Reliable Data Transmission in Challenging Vehicular Network using Delay Tolerant Network

SIHAM ABDELHADI HASAN

This thesis is submitted in partial fulfilment of the requirements of

De Montfort University for the award of

Doctor of Philosophy

Supervised by

Dr Ali Al-Bayatti & Dr Sarmadullah Khan

Faculty of Technology, School of Computer Science, and Informatics

De Montfort University

Leicester, UK

December, 2022

Abstract

In the 21st century, there has been an increasing tendency toward the wide adoption of wireless networks and technologies due to their significant advantages such as flexibility, mobility, accessibility, and low cost. Wireless technologies have therefore become essential factors in the improvement of intra-vehicle road safety in Vehicular Ad-hoc Network (VANET), which potentially reduce road traffic accidents by enabling efficient exchange of information between vehicles in the early stages. However, due to the inherent high mobility and rapid change of topology, there are numerous challenges in VANET. Hence, different software packages have been combined in this project to create the VANET environment, whereby the Objective Modular Network Testbed (OMNeT++) and the Simulation of Urban Mobility (SUMO), along with Vehicles in Network Simulation (VEINS) are integrated to model the VANET environment.

Also, Delay Tolerant Network (DTN) are implemented in the Opportunistic Network Environment (ONE) simulator, where the Store-Carry-Forward technique is used to route traffic. When network resources are not limited, a high delivery ratio is possible. However, when network resources are scarce, these protocols will have a low delivery ratio and high overhead. Due to these limitations, in this research, an extensive performance evaluation of various routing protocols for DTN with different buffer management policies, giving insight into the impact of these policies on DTN routing protocol performance has been conducted. The empirical study gave insight into the strengths and limitations of the existing protocols thus enabling the selection of the benchmark protocols utilized in evaluating a new Enhanced Message Replication Technique (EMRT) proposed in this thesis.

The main contribution of this thesis is the design, implementation, and evaluation of a novel EMRT that dynamically adjusts the number of message replicas based on a node's ability to quickly disseminate the message and maximize the delivery ratio. EMRT is evaluated using three different quota protocols: Spray&Wait, Encounter Based Routing (EBR), and Destination Based Routing Protocol (DBRP). Simulation results show that applying EMRT to these protocols improves the delivery ratio while reducing overhead ratio and latency average. For example, when combined with Spray&Wait, EBR, and DBRP, the delivery probability is improved by 13%, 8%, and 10%, respectively, while the latency average is reduced by 51%, 14%, and 13%, respectively.

COVID-19 Impact Statement

The lockdown in 2020–2021 due to COVID-19 prevented the continuation of the work in this research. Furthermore, maternity interrupted my work on two occasions, while during the pregnancy period, I suffered from gestational diabetes, which caused considerable stress and challenges since it required time to monitor and control my glucose blood levels. In addition, due to the restrictions and measures of governments and the management of De Montfort University to protect people from infection, an inevitable delay in this work occurred. Nevertheless, despite these obstacles, I have successfully managed to complete the work and the writing-up of this thesis within the submission requirements of De Montfort University.

Dedication

I dedicate this work to my mother, my brothers, my sisters, my husband, and my children, as well as to the soul of my beloved father. May Allah rest his soul in peace and heaven.

Acknowledgements

I wish to thank God (Allah), the most merciful and the most gracious, who provided me with the patience, strength, and support to complete this scientific research.

I offer my sincerest and deepest gratitude to my supervisors, Dr. Ali Al-Bayati and Dr. Sarmadullah Khan, who have supported me throughout this thesis with their continued patience. Thanks, are also extended to Dr. Al-Bayati for his valuable supervision during the challenging journey of my PhD study.

There are insufficient words to thank my first ever teacher, my mother, who has continuously inspired and encouraged me to progress and excel. My loving parents' prayers and blessings are undoubtedly the true reason behind any success I have achieved in my life.

Finally, I am indeed grateful to all my family members, including my children and my husband, for their kind support, patience, and encouragement that have provided me with the energy and motivation to persevere until I reach the completion of this work.

Table of Abbreviations

ABR	Associativity-Based Routing
ADV	Ad-hoc Distance Vector
AL	Average Latency
AMRT	Adaptive Message Replication Technique
AODV	Ad-hoc On-demand Distance Vector
A-STAR	Anchor-based Street and Traffic Aware Routing
AU	Application Unit
AV	Abnormal Vehicle
CAR	Connectivity-Aware Routing
CBDRP	Cluster-Based Directional Routing Protocol
CBLR	Cluster-Based Location Routing
CBR	Cluster-Based Routing
CH	Cluster Head
C-ITS	Cooperative-Intelligent Transport System
CM	Cluster Member
CST	Customs Service Time
C-V2X	Cellular Vehicle-to-Everything
DAER	Distance Aware Epidemic Routing
DBRP	Destination-Based Routing Protocol
DL	Drop Largest
DO	Drop Oldest
DR	Delivery Ratio
DRG	Distributed Robust Geocast
DSDV	Destination Sequenced Distance Vector
DSR	Dedicated Short Range
DSRC	Dedicated Short-Range Communication
DTN	Delay Tolerant Network
DTSG	Dynamic Time-Stable Geocast
DV-CAST	Distributed Vehicular Broadcast

TABLE OF ABBREVIATIONS

DY	Drop Youngest
EBMP	Enhanced Buffer Management Policy
EBR	Encounter-Based Routing
EDR	Encounter and Distance-based Routing
EED	End-to-End Delay
EMRT	Enhanced Message Replication Technique
FFRDV	Fastest-Ferry Routing in DTN-enabled VANET
FIFO	First-In First-Out
FSR	Fisheye State Routing
GEOADV	Geographical Ad-Hoc On-demand Distance Vector
GEOPR	Geographical Opportunistic Routing
GPCR	Greedy Perimeter Coordinator Routing
GPS	Global Position System
GPSR	Greedy Perimeter Stateless Routing
GSR	Geographic Source Routing
GUI	Graphical User Interface
HBD	History-Based Drop
HCB	Hierarchical Cluster-Based
I2I	Infrastructure-to-Infrastructure
I2V	Infrastructure-to-Vehicle
IEEE	Institute of Electrical and Electronics Engineers
IF	Initial Ferry
ITS	Intelligent Transportation System
IVG	Inter-Vehicle Geocast
LIFO	Last-In First-Out
LOS	Line Of Sight
LPS	Less Probable Spray
LRF	Least Recent Forward
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network
MDC-SR	Message Drop Control Source Relay

TABLE OF ABBREVIATIONS

MDRP	Minimum Delay Routing Protocol
METD	Minimum Estimated Time of Delivery
MOFO	Most Forwarded First
MOVE	Motion Vector Routing Algorithm
NDM	Number of Delivered Messages
N-DTN	Non-Delay Tolerant Network
NED	Network Description
NIC	Network Interface Card
NWBBMP	Novel Weight-Based Buffer Management Policy
NGM	Number of Generated Messages
NRN	Number of Relayed Nodes
NS	Navigation System
OBU	On-Board Unit
OLSR	Optimised Link State Routing
OMNeT	Objective Modular Network Testbed
ONE	Opportunistic Network Environment
OR	Overhead Ratio
OSM	OpenStreetMap
PD	Packet Drop
PDR	Packet Delivery Ratio
PG	Priority Greedy
PGB	Preferred Group Broadcasting
PQB-R	Priority Queue-Based Reactive
PREP	Prioritized Epidemic
RI	Reliability Index
RL-ASC	Remaining Lifetime Ascending Order
RL-DESC	Remaining Lifetime Descending Order
ROMSGP	Receive On Most Stable Group-Path
RR	Round Robin
RSU	Road-Side Unit
SCF	Store-Carry-Forward

TABLE OF ABBREVIATIONS

SHLI	Shortest Lifetime First
SUMO	Simulation of Urban Mobility
TARS	Traffic Accidents Reduction Strategy
TCP-IP	Transmission Control Protocol/Internet Protocol
TORA	Temporally Ordered Routing Algorithm
TraCI	Traffic Control Interface
TT	Time Threshold
TTL	Time-To-Live
UB	Upper Bound
UMB	Urban Multihop Broadcast
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2R	Vehicle-to-Roadside
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VADD	Vehicle-Assisted Data Delivery
VANET	Vehicular Ad-hoc Network
VBN	Vehicle Backbone Network
VDTN	Vehicular Delay Tolerant Network
VEINS	Vehicles in Network Simulation
V-TRADE	Vector-based Tracing Detection
WAVE	Wireless Access in Vehicular Environments

Thesis Contents

Abstract I

COVID-19 Impact Statement II

Dedication III

Acknowledgements IV

Table of Abbreviations V

Thesis Contents IX

List of Figures XIV

List of Tables XVI

Chapter 1 Thesis Introduction 1

1.1 Introduction 2

1.2 Research Motivation 5

1.3 Research Problem 8

1.4 Aim and Objectives 10

1.5 Research Contribution 12

1.6 Thesis Outline 12

Chapter 2 Background and Related Work 18

2.1 Introduction 19

2.2 Part 1: Overview of Vehicular Ad-hoc Network 20

2.2.1 *VANET Architecture* 20

2.2.2 *VANET Applications* 25

2.2.3 *VANET Communication Categories* 29

2.2.4 *Wireless Access in Vehicular Environments* 32

2.2.5 *VANET Characteristics* 33

2.3 Part 2: Critically Analysing Routing Protocols in a Vehicular Ad-hoc Network.. 36

2.3.1 *Data Transmission in VANET* 36

2.3.2 *Overview of Routing Protocols in VANET* 36

2.3.3 *Classification of Routing Protocols in VANET* 37

2.4 General Performance Metrics/Simulation Parameter 49

2.5 Challenges in VANET 52

2.6 Summary 54

Chapter 3 Simulation Design and Implementation of High Density and Sparse Vehicular Networks 55

3.1 Introduction 56

3.2 Methodology 1: Different Packages to Model the VANET Environment 58

3.2.1 *Objective Modular Network Testbed* 59

3.2.2 *Simulation of Urban Mobility* 60

3.2.3 *Vehicles in Network Simulation* 60

3.3 Methodology to Integrate VEINS and SUMO with the OMNeT++ simulator 61

3.3.1 *Pre-Simulation Steps* 63

3.3.2 *SUMO Simulator Setup* 64

3.3.3 *Integrated OMNeT++, SUMO, and VEINS* 66

3.3.4 *The Implementation Steps* 67

3.4 Scenarios of the VANET Communication Using OMNeT++, INET, and VEINS 69

3.5 Discussion of the Safety Application Implementation Steps 72

3.6 Methodology 2: The ONE Simulator....74

3.6.1 *Justifications for Selecting the ONE Simulator*....76

3.6.2 *Compile the ONE Simulator*....76

3.6.3 *The Methodology and Evaluation of EMRT*....77

3.7 Summary....78

Chapter 4 Performance Evaluation of DTN Routing Protocols and Buffer Management Policies....79

4.1 Introduction....80

4.2 Overview of DTN....82

4.2.1 *Characteristics of DTN*....82

4.2.2 *Comparison Between the Conventional and DTN Routing Protocols*....83

4.2.3 *Store-Carry-Forward Mechanism in DTN*....85

4.3 Delay-Tolerant Routing Protocols....86

4.3.1 *Simulation Tools*....95

4.3.2 *Simulation Parameters*....95

4.3.3 *Performance of Employed Metrics*....96

4.3.4 *Acquired Simulation Results and Discussion*....96

4.4 Buffer Management Policies....111

4.4.1 *Dropping Buffer Management Policies*....112

4.4.2 *Simulation Works*....115

4.4.3 *Simulation Scenario Parameters*....115

4.4.4 *Metrics for Performance Evaluation*....116

4.4.5 *Performance Analysis and Discussion of the Results* 116

4.5 Challenges and Open Issues in DTN 127

4.5.1 *The Challenges and Open Issues in DTN Routing Protocols* 127

4.5.2 *Challenges and Limitations of Buffer Management* 129

4.6 Summary 131

Chapter 5 Novel Enhanced Message Replication Technique for DTN Routing Protocols 134

5.1 Introduction 135

5.2 Review and Clarification of the Limitations in the Related Work 136

5.2.1 *Flooding-based Protocols* 136

5.2.2 *Quota-based protocols* 139

5.3 Enhanced Message Replication Technique 145

5.4 Summary 148

Chapter 6 Implementation, Evaluation, and Validation of Results 150

6.1 Introduction 151

6.2 The Evaluation of EMRT 151

6.2.1 *Metrics Performance* 153

6.2.2 *Simulation Results* 154

6.3 Summary 161

Chapter 7 Conclusion, Recommendations, and Future Works 162

7.1 Conclusion 163

THESIS CONTENTS

7.2 Research Contribution 166

7.3 Future Works 168

List of Author's Publications 172

References 174

Appendices 192

List of Figures

Figure 1-1: Death rates from road traffic accidents by country, per 100 000 inhabitants 7
Figure 1-2: The flow of the thesis 14
Figure 2-1: Various types of communications in VANET 21
Figure 2-2: RSUs expand the range of the ad hoc network by forwarding the OBUs' data 23
Figure 2-3: RSUs function as a data source 23
Figure 2-4: The RSU connects the OBUs to the internet 24
Figure 2-5: Network architectures for VANET 25
Figure 2-6: Examples of VANET applications 26
Figure 2-7: Examples of VANET safety applications based on V2V 28
Figure 2-8: Examples of VANET safety applications based on V2I/I2V 28
Figure 2-9: Examples of VANET non-safety applications 28
Figure 2-10: Different categories of communications in VANET 30
Figure 2-11: The stack of DSRC and main standards 31
Figure 2-12: The DSRC spectrum 32
Figure 2-13: An example of variable network density in VANET 36
Figure 2-14: Categorisation of VANET routing protocols 39
Figure 2-15: The greedy forwarding operation mode 47
Figure 3-1: The classification of VEINS-based safety 61
Figure 3-2: The simulation package for VANET 62
Figure 3-3: The network simulation coupled with the traffic simulator using TraCI 63
Figure 3-4: Leicester city region from OpenStreetMap considered for the simulation 64
Figure 3-5: Leicester map network in SUMO 64
Figure 3-6: Leicester map from OSM to SUMO 65
Figure 3-7: Generating random trips 66
Figure 3-8: The OMNeT++ command screen to launch the SUMO script 67
Figure 3-9: Vehicle compound module in OMNeT++ 67
Figure 3-10: The IEEE802.11p compound module in OMNeT++ 68
Figure 3-11: The V2V communications in a simulated network 71
Figure 3-12: The V2R communications in a real network 72
Figure 3-13: The acquired results of using the road accident scenario for Leicester city 74
Figure 3-14: The GUI of the ONE Simulator 75
Figure 4-1: The strategies of traditional routing protocols 84
Figure 4-2: The strategies of DTN routing protocols 84
Figure 4-3: The mechanisms of SCF approach 86

LIST OF FIGURES

Figure 4-4: The different DTN routing protocols 89

Figure 4-5: Mechanism of the Spray&Wait operation 91

Figure 4-6: The node's buffer in the MaxProp routing protocol 93

Figure 4-7: An example of MaxProp calculating the cost of the paths 94

Figure 4-8: The performance of different DTN routing protocols in the shortest path-based movement model with different numbers of nodes 100

Figure 4-9: The performance of different DTN routing protocols in the shortest path-based movement model with different buffer sizes 104

Figure 4-10: The performance of different DTN routing protocols in the cluster model with different numbers of nodes 107

Figure 4-11: The performance of different DTN routing protocols in the cluster model with different buffer sizes 111

Figure 4-12: The performance of various drop policies in the MaxProp routing protocol with different TTL values 119

Figure 4-13: The performance of various drop policies in the Spray&Wait routing protocol with different TTL values 125

Figure 5-1: Network's circumstances from each node's perspective 148

Figure 6-1: The delivery ratio in different node densities 156

Figure 6-2: The overhead ratio in different node densities 157

Figure 6-3: The latency average in different node densities 158

Figure 6-4: The Delivery/Latency composite metric 159

Figure 6-5: The Delivery/Overhead composite metric 160

Figure 6-6: The Delivery/Latency/Overhead composite metric 161

List of Tables

Table 2-1: Summary of five routing protocols in VANET 48
Table 3-1: Summary of vehicular network simulators and simulation systems 59
Table 4-1: Parameters used to simulate five DTN routing protocols 96
Table 4-2: Elements of modelling works 116
Table 5-1: Comparison of the various DTN strategies 144
Table 6-1: Parameters of the simulation works 152

Chapter 1 Thesis Introduction

Objectives

- Provide an introduction and motivation for this research
- Define the research problem
- Present the aim and objectives of this research
- Summarize the contributions of this thesis
- Outline the thesis structure

CHAPTER 1 THESIS INTRODUCTION

1.1 Introduction

Transportation and the use of vehicles are essential in terms of social and economic activities. Therefore, reducing the impact of such transportation on climate change, as well as road traffic accidents will improve citizens' quality of life. The Intelligent Transportation System (ITS), which is a system created to provide a creative and sustainable solution for the current transportation industry, has recently attracted a lot of interest from the research community and academics [1, 2]. The ITS aims to introduce Vehicular Ad-hoc Network (VANET) as an emerging technology to achieve traffic efficiency by minimizing traffic issues [3]. A VANET is defined as a sub-class of Mobile Ad-hoc Network (MANET) that enables vehicles to exchange different types of information with each other. In VANET, moving vehicles can be connected wirelessly with each other through Dedicated Short-Range Communication (DSRC), which is fundamentally IEEE802.11 modified to IEEE802.11p for low overhead operation [4]. The applications of VANET have been categorized into (i) safety applications related to safety, and (ii) non-safety applications (comfort applications) related to increasing traffic efficiency [5, 6].

