Vehicle-to-vehicle Broadcast for Highway Safety Applications

Hien Phuong Luong

A thesis submitted in total fulfilment of
the requirements for the degree of
Doctor of Philosophy

Centre for Advanced Internet Architectures
Swinburne University of Technology
Melbourne, Australia

2017

Vehicle-to-vehicle Broadcast for Highway Safety Applications

by

Hien Phuong Luong

Swinburne University of Technology

Melbourne, Australia

Abstract

Vehicle-to-vehicle (V2V) communication is a potential method to improve road safety, and reduce car accidents by informing drivers about the danger ahead. In V2V communication, vehicles broadcast beacon and (event-driven) safety messages to exchange information. Safety applications based on the dedicated short-range communication (DSRC) in vehicular networks have very strict performance requirements for safety messages (in terms of delay and reliability). However, meeting the reliability requirement is challenging due to the effect of packet collisions caused by hidden terminals and direct collisions, especially at high vehicle density. In this thesis, we analyse, design, and develop different techniques to improve the reliability of vehicular safety applications.

In a multi-hop broadcast, we propose a generic probabilistic forwarding scheme that achieves the requirements for safety messages, is compatible with the IEEE 802.11 broadcasting protocol, and inherits some of the best features of solutions proposed so far for vehicular safety applications. We then develop a unified and comprehensive analytical model to evaluate the performance of the proposed scheme taking into account the effect of hidden terminals, direct collisions, vehicle densities and the spatial distribution of the multiple forwarders, in a one-dimensional highway scenario. To the best of our knowledge, the proposed model is the first comprehensive analytical model in V2V networks, and considers multiple aspects ignored in the previous models in the literature. The proposed model is compatible with both the single-class IEEE 802.11p EDCA and the IEEE 802.11p MAC protocol. The accuracy of the proposed model is confirmed by extensive simulations using real traffic traces.

In a single-hop broadcast, we investigate the effect of the beacon rate on the network performance of safety messages, and develop an optimization problem to recommend optimal beacon rates based on a utility maximization framework. The message utility is constructed to account for the reliability requirement of safety messages and maintain the accuracy of neighbourhood information collected by beacons. In the literature, there is a need for a comprehensive framework to suggest beacon rate considering the effect of hidden terminals, direct collisions, the requirements of safety messages, and the accuracy of neighbourhood information collected by beacons. The proposed framework fulfils this requirement and therefore has many advantages over prior proposals. Besides, by means of the proposed models, we suggest effective broadcast protocols and provide optimal designs for both multi-hop broadcast and single-hop broadcast protocols that can satisfy the strict requirements of safety applications.

Declaration

I hereby declare that this PhD thesis is my own work and has not been submitted for any degree at any University or Institution. All other material used in the thesis has been acknowledged in the text.

I warrant that I have obtained, where necessary, permission from the copyright owners to use any third party copyright material reproduced in the thesis, or to use any of my own published work in which the copyright is held by another party.

Signature: ______________________

Date : ______________________

Dedication

This thesis is dedicated to my Mom, my Dad, and my Aunt, Co Nam, for their permanent love, support, and encouragement.

Acknowledgements

First and foremost, I would like to express my gratitude to my principal supervisor, Professor Hai Vu, who supported my PhD application when I was a research assistant at University of Science, Vietnam. Since then, he has provided continuous guidance, support, and constructive comments for my PhD research. I also wish to thank my co-supervisors, Associate Professor Bao Vo, Doctor Manoj Panda, and Doctor Suong Nguyen, for their guidance, endless patience, constant encouragement, research and life advice. Their attitude to research inspired me to become a researcher.

I would like to thank the Faculty of Science, Engineering and Technology, the Centre for Advanced Internet Architectures (CAIA) for providing me facilities for my research. In addition, I would like to thank my annual review panel, Doctor Philip Branch, Doctor Tony Cricenti, Doctor Jason But, for their valuable input, feedback, and advice for my research. I wish to thank Professor Grenville Armitage for his advice and support during my PhD at CAIA. I wish to thank Professor Ivan Stojmenovic for his valuable input and comments for my research through his visits.

I would like to thank Doctor Jessie Nghiem for her research advice, and for being a good friend. I also thank my CAIA labmates, Doctor Tuan Dinh, Tung Le, Radika Veera Valli, Shiva Raj Pokhrel, for interesting discussions about research and life.

Last but not the least, I would like to thank my family in Vietnam, my parents, my aunt, and my sisters, for their permanent love, understanding, and countless encouragement. Without them, this thesis would not be finished on time. I would like to express my gratitude to them in Vietnamese.

Con xin gửi lời cảm ơn chân thành đến Ba, Má, và cô Năm. Nếu không có tình yêu thương, sự chia sẻ của gia đình, có lẽ, cuốn luận văn này đã không hoàn thành đúng hạn. Gia đình đã luôn là chỗ dựa vững chắc cho con trong suốt hành trình vừa qua. Con cảm ơn Ba, Má đã là nguồn cảm hứng và sức mạnh để con vượt qua những lúc khó khăn. Con cảm ơn Cô Năm, người mẹ thứ hai, đã yêu thương, chăm sóc con như con gái. Em cảm ơn chị Hiếu, chị Hạnh, đã bầu bạn, quan tâm, và chia sẻ cùng em gái. Con mong gia đình mình nhiều sức khoẻ, và niềm vui.

Con cảm ơn chú Tiến, đã khuyến khích, động viên con trên con đường học vấn từ những ngày đầu tiên đến trường. Con cảm ơn cô Thủy, đã bên cạnh, bầu bạn cùng Ba Má con, giúp chúng con yên tâm khi học tập, làm việc nơi xa xứ. Và cuối cùng, em cảm ơn anh, Luân Lâm, người đã ở bên cạnh, yêu thương, và chia sẻ cùng em.

Contents

Abstract **ii**

Declaration **iv**

Dedication **v**

Acknowledgements **vi**

1 Introduction **1**

1.1 Motivation 1

1.2 Introduction 2

1.2.1 Major Challenges 3

1.3 Scope of the Study 5

1.3.1 Broadcast Protocols 5

1.3.2 Performance Analysis 5

1.3.3 Beacon Rate Optimization 5

1.4 Contributions 6

1.4.1 Generic Probabilistic Forwarding Scheme 6

1.4.2 Performance Analysis of a Single-hop Broadcast 6

1.4.3 Performance Analysis of a Multi-hop broadcast (i.e. the Generic Probabilistic Forwarding scheme) 7

1.4.4 Transmission round approximation 7

1.4.5 Model Simplification 8

1.4.6 Contention-Window Priority 8
1.4.7 Optimization of Beacon Rate 8
1.4.8 Optimal designs 9
1.5 Organisation of the thesis 9
1.6 Publications 11

2 Literature Review 12

2.1 Overview 12
2.2 Vehicle-to-vehicle Communication Technology 13
2.2.1 Vehicle-to-vehicle Technology 13
2.2.2 The IEEE 802.11p Standard 14
2.3 Existing techniques to improve V2V Performance 17
2.4 Broadcast Protocols 17
2.4.1 Classification 17
2.4.2 Delay-based Multi-hop Scheme 19
2.4.3 Topology-based Multi-hop Scheme 20
2.4.4 Probability-based Multi-hop Scheme 24
2.5 Performance Analysis 26
2.5.1 Analytical Models for Unicast Communication 28
2.5.2 Analytical Models for Broadcast Communication 29
2.6 Beacon approaches 32
2.6.1 Transmission Power 33
2.6.2 Contention Window 34
2.6.3 Beacon Rate 35
2.6.4 Combination 37
2.7 Limitations of Existing Work 38
2.7.1 Limitations of Existing Broadcast Protocol 39
2.7.2 Limitations of Existing Performance Analysis 39
2.7.3 Limitations of Existing Adaptive Beacon Rate 40
2.8 Chapter Summary 40

3 Performance Analysis of a Generic Probabilistic Forwarding scheme 41

3.1 Overview 41

3.2 Motivation for the multi-hop probabilistic forwarding scheme 42

3.3 System Model and Assumptions 44

3.3.1 The Network Scenario 44

3.3.2 Assumptions 44

3.4 Generic Probabilistic Forwarding Scheme 46

3.5 Analytical Modeling 48

3.5.1 Transmission rounds 49

3.5.2 Overview of the analysis 49

3.5.3 Analysis of the first round 53

3.5.4 Analysis of the second round 58

3.5.5 PDR after the third round 64

3.5.6 Delay analysis 65

3.6 Model Validation 66

3.7 Chapter Summary 76

4 Model Simplification and Extensions 78

4.1 Overview 78

4.2 Model Simplification 80

4.2.1 Analytical Model 80

4.2.2 Model Validation 82

4.3 Optimization of Beacon Rate in a Single-hop Broadcast 83

4.3.1 The Utility Function 85

4.3.2 Optimization Problem 86

4.3.3 Numerical Results and Model Validation 91

4.4 Contention-Window Priority in a Multi-hop Broadcast 96

4.4.1 Analytical Model 97

4.4.2 Model Validation 100

4.5 Chapter Summary 105

5 Optimal Designs **107**

5.1 Overview 107

5.2 Single-hop Designs 108

5.2.1 PDR Designs with Contention Window 108

5.2.2 PDR Designs with a combination of Contention Window and Beacon Rate 110

5.3 Multi-hop Designs 111

5.3.1 PDR Comparison between multiple Probabilistic Schemes 111

5.3.2 PDR Designs with Coefficient c 112

5.3.3 PDR Designs with Contention Windows 113

5.3.4 PDR Designs with a combination of Coefficient c and Window Priority 117

5.4 Chapter Summary 119

6 Conclusion **120**

6.1 Overview 120

6.2 Contributions 120

6.2.1 Generic probabilistic forwarding scheme 121

6.2.2 Performance analysis of a generic probabilistic forwarding scheme 121

6.2.3 Optimization of beacon rate 121

6.2.4 Contention-window priority 122

6.2.5 Optimal Designs 122

6.3 Future Work 123

A Obtaining specific schemes from the generic probabilistic forwarding function **138**

B Hidden collision analysis with retransmission region **140**

C PDR after the third round **142**

D The average number of forwarders after the third round **145**

E Solving the optimization problem **147**

List of Figures

1.1 The thesis structure. 10

2.1 A classification of broadcast protocols for VANETs. 18

2.2 An example to identify a dominating set. 22

2.3 The forwarding probability for vehicles in the IF scheme with different distances from the source and different values of coefficient c, given Tx = 200m. 25

2.4 A classification of analytical models for the performance of the IEEE 802.11. 28

2.5 A classification of beaconing congestion control for VANET. 33

3.1 The overall PDR for the Irresponsible Forwarding (Panichpapiboon and Ferrari, 2008), Dominating Set (Stojmenovic et al., 2002) and the Single-hop broadcast schemes. 43

3.2 Summary of the analysis with different blocks representing different steps and sub-steps. 50

3.3 Direct and hidden collision areas for a node with distance x from the source. 54

3.4 Direct and hidden collision areas in round 2 for different forwarder's positions. The source is at 0, the tagged receiver is at x and the potential forwarder is at f. 59

3.5 The overall PDR after all retransmission rounds for various multi-hop probabilistic forwarding schemes, and the PDR of a single-hop broadcast scheme. 69

3.6 The overall PDR after all retransmission rounds with different values of c in the IF scheme. 69

3.7 The average number of forwarders in the second transmission round with different values of c in the IF scheme. 70

3.8 The overall probability that a node receives the safety message, given its distance from the source, with $c = 7$ in the IF scheme. 71

3.9 The unconditional forwarding probability of nodes as a function of the distance from a tagged receiver located at a distance $R/2$ from the source in the second transmission round with $c = 20$ in the IF scheme. 72

3.10 The mean delay after all retransmission rounds with multiple probabilistic forwarding schemes, and that of the single-hop broadcast scheme. 73

3.11 The overall PDR for the IF ($c = 20$) and the single-hop schemes under non-uniform densities and fading. 74

3.12 The overall PDR for the IF scheme ($c = 20$) and the single-hop scheme with the real traces (Gramaglia et al., 2014) and fading. 76

3.13 A comparison of the Average PDR and Worst-Case PDR via simulation and analytical results for multiple probabilistic forwarding schemes. 77

4.1 The PDR obtained by the simplified model, the full model, and the simulation for the IF scheme ($c = 20$) and the single-hop broadcast scheme, given $W = 15$, $AIFSN = 7$, Slot time = 20 μs. 82

4.2 The mean delay obtained by the simplified model, the full model, and the simulation for the IF scheme ($c = 20$) and the single-hop broadcast scheme, given $W = 15$, $AIFSN = 7$, Slot time = 20 μs. . . 83

4.3 The PDR for safety messages with multi-class EDCA using a fixed beacon rate of 10 messages/second, with three retransmissions and a fixed beacon rate of 10 messages/second, and with single-class EDCA with the appropriately chosen density-dependent beacon rates. 84
4.4 The effect of beacon rate on the PDR_1 with different values of vehicle density, given $\alpha = 0.3, L = 1.0$ and $W = 31$. 87
4.5 The maximum values of λ satisfying different values of safety requirement (i.e. $\sigma_1 = 90\%$ and $\sigma_1 = 95\%$). 87
4.6 The minimum values of λ satisfying two different values of the neighbourhood estimation error (i.e. $\sigma_2 = 5\%$ and $\sigma_2 = 20\%$). 89
4.7 The main findings of the optimization problem. 91
4.8 The feasible regions for different requirements of σ_1 and σ_2, with two vehicle densities of 130 and 250 vehicles/km. 92
4.9 The optimal values of λ with multiple vehicle densities that satisfy $\sigma_1 = 90\%$ and $\sigma_2 = 20\%$. 93
4.10 The PDR of safety messages using real traces for the optimal beacon rates, and the rate of 10 messages/second. 94
4.11 The effect of weight (α) on optimal values of λ with multiple vehicle densities, given $\sigma_1 = 90\%$ and $\sigma_2 = 20\%$. 95
4.12 The PDR for the standard EDCA using both a single-hop broadcast and a multi-hop broadcast, and that of the multi-hop broadcast with appropriate contention windows. For the multi-hop broadcast, we use the IF scheme ($c = 20$). 96
4.13 Summary of the analysis for the contention-window priority. 98
4.14 The overall PDR for various multi-hop probabilistic forwarding schemes, given a higher priority for safety messages ($W_s = 7$, $W_b = 255$). 101
4.15 The overall PDR with different values of contention-window priority for beacon and safety messages, given the IF scheme with different values of c ($c = 3$ and $c = 30$). 102
4.16 The mean delay for various probabilistic forwarding schemes, given a higher priority for safety messages ($W_s = 7$, $W_b = 255$). 103

4.17 The overall probability that a node receives the safety message given an interval distance from the source, for the IF scheme with $c = 3, W_s = 7, W_b = 255$. 104
4.18 The average number of forwarders in the second transmission round with different values of c, given $W_s = 7$, $W_b = 255$. 104

5.1 The PDR for the single-hop broadcast with multiple values of contention window for beacon messages, given $W_s = 3$, and Slot time = 20μs. 108
5.2 The PDR for the single-hop broadcast with multiple values of contention window for safety messages, given $W_b = 255$, and Slot time = 20μs. 109
5.3 The comparison of the PDR with different values of beacon rate, contention windows for safety and beacon messages, given $\sigma_1 = 90\%, \sigma_2 = 20\%$. 110
5.4 A fundamental comparison of the PDR between multiple probabilistic forwarding schemes based on the analytical results, given $W_s = W_b = 31$, $\lambda = 10$ messages/second, and slot time = 20 μs. 112
5.5 The best broadcast protocol and/or optimal values of coefficient c (if using the IF scheme), at different vehicle densities, given different requirement thresholds for PDR and $W_s = W_b = 31$, $\lambda = 10$ messages/second, and slot time = 20μs. 113
5.6 The overall PDR with different values of W_s for multiple vehicle densities, given $c = 20$, $W_b = 255$, and Slot time = 20μs. 114
5.7 The mean delay with different values of W_s for multiple vehicle densities, given $c = 20$ and $W_b = 255$. 115
5.8 The overall PDR with different values of W_b for multiple vehicle densities, given $c = 3$, $W_s = 3$, and Slot time = 20μs. 116
5.9 The appropriate values of (c, W_s, W_b) that satisfy the PDR and mean delay requirements at the density of 25 vehicles/km. 117
5.10 The appropriate values of (c, W_s, W_b) that satisfy the PDR and mean delay requirements at the density of 130 vehicles/km. 118

5.11 The appropriate values of (c, W_s, W_b) that satisfy the PDR and mean delay requirements at the density of 250 vehicles/km. 118

C.1 Possible locations of forwarders for a node at point f in the second round is the interval $[-(R-f), R]$. 143

List of Tables

2.1 Default parameters in the IEEE 802.11p EDCA. 16
2.2 Forwarding probability functions for schemes in the probability-based group, where $p_b(x)$ is the forwarding probability, R is the transmission range, x is the distance from the sender, c is a coefficient, and β is the vehicle density. 24
2.3 The existing literature for broadcast protocols that can be used for vehicular communications. 27
2.4 Comparison our model with other models in the literature. 30
2.5 Comparison existing algorithms for beacon rate adaptation. 36

3.1 Choice of functions $h(\cdot)$ and parameters c_1 and c_2 for different forwarding probability functions. 47
3.2 Parameter Setup for Simulation. 68

4.1 Parameter Settings for the Optimization of Beacon Rate. 92
4.2 Parameter Setup for Simulation. 92
4.3 Parameter Setup for Simulations. 101

"If we knew what it was we were doing, it would not be called research, would it?"

Albert Einstein

1 Introduction

1.1 Motivation

Since the beginning of automobiles, road accidents have become a serious problem around the world. In the United States, the average number of deaths due to car accidents was 36,000 annually from 1994 to 2012, according to the National Highway Traffic Safety Administration (NHTSA, 2013). Similarly, in Australia, there have been over 187,000 road fatalities since 1925, and car accidents cost about $27 billion annually, which were reported by the Department of Infrastructure and Regional Development (DIRD, 2016). In 2010, about 1.33 million people died globally due to car accidents, making road incidents the eighth-leading cause of death (Bhalla et al., 2014). Besides, in developing countries, approximately 1% to 5% of the total GDP is spent on costs related to car accidents (Bhalla et al., 2014). This serious issue has impacted both directly and indirectly many people's lives. Therefore, a large number of researchers in industry and academia are motivated to develop new technologies to improve road safety.

Research has shown that car accidents can be avoided to a large extent if drivers receive warning information at least two seconds in advance (Vehicle Safety Communications Consortium, 2005; Yuan, 1997). Nowadays, advanced technologies such as vehicle-to-vehicle (V2V) wireless communications can be used to improve road safety. In V2V communications, vehicles communicate with each other within a certain communication range and can exchange warning information about the danger ahead. In addition, as the demand increases, V2V technologies will be affordable in near future due to economies of scale. The National Highway Traffic Safety Administration in the United States approximates that V2V devices and supporting equipment would only cost about $341 to $350 per vehicle in 2020 (Harding et al., 2014, page 58). Therefore, it is expected that road safety, in practice, can significantly be improved by using V2V communications. In this thesis, we analyse, design, and develop different techniques to facilitate safety applications in V2V networks.

1.2 Introduction

Dedicated Short Range Communication (DSRC) refers to the use of wireless communication among vehicles (V2V) or communication between vehicles and infrastructure (V2I) to improve the safety and efficiency of road traffic. V2V communication raises interesting challenges for the research community due to high mobility, unstable topology and fast changing density (Yousefi et al., 2006). Each vehicle can broadcast either a *beacon* or *safety* (also referred to as *event*) message at a time. Beacon messages are periodically sent by every vehicle to inform others about its position, speed, and direction of movement. In contrast, safety messages are broadcast to provide the drivers with emergency/safety related information and the danger ahead, and only by those vehicles that are involved in an emergency situation.

There are two main types of V2V applications: *safety* and *non-safety*. Non-safety applications provide drivers comfort and entertainment. Some examples of non-safety applications are traffic information system, parking slot assistant, weather related information, and music download. On the other hand, safety applications attempt to improve driver safety by exchanging information via safety messages between vehicles. Examples of these applications include but not limited to: entering intersection warning, departing highway warning, obstacle discovery, and lane change warning. Due to the critical nature of the information for safety applications, the requirements for the network performance on reliability and delay for safety messages are very strict. It is required that at least 90% of vehicles (also referred to as nodes) in the targeted area receive the information within a 100 ms delay (Hassan et al., 2011; Harding et al., 2014, page 98). Meeting these requirements is challenging due to the high mobility, unstable topology and fast changing density in V2V networks (Yousefi et al., 2006). In this thesis, we focus on safety applications due to their significant impact on both social and economic aspects.

The physical (PHY) and medium access control (MAC) layer standards for DSRC are specified in IEEE 802.11p (IEEE Standard 802.11, 2012). The IEEE 802.11p MAC is defined based on a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) principle. In the IEEE 802.11p MAC layer, the Distributed Coordination Function (DCF) is the fundamental access mechanism, and the Enhanced Distributed Channel Access (EDCA) is commonly used to support service differentiation. The impact of MAC layer contentions on the performance of safety message broadcast is one of the main topics studied in this thesis.

1.2.1 Major Challenges

The major challenges for vehicular safety applications considered in this thesis are described as follows.

Disseminating safety messages using V2V communications can adopt a one-hop (also referred to as single-hop) broadcasting method. The use of one-hop method can satisfy the delay but not the reliability requirements (Huang et al., 2010; Luong et al., 2014). This is because the reception of safety messages is seriously affected by packet collisions, especially at high vehicle density (Hassan et al., 2011). Packet collisions happen when multiple transmissions overlap in time at a receiving node. There are two types of collisions: *direct* and *hidden*. Direct collisions are caused when nodes that are within the transmission range of each other start transmitting their messages at (almost) the same time. In contrast, hidden collisions are caused by nodes that are outside the range of each other (i.e., hidden), whose packet transmissions might overlap in time. In V2V broadcasting, hidden collisions are known to be the main cause for the degradation of reliability (Hassan et al., 2011; Ma et al., 2012). Therefore, there is an urgent need for the development of methods to reduce the impact of packet collisions and to improve the reliability.

Multi-hop broadcasting methods can be used to improve the reliability in V2V communications (Luong et al., 2016). Developing an analytical model for a multi-hop broadcast is needed to study the effect of multiple network parameters on the performance, but it is challenging. This is because in the multi-hop broadcast, there are multiple potential forwarders and receivers. Each potential receiver-forwarder pair has its own set of hidden nodes. In multi-hop broadcast communication, the network changes over space and time which is difficult to model and makes the analysis of hidden node collisions even harder. Furthermore, identifying the spatial distribution of forwarders that determines the distribution of hidden nodes is also challenging. In this thesis, we develop an analytical model to evaluate the network performance of a generic probabilistic forwarding scheme for multi-hop broadcasting.

Finally, beacon messages affect significantly the network performance of vehicular safety applications, as beacons are the main traffic in the network, and safety messages and beacons share the same channel. Identifying appropriate beacon rates is challenging. On one hand, a high rate of beacons can degrade the reliability of safety messages due to an increase in packet collisions. On the other hand, a low rate of beacon messages may not provide an accurate and up-to-date neighbourhood information, where the accurate neighbourhood information is required to support safety applications. Besides, due to the significant effect of hidden nodes in V2V communications, identifying appropriate beacon rates becomes more challenging. Therefore, there is a need for capturing the effect of beacon rate on the network performance with hidden nodes, and suggest appropriate beacon rates.

1.3 Scope of the Study

The objective of this research is to improve the reliability of broadcast for V2V safety applications. In this thesis, we will investigate three main research questions described as follows.

1.3.1 Broadcast Protocols

How to disseminate messages in V2V safety applications that can satisfy the strict requirements of delay and reliability? To answer this, we first study the network performance of one-hop and multi-hop broadcast based on the IEEE 802.11p MAC protocol. From the obtained results, we provide observations and further insights for exchanging information in V2V communications. Our results show that multi-hop broadcast protocols, when appropriately tuned, clearly outperform the single-hop protocols. Then, we propose a generic multi-hop probabilistic forwarding scheme that can significantly improve the reliability, while retaining the best features of various existing multi-hop broadcasting protocols.

1.3.2 Performance Analysis

How the network performance of broadcast protocols for vehicular safety applications are affected by the choice of parameters and network conditions? To answer this, we develop an accurate analytical model to evaluate the network performance of both single-hop broadcast and the proposed generic probabilistic forwarding scheme with different vehicle densities and parameter values. The proposed model takes into account the key factors that affect the network performance such as hidden terminals, direct collisions, vehicle densities and the spatial distribution of forwarders in a multi-hop broadcast. We then extend the proposed model to capture the effect of message prioritization using contention windows on the network performance.

1.3.3 Beacon Rate Optimization

Beacon messages constitute the main traffic in vehicular networks. The beacon rate, therefore, will significantly affect the network performance. How does a beacon rate impact on the performance? How to identify an optimal beacon rate for a given network context? How much the network performance of V2V safety applications can be improved by using optimally designed beacon rate? To answer these questions, we first develop an analytical model to investigate the effect of beacon rate on the network performance. We then develop a framework to suggest optimal beacon rate based on a utility maximization. In addition, by means of the proposed framework, we suggest the optimal broadcast protocol and the optimal values of parameters (e.g. contention window, beacon rate) based on the network conditions such as vehicle densities.

1.4 Contributions

To improve the broadcast performance in vehicular networks, we analyse, design and develop different techniques for V2V enable safety applications. The original contributions made by this thesis are summarised as follows.

1.4.1 Generic Probabilistic Forwarding Scheme

We propose a generic probabilistic forwarding scheme to disseminate messages in V2V networks for both safety and non-safety applications. Specifically, the proposed scheme assigns an appropriate probability for every vehicle to retransmit safety messages. It inherits some of the best features of other broadcast schemes in the literature, while retaining simplicity and robustness. Multiple existing probabilistic broadcasting schemes in the literature can be obtained from the proposed generic scheme as special cases by varying its parameters.

1.4.2 Performance Analysis of a Single-hop Broadcast

We develop a comprehensive analytical model to evaluate the network performance of single-hop broadcast for safety applications. Specifically, the proposed model is compatible with both the single class IEEE 802.11p EDCA and the IEEE 802.11p DCF MAC protocols. The effect of direct collisions, hidden terminals, vehicle densities, and the details of the back-off process is taken into account in the analysis of the proposed model. Besides, the analytical model can be used in an unsaturated network condition where a vehicle may or may not always have a message to send. The accuracy of the model is confirmed by simulation with real traffic traces.

Note that developing an analytical model to evaluate the network performance of a single-hop broadcast is important although the single-hop broadcast cannot satisfy the safety requirements via using the default values suggested by the standard. This is because the proposed analytical model can be used as a reference for comparing the analytical model of the proposed multi-hop broadcast later.

1.4.3 Performance Analysis of a Multi-hop broadcast (i.e. the Generic Probabilistic Forwarding scheme)

We develop a comprehensive analytical model to evaluate the network performance of a generic probabilistic forwarding scheme for vehicular safety applications in a multi-hop broadcast setting. The model is compatible with both the single class IEEE 802.11p EDCA and the IEEE 802.11p DCF MAC protocols. The model can be used to evaluate the network performance for several multi-hop broadcast schemes in the probabilistic forwarding group. To the best of our knowledge, the proposed work is the first comprehensive analytical model for multi-hop broadcast in V2V networks, taking into account hidden terminals, direct collisions, the details of backoff process in the analysis of direct collision, vehicle densities, the spatial distribution and the effect of multiple forwarders. In contrast to the single-hop broadcast where packet collisions happen only between beacon and safety messages, in the multi-hop broadcast, packet collisions may also occur between safety messages. Our model can capture this effect. The accuracy of the model is validated by extensive simulations using real traffic traces.

1.4.4 Transmission round approximation

To overcome the challenges of multiple forwarders when evaluating the network performance of a multi-hop broadcast protocol, we introduce a transmission round approximation that works accurately in the multi-hop broadcast setting. The proposed model is then validated by multiple forwarding schemes, different vehicle densities, and different values of coefficient to control the number of forwarders.

1.4.5 Model Simplification

A simplified model is proposed to reduce the complexity while ensuring high accuracy, except at extremely high vehicle densities. The simplified model considers all relevant factors such as hidden terminals, direct collisions, vehicle densities, and the spatial distribution of forwarders. The simplified model can be used to evaluate the performance of both the single-hop and multi-hop broadcast protocols.

1.4.6 Contention-Window Priority

We study the effect of contention window on the network performance of the multi-hop broadcast protocol and provide further insights. In addition, we extend the model simplification to evaluate the performance of a multi-hop broadcast protocol where messages are classified into multiple priority groups using contention windows.

1.4.7 Optimization of Beacon Rate

We investigate whether single hop broadcast can also satisfy the stringent requirements of safety applications if the beacon rates were appropriately designed. We develop an optimization problem to seek optimal beacon rates based on a utility maximization framework, and investigate the effect of beacon rate on the network performance. The message utility takes into consideration the reliability of safety messages and the accuracy of neighbourhood information. Our results show that by using optimal beacon rates computed using the optimization problem, a single-hop broadcast can indeed satisfy the safety requirements. To the best of our knowledge, there is no existing work in the literature that considers all of the critical issues, viz., direct collisions, hidden terminals, and vehicle densities together for finding optimal beacon rates.

1.4.8 Optimal designs

By means of the analytical models mentioned earlier, we suggest effective broadcast protocols and provide optimal designs for both multi-hop broadcast and single-hop broadcast protocols. Our results show that both multi-hop and single-hop protocols can satisfy the strict requirements of safety applications by using appropriate parameters and broadcast schemes.

1.5 Organisation of the thesis

Fig. 1.1 describes the structure of the thesis and highlights the main contributions in brief for each chapter. Specifically, the remaining chapters of the thesis are structured as follows.

In Chapter 2, we first present the background information for vehicle-to-vehicle safety applications, and then review the related works for broadcast protocols, performance analysis, and beacon rate adaptation in vehicular safety applications. In addition, the limitations of some existing works are highlighted.

In Chapter 3, we propose a generic probabilistic forwarding scheme to re-transmit safety messages. Then, we develop a comprehensive analytical model to evaluate the network performance of both the generic probabilistic forwarding scheme and the single-hop broadcast scheme in V2V networks. In this chapter, we also introduce the transmission round approximation that works effectively in the performance analysis of a multi-hop broadcast protocol. Then we validate the model and provide further insights.

In Chapter 4, we provide a simplification of the comprehensive model while retaining its high accuracy. Then, we propose two extensions for the simplified model to improve the reliability of V2V safety applications, by optimizing the rate of beacon messages, and using the priority of contention window.

In Chapter 5, we provide optimal designs for both the single-hop and multi-hop broadcast protocols. Specifically, based on the network context, we suggest optimal broadcast protocol and parameter settings that satisfy the requirements of safety applications. By means of the proposed model, we provide insights and a comparison

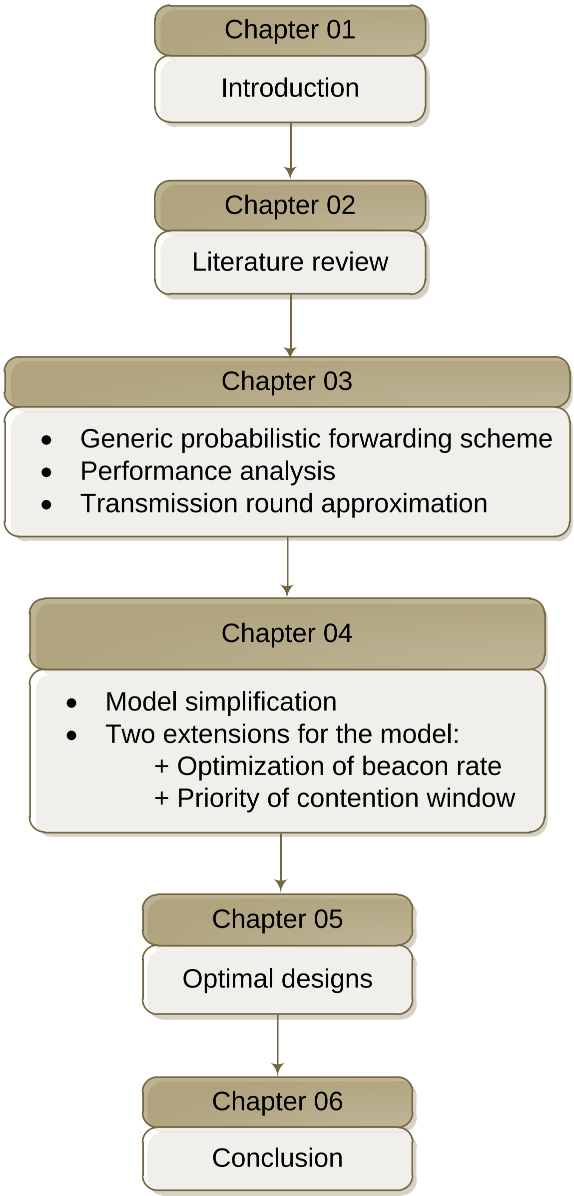


Figure 1.1: The thesis structure.

between different techniques.

In Chapter 6, we summarise our work, discuss the main observations, results, and insights presented in this thesis. Besides, we identify the limitations and suggest potential directions for the future works.

1.6 Publications

Most of the work presented in this thesis has been published. My publications related to this thesis are as follows.

- H. P. Luong, S. H. Nguyen, H. L. Vu and B. Q. Vo "One-hop vs. multi-hop broadcast protocol for DSRC safety applications", in *Proc. 15th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Sydney, Australia, June 2014.

- H. P. Luong, M. Panda, H. L. Vu and B. Q. Vo "Analysis of Multi-hop Probabilistic Forwarding for Vehicular Safety Applications on Highways", accepted to *IEEE Transactions on Mobile Computing*, June 2016.

- H. P. Luong, M. Panda, H. L. Vu and B. Q. Vo "Beacon Rate Optimization for Vehicular Safety Applications in Highway Scenarios",under review of *IEEE Transactions on Vehicular Technology*, 2016.

"Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning."

Albert Einstein

2

Literature Review

2.1 Overview

In this chapter, we review the relevant literature for V2V communications, especially when it is related to safety applications. Several techniques to improve the network performance in V2V are surveyed. First, in Sec. 2.2, we provide a brief background on V2V technology for message dissemination. Next, in Sec. 2.3, we review the existing techniques to improve the network performance of V2V safety applications. In Sec. 2.4, a survey of existing work in the field of broadcast protocol is conducted. Then, Sec. 2.5 summarises the literature of performance analysis that is classified into unicast and broadcast communications. In Sec. 2.6, the current approaches to congestion control for beacon traffic are presented. Sec. 2.7 points out the limitations of the existing work. Finally, in Sec. 2.8, we summarise this chapter.

2.2 Vehicle-to-vehicle Communication Technology

With the intention of improving road safety, several public and private organizations have been established around the world to study vehicular networks. For example, there are a number of groups such as the ITS Australia[1], the Intelligent Transportation Systems - Joint Program Office[2] in the USA, the Car 2 Car - Communication Consortium[3] in Europe, and the Vehicle Information and Communication System (VICS)[4] in Japan. These organizations have been studying for years to improve the dissemination methods and technologies of V2V communications. In the following, we provide a brief background on V2V technologies to disseminate messages.

2.2.1 Vehicle-to-vehicle Technology

There have been a large number of proposed communication methods for ITS communication which are collectively called Communication Access for Land Mobiles (CALM)[5]. These communication modes include Bluetooth, satellite, cellular, and the Dedicated Short Range Communication (DSRC).

The current IEEE technology to support V2V communications is the Wireless Access in Vehicular Environment (WAVE) (IEEE Standard 1609.0-2013, 2014). In vehicular safety applications, there are two types of messages that are *beacon* and *safety* messages. Each vehicle broadcasts periodically beacon messages to inform other vehicles about its position, speed, and direction of movement. In contrast, safety (also referred to as event) messages are broadcast to provide the drivers with emergency/safety related information and the danger ahead, and only by those vehicles that are involved in an emergency situation. In WAVE, beacon and safety messages are WAVE Short Messages. The WAVE Short Message Protocol is provided to support priority and time-sensitive communications for WAVE Short Mes-

[1]The ITS Australia, `http://www.its-australia.com.au/`, accessed on October 30, 2016.

[2]The ITS-Joint Program Office, `http://www.its.dot.gov/`, accessed on October 30, 2016.

[3]The Car 2 Car-Communication Consortium, `https://www.car-2-car.org/`, accessed on October 30, 2016.

[4]The VICS, `http://www.vics.or.jp/`, accessed on October 30, 2016.

[5]The CALM, `http://calm.its-standards.info/`, accessed on October 30, 2016.

sages. The WAVE standard includes the IEEE 1609 and the IEEE 802.11p. In the IEEE 1609, multichannel operation can be supported to disseminate messages. Specifically, the version of the IEEE 1609.1 (IEEE Standard 1609.1-2006, 2006) is developed to support the resource manager. The security services are developed in the IEEE 1609.2 (IEEE Standard 1609.2-2006, 2006). In the 1609.3 (IEEE Standard 1609.3-2007, 2007), addressing and routing services in networking services are taken into consideration. In the 1609.4 (IEEE Standard 1609.4-2006, 2006), multichannel mode is supported to disseminate information, where the 1609.4 is located on top of the IEEE 802.11p.

In contrast to the IEEE 1609 which is concerned with multichannel operation, the IEEE 802.11p (IEEE Standard 802.11, 2012) is concerned with medium access control and physical layer issues on a given channel of operation. The IEEE 802.11p is modified from the IEEE 802.11a which has been used widely to support Wifi communications. Specifically, to provide vehicular communications with low delay, the IEEE 802.11p is adjusted from the IEEE 802.11a in the specifications of both medium access control layer (MAC) and physical layer (PHY). In this thesis, we study message broadcasting using the dominant standard IEEE 802.11p to support vehicular communications.

2.2.2 The IEEE 802.11p Standard

In the IEEE 802.11p, there are two main components: the PHY layer and the MAC layer. The PHY layer can be divided further into two sub layers. The upper sub-layer is used to communicate with the MAC layer. The lower sublayer is used for data encoding and modulation. In the PHY layer, approximately 5.85 – 5.925 GHz band is provided to send information. It is interesting to note that the PHY layer is defined based on the Orthogonal Frequency Division Multiplexing (OFDM) in the IEEE 802.11a PHY layer with some adjusted parameters to support vehicular communications. Specifically, in the IEEE 802.11p, 10 MHz channels are used to replace the 20 MHz channels; the data rate is reduced to half; and the timing parameters are doubled. Besides, due to the characteristics of vehicular communications, the range of communication is also longer.

The IEEE 802.11p MAC is defined based on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) principle, with the Distributed Coordination Function (DCF) being the fundamental access mechanism, and the Enhanced Distributed Channel Access (EDCA) is used to support service differentiation.

In the IEEE 802.11p DCF, there is a single transmission queue, and a node senses the channel to determine whether or not another node is transmitting before sending a message. A message will be sent if the channel is idle for a constant period of time called Distributed Inter-Frame Space (DIFS). Otherwise, the node has to undergo a backoff process. In the backoff process, a node selects a random backoff interval between $[0, W]$, where W is the contention window (CW), with $W = 2^n - 1, n \in N, 0 \leq n \leq 15$. Every node chooses a random backoff interval which follows a uniform distribution. For each time slot when the channel is idle, the backoff counter is decremented by one. The message is sent when the counter reaches zero. The process of this random backoff can reduce the packet collisions due to contention when multiple nodes are deferring to the same 'channel busy' event. During the backoff process, if another node within the transmission range of the sender starts to transmit, the backoff counter is suspended. If the channel becomes idle again for a constant DIFS period, the backoff counter is resumed with the latest value of the backoff counter.

