 36 shows these delay timings as the distance between the sender and the forwarding node increases.

It can be observed from Figure 36 that as the distance between the sender and the forwarding nodes increases, the delay decreases sharply to a couple of milliseconds. This happens because a node closer to the boundary of the transmission range of the sender (around 300 meters) having a small CW_{max} value will more likely result in reducing the wait time before a rebroadcast occurs. This, in turn, results in lower overall delays.

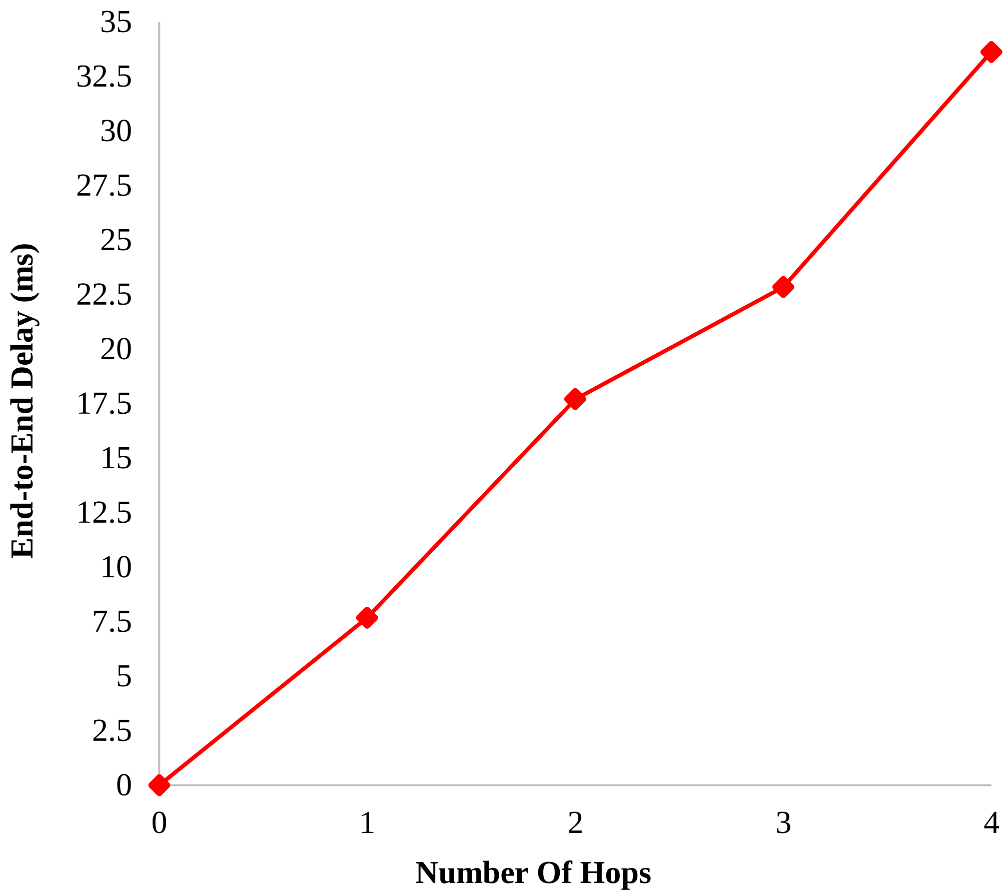


Figure 37

End-to-End Delay for Outdoor Multi-Hop Experimentation

On the other hand, Figure 37 shows the end-to-end delay across different numbers of hops as demonstrated in the topology shown in Figure 34. As expected, as the number of hops increases, the overall delay increases. This occurs because the delay across each hop gets aggregated as the number of hops increases. However, the increase in delay is not constant at each hop. This inconsistency at different hops is due to a variety of reasons, such as varying distances between the sender and forwarder, different traffic congestion and collision rates and so on.

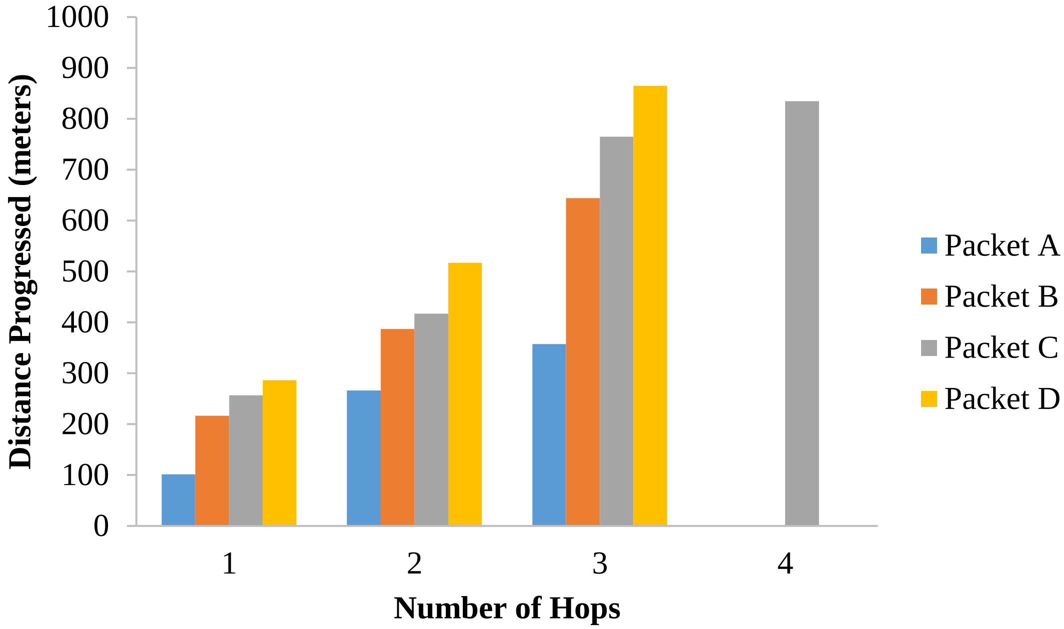


Figure 38

Distance Progressed by Various Safety Messages

Figure 38 presents the distance progressed by different safety messages/packets (i.e., A, B, C and D) across several hops before reaching an RSU during the field trials. An expected observation in this figure is that as the number of hops increases, the distance covered by the packets also increases as distance gets aggregated at each hop. Another interesting observation is that a packet (e.g., packet D) can cover a greater total distance than another packet (e.g., packet C) in fewer hops while in the same environment. This can be attributed to the difference in per-hop distance progressed by the safety messages at each hop. In this figure, some messages (A, B and D) travelled only three hops before reaching the RSU, while message C took four hops to reach the RSU.

The data captured from the field trials and experimentation has been made available for use in the continuation of this project as well as any other related project. Specifically, these research findings can be used in transportation-safety-related projects such as collision avoidance, application layer radar map development, BSM exploitation to improve communication efficiency and security and so on.

7. Demo

As part of the demonstration, a practical and usable system was designed to test the protocol in real life. A website domain was registered with the name *maphak.com* (not to be confused with maphack). MapHak takes the safety-related data in real-time from the RSU (which receives multi-hop safety messages from vehicles that drive by) and stores the data in a MYSQL database. Figure 39 portrays a screenshot of the MYSQL database at a particular instance of time. The website not only displays the contents of the safety message but also draws the location of the safety message initiator (sender) on a Google map, using the Google map APIs in the form of a marker.

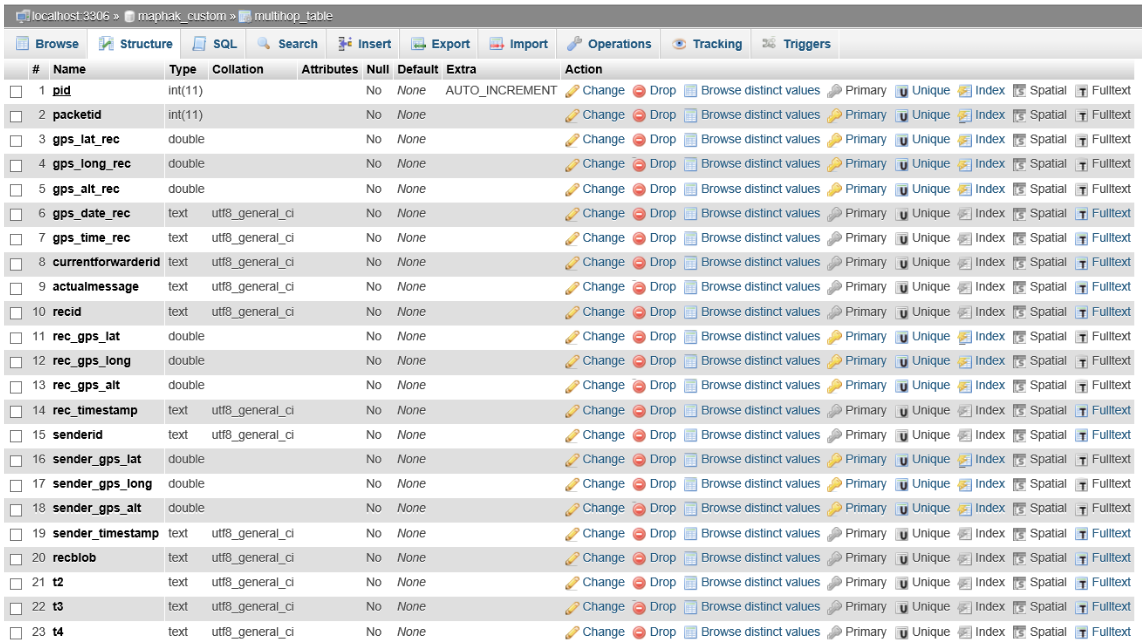
This system offers multifold benefits;

A) First, it can be used as an instantaneous emergency notification system by the emergency response units and traffic management agencies. This type of automatic notification system can help save lives, time and property.

B) The system can be used to gather large amounts of data for conducting traffic statistics and analysis.

C) The system provides a two-way communication platform for DSRC equipped vehicles.

D) The system can be utilized to provide live traffic information, such as expected drive time and travel speeds to the approaching vehicles.


localhost:3306 » maphak_custom » multihop_table

Browse | Structure | SQL | Search | Insert | Export | Import | Operations | Tracking | Triggers

#	Name	Type	Collation	Attributes	Null	Default	Extra	Action
1	pid	int(11)			No	None	AUTO_INCREMENT	Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
2	packetid	int(11)			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
3	gps_lat_rec	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
4	gps_long_rec	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
5	gps_alt_rec	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
6	gps_date_rec	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
7	gps_time_rec	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
8	currentforwarderid	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
9	actualmessage	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
10	recid	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
11	rec_gps_lat	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
12	rec_gps_long	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
13	rec_gps_alt	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
14	rec_timestamp	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
15	senderid	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
16	sender_gps_lat	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
17	sender_gps_long	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
18	sender_gps_alt	double			No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
19	sender_timestamp	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
20	recblob	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
21	t2	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
22	t3	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext
23	t4	text	utf8_general_ci		No	None		Change Drop Browse distinct values Primary Unique Index Spatial Fulltext

FIGURE 39

MYSQL Database Containing Safety Messages Related Data

Figure 40 presents a screenshot depicting the features of the website. The website *maphak.com* contains a live map to display the packets as they are received by the RSU. To differentiate between the message originator, middle-hop and RSU, each have been color coded differently. The blue markers signify the original sender, the red markers define the last forwarder before the RSU, and the green marker is the location of the RSU. The top section of the website contains the fields to aid in finding any particular packet by entering its packet id. This provides a filtering feature to show which emergency took place where and the specific details related to each emergency. Figure 41 portrays a specific emergency event that occurred.

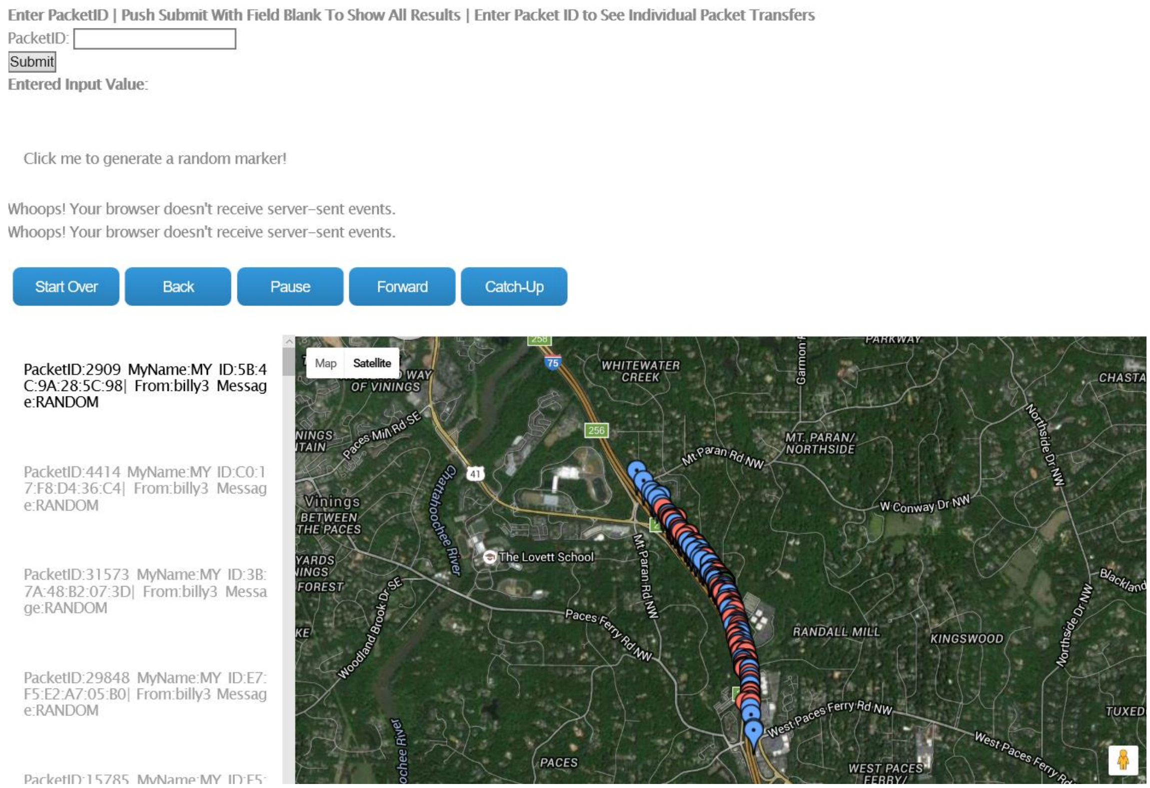


Figure 40

Live Map showing Multiple Emergency Events

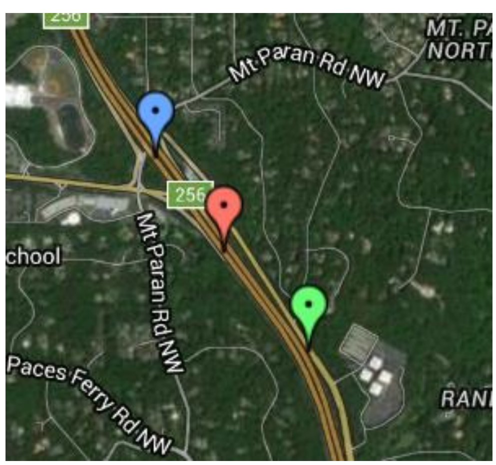


Figure 41

Single Emergency Event

Maphak.com is developed using HTML in combination with CSS and PHP. PHP is used for accessing the MYSQL database. Jscript is used to populate the maps by pulling the information from the database in combination with Google APIs to display the markers on the Google map.

A C# application is developed to get information from the Arada System's RSU. This is due to the limitations of having access to programming the lower layers that are locked by Arada Systems. This application can be omitted on a unified system and could potentially be integrated into the RSU application to submit the information to the MYSQL database directly through physical connections to the RSU. Similarly, the cellular network also can be used by connecting a cell phone to the OBUs to transmit information directly from an OBU to the MYSQL database.

Several hurdles had to be overcome for a system to be functional. A working prototype is completed, but it does contain some limitations due to the DSRC device programming limitations. Currently, the only programming access is at the application layer. However, both the protocol speed and the transmission ease could be improved significantly, if the protocol is implemented in the lower layer. Furthermore, additional features could be implemented, such as security and collision detection at a much lower level. Cross layering is another important aspect in VANETs as a standard five-layer TCP model may not be ideal as the best fit.

8. Recommendations

In this chapter, some recommendations related to the deployment of V2V and V2I technology in the state of Georgia are presented. These include but are not limited to the equipment placement, the parameter configuration, distance between devices and environmental impact, as well as a brief cost analysis. Specifically, the following section will discuss the ideal setup for the DSRC devices, both the OBUs and RSUs. Some of the important aspects that are covered in this chapter are the significance of line of sight, barrier attenuation, road topology and limited broadcast flooding, as well as data collection and storage for statistical purposes.

8.1. Antenna Placement.

For experimentation, the antennas were tested by placing them inside and outside the vehicle. Due to the lack of moisture resistance, the Arada System's DSRC devices were tested outside only during dry weather. One of the first observations is that the attenuation of the signal due to penetrating glass windshields is significant as portrayed in Figure 42. Therefore, antenna placement was tested to achieve the best possible coverage range. Additionally, due to the necessity of broadcasting messages in both forward and backward directions, the antennas should be spatially placed in a manner that is ideal for both directions. Slightly raising the antennas above the vehicles while placing them close to the center of the vehicle would be the best position. It is important to mention here that if the antennas are placed very close to the FM/AM antenna, the signal would undergo twice as much attenuation as it will experience in penetrating through the vehicle's windshield.

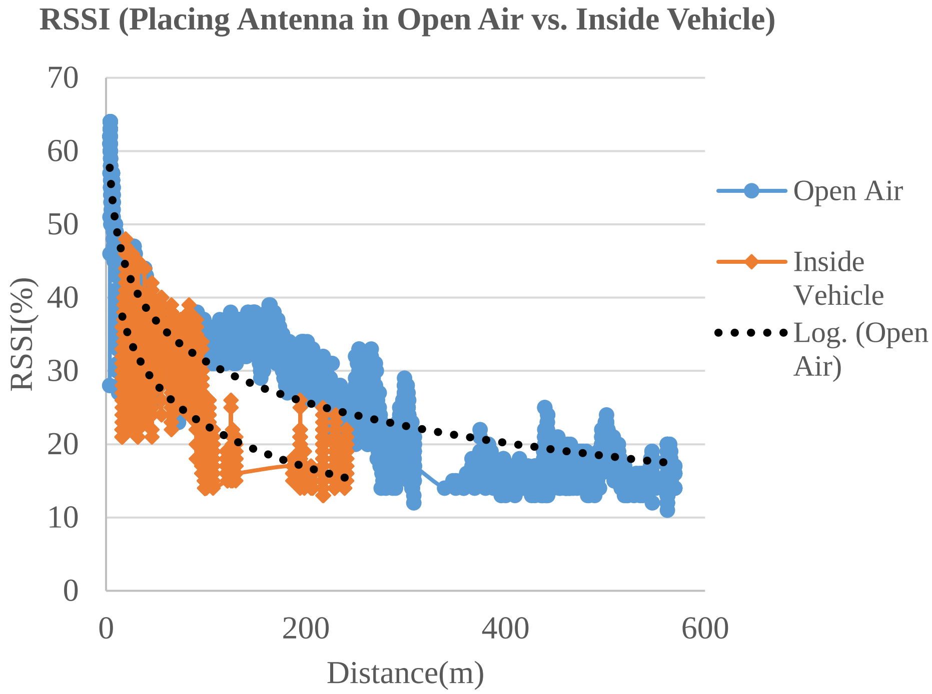


Figure 42

Attenuation due to Windshield Blockage.

Furthermore, antenna placement is even more important for some specific DSRC applications; e.g., "DSRC device as a radar" is one such application that would require specific antenna placements to extract the necessary information needed to detect objects or obstructions to avoid collisions.

8.2. RSU Placement

The Arada Systems Road Side Units provide coverage of around 1Km. However, during experimental field testing, the maximum RSU range was measured at approximately 900 meters. This loss in the range is due to the difficulty in finding 1 km long straight road stretches that offer a line of sight. The experiments were performed at Northside Parkway, Interstate 75 (I-75), Northside Drive, the roads around the Georgia Institute of Technology campus, as well as at Lawrenceville. It is often recommended that RSUs be placed every 1 km stretch along the highway road. However, if a multi-hop communication protocol such as the one presented in this report is utilized, RSUs can be deployed after every 1.6-1.8 km on busy highways without the need of maintaining a line of sight between RSUs. The OBU units in vehicles act as relays in this case. This significantly reduces the number of RSUs required to cover the whole stretch of highways without compromising the connectivity and reachability of RSUs.

On steep roads with continuously changing altitudes, the RSU is recommended to be deployed at a much higher altitude over the roads to have the best coverage. One interesting finding is that objects such as shrubs, trees and debris affect the signal propagation. Such objects can attenuate the signal by half its strength. Therefore, placing RSUs in zones where billboards or placards can block the propagation of signals should be avoided. The RSU should be placed around 20 to 30 feet above the ground to avoid the possibility of trucks, vehicles and other objects blocking the signals.