VANET has distinct characteristics such as highly dynamic network topology, high mobility, short contact duration, and variable node density [1, 3]. These VANET properties cause packet delivery to be delayed and a reduction in throughput. Hence, the routing protocol’s effectiveness will be reduced [7, 8]. Moreover, the intermittent connection in the networks causes packet losses and delays in the

delivery of the messages to the destination, especially in a sparse environment, which leads to the routing protocols designed for MANET being incompatible with VANET [9, 10]. In addition, establishing effective inter-node communication in VANET faces a range of challenges such as the wireless interface, disconnection, and the sparse environment. For these reasons, the traditional routing protocols may not work effectively in such challenging environments [11]. These issues cause barriers to the implementation of common ad hoc routing protocols such as Dedicated Short Range (DSR) and Ad-hoc On-demand Distance Vector (AODV). To overcome such issues, the Delay Tolerant Network (DTN) routing protocols must be applied due to their significant role in overcoming difficult communication environments [12, 13].

It is necessary here to clarify what is meant by DTN The DTN is intermittently connected (wireless) network, whereby there is no guaranteed end-to-end connectivity between the source and destination nodes [14-16]. This network can be disrupted by factors such as node mobility, density, and limited radio range, leading to frequent disconnections. As a result, traditional Transmission Control Protocol/Internet Protocols (TCP/IP) cannot be used, and instead, a Store-Carry-Forward (SCF) approach is employed to allow data transmission to continue despite the lack of a continuous path [16, 17]. However, this routing approach can cause issues such as buffer congestion and inefficient use of network resources due to the dissemination of multiple copies of a message across the network [16, 18, 19].

CHAPTER 1 THESIS INTRODUCTION

There are several routing techniques [20-29] available for addressing the routing problem in DTN, which can be divided into two categories: flooding-based and quota-based [30, 31]. Flooding-based protocols allow nodes to replicate messages indefinitely, which can lead to good network performance when resources are not limited. However, they may have a low delivery ratio, high overhead, and high delay when resources are limited [32, 33]. Quota-based protocols, on the other hand, set a maximum number of replicas for each message, unlike flooding-based protocols where the number of copies is determined by the number of encounters [34]. These protocols are resource-efficient and perform well when resources are limited but may experience low delivery rates and long delays when resources are insufficient. Additionally, the number of replicas is fixed for all messages and is not affected by network capacities, such as node buffer size, energy, Time-To-Live (TTL) values, and encounter rate [32, 33]. This indicates that quota-based protocols, like their flooding-based counterparts, will experience a high ratio of dropped messages if many replicas are created for each generated message when network congestion occurs. On the other hand, the quota-based protocol experiences low delivery ratios when the network traffic is light and few replicas are formed [31]. To conclude, many issues affect the performance of the network in terms of overhead, latency, and delivery ratio. The first issue is the high mobility of nodes, which means that the relay nodes must store messages and exchange them with other encountered nodes. Hence, the battery of the nodes may run out, which will

lead to the removal of the messages from the networks. The second issue is that the nodes may experience buffer overflow issues, which can lead to a high ratio of dropped messages [18, 19]. The third issue is that the nodes may not be able to send all the messages when congestion occurs on a link with limited bandwidth [35].

Based on the above limitations of each category of routing protocols, we carried out the investigation to improve the overall network performance. Therefore, in this research, different DTN routing protocols will be investigated and implemented that belong to a range of classes, and their performance evaluated. Then, the impact of different dropping policies on two DTN routing protocols will be studied. Finally, a novel Enhanced Message Replication Technique (EMRT) will be proposed, which dynamically adjusts the number of message replicas based on a node's ability to quickly disseminate the message, taking into consideration various parameters such as existing connections, encounter history, buffer size history, energy, and TTL values. This can improve the delivery ratio and enhance network resource utilization.

1.2 Research Motivation

Due to continuing increases in road collisions that lead to serious injuries, loss of life, and cost, governments, and many analysts have become concerned with the increasing fatalities and have thus sought to minimize the number of road traffic accidents [36]. This motivates us to understand the emerging technology that can help to improve road safety. The technology referred to as VANET allows vehicles

to communicate wirelessly and exchange vital information periodically. Enabling vehicles to cooperate and share safety messages can lead to the mitigation of road traffic accidents and the avoidance of road congestion.

It is important to highlight the impact of road traffic accidents since this can motivate researchers to contribute to mitigating and finding opportunities to reduce such incidents; for example, Libya has a high national rate of accidents at 20–25 fatalities per 100 000 inhabitants, as shown in **Figure 1-1**. Unfortunately, I am a victim of one of those accidents, where my father lost his life due to a car accident in Libya when I was only three months old. Furthermore, many analysts report that the number of road traffic accidents has significantly increased, leading to over 1.25 million deaths globally each year [37-40]. In 2015, according to [41] more than 1.2 million people lose their lives annually as a result of road traffic accidents, while an estimation of the cost of traffic congestion was determined by the Texas Transportation Institute to reach $160 billion, with 6.9 billion productive hours lost and 11.7 billion litres of petrol wasted in the United States of America [42, 43]. Recently, according to Road Safety Annual Report on 2020 at International Transport Forum [44], the 3rd Global Ministerial Conference on Road Safety recommended positioning road safety as the top political agenda in order to reduce deaths and serious injuries. Annual deaths due to road traffic accidents of 1.35 million were reported in [45], which remains unacceptably high. Moreover, the World Health Organization reports that road traffic accidents will become the 7th

leading cause of death by 2030 [46, 47]. Based on the statistical trends, the death rate due to road traffic accidents will continue to rise [3], and thus urgent action is required to tackle this serious issue.

According to the Organization for Economic Co-operation and Development, road deaths should be reduced by 50% by 2030 [44]. Therefore, this research is motivated to reduce road traffic accidents in the VANET environment via an in-depth study of the communication and routing protocols, transmitting messages efficiently in the network to carry safety warning messages in an intermittent network, preventing the messages from dropping and addressing the absence of end-to-end communications that can help to prevent fatal road traffic accidents.

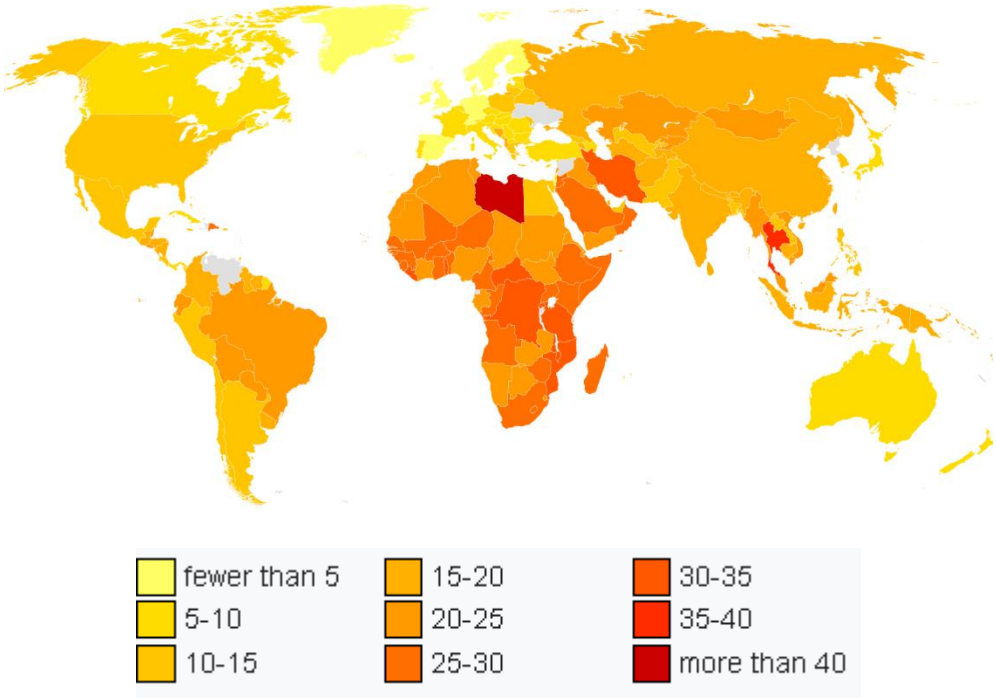


Figure 1-1: Death rates from road traffic accidents by country, per 100 000 inhabitants [48]

1.3 Research Problem

As mentioned above, the most serious issue in the transport sector is road traffic accidents. Such collisions are primarily due to a lack of information-processing capacities and the drivers' limited response times in emergencies. The delayed response to emergencies on the road is caused by driver inexperience in dealing with such scenarios or dealing with these cases too slowly to avoid road traffic accidents [49]. Due to the unique characteristics of VANET such as high mobility and dynamic topology that cause disconnections and long delays in the VANET environment, there are still challenges in existing VANET routing protocols that require further investigation. The currently identified issues in VANET in this project involve the absence of end-to-end connectivity, interrupted network, buffer congestion (storage capacity constraints), message drop, network resource consumption, and determining an adaptive number of replicas. These problems are discussed in greater detail as follows:

- In high-density traffic, data delivery will be achieved successfully in VANET because there are a large number of vehicles that are available and act as a relay to easily contact and forward messages to each other. However, in a low-density environment, end-to-end communication may not be available and there may not be any neighbouring vehicles that can forward messages to each other. As a result, the traditional VANET routing protocols face a challenge in scenarios that require end-to-end connectivity

among vehicles [50]. Due to these limitations, improved data delivery is required, even in a sparse network environment where direct end-to-end communication between vehicles does not exist.

- Due to the existence of many copies of the messages in the network and their unnecessary retransmission, buffer congestion may occur and cause the dropping of important messages. Therefore, controlling the number of replicas is required to avoid buffer congestion and reduce the phenomenon of message drop.
- As the most significant objective of a DTN routing protocol is to maximize the message delivery probability and minimize the message delay, an EMRT is investigated to render the number of replicas dynamically rather than fixed with every generated message.
- To forward messages effectively, the history of encounters can be efficiently employed, while network congestion should also be considered to determine the proper number of replicas and enhance network resource utilization.
- An efficient DTN routing algorithm that can be employed to deal with a lack of persistent end-to-end connection between the source and destination nodes is required [49, 51]. DTNs utilize the SCF method to deal with the interrupted network that leads to long-term storage. However, the DTN routing and SCF strategies can be inefficient in terms of resource usage (i.e., storage, bandwidth, and energy). Therefore, to avoid SCF scheme issues

such as buffer congestion and message drop, buffer management policies are required to improve the DTN routing performance because if the buffer is well controlled, this will impact positively on the routing performance by avoiding the buffer congestion issue.

- Forwarding messages through the network based on a quota-based protocol strategy will reduce network resource consumption. The quota-based strategy disseminates only a limited number of replicas to avoid the overhead that is caused by transmitting extra replicas of the same message in the network, especially in the case of restricted network resources.

1.4 Aim and Objectives

This thesis aims to enhance a position-based routing protocol technique to improve road safety. Various studies related to the VANET routing protocol have been proposed to improve road safety. However, the majority of the existing VANET routing protocols suffer from a range of issues such as selecting the optimal next-hop node to forward the message, the absence of end-to-end communication, and buffer congestion, which causes message loss or additional delays in the data transmission. Therefore, the current study aims to develop a DTN routing algorithm that can enhance road safety by increasing the delivery ratio and avoiding the dropping of emergency messages. To overcome the end-to-end transmission issue, the DTN routing protocol depends on the SCF approach that is utilized to carry the messages until new neighbouring vehicles appear to receive these messages. The

transmission of the messages should be successfully achieved to avoid message drop issues while promoting low latency, minimum bandwidth consumption, and high successful delivery rate and throughput. As this project includes various topics such as ITS, VANET, and DTN, the aim of the research will be achieved by pursuing the following objectives:

1. To provide an outline of the gaps in the existing literature on VANET, and especially routing protocols, to be achieved through a comprehensive study of the modern technology of the VANET including a review of the state of the art, the features, the characteristics and routing protocols.
2. To improve road safety via Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (V2R) communications that are used to send safety messages between vehicles in a real network of the Leicester map scenario.
3. To extend the knowledge of different DTN routing protocols including aspects such as their properties, their principle to transmit data, and their strengths and weaknesses.
4. To study the impact of TTL value by applying various dropping buffer management policies on DTN routing protocols.
5. To improve the performance of the quota-based routing protocol in DTN by proposing a novel technique that is adaptively adjusting the maximum initial number of replicas for each generated message based on network circumstances such as density, buffer availability, energy, and TTL values.

1.5 Research Contribution

The main contributions of the thesis are summarised as follows:

1. Conducted an extensive performance evaluation of state-of-the-art routing protocols for DTNs with different buffer management policies, giving insight into the impact of these policies on DTN routing protocol performance. The empirical study gave insight into the strengths and limitations of the existing protocols and also enabled the selection of the benchmark protocols utilized in evaluating the new proposed Enhanced Message Replication Technique (EMRT) scheme.
2. A novel EMRT is proposed that improves the efficiency of message transmission in DTNs thus enhancing vehicular safety; EMRT is a dynamic quota-based technique that considers not only encounter-based routing metrics, but also network congestion and capacity, to minimize overhead, maximize delivery ratio, and efficiently utilize network resources.
3. An in-depth evaluation of the EMRT approach via extensive experiments with conventional metrics and composite metrics, giving insight into the performance of EMRT and its capacity to enhance the state-of-the-art DTN routing protocols.

1.6 Thesis Outline

This thesis consists of seven chapters. **Figure 1-2** displays the flow of the chapters of this thesis as follows. First, the VANET routing protocols are classified into five

categories: geocast-based routing protocols, topology-based routing protocols, position-based routing protocols, broadcast-based routing protocols, and cluster-based routing protocols. Second, the class of position-based routing protocols is considered. Third, one of the position routing protocols, namely the DTN protocols, is carried out, which involves position routing protocols that utilize the SCF approach to transmit the data packet between vehicles in a VANET environment. Finally, due to the disconnection and varied mobility patterns, long queuing delay, and limited network resources in DTNs, the SCF may cause issues such as buffer congestion, transmission date delay, and message drop. Therefore, buffer management is vital to manage the node's buffer, which can help to tackle the buffer congestion problem and reduce the loss of messages.