In contrast, the IEEE 802.11p EDCA is modified to support message prioritization. Specifically, different from the IEEE 802.11p DCF, where messages have the same priority, in EDCA, messages are classified into multiple priority groups with four access categories (AC): *background traffic, best effort, video, and voice* (IEEE Standard 802.11, 2012, page 820). In EDCA, messages in the classes of voice and background traffic obtain the highest and lowest priorities respectively (see Table 2.1). In the IEEE 802.11p EDCA, a message will be sent if the channel is idle for a period of time that is called the Arbitration inter-frame spacing (AIFS). A message with a higher priority will be assigned a smaller Contention Window (W) and a smaller AIFS. The default parameters for different access classes in 802.11p EDCA are shown in Table 2.1. These values are taken from Table 8-105 in (IEEE Standard 802.11, 2012), together with the default values of $Wmin = 15$ and $Wmax = 1023$

Table 2.1: Default parameters in the IEEE 802.11p EDCA.

Class Number	Access Class	Wmin	Wmax	AIFSN
AC_BK	Background Traffic (BK) (e.g., Beacon messages)	15	1023	7
AC_BE	Best Effort (BE)	15	1023	3
AC_VI	Video (VI)	7	15	2
AC_VO	Voice (VO) (e.g., Safety messages)	3	7	2

from (IEEE Working Group and others, 2010).

There is one minor difference in the backoff countdown process between EDCA and DCF. In DCF, at the end of an idle slot, there is a case when both a backoff countdown and a transmission occur at the same time, that is, when a backoff countdown is decreased to zero and the channel is sensed idle. In EDCA, on the other hand, either a backoff countdown or a transmission can occur (Bianchia et al., 2007). In both EDCA and DCF, during the backoff process, the counter is decreased when the channel is idle (IEEE Standard 802.11, 2012).

Each class in the EDCA, however, can be considered an enhanced variant of the DCF despite the difference (IEEE Standard 802.11, 2012, page 820). Therefore, the analytical models that are proposed in this thesis can be used for both the IEEE 802.11p DCF and a single class IEEE 802.11p EDCA.

Unicast and Broadcast protocols

The IEEE 802.11p can support both unicast and broadcast communication modes. However, broadcast protocols are usually used in V2V communications. In a unicast communication, there is only one destination. Different from the unicast communication, in the broadcast mode, a number of destinations are observed. Broadcast communication is more appropriate for safety applications, as multiple vehicles can gain benefit from the safety related information. In addition, to reduce hidden node collisions, a unicast communication can use the Request-to-Send (RTS)/ Clear-to-Send (CTS) mechanism, which is not used in a broadcast communication. From the modelling point of view, broadcast communication is significantly different from the unicast one, as hidden terminals in a broadcast communication are more sensitive than those of a unicast communication.

2.3 Existing techniques to improve V2V Performance

Packet collision is a serious issue in disseminating messages in vehicular communications. With the purpose of improving the reliability of broadcasting, there have been many approaches in the literature to reduce the impact of packet collisions, including the use of *additional signalling* prior to the broadcast (Korkmaz et al., 2004; Ma et al., 2012; Ota et al., 2015), *retransmissions* (Panichpapiboon and Ferrari, 2008; Slavik and Mahgoub, 2010; Hassan et al., 2011), *beacon rate adaptation* (Drigo et al., 2009; Le et al., 2011; Chaabouni et al., 2013), and *message priorities* by using multi-class EDCA (Yao et al., 2013).

In this thesis, we will be focusing on the retransmissions, beacon rate adaptation, and message prioritization, excluding the use of additional signalling. This is because introducing additional signalling requires significant overhead or additional bandwidth. The literature for retransmissions, beacon rate adaptation, and performance analysis are reviewed next.

2.4 Broadcast Protocols

In this section, we review the existing work for retransmissions (or broadcast protocols) in the literature.

2.4.1 Classification

Broadcast protocols for vehicular communications with retransmissions can be classified into two types: *one-hop*, where the same vehicle will retransmit the message multiple times (Hassan et al., 2011); and *multi-hop*, where other vehicles will retransmit the received message (Füßler et al., 2004; Osafune et al., 2006; Wisitpongphan et al., 2007). There are a number of surveys for the vehicular broadcast protocols

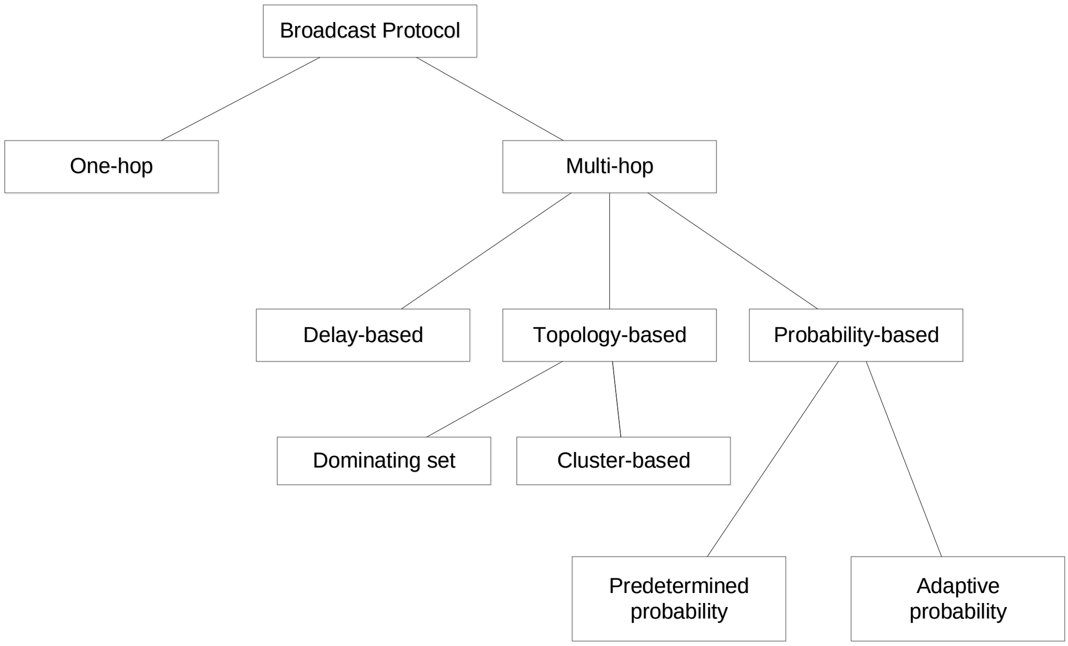


Figure 2.1: A classification of broadcast protocols for VANETs.

in the literature (Panichpapiboon and Pattara-Atikom, 2012; Chaqfeh et al., 2014; Ahmed et al., 2014). In Fig. 2.1, we summarise the existing broadcast protocols that can be used for V2V communications.

In one-hop retransmission, even though a message is typically retransmitted multiple times by the same vehicle (Hassan et al., 2011), a single broadcast protocol without any retransmissions can also be considered the simplest case in this group. In the one-hop broadcast, the source retransmits a message based on a broadcast interval time. The challenging question is how to choose the interval effectively. The literature for one-hop retransmissions has been extensively reviewed in the survey (Panichpapiboon and Pattara-Atikom, 2012).

In (Hassan et al., 2011), the source blindly retransmits a safety message several times to improve the reliability. However, the problem with one-hop retransmissions is that the *boundary nodes* still have a low probability of receiving the safety message due to the high probability of packet collisions caused by hidden terminals, especially at high density. Boundary nodes are nodes located (almost) at the boundary of the transmission range of the source. During multiple retransmissions, the sets of hidden terminals for the boundary nodes in the one-hop retransmission remain unchanged. Therefore, to improve the reliability, multi-hop retransmissions, where different nodes retransmit the safety message, should be used, as the source and retransmitting nodes have different sets of hidden nodes.

In multi-hop retransmission, the original idea is *flooding* in which every node retransmits the message after receiving (Ho et al., 1999). However, the network performance of the flooding scheme is not robust. For example, at low density, the reliability of flooding seems to be reduced due to dis-connectivity (Cooper et al., 2004). Therefore, in (Cooper et al., 2004; Hahner et al., 2003; Viswanath and Obraczka, 2002) hyper-flooding schemes are proposed to solve the issue. Specifically, in a hyper-flooding scheme, each node will retransmit additionally when it discovers a new neighbour. In contrast, at high density, both flooding and hyper-flooding schemes may lead to the *broadcast storm* problem (Ni et al., 1999), where a successful reception of safety message is prevented by high packet/frame collisions, contentions, and redundancy. This is caused by many redundant forwarders rebroadcasting messages. To alleviate this issue, several schemes in the multi-hop group have been devised to reduce the number of forwarding nodes. Such multi-hop schemes can be classified into three groups: *delay-based*, *topology-based*, and *probability-based*.

2.4.2 Delay-based Multi-hop Scheme

In the delay-based scheme, every forwarding vehicle is assigned a delay-timer to retransmit messages. This delay typically depends on the distance between its own location and that of the sender node (Füßler et al., 2004; Wisitpongphan et al., 2007; Osafune et al., 2006; Khakbaz and Fathy, 2008). In general, a forwarding vehicle will use a smaller delay for a larger distance from the sender. In (Osafune et al., 2006; Khakbaz and Fathy, 2008), a vehicle retransmits a message with a delay based on the distance between itself and the sender. The paper also suggests a cancellation method to reduce redundant forwarders. If a vehicle receives a message more than one time and the locations of the senders are in the same region, the vehicle will cancel its retransmissions. Besides, (Osafune et al., 2006) also adds a new feature, called traffic congestion detection, to adjust the broadcast delay. Basically, the congestion for a vehicle is determined by the number of neighbours and the vehicle speed. When the congestion is confirmed, vehicles increase their broadcast delays to avoid packet collisions.

In (Khakbaz and Fathy, 2008), in addition to retransmitting messages based on the delay timer, authors propose a feature to solve the network fragmentation problem by identifying connection gaps. If a vehicle is in the direction of information dissemination, it is defined in a connection gap if it does not receive any duplicate messages from any other forwarders. To solve the network fragmentation, a vehicle in a connection gap will keep the message and retransmit it when a new vehicle moves into its communication range within the message lifetime.

In (Wisitpongphan et al., 2007), a vehicle retransmits a message with a time-slot delay based on the distance from the sender, and the total number of time slots. A node that has a higher distance from the sender will obtain a smaller number of time slots to retransmit the message. Other similar works in the literature that also use the time-slot delay to disseminate information can be found in (Tseng et al., 2010; Schwartz et al., 2010).

Limitations

A delay-based scheme can be a good solution for broadcasting messages for non-safety applications in V2V communications due to its simplicity and robustness. For some safety applications where the delay requirement is extremely strict (e.g. 20 ms (Harding et al., 2014, page 98)), a delay-based scheme, however, is not a good choice as the scheme will add additional delay when transmitting messages.

2.4.3 Topology-based Multi-hop Scheme

Different from the delay-based approach, in topology-based schemes, a vehicle will be chosen to forward messages based on the detailed neighbourhood information (i.e. *topology*). In V2V communications, beacon messages provide the neighbourhood information for vehicles. Specifically, in TRADE (Sun et al., 2000), only the furthest node is chosen to forward messages. The ID of the furthest neighbour is implemented by piggybacking in a message sent by a vehicle. However, (Daraghmi et al., 2013) points out that this protocol is not robust because the furthest node may not receive the message due to hidden terminal collisions and channel errors. Therefore, instead of the furthest vehicles, it has been suggested to choose a higher number of forwarders to broadcast messages (Stojmenovic et al., 2002; Zhang et al., 2011). The topology-based schemes in the literature can be further classified into *Dominating Set* and *Cluster* groups.

Dominating Set

In general, in a dominating set scheme, a node in the *dominating set* will be selected to retransmit messages. A *Dominating Set* (DS) is a set where each node in the considered network either belongs to this set or has a neighbour belonging to this set (Stojmenovic et al., 2002). The dominating set is considered a promising method that minimizes the number of forwarders while retains the coverage of broadcasting area (Wu and Li, 2001). It is important to note that schemes in the DS approach only gain high performance when the network is connected. In the literature, it is also shown that the dominating set approach holds the potential to solve the broadcast storm problem (Osafune et al., 2006; Lim and Kim, 2001). Examples of dominating-set schemes can be found in (Stojmenovic et al., 2002; Liu et al., 2012; Stojmenovic et al., 2012).

In (Stojmenovic et al., 2002; Liu et al., 2012; Stojmenovic et al., 2012), the DS-based approach requires a collection of two-hop neighbourhood information via beacon messages. Every vehicle in the network transmits periodically beacon messages to report its position, speed, direction of movement, and the list of one-hop neighbourhood information. Different methods of determining DS will lead to different sets of nodes in the DS (Wu and Li, 2001), (Stojmenovic et al., 2002). In (Stojmenovic et al., 2002), all nodes in the DS will be chosen as forwarders. Three steps are used to identify the dominating set in (Stojmenovic et al., 2002) as follows.

- Step 1: A node is in the dominating set if it has at least two neighbours that are not direct neighbours themselves (i.e., are not within the transmission range of each other). The two following steps are used to eliminate the redundant forwarders in the set. Note that the DS in (Stojmenovic et al., 2002) is close to the minimum DS, not exactly the minimum DS.

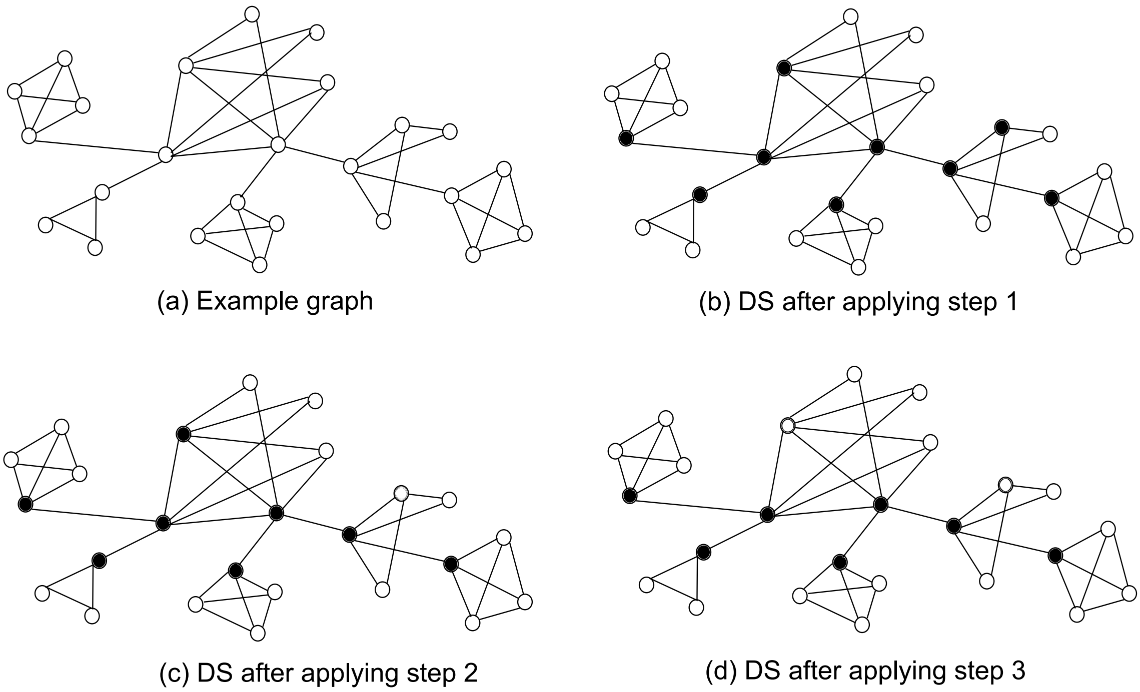


Figure 2.2: An example to identify a dominating set.

- Step 2: After Step 1, let $A, B \in$ DS. Let $N(A)$, $N(B)$ be sets of all neighbours of node A and node B respectively. Remove A from the DS if $N(A) \subseteq N(B)$ and $key(A) < key(B)$, where $key(A)$ is given by $(degree_A, x_A, y_A)$, $degree_A$ is the number of neighbours of A, and x_A and y_A are its two coordinates in the planes. If $N(A) = N(B)$, then x_A and x_B will be considered to remove either A or B. If $x_A = x_B$, then y_A and y_B will be compared.

- Step 3: After step 2, let $B, D, E \in$ DS. Remove B if $N(B) \subseteq \{N(D) \cup N(E)\}$ and $key(B) = min\{\ key(B),\ key(D),\ key(E)\}$.

As an example, Fig. 2.2 demonstrates the details on how to identify a dominating set by following the three steps proposed in (Stojmenovic et al., 2002). The example graph is shown in Fig. 2.2a, while in Fig. 2.2b, Fig. 2.2c, and Fig. 2.2d, a dominating set for the graph is identified after applying Steps 1, 2, and 3, respectively. In the figure, a vehicle is represented by a node; the solid nodes are the nodes in the dominating set. If two nodes are connected, there is a path connecting these two nodes. As can be seen from the figure, if there is no packet collision, retransmitting nodes in the dominating set can cover the full network.

In (Liu et al., 2012; Stojmenovic et al., 2012), the set of forwarders is extended to include both nodes in the DS and nodes outside the DS with high ranking. The ranking is based on the information of geographical locations. In (Liu et al., 2012; Stojmenovic et al., 2012), a node in the DS obtains a shorter time to retransmit messages than a node outside the DS.

Clustering schemes

In the literature, multiple clustering schemes for VANETs have been proposed (Zhang et al., 2011; Shea et al., 2009; Arkian et al., 2014; Ghodrati, 2013; Vegni et al., 2012; Chen et al., 2015). Note that the clustering approach has been studied widely in mobile ad hoc networks (Yu and Chong, 2005). In clustering schemes, vehicles are classified into different clusters. A vehicle in a clustering scheme can be one of three types: a cluster head, a cluster member, or a cluster undecided (Zhang et al., 2011). In general, a cluster head will retransmit messages. A vehicle with low mobility will be considered a cluster head. In an N-hop clustering, a cluster head can send a message up to its N-hop neighbours. In other words, the maximum number of hops between the cluster head and an arbitrary member is N.

In (Zhang et al., 2011; Shea et al., 2009), the cluster head identification considers mobility. A node with the lowest aggregate mobility is chosen as a cluster head in (Zhang et al., 2011). In (Shea et al., 2009), cluster heads are identified by minimizing both the relative mobility and the distance to the cluster members. This paper is based on the technique of Affinity Propagation proposed in (Frey and Dueck, 2007). In (Vegni et al., 2012), cluster heads are selected to minimize the number of forwarders by utilizing the distance between vehicles and the time delay.

Limitations

The topology-based schemes that are based on the neighbourhood information can be a good solution for disseminating information in the network regarding the network resources. However, this approach may not work well in the high mobility and fast changing topology in V2V networks (Yousefi et al., 2006). This is because it will be challenging for a vehicle to obtain an accurate and up-to-date neighbourhood information. Therefore, the topology-based approach might suffer significant performance degradation and does not represent the optimal choice for vehicular

Table 2.2: Forwarding probability functions for schemes in the probability-based group, where $p_b(x)$ is the forwarding probability, R is the transmission range, x is the distance from the sender, c is a coefficient, and β is the vehicle density.

Scheme	**Controlling parameters**	**Forwarding probability function**, $p_b(x)$
(Slavik and Mahgoub, 2010), (Fracchia and Meo, 2008)	-	$p_b(x) = const$
(Wisitpongphan et al., 2007), (Slavik and Mahgoub, 2010)	Distance, transmission range	$p_b(x) = \frac{x}{R}$
(Panichpapiboon and Ferrari, 2008)	Distance, transmission range, vehicle density	$p_b(x) = e^{-\frac{\beta(R-x)}{c}}$

safety applications.

2.4.4 Probability-based Multi-hop Scheme

The probabilistic approach inherits the simplicity of the delay-based scheme while does not require the detailed topology information as in the topology-based approach. In the probabilistic approach, every vehicle is assigned a certain probability to retransmit messages. The schemes in the probabilistic group can be divided further into two groups: *predetermined probability*, and *adaptive probability.* In the predetermined group, the probability for vehicles to transmit messages can be fixed (Slavik and Mahgoub, 2010; Fracchia and Meo, 2008). In contrast, in the adaptive group, the probability for vehicles to transmit messages can be adaptively determined based on receiver and/or network information (Wisitpongphan et al., 2007; Slavik and Mahgoub, 2010; Panichpapiboon and Ferrari, 2008). In Table 2.2, we summarise the forwarding probability functions to retransmit messages which are proposed from schemes in the probabilistic group for V2V networks. A recent survey for probabilistic broadcast schemes for a wider range of wireless ad hoc networks has been reviewed in (Reina et al., 2015).

Specifically, in the *adaptive probability* approach, (Wisitpongphan et al., 2007;

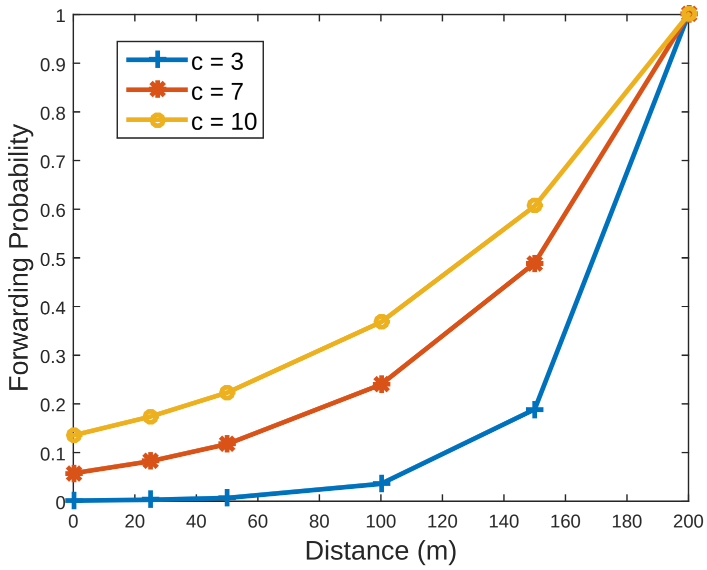


Figure 2.3: The forwarding probability for vehicles in the IF scheme with different distances from the source and different values of coefficient c, given Tx = 200m.

Slavik and Mahgoub, 2010; Panichpapiboon and Ferrari, 2008) propose schemes where the probability of becoming a forwarding node depends on the distance to the source and/or the average number of its neighbours. The information can be estimated based on beacon messages. Specifically, (Wisitpongphan et al., 2007; Slavik and Mahgoub, 2010) assign forwarding probability based on the distance between vehicle's location and that of the sender. A node that has a higher distance from the sender will obtain a higher probability to retransmit messages. More generally, a so-called *Irresponsible Forwarding* scheme has been proposed (Panichpapiboon and Ferrari, 2008), where the forwarding probability is computed based on not only the distance from the sender but also vehicle density. In (Panichpapiboon and Pattara-Atikom, 2012), the network performance of the IF scheme has been studied, and the results show that the IF outperforms the Weighted p-Persistence scheme proposed in (Wisitpongphan et al., 2007).

In (Panichpapiboon and Ferrari, 2008), the IF scheme suggests that increasing the distance from the source will increase the forwarding probability. This implies that the farther nodes from the source should be more responsible for forwarding messages, which can be seen from Fig. 2.3. This figure also shows the effect of coefficient c on the forwarding probability. Given the same distance from the source and vehicle density, increasing coefficient c will lead to an increase in the forwarding probability (see Table 2.2). Besides, given the same distance from the source and transmission range, a node will obtain different forwarding probabilities when the vehicle density changes. Specifically, in sparse networks, a node will obtain a higher forwarding probability than that in dense networks. Although Panichpapiboon and Ferrari (2008) observe that a forwarding probability also depends on the value of coefficient c, finding an optimal value for c in a given network scenario is not addressed in (Panichpapiboon and Ferrari, 2008). In this thesis, we provide optimal values for c for multiple network conditions (see Sec. 5.3.2).

In the predetermined probability approach, all vehicles have a constant forwarding probability (Slavik and Mahgoub, 2010; Fracchia and Meo, 2008). Despite its simplicity, these schemes show that their network performance highly depends on network conditions such as vehicle densities and system parameters such as packet sizes and date rates. Therefore, a fixed forwarding probability can only perform well under a narrow range of scenarios (Slavik and Mahgoub, 2010).

Note that the neighbourhood information required in the probabilistic scheme is not so sensitive to the topology change, as it only requires the information of one-hop neighbours. This is in contrast to the topology-based approach, where detailed topology information of the two-hop neighbourhood is required.

In this section, we have reviewed the related works with a focus on message dissemination for vehicular safety applications. Due to the characteristics of V2V communications such as fast-changing topology, high mobility, the probability-based approach is a promising method. In Table 2.3, we summarise the existing broadcast protocols for disseminating information in V2V communications.

2.5 Performance Analysis

There have been various analytical models developed in the literature to study the performance of the IEEE 802.11 protocol and its variants. The IEEE 802.11 supports two modes, which are *unicast* protocol and *broadcast* protocol. Therefore, the

Table 2.3: The existing literature for broadcast protocols that can be used for vehicular communications.

Scheme	One-hop	Multi-hop		
		Delay-based	Topology-based	Probability-based
(Hassan et al., 2011)	✓	-	-	-
(Ho et al., 1999)	-	-	-	✓
(Füßler et al., 2004)	-	✓	-	-
(Wisitpongphan et al., 2007)	-	✓	-	-
(Osafune et al., 2006)	-	✓	-	-
(Khakbaz and Fathy, 2008)	-	✓	-	-
(Tseng et al., 2010)	-	✓	-	-
(Schwartz et al., 2010)	-	✓	-	-
(Sun et al., 2000)	-	-	✓	-
(Stojmenovic et al., 2002)	-	-	✓	-
(Liu et al., 2012)	-	-	✓	-
(Stojmenovic et al., 2012)	-	-	✓	-
(Zhang et al., 2011)	-	-	✓	-
(Shea et al., 2009)	-	-	✓	-
(Arkian et al., 2014)	-	-	✓	-
(Ghodrati, 2013)	-	-	✓	-
(Vegni et al., 2012)	-	-	✓	-
(Chen et al., 2015)	-	-	✓	-
(Slavik and Mahgoub, 2010)	-	-	-	✓
(Fracchia and Meo, 2008)	-	-	-	✓
(Wisitpongphan et al., 2007)	-	-	-	✓
(Panichpapiboon and Ferrari, 2008)	-	-	-	✓

analytical models for the network performance of the IEEE 802.11 can be classified into two groups: analytical models for unicast communication, and analytical models for broadcast communication. In Fig. 2.4, we summarise the current analytical models in the literature for the IEEE 802.11.

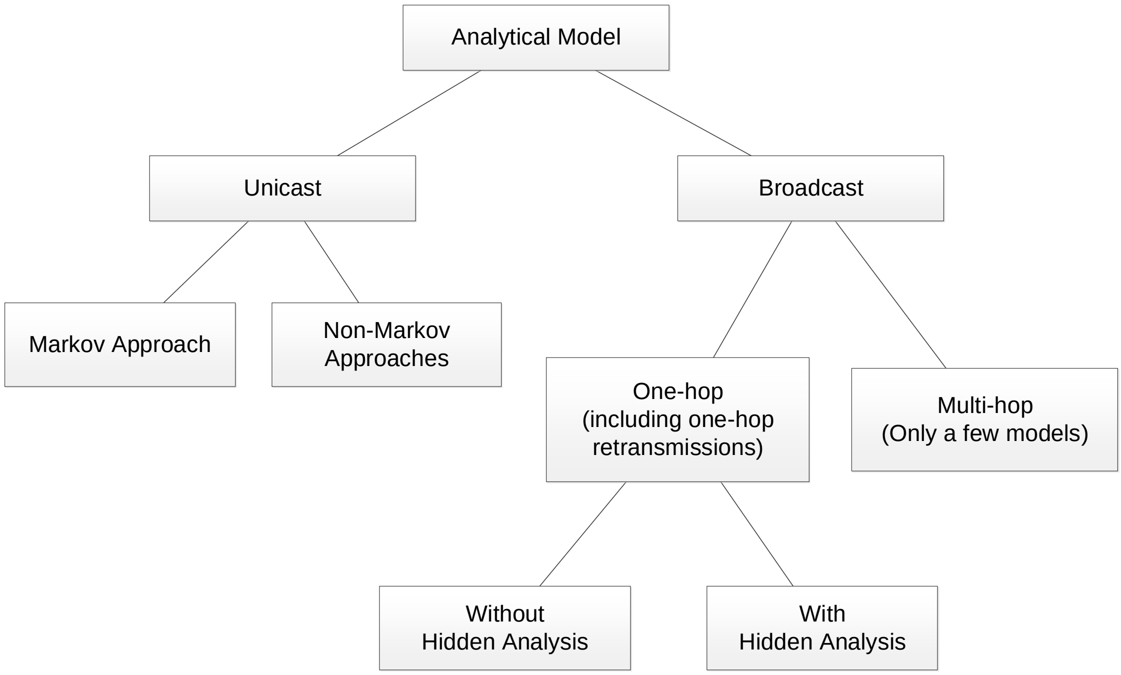


Figure 2.4: A classification of analytical models for the performance of the IEEE 802.11.

2.5.1 Analytical Models for Unicast Communication

For unicast communication where there is a single destination per source, a large number of analytical models have been proposed in the literature (Bianchi, 2000; Hadzi-Velkov and Spasenovski, 2003; Lee et al., 2006; Tay and Chua, 2001; Tickoo and Sikdar, 2004; Xiao, 2003). Among them, a Markovian model was first proposed in a seminal paper by Bianchi (Bianchi, 2000). The model accurately estimates the throughput of a 802.11 DCF network in a saturated network condition where every node always has packets to send. The key approximation in this paper is that every packet has a constant and independent collision probability. This model is a dominant approach for modelling the 802.11 protocols that inspires many other related works. However, the Bianchi model (Bianchi, 2000) cannot deal with hidden terminals. In (Alazemi et al., 2007; Dao and Malaney, 2008; Ling et al., 2007; Malone et al., 2007; Zhai et al., 2004), the Bianchi's approach is extended to the unsaturation condition, by calculating the probability that each vehicle has a message to send. Specifically, in (Alazemi et al., 2007), authors analyse the system where nodes may have an asymmetric finite of arrival rate, taking into account the heterogeneous nature of the wireless access points. In (Dao and Malaney, 2008), a new Markov approach is proposed to improve the analysis of the post backoff process.

There exist other non-Markovian approaches for both saturated and non-saturated networks (Sakurai and Vu, 2007; Xie and Jiang, 2010; Kim and Hou, 2003; Tickoo and Sikdar, 2008). Specifically, in a saturated network condition, the access delay in the IEEE 802.11 DCF MAC is analysed by using a detail stochastic model in (Sakurai and Vu, 2007). In (Xie and Jiang, 2010), authors analyse the system delay in both the constant and the Poisson arrival processes. In this paper, the delay bounds are provided by using the stochastic network calculus that is also used in (Fidler, 2006; Bredel and Fidler, 2009; Xie and Jiang, 2009; Goyal and Vin, 1997). In an unsaturated condition, to improve the system throughput, authors in (Kim and Hou, 2003) develop an analytical model to evaluate the current network utilization and suggest an appropriate scheduling delay to defer transmission of the current pending frame. In (Tickoo and Sikdar, 2008), the delays and channel access time are studied. Tickoo and Sikdar (2008) evaluated the network performance by using a queueing model where each node is modelled as a discrete time G/G/1 queue in an unsaturated network condition.

2.5.2 Analytical Models for Broadcast Communication

The aforementioned models for unicast communication, however, cannot be used or extended straightforwardly for modelling multi-hop broadcast communication (Yin et al., 2013; Hafeez et al., 2013). As mentioned earlier, with multi-hop, there are many potential forwarders and receivers, each forwarder-receiver pair has its own set of hidden nodes. Consequently, the collisions due to hidden terminals are relatively difficult to model. In addition, the network changes over space and time due to multi-hop forwarding which itself is difficult to model and makes hidden node analysis even harder. For this reason, there have been much less work on modelling of multi-hop broadcasting.

A summary of existing representative models for broadcast protocols is given in Table 2.4. In the table, we summarise the analytical models for both single-hop and

Table 2.4: Comparison our model with other models in the literature.

Model	Broadcast	Single-hop	Multi-hop	Hidden Analysis	Unsaturated	MAC type
Ma and Chen (2007)	✓	✓	-	-	-	DCF
Fracchia and Meo (2008)	✓	✓	✓	-	✓	CSMA
Tahmasbi-Sarvestani et al. (2015)	✓	✓	✓	-	✓	a single class EDCA
Vinel et al. (2008)	✓	✓	-	-	✓	DCF
Felemban and Ekici (2011)	✓	✓	-	-	✓	DCF
Rao et al. (2008)	✓	✓	-	-	✓	DCF
Hassan et al. (2011)	✓	✓	-	✓	✓	DCF
Yin et al. (2013)	✓	✓	-	✓	✓	DCF
Hafeez et al. (2013)	✓	✓	-	✓	✓	DCF
Chen et al. (2007)	✓	✓	-	✓	✓	DCF
Yao et al. (2013)	✓	✓	-	✓	✓	EDCA
Fallah et al. (2011)	✓	✓	-	✓	✓	DCF
Khabazian et al. (2011)	✓	✓	✓	✓	✓	EDCA
Proposed model	✓	✓	✓	✓	✓	DCF/a single class EDCA

multi-hop communications. In particular, (Ma and Chen, 2007; Fracchia and Meo, 2008; Tahmasbi-Sarvestani et al., 2015; Felemban and Ekici, 2011; Vinel et al., 2008) and (Rao et al., 2008) are models for the IEEE 802.11 broadcasting protocol but without considering the hidden terminal problem. Specifically, (Ma and Chen, 2007) calculates throughput and packet delivery ratio in a saturated network by applying a Markov chain model. (Tahmasbi-Sarvestani et al., 2015; Vinel et al., 2008) and (Rao et al., 2008) consider network in an unsaturated condition. In (Tahmasbi-Sarvestani et al., 2015), the packet error ratio is analysed by approximating via a fraction of the number of missed packets and the total number of packets expected to be received. (Vinel et al., 2008) proposes a model to calculate the probability of a successful packet transmission, and studies the impact of beacon rate on the reliability. (Rao et al., 2008) analyses the collision probability by using a two-state Markov chain. In (Felemban and Ekici, 2011), authors proposed two analytical models to evaluate the network performance under both saturated and unsaturated network conditions. A Markov approach is used to analyse the performance in the saturated condition, while in the unsaturated condition, authors suggest to use an iterative approach.

The models in (Hassan et al., 2011; Yin et al., 2013; Hafeez et al., 2013; Chen et al., 2007; Yao et al., 2013) and (Fallah et al., 2011) consider a more realistic network where the hidden terminal problem is modelled for an unsaturated network.

However, these models are restricted to one-hop broadcasting which again is not appropriate for evaluating the performance of multi-hop broadcast. Furthermore, the hidden analysis in (Yin et al., 2013; Chen et al., 2007) and (Yao et al., 2013) are based on a *renewal-theory argument* which is not entirely suitable for the hidden collision analysis as pointed out in (Tsertou and Laurenson, 2008; Hassan et al., 2011). Hafeez et al. (2013) propose a model to calculate the probability that a node receives a message given a distance from the source, and the probability of successful reception from all vehicles. Besides, this paper suggests an adaptive algorithm to increase the system reliability by changing parameters (e.g. message rate, transmission range) based on vehicle density.

Yao et al. (2013) analyse the reliability for the IEEE 802.11 EDCA where messages are set with different priorities according to different access classes. The authors also claim that single-hop is unable to provide reliable communication for safety applications. Fallah et al. (2011) give an insight into the effect of transmission range and message rate on the performance. (Hassan et al., 2011) considers two scenarios in the one-hop retransmission: with and without retransmitting the message, taking into account hidden terminal problem in an unsaturated network. In (Hassan et al., 2011), authors suggest that retransmitting the message blindly several times can indeed increase the reliability. Besides, the model proposed in (Hassan et al., 2011) captures the performance well in terms of packet delivery ratio. However, the drawback of this protocol is that the boundary nodes still have low probability to receive messages due to the same hidden nodes during multiple transmissions. Using different retransmitting nodes to cover different regions could help to increase the reliability as the source and retransmitting nodes are likely to have different hidden nodes.

In the multi-hop retransmission, there exists only one analytical model that considers the hidden terminal problem (Khabazian et al., 2011). In this work, authors propose an analytical model for multi-hop broadcast where every node is assigned a delay timer to retransmit the message based only on the distance to the sender. Nevertheless, this model ignores the detailed operation of the 802.11p MAC protocol (i.e., the backoff process) by assuming that the backoff time is part of the message inter-arrival time. However, the backoff delay depends on the level of congestion in the network which in turn is a function of the number of competing nodes and the probability that a node has a message to send. The simplification in (Khabazian et al., 2011) has led to a rather problematic observation where all nodes within the transmission range of the sender would see the same collision probability independent from the distance between their positions and the sender. As shown later in our analysis, it is indeed not the case as a receiver farther from the sender has a higher collision probability due to a larger number of hidden terminals. This fact has also been observed in (Hafeez et al., 2013).

As can be seen from the literature, a comprehensive analytical model for multi-hop broadcasting is still lacking due to the complexity in dealing with multiple hidden nodes seen by both the source and various other retransmitting nodes. In this thesis, we will fill this gap and propose a comprehensive analytical model for a multi-hop broadcasting protocol in Chapter 3.

2.6 Beacon approaches

The effect of beacon messages on the network performance of vehicular safety applications is significant as beacon messages are considered the main traffic in the network (Bouk et al., 2015). In addition, beacon and safety messages share the same wireless channel which makes beacons have an even greater impact on the performance. Using a fixed parameter such as a fixed beacon rate cannot satisfy the safety requirements for all scenarios. For example, via a single-hop broadcast, the default beacon rate of 10 messages/second can meet the safety requirements at low density (e.g. 25 vehicles/km), but cannot satisfy the requirements at high density (e.g. 130 vehicles/km) (Luong et al., 2016). Therefore, to control data traffic congestion, there is a need to adapt network parameters based on the network context.

Adapting network parameters is difficult, as the data congestion is affected by multiple network factors such as vehicle density, messages size, and packet collisions. Besides, in a large scale network, adapting these parameters becomes more challenging, due to an increase in packet collisions (Taherkhani and Pierre, 2015;

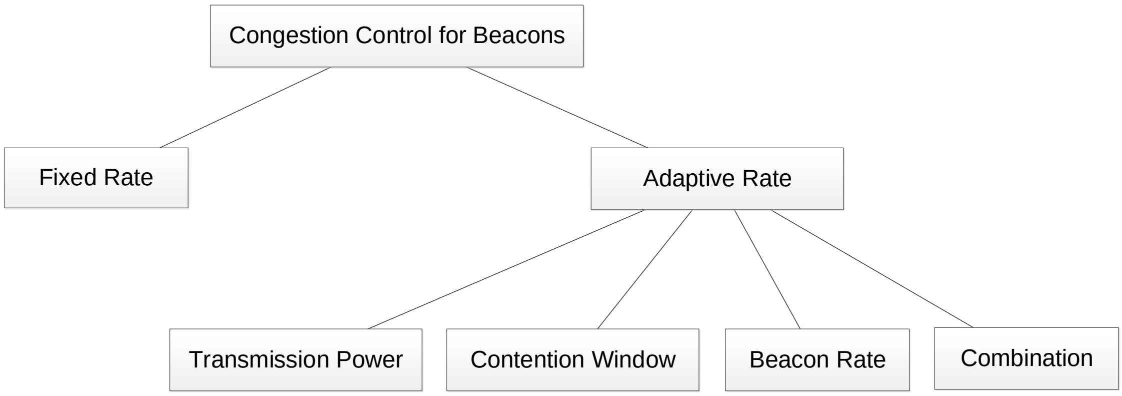


Figure 2.5: A classification of beaconing congestion control for VANET.

Huang et al., 2009; Baldessari et al., 2010).

In the literature, the current work on beacon congestion control has been reviewed in recent surveys (Bouk et al., 2015; Ghafoor et al., 2013; Sepulcre et al., 2011). For vehicular safety applications, congestion control for beacon messages can be classified into four groups: *transmission power*, *contention window*, *beacon rate*, or *a combination of them*. Fig. 2.5 shows a classification of the current representative schemes for beacon congestion control.