8.3. Manufacturer

There are several manufacturers available for DSRC-compatible OBUs and RSUs. Since the devices that were used in this field-testing experiment are from Arada Systems, the recommendations are mostly centered around them. Arada Systems has developed DSRC-compatible devices and a top layer SDK that allows for application layer apps to be developed and tested. The units are equipped with the capability of an external USB

Bluetooth module and runs a modified Linux kernel. Arada Systems does not allow access to the platform for programming lower layers, such as the MAC layer. This is important if an algorithm is necessary to be implemented at a lower level for better performance. Additionally, some of the experimentation requires access to the physical layer for signal analysis. Again, this is something that is restricted. Lastly, the backbone operating system of the Arada boxes are far from complete, but functional with several bugs. The devices would require severe modification if a complete system is to be implemented. Additionally, the hardware may need to be upgraded to allow better thread handling if multi-thread applications are to be developed.

Choda Wireless, Savari Networks, Kapsch and ITRI are several other manufacturers that are developing different kinds of devices for the DSRC based communication. Choda Wireless and Kapsch provide reliability through testing and integration in several pilots. ITRI is developing a DSRC card that is PCI-E based, which may allow lower-level control for DSRC innovations. Savari has developed a more unified system with video output and modular control. Depending on the application, testing out other manufacturers would be recommended for easier deployment.

8.4. Deployment Requirements

First, the software must be reprogrammed on the OBUs and RSUs as a complete system, which will exploit the standard usages of BSMs and implement additional features, such as collision avoidance and Bluetooth, in addition to the implementation of the proposed multi-hop algorithm and safety/emergency message dissemination application in the MAC layer. This process requires a programming team working in collaboration with the DSRC device manufacturers to get access to the device's source code for the lower physical (PHY) and MAC layers. Additionally, the RSU must be reprogrammed to have a unified packet used for TCP transmission to a local server for data collection and display. Currently, the application developed extracts the data from the RSU and uploads it to the web server to display the results on the website by using an internet hotspot. Secondly, additional manufacturers' devices should be tested and programmed to find a better set of equipment with reduced limitations. Currently, Arada Systems devices have a few limitations as threads are not controllable. Due to the lack of underlying source code, it is difficult to determine why certain threads do not close as intended. This can cause the application to fail and would require restarting. Hence, there is an additional necessity to redevelop the application as a core system application that will run at all times in the RSU and OBU.

Furthermore, the method of device installation in the vehicles has to be determined, and an embedded system has to be developed to make use of the devices. In other words, a system in which the driver can interact with the onboard unit is necessary. This system may be as straightforward as a phone application connected via Bluetooth or, more specifically, an embedded system with functions set to make use of the communication devices.

In the test-bed, DSRC devices are chosen from a vendor, Arada Systems, and all the source codes are written in accordance with the vendor-specific libraries and applications. Therefore, it is required to work with the vendor to optimize the algorithm at the MAC level and remove some technical issues from their systems, if a large scale deployment is needed. In addition, collaboration with various DSRC vendors is necessary to implement the proposed protocols in their DSRC devices to deploy a large scale multi-hop connected vehicle test bed in Georgia for unified complete connected vehicle systems. This next research step requires additional intensive labor, equipment and resources.

8.5. Data Collection

To improve transportation safety, efficient storage, retrieval and analysis of vehicle-related data, such as speed, is necessary. For example, suppose a sharp curve in a highway causes more than 80% of the drivers to slow down. Due to the real-time data from the vehicles, the relevant authorities could be alerted to this defect in the road, and thus, the error in the road can be corrected. This is a simple application, but other similarly innovative applications are possible through gathering sufficient statistical data. There are two methods of data collection in DSRC devices. One is through the collection of the BSM packets that are periodically transmitted by every vehicle. This can be a challenge as an OBU's range is around 300 meters on the road. In other words, to collect such data, several RSUs need to be placed close to each other, resulting in high costs. Alternatively, an application that takes the essential BSM data of the surrounding vehicles and propagates the data further within its own BSM is possible. This concept of a virtual radar map uses the BSMs to transmit the information that a vehicle obtains from other vehicles in a multi-hop type scenario by just using a few optional fields. Once this information reaches an RSU, the information can be transmitted and stored permanently. Simulation work was performed to see how fast a BSM would grow in size and how quickly it can propagate the information over a 1Km span based on the number of vehicles in the zone. Figure 43 demonstrated that it is possible to develop a system that can take information about other vehicles and store it and transmit it farther with very low delays. Additional work is necessary to reduce the size of the BSM by taking only the necessary information and propagating it farther. However, this demonstrates that RSUs can be placed at 1.6-1.8 Km distance apart and can still be used to collect much data of the surrounding vehicles and traffic.

An additional form of data collection is having a specific service channel used for transmitting data about the vehicles' positions, speed, movements, braking, sensory data and more to the RSUs for developing systems that can analyze such data for corrections, traffic control, safety applications, and future expansions. This system can function alongside the current standards and can be used to collect data a BSM omits.

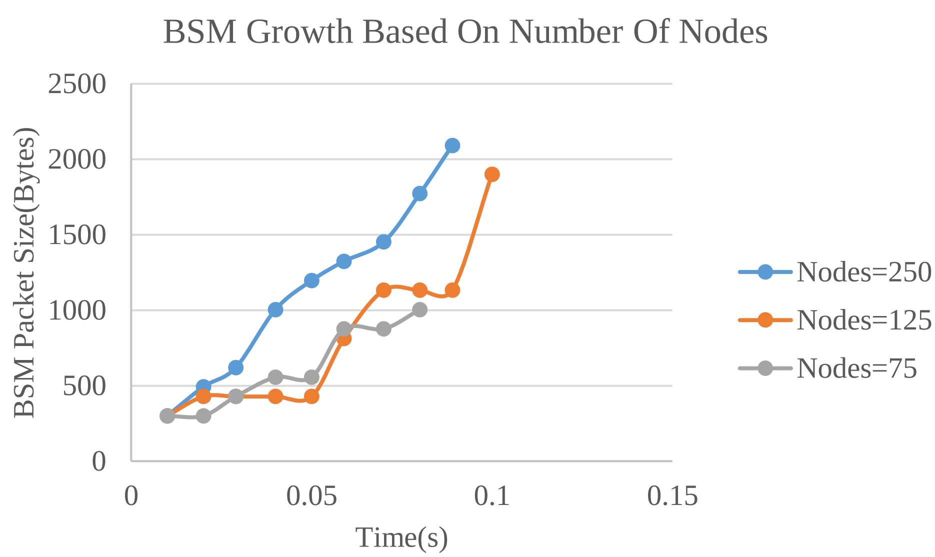


Figure 43

BSM Radar Map Development Simulation

8.6. Cost

Since the cost is a key aspect of having the overall system implemented, a study is required to determine the exact location, labor cost, material cost, installation and maintenance costs, as well as any other miscellaneous costs. This would determine both the location and method of installation of the roadside units (RSUs) and the exact height and direction, as well as any future maintenance needed to clear the line of sight. The typical cost of an OBU is around $1,500, while that of an RSU is $3,000. However, these devices would cost significantly lower once produced and deployed on a large scale.

Since the distance covered by one RSU is just above half a mile, placing the RSU devices every one mile would provide optimum coverage, especially for a road section such as Interstate 285. Interstate 285 would be an ideal location for a pilot test to gather vehicular data and for testing possible mass implementation everywhere. The road section contains beneficial line of sight, and it would help deploy a system used for information collection and safety measures, such as, but not limited to, the vehicular speeds, locations, zones of traffic congestions, lane usages, possible detection of dangerous zones, and zones that require improvement for better traffic control. Furthermore, it could provide analysis for travel time by tracking individual vehicles from point A to point B. The time it takes to travel such a distance can be recorded as well. This average across several vehicles can provide a more accurate and adaptive travel time. In addition, a cloud-based app could provide instantaneous tracking that would allow information about a specific zone to be acquired by everyone at all times. The next step would be a pilot implementation to further the possibility of intelligent transportation. The main recommendations mentioned in this report are on the basis of the research performed in this project. There are several other applications that could be developed from the research, such as connecting DSRC devices to cellular networks, using DSRC devices as detection devices for security alertness and for locating and tracking certain vehicles. The bare minimum infrastructure would first have to be installed and prepared to accommodate such applications.

9. Collision Avoidance

Part of the project's equipment and resources are allocated to develop a new method for providing collision avoidance services to drivers in the event that the information received in a BSM is erroneous. The existing Arada System's OBUs were used in addition to the purchase of vehicle-mounted antennas, a student MATLAB license, a software-defined radio, and a new laptop for developing the digital signal processing algorithms.

9.1.Introduction

Collision avoidance from the physical layer perspective in V2V networks is currently not being investigated within V2V. Instead, V2V networks rely heavily on safety message passing and the contents contained within the safety messages. Based on existing V2V protocol standards and using the allocated spectrum for V2V, the proposed framework can add to the safety benefits of V2V networks in the event that other V2V devices are misbehaving. By observing the received signal characteristics of safety messages, a driver could be alerted of a collision. The periodic broadcast of a safety message at a known transmit power is leveraged to identify events indicative of a collision. Preliminary research was conducted, and it revealed that false-alarm rates need to be lowered and detection rates need to be increased; however, the work conducted will allow future projects to design their own methods to improve upon. Accidents could be reduced and V2V enhanced to provide collision avoidance not just at the application layer, but also from the physical layer of the communication stack. By enabling V2V devices to sense the whereabouts of other transmitters regardless of the authenticity or accuracy of the data within safety messages, the reliability of V2V networks can advance toward making connected transportation safer.

9.2.Doppler Domain Analysis for Collision Avoidance

A collision avoidance method using the Doppler shift, published by Kihei et al. [14], focused on tracking the Doppler shift experienced at the receiver as the sender and receiver moved relative to each other to predict if a collision was likely. In work, a creative architecture is proposed that employs Doppler domain analysis to determine the threat of collision, without suggesting any changes to existing DSRC protocols. Prior to this study, tracking the Doppler shift changes over time had not been considered for DSRC collision avoidance applications.

A. The Doppler Effect

The Doppler Effect is a phenomenon that signals either transmitted or received from a moving vehicle experience. As vehicles move relative to each other, the received carrier signal containing an SM is either compressed or expanded. The carrier frequency becomes offset $\pm\Delta f$ (known as the Doppler shift), hereafter referred to as F_D. The Doppler shift for two vehicles approaching each other on a two-lane highway is featured in the equation below, where the carrier wavelength is λ, S is the speed, φ is the bearing angle, and ψ is the angle of V_{T_x} off of the bearing angle.

$$F_D = \frac{V_{R_x}^S \cos\left(V_{T_x}^{\varphi}\right) + V_{T_x}^S \cos\left(V_{T_x}^{\psi}\right)}{\lambda} \quad (9.1)$$

B. Tracking Doppler Shift

Once carrier recovery is performed, the receiver can estimate the Doppler shift, denoted as $\widehat{F_D}$. Tracking the Doppler shift over time can provide the system with an estimation of a collision likelihood as the sender approaches, as illustrated in Figure 44. During normal travel, when the receiving vehicle, V_{R_x} and transmitting vehicle, V_{T_x} are far away, the angle between them is very small for a typical highway; thus, $\widehat{F_D}$ is at the highest possible value for their speeds. As V_{R_x} and V_{T_x} approach, the angle between them increases, and $\widehat{F_D}$ decreases. If V_{T_x} departs the lane and maintains a *constant bearing* on V_{R_x}, $\widehat{F_D}$ will not change over time.

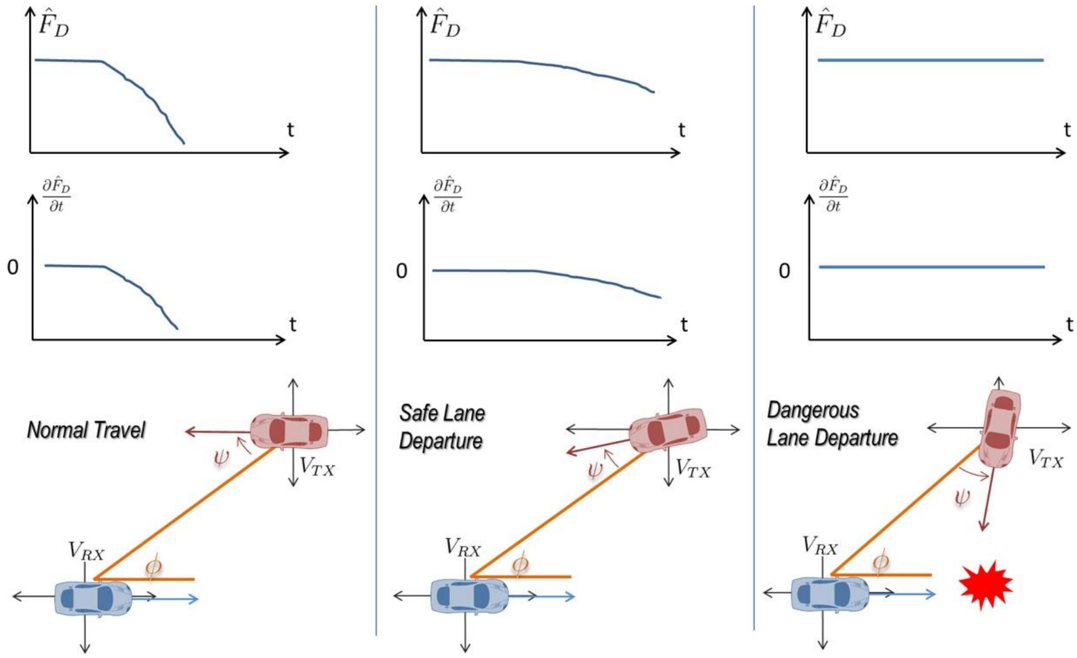


FIGURE 44

Tracking Doppler Shift for Several Scenarios

C. Likelihood Estimation

By tracking the rate of change of the Doppler shift using a sliding observation window, a collision estimator was created to map the rate of change in the Doppler shift, $D_{\Delta rate}$, to an angle off of the bearing angle between V_{R_x} and V_{T_x}, to estimate the angle that the heading of V_{T_x} makes with the collision line. A timeline of the collision likelihood estimation can be seen in Figure 45A.

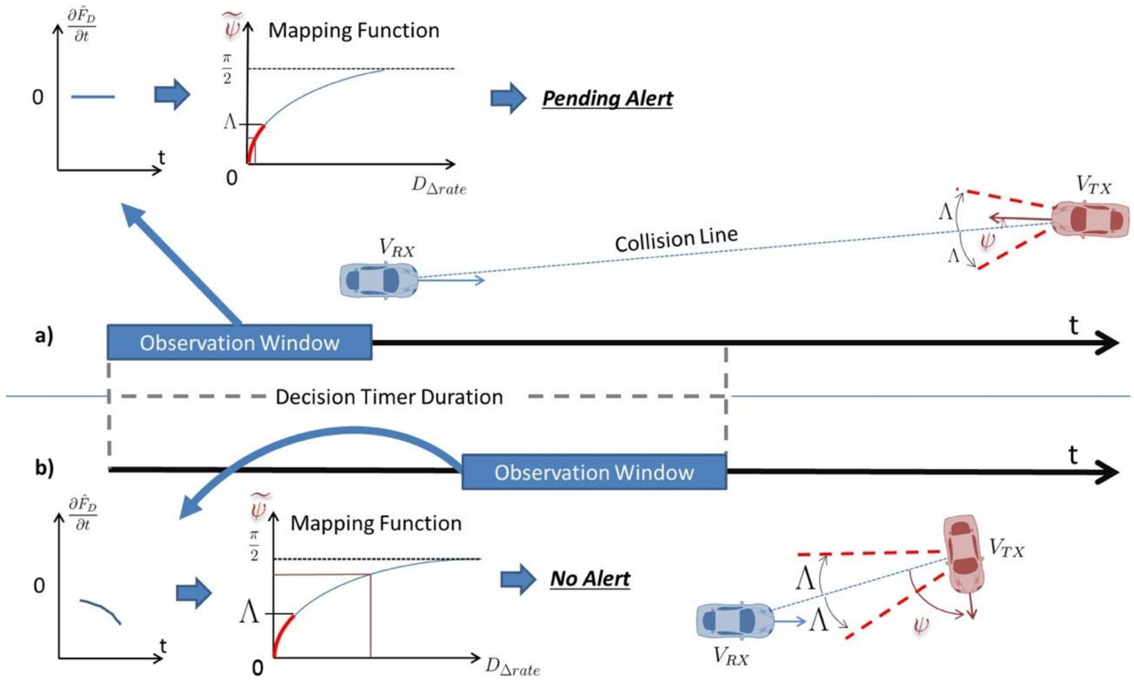


FIGURE 45

Estimating Collision Likelihood from: A) Initial Detection Far-Away and B) At End of Decision Timer Duration

Decision Timer Duration: At the first few receptions of an SM, $\widehat{F_D}$ will tend not to change much, given large transmission ranges. With $\widehat{F_D}$ being positive, the system begins a decision timer that counts down how long $\widehat{F_D}$ is allowed to stay constant before an alert is given to the driver of V_{R_x}. If V_{T_x}stays on the collision line when the timer expires, $\widehat{F_D}$ will remain relatively the same as initially estimated; thus, a collision is likely to happen.

Sliding Observation Window: The observation window captures $\widehat{F_D}$ measurements from successive receptions of SMs at the beaconing rate and is represented as $\overline{\widehat{F_D}}$. The observation window is how far back in sample time the system will go to estimate the rate of change of $\widehat{F_D}$. The derivative of those samples over sample time estimates the slope and denoted as $\frac{d\overline{\widehat{F_D}}}{dt}$, which is then averaged to estimate the Doppler change rate, $D_{\Delta rate}$.

Mapping Function: The mapping function relates to the $D_{\Delta rate}$ to the angle that V_{T_x} the heading is off from the collision line. The function is initially chosen as a side-parabola that ranges from *0 to* $\frac{\pi}{2}$, because of preliminary results from this study modeling $D_{\Delta rate}$versus ψ reveal a parabolic relationship.

Divergent Angle Threshold: After the Doppler change rate makes an estimate, the angle is compared to a threshold, denoted as Λ. Λ sets the limit as to how far V_{T_x} heading, denoted as $\tilde{V}_{T_x}^{\psi}$, needs to be off the collision line to ensure a collision will not happen. When the decision timer reaches 0, if $0 \leq \tilde{V}_{T_x}^{\psi} \leq \Lambda$, then V_{T_x} is assumed to still be at a collision heading with V_{R_x}, and the driver is alerted. If $\tilde{V}_{T_x}^{\psi} > \Lambda$, then it is assumed that V_{T_x} is not on a collision course with V_{R_x}, as depicted in Figure 45B.

D. Expected Performance

The expected performance of the theoretical system in detecting a collision was analyzed in a custom MATLAB simulation. Local oscillator and sampling offset errors were introduced to simulate the errors in the measurement of the bearing angle and $\widehat{F_D}$. The decision from the system was compared against a real collision outcome. The best achievable detection rate was 60.87%. As shown in Figure 46, the optimum Λ and observation window would be about .5236 radians and 7.82 to 8.911 seconds, respectively, to obtain a probability of detection of 43.6% and the best probability of false alarm of 41.7%. Due to the close horizontal spacing between vehicles traveling on opposite lanes, it will be difficult for the current mapping function, which was determined from simulations of farther spaced vehicles, to properly map the Doppler change rate to the

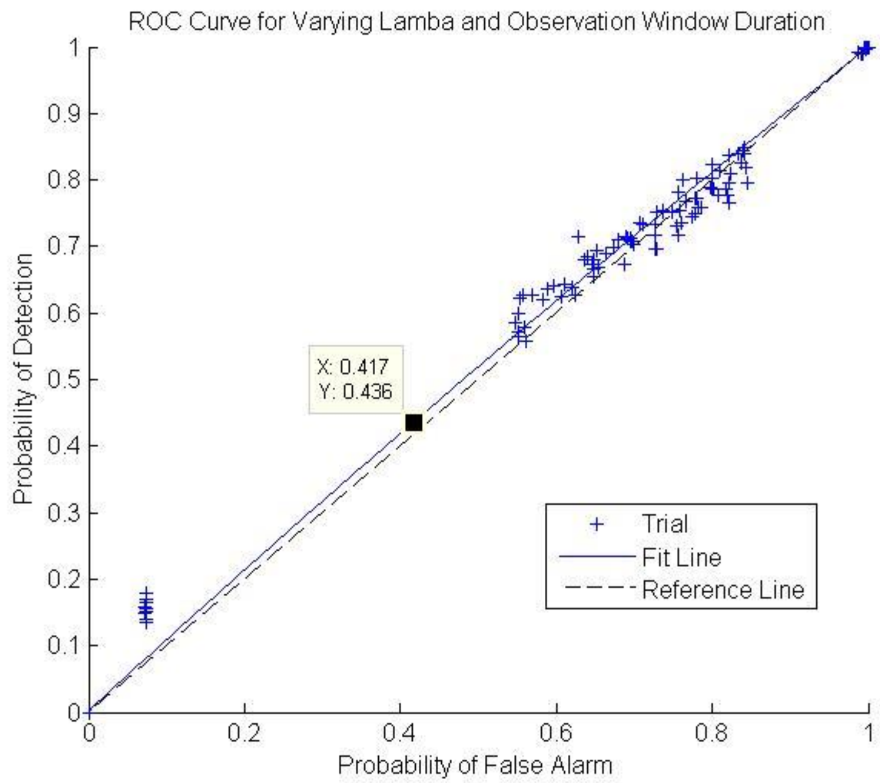


FIGURE 46

System Performance Under Multiple-Combinations

heading displacement angle correctly. If the proper mapping function is not used, the system could exhibit more false-alarms.