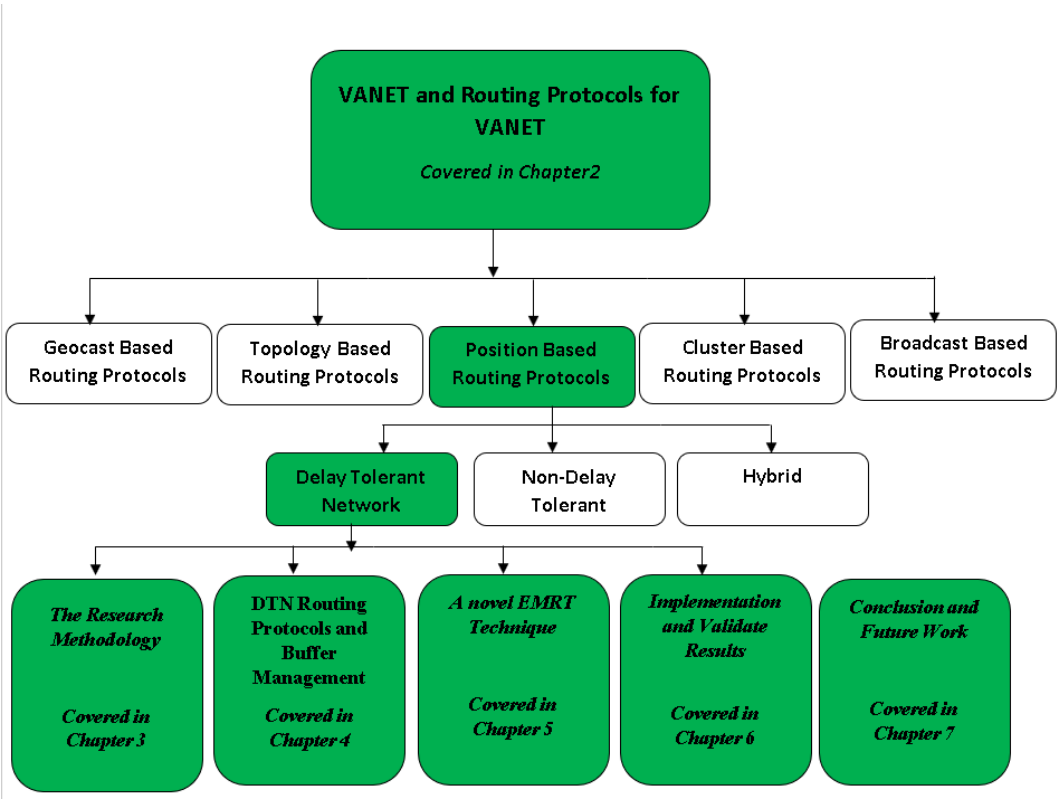


Figure 1-2: The flow of the thesis

A summary of Chapters 2–7 is described as follows:

Chapter 2 consists of two parts. In part 1, a general background of VANET is presented concerning different aspects such as the architecture, applications, communications, characteristics, and challenges. In part 2, the data transmission and the main routing protocols in VANET are discussed. Furthermore, the taxonomy of the existing VANET routing protocols is investigated by critically examining the strengths and weaknesses of these protocols and distinguishing between them.

Chapter 3 presents the details of the methodology and its implementation. Two different methodologies will be utilized in this project. The first methodology involves implementing an innovative system for VANET. Hence, an overview of the simulations considered to simulate the VANET environment will be presented concerning different aspects such as defining and integrating the OMNeT++, SUMO, and VEINS simulations. In addition, the proposed scenarios regarding road traffic accidents with high-density traffic in VANET are considered where an end-to-end connection exists. Therefore, the vehicles can communicate with each other via V2V or with the roadside unit (V2R) directly. The second methodology regards the ONE simulator, which is designed specifically to implement DTN. The ONE simulator will be employed to implement the proposed novel EMRT, with the EMRT technique applied to different quota-based protocols to control the number of replicas and enhance the network resource utilization.

Chapter 4 presents a literature review that provides essential background on the DTN regarding different facets such as the DTN principle, features, characteristics, architecture, routing, and buffer management. The various DTN routing protocols that belong to a different class will be analyzed and evaluated for their performance using ONE simulator, which will help in the selection of the benchmark routing protocol and for further improvement. The chapter also offers insight into each DTN routing technique, while discussing the performance criteria employed in the thesis and providing details of the process of selecting an appropriate routing

protocol. A number of methodologies for various DTN routing protocols are then reviewed. Moreover, the evaluation of the benchmarked protocols that achieved the top and second rating will be carried out to analyze the impact of TTL on different drop policies for a range of DTN routing protocols by applying different dropping policies, with extensive simulation results provided. Finally, the chapter concludes by discussing and analyzing the results depending on the different metrics' performance, such as packet delivery ratio, average latency, hop count average, and overhead ratio. This will help in the selection of the quota-based routing protocol to apply our novel technique to achieve further improvement in the delivery ratio and utilization of the network resources.

In **Chapter 5** an EMRT that fits into quota-based protocols is proposed. EMRT aims to determine the number of replicas for dissemination based on the capability of nodes for quick dissemination. Our proposed technique of EMRT is applied to the different quota-based protocols, namely, Spray&Wait, Encounter Based Routing (EBR), and Destination-Based Routing Protocol (DBRP). where the network performance of the three quota-based protocols is improved in terms of delivery ratio, overhead ratio, and delay ratio.

Chapter 6 illustrates the validity of the proposed technique using the ONE simulator. It explains how EMRT is able to determine the proper number of replicas based on the network capability (i.e., the available network resource). Furthermore,

extensive simulation results will be presented by applying our proposed technique to different quota-based routing protocols to facilitate validation.

Chapter 7 summarises the work carried out in this thesis. In addition, future works are reported to enable other researchers with an interest in the same topic to proceed with further investigations. Finally, the author's publications are listed.

Chapter 2 Background and Related Work

Objectives

- Provide a general background of VANET
- Present the VANET architecture, applications, and characteristics
- Clarify the VANET communications
- Provide an overview of the routing protocols in VANET
- List the general performance metrics/simulation parameter
- Outline of the challenges of VANET
- Summarize the chapter

CHAPTER 2 BACKGROUND AND RELATED WORK

2.1 Introduction

In recent years, VANET has become an emerging modern technology with unique characteristics that differentiate it from MANET, which is a network that has no infrastructure [52-55] and has the ability to configure itself by utilizing wireless channels to connect mobile devices [56]. Meanwhile, VANET is defined as an application of MANET, which is invariably employed for vehicles to improve road safety and provide passengers with additional comfort. MANET and VANET are both wireless networks, whereby the vehicles in the latter have to follow a specific path, whereas in the former the nodes move in a completely random manner [57]. Vehicles can communicate with other vehicles directly, which is known as V2V, or with the infrastructure known as V2I. Every vehicle is supplied with an On-Board Unit (OBU) to be able to communicate with other vehicles or with equipment fixed in the road known as a Road-Side Unit (RSU) [58]. The main benefit of both V2V and V2I communications is the ability to share various information (e.g. position, speed and direction) between vehicles [59, 60]. The benefit of sharing such information is to disseminate warning messages that can be employed to warn the drivers of other vehicles in order to enable quick reaction and the avoidance of hazardous situations.

The information in VANET can be sent through different routing protocols, which are utilized to locate effective routes between nodes to send the packet messages between them in a timely manner [58]. Routing protocols are responsible for

selecting and maintaining routes, as well as for forwarding messages through the chosen routers [61]. Due to the unique characteristics of VANET such as dynamic topology, high mobility, and variable density, the conventional routing protocols proposed for MANET are not suitable for VANET [9, 10]. Moreover, identifying and maintaining routes to facilitate network communications and data transmission in VANET are extremely challenging due to these aforementioned characteristics [58, 62]. This chapter consists of two main parts. In part one, a comprehensive review of VANET including different aspects such as the architecture, applications, communications, characteristics, and challenges is provided. While in part two, an overview of the various categories of VANET routing protocols is described.

2.2 Part 1: Overview of Vehicular Ad-hoc Network

2.2.1 *VANET Architecture*

Basically, communications in VANET that are facilitated by waves could be V2V or V2I, as shown in **Figure 2-1**. These communications are achieved by utilizing two units: the RSU and OBU. The RSU is existing on the road, while the OBU is installed inside the vehicle to allow the vehicles to communicate with each other or with the RSU. In communication technologies, provided that the nodes in VANET are vehicles, then the vehicles can connect with others on the road through OBU, which enables the wireless communication fully distributed technique whereby all vehicles can send and receive messages through wireless communication. Furthermore, OBU can communicate with nearby RSU to extend the

communication range and participate in forwarding messages to other vehicles [63, 64].

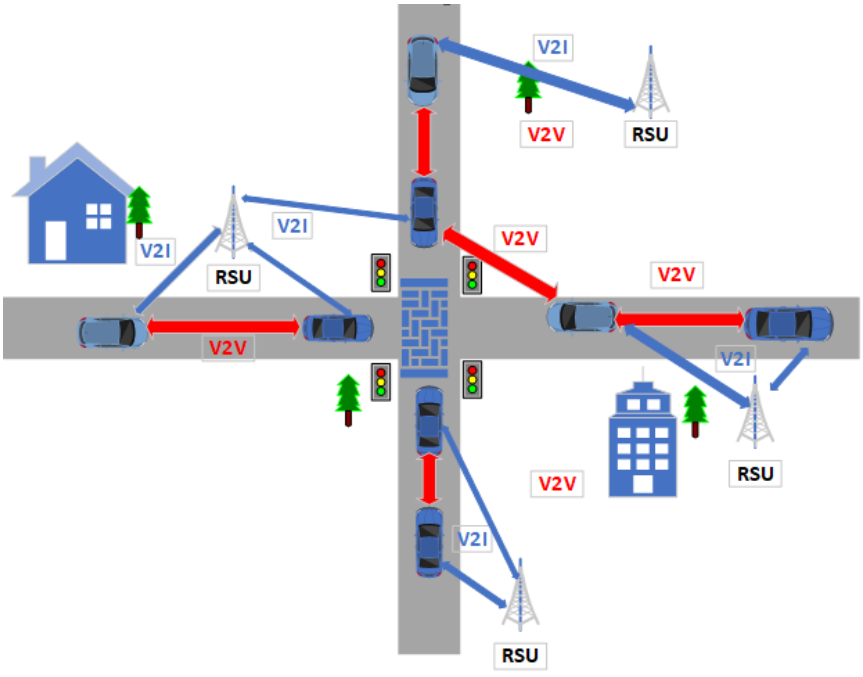


Figure 2-1: Various types of communications in VANET [65]

- *On-Board Unit*

It is important to define the OBU, which is a mobile device installed in the vehicle to exchange data with RSU or with other OBU. OBU is connected to other OBU or RSU through wireless technology based on IEEE802.11P. Each OBU device is equipped with memory, storage, processing, an interface, and communication capability [57, 63, 64, 66]. The OBU device is responsible for forwarding data messages to Application Units (AUs), receiving services from RSU, and forwarding data messages to the OBU of other vehicles [67, 68].

- *Application Unit*

The AU is defined as a device fixed inside the vehicle like the OBU device that utilizes the applications given by the supplier while using the communication capabilities of the OBU [59]. The AU can be a devoted device for safety applications or a normal device and is connected with the OBU via a wired or wireless connection [63]. The AU communicates with the system exclusively through the OBU, which takes responsibility for all networking functions [4, 66].

- Road-Side Unit

The RSU is a wave device mounted either along the roadside or in specified locations such as intersections, junctions, and curves in the road in order to simplify the wireless communications between vehicles and the infrastructure [69]. Moreover, connectivity support is provided from the RSU to the passing vehicles through the short-range wireless communication IEEE802.11p and antenna. For example, when the RSU is fixed at every intersection path, in cases where the path breaks, all the information regarding that path will be presented in the RSU, and then the vehicles can more easily and promptly communicate through various RSUs [58, 66, 70]. The benefits of using RSU can be summarised as follows:

1- To expand the ad hoc network range communication for redistributing the data to other OBU, as well as transmitting the information to other RSU in order to efficiently forward this information to other OBU, as presented in **Figure 2-2** [58, 63, 66].

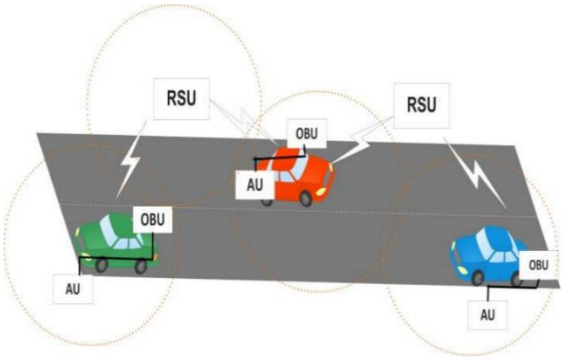


Figure 2-2: RSUs expand the range of the ad hoc network by forwarding the OBUs' data [66]

2- To run safety applications such as alerts of low bridges, accidents ahead, or road works, by means of the utilization of Infrastructure-to-Vehicle (I2V) communications and functioning as an information source, as shown in **Figure 2-3** [63, 66]. This procedure will be considered and employed in Chapter 3, where a simulated road traffic accident has occurred, and a warning message is created and broadcast by the RSU to the neighbour vehicles.

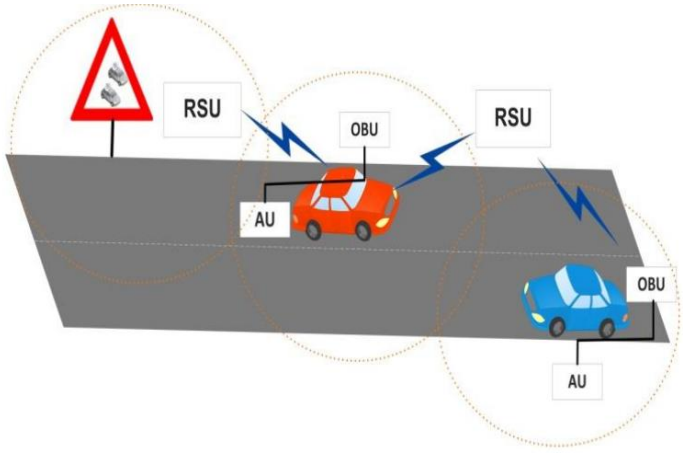


Figure 2-3: RSUs function as a data source [66]

3- To provide internet connectivity to OBU, as demonstrated in **Figure 2-4** [63, 66].

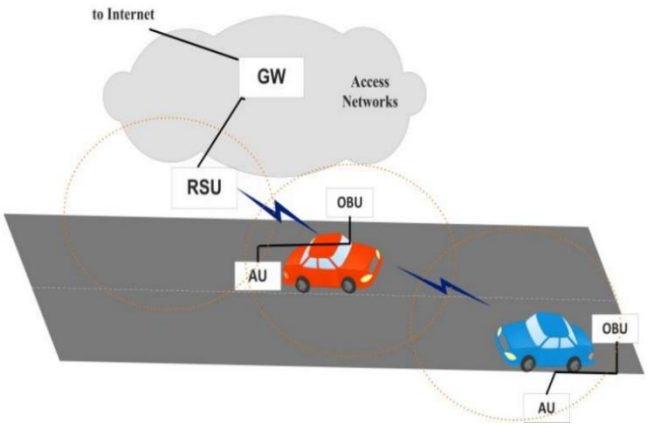


Figure 2-4: The RSU connects the OBUs to the internet [66]

Additionally, the VANET architectures have been classified into three types: pure cellular/WLAN architecture, pure ad-hoc architecture, and hybrid architecture [10], which are described as follows:

A. Cellular/WLAN Architecture

Cellular/WLAN architecture is also known as V2I communication, as shown in **Figure 2-5** (A). In order to connect to the internet, collect traffic information, or for routing purposes, the network employs cellular gateways and WLAN access points [10]. The RSU device can be employed to extend the communication range and participate in forwarding the message to other vehicles or RSUs [64].