2.6.1 Transmission Power

Various existing schemes for the beacon transmission power have been proposed (Torrent-Moreno et al., 2009; Kloiber et al., 2012; Haghani and Hu, 2012; Artimy et al., 2005; Rawat et al., 2011). However, these schemes do not consider the effect of hidden terminals and direct collisions when adapting transmission power. In (Torrent-Moreno et al., 2009), the power transmission level is controlled following a strict fairness criterion. All vehicles obtain the same maximum transmission power that can minimize the channel load sent by beacons. This paper uses the "water-filling" approach to control the transmission power proposed in (Torrent-Moreno et al., 2005; Bertsekas et al., 1992).

In (Kloiber et al., 2012), to avoid the chances of recurring packet collisions, the transmission ranges of vehicles in the targeted area are selected randomly based on a given probability distribution. To obtain the fairness, the mean and variance of the probability distribution are adjusted. In (Artimy et al., 2005; Rawat et al., 2011), each vehicle estimates its local density and adapts the transmission range dynamically based on the estimated density. Deviating from other work where the transmission power is adapted based on the IEEE 802.11 MAC, the transmission power adaptation in (Haghani and Hu, 2012) is based on the Dynamic Channel Reservation (Lam and Kumar, 2010).

However, studying the effect of transmission power on the network performance is out of scope of this thesis.

2.6.2 Contention Window

There are a few schemes in the literature to control beacon congestion by adjusting contention window (Bouk et al., 2015). However, contention window significantly affects the network performance (Stanica et al., 2011). For example, using a small value of contention window will degrade the reliability due to an increase in direct collisions (Stanica et al., 2011). In contrast, a large contention window will increase the transmission delay. Therefore, there is a need to identify appropriate values of contention window.

In (Balon and Guo, 2006; Stanica et al., 2011), contention window is adapted to control data traffic congestion. Specifically, to detect the network congestion, in (Balon and Guo, 2006), a vehicle analyses the sequence number of packets that were received from its neighbours to obtain a reception rate. The contention window is then adapted locally based on the reception rate. Stanica et al. (2011) study the effect of contention window on the network performance, and propose a solution to adapt contention window. Specifically, the contention window is adapted based on a function of vehicle density and a parameter suggested from their simulations.

However, these schemes do not take into account the effect of hidden terminals and direct collisions. In this thesis, we study the effect of contention window on the network performance of vehicular safety applications, and proposed an analytical model to evaluate the network performance when messages are classified into different priority groups of contention windows (see Chapter 4). The proposed analytical model considers hidden terminals, direct collisions, and vehicle densities. Besides, in

Chapter 5, we suggest appropriate contention windows based on network parameters that can satisfy the requirements of safety applications.

2.6.3 Beacon Rate

A number of schemes for beacon rate adaptation have been proposed in the literature. These schemes can be classified further into two groups: *fixed rate* and *adaptive rate*.

In the fixed rate group, each vehicle broadcasts its own beacons regularly by a predefined rate suggested by the European ITS system (Ghafoor et al., 2013). In the cooperative active safety system (CASS), a fixed rate of 10 messages/second has been suggested (Reumerman et al., 2005). However, at high density, a lower beacon rate is suggested to reduce packet collisions. For example, at the high density of 130 vehicles/km, the channel experiences high data load and packet collisions, given the default beacon rate of 10 messages/second (Luong et al., 2016). The challenging question is how to identify an effective beacon rate where vehicles can obtain the updated neighbourhood information while the safety requirements are still satisfied. In fact, there is a trade-off between the accuracy of neighbour information and the reliability for safety messages when varying the beacon rate. A low beacon rate can cause imprecise neighbour information, but a high rate will decrease the reliability for safety messages due to packet collisions.

Due to the fast-changing network context, a fixed-rate approach is not entirely suitable for V2V communications. This is because different network contexts (e.g. vehicle densities) require different beacon rates. Therefore, adapting beacon rate based on the network context is needed to improve the network performance.

In the adaptive rate group, the schemes for beacon congestion control can be divided further into two groups: schemes without considering vehicle density (Drigo et al., 2009; Guan et al., 2011), and schemes with vehicle density (Le et al., 2011; Chaabouni et al., 2013). Vehicle density is estimated by the number of one-hop neighbours collected by beacons. In Table 2.5, we summarise algorithms for beacon rate adaptation in the literature.

In (Drigo et al., 2009; Guan et al., 2011), beacon rate is adapted based on the

Table 2.5: Comparison existing algorithms for beacon rate adaptation.

Paper	**Required parameter(s)**	**Hidden collision effect**	**Performance analysis**	**Year**
Drigo et al. (2009)	Channel load	No	No	2009
Guan et al. (2011)	Channel busy time	No	No	2011
Le et al. (2011)	Vehicle density, channel busy time	No	No	2011
Chaabouni et al. (2013)	Vehicle density, the number of packet collisions	No [6]	No	2013
Schmidt et al. (2010)	Vehicle density, vehicle speed	No	No	2010
Lv et al. (2012)	Vehicle density, vehicle speed, reception rate	No	No	2012
Puthal et al. (2013)	Vehicle density, channel usage	No	No	2013

estimation of the network load without considering vehicle density. Specifically, in (Drigo et al., 2009), each vehicle locally estimates the channel load and monitors the beacon rate based on the channel load estimation. To meet a target channel load, beacon rate is adapted between the two pre-defined thresholds that are the maximum rate and minimum rate. In (Guan et al., 2011), each vehicle locally estimates the channel busy time as an indicator of network congestion. The beacon rate is then adapted to ensure that the channel busy time does not exceed a pre-defined threshold.

In (Le et al., 2011; Chaabouni et al., 2013; Schmidt et al., 2010; Lv et al., 2012), and (Puthal et al., 2013), vehicle density is taken into account when adapting beacon rate. In (Le et al., 2011), beacon rate is adapted based on both the channel busy time and the vehicle density. Specifically, each vehicle adapts beacon rate individually based on the following three steps: 1) observing the channel conditions during a fixed monitoring interval, 2) estimating the channel load from the observed channel conditions, and 3) adjusting beacon rate based on a proposed function in the next monitoring interval. Beacon rate is adapted by a function of the vehicle density, channel busy time, packet size, and channel bandwidth.

In (Chaabouni et al., 2013), each vehicle adapts its beacon rate based on the estimated vehicle density, and the number of packet collisions recorded at its lower layers. In Schmidt et al. (2010), a vehicle adapts beacon rate based on its own

[6] This algorithm only considers the number of packet collisions, obtained from vehicle's lower layers, which is simple and not comprehensive to study the effect of hidden collisions.

movement information (i.e. speed, acceleration), and the information of surrounding vehicles' movement. Then, they provide a situation-adaptive-beaconing framework to identify the optimal adaptation for beacons.

Lv et al. (2012) proposed an algorithm to adjust beacon rate based on vehicle density, driving speed and the reception rate of messages. Specifically, each vehicle locally estimates vehicle density and the reception rate based on the number of beacon messages received from its neighbours during a time interval. In general, beacon rate is reduced to increase the reliability when the reception rate is low and the vehicle has a low driving speed. In (Lv et al., 2012), the channel estimation is based on the sequence number mechanisms in proposed (Bouassida and Shawky, 2009). In (Puthal et al., 2013), each vehicle adapts beacon rate based on vehicle density, and congestion level. Beacon rate is adapted based on a function of vehicle density, channel busy time and the average outgoing data rate.

Limitations

However, these works do not study the effect of hidden terminals and direct collisions. For beacon congestion control in V2V networks, to the best of our knowledge, there is no work considering hidden terminals, direct collisions, and vehicle densities when adapting beacon rate. In addition, there is no work analysing the trade-off between the accuracy of neighbourhood information and the reliability of safety messages for vehicular safety applications. In this thesis, we will fill the gap and propose a framework to identify optimal beacon rates based on network parameters. The proposed framework in Chapter 4 is the first work in the literature considering hidden terminals, direct collisions, and vehicle densities. Besides, the proposed framework also analyses the trade-off between the accuracy of neighbourhood information and the reliability of safety messages when varying beacon rate.

2.6.4 Combination

In this section, we review a joint adaptation for beacon congestion control. In (Rawat et al., 2011), transmission power and contention window are adapted based on the observed rate of data collisions on the network. On the other hand, in (Taherkhani and Pierre, 2015; Javed and Khan, 2014; Le et al., 2011; Qian et al., 2016), a combination of transmission power and transmission rate are monitored to control the congestion. Specifically, in (Taherkhani and Pierre, 2015), congestion is detected if the level of channel usage exceeds 70%. Then, the optimal parameters of transmission power and rate are used to control the congestion. These optimal values are obtained by a Tabu search algorithm via minimizing the delay and jitter.

In (Javed and Khan, 2014), transmission power and beacon rate are adapted based on the estimation of vehicle density, and a *time headway.* Time headway is an indication of the vehicle safety in a traffic situation, which is defined as the period of time between a chosen vehicle passing a particular location on the road and the following vehicle passing the same location (Ayres et al., 2001; Vogel, 2003). Time headway becomes an important safety metric for drivers, as Taieb-Maimon and Shinar (2001) suggest that at least 1.5 - 2 seconds of time headway is sufficient for drivers to avoid a car accident.

In (Qian et al., 2016), a combination of transmission power and beacon rate are monitored based on the traffic environment parameters. The future parameters are predicted according to the current and historical parameters for traffic environment such as the traffic density and vehicle velocity. In their system, there are two main parts that are the offline part, to collect the statistics of historical traffic parameters, and the online part, to detect the network congestion and adapt parameters.

In this thesis, we focus on controlling congestion control by identifying appropriate values of contention window and beacon rate for messages.

2.7 Limitations of Existing Work

In previous sections, we reviewed the literature for broadcast protocol, performance analysis, and beacon congestion control that can be used for V2V communications. In this section, the limitations of the current work for broadcast protocol, performance analysis and beacon rate in the literature are pointed out. These limitations also motivate us to propose our contributions in the field.

2.7.1 Limitations of Existing Broadcast Protocol

As mentioned earlier, due to the characteristics of V2V communications (e.g. fast changing topology, high mobility), the details of required neighbourhood information (e.g. 2-hop neighbourhood information) in the topology-based schemes are not entirely suitable for vehicular safety applications. Besides, the delay-based schemes may not suitable for some safety applications that require a very strict delay (e.g. 20 ms (Harding et al., 2014, page 98)), as delay-based schemes will add additional delay when forwarding messages. Therefore, in a multi-hop retransmission, the probability-based approach is a promising method for message dissemination in vehicular safety applications which will be studied in this thesis.

2.7.2 Limitations of Existing Performance Analysis

Through analysing existing works in the literature, we have learnt that there is a need to develop a comprehensive analytical model to evaluate the network performance of a multi-hop broadcast. Although various analytical models have been developed in the literature to study the performance of unicast communication, these models cannot be used to model a multi-hop broadcast communication (Yin et al., 2013; Hafeez et al., 2013). This is due to the different characteristics between unicast and broadcast communications. Firstly, in unicast, sender and receiver usually use the RTS/CTS before sending a message to reduce the collisions. In contrast, RTS/CTS is not used in broadcast communication. Secondly, hidden terminals in broadcast mode are more sensible than that of in unicast communication as there are many potential receivers.

Besides, in a broadcast communication, the existing models for single-hop broadcast cannot be used for multi-hop broadcast. In contrast to a single-hop broadcast, there are many potential forwarders in a multi-hop broadcast communication. In addition, the analyses of hidden terminals and direct collisions in a multi-hop broadcast is more challenging than those of in a single-hop broadcast.

2.7.3 Limitations of Existing Adaptive Beacon Rate

To the best of our knowledge, in V2V communications, there is no scheme in the literature that analyses the trade-off between the accuracy of neighbour information and reliability of safety messages when adapting beacon rates. Besides, the existing schemes do not take into account the effect of main factors such as hidden collisions and direct collisions on the network performance. In this thesis, we develop an optimization problem to suggest optimal beacon rate that considers both neighbour information and reliability for safety messages. Besides, the proposed framework analyses both the impact of hidden terminals and direct collisions on the network performance.

2.8 Chapter Summary

In this chapter, we have reviewed the literature for message dissemination in vehicular communications, especially for safety applications. The gaps and limitations of the existing works in the literature have also been identified and discussed. In the following chapters, we will develop a comprehensive analytical model, evaluate, design and optimise parameters and compare performance of the V2V broadcasting protocol in different scenarios.

"Laughter is sweet when enjoyed alone. But it becomes sweeter when you enjoy it together with the people around you. Your success must lead to the success others."

Israelmore Ayivor

3

Performance Analysis of a Generic Probabilistic Forwarding scheme

3.1 Overview

In this chapter, we propose a generic probabilistic forwarding scheme to disseminate safety messages in a multi-hop broadcast vehicular network for safety applications. Then, a comprehensive analytical model is developed to evaluate the network performance of that scheme based on the IEEE 802.11p protocol. The network performance of a multi-hop broadcast is mainly affected by hidden terminals, direct collisions and the spatial distributions of forwarders. Modelling a multi-hop broadcast protocol is challenging because there are many potential forwarders and receivers; each forwarder-receiver pair has its own set of hidden nodes and direct collision area. The network changes over space and time due to multi-hop forwarding which itself is difficult to model and makes hidden and direct analyses even harder. In addition, the spatial distribution of forwarders is also a question that should be studied carefully. The aggregate hidden and direct collisions are therefore difficult to model.

We only consider a one-dimensional highway network in this thesis as the traffic environment varies dramatically depending on the type of roads (e.g. highway, urban road, country road), which is difficult to incorporate in a single model. Besides, the analytical model ignores vehicle mobility, which is a reasonable assumption as vehicle's mobility is negligible during the packet transmission time of less than 20ms. The main contributions in this chapter are as follows.

- We propose a generic probabilistic multi-hop forwarding scheme for safety applications that retains the best features of various existing schemes such as the ones proposed in (Wisitpongphan et al., 2007; Panichpapiboon and Ferrari, 2008; Slavik and Mahgoub, 2010), and (Fracchia and Meo, 2008) (Sec. 3.4). The proposed scheme remains simple and compatible with the IEEE 802.11p DCF, and a single class IEEE 802.11p EDCA standard where messages are in the same priority group.

- We develop a comprehensive analytical model to evaluate the network performance of the proposed generic scheme (Sec. 3.5), in a one-dimensional highway scenario. Our model takes into account the effect of vehicle densities, hidden terminals, and the details of 802.11p back-off and carrier sensing mechanisms in direct collisions in a multi-hop setting.

3.2 Motivation for the multi-hop probabilistic forwarding scheme

In Fig. 3.1, we compare by simulations the Packet Delivery Ratio (PDR) that is a performance measure defined later in Sec. 3.5 of a single-hop broadcast scheme and two multi-hop broadcast schemes at different vehicle densities. In the single-hop broadcast scheme, a safety message will be broadcast one time only by the source.

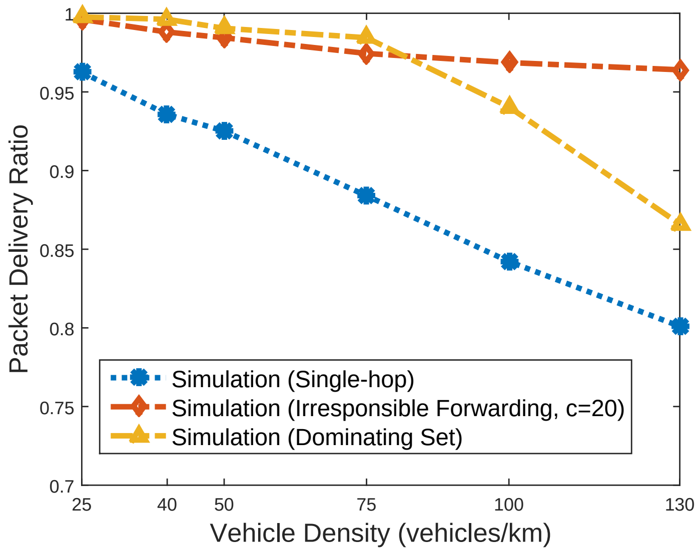


Figure 3.1: The overall PDR for the Irresponsible Forwarding (Panichpapiboon and Ferrari, 2008), Dominating Set (Stojmenovic et al., 2002) and the Single-hop broadcast schemes.

In multi-hop broadcast schemes, a safety message will be retransmitted by other chosen vehicles. A vehicle only retransmits a safety message maximum one time. In other words, multiple copies of the same message are not forwarded. In multi-hop broadcasting schemes, we choose the two representatives of the existing schemes in the literature due to their simplicity and reasonably good performance (Luong et al., 2014), namely the Dominating Set (Stojmenovic et al., 2002) in the topology group and the Irresponsible Forwarding (IF) with coefficient $c = 20$ (Panichpapiboon and Ferrari, 2008) in the probabilistic group as summarised in Chapter 2. Our simulation results show that single-hop protocol can only satisfy the PDR requirement (i.e. $\geq$ 90%) at low densities (e.g. $<$ 65 vehicles/km). In contrast, multi-hop protocols outperform the single-hop broadcast, and can satisfy the PDR requirement for safety applications at all densities considered.

Besides, in contrast to the Dominating Set scheme, where detailed topology information of the two-hop neighbourhood is required, the information required in the IF scheme is not so sensitive to the topology change as shown later in Sec. 3.6. This motivates us to study the probabilistic forwarding schemes represented by the IF scheme in the multi-hop group.

3.3 System Model and Assumptions

In this section, we describe the network scenario and assumptions that are used to develop a tractable analytical model.

3.3.1 The Network Scenario

We consider one-dimensional highway scenarios where moving vehicles communicate by broadcasting messages using either the IEEE 802.11p DCF or a single class EDCA MAC protocol (IEEE Standard 802.11, 2012). All the vehicles use the same transmit power (which is typically the maximum allowed transmit power as per the 802.11 standard). We develop an analytical model for studying the performance of a generic probabilistic message forwarding scheme (Sec. 3.4), under which the aggregate transmission process in the network is a highly complex spatio-temporal branching process. In the literature, analysis has been done by assuming an exogenous Poisson packet arrival process of given rate (Ma et al., 2012; Chen et al., 2007; Khabazian et al., 2011). The problem addressed in this thesis is far more challenging than that. The packet arrival process to the MAC queues of the nodes at any point in time is a function of the probability of successful reception at the nodes, and its effective distance from the sender. They, in turn, are dependent on the MAC layer contentions as per the 802.11p protocol, leading to losses due to direct and hidden node collisions and waiting times due to carrier sensing and backoffs.

3.3.2 Assumptions

In order to develop a tractable analytical model, we make the following assumptions:

- A1 The vehicular network is one-dimensional (1D), where vehicles are uniformly distributed on the road with density β.
- A2 All nodes (or vehicles) have the same mean communication range and receiving range, collectively called the communication range and denoted by R.
- A3 Packet lengths are constant and equal for both beacons and safety messages.

A4 All nodes are assumed to know the average vehicle density, β. There exist several approaches in the literature to estimate the vehicle density such as those mentioned in the survey paper (Darwish and Abu Bakar, 2015).

A5 There is at the most one safety message at any point in time as the rate of safety messages is very small.

A6 All vehicles have the same rate to transmit beacon messages (e.g. 10 messages/second).

Note that A1 is commonly used in the relevant literature such as (Fallah et al., 2011). In reality, vehicles can have different transmission ranges due to different manufacturers, the effect of fading, interferences, and obstacles (Garca-Campos et al., 2015). In A2, for simplicity, we assume that all vehicles have the same transmission range. However, it still allows for randomness. At any given point in time, different nodes can obtain different communication ranges due to randomness. Over a long period of time, however, all nodes will experience the same mean communication range. A2 can be justified by recalling our network scenario where all nodes use the same transmit power. The importance of A4 is studied in Sec. 3.6. In Sec. 3.6, we also discuss the impact of vehicle density when A4 is relaxed. In A5, there is maximum one safety message at a time. However, multiple copies of the same safety message could be sent by multiple vehicles when an incident happens. Further note that our assumptions are consistent with the assumptions used in (Wisitpongphan et al., 2007; Panichpapiboon and Ferrari, 2008; Slavik and Mahgoub, 2010) and (Fracchia and Meo, 2008). Therefore, the proposed analytical model in Sec. 3.5 can be used to evaluate the network performance of the schemes listed in Table 3.1. In A6, all vehicles have the same rate to broadcast beacons. The effect of beacon messages is studied in Sec. 4.3. In addition, the optimal beacon rate given a network context is also provided in Sec. 4.3.

Remarks: Our analytical model can be easily extended to evaluate the network performance when A3 is relaxed. However, investigating the effect of packet size is out of scope of this thesis.

3.4 Generic Probabilistic Forwarding Scheme

In this section, we propose a generic probabilistic forwarding scheme for safety applications in vehicular networks as follows. A safety message originates at a vehicle called the *source* node, which broadcasts the message. Every vehicle that successfully receives the message for the first time, computes a *forwarding probability* and re-broadcasts the message with that probability. For the simplicity, in this thesis, we assume that all vehicles will use the same probabilistic forwarding function. Transmissions of both the safety messages and beacons follow the rules of IEEE 802.11p (IEEE Standard 802.11, 2012), which include carrier sensing and random backoffs. A node (or vehicle) may receive multiple copies of the same message, but the copies are not forwarded.

Suppose that vehicle j successfully receives the message from vehicle i. Then the forwarding probability computed by vehicle j, in general, is a function of

- Its distance from vehicle i, denoted by x,
- The average density of vehicles, denoted by β, and
- The mean communication range, denoted by R.

In this section, we propose a generic forwarding probability function that can be adapted to obtain the specific forwarding probability functions reported in the literature, and is given by

$$p_b(x) = c_1 g(x, \beta, R, c_2), \tag{3.4.1}$$

where $g(\cdot)$ is a function to be appropriately chosen (see below), and c_1 and c_2 are fixed parameters that can be adjusted to obtain various specific forms of forwarding functions. The forwarding probability $p_b(\cdot)$ is considered, essentially, to be a function only of x, assuming β and R to be fixed parameters. Note that β and R are mean values of the actual density and communication range that are in fact random variables.

Table 3.1 shows that the specific forwarding probability functions reported in (Wisitpongphan et al., 2007; Panichpapiboon and Ferrari, 2008; Slavik and Mahgoub, 2010; Fracchia and Meo, 2008), can be obtained by choosing the function

Table 3.1: Choice of functions $h(\cdot)$ and parameters c_1 and c_2 for different forwarding probability functions.

Scheme	**Forwarding probability function**, $p_b(x)$	**Choice of** $h(\cdot)$, c_1 **and** c_2
Panichpapiboon and Ferrari (2008)	$p_b(x) = e^{-\frac{\beta(R-x)}{c_2}}$	$\begin{cases} c_1 = 1 \\ 1 \leq c_2 < \infty \\ h(x,\beta,R) = \beta(R-x) \end{cases}$
Wisitpongphan et al. (2007), Slavik and Mahgoub (2010)	$p_b(x) = \frac{x}{R}$	$\begin{cases} c_1 = 1 \\ c_2 = 1 \\ h(x,\beta,R) = \ln(\frac{R}{x}) \end{cases}$
Slavik and Mahgoub (2010), Fracchia and Meo (2008)	$p_b(x) = c_1 = const$	$\begin{cases} 0 \leq c_1 \leq 1 \\ c_2 \to \infty \\ h(x,\beta,R) < \infty \end{cases}$
Power Law	$p_b(x) = \left(\frac{x}{R}\right)^{\alpha}$	$\begin{cases} c_1 = 1 \\ c_2 = \alpha \\ 1 \leq \alpha < \infty \\ h(x,\beta,R) = \ln(\frac{R}{x}) \end{cases}$

$g(x, \beta, R, c_2)$ as

$$g(x, \beta, R, c_2) = e^{-\frac{h(x,\beta,R)}{c_2}}, \qquad (3.4.2)$$

and then choosing the function $h(\cdot)$, $0 \leq h(\cdot) < \infty$, and the parameters c_1 and c_2, $0 \leq c_1 \leq 1$, $c_2 \geq 1$, appropriately (see Appendix A for details). With the choice of $g(x, \beta, R, c_2)$ as given by (3.4.2), it is easy to see that $g(x, \beta, R, c_2)$ is a monotonically increasing function of c_2, and one can think of c_2 as a *shape parameter* of the function $g(x, \beta, R, c_2)$ such that

$$\lim_{c_2 \to \infty} g(x, \beta, R, c_2) = 1.$$

Similarly, one can think of c_1 as a *scale parameter* such that $c_1 = 1$ for all finite c_2; otherwise, if $c_2 \to \infty$, then c_1 represents the constant forwarding probability of all nodes.

Our generic scheme can also suggest certain new forwarding schemes not yet reported in the literature. For example, as shown in the last row in Table 3.1, from our generic equations (3.4.1) and (3.4.2), one could derive a new probabilistic forwarding scheme based on a power law function and is herein referred to as the *Power Law* scheme.

3.5 Analytical Modeling

In this section, we develop an analytical model to obtain several performance metrics, namely the Packet Delivery Ratio (PDR), the probability that a node receives the safety message given a distance from the source, and the mean delay until its reception. The PDR is defined as the percentage of nodes in the transmission range of the source that receives the safety message. The PDR is computed as the probability that an arbitrary node (i.e., a node located at an arbitrary point in the range of the source) receives the message.

At the outset, let us clearly distinguish between the following probabilities:

- The probability that a node receives the safety message given its distance from the source: this is a measure of how well the forwarding scheme performs spatially.

- The probability that an arbitrary node receives the safety message: this is an overall performance measure and is obtained by averaging the above probability over all possible distances from the source.

- The *conditional forwarding probability* that a node forwards the message given that it has successfully received the message: this is given by Eqn. (3.4.1).

- The *unconditional forwarding probability* that a node forwards the safety message: this is the product of the probabilities that the node successfully receives the message and then forwards it.

To simplify the analysis, we introduce a novel concept, which we call the *transmission rounds*, and discuss it next.

3.5.1 Transmission rounds

Let $\mathcal{R}_1$ denote the set of nodes that successfully receive the safety message for the first time directly from the source. Let $\mathcal{R}_{i+1}$, $i = 1, 2, \ldots$, denote the set of nodes that successfully receive the safety message for the first time from a node in $\mathcal{R}_i$. In reality, the transmissions by nodes belonging to different sets $\mathcal{R}_i$ and $\mathcal{R}_j$, $i \neq j$, can be randomly interspersed in time. For example, the transmission by a node belonging to $\mathcal{R}_2$ may occur after the transmission by a node belonging to $\mathcal{R}_3$, or they may overlap in time and space leading to collisions. The analysis of such a process is intractable due to its combinatorial complexity. Our key simplifying approximation is that

Approximation 1 (Transmission Rounds) *The transmissions belonging to the nodes in $\mathcal{R}_{i+1}$ begin only after the transmissions belonging to the nodes in $\mathcal{R}_i$ have finished.*

Applying Approximation 1, we define the first transmission round $\mathcal{R}_1$ to consist of the transmission of the safety message by the source, and define the $(i + 1)$th transmission round, $i \geq 1$, to consist of the transmissions of the safety message by the nodes in $\mathcal{R}_i$. Essentially, the nodes that receive the safety message in the ith round are potential forwarders in the $(i+1)$th round. In this thesis, the performance metrics will be obtained round-by-round and our numerical results later show the high accuracy of this approximation. The various steps and sub-steps of analysis are summarised in Fig. 3.2 and are explained next.

3.5.2 Overview of the analysis

3.5.2.1 Round 1

Consider the blocks corresponding to the first transmission round in Fig. 3.2. For a node to successfully receive a message, it should be free from direct collisions as well as hidden node collisions. It turns out that the analysis of hidden node collisions in the first round requires only the beacon arrival rate λ because the original source of the safety message is the only node having the safety message in the first round (by

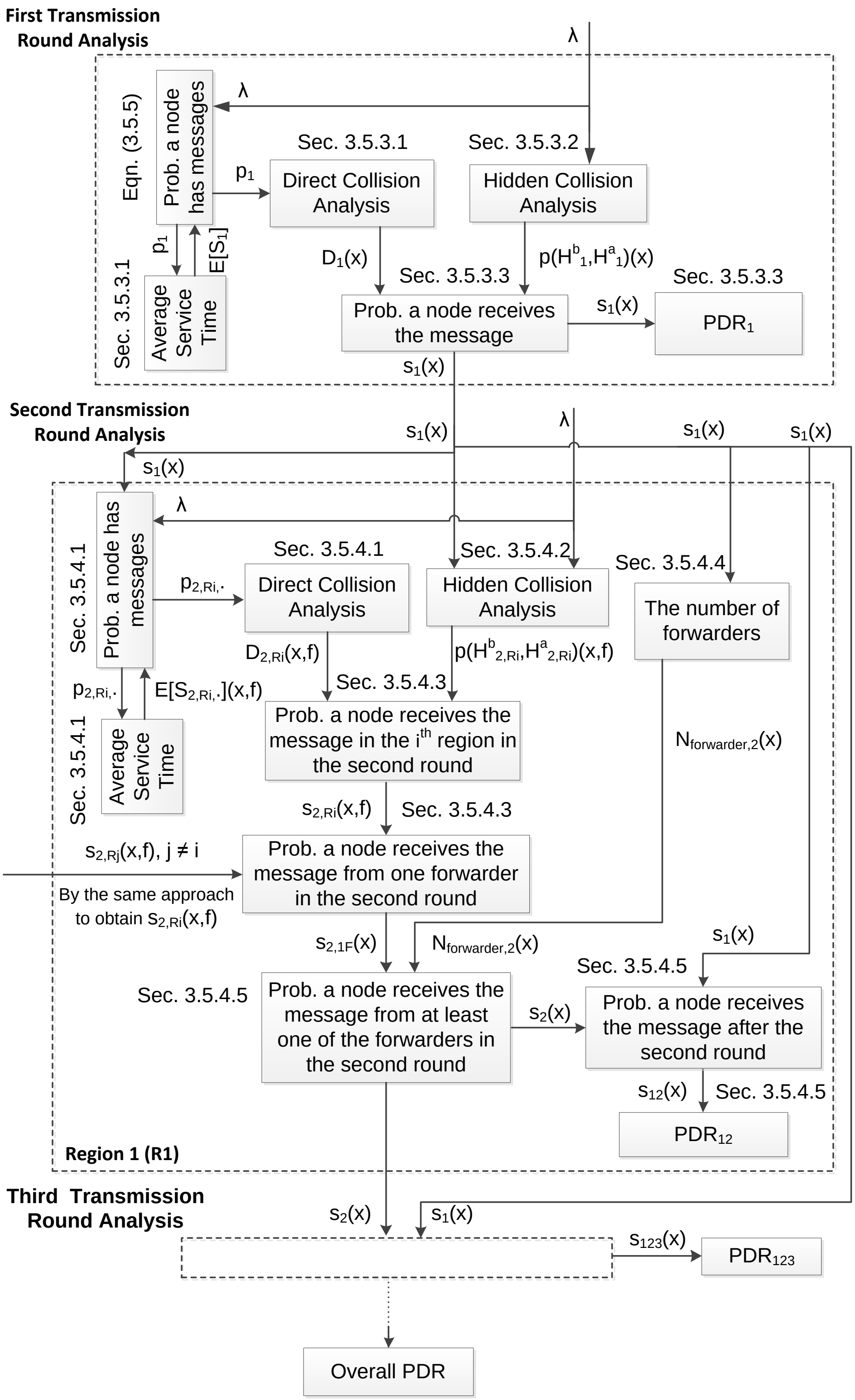


Figure 3.2: Summary of the analysis with different blocks representing different steps and sub-steps.

applying Assumption (A5)).

The analysis of direct collisions, however, requires the probability that an arbitrary node has a packet (in this case, a beacon) in its queue in a randomly chosen MAC-level time slot, denoted by p_1. The probability p_1 depends on the beacon arrival rate, λ, and the average service time, $E[S_1]$. The average service time, in turn, depends on the time spent in MAC contention for accessing the channel. Since a node contends for channel access only when it has a packet in its queue, $E[S_1]$ depends on the probability p_1. Due to this inter-dependence between p_1 and $E[S_1]$, the probability p_1 has to be obtained by solving a fixed-point equation as shown in the two left-most blocks corresponding to the first transmission round in Fig. 3.2.

The probability that a node at a given distance x from the source successfully receives the message, denoted by $s_1(x)$, is obtained by combining the analyses of direct and hidden node collisions in Sec. 3.5.3. The PDR after the first round, PDR_1, is obtained from $s_1(x)$ by averaging over all x.

3.5.2.2 Round 2

The analysis of round 2 is more complicated than that of round 1 because there are many potential forwarders of the message in round 2 who receive the message directly from the source in round 1. The analysis of round 2 requires

1. The probability that a potential forwarder at distance f from the source has successfully received the message from the source, which is given by $s_1(f)$, computed in the analysis of the first round, and
2. The conditional forwarding probability of a potential forwarder, $p_b(f)$, which depends only on its distance f from the source and is given by Eqn. (3.4.1).

However, given the location of a tagged receiver at distance x from the source, the location f of the potential forwarder may belong to one of three regions:

R1: $f \in [0, x]$,

R2: $f \in (x, R]$, and

R3: $f \in [-(R - x), 0)$.

As explained further in Sec. 3.5.4, one must distinguish between the above three regions for the location of the forwarder to be able to determine the locations of the nodes whose transmissions can cause direct and hidden node collisions with the transmissions of the forwarder at the tagged receiver. The blocks corresponding to the second transmission round in Fig. 3.2 show only the analysis for region R1. The analyses of regions R2 and R3 follow the same structure.

The analyses for all three regions are combined to obtain the probability that a receiver located at a distance x from the source successfully receives the message from one arbitrary forwarder in the second round, denoted by $s_{2,1F}(x)$. The average number of forwarders in round 2 for a receiver located at x, denoted by $N_{forwarder,2}(x)$ and computed in Sec. 3.5.4.4, together with $s_{2,1F}(x)$, then provide the probability that a receiver at a distance x from the source successfully receives the message from *at least one of the forwarders* in the second round, denoted by $s_2(x)$.

The PDR after the second round, PDR_{12}, which corresponds to the fraction of nodes that successfully receives the message either in the first round or in the second round, is obtained from $s_1(x)$ and $s_2(x)$ (see Eqns. (3.5.35), (3.5.37) and (3.5.38)).

3.5.2.3 Round 3 and beyond

An accurate analysis of round 3 is much more challenging than that of round 2 because of the following reason.

In round 1, the source is the only node that can transmit the safety message. In round 2, however, there are multiple forwarders. A receiver may successfully receive the message for the first time in round 2 from any of these forwarders. The receivers in round 2 are potential forwarders in round 3. However, it is highly difficult to track the forwarder from which the message is successfully received for the first time in round 2, and pass this information over to the analysis of round 3 so that the conditional forwarding probabilities of the potential forwarders in round 3 can be computed.

To overcome the above challenge, for each potential forwarder in round 3, we compute an *effective* conditional forwarding probability, which is an average over all possible locations of the forwarders in round 2 from which the forwarder in round

3 might have received the message for the first time in round 2. The remainder of the analysis for round 3 is very similar to that of round 2. The analyses of round i, $i \geq 3$, are identical. However, we stop at round 3 because the overall PDR after round 3 turns out to be extremely close to the actual PDR for a wide range of densities, which will be verified in the section of model validation (Sec. 3.6).

Next, we discuss the analysis of each round in detail.

3.5.3 Analysis of the first round

Without loss of generality, assume that the source is located on the 1D road at point 0. Let I_0 denote the set of points within the range of the source. Let I_0^c denote the complement of I_0, i.e., I_0^c denotes the set of points outside the range of the source. Consider a tagged receiver at a distance x from the source. There are two such points, x and $-x$. Without loss of generality, we consider the point x, and let I_x denote the set of points within its range. The analysis for the point $-x$ is identical to that for the point x due to symmetry.

The Direct Collision Area for the receiver at x w.r.t. the source's transmission is given by

$$DA_1(x) = I_x \cap I_0,$$

which is the set of points within the range of both the receiver at x and the source. Similarly, the Hidden Collision Area for the receiver at x w.r.t. the source's transmission is given by

$$HA_1(x) = I_x \cap I_0^c,$$

which is the set of points within the range of the receiver at x, but outside the range of the source. Note that the subscript '1' in the notation $DA_1(x)$ and $HA_1(x)$ represents the transmission round 1. Fig. 3.3 depicts the collision areas $DA_1(x)$ and $HA_1(x)$. In the following, we analyse the direct and hidden node collisions separately.

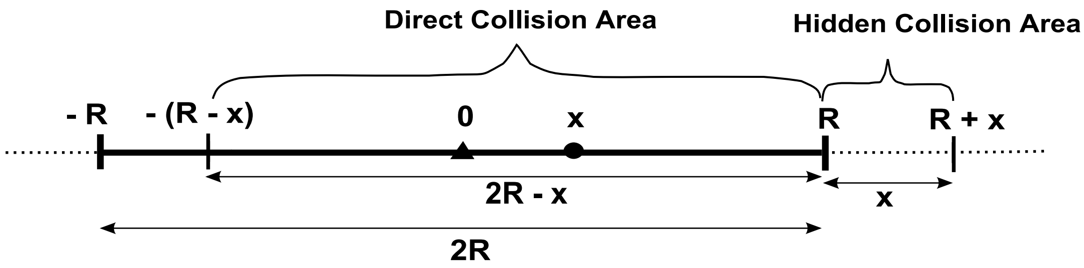


Figure 3.3: Direct and hidden collision areas for a node with distance x from the source.

3.5.3.1 Direct collision in round 1

Note that every packet transmission is preceded by a backoff time when time is divided into the so-called backoff slots. For each head of the line packet in the transmission queue, a random number of backoff slots is sampled uniformly between 0 and a positive integer called the *contention window*. A backoff counter is initialized with this sampled random backoff. For every *idle* backoff slot sensed on the channel, the backoff counter is decremented by one. The head of the line packet is transmitted when the backoff counter attains the value 0.

The transmission of the source is free from direct collisions at the receiver located at x if none of the nodes in $DA_1(x)$ begins transmission in the same slot as the source.

Let p_1, $0 \leq p_1 \leq 1$, denote the probability that a vehicle has a packet in its queue (i.e. non-saturated network) at an arbitrary time in the first transmission round. Note that nodes other than the source can only have a beacon in their queue in the first round. Let τ denote the probability that the vehicle attempts to transmit at an arbitrary slot given that there is a beacon in its queue. Then, the probability that the vehicle attempts a transmission at an arbitrary slot is equal to $p_1\tau$.

The probability that none of the vehicles in $DA_1(x)$ attempts a transmission at an arbitrary slot is equal to $(1-p_1\tau)^{N_{direct,1}(x)}$, where $N_{direct,1}(x)$ denotes the average number of nodes in $DA_1(x)$. Then, the direct collision probability for a receiver located at x in the first round, denoted by $D_1(x)$, is given by

$$D_1(x) = 1 - (1-p_1\tau)^{N_{direct,1}(x)}, \tag{3.5.3}$$

which is equal to the probability that at least one node in $DA_1(x)$ transmits at the same time slot as the source. The computation of τ, $N_{direct,1}(x)$ and p_1 is discussed below.