9.3.Received Signal Strength-based Collision Avoidance

The received signal strength indication (RSSI) was investigated for its capability to provide collision avoidance to drivers in V2V networks and is currently pending publication by Kihei et al. [15]. Experimental observations of RSSI during collision and no-collision outcomes were analyzed to develop the system's prediction methodology. The system is not a misbehavior detection scheme (MDS), but could complement one by independently providing real-time collision avoidance from misbehaving nodes, even if the receiver is also misbehaving. The system does not use traditional RSS distance estimation, fingerprinting, or cooperative methods, which depend heavily on prior knowledge of path loss conditions. Instead, the decentralized system identifies specific trends in RSSI indicative of a collision, which circumvents the need to know the path loss. The 802.11 standard specifies that RSSI is to be measured from the preamble of received packets, but does not specify how to interpret RSSI or the maximum value. Due to this open definition, RSSI functions as a proxy of the actual signal quality or strength. An RSSI value is typically a unit-less value from an arbitrary scale decided by the radio manufacturer. The key property of RSSI is that for both LOS and NLOS conditions, RSSI is inversely proportional to the separation distance between transmitter and receiver.

A. Experimental Observations

An RSSI measurement campaign was conducted in a suburban environment while performing pre-crash scenarios that could result in a collision or no-collision outcomes. Figure 47 reveals the RSSI logged only by one car for both collision and no-collision outcomes. The first observation is that using the raw RSSI value is not desirable for discerning between a collision and no-collision outcome. The curvature (or shape) of the RSSI trend line reveals a more discernable characteristic across the pre-crash scenarios. For each no-collision outcome, the dilemma zone captures the conservative driver behavior of the receiver as a slower rate of increase toward the maximum RSSI value, contrasted with the collision outcome in which the driver of the receiver maintains a constant velocity, causing a faster rate of increase toward the maximum RSSI value.

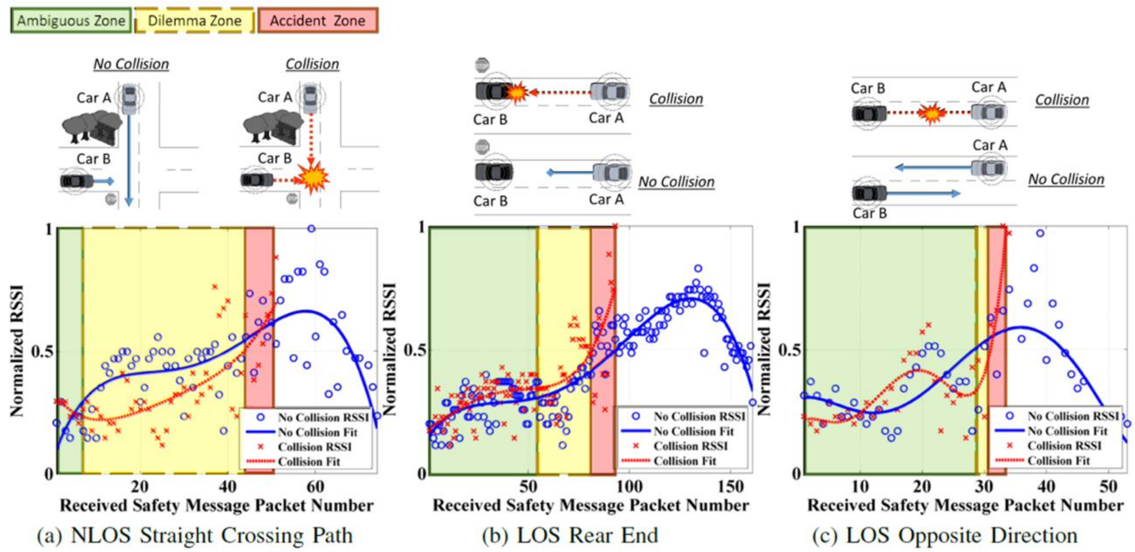


FIGURE 47

RSSI Trend between Two Cars for: Collision (Dashed, X's) and No-Collision (Solid, Circles) Outcomes in Three Pre-Crash Scenarios.

B. Relating vehicle dynamics to RSSI

The study discovered that RSSI must be treated as a proxy for the received signal power, P_r, to understand how vehicle dynamics affect what is observed in the RSSI trend. The classic power law path loss model is

$$P_r(t) = P_t + G_t + G_r + PL(t) \tag{9.2}$$

where P_t is the transmit power in dBm, G_t and G_r are antenna gains in dBi, and $PL(t)$ is the time-dependent path loss in dB modeled as

$$PL(t) = PL_0 + 10\gamma log\left(\frac{c_0}{f_c 4\pi \frac{d(t)}{d_0}}\right) + X_\sigma(t), for\ d(t) \geq d_0 \tag{9.3}$$

This study described the relationship between vehicle dynamics and the RSSI curvature (i.e., RSSI trend "acceleration") by taking the 2nd derivative to obtain

$$\ddot{P}_r(t) = \frac{10\gamma(\dot{d}(t)^2 - d(t)\ddot{d}(t))}{d(t)^2} \quad (9.4)$$

As shown by the previous equation, the path loss exponent (γ) acts as a gain factor for the curvature, indicating that for high path loss environments, such as NLOS, the curvature will increase or decrease faster for the same separation distance. At large separation distances, $d(t)^2$ dominates to reduce the curvature to a small value. This is analogous to the ambiguous zones from Figure 47, in which both collision and no-collision outcomes appear similar. In the dilemma zone, where the distance between the vehicles is shorter, the sign of $\ddot{P}_r(t)$ is determined by the relative velocity between the vehicles, $\dot{d}(t)^2$, which dominates how fast the received signal power will increase to reveal either a positive curvature, indicating a potential collision, or negative curvature, indicating no-collision. Higher speeds will increase $\ddot{P}_r(t)$, but when vehicles brake as captured by the relative acceleration, $\ddot{d}(t)$, the curvature will decrease.

A set of criteria to predict a potential collision was then developed. Any transmitter moving away from the receiver at a faster rate than the receiver is approaching poses no threat, indicated by $\ddot{P}_r(t) < 0$. If the curvature is observed to be $\ddot{P}_r(t) = 0$, such as when vehicles convoy at the same speed, a collision will not occur. Another observation is that $\ddot{P}_r(t) > 0$ does not always indicate that a collision will occur; for example, during vehicle braking, $\ddot{P}_r(t)$ will have decreasing positive values until $\dot{d}(t)^2 = d(t)\ddot{d}(t)$. Therefore, an additional condition must be placed on $\ddot{P}_r(t)$ to correctly predict a collision: if $\ddot{P}_r(t) > 0$ and is either increasing or remaining constant, a collision will occur. This concept is the relative "jerk" between the vehicles, $\dddot{P}_r(t)$.

9.4.Reducing False Alarms Using DOA

False alarms can arise in the ambiguous zone when a car first begins receiving packets where a collision is indistinguishable from a no-collision outcome. A false alarm can also occur during the Opposite Direction scenario, as seen in Figure 47B, in which the ambiguous zone is large and the dilemma zone is small. Because vehicles often travel in the opposite lane configuration, this particular source of false alarms was further investigated.

The RSSI measurement campaign was expanded past the two-vehicle study to observe RSSI for multiple vehicles transmitting. Four vehicles were equipped with either a dome (6dBi) or whip (9dBi) omnidirectional antenna. Figure 48A depicts the experiment for a no-collision outcome, and Figure 48B depicts the collision outcome. The Rear End pre-crash scenario between Car A and Car B is observed, with one non-threating vehicle, Car D, following behind Car A in a convoy formation, while another non-threating vehicle, Car C, travels in the opposite direction in the opposite lane at high speed.

Using the direction of arrival (DOA) to segment the region of reception reduces the prediction complexity from three to one, which would allow predicting an accident for a specific region of Car A. Under NLOS, the packet reception could come from any angle; therefore, an additional stream should consider the RSSI from all DOA regions to detect large spikes above the noise of RSSI from other non-threatening vehicles. The system block diagram is presented in Figure 49.

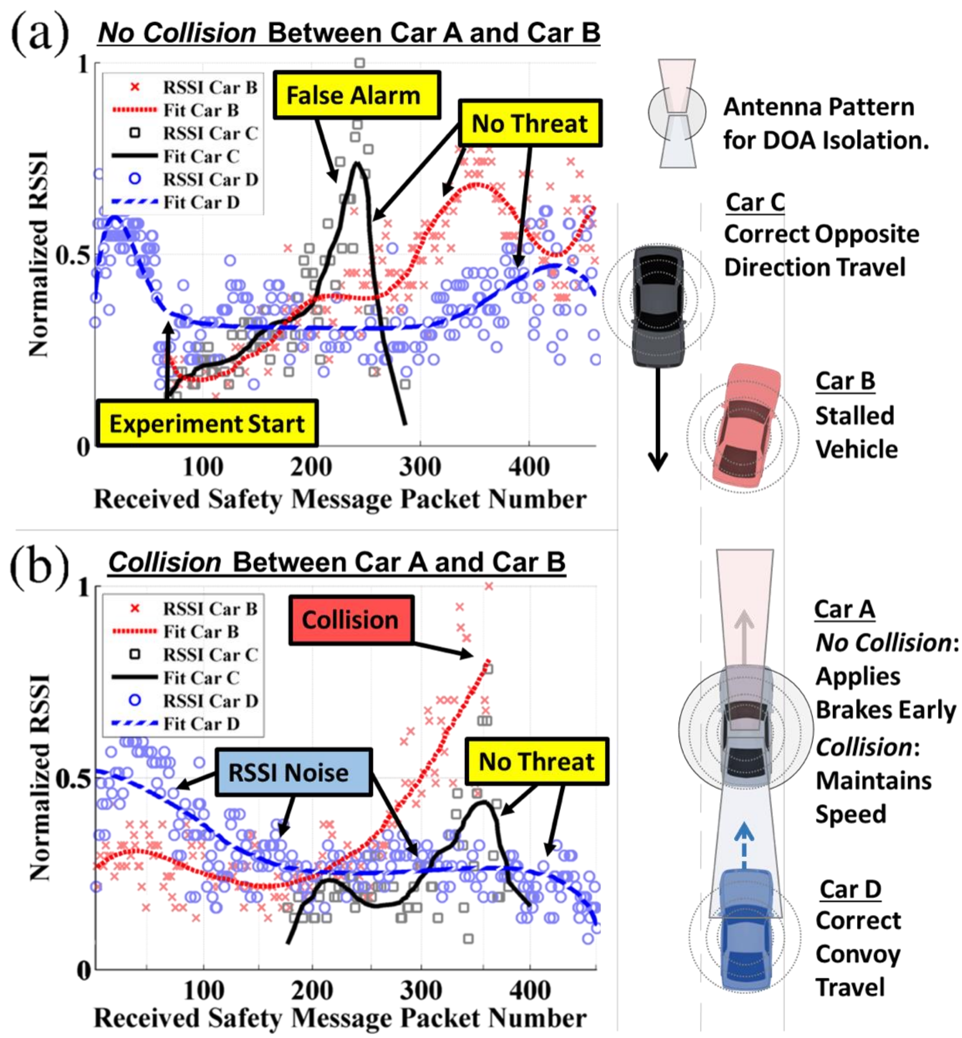


FIGURE 48

RSSI trends as recorded by Car A among multiple nodes for Rear End pre-crash scenario. If DOA is available, then RSSI values from Car C could be localized to the opposite lane to suppress a false-alarm and reduce prediction complexity among multiple nodes.

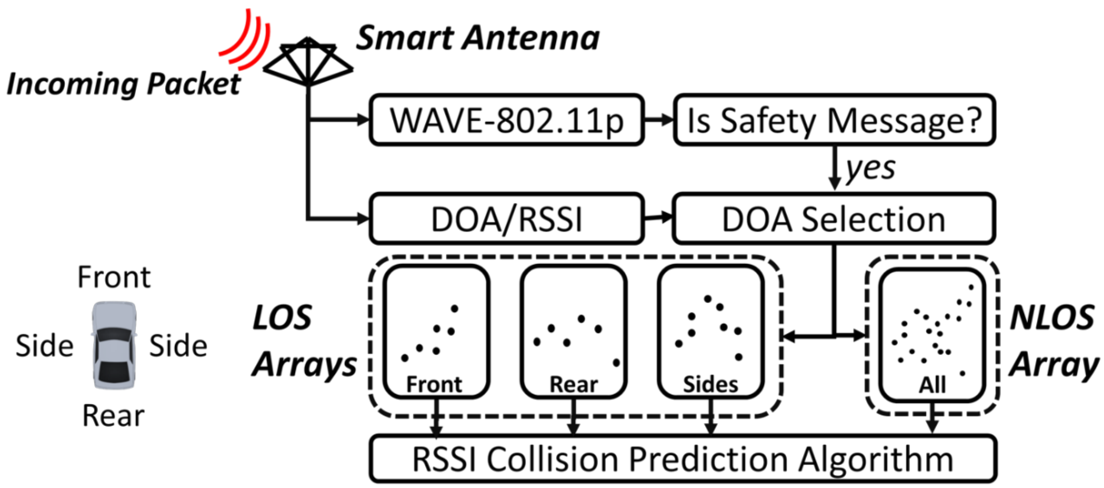


FIGURE 49

RSSI Collision Prediction System

A. Expected Performance

The theoretical system and RSS-distance method were evaluated under various channel conditions in a custom MATLAB script. The results are reported in Figure 50. For LOS and NLOS, the system sustains a detection rate above 45% across each speed test, outperforming the RSS-distance method by reliably predicting on average over 35% more collisions. In contrast, the RSS-distance method performs poorly in LOS with a very low detection rate. Though detection and false-alarm rates are low for higher speeds, this is attributed to the SM beacon rate (f_{SM}) not providing enough RSSI samples, indicating that a higher f_{SM} would be needed to provide more accurate estimations. In NLOS, the RSS-distance method suffers from very poor detection rates and high false-alarm rates. This is expected because the variance in the path loss exponent is higher for NLOS than for LOS, which increases the estimation error.

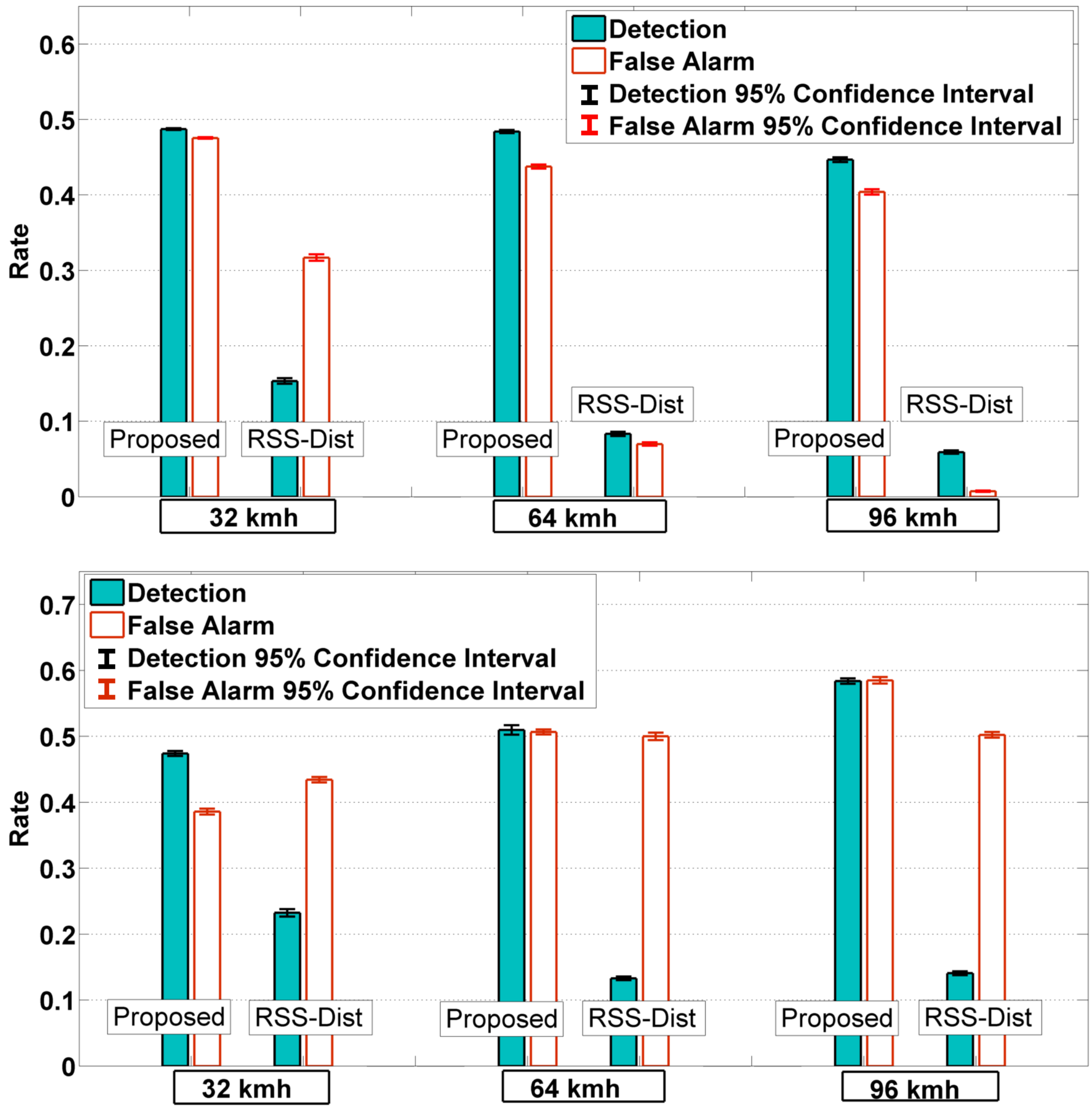


FIGURE 50

Performance Outcome for: A) LOS Rear End, and B) NLOS Straight Crossing Path (Intersection).

10. Conclusion

The objective of this research is to provide feasible solutions to disseminate emergency messages through connected vehicle V2V and V2I communications to improve transportation safety on the road. To create a reliable platform/testbed to develop and experiment with innovative networking technologies, novel algorithms are designed, simulated, implemented and tested on Georgia highways and local roadways to verify the feasibility of the proposed methods. Through the rigorous analysis and field trials, it is shown that the implemented connected vehicle technologies for V2V and V2I are effective and feasible solutions that could be deployed on Georgia highways and local roadways. In typical scenarios, the placement of an RSU in each mile is sufficient to deliver emergency messages among the vehicles in the area. By integrating and processing the IEEE 802.11p DSRC physical layer signals in a novel way, V2V and V2I safety functionality could be even further improved to provide collision avoidance services to drivers or autonomous systems on the roads.

In addition, ITS applications for collision warning and avoidance can be easily incorporated into this system. Traffic information can be also propagated through V2V and V2I connected vehicle communications that can be used to perform statistical analysis of real-world data to optimize transportation traffic flows. Human causalities and social expenses will be dramatically reduced. USDOT expects to reduce vehicular collisions through the implementation of DSRC by 76%. Furthermore, over 415 million metric tons of carbon emissions could be eliminated. These innovative technologies will deliver real-time traffic information to optimize transportation traffic flows, which will contribute to sustainable environments.

References:

1) J. Zhu and S. Roy, "MAC for dedicated short-range communications in intelligent transport system," *Communications Magazine, IEEE*, vol. 41, no. 12, pp. 60–67, 2003.
2) E. Fasolo, A. Zanella, and M. Zorzi, "An effective broadcast scheme for alert message propagation in vehicular ad hoc networks," in *ICC'06. IEEE International Conference on Communications, 2006.*, vol. 9. IEEE, 2006, pp. 3960–3965.
3) J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1162–1182, 2011.
4) F. Khan, Y. Chang, S.J. Park, and J. Copeland, "Handshaking vs. instant broadcast in VANET safety message routing," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*. IEEE, 2011, pp. 724–729.
5) G. Korkmaz, E. Ekici, F. Ozguner, and U. Ozguner, "Urban multi-hop broadcast protocol for inter-vehicle communication systems," in *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks*. ACM, 2004, pp. 76–85.
6) S. Bai, Z. Huang, D. Kwak, S. W. Lee, H. Oh, and J. Jung, "Vehicular multi-hop broadcasting protocol for safety message dissemination in VANETs," in *Vehicular Technology Conference (VTC 2009-Fall), 2009 IEEE 70th*. IEEE, 2009, pp. 1–5.
7) M. Li, W. Lou, and K. Zeng, "Oppcast: Opportunistic broadcast of warning messages in VANETs with unreliable links," in *Mobile Adhoc and Sensor Systems, 2009. MASS'09. IEEE 6th International Conference on*. IEEE, 2009, pp. 534–543.
8) M. Durresi, A. Durresi, and L. Barolli, "Emergency broadcast protocol for inter-vehicle communications," in *Parallel and Distributed Systems, 2005. Proceedings. 11th*

International Conference on, vol. 2. IEEE, 2005, pp. 402–406.