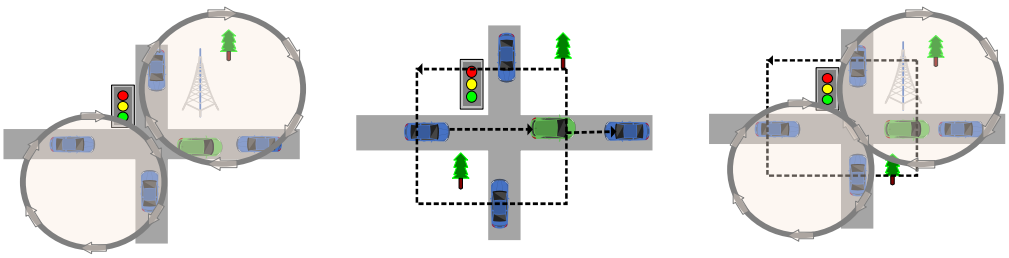
B. Ad-hoc Architecture

Ad-hoc architecture is referred to as V2V communications, as shown in **Figure 2-5** (B) [10]. Ad hoc networks are self-organized with a limited communication range,

where the vehicle behaves like a router and establishes the connections to exchange messages between the other vehicles.

C. Hybrid Architecture

Hybrid architecture is also known as Vehicle-to-Roadside (V2R) communication [10]. In hybrid architecture, the wireless network devices such as the access points and cellular towers are fixed in an RSU, which communicates with the moving vehicles, as shown in **Figure 2-5** (C).



(A) Cellular/WLAN **(B) Ad hoc** **(C) Hybrid**

Figure 2-5: Network architectures for VANET [65]

2.2.2 *VANET Applications*

Generally, VANET applications have been categorized into (i) safety applications that are related to safety, and (ii) non-safety (comfort) applications that relate to increasing traffic efficiency (see **Figure 2-6**). These applications are explained in greater detail as follows:

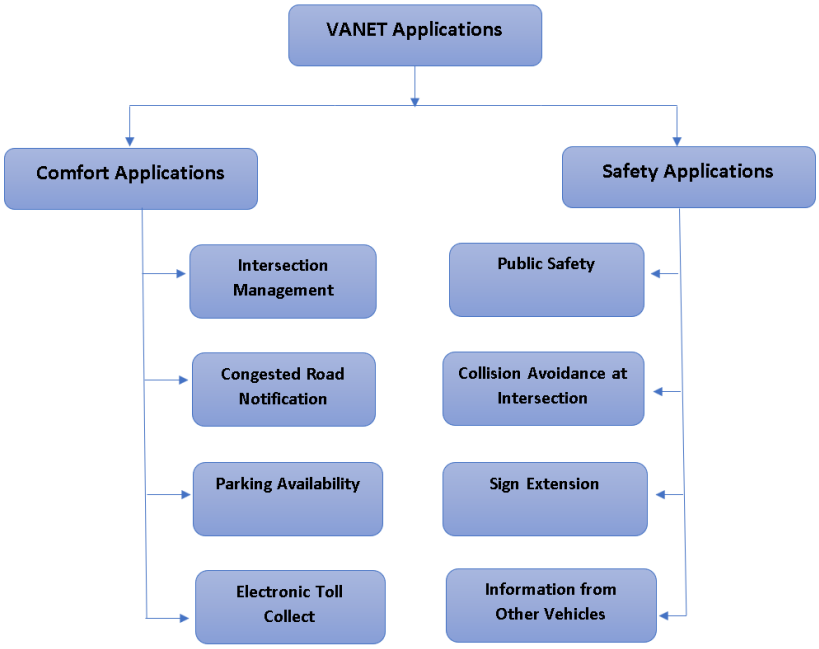


Figure 2-6: Examples of VANET applications

- *Safety Applications*

There are several applications of VANET related to safety, as shown in **Figure 2-7** and **Figure 2-8**, including lane changing, collision avoidance, and pre-crash sensing, which are employed to assist drivers in avoiding possible dangers ahead, the prevention of road traffic accidents, and the improvement of road safety [4]. These applications thus advance drivers' knowledge of their direct environments to prevent road traffic accidents. Factors in the driver's direct environment include obstacles, road traffic accidents, pedestrians, animals, road construction and maintenance, and inclement weather. Therefore, these applications require high reliability and a short delay in order to exchange safety messages between nearby

vehicles and RSUs. To improve road safety and avoid road traffic accidents, several of these applications were presented by [4, 63], and can be summarised as follows:

- **Public safety:** The goal of these applications is to support drivers in the case of road traffic accidents, while also supporting rescue teams in their provision of efficient services.
- **Collision avoidance at intersections:** These applications are based on V2I communications to avoid road traffic accidents. When the vehicles are approaching an intersection, they send information to the infrastructure, which is then analyzed by sensors to check for the probability of any accidents occurring. Next, a cautioning signal is sent to those vehicles heading toward the intersection. Therefore, by warning these vehicles to take proper action, collisions can be avoided at the intersection.
- **Sign extension:** These applications are employed to alert drivers that are not focused on street signs such as curves, road works, zone warnings, and speed limits.
- **Information from other vehicles:** These applications rely on V2V and V2I to implement safety application messages.
- **Diagnostics and maintenance of vehicles:** These applications are employed to transmit alerting notifications to vehicles to remind the driver of the need for the vehicle to receive periodic maintenance.

(A) Post-Crash Warning (B) Blind Intersection Warning (C) Do Not Pass Warning

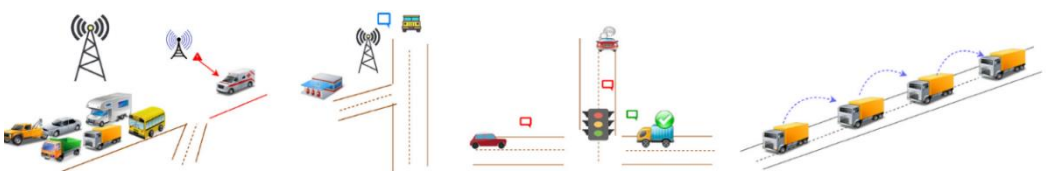
Figure 2-7: Examples of VANET safety applications based on V2V [64]

(A) Work Zone Warning (B) Pedestrian in Signalised Crosswalk Warning (C) Curve Speed Warning

Figure 2-8: Examples of VANET safety applications based on V2I/I2V [64]

- *Comfort Applications*

The main goal of comfort applications is to improve passenger comfort and infotainment, which could include current traffic conditions or weather updates, as well as interactive communications. Moreover, a significant feature of comfort applications is that they should not overlap with their safety counterparts [5, 6]. **Figure 2-9** presents a number of examples of non-safety (comfort) applications [64].



(A) Congestion Warning (B) Service Finder (C) Traffic-Light-To-Vehicle Communication (D) Cooperative Adaptive Cruise Control

Figure 2-9: Examples of VANET non-safety applications [64]

2.2.3 *VANET Communication Categories*

To improve traffic flow and road safety, ITS is focused on providing secure communications by utilizing different networking systems (e.g. VANET [71]). These communications can be described as follows:

- **Vehicle-to-Vehicle Communications:** Vehicles can transmit valuable information directly without the use of any infrastructure, such as crash detection, road traffic situations, and the occurrence of emergency braking. Furthermore, the transmission medium is characterized by short latency and a high transmission rate [59, 72].
- **Vehicle-to-Infrastructure Communications:** A vehicle can transmit information between vehicles and fixed infrastructure on the road, and vice versa. Due to the connection with the infrastructure, V2I requires a larger bandwidth than V2V but is less vulnerable to attack [72].
- **Vehicle-to-Pedestrian Communications:** Communication is possible between vehicles and devices that are carried by cyclists, passengers, and pedestrians [59, 64]. These communications help vehicles to localize the bicyclists and pedestrians which can help to avoid crashing with them.
- **Vehicle-to-Everything Communications:** Vehicle-to-Everything (V2X) communication plays a significant role in ITS to enhance traffic road safety and traffic efficiency while improving the driving experience by providing real-time information relating to incidents, traffic congestion, emergencies,

other transportation services, and so forth [72, 73]. V2X communication can disseminate information among V2V, V2I, and V2P, as shown in **Figure 2-10**. Cooperation between V2V and V2R communications is used in this chapter to address the shortcomings of the stand-alone V2V and V2R networks [58, 69]. If the vehicles are in the same communication range, they will communicate directly; if not, multi-hop communication is required to forward the data between the vehicles [51, 64].

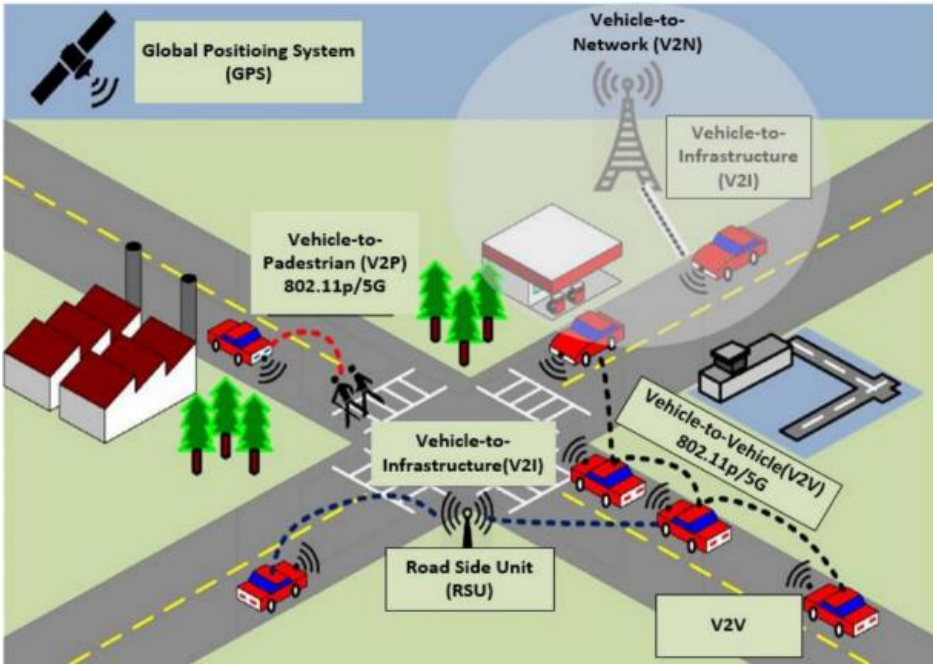


Figure 2-10: Different categories of communications in VANET [74]

- *Standards for Wireless Access in VANET*

Recently, VANET technology has been gaining considerable attention due to its role in designing ITS [75]. There are different wireless standards available to offer the radio access necessary for vehicles to communicate via V2V, V2I, and

Infrastructure-to-Infrastructure (I2I) [76]. VANET deals with two wireless standards: (i) IEEE802.11p, which is utilized to manage the physical and Medium Access Control (MAC) layers that primarily support IEEE802.11a; and (ii) IEEE1609, which is employed to manage higher-layer protocols [59, 62, 75]. The stack of DSRC is presented in **Figure 2-11**.

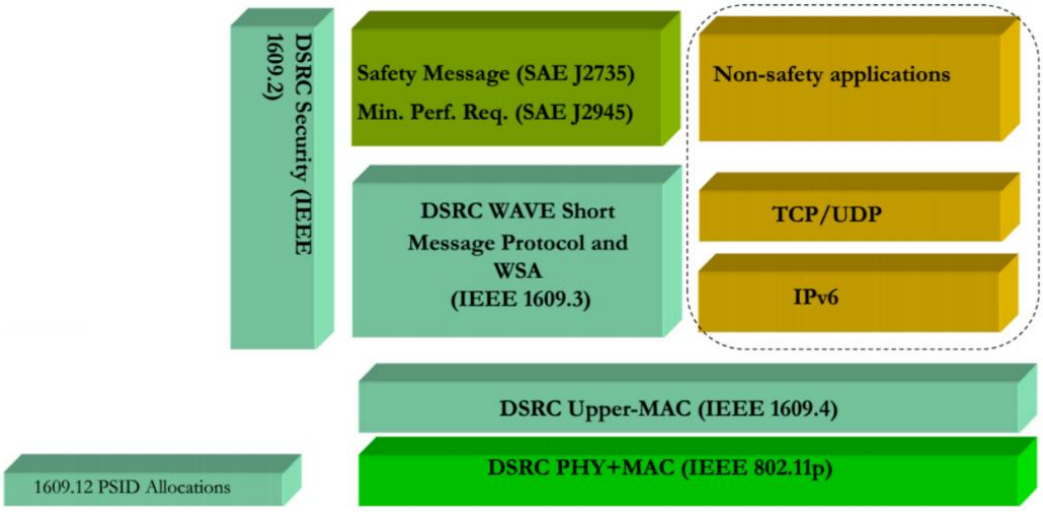


Figure 2-11: The stack of DSRC and main standards [43]

- *Dedicated Short-Range Communications*

DSRC can be defined as radio techniques that facilitate the transmission of information over short distances between vehicles and the RSU in order to achieve a range of operations such as the enhancement of traffic safety, improved traffic flows, and other intelligent transportation service applications [77]. DSRC originated from IEEE802.11a and was then improved for IEEE802.11p [4, 75], offering benefits in terms of its ability to allow high-speed communications, as well as the ability to see around corners and to operate in extreme weather conditions

[75]. DSRC was developed to meet the requirements of VANET such as high mobility, self-configuration, and dynamic topology [78]. It functions by using a 75 MHz spectrum in the 5.9 GHz frequency band in the United States, while in Europe and Japan, it employs the 30 MHZ spectrum in the 5.8 GHz band [78]. DSRC is extensively utilized for road safety applications due to its reliability, low latency, and secure data transmission [2, 75, 76]. The DSRC spectrum is separated into seven channels, whereby one channel is known as the control channel, while the other six channels are referred to as the service channels [59], as shown in **Figure 2-12**. Each channel has a 10 MHz width, with the control channel being responsible for the dissemination of high-priority messages and management information. Meanwhile, the service channels are switched to observe the control channel and enable the transfer of other information [63, 79].

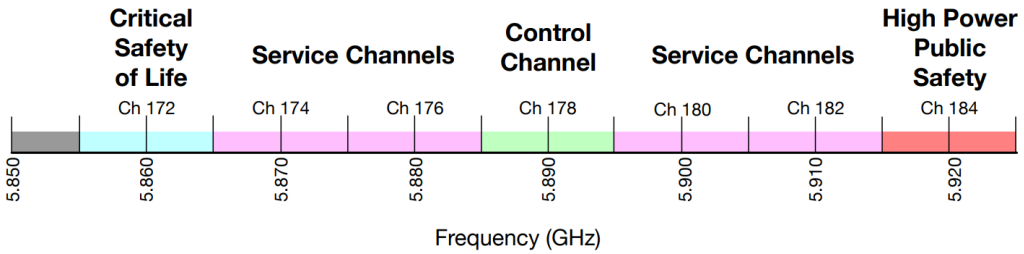


Figure 2-12: The DSRC spectrum [2]

2.2.4 *Wireless Access in Vehicular Environments*

Wireless Access in Vehicular Environments (WAVE) is utilized so that wireless access in vehicular networks can facilitate V2V or V2I communications. WAVE is the standard obtained by combining the entire DSRC protocol stack that comprises

both the IEEE802.11p and IEEE1609 standards [64, 72]. WAVE is a collection of special standards developed by the IEEE research group for VANET.[75, 80] reported that the WAVE family consists of several standards, which can be described as follows:

- IEEE1609.1: Enables applications to establish communication among OBU and RSU, utilizing a particular WAVE application known as a resource manager.
- IEEE1609.2: Comprises safety and security mechanisms.
- IEEE1609.3: Specifies services that operate at the network and transport layers, utilized to facilitate the creation of wireless communication between vehicles, and between vehicles and RSU.
- IEEE1609.4: Allows multi-channel wireless communication among WAVE devices by defining and supporting MAC sub-layer services and functions.