Let W denote the contention window. The number of backoff slots before a packet transmission is chosen uniformly randomly between 0 and $W-1$. Then, the average number of backoff slots per packet transmission, $\overline{W}$, is given by

$$\overline{W} = (W-1)/2.$$

The probability that a vehicle attempts a transmission following an arbitrary backoff slot given that the vehicle has a packet in its queue, can be computed by

$$\tau = 1/(\overline{W}+1).$$

Let β denote the density, defined as the number of vehicles per unit of length (e.g. vehicles per kilometer). Applying Assumptions (A1) and (A2), the average number of nodes in $DA_1(x)$, except the source, denoted by $N_{direct,1}(x)$, is obtained by

$$N_{direct,1}(x) = \beta(2R - x) - 1. \tag{3.5.4}$$

Let $E[S_1]$ denote the average packet service time in the first transmission round, which is defined as the interval between the time when the packet (in this case, a beacon) reaches the head of the queue and until the time it is either transmitted successfully or suffers a collision; in either case, the packet is evicted from the queue. Let λ denote the rate of arrival of beacons (e.g. in number of beacons per second). Then, the probability that a vehicle has a beacon in its queue at an arbitrary time is given by

$$p_1 = \lambda E[S_1]. \tag{3.5.5}$$

Computation of the Average Service Time $E[S_1]$:

The service time consists of the backoff time, B_1, and the transmission time, T, i.e.,

$$S_1 = B_1 + T, \tag{3.5.6}$$

where B_1 is defined as the period between the time the beacon reaches the head of the queue until the time its transmission starts, and T is defined as the sum of the beacon transmission time, and one inter-frame spacing. T can be obtained by

$$T = t_{data} + t_{difs}, \text{or } T = t_{data} + t_{aifs}, \tag{3.5.7}$$

where t_{data} is given by

$$t_{data} = \frac{\text{Packet Size}}{\text{Data Rate}}, \tag{3.5.8}$$

and t_{difs}, t_{aifs} are the distributed inter-frame spacing (DIFS) for the DCF, and the arbitration inter-frame spacing (AIFS) for the single class EDCA respectively, that are physical layer parameters defined in the DSRC standard (IEEE Standard 802.11, 2012). The transmission time for beacon and safety messages are equal as they have the same packet size.

Let U denote the random number of backoff slots sampled by a tagged node. The counting down of the backoff counter may be interrupted in each of these U backoff slots due to the transmissions by other nodes. Let Y_1 denote the random duration of interruption per backoff slot. Let l denote the duration of a backoff slot. Then, B_1 is approximated by

$$B_1 = \sum_{n=1}^{U} (l + Y_1^n), \tag{3.5.9}$$

where Y_1^n, $n = 1, \dots, U$, are i.i.d. random variables having the same distribution as Y_1.

Clearly, if none of the other nodes transmits, then $Y_1 = 0$; otherwise, $Y_1 = T$ because each successful transmission or collision lasts for a duration T. Then, Y_1 is given by

$$Y_1 = \begin{cases} 0 \;\; with \;\; (1 - p_1\tau)^{N_{total}} \\ T \;\; with \;\; 1 - (1 - p_1\tau)^{N_{total}} \end{cases} \tag{3.5.10}$$

where N_{total} denotes the average number of other nodes in the tagged node's range, and is given by

$$N_{total} = \beta 2R - 1. \tag{3.5.11}$$

Therefore, the expected service time $E[S_1]$ is given by

$$E[S_1] = E[B_1] + T = (l + E[Y_1])\overline{W} + T, \tag{3.5.12}$$

where $E[Y_1]$ is given by

$$E[Y_1] = \left[1 - (1 - p_1\tau)^{N_{total}}\right] T. \tag{3.5.13}$$

Clearly, the computation of $E[S_1]$ requires $E[Y_1]$, whose computation, in turn, requires p_1. As indicated by (3.5.5), the computation of p_1 requires $E[S_1]$. Due to this inter-dependence between p_1 and $E[S_1]$, the computation of p_1 requires solving a fixed-point equation.

3.5.3.2 Hidden collision in round 1

The transmission of the source is free from hidden node collisions at the receiver located at x if none of the nodes in $HA_1(x)$ is already in the transmitting state when the source starts transmitting and none of the nodes in $HA_1(x)$ starts transmitting during the source's transmission. We denote the probability of the former event by $p(H_1^b)(x)$ and that of the latter event by $p(H_1^a)(x)$, where the superscripts 'a' and 'b' represent 'after' and 'before', respectively.

The total number of nodes in $HA_1(x)$, denoted by $N_{hidden,1}(x)$, is obtained by

$$N_{hidden,1}(x) = \beta x. \tag{3.5.14}$$

We approximate the *aggregate* beacon transmission process by the nodes in $HA_1(x)$ as a homogeneous Poisson process of rate $\lambda N_{hidden,1}(x)$, where recall that λ is the beacon arrival rate per node.[1] Then, $p(H_1^b)(x)$ and $p(H_1^a)(x)$ are given by

$$p(H_1^b)(x) = \exp\left[-\lambda T N_{hidden,1}(x)\right], \tag{3.5.15}$$

and

$$p(H_1^a)(x) = \exp\left[-\lambda t_{data} N_{hidden,1}(x)\right]. \tag{3.5.16}$$

The probability that the transmission of the source is free from hidden node collisions at the receiver located at x is given by

$$p(H_1^b, H_1^a)(x) = p(H_1^b)(x)p(H_1^a)(x). \tag{3.5.17}$$

[1]Here, we assume that λ is sufficiently small so that each node's queue is stable. In that case, the total arrival rate of beacons is equal to the total rate of transmission of beacons.

3.5.3.3 Packet delivery ratio in round 1

The probability that a node at x successfully receives the message from the source in the first round, i.e., without direct collisions and hidden collisions, is denoted by $s_1(x)$ and given by

$$s_1(x) = [1 - D_1(x)]\, p(H_1^b, H_1^a)(x). \tag{3.5.18}$$

By symmetry, the probability that a node at $-x$ successfully receives the message from the source in the first round is equal to $s_1(x)$. Then, the Packet Delivery Ratio in the first transmission round, which is equal to the probability that an arbitrary node in the range of the source successfully receives the message in round 1, is obtained by averaging $s_1(x)$ over all possible values of x, i.e.,

$$PDR_1 = s_1 = \frac{1}{R}\int_0^R s_1(x)dx. \tag{3.5.19}$$

3.5.4 Analysis of the second round

The nodes that successfully receive the message from the source in round 1 become potential forwarders in round 2. In general, there are multiple forwarders in round 2 and a receiver successfully receives a message in round 2 if it does so from *at least one* of the forwarders.

Consider a tagged receiver at point x. The potential forwarders from which it can receive the safety message must be located in the interval $[-(R-x), R]$, i.e., within its own range as well as within the range of the source. As pointed out in Sec. 3.5.2.2, we must distinguish between the three cases when the location f of the forwarder lies in three different regions R1, R2 and R3, given by

R1: $f \in [0, x]$,

R2: $f \in (x, R]$, and

R3: $f \in [-(R-x), 0)$.

Such a distinction is necessary because, depending on whether f belongs to region R1, or R2 or R3, the associated direct and hidden collision areas are defined accordingly, as shown in Fig. 3.4.

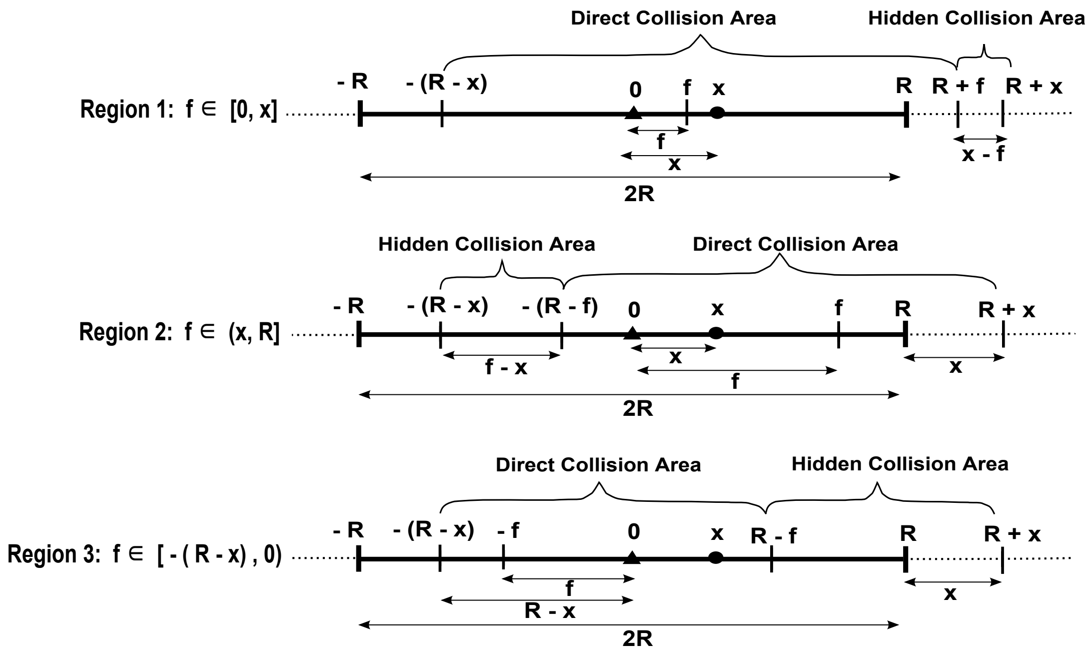


Figure 3.4: Direct and hidden collision areas in round 2 for different forwarder's positions. The source is at 0, the tagged receiver is at x and the potential forwarder is at f.

Let $s_{2,R1}(x, f)$ denote the probability that the receiver at x successfully receives the message in round 2 from exactly one forwarder at f in region R1. We define $s_{2,R2}(x, f)$ and $s_{2,R3}(x, f)$ in a similar way. In the following, we explain the analytical steps to obtain $s_{2,R1}(x, f)$. The steps to obtain $s_{2,R2}(x, f)$ and $s_{2,R3}(x, f)$ are very similar.

3.5.4.1 Direct collision in round 2 when f is in region R1

Consider the case when the location of the potential forwarder f is in region R1. We decompose the associated direct collision area, i.e., the interval $[-(R-x), R+f]$ into the following two sub-regions:

NoReTx: This sub-region is the interval $(R, R + f]$ where the nodes lie outside the range of the source and can only have a beacon. The nodes in this area cannot re-transmit the message.

ReTx: This sub-region is the interval $[-(R - x), R]$ where the nodes lie inside the range of the source and might re-transmit the safety message or transmit a beacon.

We denote the probability that a node in the NoReTx area has a packet (in this case, a beacon) in its queue at an arbitrary time by $p_{2,NoReTx}(x,f)$. Similarly, the probability that a node in the ReTx area has a packet (in this case, a beacon or a safety message) in its queue at an arbitrary time is denoted by $p_{2,ReTx}(x,f)$. Note that these probabilities depend on (x,f) because the NoReTx and ReTx areas are defined through (x,f).

As in round 1, $p_{2,NoReTx}(x,f)$ is given by

$$p_{2,NoReTx}(x,f) = \lambda E[S_{2,NoReTx}(x,f)], \tag{3.5.20}$$

where $E[S_{2,NoReTx}(x,f)]$ denotes the average service time for an arbitrary node in the NoReTx area. The probability $p_{2,ReTx}(x,f)$ is obtained as follows.

Let f_L denote the distance from the source of a generic node in the ReTx area and on the left side of the source. The probability that a node in the ReTx area and at point $-f_L$ successfully receives the safety message from the source is equal to $s_1(f_L)$, which can be obtained by (3.5.18), and its conditional forwarding probability is equal to $p_b(f_L)$, which can be obtained by (3.4.1). Therefore, its unconditional forwarding probability in round 2 is equal to $s_1(f_L)p_b(f_L)$, which can be considered as the probability that there is a safety message in its queue. Then, the probability that a node in the ReTx area and at point $-f_L$ has a packet (i.e., a beacon or a safety message) in its queue in round 2, denoted by $p_{2,ReTx}(x,f;f_L)$, is given by

$$p_{2,ReTx}(x,f;f_L) = s_1(f_L)p_b(f_L) + [1 - s_1(f_L)p_b(f_L)]\,\lambda E[S_{2,ReTx}(x,f)], \tag{3.5.21}$$

where $E[S_{2,ReTx}(x,f)]$ denotes the average service time for an arbitrary node in the ReTx area.

Similarly, let f_R denote the distance from the source of a generic node in the ReTx area and on the right side of the source. By the same approach as above, the probability that a node in the ReTx area and at point f_R has a packet in its queue in round 2, denoted by $p_{2,ReTx}(x,f;f_R)$, is given by

$$p_{2,ReTx}(x,f;f_R) = s_1(f_R)p_b(f_R) + [1 - s_1(f_R)p_b(f_R)]\,\lambda E[S_{2,ReTx}(x,f)]. \tag{3.5.22}$$

Combining the above, we obtain $p_{2,ReTx}(x,f)$ as

$$p_{2,ReTx}(x,f) = \frac{1}{2R-x}\left[\int_0^{R-x} p_{2,ReTx}(x,f;f_L)df_L + \int_0^{R} p_{2,ReTx}(x,f;f_R)df_R\right]. \tag{3.5.23}$$

The average service times $E[S_{2,NoReTx}(x,f)]$ and $E[S_{2,ReTx}(x,f)]$ can be computed in the same way as $E[S_1]$ is computed in round 1, by replacing p_1 with the probabilities $p_{2,NoReTx}(x,f)$ and $p_{2,ReTx}(x,f)$, respectively. Furthermore, as in round 1, the service times $E[S_{2,NoReTx}(x,f)]$ and $E[S_{2,ReTx}(x,f)]$ and the probabilities $p_{2,NoReTx}(x,f)$ and $p_{2,ReTx}(x,f)$ are inter-dependent, and therefore, they are obtained by solving fixed point equations in the same way as p_1 is obtained in round 1.

Remarks: In principle, one has to solve a fixed-point equation for every pair of (x,f), and there are uncountably infinite number of such pairs. In our numerical solutions, we divide the one dimensional space into a finite number of intervals and solve for a finite number of pairs (x_j, f_k), $j = 1,\ldots,M_x$, $k = 1,\ldots,M_f$. Also, the integrations are approximated with finite sums.

The average number of nodes in the NoReTx and ReTx areas are given by

$$N_{NoReTx}(x,f) = \beta f, \quad \text{and} \quad N_{ReTx}(x,f) = \beta(2R-x) - 1. \tag{3.5.24}$$

Then, the probability that the transmission by the forwarder at f in region R1 is received without direct collisions at the receiver located at x is given by

$$1 - D_{2,R1}(x,f) = [1 - D_{2,NoReTx}(x,f)]\,[1 - D_{2,ReTx}(x,f)], \tag{3.5.25}$$

where

$$1 - D_{2,NoReTx}(x,f) = (1 - p_{2,NoReTx}(x,f)\tau)^{N_{NoReTx}(x,f)}, \tag{3.5.26}$$

and

$$1 - D_{2,ReTx}(x,f) = (1 - p_{2,ReTx}(x,f)\tau)^{N_{ReTx}(x,f)}. \tag{3.5.27}$$

3.5.4.2 Hidden collision in round 2 when f is in region R1

As shown in Fig 3.4, given that the tagged receiver is located at x and the forwarder is located at f in region R1, the hidden collision area is the interval $(R+f, R+x]$.

Then, the total number of hidden nodes, denoted by $N_{hidden,R1}(x,f)$, is given by

$$N_{hidden,R1}(x,f) = \beta(x-f). \tag{3.5.28}$$

Note that when the forwarder's location f lies in region R2 or R3, then a hidden node can also have a safety message in its queue (see Fig. 3.4), and the analyses of hidden node collision for those cases have been relegated to Appendix B. In this case, however, f lies in region R1 and a hidden node can have only a beacon in its queue because it is outside the range of the source.

As in round 1, we approximate the aggregate transmission process of the hidden nodes as a homogeneous Poisson process of rate $\lambda N_{hidden,R1}(x,f)$. Then, the probability that the forwarder at f in region R1 is received without hidden collisions at the receiver located at x is obtained by

$$p(H^b_{2,R1}, H^a_{2,R1})(x,f) = \left[p(H^b_{2,R1})(x,f)\right]\left[p(H^a_{2,R1})(x,f)\right], \tag{3.5.29}$$

where

$$\begin{aligned} p(H^b_{2,R1})(x,f) &= \exp\left[-\lambda T N_{hidden,R1}(x,f)\right] \\ &= \exp\left[-\lambda T \beta(x-f)\right], \end{aligned}$$

and

$$\begin{aligned} p(H^a_{2,R1})(x,f) &= \exp\left[-\lambda t_{data} N_{hidden,R1}(x,f)\right] \\ &= \exp\left[-\lambda t_{data} \beta(x-f)\right]. \end{aligned}$$

3.5.4.3 Probability of successful reception from one arbitrary forwarder in round 2

The probability that a tagged receiver located at x receives the message without collisions in round 2 from a forwarder at f in region R1 is given by

$$s_{2,R1}(x,f) = (1 - D_{2,R1}(x,f))p(H^b_{2,R1}, H^a_{2,R1})(x,f)s_1(f)p_b(f), \tag{3.5.30}$$

where $s_1(f)p_b(f)$ denotes the unconditional forwarding probability of the forwarder at f in region R1. The probabilities $s_{2,R2}(x,f)$ and $s_{2,R3}(x,f)$ are obtained in a similar way. Then, the probability that a tagged receiver located at x receives the message without collisions in round 2 from one arbitrary forwarder, i.e., a forwarder located in region R1 or R2 or R3, is denoted by $s_{2,1F}(x)$ and obtained by

$$s_{2,1F}(x) = \frac{1}{2R-x}\left[\int_0^x s_{2,R1}(x,f)df + \int_x^R s_{2,R2}(x,f)df + \int_{-(R-x)}^0 s_{2,R3}(x,f)df\right]. \tag{3.5.31}$$

3.5.4.4 Number of forwarders in round 2

The unconditional forwarding probability in round 2 for a node located at a distance x from the source is equal to $s_1(x)p_b(x)$. Therefore, the average unconditional forwarding probability for an arbitrary node is given by

$$\frac{1}{R}\int_0^R s_1(x)p_b(x)dx.$$

Recall that the total number of nodes in the range of the source, excepting the source, is $N_{total} = \beta 2R - 1$. Then, the average number of forwarders in the second transmission round, denoted as $N_{forwarder,2}$, can be computed by

$$N_{forwarder,2} = (\beta 2R - 1)\left[\frac{1}{R}\int_0^R s_1(x)p_b(x)dx\right]. \tag{3.5.32}$$

The average number of forwarders in the second transmission round for a particular receiver located at x, denoted by $N_{forwarder,2}(x)$, is obtained by considering only the forwarders in its range, i.e.,

$$N_{forwarder,2}(x) = \left[\beta R\int_0^R [s_1(f_1)p_b(f_1)]\frac{df_1}{R}\right] + \left[\beta(R-x)\int_0^{R-x} [s_1(f_2)p_b(f_2)]\frac{df_2}{R-x}\right] - 1, \tag{3.5.33}$$

where the '−1' represents the tagged receiver.

3.5.4.5 PDR after the second transmission round

The probability that a receiver at x successfully receives the message from at least one forwarder in the second transmission round, denoted by $s_2(x)$, is obtained by

$$s_2(x) = 1 - [1 - s_{2,1F}(x)]^{N_{forwarder,2}(x)}. \tag{3.5.34}$$

The probability that a receiver at x successfully receives the message in the first or the second transmission round, denoted by $s_{12}(x)$, is obtained by

$$s_{12}(x) = s_1(x) + [1 - s_1(x)]\, s_2(x). \tag{3.5.35}$$

The probability that a receiver located at an arbitrary point in the range of the source successfully receives the message from at least one forwarder only in the second transmission round, denoted by s_2, is obtained by

$$PDR_2 = s_2 = \frac{1}{R}\int_0^R s_2(x)dx. \tag{3.5.36}$$

Similarly, the probability that a receiver located at an arbitrary point in the range of the source successfully receives the message in the first or the second transmission round, denoted by s_{12}, is obtained by

$$s_{12} = \frac{1}{R}\int_0^R s_{12}(x)dx. \tag{3.5.37}$$

The Packet Delivery Ratio after the second transmission round is given by

$$PDR_{12} = s_{12}. \tag{3.5.38}$$

3.5.5 PDR after the third round

As pointed out in Sec. 3.5.2.3, it is highly difficult to track the forwarder from which the message is successfully received for the first time in round 2, and pass this information over to the analysis of round 3 so that the conditional forwarding probabilities of the potential forwarders in round 3 can be computed. Specifically, the location f' of the forwarder from which the forwarder in round 3 located at f received the message for the first time in round 2 is a random variable over the support set $[-(R-f), R]$, and its actual distribution is intractable. To get around this difficulty, for each potential forwarder at point f in round 3, we compute an *effective* conditional forwarding probability as follows. We approximate the distribution of f' as a uniform random variable over $[-(R-f), R]$ and then obtain the the effective conditional forwarding probability of the forwarder in round 3 located at f by averaging over all possibilities of f' (see Appendix C for details).

Let PDR_{123} denote the probability that an arbitrary node in the range of the source receives the message after the third transmission round (i.e., in the first or second or third round). Then, the overall Packet Delivery Ratio, $PDR_{overall}$, is approximated

$$PDR_{overall} \approx PDR_{123}, \tag{3.5.39}$$

which is clearly an approximation because we consider only up to round 3. However, the high accuracy of this approximation is confirmed by simulation results, where the performance metrics are collected when all forwarders including the ones after round 3 finish their re-transmissions (Sec. 3.6). The detailed analysis for obtaining PDR_{123} is provided in the Appendix C.

3.5.6 Delay analysis

In this section, the *mean delay* for the safety message is analysed. We approximate the mean delay as the average delay after which an arbitrary node receives the message, but considering only up to round 3. Recalling that s_1 and s_2 are the probabilities that an arbitrary node in the range of the source successfully receives the message in round 1 and round 2, respectively, we approximate the mean delay by

$$E[D] = E[S_1^*] + (1 - s_1)\left(E[S_2^*] + (1 - s_2)E[S_3^*]\right), \tag{3.5.40}$$

where S_i^*, $1 \leq i \leq 3$, is the maximum possible service time for a safety message in round i. As defined earlier in Sec. 3.5.3.1, the service time for any packet is the time interval between the instant when the packet reaches the head of the queue and until the instant the packet finishes its transmission.

The maximum service time in round i is obtained next. Recall that $N_{forwarder,i}$ is the average number of forwarders in round i. Let $U_{i,j}$, $1 \leq j \leq N_{forwarder,i}$, denote the random number of backoff slots sampled by the j^{th} forwarder in round i, where we round-off the average number of forwarders to the nearest integer. Define

$$U_i^* = \max_{1 \leq j \leq N_{forwarder,i}} U_{i,j}.$$

Then,

$$S_i^* = B_i^* + T = \sum_{n=1}^{U_i^*}(l + Y_i^n) + T, \tag{3.5.41}$$

where Y_i^n, $1 \leq n \leq U_i^*$, are i.i.d. random variables having the same distribution as Y_i, the random duration of interruption per backoff slot in round i. Then, the expected maximum service time in round i is obtained by

$$E[S_i^*] = E[B_i^*] + T = (l + E[Y_i])E[U_i^*] + T, \tag{3.5.42}$$

where $E[Y_i]$ is computed by the same approach as that for $E[Y_1]$ in round 1 (see Eqn. (3.5.13)).

It only remains to compute $E[U_i^*]$. Note that in the first transmission round, since the source is the only node with the message, we have $U_1^* = U$ and the maximum service time S_1^* can be obtained by applying Eqn. (3.5.12) in Sec. 3.5.3.1. In general, however, U_i^* is to be obtained from the *order statistics* of discrete Uniform random variables. Then, $E[U_i^*]$ is given by

$$\begin{aligned} E[U_i^*] &= \sum_{k=0}^{W-1} kP(U_i^* = k) \\ &= \sum_{k=0}^{W-1} k\left[P(U_i^* \leq k) - P(U_i^* < k)\right] \\ &= \sum_{k=0}^{W-1} k\left[\left(\frac{k+1}{W}\right)^{N_{forwarder,i}} - \left(\frac{k}{W}\right)^{N_{forwarder,i}}\right] \end{aligned} \tag{3.5.43}$$

where $P(\cdot)$ is the probability that the event $(\cdot)$ happens.

3.6 Model Validation

In this section, we confirm the accuracy of the proposed model and discuss observations. The objectives of this section are as follows:

- to validate our analytical model with multiple probabilistic forwarding schemes with extensive simulations in a wide range of parameter settings,
- to verify the assumption that the spatial distribution of the forwarders is uniform, and

- to study the impact of mobility patterns as observed in real traces and reported in (Gramaglia et al., 2011) and that of fading channel.

The equations of our analytical model are numerically solved using Matlab (version R2012b), where integrations over the 1D space are implemented as summations with the discretization interval of 0.8 meters. This particular choice was made to strike a balance between numerical accuracy and computation time after considering several trial values.

For the simulation, we use the Network Simulator ns-2, version 2.33 (ns2) with the EDCA module provided by the TKN group (Wiethölter and Hoene, 2011). Our network represents a section of a one-lane highway of length 4 km, where vehicles are moving in the same direction with a constant speed chosen uniformly randomly in the range of 60 and 80 km/hour. Later we shall consider simulations driven by real data traces wherein the constant speed condition will be relaxed. We consider the cases of *low*, *medium* and *high* node density, with the node density β (in vehicles/km) belonging to the sets $\{25\}$, $\{40, 50\}$, and $\{75, 100, 130\}$, respectively. In each case, vehicles enter into the 1D road at a fixed rate of $\mu = \beta\bar{v}$ vehicles/hour, where $\bar{v}$ denotes the average speed of vehicles. The value of μ is chosen such that the average density β is equal to the desired value of 25, or 40, and so on. The mean communication range, R, is set to 200 meters (Hartenstein and Laberteaux, 2008).

Two types of messages, namely, beacon and safety messages, with the same packet size of 400 bytes are simulated. However, in this chapter, only the network performance for safety messages is evaluated. The network performance for beacon messages is studied in Sec. 4.3. In a single class EDCA, we set both beacon and safety message parameters in the same class of the Background Traffic (AC_BK) ($W_{min} = 15$, $AIFSN = 7$, taken from Table 8-105 in the standard (IEEE Standard 802.11, 2012) and (IEEE Working Group and others, 2010)), which is the class with the lowest priority.

Each vehicle in the network broadcasts a beacon message every 100 milliseconds (Vehicle Safety Communications Consortium, 2005, page 4) which corresponds to $\lambda = 10$ beacons/second. Safety messages, on the other hand, occur occasionally in emergency situations. For each density and for each setting of parameters, we

Table 3.2: Parameter Setup for Simulation.

Parameter	**Value**
Road length	4 km
Vehicle density	25/ 40/ 50/ 75/ 100/ 130 vehicles/km
Speed	60 km/h to 80 km/h
Data rate	6 Mbps
Basic rate	6 Mbps
Contention window	15
AIFSN	7
Slot time	20 μs
SIFS time	10 μs
Packet length	400 bytes

study the performance of the network simulating for 5000 safety messages. For each safety message, a source is chosen uniformly randomly in the [0.5, 3.5] km range with the 0.5 km at the two ends of the 4 km highway section excluded to avoid boundary effects. The performance metrics are evaluated w.r.t. nodes that are located within the 200 m range on either side of the source. This corresponds to a coverage area of 400 m which is sufficient for most of the current safety applications in V2V networks (Hartenstein and Laberteaux, 2008). Unlike the analytical model, where the performance metrics are approximated after the first three rounds, in the simulation, results are collected when all forwarders finish their re-transmissions, including retransmissions after the third round. The main simulation parameters are summarised in Table 3.2.

Fig. 3.5 compares the PDRs computed by our analytical model and that from simulations as functions of vehicle density for several multi-hop probabilistic forwarding schemes and the single-hop broadcast without any retransmissions. Fig. 3.6 does so for the IF scheme with different values of the coefficient c. The PDR for the single-hop broadcast is the PDR in the first transmission round (i.e., without any re-transmissions), and the analytical results for the single-hop broadcast are computed

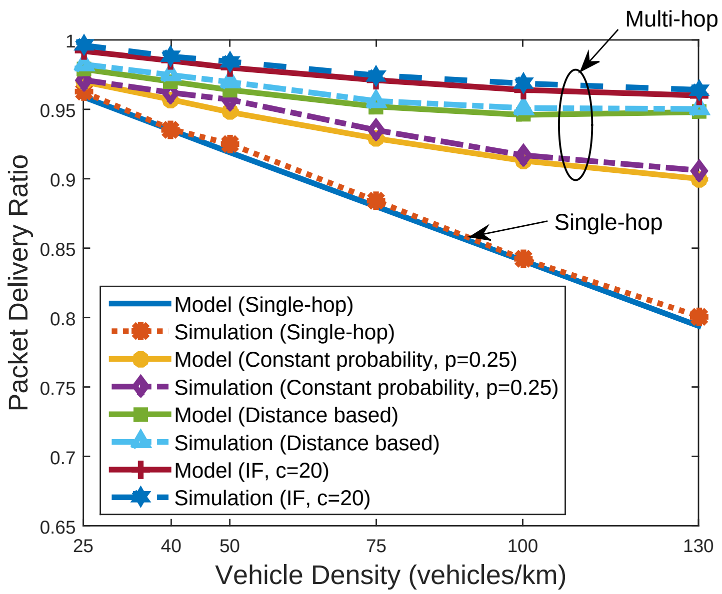


Figure 3.5: The overall PDR after all retransmission rounds for various multi-hop probabilistic forwarding schemes, and the PDR of a single-hop broadcast scheme.

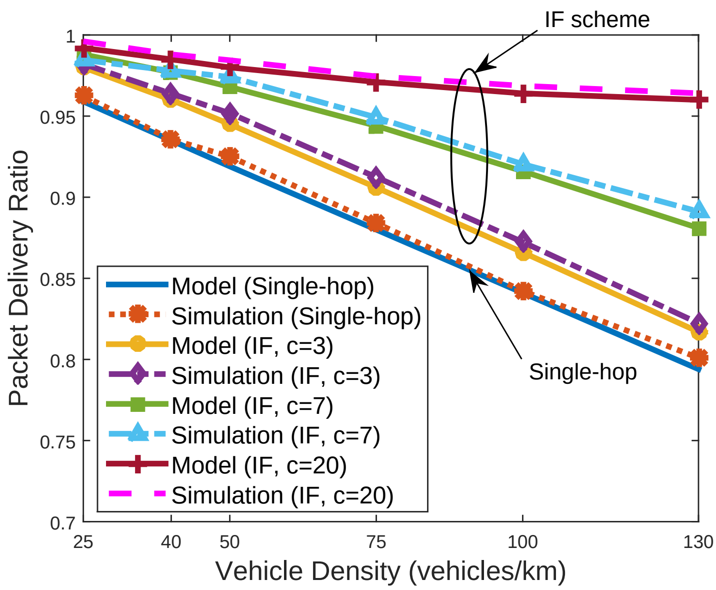


Figure 3.6: The overall PDR after all retransmission rounds with different values of c in the IF scheme.

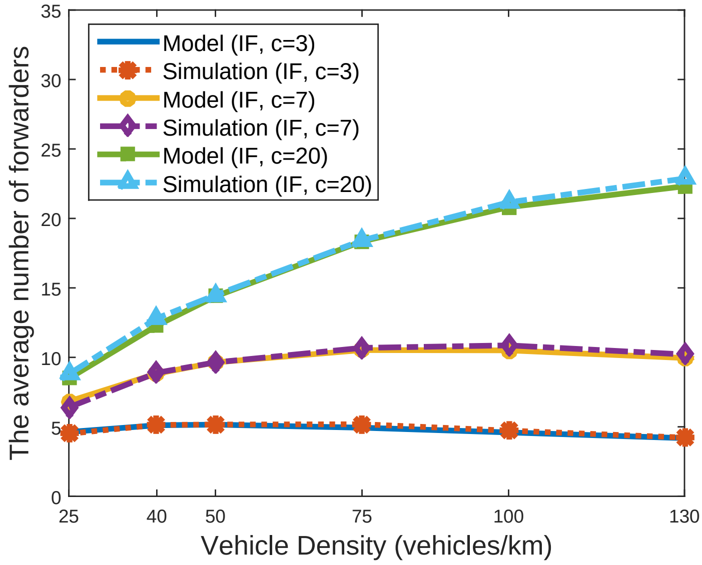


Figure 3.7: The average number of forwarders in the second transmission round with different values of c in the IF scheme.

by (3.5.19). The following insights are obtained.

Firstly, the analytical results (solid lines) are extremely close to the simulation results (dashed lines), and thus validate the accuracy of our analytical model. The highest error is only 1.2% which corresponds to the density of 130 vehicles/km and $c = 7$ (Fig. 3.6).

Secondly, the PDRs degrade with an increase in the vehicle density due to the increase in packet collisions. In particular, both the model and the simulations suggest an almost linear decrease in the PDR with increase in vehicle density.

Thirdly, a pure single-hop broadcast scheme is not an appropriate solution for safety applications at high enough densities (e.g. >65 vehicles/km) and multi-hop retransmissions are required. At densities above 65 vehicles/km, the PDR falls below 90%, which is clearly unacceptable for safety applications (IEEE Working Group and others, 2010; Hassan et al., 2011).

Fig. 3.7 shows the accuracy of our analytical model for the average number of forwarders in round 2 for the IF scheme with different values of c. From Fig. 3.7, it can be observed that the average number of forwarders increases with the increase in the value of c, which is accurately captured by our model. We also studied

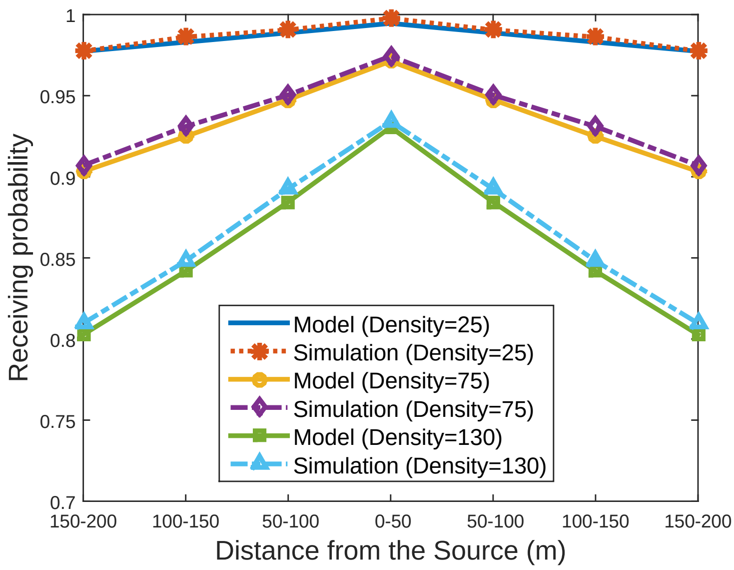


Figure 3.8: The overall probability that a node receives the safety message, given its distance from the source, with $c = 7$ in the IF scheme.

the average number of forwarders in round 3, and after all transmission rounds (in simulations). The key observations from our simulation results are summarised as follows: (i) the average number of forwarders in the third round is less than or equal to 3.5 for $c \leq 20$ and for all considered densities, and (ii) the average number of forwarders after round 3 (in simulations) is small enough such that the PDR is well approximated by considering only the first three rounds. Those results also indicate why the approximation of three rounds of analysis is enough for the network evaluation.

Fig. 3.8 depicts the probability that a node successfully receives the safety message after all retransmissions as a function of its distance from the source for the IF scheme with $c = 7$. It can be observed that the model accurately captures the variation of probability of successful reception at a node with its distance from the source. Two important behaviours are observed. Firstly, for a given distance from the source, increasing node density results in the reduction of average probability of successful reception due to the increase in packet collisions. Secondly, for a given node density, increasing the distance leads to a decrease in the probability of successful reception due to the fact that a node farther away from the source is affected

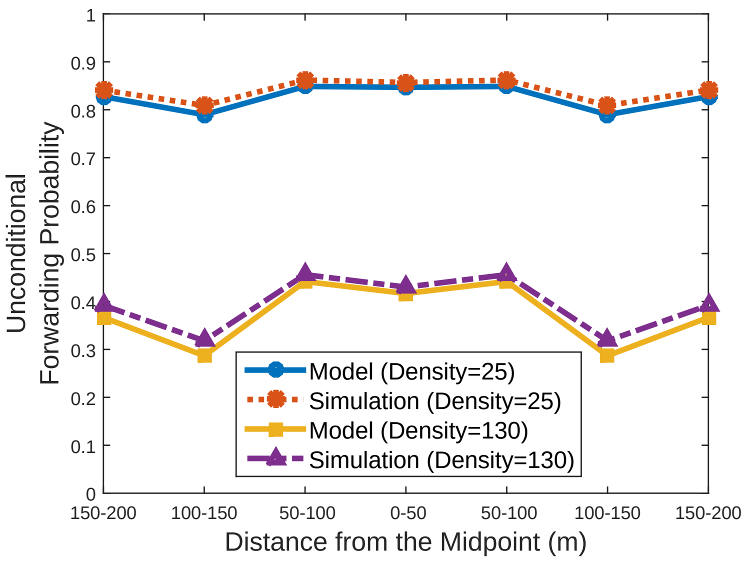


Figure 3.9: The unconditional forwarding probability of nodes as a function of the distance from a tagged receiver located at a distance $R/2$ from the source in the second transmission round with $c = 20$ in the IF scheme.

by a larger number of hidden terminals.

To verify our approximation that the spatial distribution of the forwarders in the second transmission round from the point of view of an arbitrary fixed receiver is a uniform distribution, in Fig. 3.9, we present the unconditional forwarding probability of nodes in round 2 as a function of the distance from a tagged receiver. Note that in Fig. 3.9 we distinguish between the nodes on the left and the right of the tagged receiver. Fig. 3.9 shows that the spatial distribution of the forwarders is almost uniform and that this distribution is captured well by the model. In general, this distribution exhibits small variations over different locations of the tagged receiver. But if the density is not too high they are close to the uniform distribution.

Fig. 3.10 compares the mean delays from analysis and simulation for various forwarding schemes. The results show the accuracy of the delay analysis. Besides, it reveals that the multi-hop schemes, while significantly improve the PDR (Figs. 3.5 and 3.6) as compared to single-hop broadcast, the worst mean delay observed with the high density of 130 vehicles/km is still smaller than 11 ms which is well within the acceptable value ($\leq$ 100 ms) for safety applications.

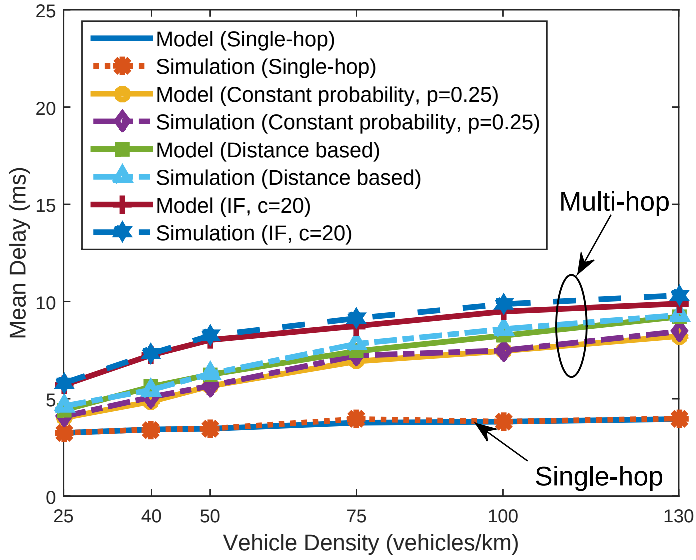


Figure 3.10: The mean delay after all retransmission rounds with multiple probabilistic forwarding schemes, and that of the single-hop broadcast scheme.

Sensitivity of PDR to node density

Let $\hat{\beta}$ denote the estimated vehicle density which, in general, is different from the actual density β. Let PE denote the percentage error in the density estimate, i.e.,

$$PE = \left(|\hat{\beta} - \beta|/\beta\right) \times 100.$$

We studied the percent error in analytically computed PDR for the IF scheme, when the densities are estimated with PE in the range of $[0, 20\%]$. Our analytical results show that with PE as high as 20%, the highest error in PDR for the densities in the range [25, 400] vehicles/km is only 3%, and they correspond to $c = 20$.