9) M.-R. Park, D. Kim, and S.H. Kim, “A Simple SNR Based Linear Back-Off to Propagate Multi-hop Emergency Messages on the Distributed VANETs,” in *Computer Applications for Modeling, Simulation, and Automobile*. Springer, 2012, pp. 34–41.

10) C. Jang and J. H. Lee, “Path selection algorithms for multi-hop VANETs,” in *Vehicular Technology Conference (VTC 2010-Fall), 2010 IEEE 72nd*. IEEE, 2010, pp. 1-5.

11) R. Voicu, H. Abbasi, H. Fang, B. Kihei, J. Copeland, and Y. Chang, “Fast and Reliable Broadcasting in VANETs using SNR with ACK Decoupling,” in *Int’l Conference on Communications (ICC)*. IEEE, 2014.

12) National Highway Traffic Safety Administration, "2011 motor vehicle crashes: overview. *Report no. DOT HS-811-701," US Department of Transportation*, Washington, D.C., USA, 2012.

13) L. Blincoe, A. Seay, E. Zaloshnja, T. Miller, E. Romano, S. Luchter and a. Spicer, "The economic impact of motor vehicle crashes 2000. *Report no. DOT HS-809-446," National Highway Traffic Safety Administration*, Washington, D.C., USA, 2002.

14) Kihei, B.; Copeland, J.A.; Yusun Chang, "Doppler domain localization for collision avoidance in VANETs by using omnidirectional antennas," in *Connected Vehicles and Expo (ICCVE), 2014 International Conference on*, vol., no., pp.331-337, 3-7 Nov. 2014

15) Kihei, B.; Copeland, J.A.; Yusun Chang, “Predicting Accidents in VANETs with RSS”, IEEE GlobeCom 2015, San Diego, CA, USA

16) H. Yoo and D. Kim, “ROFF: Robust and Fast Forwarding in vehicular ad-hoc networks,” IEEE Trans. Mobile Computing, DOI:10.1109/TMC.2014.2359664, 2014.

17) N. Wisitpongphan , "Routing in sparse vehicular ad hoc wireless networks" , *IEEE 1. Sel. Areas Commun.* , vol. 25 , no. 8 , pp.1538 -1556 , 2007

18) D. Li, H. Huang, X. Li, M. Li, and F. Tang, "A distance-based directional broadcast protocol for urban vehicular ad hoc network," in *Proc. IEEE Int'l Conf. on Wireless Comm., Networking and Mobile Computing (WiCom)*, Shanghai, China, Sep. 2007, pp. 1520–1523.

19) N. Wisitpongphan, O. K. Tonguz, J. S. Parikh, P. Mudalige, F. Bai, and V. Sadekar, "Broadcast storm mitigation techniques in vehicular ad hoc networks," *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 84–94, Dec. 2007.

20) H. Alshaer and E. Horlait, "An optimized adaptive broadcast scheme for inter-vehicle communication," in Proc. IEEE Vehicular Technology Conf. (VTC), Stockholm, Sweden, May 2005, pp. 2840–2844.

21) A. Wegener, H. Hellbr¨uck, S. Fischer, C. Schmidt, and S. Fekete, "AutoCast: An adaptive data dissemination protocol for traffic information systems," in Proc. IEEE Vehicular Technology Conf. (VTC), Baltimore, MD, Sep. 2007, pp. 1947–1951.

22) R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000.

23) R. W. Yeung, "Network coding: A historical perspective," *Proc. IEEE*, vol. 99, no. 3, pp. 366–371, Mar. 2011.

24) Katti, H. Rahul, W. Hu, D. Katabi, M. Medrad, and J. Crowcroft, "XORs in the air: Practical wireless network coding," *IEEE/ACM Trans. Netw.*, vol. 16, no. 3, pp. 497–510, Jun. 2008.

25) Georgios Karagiannis, Onur Altintas, Eylem Ekici, Geert Heijenk, Boangoat Jarupan, Kenneth Lin, and Timothy Weil, *"Vehicular Networking: A Survey and Tutorial on Requirements, Architectures, Challenges, Standards and Solutions"*

26) Sooksan Panichpapiboon, and Wasan Pattara-atikom, *"A Review of Information Dissemination Protocols for Vehicular Ad Hoc Networks"*

27) Rex Chen, Wen-Long Jin, and Amelia Regan, *"Broadcasting Safety Information in Vehicular Networks: Issues and Approaches"*

28) Arada Systems, "LocoMate™ ASD with Dual DSRC Radios | On-Board Unit" Part No. ASD 205

http://www.aradasystems.com/wp-content/uploads/2014/05/Arada_datasheet_ASD_v2.05.pdf

29) Arada Systems, "LocoMate™ RSU | Road Side Unit with NEMA Enclosure" Rev. 2.0.6

http://www.aradasystems.com/pdfs/ARADA_LocoMate_RSU_Datasheet_v2.0.pdf

30) H. Abbasi, R. Voicu, J. Copeland, and Y. Chang, "*Performance Analysis and Optimization of a Contention Window based Broadcasting Algorithm in VANETs*," in Proceedings of IEEE Global Communication Conference (Globecom), San Diego, CA, Dec. 2015.

31) H. Abbasi, R. Voicu, J. Copeland, and **Y. Chang**, "Towards fast and reliable multi-hop routing in VANETs." IEEE Transactions on Mobile Computing. 2019 Jun 17.

APPENDICES:

Appendix A: Sample Log Data from an OBU during a Multi-Hop Field Experimentation

The following log was captured during an experimental run on Highway Interstate 75 N/S Between exits 254 to 258. The experiment was run from 3:30PM to 6:30PM on December 12, 2015. The following vehicles were equipped with OBU: Billy, Brian, Amanda, Andrew, Lucian and Hamza. One RSU was placed on the side of Interstate 75N approximately mid-way between exit 255 and 256. This allowed for sufficient visibility to the OBUs from the RSU. The RSU was set up with a vehicle labeled (Chris). Messages were exchanged during the driving tests to perform multi-hop transmissions for data collection and proof of concept. The following log presents the data that was captured on one OBU installed in the vehicle named “Hamza”.

#	Sys Time	µs	SID	Ver	Channel	TX_Power	PKT ID	Lat	Long	Alt	Date	Sender	Forwarder	Message	Alt			Distance	Cwmax	CWChosen	Type
1	1449962014	741895	5	2	172	14	21237	33.848427	-84.429142	215.5	121215	billy3	lucian3	RANDOM	216.3	RSSI	32	45.958113	71	1	1
2	1449962014	744808	0	1	0	0	21237	33.848085	-84.429422	212.7	121215	billy3	hamza3	RANDOM	216.3	Type	2				
3	1449962017	819743	5	2	172	14	19814	33.848596	-84.429193	216.2	121215	billy3	amanda3	RANDOM	215.9	RSSI	29	64.001526	46	5	1
4	1449962017	825773	0	1	0	0	19814	33.848068	-84.42947	212.4	121215	billy3	hamza3	RANDOM	215.9	Type	2				
5	1449962023	419718	5	2	172	14	20051	33.848792	-84.429253	215.6	121215	billy3	N	RANDOM	215.6	RSSI	24	86.005522	29	2	1
6	1449962023	422773	0	1	0	0	20051	33.84805	-84.429518	212.2	121215	billy3	hamza3	RANDOM	215.6	Type	2				
7	1449962046	256746	5	2	172	14	12292	33.848112	-84.429371	213.1	121215	billy3	lucian3	RANDOM	213.9	RSSI	36	53.569378	69	23	1
8	1449962046	283808	0	1	0	0	12292	33.847637	-84.42947	211.7	121215	billy3	hamza3	RANDOM	213.9	Type	2				
9	1449962150	16540	5	2	172	14	4879	33.846995	-84.429073	212.1	121215	billy3	brian3	RANDOM	211.9	RSSI	31	43.952482	71	34	1
10	1449962150	51690	0	1	0	0	4879	33.84668	-84.428785	209.7	121215	billy3	hamza3	RANDOM	211.9	Type	2				
11	1449962164	16410	5	2	172	14	10845	33.846798	-84.428872	211.9	121215	billy3	N	RANDOM	211.9	RSSI	33	55.90274	60	12	1
12	1449962164	30771	0	1	0	0	10845	33.846303	-84.42898	210.3	121215	billy3	hamza3	RANDOM	211.9	Type	2				
13	1449962164	360469	5	2	172	14	10845	33.846685	-84.428769	212	121215	billy3	brian3	RANDOM	211.9	RSSI	22	50.753022	49	0	1
14	1449962166	823801	5	2	172	14	12860	33.84672	-84.428796	211.8	121215	billy3	N	RANDOM	211.8	RSSI	28	69.213637	41	37	1
15	1449962166	837088	5	2	172	14	12860	33.846293	-84.428997	212.6	121215	billy3	lucian3	RANDOM	211.8	RSSI	47	25.379719	212	8	1
16	1449962179	951759	5	2	172	14	1899	33.84685	-84.430111	214.7	121215	billy3	lucian3	RANDOM	213	RSSI	47	51.599086	104	10	1
17	1449962179	968236	0	1	0	0	1899	33.847291	-84.430286	214.4	121215	billy3	hamza3	RANDOM	213	Type	2				
18	1449962180	17634	5	2	172	14	1899	33.846351	-84.429706	214.1	121215	billy3	amanda3	RANDOM	213	RSSI	40	117.37473	36	15	1
19	1449962182	766003	5	2	172	14	8827	33.846223	-84.42945	213.5	121215	billy3	N	RANDOM	213.5	RSSI	27	180.564993	15	14	1
20	1449962182	785772	0	1	0	0	8827	33.847643	-84.430401	215.5	121215	billy3	hamza3	RANDOM	213.5	Type	2				
21	1449962182	817967	5	2	172	14	8827	33.847214	-84.430259	215.4	121215	billy3	lucian3	RANDOM	213.5	RSSI	47	49.441249	108	49	1
22	1449962182	820404	5	2	172	14	8827	33.846589	-84.429944	214.6	121215	billy3	amanda3	RANDOM	213.5	RSSI	41	124.488637	35	1	1
23	1449962186	316383	5	2	172	14	24685	33.846337	-84.429692	213.9	121215	billy3	N	RANDOM	213.9	RSSI	24	225.186882	11	6	1
24	1449962186	324770	0	1	0	0	24685	33.848228	-84.430569	218	121215	billy3	hamza3	RANDOM	213.9	Type	2				
25	1449962186	343265	5	2	172	14	24685	33.846696	-84.43002	214.1	121215	billy3	brian3	RANDOM	213.9	RSSI	42	177.623721	25	12	1
26	1449962189	148385	5	2	172	14	16265	33.847344	-84.430302	215.9	121215	billy3	amanda3	RANDOM	214.3	RSSI	30	164.333023	18	17	1
27	1449962189	176777	0	1	0	0	16265	33.84879	-84.430675	220.6	121215	billy3	hamza3	RANDOM	214.3	Type	2				
28	1449962189	247952	5	2	172	14	16265	33.847983	-84.4305	218.1	121215	billy3	lucian3	RANDOM	214.3	RSSI	44	91.120745	53	8	1
29	1449962196	319293	5	2	172	14	8789	33.847048	-84.4302	215.5	121215	billy3	N	RANDOM	215.5	RSSI	18	361.94287	6	3	1
30	1449962196	324198	0	1	0	0	8789	33.85027	-84.430774	223.7	121215	billy3	hamza3	RANDOM	215.5	Type	2				
31	1449962196	331054	5	2	172	14	8789	33.848426	-84.430633	220.5	121215	billy3	amanda3	RANDOM	215.5	RSSI	30	205.327478	14	3	1
32	1449962202	555068	5	2	172	14	31607	33.850439	-84.430778	224.9	121215	billy3	lucian3	RANDOM	218	RSSI	41	131.094527	33	29	1
33	1449962202	598707	0	1	0	0	31607	33.851618	-84.430827	222.9	121215	billy3	hamza3	RANDOM	218	Type	2				
34	1449962222	220045	5	2	172	14	10380	33.85093	-84.430791	224.9	121215	billy3	N	RANDOM	224.9	RSSI	24	589.6353	5	2	1
35	1449962222	223779	0	1	0	0	10380	33.856113	-84.432159	219.4	121215	billy3	hamza3	RANDOM	224.9	Type	2				
36	1449962222	434705	5	2	172	14	10380	33.854721	-84.431665	217.3	121215	billy3	lucian3	RANDOM	224.9	RSSI	39	161.263987	30	23	1
37	1449962229	927062	5	2	172	14	12245	33.853966	-84.431429	216.1	121215	billy3	brian3	RANDOM	221	RSSI	25	441.863975	6	3	1
38	1449962229	931776	0	1	0	0	12245	33.857714	-84.433028	221.9	121215	billy3	hamza3	RANDOM	221	Type	2				
39	1449962232	258608	5	2	172	14	4028	33.854905	-84.431715	217.2	121215	billy3	amanda3	RANDOM	218.8	RSSI	29	379.206427	9	4	1
40	1449962232	265800	0	1	0	0	4028	33.858064	-84.433269	222.5	121215	billy3	hamza3	RANDOM	218.8	Type	2				
41	1449962234	416268	5	2	172	14	5390	33.85341	-84.431253	217.4	121215	billy3	N	RANDOM	217.4	RSSI	24	607.753128	5	0	1
42	1449962234	417817	0	1	0	0	5390	33.858513	-84.433622	223.4	121215	billy3	hamza3	RANDOM	217.4	Type	2				
43	1449962261	116195	5	2	172	14	14350	33.862343	-84.436984	244	121215	billy3	lucian3	RANDOM	224.7	RSSI	47	69.265539	94	20	1

44	1449962261	137774	0	1	0	0	14350	33.862848	-84.437424	246.7	121215	billy3	hamza3	RANDOM	224.7	Type	2				
45	1449962267	925424	5	2	172	14	28341	33.861828	-84.436513	241.6	121215	billy3	amanda3	RANDOM	230.3	RSSI	23	271.021559	11	6	1
46	1449962267	933770	0	1	0	0	28341	33.863791	-84.438256	250.6	121215	billy3	hamza3	RANDOM	230.3	Type	2				
47	1449962272	23676	5	2	172	14	28780	33.864044	-84.438482	250.8	121215	billy3	lucian3	RANDOM	234.9	RSSI	47	35.740664	183	172	1
48	1449962272	202696	0	1	0	0	28780	33.864399	-84.438791	252	121215	billy3	hamza3	RANDOM	234.9	Type	2				
49	1449962293	545764	5	2	172	14	28008	33.867415	-84.441374	245.4	121215	billy3	lucian3	RANDOM	252.1	RSSI	31	117.184911	32	29	1
50	1449962293	580691	0	1	0	0	28008	33.868333	-84.441999	240.7	121215	billy3	hamza3	RANDOM	252.1	Type	2				
51	1449962294	829048	5	2	172	14	10319	33.866002	-84.440187	251.4	121215	billy3	brian3	RANDOM	252.5	RSSI	20	339.37129	9	5	1
52	1449962294	835775	0	1	0	0	10319	33.868582	-84.442155	239.5	121215	billy3	hamza3	RANDOM	252.5	Type	2				
53	1449962294	847428	5	2	172	14	10319	33.866559	-84.440663	250.3	121215	billy3	amanda3	RANDOM	252.5	RSSI	24	263.609667	11	7	1
54	1449962296	343070	5	2	172	14	11084	33.866313	-84.440459	250.5	121215	billy3	brian3	RANDOM	252.9	RSSI	18	343.187632	8	4	1
55	1449962296	349300	0	1	0	0	11084	33.86896	-84.442375	237.5	121215	billy3	hamza3	RANDOM	252.9	Type	2				
56	1449962302	732921	5	2	172	14	18043	33.867403	-84.441354	246.2	121215	billy3	brian3	RANDOM	252.5	RSSI	23	347.342234	8	1	1
57	1449962302	734800	0	1	0	0	18043	33.870196	-84.443044	231.5	121215	billy3	hamza3	RANDOM	252.5	Type	2				
58	1449962302	816679	5	2	172	14	18043	33.867986	-84.441754	243.5	121215	billy3	amanda3	RANDOM	252.5	RSSI	28	272.910325	12	2	1
59	1449962305	316311	5	2	172	14	21707	33.867978	-84.441766	243.4	121215	billy3	brian3	RANDOM	251.6	RSSI	25	347.765028	9	1	1
60	1449962305	319953	5	2	172	14	21707	33.868426	-84.442046	241.3	121215	billy3	amanda3	RANDOM	251.6	RSSI	25	291.723857	10	5	1
61	1449962306	616336	5	2	172	14	5868	33.868215	-84.441922	242.3	121215	billy3	brian3	RANDOM	251	RSSI	28	347.670429	9	6	1
62	1449962306	624771	0	1	0	0	5868	33.871053	-84.443508	228	121215	billy3	hamza3	RANDOM	251	Type	2				
63	1449962308	827369	5	2	172	14	15544	33.869159	-84.442463	237.7	121215	billy3	amanda3	RANDOM	249.4	RSSI	32	276.460637	14	2	1
64	1449962308	831770	0	1	0	0	15544	33.87142	-84.443713	226.4	121215	billy3	hamza3	RANDOM	249.4	Type	2				
65	1449962310	350217	5	2	172	14	10184	33.86712	-84.441138	248.4	121215	billy3	N	RANDOM	248.4	RSSI	25	578.868937	5	0	1
66	1449962310	355208	0	1	0	0	10184	33.871782	-84.443937	224.9	121215	billy3	hamza3	RANDOM	248.4	Type	2				
67	1449962310	416444	5	2	172	14	10184	33.86942	-84.442594	236.5	121215	billy3	amanda3	RANDOM	248.4	RSSI	29	290.257249	12	6	1
68	1449962313	26695	5	2	172	14	16074	33.871492	-84.44373	228.3	121215	billy3	lucian3	RANDOM	245.6	RSSI	44	98.198888	60	1	1
69	1449962313	28799	0	1	0	0	16074	33.872253	-84.444271	222.9	121215	billy3	hamza3	RANDOM	245.6	Type	2				
70	1449962322	816268	5	2	172	14	21435	33.869712	-84.442736	235.7	121215	billy3	N	RANDOM	235.7	RSSI	24	593.699083	5	0	1
71	1449962322	817800	0	1	0	0	21435	33.874251	-84.44613	216.3	121215	billy3	hamza3	RANDOM	235.7	Type	2				
72	1449962322	916122	5	2	172	14	21435	33.871549	-84.443752	228.2	121215	billy3	brian3	RANDOM	235.7	RSSI	24	371.879903	8	3	1
73	1449962329	789660	0	1	0	0	28239	33.875404	-84.447311	218	121215	hamza3	N	RANDOM	218	Type	0				
74	1449962329	825972	5	2	172	14	28239	33.871018	-84.443435	230.4	121215	hamza3	billy3	RANDOM	218	RSSI	27	604.518661	5	4	1
75	1449962331	73669	0	1	0	0	27950	33.875601	-84.44751	218.2	121215	hamza3	N	RANDOM	218.2	Type	0				
76	1449962333	256665	0	1	0	0	24941	33.875985	-84.447901	218.7	121215	hamza3	N	RANDOM	218.7	Type	0				
77	1449962334	949660	0	1	0	0	29901	33.876268	-84.448175	219.1	121215	hamza3	N	RANDOM	219.1	Type	0				
78	1449962335	676660	0	1	0	0	26593	33.876363	-84.448261	219.2	121215	hamza3	N	RANDOM	219.2	Type	0				
79	1449962337	217662	0	1	0	0	19244	33.876553	-84.448431	219.4	121215	hamza3	N	RANDOM	219.4	Type	0				
80	1449962338	847817	0	1	0	0	28547	33.87683	-84.448678	219.7	121215	hamza3	N	RANDOM	219.7	Type	0				
81	1449962341	137778	0	1	0	0	23602	33.877186	-84.448995	220.2	121215	hamza3	N	RANDOM	220.2	Type	0				
82	1449962341	159105	5	2	172	14	23602	33.875301	-84.447196	219	121215	hamza3	amanda3	RANDOM	220.2	RSSI	30	267.257397	13	5	1
83	1449962341	216280	5	2	172	14	23602	33.876511	-84.448406	220	121215	hamza3	lucian3	RANDOM	220.2	RSSI	45	92.625013	66	22	1
84	1449962341	218684	5	2	172	14	23602	33.874928	-84.446826	219	121215	hamza3	brian3	RANDOM	220.2	RSSI	24	320.946795	9	3	1
85	1449962350	334663	0	1	0	0	23555	33.878403	-84.450101	222.7	121215	hamza3	N	RANDOM	222.7	Type	0				
86	1449962350	350180	5	2	172	14	23555	33.877004	-84.448822	221.1	121215	hamza3	amanda3	RANDOM	222.7	RSSI	37	195.174251	24	14	1
87	1449962350	416189	5	2	172	14	23555	33.878182	-84.449909	221.9	121215	hamza3	lucian3	RANDOM	222.7	RSSI	43	30.280378	189	142	1