2.2.5 *VANET Characteristics*

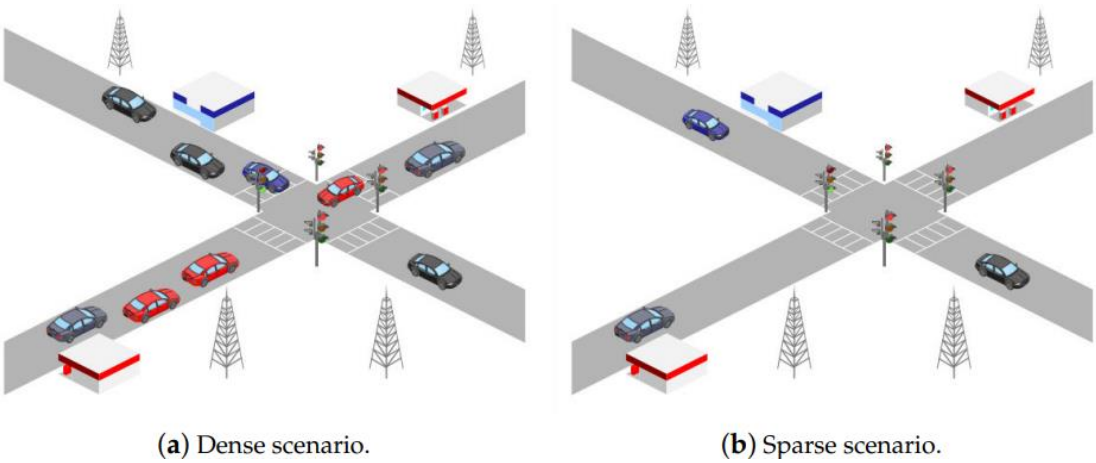
VANET has unique features that differentiate this technology from the other ad hoc networks, which are presented as follows:

- **No battery power constraints:** As the nodes in VANET are vehicles, these nodes have the capability to offer continuous power to the OBU through a larger long-life battery due to the OBU devices being installed inside the vehicles. This is considered to be a positive characteristic since there are no critical power challenges, as seen in MANET [63, 81].

- **Providing safe driving, enhancing traffic efficiency, and improving passenger comfort:** VANET allows moving vehicles to communicate with one another directly, and thus different applications have been applied to direct communication between vehicles over the network, which provides cautioning messages to those vehicles traveling in the same direction when there is the need for an emergency stop or an accident or other hazardous situation is ahead. These applications also provide useful information regarding the weather, nearby restaurants, shops, parks, and fuel stations [5, 81].
- **Extremely active topology:** The nature of VANET leads to changes in topology and the availability of multiple paths, which renders VANET as an extremely active topology. In other words, there is a rapid change in network topology dependent upon the velocity of the vehicle [5, 63, 82, 83].
- **Predictable motion patterns:** The nodes in VANET are random, as the vehicle is controlled by various factors such as the road lane, traffic lights, traffic system, and so forth. Furthermore, the response to other moving vehicles leads to predictability in terms of their mobility [59, 81].
- **High communication ability:** Due to the nodes in VANET being vehicles, the vehicles can be equipped with a number of sensors and computational resources such as large memory capacity, processors, advanced antenna, and Global Position System (GPS) devices. This is considered to be the

main reason for VANET's ability to obtain reliable wireless communications and gain information regarding the speed, direction, and current position of vehicles [62, 81].

- **Variable network density:** The network density in VANET changes depending on the traffic density, whereby the network density is higher in the case of traffic congestion, while the network density is lower in the case of normal traffic [63, 81, 82]. The VANET expression of the highly variable density of traffic results in extreme disturbance to the connectivity and coverage of the ad hoc networking, as demonstrated in **Figure 2-13**. In high-density traffic, data delivery can be achieved successfully. While in low-density traffic, end-to-end communications through intermediate nodes cannot be determined [62, 84]. Therefore, this project aims to improve data delivery even in sparse networks and where direct end-to-end communication between vehicles is non-existent, by depending on the DTN routing protocol mechanism.



(a) Dense scenario. (b) Sparse scenario.

Figure 2-13: An example of variable network density in VANET [85]

2.3 Part 2: Critically Analysing Routing Protocols in a Vehicular Ad-hoc Network

2.3.1 *Data Transmission in VANET*

In VANET, data dissemination can be employed to inform drivers or vehicles regarding a range of road situations such as traffic congestion and road traffic accidents, thus assisting in the prevention of road traffic accidents and the avoidance of congestion ahead [86]. Numerous studies have been conducted to design routing protocols in VANET in order to transmit messages between vehicles [37, 61, 67, 87-89]. Nevertheless, a number of limitations remain outstanding that require further investigation.

2.3.2 *Overview of Routing Protocols in VANET*

This section defines the routing protocols, which are the set of rules that determine the inter-node connection technique and how the data messages are distributed

through these nodes [62, 87, 90]. The fundamental aim behind routing protocols is to identify optimal paths between the network nodes, which have a minimum number of hops between the source and destination and have minimum overhead and delay to transmit messages with critical information between different nodes. However, VANET features unique attributes such as an extremely dynamic topology and high mobility, which cause a delay in packet delivery and a reduction in the throughput, thus decreasing the effectiveness of the route [7, 8]. Additionally, different aspects such as internal factors (e.g. mobility of nodes), external factors (e.g. road topology), and obstacles (e.g. trees, buildings, and large vehicles) restrict the signal, which affects the routing protocol's performance [56, 91]. Therefore, it is important to consider these limitations during the design of a novel VANET routing protocol.

2.3.3 *Classification of Routing Protocols in VANET*

The classification of VANET routing protocols is essential in order to individually understand the various types of such protocols. The performance of the vehicular network is dependent upon the routing protocol utilized [92]. Fundamentally, the routing protocols are affected by a range of factors such as the delivery ratio, latency, and bandwidth consumption, whereby effective routing protocols should maximize the delivery ratio while minimizing the latency and bandwidth consumption.

CHAPTER 2 BACKGROUND AND RELATED WORK

Designing an effective routing protocol for routing information among vehicles in VANET is inherently challenging due to the rapid changes and frequent disconnection between nodes [62]. Moreover, joining and leaving nodes in VANET frequently causes path disruption, which affects the total network performance. To establish communication between vehicles for road safety, effective routing protocols are required. As seen in **Figure 2-14**, the routing in VANET has been classified into five categories: geocast-based, position-based, topology-based, cluster-based, and broadcast-based routing protocols [53] which are explained in greater detail in sub-sections A-E below.

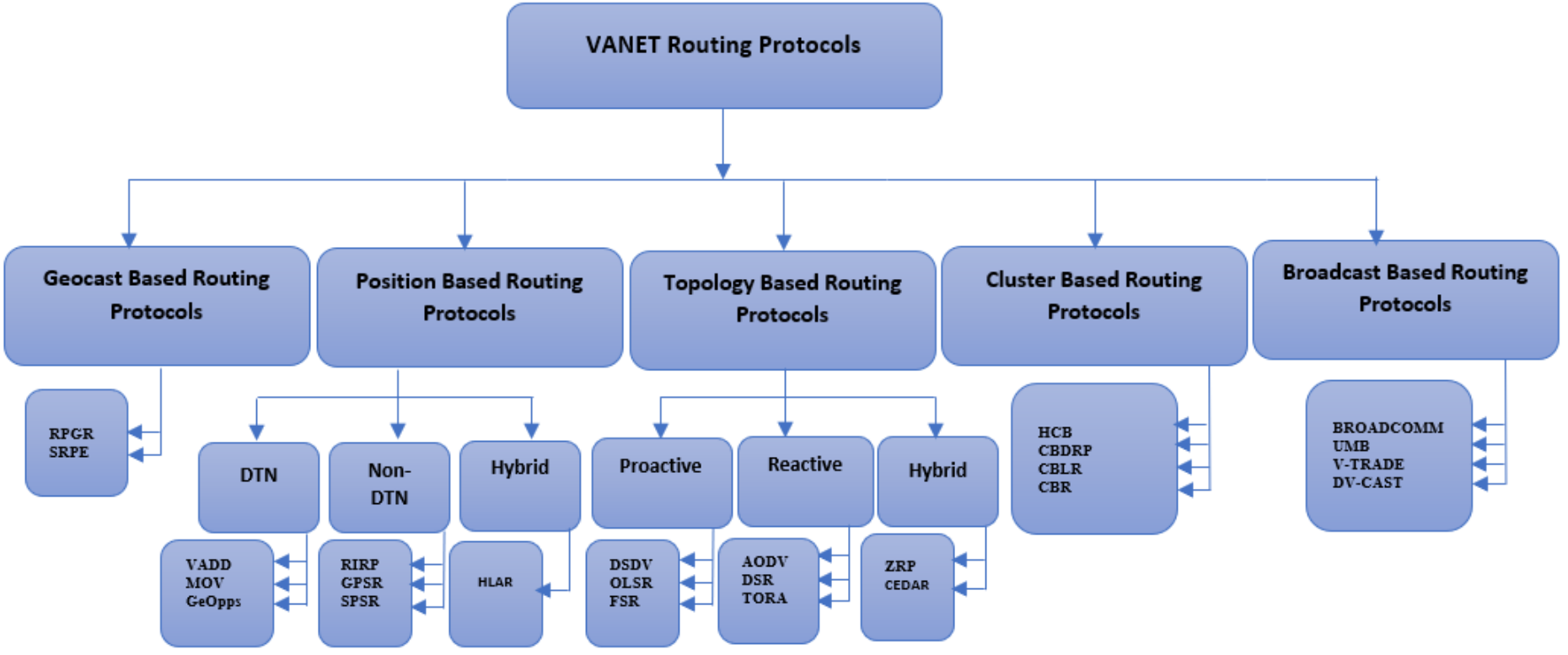


Figure 2-14: Categorisation of VANET routing protocols [65]

A. Topology-Based Routing Protocols

Topology-based routing protocols are utilized to save source-to-destination information in the routing table [93]. Their key function is to employ the link information that exists in the network in order to execute packet forwarding from the source node to the destination node. However, a number of studies [61, 87, 94] have claimed that topology-based routing protocols are not appropriate for the high mobility nodes in VANET since they cause overhead when attempting to discover routes. Three categories have been classified from topology routing protocols and are described below, namely, proactive, reactive, and hybrid routing protocols.

• Proactive Routing Protocols

Proactive routing protocols are known as table-driven routing protocols that allow each node to make a routing to record the route information in the entire nodes in the network [95]. These protocols retain the information regarding all the connected nodes in the routing table and share this with their neighbouring nodes [96]. Therefore, all nodes in the network can save the routing information for all nodes regarding the entire route in their routing table [87]. The information regarding the available routes in the network is maintained by the proactive routing protocol, even if these paths are not currently utilized [61]. Furthermore, the routing table of each node is updated and broadcast periodically to the neighbours in the network whenever a change in the network topology occurs [8, 87]. In the proactive routing protocol, shortest path algorithms are employed to determine the optimum route to

forward the packet to the destination. However, the routing table in the proactive routing protocol is periodically built and maintained within a node, which causes overhead and ineffective use of the network's bandwidth. Therefore, each entry in the routing table shows the next-hop node on the path to a confirmed destination node. It additionally leads to the maintaining of unutilized routes, which causes a decrease in the accessible bandwidth that impacts on the network performance. The various proactive routing protocols are Destination Sequenced Distance Vector (DSDV) routing, Fisheye State Routing (FSR) and Optimised Link State Routing (OLSR) [96].

• **Reactive Routing Protocols**

Reactive routing protocols are referred to as on-demand routing protocols. Their primary function is to ensure that the route is only established when the nodes need to communicate with one another. These protocols only maintain the routes that are presently in use and are unaware of the topology of the entire network [93]. Therefore, the advantages of this protocol involve reducing the burden on the network and conserving the bandwidth [8, 61]. Reactive routing comprises a path discovery phase in which the query messages are flooded into the network for path research. This stage is complete when the path is found. Transmission of the packet information in the reactive routing protocol is by forwarding a route request message, after which all existing nodes in the direction of the destination node receive the request message and forward back a route reply message to the source

node via unicast communication [56, 97]. The common reactive routing protocols in V2V communication are Associativity-Based Routing (ABR), AODV, DSR, Preferred Group Broadcasting (PGB), and the Temporally Ordered Routing Algorithm (TORA) [95].

• **Hybrid Routing Protocols**

Hybrid protocols are a mixture of protocols that combine the benefits of both proactive and reactive protocols in order to improve efficiency and scalability [61, 98]. Each node partitions the network into regions; then, inside every region, the hybrid protocols employ the reactive technique to reach the nodes outside the region, while the proactive technique is utilized to reach the nodes within the region [99, 100].

B. Broadcast-Based Routing Protocols

Broadcast-based routing protocols are frequently employed in VANET, particularly to communicate safety-related messages [93]. Basically, the broadcast routing protocol utilizes the flooding technique to transmit the data packet. Hence, the packet (message) is transmitted to all nodes in the network, inclusive of unknown or unspecified nodes. In addition, each node re-broadcasts the packet to the other nodes that exist in the network [98]. The benefits of broadcasting in VANET include not only transmitting the data packet but also delivering information without the construction of a data path [56]. Despite the reliable packet transmission in broadcast routing protocols, congested channels, extra bandwidth consumption,

and a drop in the overall performance could occur [7, 98]. The broadcast routing protocol is commonly utilized in VANET to accomplish a number of tasks, inclusive of sharing different information among vehicles such as that related to traffic and weather conditions [96]. Various examples of broadcast routing protocols include Urban Multihop Broadcast (UMB), Vector-based Tracing Detection (V-TRADE), and Distributed Vehicular Broadcast (DV-CAST) [95].

C. Geocast-Based Routing Protocols

Geocast routing protocols are also referred to as multi-cast routing protocols, whereby the functionality is the messages' dissemination from a single node (the source node) to a group of interested destination nodes [93, 101]. Fundamentally, geocast routing protocols are location-based multi-cast routing protocols, whereby their objective is to send the message from a source node to all nodes belonging to a specified geographical region, referred to as a Zone of Relevance, in order to decrease packet overhead and network congestion [56]. However, alert messages are not delivered to the nodes outside the Zone to avoid any unnecessary rapid reaction [93, 94]. The geocast routing protocol is only suitable for large networks [91], with examples including the Distributed Robust Geocast (DRG), Dynamic Time-Stable Geocast (DTSG), Inter-Vehicle Geocast (IVG), and Mobicast.

D. Cluster-Based Routing Protocols

In VANET, clustering can be defined as the virtual organization of the moving nodes into several clusters. In other words, in cluster routing protocols the nodes in

the network are grouped to become part of the cluster [86, 96]. The nodes inside the cluster are called cluster members, and every cluster has a node designed as the cluster leader, referred to as the cluster head, which will be responsible for all the network communications; for example, broadcasting the packet to its cluster member nodes or the nodes in other clusters [102]. However, the cluster head needs to be re-selected as the cluster head is dynamic and may leave its current cluster [86, 96, 103]. The benefit of using the cluster protocol and grouping the nodes is good scalability in a large network. However, the network delays and overhead increase due to the structure of clustering and the cluster head [98, 104]. Common types of cluster-based routing protocols include the Hierarchical Cluster-Based (HCB) protocol, Cluster-Based Location Routing (CBLR), Cluster-Based Directional Routing Protocol (CBDRP), and Cluster-Based Routing (CBR).