Studying the impact of mobility patterns and fading:

We conclude this section by comparing the analytical model under more elaborate simulation settings. Firstly, a fading environment is simulated such that the communication range has a mean value of 200 meters (Hartenstein and Laberteaux, 2008) as before, but now has a standard deviation of 10% of the mean. Secondly, the inter-arrival time distribution is changed to a Gaussian-exponential mixture model as observed in real traffic traces (Gramaglia et al., 2011, 2014). Consequently, vehicle densities significantly differ from the uniform distribution. The probability density function, $f_A(\cdot)$, of the inter-arrival time random variable, A, is as in (Gramaglia

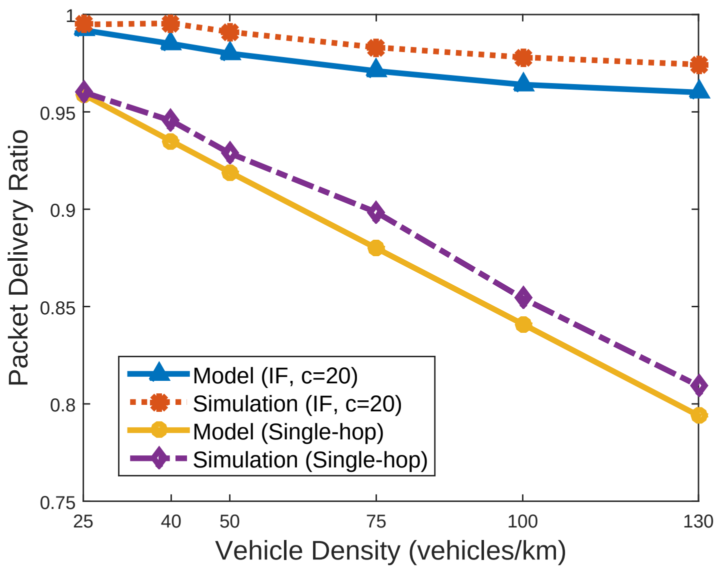


Figure 3.11: The overall PDR for the IF ($c = 20$) and the single-hop schemes under non-uniform densities and fading.

et al., 2011, page 5), and is given by

$$f_A(t) = w_G \frac{1}{\sqrt{2\pi\sigma_A^2}} e^{-\frac{(t-\mu_A)^2}{2\sigma_A^2}} + w_E \lambda_A e^{-\lambda_A(t-m_A)},$$

where w_G and w_E are weights for Gaussian and exponential distributions, respectively; μ_A and σ_A are the mean and standard deviation for the Gaussian random variable; λ_A and m_A are the rate and the shift parameter of the exponential random variable. In the simulation, the parameters are chosen so that the desired average vehicle densities from the set $\{25, 40, 50, 75, 100, 130\}$ vehicles/km are attained, which requires that

$$\left(w_G \mu_A + w_E e^{\lambda_A m_A} \lambda_A^{-1}\right)^{-1} = \beta \bar{v},$$

where, as before, β and $\bar{v}$ denote the density and average speed. We choose the parameters as follows: $w_G = 0.75$, $w_E = 0.25$, $m_A = 0.5$, $\sigma_A = 20\%$ of μ_A and $\lambda_A = \beta\bar{v}$, and μ_A is chosen to satisfy the above equation. In Fig. 3.11, the analytical results are compared with those from the new simulation settings. These results confirm the accuracy of our analytical model and show its robustness against the impact of fading and generic arrival patterns with a maximum error of 2% for the cases studied.

In Fig. 3.12, we validate the proposed model by using the real datasets provided in (Gramaglia et al., 2014). Four real datasets from two three-lane highways in Madrid, Spain on the 10th and 12th May 2010 (Gramaglia et al., 2014) are studied, that are:

- the M40 high way, on the Wednesday 12th, May 2010, from 8:30 a.m. to 9:00 p.m., denoted by M40-h8, with the average speed of 84.98 km/h and the average vehicle density of 60 vehicles/km,
- the M40 high way, on the Wednesday 12th, May 2010, from 11:30 a.m. to 12:00 p.m., denoted by M40-h11, with the average speed of 87.71 km/h and the average vehicle density of 48 vehicles/km,
- the A6 high way, on the Monday 10th, May 2010, from 8:30 a.m. to 9:00 p.m., denoted by A6-h8, with the average speed of 68.73 km/h and the average vehicle density of 62 vehicles/km,
- the A6 high way, on the Monday 10th, May 2010, from 11:30 a.m. to 12:00 p.m., denoted by A6-h11, with the average speed of 77.01 km/h and the average vehicle density of 40 vehicles/km,

where the inter-interval time distribution of vehicles follows a mixture of Gaussian-exponential model, and vehicles can change the speed and the driving lane during their travel. Besides, in the simulation, a fading wireless channel (with an average communication range of 200m [41] and with 10% standard deviation) is used as before. Our results show the high accuracy of the analytical model with the highest error of 3.5% for the M40-h8 dataset.

PDR Comparison with Worst-case PDR Analysis:
The PDR definition used up to now is the PDR in the sense of an *average case analysis*. For safety applications, a *worst-case analysis* might be more pertinent. We define the worst-case PDR as the fraction of time when at least x percent of all nodes in the communication range of the source successfully receives the safety message. For safety applications, good designs would set x to be high, e.g., $x = 95$ or $x = 99$, etc. In Fig. 3.13, we compare the analytical values of PDRs for various

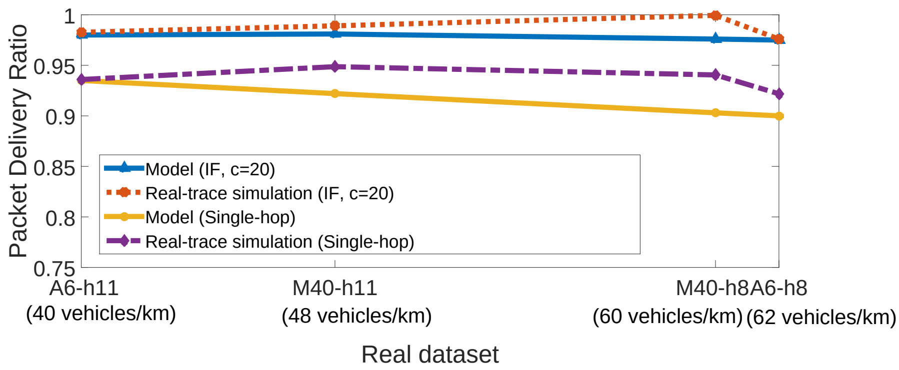


Figure 3.12: The overall PDR for the IF scheme ($c = 20$) and the single-hop scheme with the real traces (Gramaglia et al., 2014) and fading.

schemes (that are computed using the average case approach developed in Sec. 3.5) with the worst-case PDRs obtained from simulations with $x = 95$ percent. Two interesting observations can be made. Firstly, the ordering between schemes based on the analytically computed average PDR is the same as the ordering based on the worst case PDR obtained from simulations. Secondly, analytically computed average PDR provides a good approximation for the worst case PDR obtained from simulations in that the error is at most 3%. Therefore, our analytical model can be used to evaluate the worst-case PDR for safety applications with appropriate parameters for the PDR definition (e.g. $x = 95$ percent).

3.7 Chapter Summary

In this chapter, we propose a generic multi-hop probabilistic forwarding scheme for broadcasting safety messages in vehicular networks and develop a framework for performance analysis of the scheme. Our forwarding scheme is compatible with either the IEEE 802.11p DCF, or a single class EDCA MAC protocol, and can be adapted to achieve the best features of the multi-hop broadcasting schemes so far proposed in the literature.

The proposed framework provides an analytical model for network performance for safety applications, including reliability (measured via Packet-Delivery-Ratio and the probability that an node receives the safety message given a distance from the

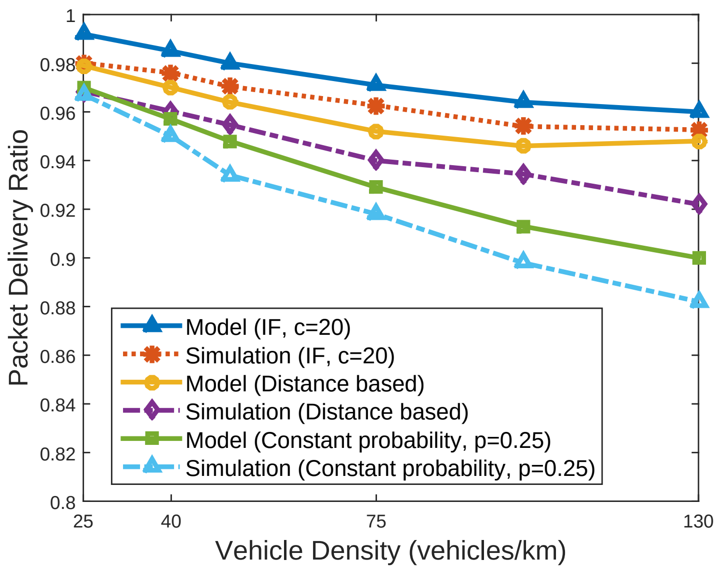


Figure 3.13: A comparison of the Average PDR and Worst-Case PDR via simulation and analytical results for multiple probabilistic forwarding schemes.

source), and delay. Our framework is sufficiently general, takes into account the impact of hidden terminals, direct collisions, vehicle densities and also provides insight into the spatial distribution of forwarders in one-dimensional highway scenarios with unsaturated nodes. The accuracy of the proposed analytical model is confirmed by extensive simulations. Despite these inherent complexities, our analytical model provides highly accurate predictions of Packet Delivery Ratio with the highest error being only 3.5% compared to simulations.

We observe that the performance of the standard IEEE 802.11p using a single-hop broadcasting is not optimal for safety applications. On the other hand, multi-hop broadcasting with an appropriate choice of the forwarding probability function can provide improvements in PDR and satisfy safety requirements. The proposed model is generic in the sense that it can be used to evaluate the network performance of a variety of probabilistic forwarding schemes.

"No one undertakes research in physics with the intention of winning a prize. It is the joy of discovering something no one knew before."

Stephen Hawking

4

Model Simplification and Extensions

4.1 Overview

In previous chapter, we have developed an analytical model to evaluate the network performance of a generic probabilistic forwarding scheme in DSRC environment. Our results show that the model is accurate although the computation complexity is high due to multiple fixed-point calculations involved in the analysis of direct collisions. This motivates us to simplify the proposed model by avoiding fixed-point calculations, and trading accuracy against complexity. The simplified model is compatible with both the IEEE 802.11p DCF, and a single class IEEE 802.11p EDCA MAC.

In addition, to improve the reliability of message dissemination, in this chapter, we also study the effect of beacon rate and contention window on the network performance. The main contributions in this chapter are as follows.

- We propose a simplification that avoids the time-consuming fixed-point calculations in the analysis of direct collisions. This simplification can be applied to evaluate the network performance of both a single-hop broadcast and a generic probabilistic forwarding scheme. The proposed model takes into account the effect of hidden terminals, direct collisions and vehicle densities. The accuracy of the simplified model is validated by extensive simulations (Sec. 4.2.2).

- For single-hop broadcast, we develop a framework to identify optimal beacon rates based on the concept of utility maximization, and investigate the effect of beacon rate on network performance. Specifically, we formulate the optimization problem by defining a message utility considering the reliability of safety messages and the accuracy of neighbourhood information, and provide an analytical solution by applying the Karush-Kuhn-Tucker conditions. Our results show that beacon rate influences significantly the network performance, and using optimal beacon rates that result from the utility maximization can satisfy the safety requirements, even without retransmissions or message prioritization. The framework is validated by simulations using real traffic traces.

- In a multi-hop broadcast, we study the effect of contention windows on the network performance, and develop an analytical model to evaluate the network performance of a generic probabilistic forwarding scheme with the multi-class IEEE 802.11p EDCA (or the EDCA standard), where safety and beacon messages are classified into different priority groups through the use of different contention windows.

- We found that at high densities (e.g. 200 vehicles/km), the EDCA standard using default parameters (IEEE Standard 802.11, 2012) cannot satisfy the PDR requirement even via multi-hop broadcast, due to high probability of packet collisions.

4.2 Model Simplification

In this section, to simplify the proposed model in Chapter 3, we develop a new approach to analyse direct collisions which avoids the fixed-point calculations. The simplified model is then validated by extensive simulations.

4.2.1 Analytical Model

Let us recall that the probability that a vehicle has a beacon in its queue at an arbitrary time in round 1 is denoted by p_1 and obtained from Eqn. (3.5.5) as

$$p_1 = \lambda E[S_1].$$

Then the expected service time $E[S_1]$, obtained from Eqn. (3.5.12), is given by

$$E[S_1] = E[B_1] + T = (l + E[Y_1])\overline{W} + T,$$

where $E[B_1]$ is the expected backoff time, and the interruption time $E[Y_1]$ obtained from Eqn. (3.5.13) is given by

$$E[Y_1] = \left[1 - (1 - p_1\tau)^{N_{total}}\right] T.$$

Clearly, the computation of $E[S_1]$ requires $E[Y_1]$, whose computation requires p_1. Also, the computation of p_1 requires $E[S_1]$. Due to this inter-dependence between p_1 and $E[S_1]$, the computation of p_1 requires solving a fixed-point equation. In a multi-hop broadcast, multiple fixed-point calculations, which are time-consuming, are required as each forwarder has its own fixed-point calculation.

To avoid the need for fixed-point computations in the analysis of direct collisions, we propose an approach to calculate $E[Y_1]$ by not involving p_1. Let $p_{suc,1}$ denote the probability that none of the other nodes in the direct collision area transmits messages in a time slot of duration l. If none of those nodes transmits, then the interruption time denoted by Y will be $Y = 0$; otherwise, $Y = T$ because each successful transmission or collision lasts for a duration T. Then, Y is given by

$$Y_1 = \begin{cases} 0 \;\; with \;\; p_{suc,1} \\ T \;\; with \;\; 1 - p_{suc,1} \end{cases} \tag{4.2.1}$$

Then the expected interruption time is given by

$$E[Y_1] = T(1 - p_{suc,1}). \tag{4.2.2}$$

The probability that none of nodes in the direct collision area transmits the message during a slot length l is approximated as follows. We approximate the aggregate beacon transmission process by the all nodes as a homogeneous Poisson process of rate λN_{total}, where recall that λ is the beacon arrival rate per node. Therefore, the total arrival rate of beacons is equal to the total rate of transmission of beacons, λN_{total}. The probability that none of the other nodes in the direct collision area transmits messages during a slot length l is as follows

$$p_{suc,1} \approx \exp\left\{-\lambda l N_{total}\right\}. \tag{4.2.3}$$

Then the average interruption time $E[Y_1]$ can be obtained as

$$E[Y_1] \approx T\left[1 - \exp\left\{-\lambda l N_{total}\right\}\right]. \tag{4.2.4}$$

Note that in the second transmission round, a node receives the safety message if none of nodes in the direct area transmits messages (including both beacon and safety messages) during a slot length l. Therefore, the probability that none of the other nodes in the direct collision area transmits messages in a time slot of duration l in round 2, denoted as $p_{suc,2}$, can be obtained as

$$p_{suc,2} \approx \exp\left\{-\lambda l N_{total}\right\}\left[1 - p_{2,ReTx,s}(x,f)\right]^{N_{ReTx}(x,f)}, \tag{4.2.5}$$

where $N_{ReTx}(x,f)$ is the average number of nodes in the ReTx area, and $p_{2,ReTx,s}(x,f)$ is the probability that a node in the ReTx area has a safety message in its queue in round 2. Note that this probability depends on (x,f) because the NoReTx and ReTx areas are defined through (x,f).

Remarks: Note that in the simplified model, we use the Poisson packet arrival process for both beacon and safety messages. However, the analyses for safety messages are more complicated than those for beacon messages, where the probability that a node transmits a safety message is a product of the probability that the node receives the safety message from an arbitrary forwarder, and the forwarding probability given by Eqn. (3.4.1).

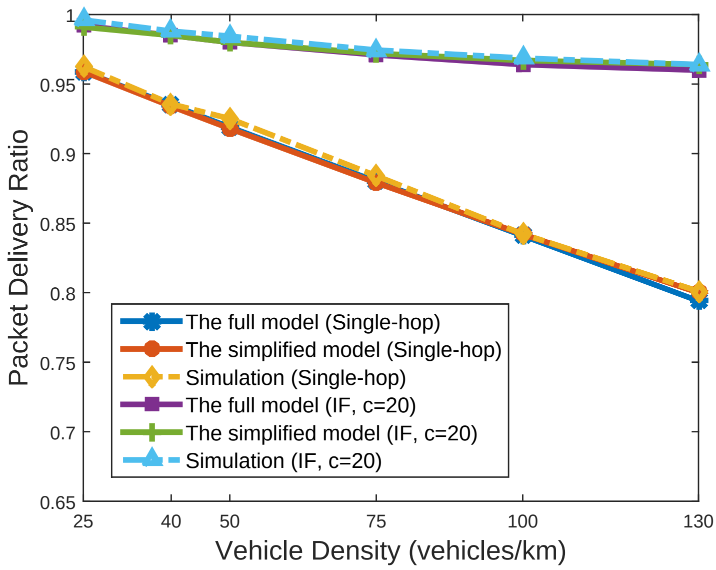


Figure 4.1: The PDR obtained by the simplified model, the full model, and the simulation for the IF scheme ($c = 20$) and the single-hop broadcast scheme, given $W = 15$, $AIFSN = 7$, Slot time = 20 μs.

4.2.2 Model Validation

In this section, we confirm the accuracy of the simplified model by simulation and the full model. As before, two performance metrics (i.e. the PDR and the mean delay) are studied for several broadcasting schemes and vehicle densities. In Figs. 4.1 and 4.2, our simulation and analytical results show the high accuracy of the simplified model for the PDR and the mean delay. Furthermore, by avoiding fixed-point calculations, the computation time for a scenario reduces significantly about 57%, while the negligible errors between the simplified model and the full model are observed.

The trade-off between Complexity and Accuracy

There is a trade-off between the complexity and accuracy. At high density (e.g. 400 vehicles/km), the full model outperforms the modified model in terms of model accuracy, even though its complexity and computation time are high due to fixed-point calculations. This is because at extremely high density, where the direct collisions are high, the fixed point approach is more accurate than the approximation of the interruption time by using the Poisson process. For example,

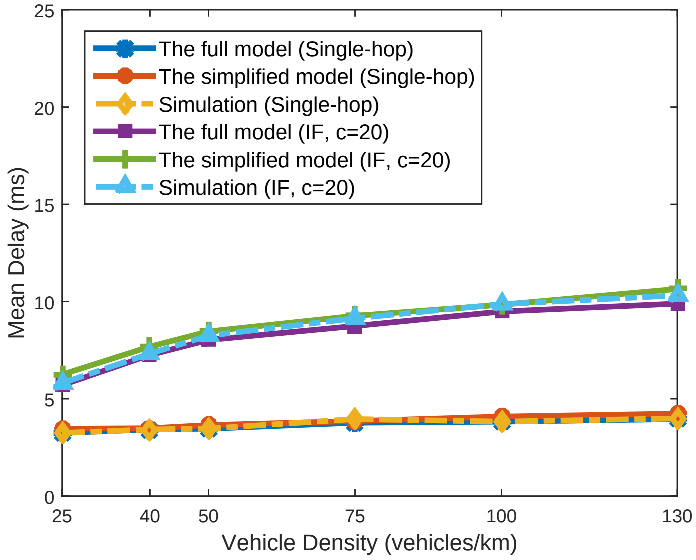


Figure 4.2: The mean delay obtained by the simplified model, the full model, and the simulation for the IF scheme ($c = 20$) and the single-hop broadcast scheme, given $W = 15$, $AIFSN = 7$, Slot time = 20 μs.

our results show that at the density of 400 vehicles/km, the highest error of PDR between simulation and the full model is about 9.6%, while that of simulation and the modified model is 15.7%. Therefore, at high density (e.g. 400 vehicles/km), the full model with high accuracy is more appropriate. However, at densities < 400 vehicles/km, it is recommended to choose the simplified model to evaluate the network performance, due to its simplicity and accuracy.

4.3 Optimization of Beacon Rate in a Single-hop Broadcast

In the follows, we study the effect of beacon rate on the network performance. Subsequently, we formulate an optimization problem, and propose a framework that systematically optimizes the beacon rate in a single-hop broadcasting scheme. The framework is underpinned by the simplified model developed in the previous section, and is compatible with both the single class IEEE 802.11p EDCA and the IEEE 802.11p DCF MAC layers.

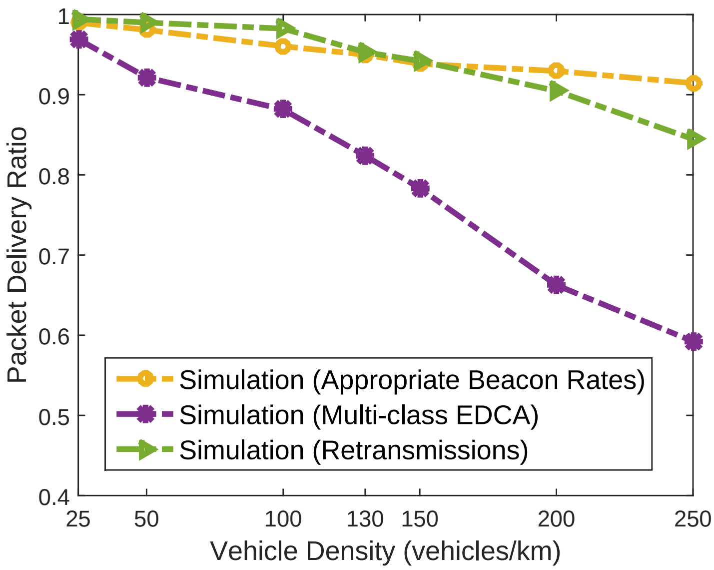


Figure 4.3: The PDR for safety messages with multi-class EDCA using a fixed beacon rate of 10 messages/second, with three retransmissions and a fixed beacon rate of 10 messages/second, and with single-class EDCA with the appropriately chosen density-dependent beacon rates.

There are several approaches proposed in the literature to improve the reliability of broadcast performance, such as, retransmissions (Zhong et al., 2008; Hassan et al., 2011, 2010), beacon rate adaptation (Drigo et al., 2009; Le et al., 2011; Chaabouni et al., 2013), and message priorities by using multi-class EDCA (Yao et al., 2013). These approaches are compared by simulation and their reliability, measured by the PDR, and shown in Fig. 4.3. For multi-class EDCA, beacon and safety messages are classified into the lowest priority class (AC_BK) and the highest priority class (AC_VO), respectively, using a pre-defined beacon rate of 10 [messages/second] and other default parameters as defined in Table 2.1. In the single class EDCA, the beacon and safety messages are in the same lowest priority class (AC_BK), and the reliability is improved either by blindly retransmitting the safety messages three times (Hassan et al., 2010), or by choosing the appropriate beacon rate depending on vehicle density as proposed later in this chapter. The simulation results in Fig. 4.3 show that blind retransmissions and the default multi-class EDCA cannot satisfy the PDR requirement at high densities (e.g. 250 vehicles/km). In contrast, by using a single class EDCA together with appropriately chosen beacon rates, the network performance can satisfy the PDR requirement (i.e. PDR $\geq 90\%$).

Remarks: In reality, there exists a wider range of vehicle densities (e.g. 200, 250 vehicles/km) that are too high for a one-lane highway considered in the previous chapters, but can be obtained in two- or three-lane highway scenarios. Deviating from the previous section, we study the PDR with multiple lanes.

The above simulation results motivate us to investigate the effect of beacon rate on the network performance, and provide a framework to identify optimal beacon rates based on a new utility maximization. Although non-critical, beacon messages play an important role in providing the broad network knowledge that are needed for many applications such as information about network topology and vehicle density (Panichpapiboon and Pattara-atikom, 2008). More importantly, the proposed utility balances the need for accurate network knowledge and the reliability of safety messages as they share the same wireless channel which will also be addressed in this section.

We first define a utility function then develop an optimization problem to obtain the optimal beacon rates.

4.3.1 The Utility Function

The beacon rate λ will affect the network performance such as the PDR and the accuracy of neighbourhood information. Therefore, the optimal λ has to support the PDR requirement for safety applications as well as the need for accurate neighbourhood information, where the latter is defined as the probability that a vehicle estimates accurately the number of one-hop neighbours.

A vehicle is aware of a neighbour if it receives at least one copy of a beacon message from the neighbour within one *lifetime* of the beacon message. The lifetime, denoted by L, is the maximum duration during which a beacon message is considered to be valid. For simplicity, we assume that all beacon messages have the same lifetime. The lifetime L should be chosen to match the time scale at which the state of the neighbourhood changes. The beacon utility is defined as the probability that an arbitrary vehicle receives at least one beacon within the message's lifetime period.

The expected number of beacon messages generated by a vehicle in a time interval of duration L is λL. Therefore, the probability that a vehicle receives at least one beacon message from an arbitrary neighbour within a period of L time units is $1 - [1 - s_1(\lambda)]^{\lambda L}$. The subscript '1' represents either the first transmission round or the single-hop broadcast. The beacon utility, denoted by $U_b(\lambda)$, is then defined as

$$U_b(\lambda) = 1 - [1 - s_1(\lambda)]^{\lambda L}, \tag{4.3.6}$$

where $s_1(\lambda)$ is the probability that a vehicle receives a beacon message from an arbitrary neighbour. Note that $s_1(\lambda)$ is also the probability that a vehicle receives a safety message from the source in a single-hop broadcast, which is equal to the probability that a vehicle receives a safety message in round 1, obtained from Eqn. (3.5.19).

The total utility, denoted by $U(\lambda)$, is a weighted sum of the beacon utility $U_b(\lambda)$ and the safety message utility $U_s(\lambda)$, and is given by

$$U(\lambda) = \alpha U_b(\lambda) + (1 - \alpha)\, U_s(\lambda), \tag{4.3.7}$$

where α is a weighting factor ($0 \leq \alpha \leq 1$), and $U_s(\lambda)$ is the PDR of the safety messages calculated as $U_s(\lambda) = PDR_1(\lambda) = s_1(\lambda)$.

4.3.2 Optimization Problem

In this section, we formulate an optimization problem and obtain a solution for the optimal values of λ by maximizing the total utility function $U(\lambda)$.

Let λ_{max} denote the maximum value of λ that satisfies the PDR requirement for safety applications (e.g., PDR $\geq$ 90%). Let σ_1 denote the required PDR. To satisfy the PDR requirement, we must have $s_1(\lambda) = PDR_1(\lambda) \geq \sigma_1$. Therefore, λ_{max} can be obtained by

$$\lambda_{max} = s_1^{-1}(\sigma_1). \tag{4.3.8}$$

Here the inversion is possible because, with increasing λ, the PDR_1 decreases monotonically as shown in Fig. 4.4. In Fig. 4.4, we study the effect of beacon rate on the PDR_1 with different values of vehicle density (i.e. 25 and 250 vehicles/km). As can

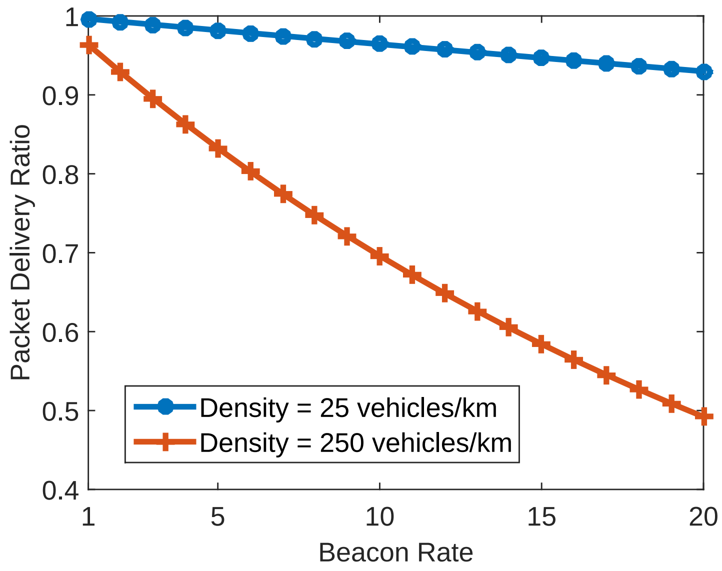


Figure 4.4: The effect of beacon rate on the PDR_1 with different values of vehicle density, given $\alpha = 0.3, L = 1.0$ and $W = 31$.

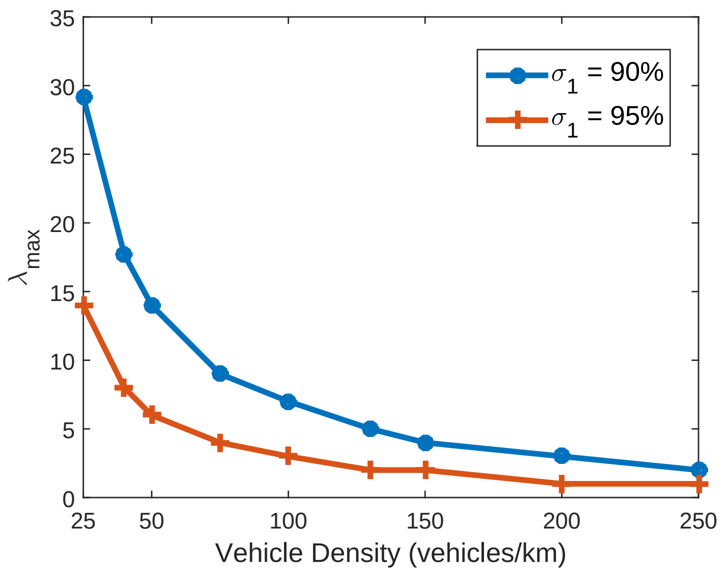


Figure 4.5: The maximum values of λ satisfying different values of safety requirement (i.e. $\sigma_1 = 90\%$ and $\sigma_1 = 95\%$).

be seen from the figure, the PDR_1 decreases monotonically when increasing λ due to the increase in packet collisions.

In Fig. 4.5, we present the maximum values of λ, obtained by Eqn. (4.3.8), that satisfy two different values of the PDR requirement (i.e. $\sigma_1 = 90\%$ and $\sigma_1 = 95\%$) for all considered densities. Our analytical results show that, for the same value of σ_1, increasing vehicle density will decrease significantly the maximum value of λ, due to an increase in packet collisions. For example, at $\sigma_1 = 90\%$, at high densities (e.g. $\geq$ 130 vehicles/km), the values of λ_{max} are less than or equal to 5 messages/second. At low densities (e.g. 25 vehicles/km), λ_{max} can reach up to about 30 messages/second. Note that the values of λ_{max} depend not only on the vehicle density but also the value of σ_1. For the same vehicle density, increasing the value of σ_1 will decrease the value of λ_{max}.

The number of one hop neighbours can be accurately estimated if a vehicle receives at least one beacon message from each one-hop neighbour during the period of L, calculated by $1 - [1 - s_1(\lambda)]^{\lambda L}$, where $s_1(\lambda)$ is the probability that the vehicle receives a beacon message from an arbitrary neighbour. Let $\varepsilon(\lambda)$ denote the probability that a vehicle estimates inaccurately the number of one-hop neighbours given λ. Then, $\varepsilon(\lambda)$ can be calculated as

$$\varepsilon(\lambda) = [1 - s_1(\lambda)]^{\lambda L} . \tag{4.3.9}$$

Let λ_{min} denote the minimum value of λ that satisfies the accuracy of neighbourhood information. Let σ_2 denote the maximum tolerance level of inaccuracy for neighbourhood information, i.e., we must have $\varepsilon(\lambda) \leq \sigma_2$. Then, λ_{min} can be obtained by

$$\lambda_{min} = \varepsilon^{-1}(\sigma_2). \tag{4.3.10}$$

In Fig. 4.6, we show the values of λ_{min}, obtained by Eqn. (4.3.10), that satisfy two different levels of $\varepsilon(\lambda)$ (i.e. 5% and 20%) for various considered densities. Given the same vehicle density, increasing the required level of accuracy of the neighbourhood information estimation will increase the value of λ_{min}. For example, at the density of 250 vehicles/km, the value of λ_{min} increases from about 1 to 2.6 message(s) per second when decreasing the maximum error from 20% to 5%. When the required

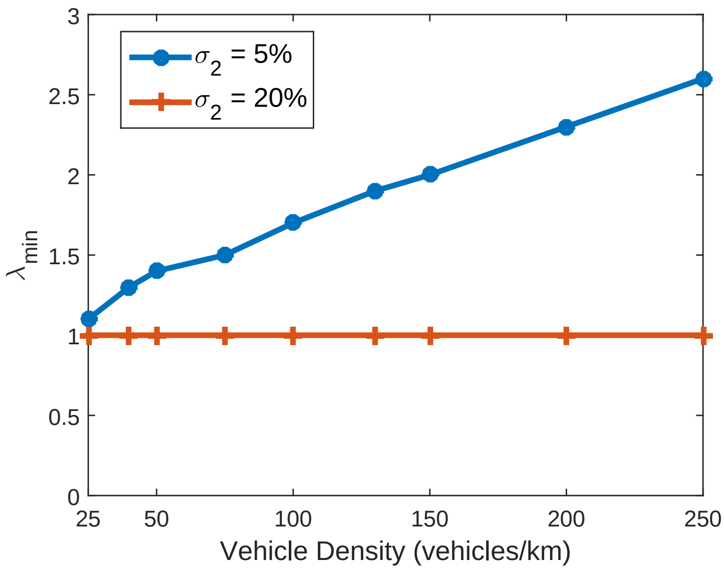


Figure 4.6: The minimum values of λ satisfying two different values of the neighbourhood estimation error (i.e. $\sigma_2 = 5\%$ and $\sigma_2 = 20\%$).

accuracy of the estimation of neighbourhood information is low, such as 80% (or the maximum error is 20%), the minimum values of λ_{min} is equal to 1 message/second for all densities considered.

The optimal beacon rate must be between λ_{min} and λ_{max}. Therefore, the non-linear optimization problem to identify the optimal values of λ is formulated as follows

$$\begin{aligned} \underset{\lambda}{\text{maximize}} \quad & U(\lambda) = \alpha U_b(\lambda) + (1-\alpha)s_1(\lambda) \\ \text{subject to} \quad & \lambda \leq \lambda_{max}, \\ & \lambda \geq \lambda_{min}. \end{aligned} \tag{4.3.11}$$

We convert the problem in (4.3.11) to the problem of minimization of $-U(\lambda)$ and obtain the *Lagrangian* $\mathcal{L}$ as

$$\begin{aligned} \mathcal{L}(\lambda, \mu_1, \mu_2) = & -\alpha \left\{1 - [1 - s_1(\lambda)]^{\lambda L}\right\} - (1-\alpha)s_1(\lambda) \\ & + \mu_1(\lambda - \lambda_{max}) + \mu_2(\lambda_{min} - \lambda), \end{aligned} \tag{4.3.12}$$

where $\mu_1, \mu_2 \geq 0$ are the *Lagrangian multipliers* or the *dual variables* associated with the problem (4.3.11). The *Karush-Kuhn-Tucker* (KKT) conditions dictate that the optimal beacon rate λ must satisfy the following conditions:

$$\lambda - \lambda_{max} \leq 0; \quad \lambda_{min} - \lambda \leq 0$$

$$\mu_1 \frac{d\mathcal{L}}{d\mu_1} = \mu_1(\lambda - \lambda_{max}) = 0; \quad \mu_2 \frac{d\mathcal{L}}{d\mu_2} = \mu_2(\lambda_{min} - \lambda) = 0$$

$$\frac{d\mathcal{L}}{d\lambda} = \alpha \frac{d}{d\lambda}\left[1 - s_1(\lambda)\right]^{\lambda L} + (\alpha - 1)\frac{d}{d\lambda} s_1(\lambda) + \mu_1 - \mu_2 = 0. \tag{4.3.13}$$

Expanding (4.3.13) it can be shown that the optimal beacon rate λ^* is obtained by comparing the value of the objective function for only three possibilities of λ, namely, λ_{max}, λ_{min}, and $\hat{\lambda}$, where $\hat{\lambda}$ must satisfy

$$\alpha L \left[1 - \left(1 - s_1(\hat{\lambda})\right)^{\hat{\lambda} L - 1}\right] \left[\left(1 - s_1(\hat{\lambda})\right) log \left(1 - s_1(\hat{\lambda})\right) - \lambda s_1'(\hat{\lambda})\right] - (1 - \alpha) s_1'(\hat{\lambda}) = 0, \tag{4.3.14}$$

and $s_1(\lambda)$ and $s_1'(\lambda) = \frac{d}{d\lambda} s_1(\lambda)$ are derived in Appendix E with and without the analysis of direct collisions. In summary, we have

$$\lambda^* = \underset{\lambda \in \{\lambda_{max}, \lambda_{min}, \hat{\lambda}\}}{\arg\max} \; U(\lambda). \tag{4.3.15}$$

Our numerical results show that the highest relative error in the optimal value of the objective function $U(\lambda)$, incurred by not considering direct collisions, is only 2.2% for all considered densities $\leq$ 100 vehicles/km. Therefore, at low densities, direct collisions can be ignored. At high densities, in contrast, direct collisions should be considered due to its significant effect on the network performance.

For the optimization problem (4.3.11), the main qualitative findings, summarised in Fig. 4.7, are as follows:

1. The value of σ_1 and σ_2 must be chosen so that

$$\lambda_{max} \geq \lambda_{min}, \text{ or, } s_1^{-1}(\sigma_1) \geq \varepsilon^{-1}(\sigma_2).$$

   This is because λ^* does not exist if $\lambda_{max} < \lambda_{min}$. The feasible region for λ is presented in Fig. 4.8.

2. λ^* increases when increasing the weighting factor α. This is because beacon reception becomes more important when α increases (see Eqn. (4.3.7)). The effect of the weighting factor α is quantitatively studied in Fig. 4.11.

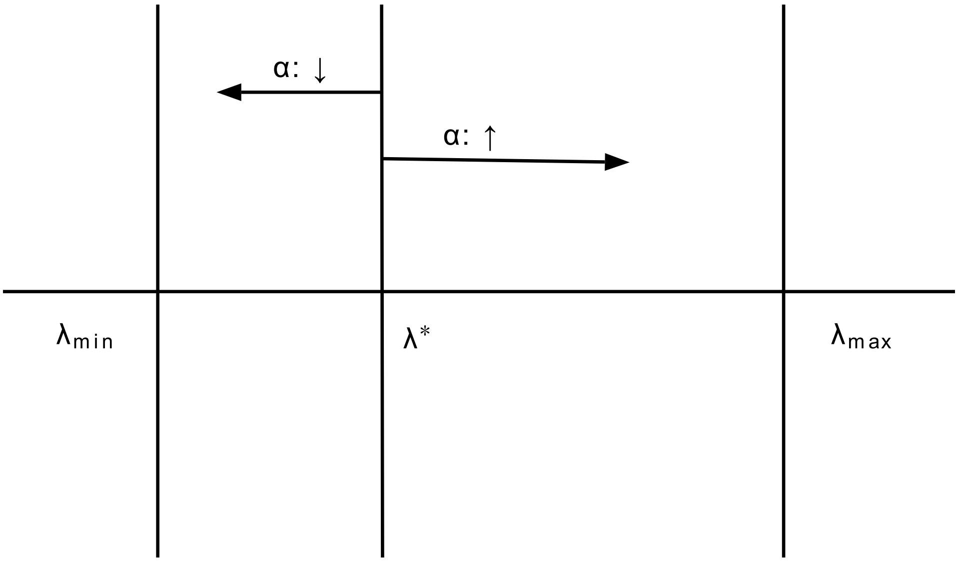


Figure 4.7: The main findings of the optimization problem.

Remarks: Although our model can be extended to the multi-hop broadcast scenario as done in our previous work (Luong et al., 2016), we discovered in this section that even a single-hop broadcast protocol can satisfy safety requirements by using appropriate beacon rates and thus eliminate the need for using a more complex multi-hop broadcast. Note that with the extended model, the optimal beacon rate can be numerically obtained, but unlike the single-hop, no closed-form expression could be expected.