88	1449962354	696672	0	1	0	0	25968	33.878919	-84.450598	226.1	121215	hamza3	N	RANDOM	226.1	Type	0				
89	1449962354	727954	5	2	172	14	25968	33.875173	-84.447074	219.5	121215	hamza3	billy3	RANDOM	226.1	RSSI	26	528.195466	6	5	1
90	1449962354	736586	5	2	172	14	25968	33.877742	-84.449487	221.8	121215	hamza3	amanda3	RANDOM	226.1	RSSI	31	166.172367	23	3	1
91	1449962354	738992	5	2	172	14	25968	33.877339	-84.449142	221.5	121215	hamza3	brian3	RANDOM	226.1	RSSI	40	221.069617	23	22	1
92	1449962357	704764	0	1	0	0	10024	33.879273	-84.450949	229	121215	hamza3	N	RANDOM	229	Type	0				
93	1449962357	737071	5	2	172	14	10024	33.878252	-84.449951	222.9	121215	hamza3	amanda3	RANDOM	229	RSSI	33	146.117914	28	17	1
94	1449962358	53660	0	1	0	0	14373	33.879346	-84.45102	229.7	121215	hamza3	N	RANDOM	229.7	Type	0				
95	1449962360	357830	0	1	0	0	23042	33.879656	-84.451318	232.2	121215	hamza3	N	RANDOM	232.2	Type	0				
96	1449962360	416134	5	2	172	14	23042	33.875956	-84.44787	220.5	121215	hamza3	billy3	RANDOM	232.2	RSSI	31	519.854561	7	4	1
97	1449962360	418784	5	2	172	14	23042	33.878638	-84.450319	225	121215	hamza3	amanda3	RANDOM	232.2	RSSI	28	145.917197	23	4	1
98	1449962360	932670	0	1	0	0	15445	33.879725	-84.451387	232.9	121215	hamza3	N	RANDOM	232.9	Type	0				
99	1449962360	943933	5	2	172	14	15445	33.876039	-84.447953	220.6	121215	hamza3	billy3	RANDOM	232.9	RSSI	30	517.833545	7	6	1
100	1449962363	857813	0	1	0	0	1167	33.880071	-84.451703	235.8	121215	hamza3	N	RANDOM	235.8	Type	0				
101	1449962368	174674	0	1	0	0	31922	33.880517	-84.452038	239.4	121215	hamza3	N	RANDOM	239.4	Type	0				
102	1449962368	239981	5	2	172	14	31922	33.879397	-84.451086	231.3	121215	hamza3	brian3	RANDOM	239.4	RSSI	42	152.329177	36	13	1
103	1449962372	728026	5	2	172	14	7171	33.879872	-84.451546	235.3	121215	billy3	brian3	RANDOM	222.3	RSSI	43	130.711039	43	40	1
104	1449962372	752301	5	2	172	14	7171	33.880764	-84.452195	241.4	121215	billy3	lucian3	RANDOM	222.3	RSSI	56	15.001048	588	253	1
105	1449962382	652744	5	2	172	14	4837	33.88118	-84.452431	244.2	121215	billy3	lucian3	RANDOM	228	RSSI	56	14.869585	593	195	1
106	1449962382	857709	0	1	0	0	4837	33.881298	-84.452507	244.4	121215	billy3	hamza3	RANDOM	228	Type	2				
107	1449962387	223418	5	2	172	14	3303	33.881208	-84.452437	244.7	121215	billy3	amanda3	RANDOM	232.5	RSSI	50	35.642079	202	71	1
108	1449962387	226816	5	2	172	14	3303	33.881389	-84.452584	245.4	121215	billy3	lucian3	RANDOM	232.5	RSSI	59	11.588257	842	166	1
109	1449962390	316253	5	2	172	14	19377	33.881475	-84.452735	246.2	121215	billy3	lucian3	RANDOM	235.8	RSSI	58	9.236226	1021	693	1
110	1449962390	319874	5	2	172	14	19377	33.881214	-84.452447	244.7	121215	billy3	brian3	RANDOM	235.8	RSSI	33	46.351723	88	58	1
111	1449962390	322578	5	2	172	14	19377	33.881348	-84.452529	245.3	121215	billy3	amanda3	RANDOM	235.8	RSSI	50	31.762518	227	187	1
112	1449962393	835073	5	2	172	14	28170	33.881397	-84.452583	245.6	121215	billy3	brian3	RANDOM	239.6	RSSI	35	40.942244	107	1	1
113	1449962393	837776	0	1	0	0	28170	33.881343	-84.453022	246.5	121215	billy3	hamza3	RANDOM	239.6	Type	2				
114	1449962394	515681	5	2	172	14	24097	33.881487	-84.452714	246.5	121215	billy3	amanda3	RANDOM	240.2	RSSI	45	36.52031	167	165	1
115	1449962394	519250	5	2	172	14	24097	33.88142	-84.452609	245.8	121215	billy3	brian3	RANDOM	240.2	RSSI	26	42.009182	77	53	1
116	1449962394	616455	5	2	172	14	24097	33.881405	-84.452985	246.3	121215	billy3	lucian3	RANDOM	240.2	RSSI	51	17.305002	431	370	1
117	1449962421	816214	5	2	172	14	27500	33.881171	-84.453101	246.2	121215	billy3	N	RANDOM	246.2	RSSI	46	40.762771	155	104	1
118	1449962421	844923	5	2	172	14	27500	33.880913	-84.453238	247.8	121215	billy3	lucian3	RANDOM	246.2	RSSI	56	9.431495	936	305	1
119	1449962428	654922	5	2	172	14	23223	33.88117	-84.453103	245.5	121215	billy3	N	RANDOM	245.5	RSSI	49	40.650806	172	52	1
120	1449962428	713842	0	1	0	0	23223	33.880835	-84.45328	247.9	121215	billy3	hamza3	RANDOM	245.5	Type	2				
121	1449962428	715611	5	2	172	14	23223	33.881031	-84.453183	246.9	121215	billy3	amanda3	RANDOM	245.5	RSSI	43	23.547239	243	232	1
122	1449962437	856736	5	2	172	14	17558	33.881164	-84.453107	244.6	121215	billy3	N	RANDOM	244.6	RSSI	41	56.437376	94	82	1
123	1449962437	944817	5	2	172	14	17558	33.880777	-84.453315	247.9	121215	billy3	lucian3	RANDOM	244.6	RSSI	55	9.349876	913	285	1
124	1449962445	215892	5	2	172	14	25905	33.880859	-84.453278	245.1	121215	billy3	N	RANDOM	245.1	RSSI	43	68.342194	83	65	1
125	1449962445	230667	5	2	172	14	25905	33.880571	-84.453409	247.3	121215	billy3	amanda3	RANDOM	245.1	RSSI	46	43.798375	144	35	1
126	1449962445	331370	5	2	172	14	25905	33.880319	-84.453334	247.6	121215	billy3	lucian3	RANDOM	245.1	RSSI	56	15.587802	566	154	1
127	1449962448	915636	5	2	172	14	5476	33.880611	-84.453401	245.6	121215	billy3	N	RANDOM	245.6	RSSI	39	88.533421	56	28	1
128	1449962448	944689	0	1	0	0	5476	33.879915	-84.452934	244.7	121215	billy3	hamza3	RANDOM	245.6	Type	2				
129	1449962450	923715	5	2	172	14	4877	33.879896	-84.4529	244.8	121215	billy3	lucian3	RANDOM	245.7	RSSI	51	23.077705	323	90	1
130	1449962451	21703	0	1	0	0	4877	33.879733	-84.452745	243	121215	billy3	hamza3	RANDOM	245.7	Type	2				
131	1449962451	116028	5	2	172	14	4877	33.880235	-84.453274	246.7	121215	billy3	brian3	RANDOM	245.7	RSSI	38	74.119924	65	54	1

132	1449962454	120744	5	2	172	14	5626	33.880204	-84.453249	245.2	121215	billy3	N	RANDOM	245.2	RSSI	32	122.64222	32	3	1
133	1449962454	124775	0	1	0	0	5626	33.879379	-84.452366	239.4	121215	billy3	hamza3	RANDOM	245.2	Type	2				
134	1449962454	415915	5	2	172	14	5626	33.879515	-84.452505	241	121215	billy3	lucian3	RANDOM	245.2	RSSI	45	31.529167	194	49	1
135	1449962455	616048	5	2	172	14	28324	33.880059	-84.45309	244.4	121215	billy3	N	RANDOM	244.4	RSSI	30	136.784479	27	21	1
136	1449962455	632093	5	2	172	14	28324	33.879378	-84.452358	239.5	121215	billy3	lucian3	RANDOM	244.4	RSSI	47	35.357971	184	59	1
137	1449962467	123723	5	2	172	14	26818	33.878765	-84.451696	232.4	121215	billy3	N	RANDOM	232.4	RSSI	36	226.441839	20	18	1
138	1449962467	142794	0	1	0	0	26818	33.877281	-84.450014	221.3	121215	billy3	hamza3	RANDOM	232.4	Type	2				
139	1449962472	115795	5	2	172	14	27174	33.878111	-84.45097	225.8	121215	billy3	N	RANDOM	225.8	RSSI	28	258.394683	13	1	1
140	1449962472	117800	0	1	0	0	27174	33.876415	-84.449054	220	121215	billy3	hamza3	RANDOM	225.8	Type	2				
141	1449962473	915651	5	2	172	14	24814	33.877261	-84.449987	222.2	121215	billy3	brian3	RANDOM	223.7	RSSI	32	182.054908	21	16	1
142	1449962473	932775	0	1	0	0	24814	33.87605	-84.448658	219.5	121215	billy3	hamza3	RANDOM	223.7	Type	2				
143	1449962491	816071	5	2	172	14	4127	33.875	-84.447496	218.6	121215	billy3	N	RANDOM	218.6	RSSI	29	343.268006	10	7	1
144	1449962491	824771	0	1	0	0	4127	33.872625	-84.445117	219	121215	billy3	hamza3	RANDOM	218.6	Type	2				
145	1449962491	844238	5	2	172	14	4127	33.874285	-84.446766	218.3	121215	billy3	brian3	RANDOM	218.6	RSSI	32	239.114784	16	5	1
146	1449962494	37048	5	2	172	14	25623	33.873668	-84.446129	217.9	121215	billy3	amanda3	RANDOM	218	RSSI	28	200.284776	17	0	1
147	1449962494	39522	0	1	0	0	25623	33.872252	-84.444786	220.8	121215	billy3	hamza3	RANDOM	218	Type	2				
148	1449962496	740114	5	2	172	14	29669	33.87346	-84.445921	218.5	121215	billy3	brian3	RANDOM	217.4	RSSI	32	256.67858	15	6	1
149	1449962496	751231	0	1	0	0	29669	33.871584	-84.444298	224	121215	billy3	hamza3	RANDOM	217.4	Type	2				
150	1449962498	915699	5	2	172	14	11079	33.872882	-84.445339	219.6	121215	billy3	amanda3	RANDOM	217.5	RSSI	35	241.924177	18	1	1
151	1449962498	919000	5	2	172	14	11079	33.873063	-84.445522	219.3	121215	billy3	brian3	RANDOM	217.5	RSSI	29	267.951714	13	1	1
152	1449962500	717731	5	2	172	14	26081	33.873381	-84.445779	217.9	121215	billy3	N	RANDOM	217.9	RSSI	23	344.485558	8	7	1
153	1449962500	725792	0	1	0	0	26081	33.870616	-84.443714	228.6	121215	billy3	hamza3	RANDOM	217.9	Type	2				
154	1449962500	735942	5	2	172	14	26081	33.872063	-84.444654	222.1	121215	billy3	lucian3	RANDOM	217.9	RSSI	33	182.696858	22	18	1
155	1449962500	744268	5	2	172	14	26081	33.872774	-84.445244	220.4	121215	billy3	brian3	RANDOM	217.9	RSSI	39	278.273088	18	3	1
156	1449962502	815947	5	2	172	14	64	33.872973	-84.445375	219.1	121215	billy3	N	RANDOM	219.1	RSSI	24	354.185062	8	5	1
157	1449962502	822774	0	1	0	0	64	33.870196	-84.443491	230.7	121215	billy3	hamza3	RANDOM	219.1	Type	2				
158	1449962502	838953	5	2	172	14	64	33.871696	-84.444385	223.7	121215	billy3	lucian3	RANDOM	219.1	RSSI	32	185.980589	21	10	1
159	1449962502	841345	5	2	172	14	64	33.872203	-84.444751	222.9	121215	billy3	amanda3	RANDOM	219.1	RSSI	31	251.509245	15	7	1
160	1449962505	716012	5	2	172	14	17793	33.872458	-84.444908	221.5	121215	billy3	N	RANDOM	221.5	RSSI	28	367.676559	9	8	1
161	1449962505	725778	0	1	0	0	17793	33.869499	-84.443125	234.3	121215	billy3	hamza3	RANDOM	221.5	Type	2				
162	1449962505	742330	5	2	172	14	17793	33.871801	-84.444447	224.8	121215	billy3	amanda3	RANDOM	221.5	RSSI	38	283.402764	17	0	1
163	1449962512	625111	5	2	172	14	31000	33.870562	-84.44368	230.3	121215	billy3	amanda3	RANDOM	226.4	RSSI	25	326.007158	9	0	1
164	1449962512	628638	0	1	0	0	31000	33.8679	-84.442195	242.5	121215	billy3	hamza3	RANDOM	226.4	Type	2				
165	1449962512	645867	5	2	172	14	31000	33.869498	-84.44313	234.2	121215	billy3	lucian3	RANDOM	226.4	RSSI	35	197.425188	22	5	1
166	1449962515	216314	5	2	172	14	29699	33.870116	-84.443441	232.3	121215	billy3	amanda3	RANDOM	228.1	RSSI	21	356.239867	8	3	1
167	1449962515	220775	0	1	0	0	29699	33.867241	-84.441733	245.8	121215	billy3	hamza3	RANDOM	228.1	Type	2				
168	1449962518	653719	5	2	172	14	31824	33.868342	-84.442482	240	121215	billy3	lucian3	RANDOM	230.8	RSSI	30	223.715753	16	7	1
169	1449962518	664800	0	1	0	0	31824	33.866614	-84.441238	248.9	121215	billy3	hamza3	RANDOM	230.8	Type	2				
170	1449962562	431113	5	2	172	14	25478	33.862001	-84.437189	243.7	121215	billy3	brian3	RANDOM	249.6	RSSI	17	519.650757	5	0	1
171	1449962562	433638	0	1	0	0	25478	33.858216	-84.433882	221.7	121215	billy3	hamza3	RANDOM	249.6	Type	2				
172	1449962570	136383	5	2	172	14	9135	33.858301	-84.43396	221.6	121215	billy3	lucian3	RANDOM	243	RSSI	33	227.402447	18	17	1
173	1449962570	163801	0	1	0	0	9135	33.8565	-84.43279	217.7	121215	billy3	hamza3	RANDOM	243	Type	2				
174	1449962574	435752	5	2	172	14	12457	33.857396	-84.433304	219.8	121215	billy3	lucian3	RANDOM	238.8	RSSI	33	228.817106	17	6	1
175	1449962574	442776	0	1	0	0	12457	33.855493	-84.432357	216.2	121215	billy3	hamza3	RANDOM	238.8	Type	2				

176	1449962578	831845	5	2	172	14	11178	33.856398	-84.43274	218.1	121215	billy3	lucian3	RANDOM	234.4	RSSI	31	225.219505	17	5	1
177	1449962578	837781	0	1	0	0	11178	33.854462	-84.432018	215.1	121215	billy3	hamza3	RANDOM	234.4	Type	2				
178	1449962604	437627	5	2	172	14	22379	33.850314	-84.431197	222.7	121215	billy3	lucian3	RANDOM	219.4	RSSI	39	139.706492	35	34	1
179	1449962604	474706	0	1	0	0	22379	33.849057	-84.43117	220.3	121215	billy3	hamza3	RANDOM	219.4	Type	2				
180	1449962606	549723	5	2	172	14	15785	33.849918	-84.431192	222.7	121215	billy3	lucian3	RANDOM	218.8	RSSI	42	148.615938	37	0	1
181	1449962606	551203	0	1	0	0	15785	33.848582	-84.431119	219.1	121215	billy3	hamza3	RANDOM	218.8	Type	2				
182	1449962696	343380	5	2	172	14	27387	33.833142	-84.427603	239	121215	billy3	amanda3	RANDOM	246.4	RSSI	32	195.427438	20	8	1
183	1449962696	358245	0	1	0	0	27387	33.831385	-84.427512	239.2	121215	billy3	hamza3	RANDOM	246.4	Type	2				
184	1449962699	224725	5	2	172	14	4553	33.831423	-84.427542	243.2	121215	billy3	lucian3	RANDOM	244.5	RSSI	53	30.68872	260	255	1
185	1449962699	490707	0	1	0	0	4553	33.831253	-84.42728	240.5	121215	billy3	hamza3	RANDOM	244.5	Type	2				
186	1449962705	954242	5	2	172	14	5397	33.831253	-84.427263	243.2	121215	billy3	lucian3	RANDOM	238.8	RSSI	55	8.024723	1064	560	1
187	1449962706	543723	0	1	0	0	5397	33.831205	-84.427196	243.3	121215	billy3	hamza3	RANDOM	238.8	Type	2				
188	1449962708	231690	5	2	172	14	13632	33.832866	-84.427569	237.4	121215	billy3	N	RANDOM	237.4	RSSI	23	187.762726	16	3	1
189	1449962708	235791	0	1	0	0	13632	33.831204	-84.427196	243.7	121215	billy3	hamza3	RANDOM	237.4	Type	2				
190	1449962708	315458	5	2	172	14	13632	33.831474	-84.427621	240.6	121215	billy3	amanda3	RANDOM	237.4	RSSI	28	49.389651	70	26	1
191	1449962710	351964	5	2	172	14	23598	33.832608	-84.427608	237.1	121215	billy3	N	RANDOM	237.1	RSSI	28	160.609894	21	16	1
192	1449962710	376775	0	1	0	0	23598	33.831204	-84.427195	244	121215	billy3	hamza3	RANDOM	237.1	Type	2				
193	1449962710	416357	5	2	172	14	23598	33.831395	-84.427499	241.2	121215	billy3	amanda3	RANDOM	237.1	RSSI	39	35.184888	142	57	1
194	1449962710	418870	5	2	172	14	23598	33.83125	-84.427265	242.5	121215	billy3	lucian3	RANDOM	237.1	RSSI	53	8.239126	969	572	1
195	1449962710	454897	5	2	172	14	23598	33.831574	-84.427738	239.4	121215	billy3	brian3	RANDOM	237.1	RSSI	27	64.830265	51	29	1
196	1449962713	15149	5	2	172	14	28862	33.832218	-84.427736	237.5	121215	billy3	N	RANDOM	237.5	RSSI	41	123.390367	43	31	1
197	1449962713	51216	5	2	172	14	28862	33.831447	-84.427593	240.2	121215	billy3	brian3	RANDOM	237.5	RSSI	30	45.735701	81	34	1
198	1449962715	115178	5	2	172	14	19442	33.83202	-84.427801	238.6	121215	billy3	N	RANDOM	238.6	RSSI	41	106.782099	50	16	1
199	1449962715	125198	5	2	172	14	19442	33.831251	-84.42727	242.5	121215	billy3	lucian3	RANDOM	238.6	RSSI	53	8.880711	899	345	1
200	1449962717	541224	5	2	172	14	2472	33.831838	-84.427838	239.3	121215	billy3	N	RANDOM	239.3	RSSI	45	92.352579	66	55	1
201	1449962717	604720	0	1	0	0	2472	33.831202	-84.427194	244.7	121215	billy3	hamza3	RANDOM	239.3	Type	2				
202	1449962717	616661	5	2	172	14	2472	33.831416	-84.427543	240.8	121215	billy3	brian3	RANDOM	239.3	RSSI	18	40.042424	76	0	1
203	1449962717	619056	5	2	172	14	2472	33.831378	-84.427482	241.7	121215	billy3	amanda3	RANDOM	239.3	RSSI	38	33.00432	146	99	1
204	1449962717	621700	5	2	172	14	2472	33.831251	-84.427272	242.5	121215	billy3	lucian3	RANDOM	239.3	RSSI	53	9.027265	885	583	1
205	1449962719	747194	5	2	172	14	32666	33.831251	-84.427275	242.8	121215	billy3	lucian3	RANDOM	239.6	RSSI	54	9.32443	885	714	1
206	1449962719	946149	5	2	172	14	32666	33.831417	-84.42754	240.7	121215	billy3	brian3	RANDOM	239.6	RSSI	20	39.960381	76	9	1
207	1449962722	215215	5	2	172	14	18476	33.831622	-84.427781	240.5	121215	billy3	N	RANDOM	240.5	RSSI	36	71.655044	63	30	1
208	1449962722	246690	0	1	0	0	18476	33.831202	-84.427192	244.7	121215	billy3	hamza3	RANDOM	240.5	Type	2				
209	1449962722	315470	5	2	172	14	18476	33.831418	-84.427537	241.1	121215	billy3	brian3	RANDOM	240.5	RSSI	22	39.879334	76	26	1
210	1449962724	615624	5	2	172	14	1421	33.831372	-84.427484	242.7	121215	billy3	amanda3	RANDOM	241	RSSI	33	32.915314	124	61	1
211	1449962724	619194	5	2	172	14	1421	33.831252	-84.427277	242.8	121215	billy3	lucian3	RANDOM	241	RSSI	53	9.614394	830	285	1
212	1449962724	621913	5	2	172	14	1421	33.831418	-84.427535	241.6	121215	billy3	brian3	RANDOM	241	RSSI	22	39.732057	76	10	1
213	1449962726	815413	5	2	172	14	21065	33.831554	-84.427722	241.2	121215	billy3	N	RANDOM	241.2	RSSI	37	62.6388	74	64	1
214	1449962726	884712	0	1	0	0	21065	33.831202	-84.427192	244.8	121215	billy3	hamza3	RANDOM	241.2	Type	2				
215	1449962727	15311	5	2	172	14	21065	33.831419	-84.42753	242.2	121215	billy3	brian3	RANDOM	241.2	RSSI	22	39.433098	77	9	1
216	1449962728	519676	5	2	172	14	26496	33.831534	-84.4277	241.5	121215	billy3	N	RANDOM	241.5	RSSI	40	59.739168	86	43	1
217	1449962728	588741	5	2	172	14	26496	33.831419	-84.427527	242.9	121215	billy3	brian3	RANDOM	241.5	RSSI	21	39.287185	77	24	1
218	1449962730	315255	5	2	172	14	2741	33.831517	-84.427681	241.8	121215	billy3	N	RANDOM	241.8	RSSI	31	57.194464	67	9	1
219	1449962730	325778	0	1	0	0	2741	33.831202	-84.427191	245	121215	billy3	hamza3	RANDOM	241.8	Type	2				