E. Position-Based Routing Protocols

Position routing protocols are also known as geographic routing protocols and have been considered a suitable routing protocol for VANET [51, 61, 105, 106]. In position-based routing protocols, the geographic location of the vehicle is considered in terms of the routing decisions and the selection of the optimum path [69]. Every node knows its' and its neighbours' positional information, with these nodes then sharing the property by utilizing geographic positioning information to choose the next forward hops [94, 100]. If the source node seeks to send a packet to the destination node, then the destination's location will be employed to identify

the nearest neighbour to the destination, which is also closer to the destination than itself, and then forward the packet to that neighbour. The packet is transmitted without any mapping knowledge to the nearest neighbouring node to the destination node [8, 69]. The establishment or maintenance of the router is not necessary in the position-based routing protocol, since it requires location services to determine the position of the target node (destination), which renders the position routing protocol superior to any other routing protocols in VANET [96, 107]. Detailed surveys of various position-based routing protocols were presented in ref. [94, 100, 105, 108], and hence the author refers the reader to these studies for further information.

Several location services can be employed to obtain geographic information: the DREAM Location Services, GPS, Reactive Location Services, and Simple Location Services [56]. Such services can help to discover an optimal path that can be utilized to send the data packet from the source node to the destination node [8]. GPS was the preferred location service employed to provide information regarding each node in the network, and that of the destination node [8]. GPS, on the other hand, is not effective in tunnels, underground, or anywhere else where satellite signals are obstructed. This project falls within the category of position-based routing protocols. The information regarding the location of vehicles is saved effectively and delivered to the destination node in a timely manner, thus rendering this protocol suitable for safety-based applications and supporting the avoidance of

road traffic accidents. Furthermore, there are three types of position-based routing protocols: DTN, Non-Delay Tolerant Networks (N-DTN), and Hybrid Routing.

• **Delay Tolerant Networks**

DTN use a packet-forwarding methodology that is dependent upon storing the message until there is a suitable node for sending the message (packet) [84, 108], thus overcoming challenges such as communication disconnections due to the dynamic topology in VANET [8, 100]. The various types of DTN are the Motion Vector Routing Algorithm (MOVE) and Vehicle-Assisted Data Delivery (VADD). In this study, the DTN routing protocols are considered.

• **Non-Delay Tolerant Networks**

The main aim of N-DTN is to address the difficulties encountered through the greedy method, as presented in **Figure 2-15**, where the source node S will send the message to node A as the closest node in order to pass the message on to the destination node D. Although the benefit of the greedy method is sending the packet to the nearest node to the destination, a problem exists whereby if the sending node is a vehicle positioned closest to the destination, it will not identify a neighbouring node to transmit the message to the destination node [52, 55]. Therefore, the N-DTN experience challenges when there is no neighbouring vehicle close to the destination, in which case the greedy strategy can fail as there is no node closer to the target node than the source node [109]. Furthermore, according to ref. [25], N-DTN routing protocols are only suitable for high-density environments, while the

DTN counterparts are appropriate for a sparse environment because routing decisions are made by taking disconnection into account [84].

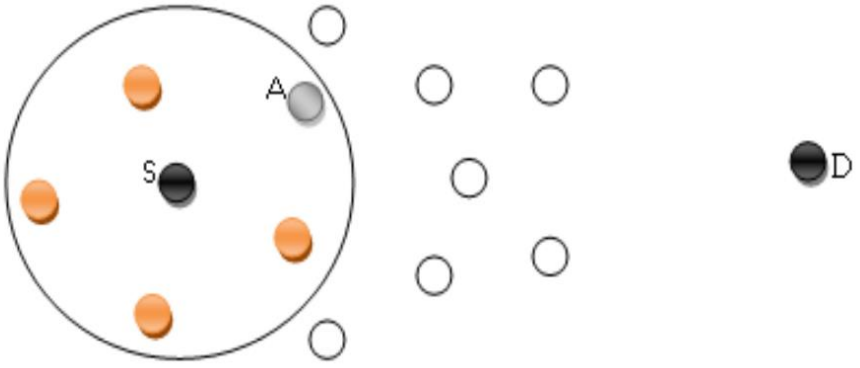


Figure 2-15: The greedy forwarding operation mode

• **Hybrid Routing**

The hybrid routing protocol benefits from DTN and N-DTN protocols, merging both strategies to resolve VANET's network disconnect problems [8, 100]. The author in ref. [56] claimed that the current routing protocols for VANET are not capable of satisfying all the traffic scenario requirements. Eventually, the comparison of various VANET routing protocol features is essential to understanding and distinguishing the different types of VANET routing protocols [8]. Therefore, **Table 2-1** presents a comparison of five routing protocol classes in VANET.

Table 2-1: Summary of five routing protocols in VANET

Type of protocol		Advantages	Disadvantages	Examples
Topology-based	Proactive	-Good performance in low-mobility networks -Routing discovery is not required since the destination route is saved in the routing table	-High overhead as the routing table is frequently updated -High bandwidth consumption	DSDV, OLSR FSR
	Reactive	-Minimises the load on the network and saves bandwidth	-High latency due to route discovery -Inability to adapt to dynamic topologies and high mobility nodes in VANET due to the overhead of the discovery routes	ABR, AODV DSR TORA, PGB
	Hybrid	-Scalability -High efficiency	-High latency for identifying new routes -Unable to operate efficiently in sparse environments where the PDR is increased	ZRP CEDAR
Position-based		-Route discovery and management are not required -Greater stable and achieves good performance in high node mobility. -Increases scalability with high mobility in the environment -Reduced overhead	-Fully dependent on GPS location service -GPS will not function in tunnels due to the absence of a satellite signal	GPSR, GSR GPCR, CAR A-STAR
Broadcast-based		-Easily implemented -Reliable packet sending as the packet is delivered through many nodes in the network	-Consumption of network bandwidth where the network size is large -Network congestion as all the nodes in the network receive the flooding message simultaneously	UMB, V-TRADE DV-CAST
Geocast-based		-Decreased congestion and overhead in the network -Reliable packet submission is achieved in highly dynamic topology	-Delay in packet transmission caused by network disconnection -Only suitable for large networks	DRG, DTSG IVG, MOBICAST
Cluster-based		-Good scalability of large networks -Good PDR -Minimised routing overhead as routes are not discovered -Suitable for large networks	-Increased delay in highly dynamic topologies	HCB, CBDRP CBLR, CBR

2.4 General Performance Metrics/Simulation Parameter

Since a system's performance can be assessed via a range of metrics, it is vital to define these metrics in this thesis as they are measured during the experiments undertaken for network evaluation. Different evaluation metrics are presented as follows:

A. Throughput

Throughput is one of the Quality-of-Service metrics utilized to analyze the performance of any system. It is calculated as the number of bits transmitted over a network per second by using **equation (2-1)**. The benefit of throughput metrics is that they provide insight into the network's capacity for transferring data, while they are also used to analyze the performance of the protocols [64]. To achieve enhanced performance, a network's throughput should thus be increased [110].

$$\text{Throughput} = \frac{\text{Total number of received packets X Packets size}}{\text{Total simulation time(s)}} \qquad (2\text{-}1)$$

B. Packet Delivery Ratio

PDR is another metric to examine the performance of any proposed approach, whereby PDR is the ratio of the total number of messages sent by a source node over the number of data messages successfully received by a destination node [13, 111]. The PDR is given by **equation (2-2)** and utilized to measure the reliability of the routing protocol in terms of routing the messages in the network, and determines the efficiency of the network [49]. It is defined as a ratio of the Number of Delivered

Messages (NDM) over the Number of Generated Messages (NGM) [112-114]. A higher PDR signifies superior network performance.

$$\text{Delivery ratio} = \frac{\text{NDM}}{\text{NGM}} \tag{2-2}$$

C. End-to-End Delay

The average time taken for a data packet to be sent successfully from a source node to a specific destination is referred to as End-to-End Delay (EED) [115] and includes the transfer time, processing time, and the path between the source and destination [112, 116]. EED is calculated using **equation (2-3)**:

$$\text{EED} = \frac{\text{Time packet received} - \text{Time packet sent}}{\text{Number of received packets}} X100 \tag{2-3}$$

D. Latency Average

Measured in seconds, the latency average is defined as the average time necessary for messages in the network to be delivered to the destination. Meanwhile, other parameters in the network are ratio values that do not have units such as delivery ratio and overhead. Therefore, the latency average is given by **equation (2-4)**:

$$\text{Latency average} = \frac{\sum_{i=1}^{\text{NDM}} t_i}{\text{NDM}} \tag{2-4}$$

Where t is the latency experienced by messages.

E. Packet Drop

The packet drop is the number of messages dropped from the node's buffer during the simulation, which should be minimized for enhanced performance. Packet drop (PD) is computed using **equation (2-5)**:

$$\text{PD} = \text{Total packets received} - \text{Total packets created} \quad (2\text{-}5)$$

F. Average Hop Count

The average hop count can be defined as the number of hops required to transmit a message from the source to the destination [117]. The hop count is defined as the number of nodes that a message has been sent to thus far. If the message is created at a node, the hop count is calculated as zero, that is, the hop count indicates the number of hops that the message passed between the source node and the destination node.

G. Overhead Ratio

The overhead ratio (OR) is another metric to evaluate the performance of various routing protocols, which is defined as a ratio of the NDM and the Number of Relayed Nodes (NRN) and can be obtained by **equation (2-6)** [114]. The optimum network performance features the smallest network overhead.

$$\text{Overhead ratio} = \frac{NDM - NRN}{\text{NDM}} \quad (2\text{-}6)$$

2.5 Challenges in VANET

Due to the dynamic network topology and rapidly changing channel conditions in VANET, various challenges still exist and require further investigation [62, 86, 118, 119], which are summarised as follows:

1. **Security and privacy:** As wireless communication is utilized to communicate between the nodes in VANET and exchange data via a wireless channel, these communications must be secure as they are exposed to threats and attacks such as phishing certain information or user access issues [57, 120]. According to Sheikh, et al. [71], a comprehensive study of VANET security has been carried out. Moreover, the implementation and challenges of various methods and approaches have been explored in detail due to the need to achieve the fundamental security requirements necessary to ensure effective security in VANET. However, certain challenges remain to achieve a level of security that meets all security requirements.
2. **Frequency path breaks:** The nodes in VANET are vehicles that result in an extremely dynamic topology. Due to these moving vehicles, the rapidly shifting topology and repeated disconnection among the nodes (vehicles) are problematic in terms of designing an efficient routing protocol for exchanging information among vehicles [70, 86].
3. **Bandwidth limitation:** Another major issue in VANET is the absence of any central buffer management system to control the communication and

transmission events between various nodes, or to take responsibility for coordinating the bandwidth and connection procedure. Consequently, VANET suffers from channel congestion, particularly in a high-density environment [63, 119, 121]. Therefore, it is vital to efficiently utilize the available bandwidth.

4. **Signal delay and fading:** Fading in the network occurs when the signal transmitted by the sender is reflected by obstacles on route to the receiver. These obstacles could be any object located along the road such as buildings, trees, or other vehicles. These obstacles are considered to be the primary reason for impacts on the efficiency of VANET because they lead to a delay in the signal reaching the receiver compared to a direct path signal. The impact of obstacles is the prevention of the signal from arriving at the receiver in a timely manner, as well as an increase in the fading of the transferred signal [63, 121].
5. **Routing protocol:** Designing a routing protocol that can be efficiently employed to transfer information between vehicles and ensure message delivery without delay and with fewer packet drops is another serious issue in VANET due to the highly dynamic and changing topologies in the VANET [59, 86].

6. **Connectivity:** The rapidly changing topology and high mobility are the main reasons for frequent disconnection in the networks that cause packet loss or drop [59, 86].

2.6 Summary

This chapter featured two parts. The first part extensively reviewed VANET from different aspects including the VANET architecture, standards for wireless access, and characteristics. An overview of the VANET applications was also presented, namely, for safety applications and comfort applications. This research focuses on the safety application of VANET since this is important to prevent road traffic accidents.

In the second part, an overview of VANET routing protocols was presented, with various types of routing protocols categorized. Moreover, the benefits and drawbacks of these routing protocols were highlighted, which can help researchers either design a new routing protocol or improve existing ones. Finally, the challenges in VANET that require additional work were highlighted.

As the proposed project is focused on a position routing protocol to improve road safety, Chapter 3 proposes an innovative system for VANET using OMNeT++ as a network simulator, SUMO as a traffic simulator, and VEINS to integrate both into the VANET model.

Chapter 3 Simulation Design and Implementation of High Density and Sparse Vehicular Networks

Objectives

- Provide an overview of the package tools to model VANET
- Discuss the frameworks or potential methodology to combine VEINS and SUMO along with the OMNeT++ simulators
- Discuss the ONE simulator
- Summarise the chapter

CHAPTER 3 SIMULATION DESIGN AND IMPLEMENTATION OF HIGH DENSITY AND SPARSE VEHICULAR NETWORKS

3.1 Introduction

In this chapter, two different methodologies that are utilized to generate our contributions are described. Hence, this chapter is structured in two parts: the first part evaluates the VANET scenario, while the second part evaluates the EMRT technique.

First, as mentioned previously, road traffic accidents represent a serious global issue. The severity of these accidents may be exacerbated due to a lack of information processing capacities and the delayed response time for abnormal events such as road traffic accidents (emergency). The delayed response in an emergency event on the road is either due to driver inexperience or panic in responding to a hazardous situation, which is considered the main reason for road traffic fatalities. Therefore, in order to improve the transportation system, VANET allows vehicles and RSU to communicate with each other wirelessly and exchange information, which can help to mitigate traffic issues such as collisions and congestion [58]. To achieve this aim, VANET technology is considered in this chapter to facilitate communications between vehicles and enable them to share updated information (e.g., location, position, and speed), as well as exchange warning messages to avoid road traffic accidents. Therefore, this chapter not only focuses on vehicles communicating wirelessly with each other (V2V) or with the roadside (V2R) but also on exchanging emergency warning messages to provide

the opportunity for other vehicles to avoid road congestion and prevent collisions by taking appropriate and timely action. Hence, the packet (message) is transmitted to all nodes in the network, inclusive of unknown or unspecified nodes. In addition, each node re-broadcasts the packet to the other nodes that exist in the network. This leads to improved road safety, reduced road traffic accidents, and the preservation of road users' lives.

Second, DTNs are networks without a contemporaneous path between the source and the destination, whereby the nodes employ the SCF method to route traffic. However, the approaches based on flooding an unlimited number of replicas of generated messages will not perform effectively if the network resources are limited. On the other hand, while quota-based approaches are resource-friendly, they suffer from low delivery ratios and high delivery delays. Therefore, this study proposes an EMRT to generate the number of replicas dynamically based on the capability of the nodes to disseminate messages promptly. Such a decision is based on the existing connections, history of encounters, history of buffer sizes, TTL values, and available energy. The EMRT technique is applied to the three different quota-based protocols, namely, Spray&Wait, Encounter-Based Routing (EBR), and DBRP. Therefore, the ONE simulator is employed to implement the EMRT and compare the results with the original protocols in order to validate our technique.

In order to implement DTN routing protocols and evaluate the proposed technique, we select the ONE simulator that is specifically designed for DTN [122].

3.2 Methodology 1: Different Packages to Model the VANET Environment

The majority of the research is concentrated on simulations to implement VANET because implementing such a system in the real environment involves high costs and unnecessary risk. Choosing the proper simulation for VANET is not an easy task. The difference between various features of simulation including enhancement capability, ease of use, accuracy, and so forth have been discussed [68, 123], which offers valuable insight for new researchers to understand the VANET simulators and also distinguish between their features. VANET simulators consist of two types: mobility/traffic simulators and networking simulators. A summary of the software that can be utilized to model and evaluate the performance of the networks is listed in **Table 3-1.**

Table 3-1: Summary of vehicular network simulators and simulation systems

Network simulator & simulation framework	ONE	NS-2	NS-3 & iTetris	OMNeT++ & VEINS	QualNet
License	GNU GPLv3	GNU GPLv2	GNU GPLv3	Academic	Commercial
Written language	Java	C++	C++	C++	C/C++
Simulation language	Java	C++/OTcI	C++/Python	C++/NED	C/C++
GUI IDE	Yes	No	Yes (with iTetris)	Yes	Yes
Officially supported wireless technology	None[b]	Wi-Fi/ Satellite/ Cellular	Wi-Fi/WiMax /LTE	Wi-Fi/802.11p/ WiMax (with VEINS)	Wi-Fi/WiMax /GSM/UMTS /LTE/Zigbee
Scalability	Small	Medium	Large	Large	Large
Coupled with a traffic simulator	No	No	Bidirectionally with SUMO	Bidirectionally with SUMO	No

[a] Allows effective interaction between dedicated simulators (network & traffic simulators).