4.3.3 Numerical Results and Model Validation

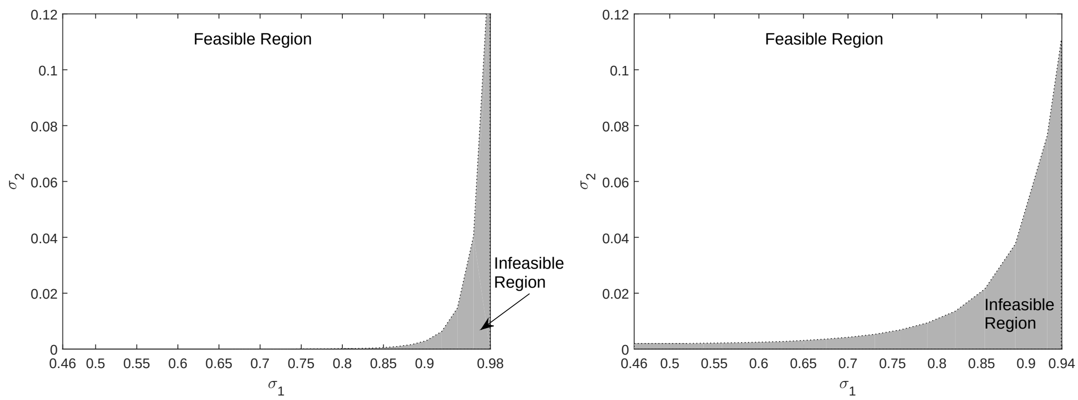
In this section, we first provide numerical results for the optimal beacon rates, and then validate the framework using simulations driven by real traffic traces. Specifically, we provide: (1) the optimal values of beacon rates for multiple vehicle densities, (2) the effect of beacon rate on the network performance metrics such as the PDR for safety messages and the probability of accurate estimation of neighbourhood information, and (3) the effect of the weighting factor α on the optimal beacon rates. We use Matlab (version R2012b) to numerically solve our analytical model, and for the simulation, we use the Network Simulator ns-2, version 2.33 (ns2) with the EDCA module provided by the TKN group (Wiethölter and Hoene, 2011). The parameter settings are summarised in Tables 4.1 and 4.2.

Table 4.1: Parameter Settings for the Optimization of Beacon Rate.

Parameter	**Value**
The required PDR (σ_1)	90%
The maximum error of the neighbourhood estimation (σ_2)	20%
α	0.3
L	1.0 s

Table 4.2: Parameter Setup for Simulation.

Parameter	**Value**
Road length	4 km
Speed	60 km/h to 80 km/h
Contention Window	31
Data rate	6 Mbps
Basic rate	6 Mbps
AIFSN	7
Slot time	20 μs
SIFS time	10 μs
Packet length	400 bytes



(a) β = 130 vehicles/km.

(b) β = 250 vehicles/km.

Figure 4.8: The feasible regions for different requirements of σ_1 and σ_2, with two vehicle densities of 130 and 250 vehicles/km.

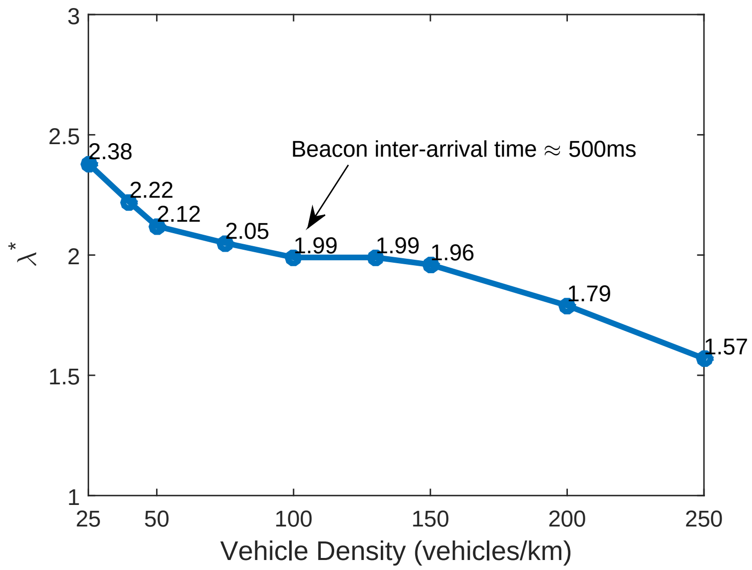


Figure 4.9: The optimal values of λ with multiple vehicle densities that satisfy $\sigma_1 = 90\%$ and $\sigma_2 = 20\%$.

In Fig. 4.8, we study the feasible regions for choosing the optimal beacon rates based on the different PDR requirements of safety messages and accuracy levels of neighbourhood information over different densities. Specifically, the figure presents the feasible regions with different requirements of σ_1 and σ_2 at the densities of 130 and 250 vehicles/km. From Fig. 4.8, it can be observed that increasing vehicle density will shrink the feasible region. For instance, the feasible region at the vehicle density of 130 vehicles/km (see Fig. 4.8a) is smaller than that of 250 vehicles/km density (see Fig. 4.8b). Some combinations of high requirements of σ_1 and σ_2 are infeasible. For instance, at the density of 250 vehicles/km, the requirements of $\sigma_1 = 94\%$ and $\sigma_2 = 2\%$ cannot be satisfied.

Fig. 4.9 shows the optimal values of beacon rate for all vehicle densities considered (i.e. ≤ 250 vehicles/km), where both the requirements of the PDR and the estimation of neighbourhood information are met. Our analytical results show that the values of λ^* decrease when the vehicle densities increase, due to the increase in packet collisions. For example, λ^* decreases from approximately 2.38 to 1.57 messages/second, when increasing the density from 25 to 250 vehicles/km. Therefore, λ^* is not so sensitive to vehicle density for a fixed value of α. Besides, the results

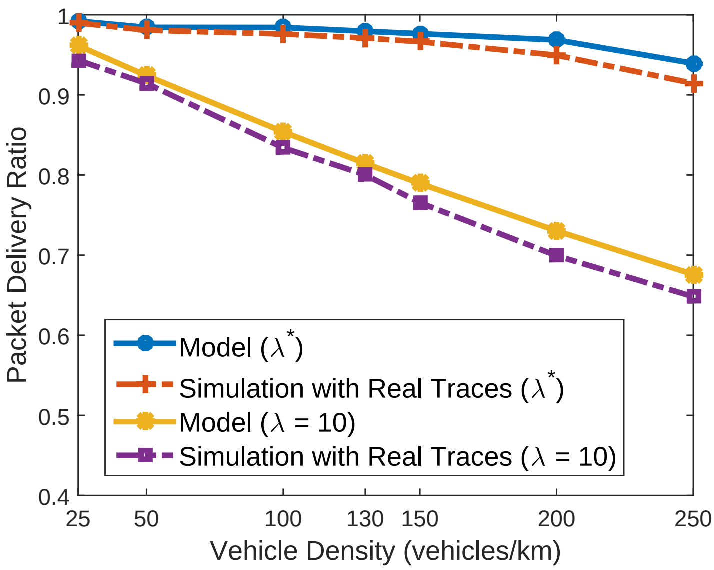


Figure 4.10: The PDR of safety messages using real traces for the optimal beacon rates, and the rate of 10 messages/second.

suggest that λ^* is less than 3 for all vehicle densities considered.

In Fig. 4.10, we investigate the performance of the optimal beacon rates by simulations using real datasets. Real traffic traces observed from (Gramaglia et al., 2011, 2014) are used, where the inter-arrival time between vehicles follows a Gaussian-exponential mixture model. Consequently, the spatial distribution of vehicles differs from the uniform distribution. The Gaussian-exponential model of the inter-arrival time for vehicles, denoted by $f_A(\cdot)$, is as follows:

$$f_A(t) = w_G \frac{1}{\sqrt{2\pi\sigma_A^2}} e^{-\frac{(t-\mu_A)^2}{2\sigma_A^2}} + w_E \lambda_A e^{-\lambda_A (t-m_A)}, \tag{4.3.16}$$

where w_G and w_E are weights for Gaussian and exponential distributions respectively; μ_A and σ_A are the mean and standard deviation for the Gaussian random variable; λ_A and m_A are the *rate* and the *shift* parameter of the exponential random variable. In the simulation, the parameters are set as follows: $w_G = 0.75$, $w_E = 0.25$, $m_A = 0.5$, $\sigma_A = 20\%$ of μ_A, and μ_A and λ_A are chosen to achieve the desired average vehicle densities from the set $\{25, 50, 100, 130\ 150, 200, 250\}$ vehicles/km. The results observed from real traces confirm the accuracy of the model that captures the decrease in the PDRs with increase in vehicle densities, with the highest error of 4%.

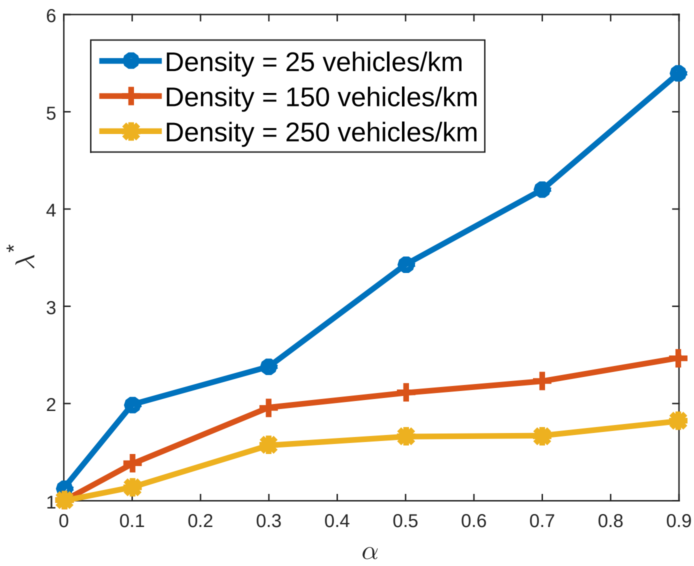


Figure 4.11: The effect of weight (α) on optimal values of λ with multiple vehicle densities, given $\sigma_1 = 90\%$ and $\sigma_2 = 20\%$.

In Fig. 4.10, we compare the PDR with the optimal beacon rate λ^* and that with the default value of beacon rate for vehicular safety communications of $\lambda = 10$ messages per second (Vehicle Safety Communications Consortium, 2005). Notice that, by using the optimal rates, the PDR is increased from about 65% to 91% (i.e., an improvement of 40%) at the highest density of 250 vehicles/km. For the accuracy of neighbourhood information, the highest error of the probability that a vehicle estimates incorrectly the number of one-hop neighbours based on beacons is about 11.1% at the highest density of 250 vehicles/km.

In Fig. 4.11, by varying the value of the weight α from 0 to 0.9, we study the effect of α on the optimal λ at the densities of 25, 150 and 250 vehicles/km. Increasing the value of α, the value of λ^* increases and gets closer to λ_{max}. Our results show that the effect of α on λ^* is significant at low densities (e.g. 25 vehicles/km), when the range of $[\lambda_{min}, \lambda_{max}]$ is large. Specifically, when varying the value of α from 0 to 0.9, the value of λ^* increases significantly from about 1.1 to 5.4 at the density of 25 vehicles/km. In contrast, at the high density of 250 vehicles/km, the value of λ^* increases from about 1.0 to 1.9. Besides, the range of the optimal values of λ is [1.0, 5.4] message(s) per second for all densities considered (i.e. $\leq$ 250 vehicles/km)

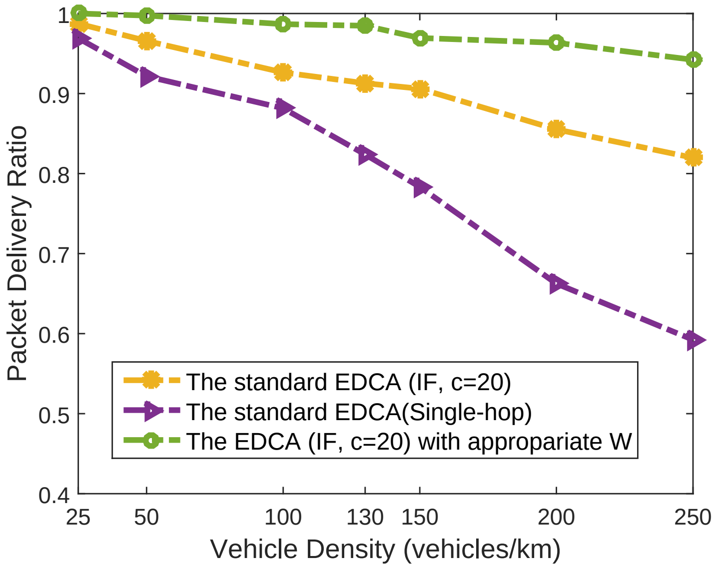


Figure 4.12: The PDR for the standard EDCA using both a single-hop broadcast and a multi-hop broadcast, and that of the multi-hop broadcast with appropriate contention windows. For the multi-hop broadcast, we use the IF scheme ($c = 20$).

which is much lower than the default value of 10 messages per second.

4.4 Contention-Window Priority in a Multi-hop Broadcast

In this section, we study the effect of contention window on the network performance, and develop an analytical model to evaluate the performance where messages are classified into different priority groups of contention windows, ignoring the effect of AIFS in the multi-class IEEE 802.11p EDCA. The proposed model can be used for both a generic probabilistic forwarding scheme (see Sec. 3.4), and a single-hop broadcast.

Fig. 4.12 shows the PDR obtained by simulations using the standard multi-class EDCA for both a multi-hop broadcast and a single-hop broadcast. Our results show the counterintuitive fact that the EDCA with standard parameter settings for priority groups of AC_BK and AC_VO (see Table 2.1) cannot satisfy the PDR requirement at high densities (e.g. $\geq$ 200 vehicles/km) even with the multi-hop retransmissions. However, by using appropriate contention windows, the EDCA with multi-hop broadcast scheme is able to meet the required PDR (i.e. PDR $\geq$ 90%).

These results also show that contention windows could significantly affect the network performance in a multi-hop broadcast especially at high densities. This motivates us to study the effect of contention windows on the network performance of a multi-class EDCA where messages are classified into different priority groups of contention windows, and develop an analytical model to evaluate the network performance that considers contention-window priorities, direct collisions, hidden terminals and vehicle densities in a multi-hop setting, based on the IEEE 802.11p EDCA. The analytical model is then validated by extensive simulations with different parameters and multiple broadcasting schemes.

4.4.1 Analytical Model

The proposed model is extended from the model developed in Chapter 3 to capture the effect of contention-window priority. A safety message with a higher priority than a beacon message will be assigned a smaller value of contention window. The analysis is summarised in Fig. 4.13 where the extension is highlighted. Specifically, in the analysis of direct collisions, the probability that a vehicle cannot receive a beacon message or safety message must be considered separately. This is because by using a smaller value of contention window, the average time to serve a safety message is smaller than that of a beacon message.

Let W^b, W^s denote the contention windows for beacon and safety messages respectively ($W^b \geq W^s$). The average number of backoff slots per a transmission for a beacon message, denoted by $\overline{W}^b$, and that of a safety message, denoted by, $\overline{W}^s$, are given by

$$\overline{W}^b = \frac{W^b - 1}{2}, \text{and } \overline{W}^s = \frac{W^s - 1}{2}. \tag{4.4.17}$$

The probability that a vehicle attempts to transmit a beacon following an arbitrary backoff slot given that the vehicle has the beacon packet in its queue is

$$\tau^b = \frac{1}{\overline{W}^b + 1}. \tag{4.4.18}$$

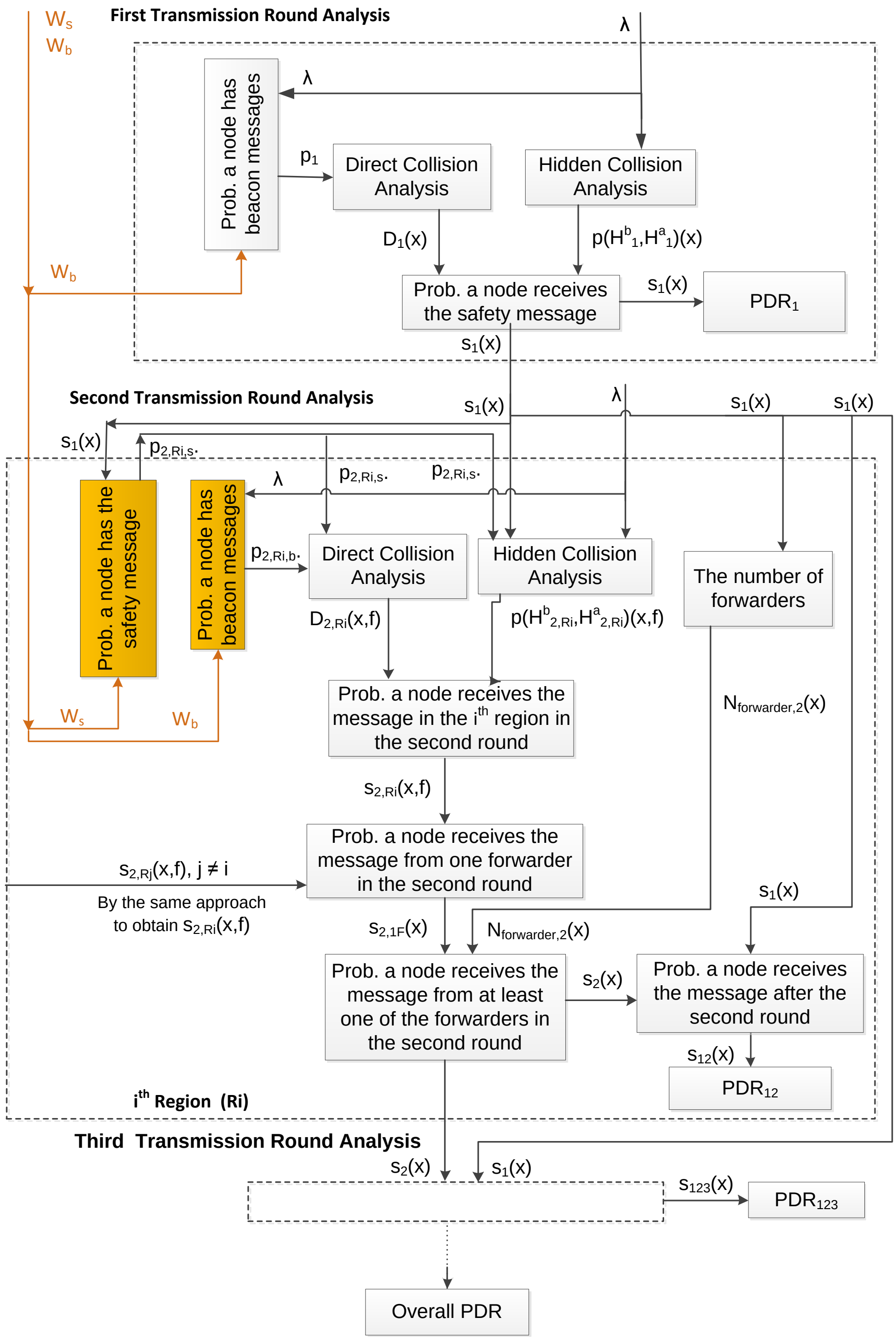


Figure 4.13: Summary of the analysis for the contention-window priority.

Similarly, the probability that a vehicle attempts to transmit a safety message given that the vehicle has the safety message in its queue is

$$\tau^s = \frac{1}{\overline{W}^s + 1}. \tag{4.4.19}$$

In the first transmission round, excepting the source, other vehicles only have beacon messages. The direct collision probability due to beacon messages for a receiver located at x in the first round, denoted by $D_1^b(x)$, where the superscript 'b' represents 'beacon', is given by

$$D_1^b(x) = 1 - (1 - p_1^b \tau^b)^{N_{direct,1}(x)}, \tag{4.4.20}$$

where p_1^b denotes the probability that a vehicle has a beacon message in its queue at an arbitrary time, and recall that $N_{direct,1}(x)$ denotes the average number of nodes in the direct collision area. The probability that a vehicle has a beacon in its queue at an arbitrary time is given by

$$p_1^b = \lambda E[S_1^b], \tag{4.4.21}$$

where $E[S_1^b]$ denotes the average packet service time for beacon messages in the first transmission round, which can be calculated using the same approach as for $E[S_1]$ in Eqn. (3.5.12), by replacing W by W^b. Note that here the analyses for safety messages are similar.

In the second transmission round, recall that the probability that the transmission by the forwarder at f in region R1 is received without direct collisions at the receiver located at x is given by

$$1 - D_{2,R1}(x, f) = [1 - D_{2,NoReTx}(x, f)]\,[1 - D_{2,ReTx}(x, f)]\,, \tag{4.4.22}$$

where $D_{2,NoReTx}(x, f)$, and $D_{2,ReTx}(x, f)$ denote the direct collision probabilities that a receiver located at x cannot receive the message from the forwarder f in the NoReTx area and ReTx area of R1 respectively which are defined in Sec. 3.5.4.1.

Let us recall that the probability that a node in the NoReTx area has a message (in this case, a beacon) in its queue at an arbitrary time by $p_{2,NoReTx}(x, f)$. The probability that a receiver located at x receives the safety message from a forwarder at f in the NoReTx area of R1 without direct collisions is as follows

$$1 - D_{2,NoReTx}(x, f) = [1 - p_{2,NoReTx}(x, f)\tau_b]^{N_{NoReTx}(x,f)} . \quad (4.4.23)$$

In the ReTx area, a node can have either a beacon message or a safety message. The probability that a receiver located at x receives the safety message from a forwarder at f in the ReTx area of R1 without direct collisions from both beacon and safety messages is

$$1 - D_{2,ReTx}(x, f) = [1 - p_{2,ReTx,b}(x, f)\tau_b]^{N_{ReTx}(x,f)} [1 - p_{2,ReTx,s}(x, f)\tau_s]^{N_{ReTx}(x,f)} , \quad (4.4.24)$$

where $p_{2,ReTx,b}(x, f)$ and $p_{2,ReTx,s}(x, f)$ are the probabilities that a node in the ReTx area has a beacon message and a safety message respectively in its queue at an arbitrary time. Note that the analyses for hidden collisions, the overall PDR and the delay are similar to those in Chapter 3.

4.4.2 Model Validation

In this section, we validate the analytical model by extensive simulations with multiple broadcasting schemes, for a wide range of vehicle densities, when varying W_s, W_b. For the simulations, the EDCA module provided by the TKN group (Wiethölter and Hoene, 2011) is used. Deviating from the previous sections, where safety and beacon messages are in the same class, in this section, safety and beacon messages are classified into different classes with different values of contention windows. For simplicity, AIFSN for both beacon and safety messages are identical. Three performance metrics are studied; they are the PDR, the mean delay, and the probability that a node receives a message given the distance from the source. Parameter settings are summarised in Table 4.3.

In Fig. 4.14, we confirm the accuracy of the model with multiple probabilistic forwarding schemes where safety messages are prioritized using a smaller value of contention window ($W_s = 7, W_b = 255, W_s < W_b$). The model captures correctly the decrease in PDR when increasing vehicle densities for all densities observed. Besides, even when given a higher priority for safety messages ($W_s < W_b$), a pure single-hop is not an optimal choice for safety applications, as it cannot satisfy the strict

Table 4.3: Parameter Setup for Simulations.

Parameter	**Value**
Road length	4 km
Vehicle Density	25/ 40/ 50/ 75/ 100/ 130/ 150/ 200/ 250 vehicles/km
Speed	60 km/h to 80 km/h
W_s	varying
W_b	varying
Data rate	6 Mbps
Basic rate	6 Mbps
AIFSN	7
Slot time	20 μs
SIFS time	10 μs
Packet length	400 bytes

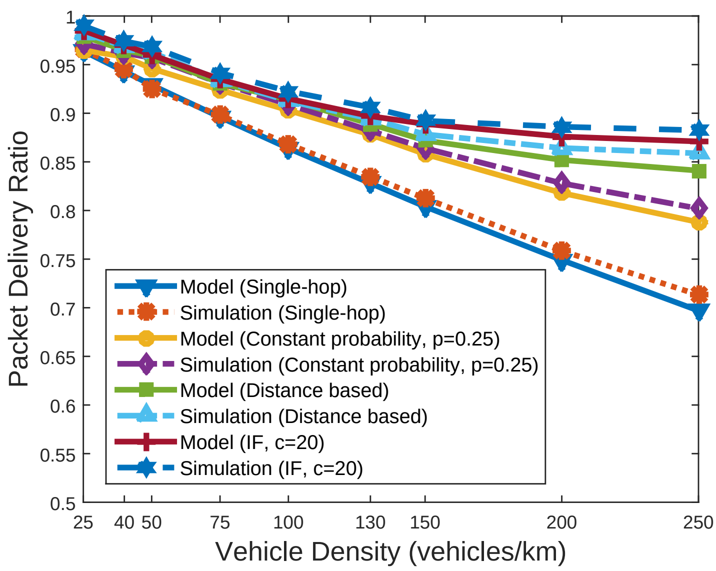


Figure 4.14: The overall PDR for various multi-hop probabilistic forwarding schemes, given a higher priority for safety messages ($W_s = 7$, $W_b = 255$).

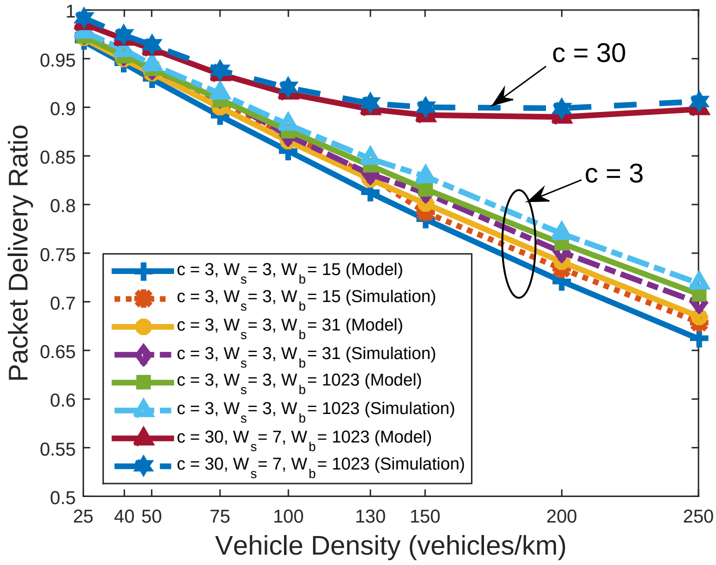


Figure 4.15: The overall PDR with different values of contention-window priority for beacon and safety messages, given the IF scheme with different values of c ($c = 3$ and $c = 30$).

requirement of the overall PDR (e.g. $\geq 90\%$, as suggested in (IEEE Working Group and others, 2010; Hassan et al., 2011)). It is important to note that this observation also holds for other choices of W_s and W_b (see Fig. 4.15). Therefore, based on both the analytical and simulation results, multi-hop re-transmissions are recommended to increase the PDR, especially at high densities (e.g. > 100 vehicles/km).

In Fig. 4.15, we show the overall PDR with different priority levels for safety messages by varying W_s, W_b, for the IF scheme with different values of c ($c = 3$ and $c = 30$). Despite some insignificant under-estimation, the proposed model shows its high accuracy. One interesting observation here is that *giving too much priority for safety messages in a multi-hop broadcast by reducing W_s does not improve the PDR, due to the increase in direct collisions between safety messages.* For example, in Fig. 4.15, at the density of 250 vehicles/km, the overall PDR with ($c = 3, W_s = 3$, $W_b = 15$) is lower than that ($c = 3, W_s = 3$, $W_b = 1023$) ($68\% < 72\%$). These results also indicate that multi-hop with inappropriate contention windows cannot satisfy the PDR requirement.

Furthermore, we observe a significant improvement in PDR by choosing an ap-

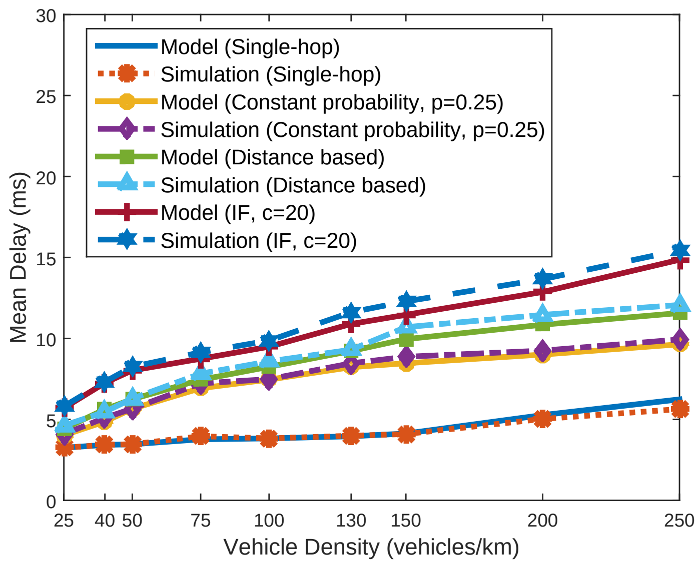


Figure 4.16: The mean delay for various probabilistic forwarding schemes, given a higher priority for safety messages ($W_s = 7$, $W_b = 255$).

propriate contention windows and coefficient c; the PDR can be increased from about 68% with ($c = 3$, $W_s = 3$, $W_b = 15$) to 91% with ($c = 30$, $W_s = 7$, $W_b = 1023$) at the density of 250 vehicles/km. Therefore, an optimal design of (c, W_s, W_b) to satisfy the PDR requirement based on the network context (e.g. vehicle densities) is needed, which will be studied in Sec. 5.3.4.

Fig. 4.16 depicts the mean delay from our analysis and simulation for multiple broadcasting schemes where safety messages are prioritized using a smaller value of contention window ($W_s = 7, W_b = 255, W_s < W_b$). The results show the high accuracy of the proposed model in terms of the mean delay for various broadcasting schemes. The worst mean delay in both the multi-hop schemes and the single-hop broadcast, observed with the high density of 250 vehicles/km, is still smaller than 16 ms which is well within the acceptable value for safety applications (i.e. ≤ 100 ms).

Fig. 4.17 presents the probability that a node successfully receives the safety message as a function of its distance from the source for the IF scheme with ($c = 3$, $W_s = 7, W_b = 255$). It can be observed that given different values of contention windows for beacon and safety messages, the model captures correctly the decrease

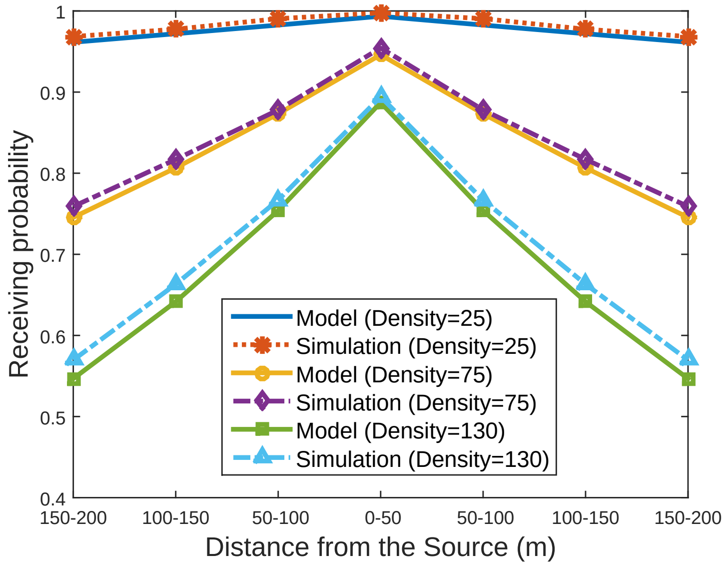


Figure 4.17: The overall probability that a node receives the safety message given an interval distance from the source, for the IF scheme with $c = 3, W_s = 7, W_b = 255$.

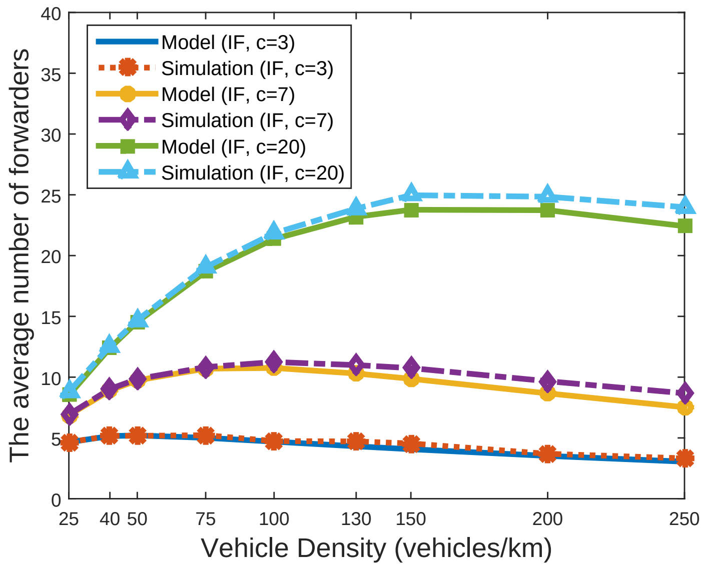


Figure 4.18: The average number of forwarders in the second transmission round with different values of c, given $W_s = 7$, $W_b = 255$.

in the average probability of successful reception when density increases due to the increase in collisions. In addition, for a given node density, increasing the distance will decrease the probability of successful reception, due to the fact that a node farther away from the source is affected by a larger number of hidden terminals.

Fig. 4.18 shows the accuracy of our analytical model for the average number of forwarders in round 2 for the IF scheme with different values of c, W_s, W_b. Our results show the high accuracy of the proposed model with multiple densities, W_s, W_b, and the model accurately captures the increase in the average number of forwarders with an increase in the value of c.

4.5 Chapter Summary

In this chapter, we propose a simplified model that avoids the fixed-point calculations in the analysis of direct collisions, while ensuring the high accuracy of the proposed model. The model is compatible with both the IEEE 802.11p DCF and a single class IEEE 802.11p EDCA. Besides, we study two different approaches to improve the reliability for safety applications in DSRC, by identifying appropriate beacon rates and contention windows.

In a single-hop broadcast, we study the effect of beacon rate on the network performance, and develop a framework to suggest the optimal beacon rates based on the utility maximization. The message utility considers the reliability requirements of safety messages, and the accuracy of neighbourhood information collected by beacon messages. The framework is underpinned by the simplified model. Our results show that a single-hop broadcast protocol can satisfy safety requirements by using appropriate beacon rates, with the improvement of up to 40% compared to that obtained with the default beacon rate of 10 messages per second. Besides, further insights regarding the trade-off between the accuracy of neighbourhood information and the reliability of safety messages are provided by means of our proposed model.

In a multi-hop broadcast, we develop a comprehensive analytical model to evaluate the network performance of the multi-class IEEE 802.11p EDCA (or the standard EDCA) for a multi-hop broadcast protocol, where messages are classified into different priority groups of contention windows, ignoring the effect of AIFS. The proposed model takes into account the impact of direct collisions, hidden terminals, vehicle densities, and the spatial distribution of forwarders. Besides, we study the effect of contention windows on the network performance of a multi-hop broadcast protocol. Our results show the significant impact of contention windows on the reliability, and reveal that a multi-hop retransmission using inappropriate contention windows cannot meet the PDR requirement for safety applications at high densities. Later in Chapter 5, by means of the model, we provide the appropriate values of contention windows for beacon and safety messages and coefficient c that satisfy the safety requirements based on the vehicle density.

"The beginning seems bitter to you, but the end is sweeter for you. However, you cannot get through to the end without having a beginning. You must begin by all means."

Israelmore Ayivor

5

Optimal Designs

5.1 Overview

In this chapter, by means of the proposed models in Chapter 3 and Chapter 4, we suggest optimal designs as a function of vehicle density. To be more specific, for each scenario, we answer the question whether either single-hop broadcast or multi-hop broadcast should be used to disseminate messages in V2V safety applications. For the chosen transmission scheme, an optimal design is provided based on our numerical study of the effect of beacon rate, contention window, and aggressiveness coefficient c on the network performance, using the models (just the simplified, or both simplified and full) proposed in the previous chapters.

We show that by using appropriate parameters, both single-hop and multi-hop broadcast protocols can meet all the strict performance requirements of the V2V safety applications. Specifically, in the single-hop broadcast, by using the default

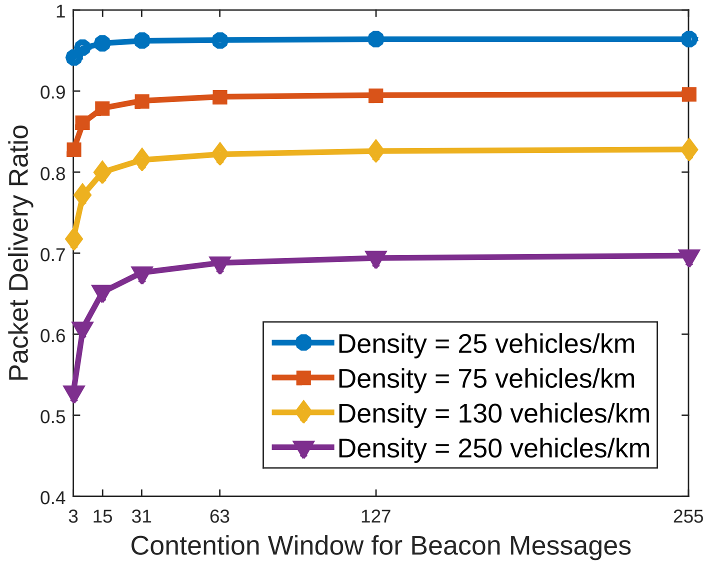


Figure 5.1: The PDR for the single-hop broadcast with multiple values of contention window for beacon messages, given $W_s = 3$, and Slot time $= 20\mu$s.

value of beacon rate (i.e. 10 messages/second) and the same contention window for both safety and beacon messages (i.e. $W_s = W_b = 31$), the PDR is approximately 64%. By using optimal values of beacon rate and appropriate contention windows, the PDR can be increased to 94% which is an improvement of 47%. Besides, a multi-hop probabilistic forwarding scheme can improve the PDR from 64% to 99% (i.e., an improvement of 55%), by appropriately choosing the values of the coefficients in the forwarding probability function (see Sec. 5.3.2). Note that in the multi-hop broadcast, only the probabilistic forwarding schemes are considered.

5.2 Single-hop Designs

In this section, we first study the effect of the contention window and beacon rate on the PDR of single-hop broadcast and then suggest the optimal parameters.

5.2.1 PDR Designs with Contention Window

In Fig. 5.1, we study the impact of contention window on the PDR and provide the optimal values of contention window in the single-hop broadcast scheme. Given

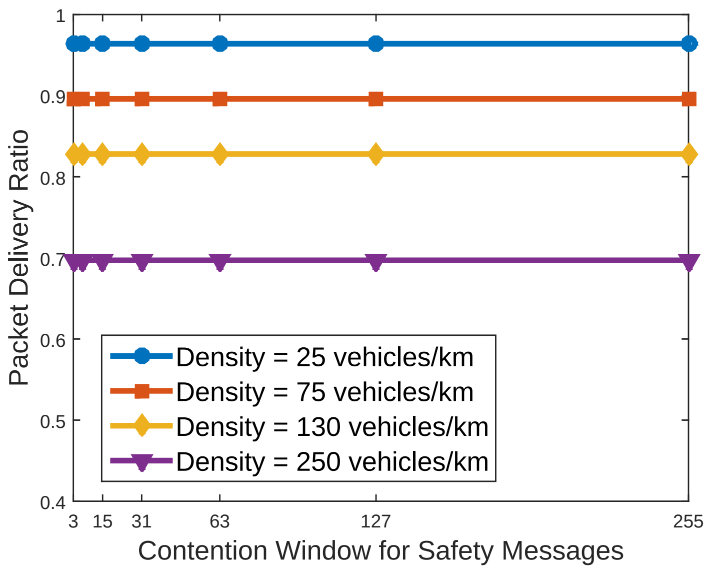


Figure 5.2: The PDR for the single-hop broadcast with multiple values of contention window for safety messages, given $W_b = 255$, and Slot time $= 20\mu$s.

a fixed value of contention window for safety messages (i.e. $W_s = 3$), by varying contention window for beacons (i.e. $W_b \in [3, 255]$), we study the PDR for a wide range of vehicle densities of 25, 75, 130, and 250 vehicles/km. Fig. 5.1 shows that W_b affects the PDR significantly, especially at high densities (e.g. 250 vehicles/km). Increasing the value of W_b will improve the PDR until an optimal point where the improvement is no longer significant. This is because beacon messages are the main traffic in the network, increasing W_b will decrease the probability that messages are sent at the same time slot. Therefore, the PDR will increase due to the decrease in direct collisions between messages. For example, at the density of 250 vehicles/km, increasing W_b from 3 to 255 increases the overall PDR from 54% to 71% (i.e., an improvement of 31%). Besides, there exists an optimal point where increasing W_b further does not improve the network performance. This is because packet collisions can be classified into groups: direct collisions and hidden collisions. Increasing W_b can only reduce the direct collisions but not the hidden collisions. For all densities studied, this optimal point is about 255.