220	1449962733	151409	5	2	172	14	18126	33.831512	-84.427674	242.1	121215	billy3	N	RANDOM	242.1	RSSI	35	56.421919	77	53	1
221	1449962733	243262	5	2	172	14	18126	33.831248	-84.427282	244	121215	billy3	lucian3	RANDOM	242.1	RSSI	52	9.935033	777	237	1
222	1449962735	118683	5	2	172	14	3681	33.831512	-84.427671	242.4	121215	billy3	N	RANDOM	242.4	RSSI	34	56.275539	75	68	1
223	1449962735	133326	5	2	172	14	3681	33.831371	-84.427489	243.3	121215	billy3	amanda3	RANDOM	242.4	RSSI	34	33.474571	126	47	1
224	1449962737	217686	5	2	172	14	14465	33.831513	-84.427669	243	121215	billy3	N	RANDOM	243	RSSI	31	56.343412	68	42	1
225	1449962737	264063	5	2	172	14	14465	33.831249	-84.427277	244.5	121215	billy3	lucian3	RANDOM	243	RSSI	53	9.833253	812	453	1
226	1449962748	615283	5	2	172	14	27838	33.831518	-84.427667	243.7	121215	billy3	N	RANDOM	243.7	RSSI	31	56.761776	67	20	1
227	1449962748	636776	0	1	0	0	27838	33.831204	-84.427182	245.7	121215	billy3	hamza3	RANDOM	243.7	Type	2				
228	1449962750	746369	5	2	172	14	26430	33.831519	-84.427665	243.4	121215	billy3	N	RANDOM	243.4	RSSI	31	57.685802	66	42	1
229	1449962750	800692	0	1	0	0	26430	33.8312	-84.427172	245.6	121215	billy3	hamza3	RANDOM	243.4	Type	2				
230	1449962750	862765	5	2	172	14	26430	33.831248	-84.427266	243.2	121215	billy3	lucian3	RANDOM	243.4	RSSI	52	10.185461	758	585	1
231	1449962758	315149	5	2	172	14	28518	33.831521	-84.427667	242.7	121215	billy3	N	RANDOM	242.7	RSSI	34	57.768727	73	39	1
232	1449962758	356728	0	1	0	0	28518	33.831204	-84.427171	244.4	121215	billy3	hamza3	RANDOM	242.7	Type	2				
233	1449962761	40702	5	2	172	14	1560	33.83152	-84.427668	242.5	121215	billy3	N	RANDOM	242.5	RSSI	29	57.847635	62	57	1
234	1449962761	54148	5	2	172	14	1560	33.831245	-84.427267	243.6	121215	billy3	lucian3	RANDOM	242.5	RSSI	53	10.046536	795	351	1
235	1449962764	53726	5	2	172	14	24979	33.83152	-84.427668	242.5	121215	billy3	N	RANDOM	242.5	RSSI	27	58.349421	57	41	1
236	1449962764	98701	0	1	0	0	24979	33.831202	-84.427165	244.6	121215	billy3	hamza3	RANDOM	242.5	Type	2				
237	1449962764	124838	5	2	172	14	24979	33.831246	-84.427266	243.6	121215	billy3	lucian3	RANDOM	242.5	RSSI	53	10.527607	758	141	1
238	1449962767	650377	5	2	172	14	15557	33.831247	-84.427264	243.4	121215	billy3	lucian3	RANDOM	242.7	RSSI	52	10.390679	743	408	1
239	1449962768	84707	0	1	0	0	15557	33.831201	-84.427165	244.8	121215	billy3	hamza3	RANDOM	242.7	Type	2				
240	1449962770	415289	5	2	172	14	6469	33.831248	-84.427263	243.3	121215	billy3	lucian3	RANDOM	242.8	RSSI	52	10.581419	730	297	1
241	1449962770	418960	5	2	172	14	6469	33.83142	-84.427521	248.4	121215	billy3	brian3	RANDOM	242.8	RSSI	22	41.032655	74	49	1
242	1449962773	914981	5	2	172	14	30485	33.831518	-84.427672	242.8	121215	billy3	N	RANDOM	242.8	RSSI	34	59.072283	71	3	1
243	1449962773	919773	0	1	0	0	30485	33.831198	-84.427161	244.7	121215	billy3	hamza3	RANDOM	242.8	Type	2				
244	1449962780	915583	5	2	172	14	25170	33.831491	-84.427638	242.9	121215	billy3	N	RANDOM	242.9	RSSI	31	77.751075	49	36	1
245	1449962780	935761	5	2	172	14	25170	33.831137	-84.427027	243.1	121215	billy3	lucian3	RANDOM	242.9	RSSI	59	12.61257	773	726	1
246	1449962780	942158	5	2	172	14	25170	33.831405	-84.427501	248.2	121215	billy3	brian3	RANDOM	242.9	RSSI	59	12.61257	773	686	1
247	1449962787	15060	5	2	172	14	13321	33.831443	-84.426671	242.1	121215	billy3	lucian3	RANDOM	243.7	RSSI	50	15.379773	470	5	1
248	1449962787	21774	0	1	0	0	13321	33.83156	-84.426582	243.2	121215	billy3	hamza3	RANDOM	243.7	Type	2				
249	1449962789	415124	5	2	172	14	4630	33.831212	-84.427183	244	121215	billy3	N	RANDOM	244	RSSI	41	94.533129	56	37	1
250	1449962789	453700	0	1	0	0	4630	33.83177	-84.42641	242.4	121215	billy3	hamza3	RANDOM	244	Type	2				
251	1449962794	43675	5	2	172	14	30423	33.831191	-84.426878	243.6	121215	billy3	N	RANDOM	243.6	RSSI	35	134.955352	32	25	1
252	1449962794	72706	0	1	0	0	30423	33.832197	-84.426059	241.4	121215	billy3	hamza3	RANDOM	243.6	Type	2				
253	1449962794	126879	5	2	172	14	30423	33.831547	-84.426591	241.8	121215	billy3	amanda3	RANDOM	243.6	RSSI	41	87.344087	61	51	1
254	1449962794	214966	5	2	172	14	30423	33.832004	-84.426227	241.3	121215	billy3	lucian3	RANDOM	243.6	RSSI	50	26.466457	273	241	1
255	1449962797	615204	5	2	172	14	25497	33.831405	-84.426707	243	121215	billy3	N	RANDOM	243	RSSI	40	144.774167	35	19	1
256	1449962797	635779	0	1	0	0	25497	33.832476	-84.425814	241	121215	billy3	hamza3	RANDOM	243	Type	2				
257	1449962797	718655	5	2	172	14	25497	33.832259	-84.426012	241	121215	billy3	lucian3	RANDOM	243	RSSI	44	30.257934	195	156	1
258	1449962801	637660	5	2	172	14	3529	33.832549	-84.425753	241	121215	billy3	lucian3	RANDOM	242.7	RSSI	60	14.320075	704	376	1
259	1449962801	745171	5	2	172	14	3529	33.831989	-84.42623	242.5	121215	billy3	brian3	RANDOM	242.7	RSSI	24	92.918151	32	28	1
260	1449962804	932631	5	2	172	14	1955	33.832712	-84.425691	241.2	121215	billy3	lucian3	RANDOM	242	RSSI	57	16.544858	551	323	1
261	1449962805	51815	5	2	172	14	1955	33.832293	-84.425986	239.8	121215	billy3	amanda3	RANDOM	242	RSSI	47	59.058623	110	99	1
262	1449962810	335175	5	2	172	14	20917	33.832253	-84.426016	241.1	121215	billy3	N	RANDOM	241.1	RSSI	30	100.283418	37	30	1
263	1449962810	374709	0	1	0	0	20917	33.833087	-84.426431	240	121215	billy3	hamza3	RANDOM	241.1	Type	2				

264	1449962810	416086	5	2	172	14	20917	33.832654	-84.425691	239.6	121215	billy3	amanda3	RANDOM	241.1	RSSI	31	83.553638	45	10	1
265	1449962810	515031	5	2	172	14	20917	33.832954	-84.426151	240.6	121215	billy3	lucian3	RANDOM	241.1	RSSI	47	29.77348	219	212	1
266	1449962810	651970	5	2	172	14	20917	33.832532	-84.425768	240.9	121215	billy3	brian3	RANDOM	241.1	RSSI	18	86.88606	35	4	1
267	1449962817	128728	5	2	172	14	16166	33.833014	-84.42626	238.8	121215	billy3	amanda3	RANDOM	240.5	RSSI	30	109.011104	34	19	1
268	1449962817	148914	0	1	0	0	16166	33.833701	-84.427103	241.7	121215	billy3	hamza3	RANDOM	240.5	Type	2				
269	1449962819	823847	5	2	172	14	9709	33.833829	-84.427174	242.5	121215	billy3	lucian3	RANDOM	240.6	RSSI	48	30.701467	220	145	1
270	1449962819	979702	0	1	0	0	9709	33.834084	-84.427302	243.4	121215	billy3	hamza3	RANDOM	240.6	Type	2				
271	1449962824	31575	5	2	172	14	22484	33.834377	-84.427457	245.3	121215	billy3	lucian3	RANDOM	240.4	RSSI	53	24.958052	320	29	1
272	1449962824	65707	0	1	0	0	22484	33.834674	-84.427606	245.8	121215	billy3	hamza3	RANDOM	240.4	Type	2				
273	1449962853	749368	5	2	172	14	28619	33.837091	-84.428857	248.8	121215	billy3	N	RANDOM	248.8	RSSI	22	347.531465	8	4	1
274	1449962853	762969	0	1	0	0	28619	33.84012	-84.429794	239.3	121215	billy3	hamza3	RANDOM	248.8	Type	2				
275	1449962862	163835	5	2	172	14	15966	33.840172	-84.429795	239.8	121215	billy3	amanda3	RANDOM	245.6	RSSI	31	199.922602	19	1	1
276	1449962862	165796	0	1	0	0	15966	33.841971	-84.429815	230.7	121215	billy3	hamza3	RANDOM	245.6	Type	2				
277	1449962883	822317	5	2	172	14	12861	33.845227	-84.42958	218.8	121215	billy3	lucian3	RANDOM	228.2	RSSI	49	36.889038	189	142	1
278	1449962883	826118	5	2	172	14	12861	33.844517	-84.429567	220.9	121215	billy3	amanda3	RANDOM	228.2	RSSI	40	115.106168	45	16	1
279	1449962890	826386	5	2	172	14	8649	33.845908	-84.429199	215.6	121215	billy3	lucian3	RANDOM	222.5	RSSI	51	32.978732	226	112	1
280	1449962890	946744	0	1	0	0	8649	33.846133	-84.428966	212.8	121215	billy3	hamza3	RANDOM	222.5	Type	2				
281	1449962898	924668	5	2	172	14	28370	33.846182	-84.428916	212.9	121215	billy3	amanda3	RANDOM	216.9	RSSI	38	40.051301	120	51	1
282	1449962898	979693	0	1	0	0	28370	33.846444	-84.428618	212.5	121215	billy3	hamza3	RANDOM	216.9	Type	2				
283	1449962904	114848	5	2	172	14	25119	33.846076	-84.429043	214.6	121215	billy3	N	RANDOM	214.6	RSSI	40	56.632878	91	43	1
284	1449962904	146333	5	2	172	14	25119	33.846383	-84.428677	214.6	121215	billy3	lucian3	RANDOM	214.6	RSSI	57	8.641858	1056	508	1
285	1449962904	230742	5	2	172	14	25119	33.846223	-84.42887	212.5	121215	billy3	brian3	RANDOM	214.6	RSSI	26	33.790682	96	15	1
286	1449962904	315113	5	2	172	14	25119	33.846308	-84.428774	212.3	121215	billy3	amanda3	RANDOM	214.6	RSSI	35	20.90644	209	152	1
287	1449962906	815120	5	2	172	14	23297	33.846184	-84.428918	214.2	121215	billy3	N	RANDOM	214.2	RSSI	30	39.877106	93	15	1
288	1449962906	831773	0	1	0	0	23297	33.846439	-84.428614	211.1	121215	billy3	hamza3	RANDOM	214.2	Type	2				
289	1449962906	846012	5	2	172	14	23297	33.846253	-84.428836	212.2	121215	billy3	brian3	RANDOM	214.2	RSSI	33	29.103637	140	41	1
290	1449962907	124552	5	2	172	14	23297	33.846309	-84.428775	212.2	121215	billy3	amanda3	RANDOM	214.2	RSSI	38	20.724151	233	164	1
291	1449962919	914661	5	2	172	14	19134	33.846209	-84.42889	213	121215	billy3	N	RANDOM	213	RSSI	42	36.157419	153	62	1
292	1449962919	980693	0	1	0	0	19134	33.846434	-84.428607	210.7	121215	billy3	hamza3	RANDOM	213	Type	2				
293	1449962920	114880	5	2	172	14	19134	33.846311	-84.428771	212.5	121215	billy3	amanda3	RANDOM	213	RSSI	36	20.39426	222	204	1
294	1449962920	141431	5	2	172	14	19134	33.846249	-84.428838	212.6	121215	billy3	brian3	RANDOM	213	RSSI	36	29.617028	153	84	1
295	1449962922	614998	5	2	172	14	10849	33.846208	-84.42889	212.6	121215	billy3	N	RANDOM	212.6	RSSI	43	36.234352	157	150	1
296	1449962922	745330	5	2	172	14	10849	33.846384	-84.428686	215.6	121215	billy3	lucian3	RANDOM	212.6	RSSI	52	9.16695	842	239	1
297	1449962923	250751	5	2	172	14	10849	33.846249	-84.428839	212.9	121215	billy3	brian3	RANDOM	212.6	RSSI	33	29.750178	137	125	1
298	1449962925	29644	5	2	172	14	5168	33.846208	-84.428889	212.4	121215	billy3	N	RANDOM	212.4	RSSI	44	36.234352	163	31	1
299	1449962925	64705	0	1	0	0	5168	33.846434	-84.428606	211	121215	billy3	hamza3	RANDOM	212.4	Type	2				
300	1449962925	314801	5	2	172	14	5168	33.846312	-84.428767	212.6	121215	billy3	amanda3	RANDOM	212.4	RSSI	38	20.114554	240	33	1
301	1449962925	814968	5	2	172	14	5168	33.84625	-84.428839	213.3	121215	billy3	brian3	RANDOM	212.4	RSSI	34	29.673496	142	52	1
302	1449962928	14668	5	2	172	14	599	33.846207	-84.428889	212.3	121215	billy3	N	RANDOM	212.3	RSSI	43	36.311462	157	62	1
303	1449962928	79593	5	2	172	14	599	33.846384	-84.428688	215.6	121215	billy3	lucian3	RANDOM	212.3	RSSI	55	9.388672	909	763	1
304	1449962928	114585	5	2	172	14	599	33.846251	-84.428839	213.9	121215	billy3	brian3	RANDOM	212.3	RSSI	31	29.597033	129	58	1
305	1449962928	414721	5	2	172	14	599	33.846312	-84.428765	212.5	121215	billy3	amanda3	RANDOM	212.3	RSSI	37	19.978582	234	131	1
306	1449962933	621656	5	2	172	14	7140	33.846204	-84.428887	211.6	121215	billy3	N	RANDOM	211.6	RSSI	42	36.477936	151	107	1
307	1449962933	745424	5	2	172	14	7140	33.846387	-84.428689	214	121215	billy3	lucian3	RANDOM	211.6	RSSI	53	9.347815	854	495	1

308	1449962933	914446	5	2	172	14	7140	33.846314	-84.428763	212.5	121215	billy3	amanda3	RANDOM	211.6	RSSI	35	19.760231	221	120	1
309	1449962933	943465	5	2	172	14	7140	33.846253	-84.428837	214.1	121215	billy3	brian3	RANDOM	211.6	RSSI	31	29.377433	130	91	1
310	1449962942	952454	5	2	172	14	21531	33.846199	-84.428888	210.7	121215	billy3	N	RANDOM	210.7	RSSI	46	36.532372	173	122	1
311	1449962943	78603	5	2	172	14	21531	33.846391	-84.428687	212.5	121215	billy3	lucian3	RANDOM	210.7	RSSI	56	8.69403	1015	798	1
312	1449962943	112567	5	2	172	14	21531	33.846318	-84.428766	213.1	121215	billy3	amanda3	RANDOM	210.7	RSSI	38	19.312368	250	99	1
313	1449962943	253927	5	2	172	14	21531	33.846247	-84.428831	214.1	121215	billy3	brian3	RANDOM	210.7	RSSI	35	29.042808	150	101	1
314	1449962946	712983	5	2	172	14	25657	33.846199	-84.428888	210.5	121215	billy3	N	RANDOM	210.5	RSSI	38	36.598647	132	81	1
315	1449962946	798691	0	1	0	0	25657	33.846428	-84.428603	214.4	121215	billy3	hamza3	RANDOM	210.5	Type	2				
316	1449962946	916617	5	2	172	14	25657	33.846321	-84.428766	213.4	121215	billy3	amanda3	RANDOM	210.5	RSSI	40	19.175423	270	163	1
317	1449962947	252047	5	2	172	14	25657	33.846246	-84.428829	213.9	121215	billy3	brian3	RANDOM	210.5	RSSI	22	29.628077	102	38	1
318	1449962953	712903	5	2	172	14	22245	33.846234	-84.42885	210.6	121215	billy3	N	RANDOM	210.6	RSSI	39	58.6019	85	31	1
319	1449962953	744810	0	1	0	0	22245	33.846711	-84.428521	213	121215	billy3	hamza3	RANDOM	210.6	Type	2				
320	1449962953	912789	5	2	172	14	22245	33.846442	-84.428627	213	121215	billy3	amanda3	RANDOM	210.6	RSSI	49	31.452806	222	119	1
321	1449962958	712861	5	2	172	14	8596	33.846438	-84.428616	210.4	121215	billy3	N	RANDOM	210.4	RSSI	39	63.170723	79	24	1
322	1449962958	737824	0	1	0	0	8596	33.846986	-84.428798	212.3	121215	billy3	hamza3	RANDOM	210.4	Type	2				
323	1449962958	746045	5	2	172	14	8596	33.84689	-84.428693	211.4	121215	billy3	lucian3	RANDOM	210.4	RSSI	52	14.412373	536	69	1
324	1449962959	19733	5	2	172	14	8596	33.846558	-84.428508	212.3	121215	billy3	brian3	RANDOM	210.4	RSSI	36	54.575275	83	20	1
325	1449962962	134612	5	2	172	14	25081	33.847111	-84.428929	211.6	121215	billy3	lucian3	RANDOM	210.2	RSSI	55	12.142973	703	538	1
326	1449962962	712705	0	1	0	0	25081	33.847241	-84.429046	212	121215	billy3	hamza3	RANDOM	210.2	Type	2				
327	1449962967	128666	5	2	172	14	876	33.846912	-84.428729	210.2	121215	billy3	N	RANDOM	210.2	RSSI	45	93.146055	65	44	1
328	1449962967	176688	0	1	0	0	876	33.847586	-84.429329	211.9	121215	billy3	hamza3	RANDOM	210.2	Type	2				
329	1449962967	213877	5	2	172	14	876	33.847453	-84.429231	211.8	121215	billy3	lucian3	RANDOM	210.2	RSSI	51	17.327514	431	227	1
330	1449962972	912455	5	2	172	14	22375	33.847301	-84.429108	210.7	121215	billy3	N	RANDOM	210.7	RSSI	46	84.569498	74	17	1
331	1449962972	931781	0	1	0	0	22375	33.847963	-84.42956	212	121215	billy3	hamza3	RANDOM	210.7	Type	2				
332	1449962973	12751	5	2	172	14	22375	33.847575	-84.429309	211.9	121215	billy3	amanda3	RANDOM	210.7	RSSI	47	48.945514	133	38	1
333	1449962973	212421	5	2	172	14	22375	33.847469	-84.429235	211.8	121215	billy3	brian3	RANDOM	210.7	RSSI	24	64.754716	46	28	1
334	1449962978	112689	5	2	172	14	2492	33.848296	-84.429765	213.6	121215	billy3	lucian3	RANDOM	211	RSSI	38	39.781047	121	67	1
335	1449962978	120026	5	2	172	14	2492	33.847868	-84.429492	212.2	121215	billy3	amanda3	RANDOM	211	RSSI	42	20.433164	270	247	1
336	1449962978	212674	5	2	172	14	2492	33.84779	-84.429451	212	121215	billy3	brian3	RANDOM	211	RSSI	34	28.781996	147	112	1
337	1449962981	712894	5	2	172	14	6276	33.847816	-84.429484	211.3	121215	billy3	N	RANDOM	211.3	RSSI	29	37.720254	95	72	1
338	1449962981	791702	0	1	0	0	6276	33.848101	-84.429262	214.2	121215	billy3	hamza3	RANDOM	211.3	Type	2				
339	1449962981	919211	5	2	172	14	6276	33.847928	-84.429536	212.2	121215	billy3	brian3	RANDOM	211.3	RSSI	22	31.765738	96	13	1
340	1449962982	21689	5	2	172	14	6276	33.848006	-84.429529	212.3	121215	billy3	amanda3	RANDOM	211.3	RSSI	42	26.807944	206	64	1
341	1449962987	315881	5	2	172	14	21643	33.847977	-84.429551	211.6	121215	billy3	N	RANDOM	211.6	RSSI	44	49.332356	119	11	1
342	1449962987	324120	5	2	172	14	21643	33.848877	-84.429998	216.7	121215	billy3	lucian3	RANDOM	211.6	RSSI	29	117.382962	30	21	1
343	1449962987	513074	5	2	172	14	21643	33.848089	-84.42932	214	121215	billy3	amanda3	RANDOM	211.6	RSSI	43	24.909136	229	159	1
344	1449962991	128672	5	2	172	14	11105	33.848028	-84.429515	212.3	121215	billy3	N	RANDOM	212.3	RSSI	33	61.436987	66	1	1
345	1449962991	131225	0	1	0	0	11105	33.848217	-84.428847	216.3	121215	billy3	hamza3	RANDOM	212.3	Type	2				
346	1449962991	312814	5	2	172	14	11105	33.848095	-84.429297	214.5	121215	billy3	brian3	RANDOM	212.3	RSSI	21	43.687855	69	31	1
347	1449962991	412605	5	2	172	14	11105	33.848131	-84.429178	214.8	121215	billy3	amanda3	RANDOM	212.3	RSSI	47	32.008379	204	100	1
348	1449962994	55545	5	2	172	14	62	33.848871	-84.429984	217.6	121215	billy3	lucian3	RANDOM	213	RSSI	24	137.5055	22	8	1
349	1449962994	67774	0	1	0	0	62	33.848249	-84.428696	216.7	121215	billy3	hamza3	RANDOM	213	Type	2				
350	1449962994	221711	5	2	172	14	62	33.848172	-84.429084	215.1	121215	billy3	amanda3	RANDOM	213	RSSI	45	39.754754	153	42	1
351	1449962996	712824	5	2	172	14	28396	33.848863	-84.429973	217.8	121215	billy3	lucian3	RANDOM	213.6	RSSI	23	143.821056	21	16	1