[b] Makes a total abstraction of the network's lower layers and instead focuses solely on the routing and applicative layers.

These simulators can be distinguished by their features, work, and design. In next subsection, the OMNeT++ network simulator, SUMO traffic simulator, and VEINS simulation framework are presented in the following subsections:

3.2.1 *Objective Modular Network Testbed*

The Objective Modular Network Testbed (OMNeT++) simulator is defined as a discrete network-based simulation framework that is implemented primarily for network simulation and various applications. OMNeT++ can be described as software written in C++ that has the ability to represent an event network simulation

system [13, 124]. The OMNeT++ software is employed in this chapter because it offers benefits such as being well structured, supporting wired and wireless communications, being highly modular and not limited to network protocol simulation, and its ability to work in parallel with traffic simulators such as SUMO [125]. Moreover, OMNeT++ is extensible and helps to develop reliable network services.

3.2.2 *Simulation of Urban Mobility*

Simulation of Urban Mobility (SUMO) is a traffic simulation that can be employed to simulate the mobility of the nodes by generating the vehicle trajectories for the network simulation. SUMO supports multi-model traffic such as pedestrians, vehicles, and bicycles [126]. The SUMO traffic simulator is employed in this chapter to enable an accurate representation of the interactions of vehicles in a realistic environment.

3.2.3 *Vehicles in Network Simulation*

Vehicles in Network Simulation (VEINS) is one of the most widely recognized VANET simulations in the scientific world. It is an integrated VANET simulator that can produce a bidirectional interaction between a network simulator (e.g. OMNeT++) and a traffic simulator (e.g. SUMO) in order to exchange vehicle mobility data [125, 127]. In terms of improving road safety in VEINS, there are three fields of focus, namely, application, service, and network, as shown in

Figure 3-1. Therefore, in order to avoid or reduce road traffic accidents in VANET, one of the intelligent vehicle safety applications is utilized in this chapter. This application enables a disabled vehicle to warn approaching vehicular traffic regarding its abnormal status, with a disabled vehicle here referring to one that has been involved in an accident [128]. This warning can be achieved by using the onboard sensors and OBU, which are components of every vehicle participating in VANET. Onboard sensors are employed to determine if the vehicle is in an abnormal situation, while the OBU devices are utilized to exchange data with RSUs or with other OBU.

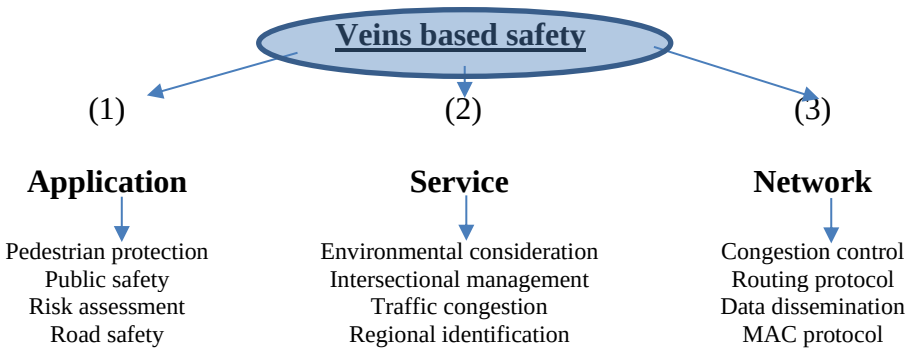


Figure 3-1: The classification of VEINS-based safety

3.3 Methodology to Integrate VEINS and SUMO with the OMNeT++ simulator

The simulation steps are considered for modelling the mobility of the vehicles employing SUMO, with the safety application then configured in OMNeT++ to run the simulation. **Figure 3-2** illustrates the full packages to model VANET. Due to the traffic on the road impacting traffic on the network, and vice versa, this chapter

utilizes a bi-directionally coupled road traffic simulator with an event-based network simulator, resulting in a realistic simulation for VANET.

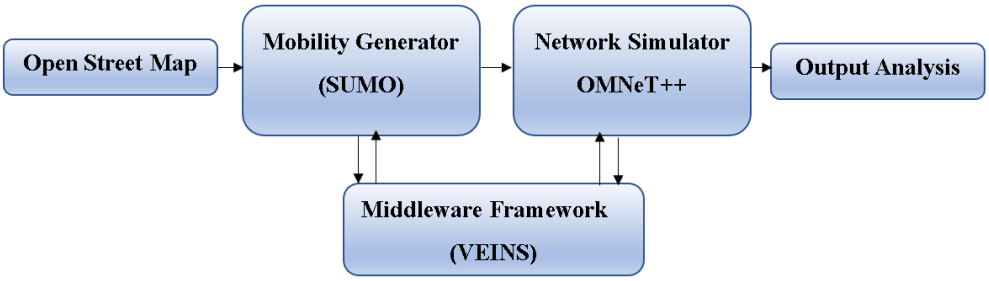


Figure 3-2: The simulation package for VANET

To this end a Traffic Control Interface (TraCI) is required, which is a standardized protocol employed for communication between both simulators, enabling the possibility of bidirectional coupling, as shown in **Figure 3-3**, which can allow the network simulation to also influence the traffic simulation, and vice versa [129]. TraCI utilizes a TCP-based client/server-based architecture to provide access to SUMO. The TraCI scenario manager module in OMNeT++ enables a network simulation running in OMNeT++ to send TraCI commands that control the traffic simulator in SUMO.

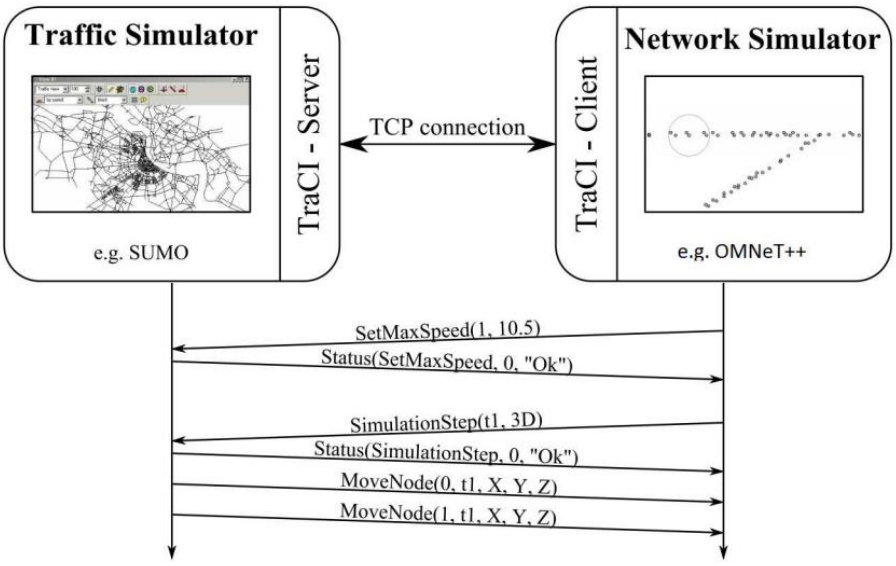


Figure 3-3: The network simulation coupled with the traffic simulator using TraCI [130]

3.3.1 *Pre-Simulation Steps*

First, SUMO (v. 1.8.0), OMNeT++ (v. 5.6.2), and VEINS (v. 5.1) were installed to enable their utilization in this chapter. Second, the INET and VEINS frameworks were downloaded and imported into OMNeT++ to reference them to our OMNeT++ projects. Thirdly, OpenStreetMap (OSM) was utilized to import real-world traffic maps. We extracted a real-world map of Leicester city from www.OpenStreetMap.org [131] for this simulation, as shown in **Figure 3-4**. This downloaded map has an *.osm* file extension. OSM is an online repository that contains real-world traffic maps.

Figure 3-4: Leicester city region from OpenStreetMap considered for the simulation

3.3.2 *SUMO Simulator Setup*

The procedures for setting up a SUMO traffic simulation for utilization to simulate VANET are described in this sub-section. The SUMO simulator is employed to generate the traffic scenario, as shown in **Figure 3-5**, where the Leicester map is downloaded with an *.osm* extension.

Figure 3-5: Leicester map network in SUMO

Then, the *.osm* file is utilized to generate the other two important files: *.net.xml* and *.rou.xml*. These files are utilized to feed SUMO and help to generate *SUMO.cfg* files. Next, when we open the *SUMO.cfg* file, we will get the network on SUMO, as shown in **Figure 3-6**.

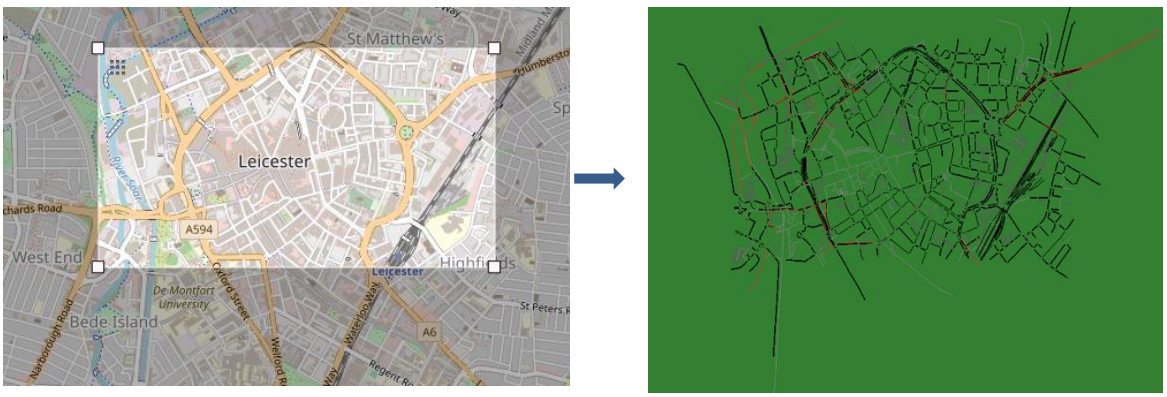


Figure 3-6: Leicester map from OSM to SUMO

Then, the *Leicester.net.xml* file can be employed to generate a *Trips* file using the randomTrips python script provided with the SUMO package, as shown in **Figure 3-7.**

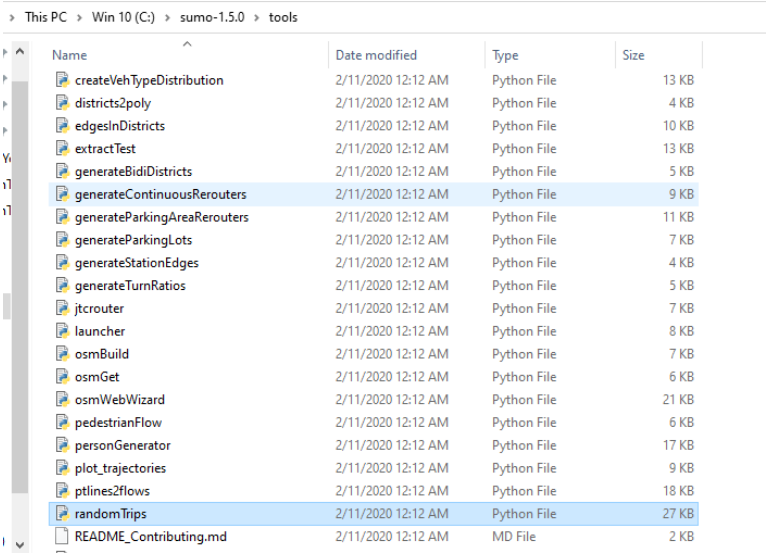


Figure 3-7: Generating random trips

3.3.3 *Integrated OMNeT++, SUMO, and VEINS*

To integrate between OMNeT++, SUMO, and VEINS we should write in the OMNeT++ command: /C/direction for sumo-launched /sumo-launchd.py -vv -c /direction for sumo.exe/sumo.exe

For example, in our work:

/C/omnetpp-5.6.1/samples/veins/sumo-launchd.py-vv-c/C/sumo-5.0/bin/sumo.exe

The SUMO script is launched to interface between the SUMO and OMNeT++ simulators. *SUMO.lanched* is designed to run in the background, listen to incoming requests, and to help facilitate the running of a number of simulations. If we get the output shown in **Figure 3-8**, SUMO is now ready to run in the playground parallel

with OMNeT++. Leaves this window open and switches back to OMNET++ IDE to finish the work.

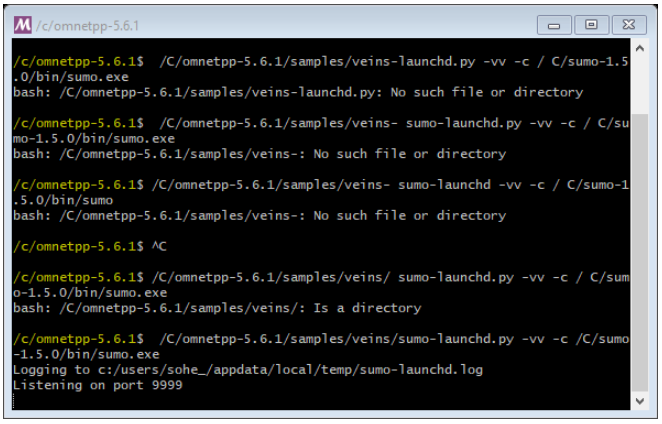


Figure 3-8: The OMNeT++ command screen to launch the SUMO script

3.3.4 *The Implementation Steps*

The safety application is implemented in the OMNeT++ simulator. A number of parameters can be provided by this safety application and can also be modified in the *.ini* file in OMNeT++. The vehicle in OMNeT++ is defined as a compound module that gathers in sub-modules, as shown in **Figure 3-9**.

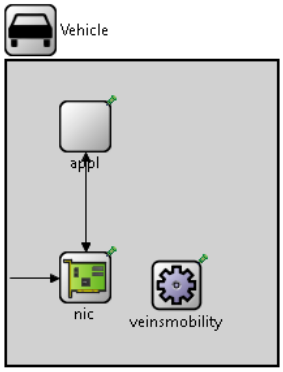


Figure 3-9: Vehicle compound module in OMNeT++

- Appl is a simple module that is implemented to model the safety application to the system.

- Veinsmobility is a mobility module for hosts, controlled by the TraCI scenario managers.

- NIC is the interface card, which is a compound module consisting of both MAC and PHY submodules. **Figure 3-10** presents the Nic IEEE802.11p that includes the MAC IEEE 1609.4 and PHY IEEE802.11p.

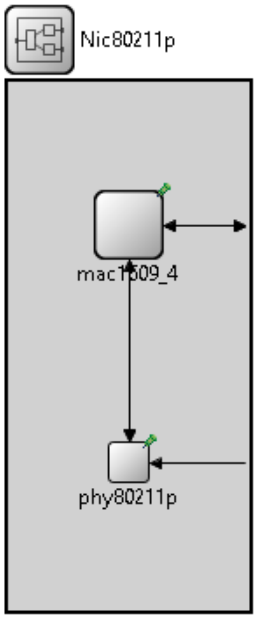


Figure 3-10: The IEEE802.11p compound module in OMNeT++

3.4 Scenarios of the VANET Communication Using OMNeT++, INET, and VEINS

As the main aim of our project is to improve road safety in VANET, one objective is determining how to transmit an alert message to the neighbouring vehicles to warn the other drivers regarding a hazardous situation ahead. Such messaging also helps drivers to take appropriate action to avoid road traffic accidents and prevent traffic congestion. Every vehicle should be equipped with GPS and OBU, with the latter a device fixed inside the vehicle to communicate and exchange information with other vehicles or with the RSU. All these communications will be wireless and the messages will be transmitted through DSRC [62], which has the nature of IEEE802.11p. Meanwhile, the GPS device is employed to update the vehicle's information such as the location, speed, and direction. OMNeT++ is employed to construct the network simulation, while SUMO is utilized to simulate road traffic, and VEINS is used to integrate both OMNeT++ and SUMO to simulate the VANET environment.