In Fig. 5.2, we study the effect of contention window for safety messages on the PDR by varying W_s. The key observations are summarised as follows. Firstly, in

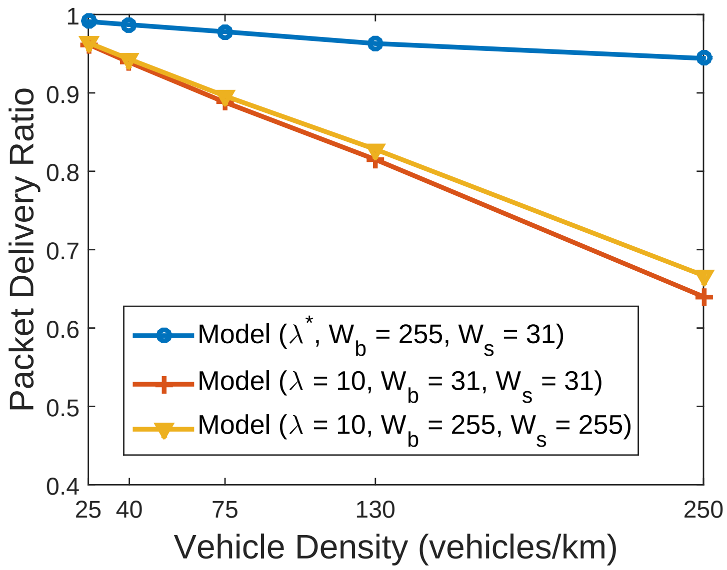


Figure 5.3: The comparison of the PDR with different values of beacon rate, contention windows for safety and beacon messages, given $\sigma_1 = 90\%, \sigma_2 = 20\%$.

contrast to W_b, in the single-hop scheme, W_s does not affect the network performance much as there is only one safety message transmitted by the source and other nodes do not forward the message. Therefore, the possibility of direct collisions between transmissions of safety message does not arise. For example, Fig. 5.2 shows that the PDRs with $W_s = 255$ are similar to those with $W_s = 3$. Secondly, as shown in Figs. 5.1 and 5.2, relying solely on appropriate values of W_s and W_b is not sufficient to make the single-hop scheme satisfy the requirements of safety applications at high vehicle densities (e.g. ≥ 130 vehicles/km).

5.2.2 PDR Designs with a combination of Contention Window and Beacon Rate

In Fig. 5.3, we provide the PDR in a single-hop broadcast by using a combination of optimal beacon rates and appropriate contention windows. Specifically, we study two values of beacon rate, one of which is the optimal beacon rate obtained from the optimization problem in Chapter 4 and the other is the default value of 10 messages/second. Two values of contention windows are used, that are 31 and 255. These values of contention windows are sufficient to reduce the direct collisions between messages (see Fig. 5.1 and its explanations).

Fig. 5.3 shows that a single-hop broadcast can meet the safety requirements by using appropriate parameters of beacon rate and contention windows. As can be seen from the figure, by using $\lambda^*, W_s = 31, W_b = 255$, the single-hop broadcast satisfies the PDR requirement for all considered densities. For example, at the highest density of 250 vehicles/km, the PDR increases from about 64%, corresponding to the default value of beacon rate of 10 messages/second, $W_s = W_b = 31$, to 94%, corresponding to the use of $\lambda^*, W_s = 31, W_b = 255$. Note that the optimal beacon rates λ^* depend on vehicle density.

5.3 Multi-hop Designs

In this section, we compare the PDRs of probabilistic forwarding schemes, and investigate the effect of coefficient c, and contention windows on the PDR in a multi-hop setting. Based on the obtained results, we suggest the corresponding optimal parameters.

5.3.1 PDR Comparison between multiple Probabilistic Schemes

In this section, based on the analytical results shown in Fig. 5.4, we provide a fundamental comparison of multiple probabilistic forwarding schemes (see Table 3.1), such as the IF scheme (Panichpapiboon and Ferrari, 2008), the distance based scheme (Wisitpongphan et al., 2007; Slavik and Mahgoub, 2010), and the constant probability scheme (Slavik and Mahgoub, 2010; Fracchia and Meo, 2008).

We obtain the following insights from Fig. 5.4: (1) When the density ≤ 130 vehicles/km, the performance of these multi-hop schemes are satisfactory as the PDRs are $\geq 90\%$. (2) When the density is sufficiently high (e.g., 250 vehicles/km), the IF scheme is superior to other probabilistic schemes because the IF scheme adapts to network condition by reducing the forwarding probability with an increase in the density. (3) The performance of the flooding scheme (where all nodes are assigned a constant probability of 1.0) rapidly degrades as the density increases due

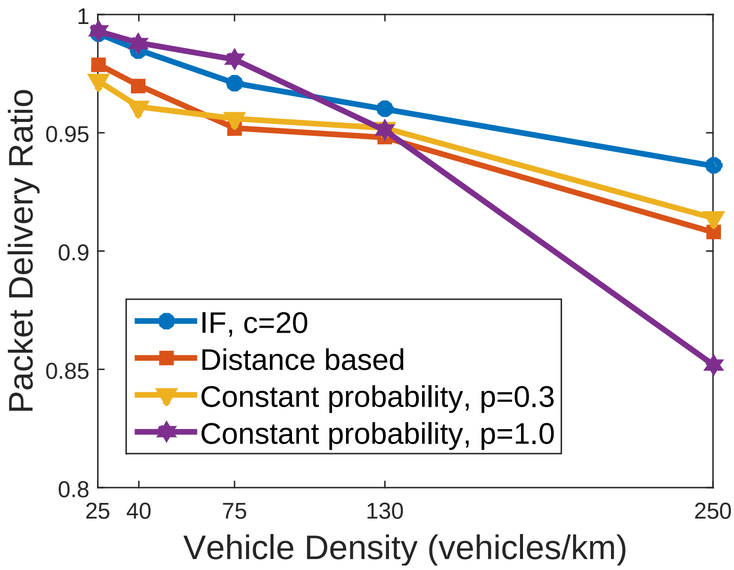


Figure 5.4: A fundamental comparison of the PDR between multiple probabilistic forwarding schemes based on the analytical results, given $W_s = W_b = 31$, $\lambda = 10$ messages/second, and slot time = 20 μs.

to the so-called broadcast storm.

5.3.2 PDR Designs with Coefficient c

It is clear from Fig. 5.4 that the IF scheme, with appropriate choice of the parameter c, performs quite well compared to the distance based scheme and the constant probability scheme. In this subsection, we apply the analytical model to suggest the minimum value of c that can achieve a required value of PDR. The idea behind seeking the minimum possible c is that a lower value of c will cause fewer collisions to the background beacon traffic, and obtain a smaller mean delay to transmit safety messages. We also examine, by means of the analytical model, if it is possible to achieve the required PDR using the much simpler single-hop broadcast scheme with the default beacon rate of 10 messages/second. The results are summarised in Fig. 5.5.

At a density of 25 vehicles/km, if PDR is not required to be greater than 96%, then Fig. 5.5 shows that even the single-hop scheme is adequate in this case. With the requirement of PDR $>$ 96%, the single-hop broadcast is not good enough and

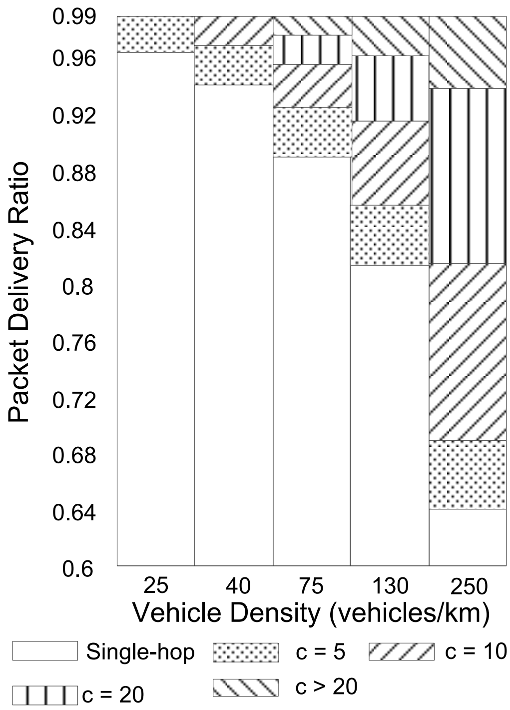


Figure 5.5: The best broadcast protocol and/or optimal values of coefficient c (if using the IF scheme), at different vehicle densities, given different requirement thresholds for PDR and $W_s = W_b = 31$, $\lambda = 10$ messages/second, and slot time $= 20\mu$s.

the multi-hop IF scheme with $c = 5$ is the optimal solution. At the high density of 250 vehicles/km, the single-hop broadcasting can only meet the requirement of PDR as low as $\leq 64\%$. For the same vehicle density, with multi-hop forwarding with $c > 20$ (e.g., $c = 25$), however, a PDR as high as 99% is achievable, which is a gain of 55% compared to the single-hop broadcast.

The idea to always use an extremely high value of c for all vehicle densities is not the optimal solution, as increasing the value of c will introduce a higher mean delay. For example, at the density of 250 vehicles/km, increasing c from 5 to 25 results in an increase of mean delay from 13 ms to 21 ms. In conclusion, for a given node density, different PDR targets require different optimal values of c.

5.3.3 PDR Designs with Contention Windows

In this section, we study the effect of contention windows for beacon and safety messages and provide optimal values for the IF scheme with multiple vehicle densities,

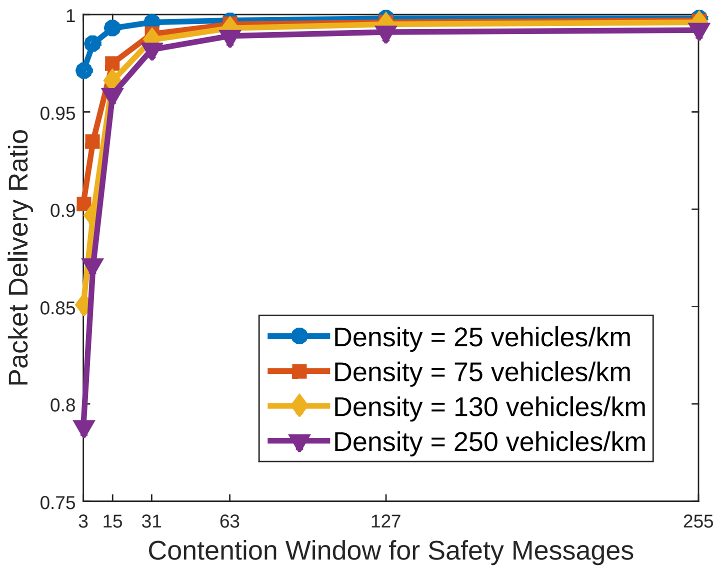


Figure 5.6: The overall PDR with different values of W_s for multiple vehicle densities, given $c = 20$, $W_b = 255$, and Slot time $= 20\mu$s.

where messages are classified into different priority groups of contention windows.

Fig. 5.6 shows that, in multi-hop broadcasting schemes, giving too much priority for safety messages by reducing the values of W_s does not increase the reliability of safety messages, especially at high densities (e.g. 250 vehicles/km). This is because a smaller value of W_s will cause a higher number of direct collisions between safety messages. For example, at the density of 250 vehicles/km, $c = 20$ and $W_b = 255$, the overall PDR decreases about 20% from 99% with $W_s = 255$ to 79% with $W_s = 3$. Therefore, in contrast to the single-hop broadcast, where there is only one safety message, in multi-hop broadcast, W_s affects significantly the PDR, as multiple copies of the safety message are transmitted.

In contrast to our observation, where giving too much priority for safety messages by using small values of W_s will decrease the PDR, in (Sun et al., 2013), the authors suggest that using a message with higher priority can improve the reliability. This paper analyses the network performance of the IEEE 802.11p EDCA MAC protocol in a saturated network condition, taking into account the differentiated channel access with different contention windows. However, the model in this paper does not consider hidden collisions which influence the reliability significantly (Hassan

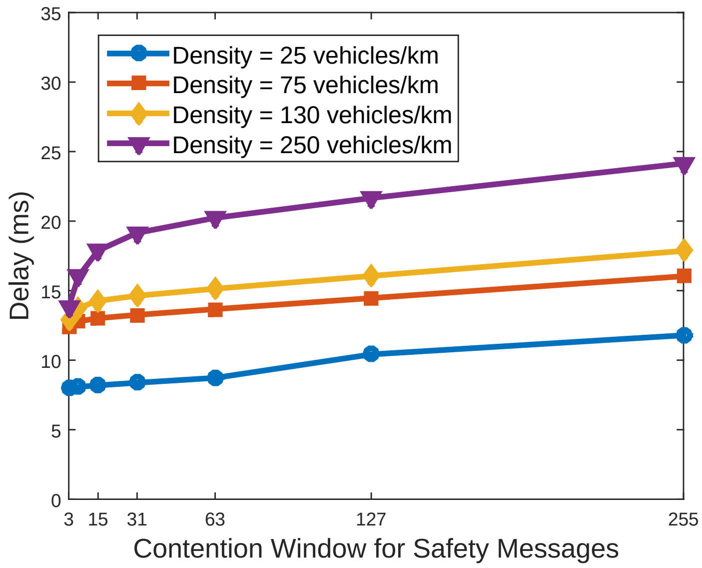


Figure 5.7: The mean delay with different values of W_s for multiple vehicle densities, given $c = 20$ and $W_b = 255$.

et al., 2011; Ma et al., 2012). This can cause the problematic observation.

Furthermore, Fig. 5.6 shows that there is an optimal value of W_s above which increasing W_s further does not improve the PDR. For a given fixed W_b (of 255), based on the obtained results, the optimal value of W_s is also 255 for all densities observed.

Note that although $W_s = 255$ provides the best performance for all the densities studied, there is a trade-off between the PDR and the mean delay. This is because increasing W_s will result in larger mean delay, especially at high density as shown in Fig. 5.7.

Fig. 5.7 studies the mean delay when varying W_s in the range of [3, 255], given $c = 20$ and $W_b = 255$. As we can see from Fig. 5.7, the mean delay increases when increasing W_s. Specifically, at the densities $\leq$ 130 vehicles/km, the mean delay slightly increases from about 12.9 ms with $W_s = 3$ to 17.9 ms with $W_s = 255$. At an extremely high density (e.g. 250 vehicles/km), on the other hand, increasing W_s results in a significant increase in the mean delay. For instance, the mean delay increases approximately 74% from 13.9 ms to 24.2 ms when increasing W_s from 3 to 255. This is because, at a higher vehicle density, a node will experience a higher

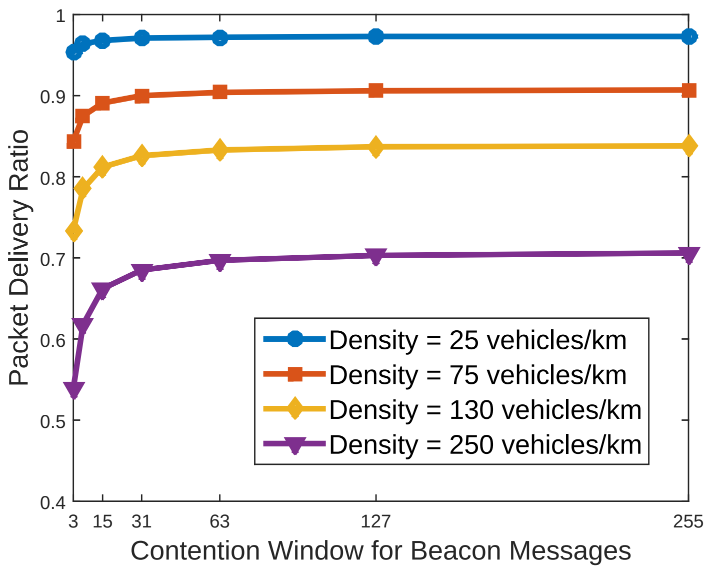
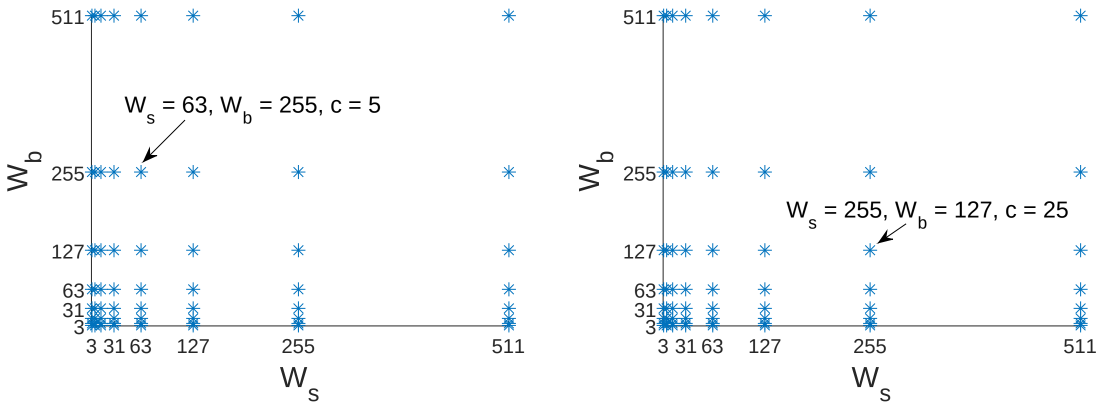


Figure 5.8: The overall PDR with different values of W_b for multiple vehicle densities, given $c = 3$, $W_s = 3$, and Slot time $= 20\mu$s.

mean delay due to a higher average interruption time. The maximum mean delay for all densities observed with $W_s \leq 255$ is 24.2 ms, which satisfies the required delay for safety applications (i.e. ≤ 100 ms). However, for some specific safety applications that require the mean delay to be less than 20 ms (Harding et al., 2014, page 98), one should choose W_s with utmost care.

In Fig. 5.8, by varying W_b, the effect of beacon contention window on the PDR is studied. As can be seen from the figure, W_b affects significantly the PDR, especially at high densities (e.g. 250 vehicles/km), as beacons are the main traffic in the network,. Besides, increasing the values of W_b will improve the PDR until an optimal point. For example, at the density of 250 vehicles/km, the overall PDR increases from about 54% with $W_b = 3$ to 71% with $W_b = 255$. This is because increasing W_b will decrease the probability that messages are sent at the same time slot. Therefore, the PDR will increase due to the decrease in direct collisions between safety messages and beacons. From Figs. 5.6 and 5.8, our results also show that only appropriate values of (c, W_s, W_b) can satisfy the safety requirements. Optimal values of (c, W_s, W_b) depend on vehicle density, which motivates us to study the optimal parameter design in the next section.



(a) $c = 5$.

(b) $c = 25$.

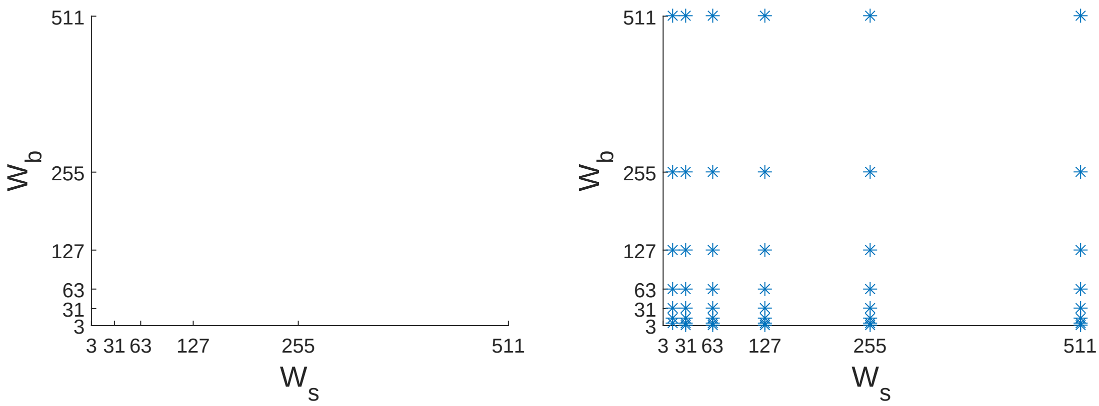
Figure 5.9: The appropriate values of (c, W_s, W_b) that satisfy the PDR and mean delay requirements at the density of 25 vehicles/km.

5.3.4 PDR Designs with a combination of Coefficient c and Window Priority

In this section, we design and suggest appropriate values for the parameter set of (c, W_s, W_b) in the IF scheme that can satisfy both requirements of safety applications (i.e. the PDR $\geq$ 90%, the mean delay $\leq$ 100 ms). Specifically, we investigate three vehicle densities (i.e. 25, 130 and 250 vehicles/km), $c \in [5, 10, 15, 20, 25]$, $W_s = 2^n - 1$, and $W_b = 2^n - 1$, with $(2 \leq n \leq 9)$.

In Figs. 5.9, 5.10, and 5.11, we plot the sets of (c, W_s, W_b) that meet the requirements of safety applications for the densities of 25, 130, and 250 vehicles/km respectively. As can be seen from Fig. 5.9, at low densities (e.g. 25 vehicles/km), all parameter settings, even with the very low values of c, W_s and W_b, can satisfy the requirements of the PDR and mean delay. In other words, there is no difference between $c = 5$ and $c = 25$ in Fig. 5.9. As a result, an arbitrary set of $c \in [5, 25]$, $W_s = 2^n - 1$, and $W_b = 2^n - 1$, with $(2 \leq n \leq 9)$ can achieve the safety requirements.

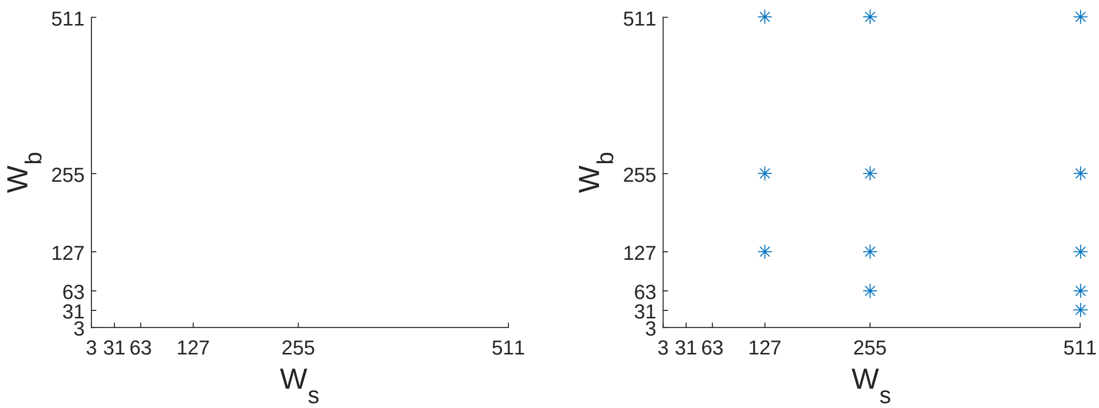
At high density, on the other hand, it is required to carefully select parameters to satisfy the required PDR. For example, at the densities of 130 and 250 vehicles/km, $c = 5$ cannot satisfy the PDR with all values of W_s and W_b (see Figs. 5.10a, 5.11a). Given the same vehicle density, increasing c until a point will result in more choices for W_s, W_b. Besides, due to packet collisions, increasing vehicle density will require



(a) $c = 5$.

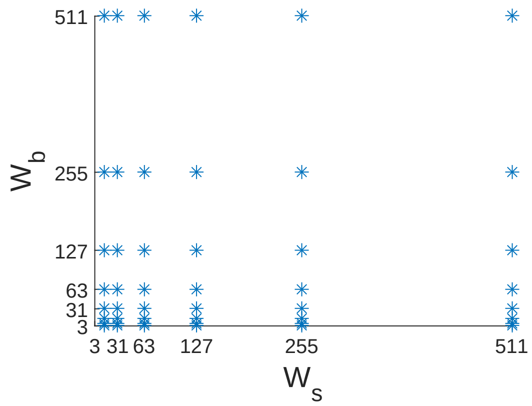
(b) $c = 10$.

Figure 5.10: The appropriate values of (c, W_s, W_b) that satisfy the PDR and mean delay requirements at the density of 130 vehicles/km.



(a) $c = 5$.

(b) $c = 10$.



(c) $c = 15$.

Figure 5.11: The appropriate values of (c, W_s, W_b) that satisfy the PDR and mean delay requirements at the density of 250 vehicles/km.

a higher c. For instance, at the density of 130 vehicles/km, given $c \geq 10$, all values $W_s, W_b \geq 15$ can meet the safety requirements. However, at the density of 250 vehicles/km, all values of $W_s, W_b \geq 15$ can only meet the safety requirements with $c \geq 15$. Furthermore, as we can see from the figure, given the same c, the number of points for the set of (c, W_s, W_b) that satisfies the safety requirements decreases when increasing vehicle density, due to the rise in packet collisions.

5.4 Chapter Summary

In this chapter, by means of the proposed models, for each scenario, we suggest appropriate broadcast protocols and provide optimal values of parameters to disseminate messages for safety applications. We consider both single-hop broadcast and multi-hop broadcast, where in the multi-hop broadcast, we take into account multiple probabilistic forwarding schemes. To suggest optimal values, we first study the effect of contention window, beacon rate, and coefficient c in the IF scheme on the network performance. Then, we provide optimal designs based on the vehicle density. Our results show that both single-hop broadcast and multi-hop broadcast can satisfy the requirements of safety applications by using appropriate parameters, such as contention window, beacon rate and coefficient c.

"Ends are not bad things, they just mean that something else is about to begin. And there are many things that do not really end, anyway, they just begin again in a new way."

C. JoyBell C.

6
Conclusion

6.1 Overview

In this chapter, we summarize the research presented in this thesis, its original contributions, and future works. Specifically, in Sec. 6.2, we summarise our contributions. Potential areas for the future works are then presented in Sec. 6.3.

6.2 Contributions

In this thesis, we provide original contributions to improve the message dissemination in vehicular networks for safety applications. Specifically, we study several approaches to improve the reliability, including retransmission, beacon rate optimization, and contention window priority. The contributions in this thesis are as follows.

6.2.1 Generic probabilistic forwarding scheme

At the beginning of Chapter 3, we proposed a generic probabilistic forwarding scheme to retransmit safety messages in vehicular networks, where every vehicle is assigned a certain probability to forward a safety message. The proposed scheme is compatible with both the IEEE 802.11p DCF and the IEEE 802.11p EDCA, and retains the best features of multiple existing schemes in the literature (Wisitpongphan et al., 2007; Panichpapiboon and Ferrari, 2008; Slavik and Mahgoub, 2010; Fracchia and Meo, 2008). Besides, new potential forwarding schemes, that have not been proposed yet in the literature, can also be obtained from the proposed scheme (e.g. the Power Law scheme in Table 3.1). More importantly, the proposed scheme is expected to be deployable in the real V2V equipment due to its simplicity and robustness.

6.2.2 Performance analysis of a generic probabilistic forwarding scheme

Later in Chapter 3, we developed a comprehensive analytical model to evaluate the network performance for both a generic probabilistic forwarding scheme and a single-hop broadcast. The proposed model takes into account the effect of hidden terminals, direct collisions, vehicle densities, and the spatial distribution of forwarders in a multi-hop broadcast, in an unsaturated network condition. The accuracy of the proposed model is confirmed by extensive simulations using real traffic traces. The model is compatible with the IEEE 802.11p DCF and a single class EDCA, and can be used to evaluate the network performance of multiple schemes in the group of probabilistic forwarding algorithms. We also developed a simplified model that avoids the computationally intensive fixed point calculations, and therefore, is suitable for use in system design.

6.2.3 Optimization of beacon rate

In Chapter 4, we investigated the effect of beacon rate on the network performance, and developed an optimization problem to recommend optimal beacon rates, based on a utility maximization framework in a single-hop broadcast. The message utility is constructed to ensure the reliability requirements for safety messages and maintain the accuracy of neighbourhood information collected by beacons. To do that, we obtained the numerical relationship between the optimal beacon rate and the system parameters (e.g. vehicle density, the weighting factor α for the optimization problem). Our results showed that the single-hop broadcast using optimal beacon rates can meet the requirements of safety applications, even without retransmissions or prioritization.

6.2.4 Contention-window priority

Also in Chapter 4, we studied the effect of contention windows on the network performance in a multi-hop broadcast setting, where messages are classified into different priority groups of contention windows. We then developed a comprehensive analytical model to evaluate the network performance that captures the effect of contention-windows, vehicle densities, direct collisions, hidden terminals in a multi-hop setting. Our results showed that contention window settings significantly affect the reliability. Besides, inappropriately chosen contention windows might lead to not meeting the PDR requirement even with multi-hop retransmissions.

6.2.5 Optimal Designs

By means of the proposed models in Chapters 3 and 4, we provided insights and optimal designs, based on the network setting and different possible requirements for safety applications in Chapter 5. Specifically, we suggest optimal broadcast protocol (e.g. single-hop broadcast and multi-hop broadcast) and optimal parameter values (e.g. for beacon rate, contention window, and coefficient c for the IF scheme) that should be used to meet the strict requirements of the PDR and the mean delay in safety applications. In fact, with different possible network requirements, these optimal parameter values can be stored as a look-up table in the on-board units of the vehicles in a real-life traffic.

6.3 Future Work

Possible future directions are listed as follows. Firstly, when a car accident happens, duplicate safety messages can be generated by multiple vehicles in the surrounding area to warn drivers about the danger ahead. The challenge is to model and evaluate the network performance when there are multiple safety messages issued by more than one source at a time.

Secondly, the analytical model proposed in Chapter 4 can be used to evaluate the network performance for the IEEE 802.11p EDCA where messages are classified into different priority groups of contention windows, ignoring the effect of AIFS. Like contention window, AIFS can be used to support service differentiation. Together with contention window, AIFS can have a greater effect on the message priority. Therefore, it is worth extending the proposed model to evaluate the network performance that takes into account the effect of both contention window and the AIFS.

Thirdly, it is assumed in this thesis that vehicle densities on the 1D road follow a uniform distribution. However, vehicles distributed on the road can follow other distributions, depending on many factors such as the road types, travel time, weather, etc. Therefore, the proposed model should be extended to evaluate the network performance with non-uniform distributions that are based on the real data collected, for example, by GPS traces.

Finally, all vehicles are assumed to retransmit safety messages by using the same probability forwarding function. However, vehicles can choose different forwarding functions to forward messages, which is based on their own information collected by the beacons. Therefore, it will be beneficial if the model can be extended to capture this scenario. Besides, investigating the network performance in a more complex topology (e.g. two-dimensional urban scenarios) and studying the effect of packet size on the network performance are also potential future works.

Bibliography

The network simulator ns-2. `http://www.isi.edu/nsnam/ns/`.

Ahmed, S. A., Ariffin, S. H., Fisal, N., Syed-Yusof, S., and Latif, N. (2014). Survey on broadcasting in vanets. *Research Journal of Applied Sciences, Engineering and Technology 7 (18)*, pages 3733–3739.

Alazemi, H. M., Margolis, A., Choi, J., Vijaykumar, R., and Roy, S. (2007). Stochastic modelling and analysis of 802.11 DCF with heterogeneous non-saturated nodes. *Computer Communications*, 30(18):3652 – 3661.

Arkian, H. R., Atani, R. E., Pourkhalili, A., and Kamali, S. (2014). Cluster-based traffic information generalization in vehicular ad-hoc networks. *Vehicular communications*, 1(4):197–207.

Artimy, M. M., Robertson, W., and Phillips, W. J. (2005). Assignment of dynamic transmission range based on estimation of vehicle density. In *Proc. 2nd ACM International Workshop on Vehicular Ad Hoc Networks*, pages 40–48.

Ayres, T. J., Li, L., Schleuning, D., and Young, D. (2001). Preferred time-headway of highway drivers. In *Proc. IEEE Intelligent Transportation Systems*, pages 826–829.

Baldessari, R., Scanferla, D., Le, L., Zhang, W., and Festag, A. (2010). Joining forces for vanets: A combined transmit power and rate control algorithm. In *6th international workshop on intelligent transportation (WIT)*.

Balon, N. and Guo, J. (2006). Increasing broadcast reliability in vehicular ad hoc networks. In *Proc. 3rd international workshop on Vehicular ad hoc networks*, pages 104–105.

Bertsekas, D. P., Gallager, R. G., and Humblet, P. (1992). *Data networks*, volume 2. Prentice-Hall International New Jersey.

Bhalla, K., Shotten, M., Cohen, A., Brauer, M., Shahraz, S., Burnett, R., Leach-Kemon, K., Freedman, G., and Murray, C. (2014). Transport for health: the global burden of disease from motorized road transport.

Bianchi, G. (2000). Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE Journal on Selected Areas in Communications*, 18(3):535–547.

Bianchia, G., Choib, S., and Tinnirello, I. (2007). Performance study of IEEE 802.11 DCF and IEEE 802.11 e EDCA. *University of Roma Tor Vergata, Italy*, pages 63–103.

Bouassida, M. S. and Shawky, M. (2009). A cooperative and fully-distributed congestion control approach within vanets. In *Proc. 9th IEEE International Conference Intelligent Transport Systems Telecommunications (ITST)*, pages 526–531.

Bouk, S. H., Kim, G., Ahmed, S. H., and Kim, D. (2015). Hybrid Adaptive Beaconing in Vehicular Ad Hoc Networks: A Survey. *International Journal Distributed Sensor Networks*, 2015.

Bredel, M. and Fidler, M. (2009). Understanding fairness and its impact on quality of service in ieee 802.11. In *IEEE INFOCOM*, pages 1098–1106.

Chaabouni, N., Hafid, A., and Sahu, P. (2013). A collision-based beacon rate adaptation scheme(cba) for vanets. In *Proc. IEEE International Conference on Advanced Networks and Telecommuncations Systems (ANTS)*, pages 1–6.

Chaqfeh, M., Lakas, A., and Jawhar, I. (2014). A survey on data dissemination in vehicular ad hoc networks. *Vehicular Communications*, 1(4):214–225.

Chen, X., Refai, H., and Ma, X. (2007). A quantitative approach to evaluate DSRC highway inter-vehicle safety communication. In *Proc. IEEE Global Telecommunications Conference (GLOBECOM '07)*, pages 151–155.

Chen, Y., Fang, M., Shi, S., Guo, W., and Zheng, X. (2015). Distributed multi-hop clustering algorithm for vanets based on neighborhood follow. *EURASIP Journal on Wireless Communications and Networking*, 2015(1).

Cooper, D. E., Ezhilchelvan, P., and Mitrani, I. (2004). High coverage broadcasting for mobile ad hoc networks. In *International Conference on Research in Networking*, pages 100–111. Springer.

Dao, N. and Malaney, R. (2008). A new Markov model for non-saturated 802.11 networks. In *Proc. 5th IEEE Consumer Communications and Networking Conference (CCNC)*, pages 420–424.

Daraghmi, Y.-A., Yi, C.-W., and Stojmenovic, I. (2013). Forwarding methods in data dissemination and routing protocols for vehicular Ad Hoc networks. *IEEE Network*, 27(6):74–79.

Darwish, T. and Abu Bakar, K. (2015). Traffic density estimation in vehicular ad hoc networks: A review. *Ad Hoc Networks 2015*, pages 337 – 351.

DIRD (2016). Department of Infrastructure and Regional Development. `https://infrastructure.gov.au/roads/safety/`.

Drigo, M., Zhang, W., Baldessari, R., Le, L., Festag, A., and Zorzi, M. (2009). Distributed Rate Control Algorithm for VANETs (DRCV). In *Proc. the Sixth ACM International Workshop on VehiculAr InterNETworking*, VANET '09, New York, NY, USA.

Fallah, Y., Huang, C.-L., Sengupta, R., and Krishnan, H. (2011). Analysis of information dissemination in vehicular ad-hoc networks with application to cooperative vehicle safety systems. *IEEE Transactions on Vehicular Technology*, 60(1):233–247.

Felemban, E. and Ekici, E. (2011). Single hop IEEE 802.11 DCF analysis revisited: Accurate modeling of channel access delay and throughput for saturated and unsaturated traffic cases. *IEEE Transactions on Wireless Communications*, 10(10):3256–3266.

Fidler, M. (2006). Wlc15-2: A network calculus approach to probabilistic quality of service analysis of fading channels. In *IEEE Globecom 2006*, pages 1–6.

Fracchia, R. and Meo, M. (2008). Analysis and Design of Warning Delivery Service in Intervehicular Networks. *IEEE Transactions on Mobile Computing*, 7(7):832–845.

Frey, B. J. and Dueck, D. (2007). Clustering by passing messages between data points. *science*, 315(5814):972–976.

Füßler, H., Hartenstein, H., Mauve, M., Effelsberg, W., and Widmer, J. (2004). Contention-based forwarding for street scenarios. In *1st International Workshop in Intelligent Transportation (WIT 2004)*.

Garca-Campos, J. M., Snchez-Garca, J., Reina, D. G., Toral, S. L., and Barrero, F. (2015). Evaluation of dissimilarity-based probabilistic broadcasting algorithms in vanets. In *Proc. 2015 International Conference on Developments of E-Systems Engineering (DeSE)*, pages 29–34.

Ghafoor, K. Z., Lloret, J., Bakar, K. A., Sadiq, A. S., and Mussa, S. A. B. (2013). Beaconing Approaches in Vehicular Ad Hoc Networks: A Survey. *Wireless Personal Communications*, 73:885–912.

Ghodrati, A. D. (2013). Reduces broadcast storm using clustering in vanets. *International Research Journal of Applied and Basic Sciences*, 7(13):979–987.

Goyal, P. and Vin, H. M. (1997). Generalized guaranteed rate scheduling algorithms: a framework. *IEEE/ACM Transactions on Networking (TON)*, 5(4):561–571.

Gramaglia, M., Serrano, P., Hernandez, J., Calderon, M., and Bernardos, C. J. (2011). New insights from the analysis of free flow vehicular traffic in highways.

In *Proc. IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pages 1–9.

Gramaglia, M., Trullols-Cruces, O., Naboulsi, D., Fiore, M., and Calderon, M. (2014). Vehicular networks on two madrid highways. In *2014 Eleventh Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, pages 423–431.

Guan, W., He, J., Bai, L., and Tang, Z. (2011). Adaptive rate control of dedicated short range communications based vehicle networks for road safety applications. In *2011 IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pages 1–5.

Hadzi-Velkov, Z. and Spasenovski, B. (2003). Saturation throughput - delay analysis of ieee 802.11 dcf in fading channel. In *Proc. IEEE International Conference on Communications*, volume 1, pages 121–126 vol.1.

Hafeez, K., Zhao, L., Ma, B., and Mark, J. (2013). Performance analysis and enhancement of the DSRC for VANET's safety applications. *IEEE Transactions on Vehicular Technology*, pages 3069–3083.

Haghani, P. and Hu, Y.-C. (2012). Power control for fair dynamic channel reservation in vanets. In *Proc. 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pages 659–667.