352	1449962996	717355	5	2	172	14	28396	33.84817	-84.429085	215.3	121215	billy3	brian3	RANDOM	213.6	RSSI	41	47.454344	112	11	1
353	1449962996	743303	5	2	172	14	28396	33.848268	-84.429061	215.5	121215	billy3	amanda3	RANDOM	213.6	RSSI	41	43.841808	122	93	1
354	1449963001	927636	5	2	172	14	32313	33.848158	-84.429109	215	121215	billy3	N	RANDOM	215	RSSI	48	67.156714	100	74	1
355	1449963002	4693	0	1	0	0	32313	33.848318	-84.428386	217.3	121215	billy3	hamza3	RANDOM	215	Type	2				
356	1449963002	112732	5	2	172	14	32313	33.848397	-84.429097	215.5	121215	billy3	brian3	RANDOM	215	RSSI	25	66.203567	47	29	1
357	1449963006	812897	5	2	172	14	19698	33.848296	-84.42906	215.8	121215	billy3	N	RANDOM	215.8	RSSI	41	68.930488	77	20	1
358	1449963006	835836	0	1	0	0	19698	33.848342	-84.42831	217.6	121215	billy3	hamza3	RANDOM	215.8	Type	2				
359	1449963006	846682	5	2	172	14	19698	33.84886	-84.429994	217.8	121215	billy3	lucian3	RANDOM	215.8	RSSI	18	165.735109	18	2	1
360	1449963008	763964	5	2	172	14	13619	33.848352	-84.429082	215.7	121215	billy3	N	RANDOM	215.7	RSSI	41	72.817716	73	55	1
361	1449963008	841948	5	2	172	14	13619	33.848855	-84.429992	217.3	121215	billy3	lucian3	RANDOM	215.7	RSSI	17	166.429617	18	15	1
362	1449963011	220678	5	2	172	14	19895	33.848429	-84.429108	215.6	121215	billy3	N	RANDOM	215.6	RSSI	35	76.617007	57	6	1
363	1449963011	227773	0	1	0	0	19895	33.84836	-84.428282	218.1	121215	billy3	hamza3	RANDOM	215.6	Type	2				
364	1449963011	253820	5	2	172	14	19895	33.848856	-84.42999	216.3	121215	billy3	lucian3	RANDOM	215.6	RSSI	21	166.991153	18	17	1
365	1449963013	751234	5	2	172	14	19045	33.848501	-84.429131	215.5	121215	billy3	N	RANDOM	215.5	RSSI	33	81.27068	50	38	1
366	1449963013	798688	0	1	0	0	19045	33.848373	-84.428264	218	121215	billy3	hamza3	RANDOM	215.5	Type	2				
367	1449963013	845743	5	2	172	14	19045	33.848879	-84.429241	216.4	121215	billy3	amanda3	RANDOM	215.5	RSSI	34	106.263888	39	33	1
368	1449963017	754419	5	2	172	14	1121	33.848625	-84.429166	215.4	121215	billy3	N	RANDOM	215.4	RSSI	30	91.586468	40	0	1
369	1449963017	762236	0	1	0	0	1121	33.848451	-84.428196	218.2	121215	billy3	hamza3	RANDOM	215.4	Type	2				
370	1449963020	712765	5	2	172	14	16498	33.84869	-84.429185	215.4	121215	billy3	N	RANDOM	215.4	RSSI	35	97.104609	45	40	1
371	1449963020	753777	0	1	0	0	16498	33.848524	-84.428152	218.3	121215	billy3	hamza3	RANDOM	215.4	Type	2				
372	1449963020	813022	5	2	172	14	16498	33.849077	-84.42913	216.7	121215	billy3	amanda3	RANDOM	215.4	RSSI	29	109.193721	32	20	1
373	1449963024	112392	5	2	172	14	68	33.848757	-84.429206	215.4	121215	billy3	N	RANDOM	215.4	RSSI	36	101.186742	44	30	1
374	1449963024	144813	0	1	0	0	68	33.848566	-84.428134	218.5	121215	billy3	hamza3	RANDOM	215.4	Type	2				
375	1449963024	163828	5	2	172	14	68	33.848874	-84.429944	218	121215	billy3	lucian3	RANDOM	215.4	RSSI	20	170.516404	17	13	1
376	1449963024	212385	5	2	172	14	68	33.849019	-84.429006	216.7	121215	billy3	amanda3	RANDOM	215.4	RSSI	38	94.924658	51	48	1
377	1449963029	512630	5	2	172	14	10211	33.848884	-84.429236	215.7	121215	billy3	N	RANDOM	215.7	RSSI	41	102.66043	52	25	1
378	1449963029	538771	0	1	0	0	10211	33.848731	-84.428139	218.9	121215	billy3	hamza3	RANDOM	215.7	Type	2				
379	1449963029	613694	5	2	172	14	10211	33.848869	-84.429951	217.7	121215	billy3	lucian3	RANDOM	215.7	RSSI	18	167.932151	18	11	1
380	1449963031	840767	5	2	172	14	4445	33.848953	-84.429238	215.8	121215	billy3	N	RANDOM	215.8	RSSI	27	101.346171	33	25	1
381	1449963031	868721	0	1	0	0	4445	33.848788	-84.428158	219	121215	billy3	hamza3	RANDOM	215.8	Type	2				
382	1449963031	940287	5	2	172	14	4445	33.849011	-84.428769	216.6	121215	billy3	amanda3	RANDOM	215.8	RSSI	31	61.594357	62	11	1
383	1449963034	812828	5	2	172	14	32512	33.849012	-84.428769	216.4	121215	billy3	amanda3	RANDOM	215.8	RSSI	41	55.709831	96	77	1
384	1449963034	892705	0	1	0	0	32512	33.848876	-84.428188	219.1	121215	billy3	hamza3	RANDOM	215.8	Type	2				
385	1449963037	49457	5	2	172	14	11115	33.849012	-84.428771	216.2	121215	billy3	amanda3	RANDOM	216	RSSI	33	51.926301	78	8	1
386	1449963037	61795	0	1	0	0	11115	33.848946	-84.428214	219	121215	billy3	hamza3	RANDOM	216	Type	2				
387	1449963042	243682	5	2	172	14	1943	33.849034	-84.429041	216.3	121215	billy3	N	RANDOM	216.3	RSSI	35	72.581355	60	15	1
388	1449963042	261800	0	1	0	0	1943	33.849056	-84.428255	218.9	121215	billy3	hamza3	RANDOM	216.3	Type	2				
389	1449963042	512619	5	2	172	14	1943	33.849011	-84.428771	215.9	121215	billy3	amanda3	RANDOM	216.3	RSSI	49	47.492345	147	141	1
390	1449963048	712705	5	2	172	14	27454	33.849047	-84.428944	216.5	121215	billy3	N	RANDOM	216.5	RSSI	36	47.808436	94	56	1
391	1449963048	726116	5	2	172	14	27454	33.848875	-84.429944	217	121215	billy3	lucian3	RANDOM	216.5	RSSI	19	141.455397	21	17	1
392	1449963049	212350	5	2	172	14	27454	33.849011	-84.428774	217	121215	billy3	amanda3	RANDOM	216.5	RSSI	50	32.234015	224	90	1
393	1449963052	52630	5	2	172	14	28575	33.849048	-84.42894	216.4	121215	billy3	N	RANDOM	216.4	RSSI	32	47.534177	83	27	1
394	1449963052	82697	0	1	0	0	28575	33.849042	-84.428425	218.5	121215	billy3	hamza3	RANDOM	216.4	Type	2				
395	1449963052	349292	5	2	172	14	28575	33.849012	-84.428773	216.7	121215	billy3	amanda3	RANDOM	216.4	RSSI	51	32.289587	231	96	1

396	1449963057	112380	5	2	172	14	16093	33.849048	-84.428942	216.4	121215	billy3	N	RANDOM	216.4	RSSI	31	47.8127	80	37	1
397	1449963057	151735	0	1	0	0	16093	33.849041	-84.428424	218.6	121215	billy3	hamza3	RANDOM	216.4	Type	2				
398	1449963057	512614	5	2	172	14	16093	33.849013	-84.428773	216.6	121215	billy3	amanda3	RANDOM	216.4	RSSI	50	32.35926	223	139	1
399	1449963059	723671	5	2	172	14	5022	33.849047	-84.428943	216.3	121215	billy3	N	RANDOM	216.3	RSSI	32	47.997257	82	21	1
400	1449963059	746824	0	1	0	0	5022	33.84904	-84.428423	218.7	121215	billy3	hamza3	RANDOM	216.3	Type	2				
401	1449963060	31452	5	2	172	14	5022	33.849013	-84.428772	216.5	121215	billy3	amanda3	RANDOM	216.3	RSSI	50	32.348764	223	81	1

Appendix B: Author's Related Publications & Posters

1. R. Voicu, H. Abbasi, H. Fang, B. Kihei, J. Copeland and **Y. Chang**, "Fast and Reliable Broadcasting in VANETs using SNR with ACK Decoupling," IEEE International Conference on Communications (ICC), June 2014.
2. H. Abbasi, R. Voicu, J. Copeland, and **Y. Chang**, "Performance Analysis and Optimization of a Contention Window-based Broadcasting Algorithm in VANETs," in Proceedings of IEEE Global Communication Conference (Globecom), San Diego, CA, Dec. 2015.
3. B. Kihei, J. Copeland, and **Y. Chang**, "Improved 5.9GHz V2V Short Range Path Loss Model." the IEEE MASS (International Conference on Mobile Ad hoc and Sensor Systems), Dallas, TX, Oct. 2015.
4. B. Kihei, J. Copeland, and **Y. Chang**, "Design Considerations for Vehicle-to-Vehicle IEEE 802.11p Radar in Collision Avoidance," in Proceedings of IEEE Global Communication Conference (Globecom), San Diego, CA, Dec. 2015.
5. B. Kihei, J. Copeland, and **Y. Chang**, "Predicting Car Collisions using RSSI," in Proceedings of IEEE Global Communication Conference (Globecom), San Diego, CA, Dec. 2015.
6. B. Kihei, J. Copeland and **Y. Chang**, "Doppler Domain Localization for Collision Avoidance in VANETs by Using Omnidirectional Antennas," IEEE International Conference on Connected Vehicles and Expo (ICCVE), November 2014.
7. H. Abbasi, R. Voicu, J. Copeland, and **Y. Chang**, "Towards fast and reliable multi-hop routing in VANETs." IEEE Transactions on Mobile Computing. 2019 Jun 17.

A Novel Approach for Efficient and Reliable Broadcasting in VANETs

Hamza Ijaz Abbasi, Billy Kihei, Yusun Chang (Georgia Institute of Technology)

INTRODUCTION

Dedicated Short Range Communications (DSRC), a set of standards for vehicles to form ad hoc networks (VANETs), will enable cars to share information and emergency alerts within a VANET using Vehicle-2-Vehicle (V2V) protocols. This research focuses on improving the dissemination of messages within a VANET where transmitters move at high speeds and the environment changes rapidly.

BACKGROUND

Broadcasting messages reliably and efficiently in a VANET presents a unique networking challenge. V2V technology will enable a vehicle to set up an instant network with other vehicles on the roadway. Consider the example below:

How can messages be efficiently disseminated through the network, while also ensuring that the messages are reliably received?

RELATED WORK

Furthest Node Forwarding - GPS or SNR Criteria

Current research exploits the topology of the VANET ***only*** in selecting the furthest car from the source as forwarder using either GPS or received signal strength (SNR), and requires additional messages to ensure delivery known as RTB/CTB and ACKs.

PROTOCOL DESCRIPTION

A. Motivation

With regards to emergency message dissemination in a highly dynamic VANET environment, reliability and speed are the most important objectives. The proposed protocol achieves these goals by:

- Utilizing a highly effective technique that uses SNR and GPS coordinates to better account for terrain interference and other geographical attributes.
- Reducing channel access times by removing the costly handshaking process.
- Proposing a novel ACK decoupling mechanism which separates the message propagation from the ACK-ing process.

B. Design

This protocol follows these design steps* :

1. The emergency message originator accesses the medium using the standard 802.11 CSMA/CA technique and broadcasts the message.
2. Upon hearing, the neighboring nodes in the vicinity of the sender calculate their corresponding maximum contention window sizes (CWmax) according to the following formula:

$$CW_{max} = k \frac{D_{max}}{D_i} CW_{base}^{\frac{(SNR_i - SNR_{thresh})}{dB}}$$

3. After each node calculates its CWmax, it randomly chooses a time slot in the range [0, CWmax] and waits for that many time slots before rebroadcasting. The node that rebroadcasts first is chosen as the forwarder.
4. If the source receives this rebroadcasted message than this serves the purpose of an acknowledgement.
5. However, if the sender fails to overhear the rebroadcasted message, an ACK Decoupling and Recovery Mechanism is proposed as shown in Fig. 1
6. If the source does not receive a message back due to unavailability of node within the communication range, repeat from step 1.

* Design Steps of proposed protocol in comparison with SB protocol displayed in Fig. 2

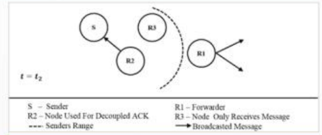


Fig. 1: ACK Decoupling and Recovery Mechanism

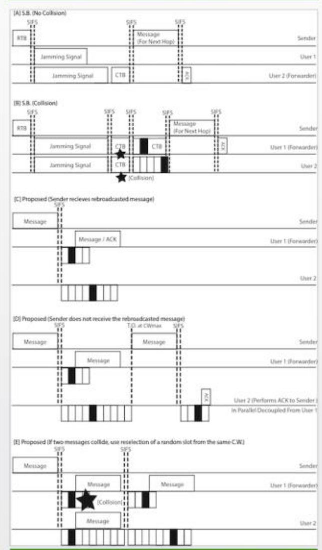


Fig. 2: Timing Diagram - Sequence of Packets being transmitted in SB (A, B) vs. Proposed Protocol (C, D, E)

PERFORMANCE EVALUATION

- Simulator: NS-3
- Rayleigh fading model
- Road Dimensions: 2 lane highway (4 Km long)
- Comparison with Smart Broadcast (SB)

❖ ***Simulation Results***

1. Mean Per Hop Delay
   - Proposed protocol perform better than SB by more than 200%
   - Reasons for improvement:
     - Removal of handshaking mechanisms
     - Better collision resolution technique
2. Throughput
   - Proposed protocol achieves twice the throughput as compared to SB
   - Reasons for improvement:
     - No RTB/CTB/ACK packets
     - Same sized packet is broadcasted with much lower average delay

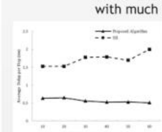


Fig. 3: Comparison of Per Hop Delay (Proposed Protocol vs. SB)

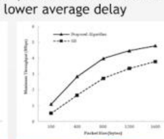


Fig. 4: Comparison of Max Throughput (Proposed Protocol vs. SB)

CONCLUSION

This paper proposed:

- An effective framework to disseminate the messages in VANETs.
- A unique process of forwarder selection, packet collision resolution mechanism, ACK decoupling and recovery.

Main References

[1] Razvan Cristian Voicu, **Hamza Ijaz Abbasi**, Huangwei Fang, Billy Kihei, John A. Copeland and Yusun Chang, "*Fast and Reliable Broadcasting in VANETs using SNR with ACK Decoupling*", accepted and to be published in IEEE Int'l Conference on Communications (ICC) 2014 in Sydney, Australia.

[2] Fasolo, E.; Zanella, A.; Zorzi, M., "An Effective Broadcast Scheme for Alert Message Propagation in Vehicular Ad hoc Networks," Communications, 2006. ICC '06. IEEE International Conference on , vol.9, no., pp.3960,3965, June 2006.

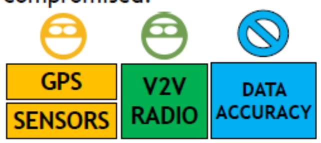
[3] F. Khan, Y. Chang, S. Park, and J. Copeland, "Handshaking vs. instant broadcast in vanet safety message routing," in Proceedings of IEEE PIMRC'11, pp. 709-714, 2011.

Message-Decoupled Collision Avoidance in V2V

Billy Kihei, John A. Copeland, Yusun Chang
{bkihei@gatech.edu, jcopeland@ece.gatech.edu, yusun@gatech.edu

PROBLEM

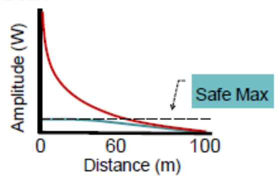
How can Vehicle-2-Vehicle (V2V) communications provide collision avoidance if safety message data is compromised?

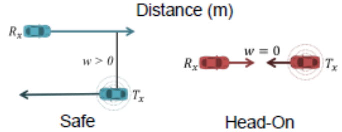


Three layers of reliability.

SOLUTION

Observe ***how*** the safety message is received, and not ***what*** the safety message contains.



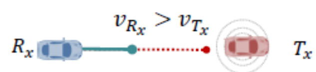


Theoretical received signal characteristics are different for Safe vs. Collision scenarios.

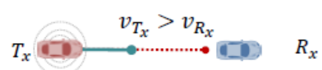
EXPERIMENTS

Captured V2V signals in safe and collision scenarios.

- Head-On Collision
- Forward Collision



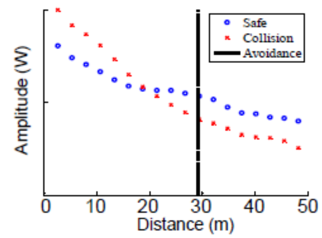
- Rear Collision



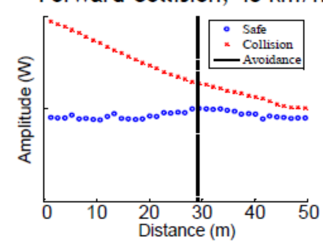
Experiment location and equipment used.

RESULTS

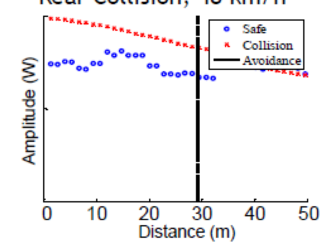
Head-On Collision, 48 km/h



Forward Collision, 48 km/h



Rear Collision, 48 km/h



CONCLUSION

Head-On collision is difficult to detect using signal amplitude due to high relative speeds.

After further processing, Head-On collision is detectable by observing rate of change.

Forward and Rear collisions are detectable using signal amplitude.

FUTURE WORK

Observe more signal characteristics to predict collisions, perform additional experiments with more vehicles, and detect threats without a V2V device.

Acknowledgements: Elizabeth Burnett, Razvan Voicu, Pedro Chavarria, Deuk Lee, George Udeochu, Joseph Burnett, and Jason Washington for their assistance in conducting the experiments. This research is partially supported by GDOT 13-02.

Improving Fast and Reliable Broadcasting in VANETs

Hamza Ijaz Abbasi, Razvan Cristian Voicu, John A. Copeland, and Yusun Chang

ABSTRACT

Exchanging emergency messages efficiently amongst vehicles on the road can lead to a significant reduction of traffic accidents. To disseminate the emergency messages in highly dynamic Vehicular Ad-Hoc Network (VANET) environment, fast and reliable propagation of the messages is the key objective. This research proposes a novel emergency message broadcasting protocol in VANETs that satisfies the above mentioned goal by:1) Using both SNR and GPS coordinates to select forwarders, 2) Removing costly handshaking process, 3) Using ACK decoupling mechanism to separate the message propagation from recovery process. The effectiveness of the protocol is investigated through mathematical model and various simulations. The real-world experiments reinforce the efficiency of the proposed algorithm and provide fundamental foundation to deploy the system in Georgia roads and highways.

BACKGROUND

Problem

- A leading vehicle with a DSRC transceiver wants to alert incoming vehicles of danger
- Hence, it should be able to efficiently broadcast the emergency message to other vehicles.
- How can the message be forwarded quickly and reliably through the VANET, while also limiting the amount of rebroadcasts ?

Furthest Node Forwarding - GPS or SNR Criteria

Source ***Forwarder***

- Previous research works exploit either the topology of the VANET (GPS) in selecting the forwarder only *or* by using SNR only.
- Also the previous research works depend on extra messages to control delivery such as RTB/CTB and ACKs.

PROTOCOL DESCRIPTION

A. Design

1. The originator broadcasts emergency message.
2. The neighboring nodes in the vicinity of the sender calculate their corresponding maximum contention window sizes (CWmax) as follows:

$$CW_{max} = k\,\frac{D_{max}}{D_i}\,CW_{base}^{\frac{(SNR_i - SNR_{thresh})}{dB}}$$

3. After each node calculates its CWmax, it waits till a randomly chosen time slot in the range [0, CWmax] before rebroadcasting. The node that rebroadcasts first is the forwarder.
4. If the source receives this rebroadcasted message than this serves the purpose of ACK.
5. However, if the sender fails to overhear the rebroadcasted message, an ACK Decoupling and Recovery Mechanism is proposed (Fig. 2)
6. If the source does not receive a message back due to node unavailability, repeat from step 1.

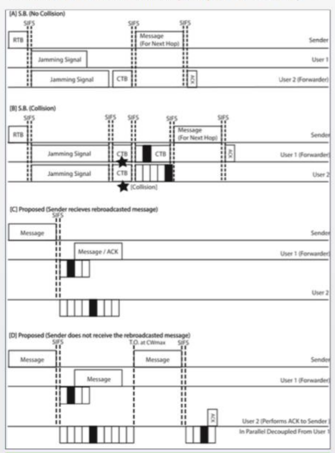


Fig. 1: Timing Diagram - SB (A, B) vs. Proposed Protocol (C, D)

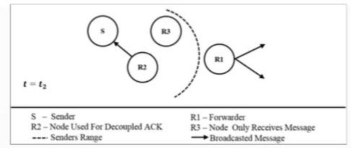


Fig. 2: ACK Decoupling and Recovery Mechanism

PERFORMANCE EVALUATION

A. Simulation Analysis

- Simulator: NS-3
- Rayleigh fading model
- Road Dimensions: 2 lane highway (4 Km long)
- Comparison with Smart Broadcast (SB)

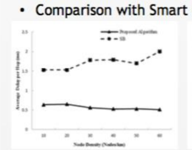


Fig. 3: Comparison of Per Hop Delay (Proposed Protocol vs. SB)

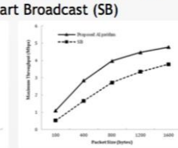


Fig. 4: Comparison of Max Throughput (Proposed Protocol vs. SB)

B. Theoretical Analysis

- Method: Standard Probabilistic Method
- Length of road strip: 4 Km long
- Node Distribution: Bi-dimensional Poisson process
- Main expressions constructed:
  - Per-Hop Rebroadcast Latency
  - Average message dissemination speed

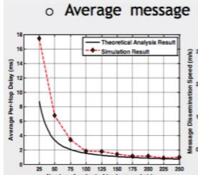


Fig. 5: Per-Hop Rebroadcast Latency (Theoretical vs. simulation results)

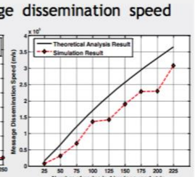


Fig. 6: Message Dissemination Speed (Theoretical vs. simulation results)

C. Experimentation

- 1-Hop, 2-Hop and 3-Hop Broadcasting
- Initial test bed with basic algorithm implemented
- Arada System Devices
  - On Board Units (OBU) and Road Side Units (RSU)
  - DSRC and WAVE standards

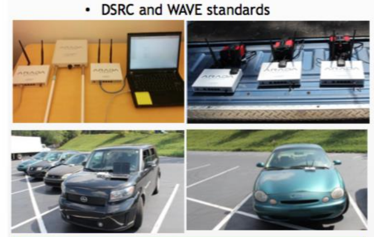


Fig. 7: Initial Field-testing Phase in Georgia

- Initial Results

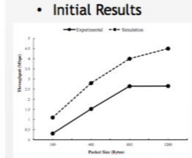


Fig. 8: Comparison of Throughput (Experimental vs Simulation)

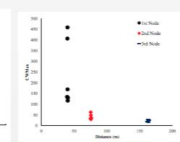


Fig. 9: Forwarder Selection (based on CWmax)

CONCLUSION

This research found:

- An effective framework to disseminate the emergency messages in VANETs.
- A unique process of forwarder selection, collision resolution mechanism, ACK decoupling and recovery.

Main References

[1] Razvan Cristian Voicu, Hamza Ijaz Abbasi, Huangwei Fang, Billy Kihei, John A. Copeland and Yusun Chang, "*Fast and Reliable Broadcasting in VANETs using SNR with ACK Decoupling*", published in IEEE Int'l Conference on Communications (ICC) 2014 in Sydney, Australia.

[2] Hamza Ijaz Abbasi, Razvan Cristian Voicu, John A. Copeland and Yusun Chang, "Improving *Fast and Reliable Broadcasting in VANETs*", to be submitted in IEEE Int'l Conference on Communications (ICC) 2015 in London, UK.

This research is supported by Georgia Department of Transportation GDOT 13-02

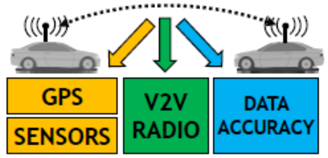
Doppler Domain Localization for Collision Avoidance in VANETs by Using Omnidirectional Antennas

Billy Kihei, John A. Copeland, Yusun Chang
bkihei@gatech.edu, jcopeland@ece.gatech.edu, yusun@gatech.edu

Published in ICCVE 2014 Vienna, Austria

PROBLEM

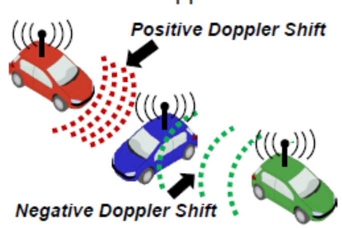
How can a Vehicle-2-Vehicle (V2V) communication radio provide collision avoidance if safety message data is compromised?



Three vulnerabilities in V2V.

SOLUTION

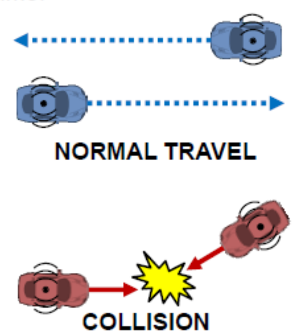
Observe ***how*** the safety message is received, and not ***what*** the safety message contains. Specifically, observe trends in the Doppler Shift.

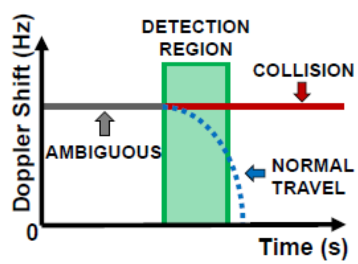


A positive Doppler Shift indicates a collision is ***possible***.

METHODOLOGY

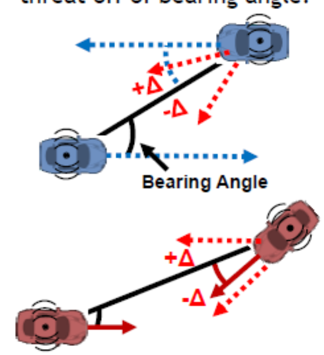
A ***possible*** collision can be ***verified*** by observing how the Doppler Shift changes over time.

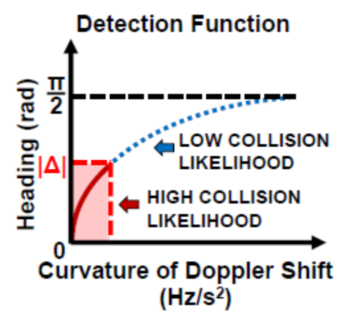




The heading needs to be estimated to ***confirm*** a collision is likely to occur.

If bearing angle is known, the detection function can then estimate the heading of the threat off of bearing angle.

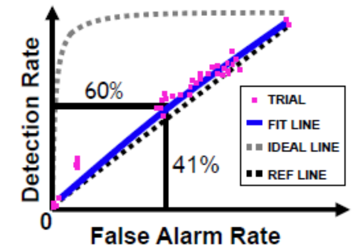




If the estimated heading is within a threshold, **Δ**, then the driver is alerted to brake.

FINDINGS

The detection method was simulated to reveal the expected performance.



IMPLICATIONS

The novel detection method shows potential to reduce car accidents, even if the safety message is compromised.

However, further research should investigate the performance under real world driving scenarios to discover ways to lower the false alarm rate.

This research would not have been possible without the insight provided by my LORD and Savior Jesus Christ.

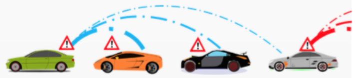
Performance Optimization of a Contention Based Broadcasting Algorithm in VANETs

Hamza Ijaz Abbasi, Razvan Cristian Voicu, John A. Copeland, and Yusun Chang

PROBLEM

- A leading vehicle with a DSRC transceiver wants to alert incoming vehicles of danger
- Hence, it should be able to efficiently broadcast the emergency message to other vehicles.
- How can the message be forwarded quickly and reliably through the VANET, while also limiting the amount of rebroadcasts ?

Furthest Node Forwarding - GPS <u>or</u> SNR Criteria



Source *Forwarder*

- Previous research works exploit either the topology of the VANET (GPS) ***or*** by using SNR only in forwarder selection.
- Also the previous research works depend on extra messages to control delivery such as RTB/CTB and ACKs.

SOLUTION

The proposed protocol exploits:

- A combination of SNR and GPS
- Handshake-less communication
- ACK decoupling and recovery process
- Novel collision resolution mechanism

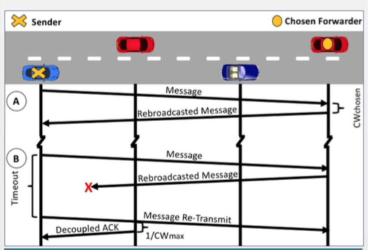


Fig. 1: Packet Sequence under: (A) Normal Rebroadcast Scenario (B) ACK Decoupling and Recovery Process. *Not drawn to scale*

PROTOCOL DESCRIPTION

Forwarder Selection Algorithm:

$$CW_{max} = k\,\frac{D_{max}}{D_i}\,CW_{base}^{\frac{(SNR_i - SNR_{thresh})}{dB}}$$

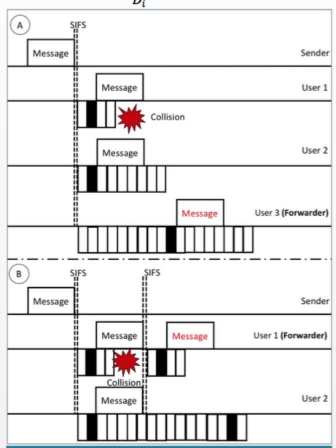


Fig. 2: Timing Diagram - Collision Resolution Mechanism.

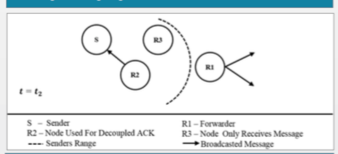


Fig. 3: ACK Decoupling and Recovery Mechanism

SIMULATION ANALYSIS

- Simulator: NS-3
- Rayleigh fading model
- Road Dimensions: 2 lane highway (4 Km long)
- Comparison with Smart Broadcast (SB)

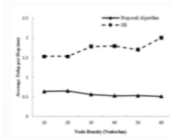


Fig. 4: Comparison of Per Hop Delay (Proposed Protocol vs. SB)

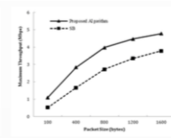


Fig. 5: Comparison of Max Throughput (Proposed Protocol vs. SB)

THEORETICAL ANALYSIS

- Method: Standard Probabilistic Method
- Length of road strip: 4 Km long
- Node Distribution: Bi-dimensional Poisson process
- Main expressions constructed:

1. Per-Hop Rebroadcast Latency (T_{HOP})

$$T_{HOP} = \frac{\sum_{i=0}^{\lambda} CW_{max,i}}{2\,\lambda^2}(T_I + T_C) + T_S + \frac{T_o}{e^{\lambda}}$$

where,

$$CW_{max,i} = k\frac{D_{max}}{D_i}\,CW_{base}^{\left(\frac{SNR_i - SNR_{thresh}}{\alpha dB}\right)}$$

2. Average message dissemination speed (s)

$$s = \frac{D_{AVG}}{T_{HOP}}$$

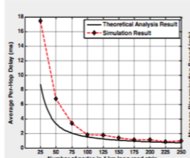


Fig. 6: Per-Hop Rebroadcast Latency (Theoretical vs. simulation results)

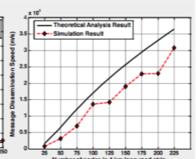


Fig. 7: Message Dissemination Speed (Theoretical vs. simulation results)

EXPERIMENTATION

Fig. 8: Multi-hop Experimentation in Atlanta, Georgia

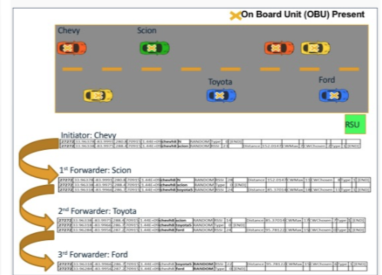


Fig. 9: Forwarder Selection in Multi-hop Communication

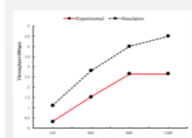


Fig. 10: Comparison of Throughput (Experimental vs Simulation)

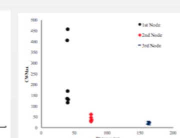


Fig. 11: Forwarder Selection (based on CWmax)

Related Publications

[1] Razvan Cristian Voicu, Hamza Ijaz Abbasi, Huangwei Fang, Billy Kihei, John A. Copeland and Yusun Chang, "*Fast and Reliable Broadcasting in VANETs using SNR with ACK Decoupling*", published in IEEE Int'l Conference on Communications (ICC) 2014 in Sydney, Australia.

[2] Hamza Ijaz Abbasi, Razvan Cristian Voicu, John A. Copeland and Yusun Chang, "Performance Optimization of a Contention Based Broadcasting Algorithm in VANETs", published in IEEE Globecom 2015 in San Diego, CA, USA

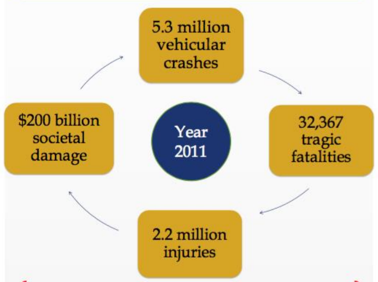
This research is supported by Georgia Department of Transportation GDOT 13-02

Efficient Safety Message Routing in VANETs

Hamza Ijaz Abbasi, John A. Copeland, and Yusun Chang

Georgia Tech · Kennesaw State University

Motivation



*"**V2V communications in VANETs** will enable active safety systems that can assist drivers in **preventing 76 percent of crashes**"- USDOT*

Problem Statement

- How can safety messages be forwarded quickly and reliably through VANET?

Furthest Node Forwarding - GPS or SNR Criteria

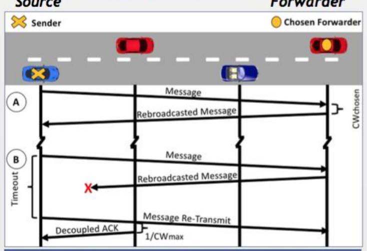


Fig. 1: Packet Sequence under: (A) Normal Rebroadcast Scenario (B) ACK Decoupling and Recovery Process. *Not drawn to scale*

Proposed Protocol

The proposed protocol exploits:

- A combination of SNR and GPS
- Handshake-less communication
- ACK decoupling and recovery process
- Novel collision resolution mechanism

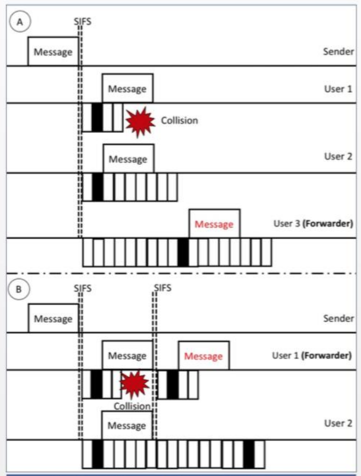


Fig. 2: Timing Diagram - Collision Resolution Mechanism.

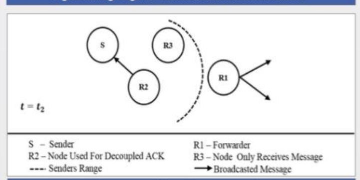


Fig. 3: ACK Decoupling and Recovery Mechanism

Simulation

- Simulator: NS-3
- Road Dimensions: 2 lane road (4km long)
- Comparison with Smart Broadcast (SB)

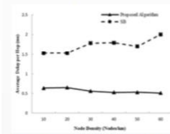


Fig. 4: Comparison of Per Hop Delay (Proposed Protocol vs. SB)

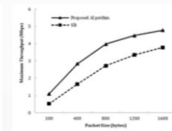


Fig. 5: Comparison of Max Throughput (Proposed Protocol vs. SB)

Theoretical Analysis

- Method: Standard Probabilistic Method
- Length of road strip: 4 Km long
- Node Distribution: Bi-dimensional Poisson process
- Main expressions constructed:

1. ***Per-Hop Rebroadcast Latency (T_{HOP})***

$$T_{HOP} = \frac{\sum_{i=0}^{\lambda} CW_{max,i}}{2\,\lambda^2}\,(T_I + T_C) + T_S + \frac{T_o}{e^{\lambda}}$$

2. ***Average message dissemination speed (s)***

$$s = \frac{D_{AVG}}{T_{HOP}}$$

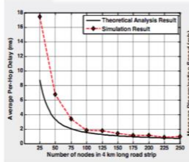


Fig. 6: Per-Hop Rebroadcast Latency (Theoretical vs. simulation results)

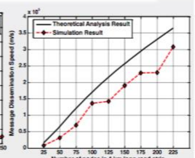


Fig. 7: Message Dissemination Speed (Theoretical vs. simulation results)

Experimentation

Fig. 8: Multi-hop Experimentation in Atlanta, Georgia

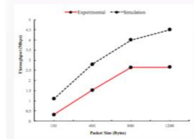


Fig. 10: Comparison of Throughput (Experimental vs Simulation)

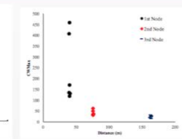


Fig. 11: Forwarder Selection (based on CWmax)

Conclusion

This research found:

- An effective framework to disseminate the safety messages in VANETs.
- A unique process of forwarder selection, collision resolution mechanism, ACK decoupling and recovery.
- Reliable and faster approach than traditional protocols

Implications

- Protocol is easily deployable.
- It can reliably and quickly assist drivers in hazardous conditions.
- It will help save lives and property.

References

[1] Razvan Cristian Voicu, Hamza Ijaz Abbasi, Huangwei Fang, Billy Kihei, John A. Copeland and Yusun Chang, *"Fast and Reliable Broadcasting in VANETs using SNR with ACK Decoupling"*, published in IEEE Int'l Conference on Communications (ICC) 2014 in Sydney, Australia.

[2] Hamza Ijaz Abbasi, Razvan Cristian Voicu, John A. Copeland and Yusun Chang, "Performance Optimization of a Contention Based Broadcasting Algorithm in VANETs", published in IEEE Globecom 2015 in San Diego, CA, USA

This research is supported by Georgia Department of Transportation GDOT 13-02

GDOT Georgia Department of Transportation · NCTSPM