Hahner, J., Becker, C., and Rothermel, K. (2003). A protocol for data dissemination in frequently partitioned mobile ad hoc networks. In *Proc. Eighth IEEE International Symposium on Computers and Communication (ISCC 2003)*, pages 633–640.

Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J., and Wang, J. (2014). Vehicle-to-vehicle communications: Readiness of V2V technology for application.

Hartenstein, H. and Laberteaux, K. (2008). A tutorial survey on vehicular ad hoc networks. *IEEE Communications Magazine*, pages 164–171.

Hassan, M. I., Vu, H. L., and Sakurai, T. (2010). Performance analysis of the IEEE 802.11 MAC protocol for DSRC with and without retransmissions. In *Proc. 2010 IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM)*, pages 1–8.

Hassan, M. I., Vu, H. L., and Sakurai, T. (2011). Performance Analysis of the IEEE 802.11 MAC Protocol for DSRC Safety Applications. *IEEE Transactions on Vehicular Technology*, 60(8):3882–3896.

Ho, C., Obraczka, K., Tsudik, G., and Viswanath, K. (1999). Flooding for reliable multicast in multi-hop ad hoc networks. In *Proc. 3rd International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications*, pages 64–71.

Huang, C.-L., Fallah, Y., Sengupta, R., and Krishnan, H. (2010). Adaptive inter-vehicle communication control for cooperative safety systems. *IEEE Network*, 24(1):6–13.

Huang, C.-L., Fallah, Y. P., Sengupta, R., and Krishnan, H. (2009). Information dissemination control for cooperative active safety applications in vehicular ad-hoc networks. In *Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, pages 1–6.

IEEE Standard 1609.0-2013 (2014). IEEE Guide for Wireless Access in Vehicular Environments (WAVE) - Architecture. pages 1–78.

IEEE Standard 1609.1-2006 (2006). IEEE Trial-Use Standard for Wireless Access in Vehicular Environments(WAVE) Resource Manager. pages 1–71.

IEEE Standard 1609.2-2006 (2006). IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE)-Security Services for Applications and Management Messages.

IEEE Standard 1609.3-2007 (2007). IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE)Networking Services. pages 1–99.

IEEE Standard 1609.4-2006 (2006). IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation. pages 1–82.

IEEE Standard 802.11 (2012). Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Standard*.

IEEE Working Group and others (2010). Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications, ASTM Standards.

Javed, M. and Khan, J. (2014). Performance analysis of an adaptive rate-range control algorithm for vanet safety applications. In *Computing, Networking and Communications (ICNC), 2014 International Conference on*, pages 418–423.

Khabazian, M., Aissa, S., and Mehmet-Ali, M. (2011). Performance Modeling of Message Dissemination in Vehicular Ad Hoc Networks with Priority. *IEEE Journal on Selected Areas in Communications*, 29(1):61–71.

Khakbaz, S. and Fathy, M. (2008). A Reliable Method for Disseminating Safety Information in Vehicular Ad Hoc Networks Considering Fragmentation Problem. In *Proc. International Conference on Wireless and Mobile Communications*, pages 25–30.

Kim, H. and Hou, J. C. (2003). Improving Protocol Capacity with Model-based Frame Scheduling in IEEE 802.11-operated WLANs. In *Proc. 9th Annual International Conference on Mobile Computing and Networking*, MobiCom '03, pages 190–204, New York, NY, USA.

Kloiber, B., Härri, J., and Strang, T. (2012). Dice the tx powerimproving awareness quality in vanets by random transmit power selection. In *Proc. IEEE Vehicular Networking Conference (VNC)*, pages 56–63.

Korkmaz, G., Ekici, E., Özgüner, F., and Özgüner, U. (2004). Urban multi-hop broadcast protocol for inter-vehicle communication systems. In *Proc. 1st ACM International Workshop on Vehicular Ad Hoc Networks*, VANET '04, pages 76–85.

Lam, R. K. and Kumar, P. (2010). Dynamic channel reservation to enhance channel access by exploiting structure of vehicular networks. In *Proc. 71st IEEE Vehicular Technology Conference (VTC 2010-Spring)*, pages 1–5.

Le, L., Baldessari, R., Salvador, P., Festag, A., and Zhang, W. (2011). Performance Evaluation of Beacon Congestion Control Algorithms for VANETs. In *Proc. IEEE Global Telecommunications Conference*, pages 1–6.

Lee, W., Wang, C., and Sohraby, K. (2006). On use of traditional M/G/1 model for IEEE 802.11 DCF in unsaturated traffic conditions. In *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, volume 4, pages 1933–1937.

Lim, H. and Kim, C. (2001). Flooding in wireless ad hoc networks. *Computer Communications Journal*, 24(3-4):353–363.

Ling, X., Cai, L., Mark, J. W., and Shen, X. (2007). Performance analysis of IEEE 802.11 DCF with heterogeneous traffic. In *Proc. 4th IEEE Consumer Communications and Networking Conference (CCNC)*, pages 49–53.

Liu, J., Yang, Z., and Stojmenovic, I. (2012). Receiver Consensus: On-time Warning Delivery for Vehicular Ad-hoc Networks. *Proc. 32 nd IEEE International Conference on Distributed Computing Systems (ICDCS)*, pages 386–395.

Luong, H., Nguyen, S., Vu, H., and Vo, B. Q. (2014). One-hop vs. multi-hop broadcast protocol for DSRC safety applications. In *Proc. 15th IEEE International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pages 1–3.

Luong, H., Panda, M., Vu, H., and Vo, B. (2016). Analysis of multi-hop probabilistic forwarding for vehicular safety applications on highways. *IEEE Transactions on Mobile Computing*.

Lv, H., Ye, X., An, L., and Wang, Y. (2012). Distributed beacon frequency control algorithm for vanets (dbfc). In *Proc. 2012 Second International Conference on In-*

telligent System Design and Engineering Application, pages 243–246, Washington, DC, USA. IEEE Computer Society.

Ma, X. and Chen, X. (2007). Saturation performance of IEEE 802.11 broadcast networks. *IEEE Communications Letters*, (8):686–688.

Ma, X., Zhang, J., Yin, X., and Trivedi, K. (2012). Design and analysis of a robust broadcast scheme for VANET safety-related services. *IEEE Transactions on Vehicular Technology*, 61(1):46–61.

Malone, D., Duffy, K., and Leith, D. (2007). Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions. *IEEE/ACM Transactions on Networking*.

NHTSA (2013). The National Highway Traffic Safety Administration. `http://www.nhtsa.gov/NCSA`.

Ni, S.-Y., Tseng, Y.-C., Chen, Y.-S., and Sheu, J.-P. (1999). The Broadcast Storm Problem in a Mobile Ad Hoc Network. In *Proc. 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, pages 151–162.

Osafune, T., Lin, L., and Lenardi, M. (2006). Multi-hop vehicular broadcast (MHVB). In *Proc. 6th International Conference on ITS Telecommunications*, pages 757–760.

Ota, K., Dong, M., Chang, S., and Zhu, H. (2015). MMCD: Cooperative Downloading for Highway VANETs. *IEEE Transactions on Emerging Topics in Computing*, pages 34–43.

Panichpapiboon, S. and Ferrari, G. (2008). Irresponsible forwarding. *In Proc. 8th IEEE International Conference on ITS Telecommunications*, pages 311–316.

Panichpapiboon, S. and Pattara-atikom, W. (2008). Evaluation of a neighbor-based vehicle density estimation scheme. In *Proc. International Conference on ITS Telecommunications*, pages 294–298.

Panichpapiboon, S. and Pattara-Atikom, W. (2012). A review of information dissemination protocols for vehicular ad hoc networks. *IEEE Communications Surveys & Tutorials*, 14(3):784–798.

Puthal, D., Mir, Z., Filali, F., and Menouar, H. (2013). Cross-layer architecture for congestion control in vehicular ad-hoc networks. In *Connected Vehicles and Expo (ICCVE), 2013 International Conference on*, pages 887–892.

Qian, J., Jing, T., Huo, Y., Li, H., Ma, L., and Lu, Y. (2016). An Adaptive Beaconing Scheme Based on Traffic Environment Parameters Prediction in VANETs. In *International Conference on Wireless Algorithms, Systems, and Applications*, pages 524–535. Springer.

Rao, A., Kherani, A., and Mahanti, A. (2008). Performance evaluation of 802.11 broadcasts for a single cell network with unsaturated nodes. In *Proc. Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet (NETWORKING)*, pages 836–847.

Rawat, D. B., Popescu, D. C., Yan, G., and Olariu, S. (2011). Enhancing vanet performance by joint adaptation of transmission power and contention window size. *IEEE Transactions on Parallel and Distributed Systems*, 22(9):1528–1535.

Reina, D., Toral, S., Johnson, P., and Barrero, F. (2015). A survey on probabilistic broadcast schemes for wireless ad hoc networks. *Ad Hoc Networks*, 25(PA):263–292.

Reumerman, H.-J., Roggero, M., and Ruffini, M. (2005). The application-based clustering concept and requirements for intervehicle networks. *IEEE Communications Magazine*, 43(4):108–113.

Sakurai, T. and Vu, H. (2007). MAC Access Delay of IEEE 802.11 DCF. *IEEE Transactions on Wireless Communications*, 6(5):1702–1710.

Schmidt, R., Leinmuller, T., Schoch, E., Kargl, F., and Schafer, G. (2010). Exploration of adaptive beaconing for efficient intervehicle safety communication. *IEEE Network,*, 24(1):14–19.

Schwartz, R. S., Barbosa, R. R., Meratnia, N., Heijenk, G., and Scholten, H. (2010). A simple and robust dissemination protocol for vanets. In *Proc. 2010 European Wireless Conference (EW)*, pages 214–222.

Sepulcre, M., Mittag, J., Santi, P., Hartenstein, H., and Gozalvez, J. (2011). Congestion and awareness control in cooperative vehicular systems. *Proceedings of the IEEE*, 99(7):1260–1279.

Shea, C., Hassanabadi, B., and Valaee, S. (2009). Mobility-based clustering in vanets using affinity propagation. In *Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, pages 1–6.

Slavik, M. and Mahgoub, I. (2010). Stochastic Broadcast for VANET. In *Proc. 7th IEEE Consumer Communications and Networking Conference (CCNC)*, pages 1–5.

Stanica, R., Chaput, E., and Beylot, A.-L. (2011). Broadcast communication in vehicular ad-hoc network safety applications. In *Proc. 2011 IEEE Consumer Communications and Networking Conference (CCNC)*, pages 462–466.

Stojmenovic, I., Khan, A. A., and Zaguia, N. (2012). Broadcasting with seamless transition from static to highly mobile wireless ad hoc, sensor and vehicular networks. *International Journal of Parallel, Emergent and Distributed Systems*, 27(3):225–234.

Stojmenovic, I., Seddigh, M., and Zunic, J. (2002). Dominating Sets and Neighbor Elimination-Based Broadcasting Algorithms in Wireless Networks. *IEEE Transactions on Parallel and Distributed Systems*, 13(1):14–25.

Sun, M.-T., Feng, W.-c., Lai, T.-H., Yamada, K., Okada, H., and Fujimura, K. (2000). GPS-based message broadcast for adaptive inter-vehicle communications. In *Proc. 52nd IEEE Vehicular Technology Conference (VTC)*, volume 6, pages 2685–2692 vol.6.

Sun, W., Zhang, H., Pan, C., and Yang, J. (2013). Analytical study of the IEEE

802.11p EDCA mechanism. In *Proc. IEEE Intelligent Vehicles Symposium (IV)*, pages 1428–1433.

Taherkhani, N. and Pierre, S. (2015). Improving dynamic and distributed congestion control in vehicular ad hoc networks. *Ad Hoc Networks*, 33:112–125.

Tahmasbi-Sarvestani, A., Fallah, Y., and Kulathumani, V. (2015). Network-Aware Double-Layer Distance-Dependent Broadcast Protocol for VANETs. *IEEE Transactions on Vehicular Technology*.

Taieb-Maimon, M. and Shinar, D. (2001). Minimum and Comfortable Driving Headways: Reality versus Perception. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 43(1):159–172.

Tay, Y. C. and Chua, K. C. (2001). A Capacity Analysis for the IEEE 802.11 MAC Protocol. *Wireless Networks*, 7(2):159–171.

Tickoo, O. and Sikdar, B. (2004). A queueing model for finite load IEEE 802.11 random access MAC. In *Proc. IEEE International Conference on Communications*, volume 1, pages 175–179.

Tickoo, O. and Sikdar, B. (2008). Modeling queueing and channel access delay in unsaturated IEEE 802.11 random access MAC based wireless networks. *IEEE/ACM Transactions on Networking (TON)*, 16(4):878–891.

Torrent-Moreno, M., Mittag, J., Santi, P., and Hartenstein, H. (2009). Vehicle-to-Vehicle Communication: Fair Transmit Power Control for Safety-Critical Information. *IEEE Transactions on Vehicular Technology*, 58(7):3684–3703.

Torrent-Moreno, M., Santi, P., and Hartenstein, H. (2005). Fair sharing of bandwidth in vanets. In *Proc. 2nd ACM international workshop on Vehicular ad hoc networks*, pages 49–58.

Tseng, Y. T., Jan, R. H., Chen, C., Wang, C. F., and Li, H. H. (2010). A vehicle-density-based forwarding scheme for emergency message broadcasts in vanets. In *Proc. 7th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS 2010)*, pages 703–708.

Tsertou, A. and Laurenson, D. I. (2008). Revisiting the hidden terminal problem in a CSMA/CA wireless network. *IEEE Transactions on Mobile Computing*, 7(7):817–831.

Vegni, A., Stramacci, A., and Natalizio, E. (2012). Srb: A selective reliable broadcast protocol for safety applications in vanets. In *Proc. 2012 International Conference on Selected Topics in Mobile and Wireless Networking (iCOST)*, pages 89–94.

Vehicle Safety Communications Consortium (2005). Vehicle safety communications project: Task 3 final report: Identify intelligent vehicle safety applications enabled by DSRC. *National Highway Traffic Safety Administration, US Department of Transportation, Washington DC.*

Vinel, A., Vishnevsky, V., and Koucheryavy, Y. (2008). A simple analytical model for the periodic broadcasting in vehicular ad-hoc networks. In *Proc. IEEE GLOBECOM Workshops*, pages 1–5.

Viswanath, K. and Obraczka, K. (2002). An adaptive approach to group communications in multi hop ad hoc networks. In *Proc. Seventh International Symposium on Computers and Communications (ISCC)*, pages 559–566.

Vogel, K. (2003). A comparison of headway and time to collision as safety indicators. *Accident analysis and prevention*, 35(3):427–433.

Wiethölter, S. and Hoene, C. (2011). An IEEE 802.11e EDCF and CFB Simulation Model for ns-2. *Available at <http://www. tkn. tuberlin. de/research/802.11e_ns2>.*

Wisitpongphan, N., Tonguz, O., Parikh, J., Mudalige, P., Bai, F., and Sadekar, V. (2007). Broadcast storm mitigation techniques in vehicular ad hoc networks. *IEEE Wireless Communications*, pages 84–94.

Wu, J. and Li, H. (2001). A Dominating-Set-Based Routing Scheme in Ad Hoc Wireless Networks. *Telecommunication Systems*, 18(1-3):13–36.

Xiao, Y. (2003). Saturation performance metrics of the ieee 802.11 mac. In *Proc. IEEE 58th Vehicular Technology Conference (VTC)*, volume 3, pages 1453–1457.

Xie, J. and Jiang, Y. (2009). Stochastic service guarantee analysis based on time-domain models. In *Proc. 17th IEEE International Symposium on Modeling, Analysis & Simulation of Computer and Telecommunication Systems*, pages 1–12.

Xie, J. and Jiang, Y. (2010). A network calculus approach to delay evaluation of IEEE 802.11 DCF. In *Proc. IEEE 35th Conference on Local Computer Networks (LCN)*, pages 560–567.

Yao, Y., Rao, L., and Liu, X. (2013). Performance and reliability analysis of IEEE 802.11p safety communication in a highway environment. *IEEE Transactions on Vehicular Technology*, pages 4198–4212.

Yin, X., Ma, X., and Trivedi, K. (2013). An interacting stochastic models approach for the performance evaluation of DSRC vehicular safety communication. *IEEE Transactions on Computers*, (5):873–885.

Yousefi, S., Mousavi, M. S., and Fathy, M. (2006). Vehicular ad hoc networks (VANETs): Challenges and perspectives. In *Proc. 6th IEEE International Conference on ITS Telecommunications*, pages 761–766.

Yu, J. Y. and Chong, P. H. J. (2005). A survey of clustering schemes for mobile ad hoc networks. *IEEE Communications Surveys & Tutorials*, 7(1):32–48.

Yuan, Z. (1997). Vehicular safety distance alarm system. US Patent 5,627,510.

Zhai, H., Kwon, Y., and Fang, Y. (2004). Performance analysis of ieee 802.11 mac protocols in wireless lans. *Wireless communications and mobile computing*, 4(8):917–931.

Zhang, Z., Boukerche, A., and Pazzi, R. (2011). A novel multi-hop clustering scheme for vehicular ad-hoc networks. In *Proc. 9th ACM international symposium on Mobility management and wireless access*, pages 19–26.

Zhong, T., Xu, B., and Wolfson, O. (2008). Disseminating real-time traffic information in vehicular ad-hoc networks. In *Proc. IEEE Intelligent Vehicles Symposium*, pages 1056–1061.

A

Obtaining specific schemes from the generic probabilistic forwarding function

In this section, we explain how the probabilistic forwarding functions in Wisitpongphan et al. (2007),Panichpapiboon and Ferrari (2008), Slavik and Mahgoub (2010), Fracchia and Meo (2008) (listed in Table 3.1) can be obtained from the proposed generic forwarding function (Eqns. 3.4.1 and 3.4.2). The proposed generic forwarding function is as follows:

$$p_b(x) = c_1 g(x, \beta, R, c_2) = c_1 e^{-\frac{h(x,\beta,R)}{c_2}}.$$

In Panichpapiboon and Ferrari (2008) the forwarding probability function is given by

$$p(x) = e^{-\frac{\beta(R-x)}{c_2}}.$$

Setting $c_1 = 1$, and $h(x, \beta, R) = \beta(R - x)$, we obtain $p_b(x)$ as

$$p_b(x) = c_1 e^{-\frac{h(x,\beta,R)}{c_2}} = e^{-\frac{\beta(R-x)}{c_2}},$$

where $1 \leq c_2 < \infty$. This is the forwarding probability used in Panichpapiboon and Ferrari (2008).

In Wisitpongphan et al. (2007), Slavik and Mahgoub (2010) the forwarding probability function is given by

$$p(x) = \frac{x}{R}.$$

Setting $c_1 = 1$, $c_2 = 1$, and $h(x, \beta, R) = ln(\frac{R}{x})$, we obtain $p_b(x)$ as

$$\begin{aligned} p_b(x) &= c_1 e^{-\frac{h(x,\beta,R)}{c_2}} = e^{-ln(\frac{R}{x})} \\ &= \frac{x}{R}, \end{aligned}$$

which is the forwarding probability in Wisitpongphan et al. (2007) and Slavik and Mahgoub (2010).

In Slavik and Mahgoub (2010), Fracchia and Meo (2008) the forwarding probability function is given by

$$p(x) = c_1 = const.$$

Setting $c_2 \to \infty$, we have $e^{-\frac{h(x,\beta,R)}{c_2}} \to 1$, and we obtain

$$p_b(x) \to c_1,$$

with $0 \leq c_1 \leq 1$. This is the forwarding probability in Slavik and Mahgoub (2010) and Fracchia and Meo (2008).

We propose a new scheme, called the Power Law scheme, whose forwarding probability function is given by

$$p(x) = \left(\frac{x}{R}\right)^{\alpha},$$

which can be obtained from the generic forwarding function by setting $c_1 = 1$, $c_2 = \alpha$, and $h(x, \beta, R) = \ln(\frac{R}{x})$ such that $p_b(x)$ becomes

$$\begin{aligned} p_b(x) &= c_1 e^{-\frac{h(x,\beta,R)}{c_2}} = e^{-\frac{ln(\frac{R}{x})}{\alpha}} = \left[e^{ln(\frac{x}{R})}\right]^{\alpha} \\ &= \left[\frac{x}{R}\right]^{\alpha}, \end{aligned}$$

with $1 \leq \alpha < \infty$.

B

Hidden collision analysis with retransmission region

As pointed out in Section 3.5.4.2, when the forwarder at f in round 2 is in region R2 or R3, the hidden nodes may also have the safety message in their queues. In this appendix, we analyse the case for region R2, i.e., when $f \in (x, R]$.

When the forwarder in round 2 lies in region R2, as shown in Fig. 3.4, the hidden nodes lie in the interval $[-(R-x), -(R-f)]$. Let $p_{2,R2}(x, f)$ denote the unconditional probability that a hidden node forwards the message. We obtain $p_{2,R2}(x, f)$ by

$$p_{2,R2}(x, f) = \frac{1}{f - x} \int_{(R-x)}^{(R-f)} [s_1(h')p_b(h')] \, dh'. \tag{B.0.1}$$

Since the hidden nodes may re-transmit the message or transmit a beacon that may collide with the transmission of the forwarder at f, the forwarder's transmission is received at the receiver located at x without hidden collisions if it does not collide with the message re-transmissions nor with the beacon transmissions of the hidden nodes.

Let $N_{hidden,R2}(x,f)$ denote the number of hidden nodes when the forwarder in round 2 is in region R2. It is easy to see that

$$N_{hidden,R2}(x,f) = \beta(f-x). \tag{B.0.2}$$

As before, we approximate the aggregate beacon transmission process by the hidden nodes as a homogeneous Poisson process of rate $\lambda N_{hidden,R2}(x,f)$. Let $p(H^b_{bc,R2}, H^a_{bc,R2})(x,f)$ denote the probability that the receiver at x receives the message from the forwarder at f without collisions due to beacon (bc) transmissions by the hidden nodes. Then, $p(H^b_{bc,R2}, H^a_{bc,R2})(x,f)$ is computed by

$$p(H^b_{bc,R2}, H^a_{bc,R2})(x,f) = p(H^b_{bc,R2})(x,f)p(H^a_{bc,R2})(x,f), \tag{B.0.3}$$

where, as before, we have

$$\begin{aligned} p(H^b_{bc,R2})(x,f) &= \exp(-N_{hidden,R2}(x,f)\lambda T) \\ &= \exp(-\beta(f-x)\lambda T), \end{aligned} \tag{B.0.4}$$

and

$$\begin{aligned} p(H^a_{bc,R2})(x,f) &= \exp(-N_{hidden,R2}(x,f)\lambda t_{data}) \\ &= \exp(-\beta(f-x)\lambda t_{data}). \end{aligned} \tag{B.0.5}$$

Let $p(H^b_{2,R2}, H^a_{2,R2})(x,f)$ denote the probability that the receiver at x receives the message from the forwarder at f without hidden node collisions (i.e., no hidden node collision with message re-transmissions or beacon transmissions). We compute $p(H^b_{2,R2}, H^a_{2,R2})(x,f)$ by

$$P(H^b_{2,R2}, H^a_{2,R2})(x,f) = [1-p_{2,R2}(x,f)]^{N_{hidden,R2}(x,f)}\, p(H^b_{bc,R2}, H^a_{bc,R2})(x,f). \tag{B.0.6}$$

C

PDR after the third round

In this appendix, PDR after the third round is analysed. First, an *effective* conditional forwarding probability is discussed. Consider a potential forwarder at point f (see Fig. C.1) in round 3 which successfully received the message for the first time in round 2. Let f' denote the location of the forwarder in round 2 from which the forwarder in round 3 located at f received the message for the first time. The location f' is a random variable over the support set $[-(R-f), R]$, and its actual distribution is intractable. We approximate the distribution of f' as a uniform random variable over $[-(R-f), R]$. Then, the effective conditional forwarding probability of the

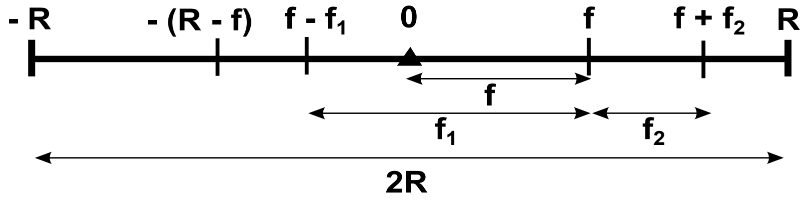


Figure C.1: Possible locations of forwarders for a node at point f in the second round is the interval $[-(R-f), R]$.

forwarder in round 3 located at f is obtained by

$$\begin{aligned} p_b^*(f) &= \frac{1}{2R-f}\int_{-(R-f)}^{R} p_b(|f-f'|)df' \\ &= \frac{1}{2R-f}\left[\int_{-(R-f)}^{f} p_b(f-f')df' + \int_{f}^{R} p_b(f'-f)df'\right] \\ &= \frac{1}{2R-f}\left[\int_{0}^{R} p_b(f_1)df_1 + \int_{0}^{R-f} p_b(f_2)df_2\right], \end{aligned} \quad \text{(C.0.1)}$$

where we have the transformation of variables as $f_1 = f - f'$ and $f_2 = f' - f$ (see Fig. C.1). Note that this effective conditional forwarding probability of the forwarder in round 3 and that of subsequent rounds are the same. As the location of the forwarder in the previous round (e.g. f') can be anywhere in the transmission round of the potential forwarder f.

Next, we calculate the average number of forwarders in the third transmission round. Note that the potential forwarders in the third transmission round are precisely the nodes that receive the message for the first time in the second round, i.e., they must not have received the message in the first round. The probability that a node at f receives the message in the second transmission round and has not received the message in the first transmission round is given by $[1 - s_1(f)]\, s_2(f)$. The unconditional forwarding probability for a node at f in the third transmission round is then given by $[1 - s_1(f)]\, s_2(f)p_{b,2}(f)$. Then, as in round 2, the average number of forwarders in the third transmission round, denoted by $N_{forwarder,3}$, is obtained by

$$N_{forwarder,3} = (\beta 2R - 1)\left[\frac{1}{R}\int_0^R [1 - s_1(f)]\, s_2(f)p_b^*(f)df\right]. \quad \text{(C.0.2)}$$

The average number of forwarders for a particular receiver at x in the third transmission round, denoted by $N_{forwarder,3}(x)$, and the probability that a receiver at x receives the message from an arbitrary forwarder in the third transmission round, denoted by $s_{3,1F}(x)$, can be obtained by following the same approach as that for $N_{forwarder,2}(x)$ and $s_{2,1F}(x)$, respectively. Then, the probability that a receiver at x successfully receives the message in the third transmission round from at least one of the forwarders, denoted by $s_3(x)$, can be computed by

$$s_3(x) = 1 - [1 - s_{3,1F}(x)]^{N_{forwarder,3}(x)}. \tag{C.0.3}$$

The probability that an arbitrary node in the range of the source receives the message only in the third transmission round, denoted by s_3, is obtained by

$$PDR_3 = s_3 = \frac{1}{R}\int_0^R s_3(x)dx. \tag{C.0.4}$$

The probability that a receiver at x successfully receives the message in the first or the second or the third transmission round, denoted by $s_{123}(x)$, is obtained by

$$s_{123}(x) = 1 - [1 - s_{12}(x)]\,[1 - s_3(x)]. \tag{C.0.5}$$

The probability that an arbitrary node in the range of the source receives the message after the third transmission round (i.e., in the first or second or third round), denoted as s_{123}, is computed by

$$s_{123} = \frac{1}{R}\int_0^R s_{123}(x)dx. \tag{C.0.6}$$

The Packet Delivery Ratio after the third transmission round, denoted by PDR_{123} is

$$PDR_{123} = s_{123}. \tag{C.0.7}$$

D

The average number of forwarders after the third round

In this appendix, we obtain the average number of forwarders after the third round. We use the same approach to obtain the average number of forwarders in the third round, described in the Appendix C.

The forwarders in round i ($i > 3$) is precisely the nodes that receive the message in the round $(i-1)$ for the first time, that means, they must not receive the message in rounds $1, 2, ..., (i-2)$. The probability that a node at f receives the message in round $(i-1)$ and has not received the message in rounds $1, 2, ..., (i-2)$, is given by

$$[1 - s_1(f)]\,[1 - s_2(f)]\,...\,\left[1 - s_{(i-2)}(f)\right]\,s_{(i-1)}(f).$$

The unconditional forwarding probability for a node at f in round i is then given by

$$[1 - s_1(f)]\,[1 - s_2(f)]\,...\,\left[1 - s_{(i-2)}(f)\right]\,s_{(i-1)}(f)p_b^*(f),$$

where $p_b^*(f)$ is the *effective* conditional forwarding probability, obtained in the Appendix C (Eqn. (C.0.1)).

Then, the average number of forwarders in the round i, denoted by $N_{forwarder,i}$, is obtained by

$$N_{forwarder,i} = (\beta 2R - 1)\left[\frac{1}{R}\int_0^R \left[1 - s_1(f)\right]\left[1 - s_2(f)\right] ... \left[1 - s_{(i-2)}(f)\right] s_{(i-1)}(f) p_b^*(f) df\right]. \quad \text{(D.0.1)}$$

E

Solving the optimization problem

In this section, we solve the optimization problem in (4.3.11) by solving the KKT conditions (4.3.13). Specifically, the optimization problem is divided into two cases: with and without considering direct collisions.

A. Analysis without Direct Collisions

Without direct collisions, the probability that a node at x receives successfully a message, obtained from Eqn. (3.5.18), is

$$\begin{aligned} s_1(\lambda, x) &= p(H_1^b, H_1^a)(\lambda, x) \\ &= \exp\left[-\beta(T + t_{data})\lambda x\right]. \end{aligned} \tag{E.0.1}$$

The probability that an arbitrary vehicle receives a message, obtained from

Eqn. (3.5.19), is

$$\begin{aligned} s_1(\lambda) &= \frac{1}{R}\int_0^R s_1(\lambda,x)dx = \frac{1}{R}\int_0^R p(H_1^b,H_1^a)(\lambda,x)dx \\ &= \frac{\exp\left[-\beta(T+t_{data})\lambda R\right]-1}{-\beta(T+t_{data})\lambda R} \\ &= \frac{e^{n\lambda}-1}{n\lambda}, \end{aligned} \tag{E.0.2}$$

where $n = -\beta(T+t_{data})R$.

Next, $\frac{d}{d\lambda}s_1(\lambda)$ and $\frac{d}{d\lambda}\left[1-s_1(\lambda)\right]^{\lambda L}$ in (4.3.13) are obtained as follows

$$\begin{aligned} \frac{d}{d\lambda}s_1(\lambda) &= \frac{d}{d\lambda}\left(\frac{e^{n\lambda}-1}{n\lambda}\right) = \frac{1}{n}\frac{d}{d\lambda}\left(\frac{e^{n\lambda}}{\lambda}-\frac{1}{\lambda}\right) \\ &= \frac{1}{n}\left[\frac{e^{n\lambda}(n\lambda-1)}{\lambda^2}+\frac{1}{\lambda^2}\right], \end{aligned} \tag{E.0.3}$$

and

$$\frac{d}{d\lambda}\left[1-s_1(\lambda)\right]^{\lambda L} = \left[1-s_1(\lambda)\right]^{\lambda L-1}\left\{\lambda L\left(-\frac{d}{d\lambda}s_1(\lambda)\right)+L\left[1-s_1(\lambda)\right]log\left[1-s_1(\lambda)\right]\right\}. \tag{E.0.4}$$

B. Analysis with Direct Collisions

In this section, we compute the probability that a node at x successfully receives a message with direct collisions. Let recall that $D_1(\lambda,x)$ is the probability of direct collisions for a node at x (see Eqn. (3.5.3)). $D_1(\lambda,x)$ is given by

$$D_1(\lambda,x) = 1-\left[1-\tau p_1(\lambda)\right]^{N_{direct,1}(x)}. \tag{E.0.5}$$

The probability that a node at x successfully receives a message with direct collisions is

$$\begin{aligned} s_1(\lambda,x) &= \left[1-D_1(\lambda,x)\right]p(H_1^b,H_1^a)(\lambda,x) \\ &= \left[1-\tau p_1(\lambda)\right]^{N_{direct,1}(x)}\exp\left[-\beta(T+t_{data})\lambda x\right] \\ &= \left[g(\lambda)\right]^{N_{direct,1}(x)}\exp\left[xh(\lambda)\right], \end{aligned} \tag{E.0.6}$$

where

$$g(\lambda) = 1-\tau p_1(\lambda), \tag{E.0.7}$$

$$h(\lambda) = -\beta(T+t_{data})\lambda, \tag{E.0.8}$$

$$N_{direct,1}(x) = \beta(2R-x)-1. \tag{E.0.9}$$

The probability that a vehicle has a message in its queue at an arbitrary time is given by

$$\begin{aligned} p_1(\lambda) &= \lambda E[S_1](\lambda) = \lambda \{E[T] + E[B_1](\lambda)\} \\ &= \lambda \left\{T + \overline{W}\left[l + E[Y_1](\lambda)\right]\right\} \\ &= \lambda \left\{T + \overline{W}\left[l + T\left[1 - \exp(-\lambda l N_{total})\right]\right]\right\} \\ &= C\lambda - D\lambda \exp(-\lambda l N_{total}), \end{aligned} \tag{E.0.10}$$

where

$$C = T + \overline{W}l + \overline{W}T, \tag{E.0.11}$$

and

$$D = \overline{W}T. \tag{E.0.12}$$

Therefore the probability that an arbitrary vehicle receives a message considering direct collisions is as follows

$$\begin{aligned} s_1(\lambda) &= \frac{1}{R}\int_0^R s_1(\lambda, x)dx \\ &= \frac{1}{R}\int_0^R \left\{[g(\lambda)]^{N_{direct,1}(x)} \exp\left[xh(\lambda)\right]\right\} dx \\ &= \frac{1}{R}\left[g(\lambda)\right]^{\beta 2R-1} \int_0^R \left\{\frac{\exp\left[xh(\lambda)\right]}{\left[g(\lambda)\right]^{\beta x}}\right\} dx \\ &= \frac{1}{R}\left[g(\lambda)\right]^{\beta 2R-1} \frac{[g(\lambda)]^{-\beta R}\exp[Rh(\lambda)] - 1}{h(\lambda) - \beta log\left[g(\lambda)\right]} \\ &= \frac{1}{R}\frac{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)] - [g(\lambda)]^{\beta 2R-1}}{h(\lambda) - \beta log\left[g(\lambda)\right]}. \end{aligned} \tag{E.0.13}$$

Next, we compute $\frac{d}{d\lambda}s_1(\lambda)$ as follows:

$$\begin{aligned} \frac{d}{d\lambda}s_1(\lambda) &= \frac{d}{d\lambda}\left\{\frac{1}{R}\frac{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)] - [g(\lambda)]^{\beta 2R-1}}{h(\lambda) - \beta log\left[g(\lambda)\right]}\right\} \\ &= \frac{1}{R}\left\{\frac{d}{d\lambda}\left[\frac{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)]}{h(\lambda) - \beta log\left[g(\lambda)\right]}\right] - \frac{d}{d\lambda}\left[\frac{[g(\lambda)]^{\beta 2R-1}}{h(\lambda) - \beta log\left[g(\lambda)\right]}\right]\right\}. \end{aligned} \tag{E.0.14}$$

We obtain $\frac{d}{d\lambda}\left[\frac{[g(\lambda)]^{\beta 2R-1}}{h(\lambda)-\beta log[g(\lambda)]}\right]$, and $\frac{d}{d\lambda}\left[\frac{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)]}{h(\lambda)-\beta log[g(\lambda)]}\right]$ as follows

$$\begin{aligned} &\frac{d}{d\lambda}\left[\frac{[g(\lambda)]^{\beta 2R-1}}{h(\lambda) - \beta log\left[g(\lambda)\right]}\right] \\ &= \frac{\{h(\lambda) - \beta log[g(\lambda)]\}\frac{d}{d\lambda}\left[g(\lambda)^{\beta 2R-1}\right]}{h(\lambda) - \beta log\left[g(\lambda)\right]} - \frac{[g(\lambda)]^{\beta 2R-1}\frac{d}{d\lambda}\{h(\lambda) - \beta log\left[g(\lambda)\right]\}}{h(\lambda) - \beta log\left[g(\lambda)\right]}, \end{aligned} \tag{E.0.15}$$

where

$$\frac{d}{d\lambda}\left\{h(\lambda)-\beta log\left[g(\lambda)\right]\right\} = \frac{d}{d\lambda}h(\lambda) - \beta\frac{d}{d\lambda}log[g(\lambda)] \\ = -\beta(T+t_{data}) - \frac{\beta}{g(\lambda)}\frac{d}{d\lambda}g(\lambda), \tag{E.0.16}$$

and

$$\frac{d}{d\lambda}\left[g(\lambda)^{\beta 2R-1}\right] = (\beta 2R-1)\left[g(\lambda)\right]^{\beta 2R-2}\frac{d}{d\lambda}g(\lambda). \tag{E.0.17}$$

Next, $\frac{d}{d\lambda}g(\lambda)$ is obtained as follows

$$\frac{d}{d\lambda}g(\lambda) = \frac{d}{d\lambda}\left[1-\tau p_1(\lambda)\right] = -\tau\frac{d}{d\lambda}p_1(\lambda). \tag{E.0.18}$$

From (E.0.10), $\frac{d}{d\lambda}p_1(\lambda)$ is obtained by

$$\frac{d}{d\lambda}p_1(\lambda) = \frac{d}{d\lambda}\left[C\lambda - D\lambda\exp(-\lambda l N_{total})\right] \\ = C - D\frac{d}{d\lambda}\left[\lambda\exp(-\lambda l N_{total})\right] \\ = C - D\left\{\exp(-\lambda l N_{total}) - \lambda l N_{total}\exp(-\lambda l N_{total})\right\}. \tag{E.0.19}$$

We now obtain $\frac{d}{d\lambda}\left[\frac{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)]}{h(\lambda)-\beta log[g(\lambda)]}\right]$

$$\frac{d}{d\lambda}\left[\frac{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)]}{h(\lambda)-\beta log\left[g(\lambda)\right]}\right] \\ = \frac{\left\{h(\lambda)-\beta log\left[g(\lambda)\right]\right\}\frac{d}{d\lambda}\left\{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)]\right\}}{h(\lambda)-\beta log\left[g(\lambda)\right]} \\ - \frac{\left\{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)]\right\}\frac{d}{d\lambda}\left\{h(\lambda)-\beta log\left[g(\lambda)\right]\right\}}{h(\lambda)-\beta log\left[g(\lambda)\right]}, \tag{E.0.20}$$

where $\frac{d}{d\lambda}\left\{h(\lambda)-\beta log\left[g(\lambda)\right]\right\}$ is analysed from (E.0.16).

We have

$$\frac{d}{d\lambda}\left\{[g(\lambda)]^{\beta R-1}\exp[Rh(\lambda)]\right\} \\ = [g(\lambda)]^{\beta R-1}R\exp[Rh(\lambda)]\frac{d}{d\lambda}h(\lambda) + \exp[Rh(\lambda)](\beta R-1)[g(\lambda)]^{\beta R-2}\frac{d}{d\lambda}g(\lambda), \tag{E.0.21}$$

and

$$\frac{d}{d\lambda}\left[1-s_1(\lambda)\right]^{\lambda L} \\ = \left[1-s_1(\lambda)\right]^{\lambda L-1}\left\{\lambda L\frac{d}{d\lambda}\left[1-s_1(\lambda)\right] + \left[1-s_1(\lambda)\right]log[1-s_1(\lambda)]\frac{d}{d\lambda}(\lambda L)\right\} \\ = \left[1-s_1(\lambda)\right]^{\lambda L-1}\left\{-\lambda L\frac{d}{d\lambda}\left[s_1(\lambda)\right] + L\left[1-s_1(\lambda)\right]log[1-s_1(\lambda)]\right\}, \tag{E.0.22}$$

where $\frac{d}{d\lambda}s_1(\lambda)$ is obtained from (E.0.14).