In this section, the safety application is presented. With this safety application, a vehicle that is involved in a road traffic accident will immediately warn the approaching vehicles regarding its hazardous state. This will help these neighbouring vehicles to react in a timely manner by either reducing their speed or changing direction, which can help to prevent road congestion and avoid other road

traffic accidents. For multi-hop to work effectively in this scenario, it is necessary to have intermediate vehicles or RSUs through which to relay the information. With V2V communications, the approaching vehicles are warned by the disabled vehicle regarding its position. While with V2R, the RSU will transmit a warning message to vehicles approaching the accident scene. Cooperation between V2V and V2R communications is used in this chapter to address the shortcomings of the stand-alone V2V and V2R networks. Vehicles can be connected to other vehicles and to a stationary RSU as follows:

Case 1: (V2V)

Figure 3-11 depicts the V2V communications in the Leicester scenario using the OMNeT++ simulator. With V2V communications, all mobile nodes will help each other to forward messages. A real map mobility model with node density values is employed to present the communications. A safety application is introduced to broadcast warning messages between the vehicles, which are utilized to alert drivers of hazardous situations ahead.

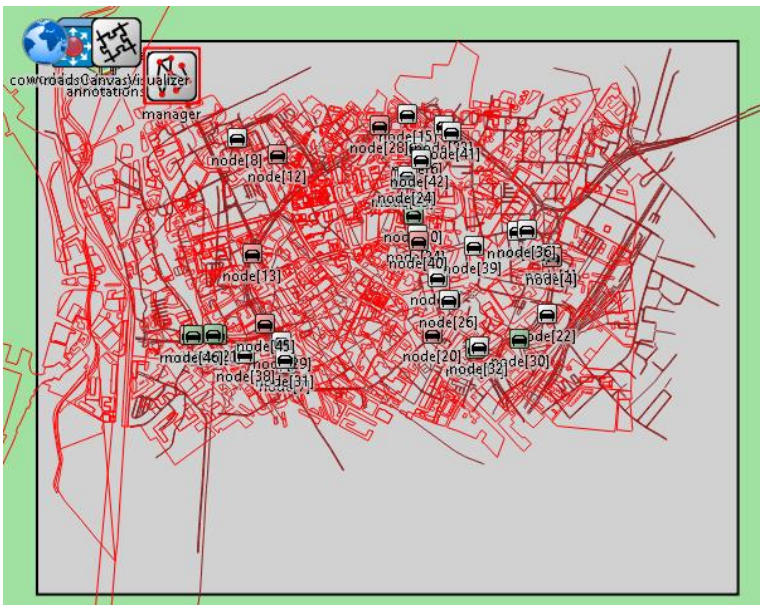


Figure 3-11: The V2V communications in a simulated network

Case 2: (V2R)

The driver in a V2V context may require additional time to react to an emergency message and take suitable action such as slowing down or selecting an alternate route. In such cases, a RSU will be authorized to generate the warning message in case there is an emergency and then transmit these messages to all the vehicles in the same communication range in order to react regarding the upcoming hazard [58, 62, 69]. **Figure 3-12** shows the V2R communications in the Leicester scenario that is used in our implementation. This figure indicates that everything worked perfectly where a working simulation scenario using OMNeT++ and SUMO has been provided to simulate the stream of vehicles that get interrupted by an accident.

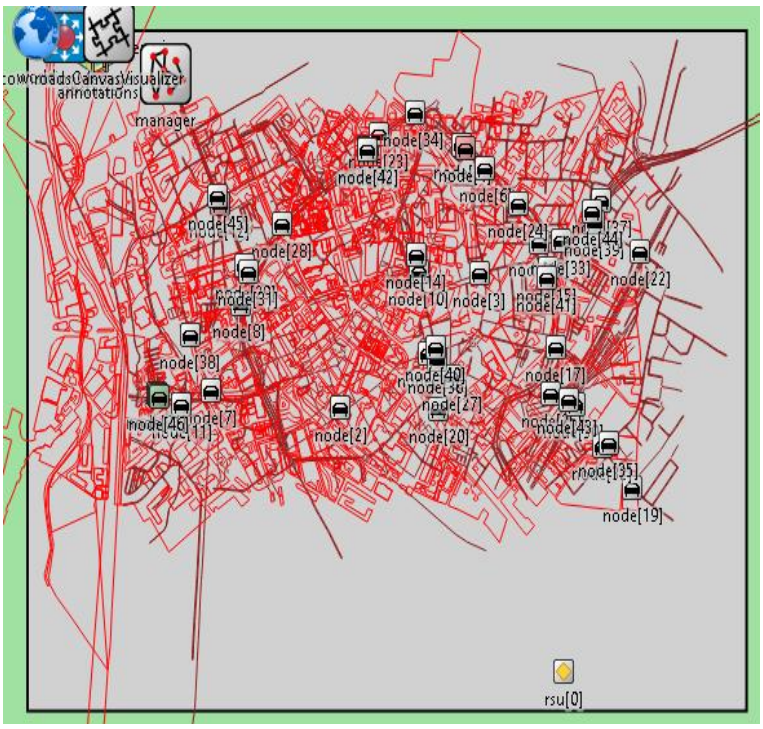


Figure 3-12: The V2R communications in a real network

3.5 Discussion of the Safety Application Implementation Steps

This section discusses how the simulation of the VANET scenario in terms of the safety application is introduced to broadcast warning messages between the vehicles and infrastructure. The emergency message will be disseminated rapidly and as widely as possible to the destination, which can prevent additional collisions and reduce traffic congestion. This simulation shows a traffic situation, where one vehicle suffers an accident and stays in that place for a given amount of time. When the accident happens, the vehicle sends out a message to the roadside unit RSU and the other vehicles. The RSU repeats the message with a bit of delay, so vehicles that

arrived after the first wave of messages would know about the accident too. When vehicles receive the message, it gets a chance to change routes, after that, they also replay the received message. This aim is implemented as follows:

1. First, the simulation commences normal running where the vehicles start to circulate (white vehicles). Then, during a certain time duration, there is an accident on the road at 73 s that is detected by vehicle (0), as shown in **Figure 3-13**. Vehicle (0) that is involved in the accident is referred to as the Abnormal Vehicle (AV). The AV detects the accident through its onboard sensors. The AV is then stopped by setting its speed to zero and its color is changed to red in SUMO. After that, the AV periodically creates and broadcasts a warning message titled "Accident" with high priority to all the neighbouring vehicles that appear in the same communication range of the accident area. This message contains important information such as the current position of the vehicle, the route ID, and the vehicle status. Finally, when a vehicle receives this warning (Accident) message, its color changes to green, and then it replies back to the AV to confirm that the message has been received.

2. The received or warned vehicles start to change their direction to save time by avoiding road congestion and thus saving lives by reducing the probability of other road traffic accidents occurring.

3. As can be noted from the **Figure 3-13**, the speed of the vehicle (0) is zero (this means that the car is stationary) at 73 s due to being informed regarding a road traffic accident.

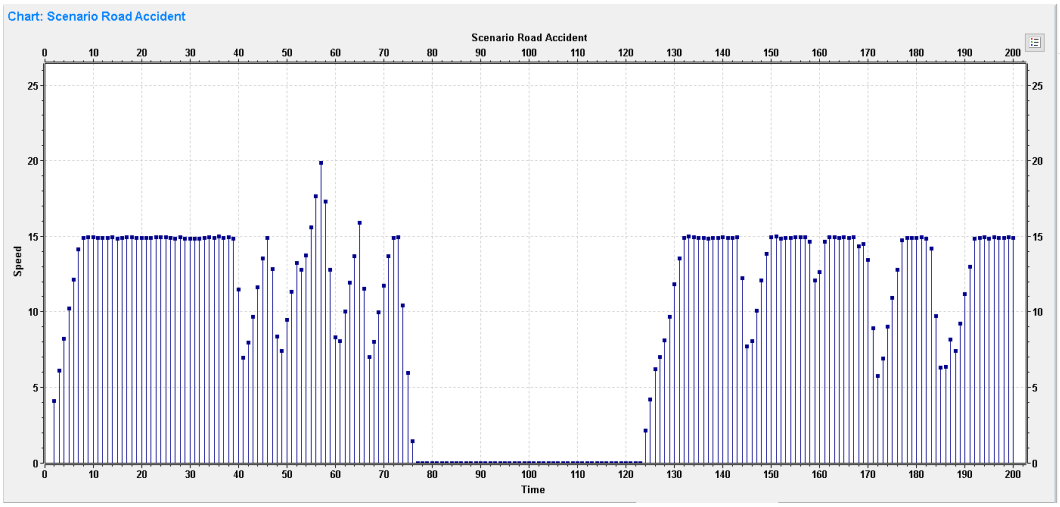


Figure 3-13: The acquired results of using the road accident scenario for Leicester city

3.6 Methodology 2: The ONE Simulator

As previously mentioned, two different methodologies are considered in this chapter, with this section utilizing the ONE simulator as the second methodology. The ONE simulator is a Java-based open-source simulator for DTN routing protocol implementation and testing. It was designed especially for the evaluation and implementation of various DTN routing protocols. The ONE simulator's main functions include modelling node mobility, inter-node communications via different interfaces, routing, message handling, and application interactions [132]. The ONE simulator has a Graphical User Interface (GUI) that is launched with Java,

as shown in **Figure 3-14**. It is possible to zoom in and out and to change the speed by using the GUI update icon in the playfield graphic. The playfield graphic features various buttons and icons to play the simulation step forward internally, enable and disable fast forward, and play the simulation for a specific period of time. Furthermore, the results of the ONE simulation can be collected, principally through reports that are created by report modules during the run time of the simulation. The report modules initially receive the events from the simulation engine and then create results based on these received events.

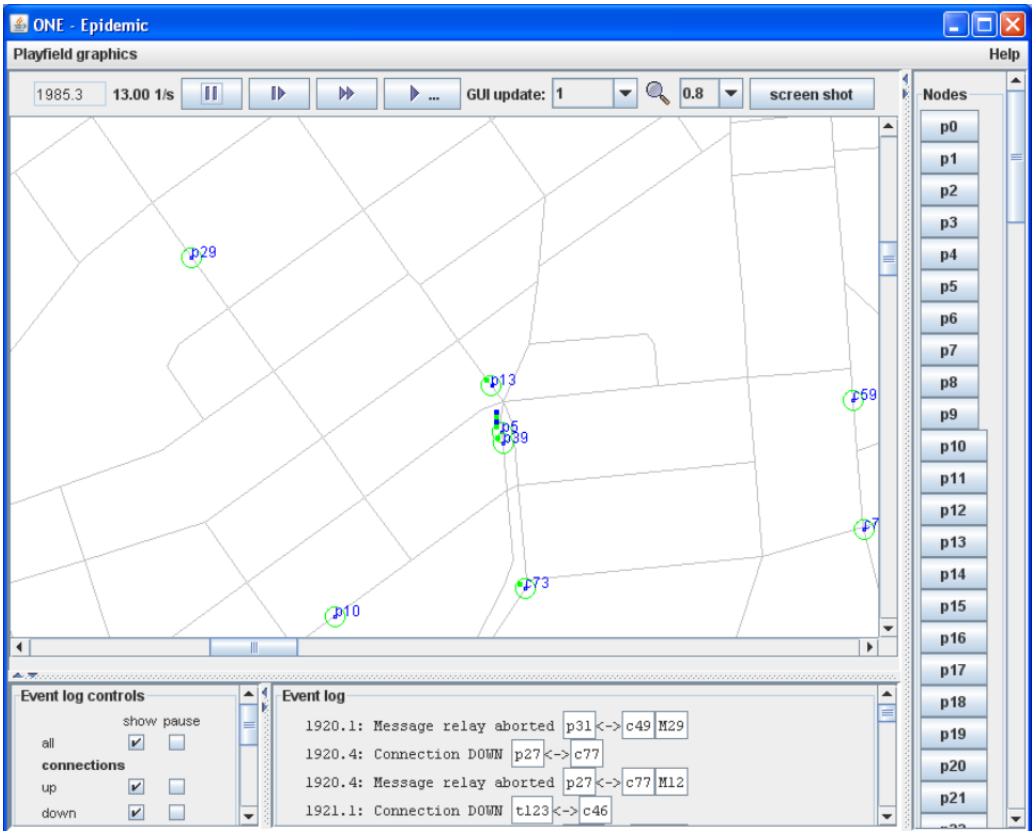


Figure 3-14: The GUI of the ONE Simulator

3.6.1 *Justifications for Selecting the ONE Simulator*

Various software can be employed to model the routing protocols. Among these packages, the ONE simulator has the advantage of modelling the DTN routing protocols. The ONE simulator has suitable simulation tools that are designed in particular for evaluating the DTN routing protocols. For this reason, in Chapters 4 and 6 the ONE simulator was considered to implement and compare various DTN routing protocols. The ONE simulator depends on mobile node movement, the density of the nodes, and the distance between the sender and receiver. These factors significantly affect the performance of the DTN routing protocols such as the reliance on latency, the probability of delivery, and the overhead ratio, among other factors. The main criteria are to identify a suitable routing and forwarding approach, and then to match these techniques with real-time mobility.

3.6.2 *Compile the ONE Simulator*

The ONE simulator software can be compiled in two ways:

1- Compile the *compile.bat* file with Java 6 JDK. However, the command prompt is required to run the ONE simulator through this method. Therefore, we utilized the basic Windows CMD command.

2- Implementing Eclipse IDE. We downloaded Eclipse IDE for Java Developers (v. 2020-06). Then, we included the Jar library in a build path

in the project by selecting the "DTN console connection. Jar". Finally, *ECLA.jar* was added and the compiler was ready to run.

3.6.3 *The Methodology and Evaluation of EMRT*

There is increasing interest in utilizing the DTN routing protocols in communications, which could overcome the challenges of the environment and resolve the limitations of traditional protocols. The DTN routing protocol requires high performance and developing routing to deal with mobility, intermittency, and node characteristics. One of the important works conducted to develop a novel powerful tool led to the ONE simulator, as presented by Keränen, *et al*. [122]. This software package facilitates the modelling and the creation of different scenarios where a number of DTN routing protocols (i.e. Epidemic, Spray&Wait, PROPHET, MaxProp, and Rapid) can be tested and investigated. The GUI provided by the ONE simulator allows the visualization of the node's movement during the simulations, which facilitates the understanding of the simulation [133]. In addition, visualization, reporting, and post-processing tools are utilized to collect and analyze the data [132]. The ONE simulator employs a map of Helsinki and includes various mobility models, such as the Shortest Path Map-Based Movement, the Cluster Model, the Map-Based Movement Model, and the Random Waypoint Model [134]. The software is flexible for use with DTN routing protocols when compared with

the alternatives such as OMNeT++, NS2, and NS3 [122]. Therefore, the ONE simulator is used in this thesis to evaluate the proposed EMRT.

3.7 Summary

In this chapter, an overview of the simulations considered to simulate VANET was discussed. From the simulations, it was established that we can integrate OMNeT++ with SUMO and VEINS to simulate the VANET environment, with SUMO employed to generate the movement of the vehicle and OMNeT++ generating the network. In addition, a real-world network with high-density traffic in VANET was considered where the end-to-end connection exists so that vehicles can communicate with each other through V2V or V2R means, and thus data delivery can be successfully achieved. Meanwhile, in a low-density environment, the traditional VANET routing protocols face a significant issue that requires end-to-end connectivity between vehicles. To address these limitations, in the second part of this chapter, the ONE simulator was proposed as the second methodology in this research. Moreover, DTN routing protocols were considered since these are the optimum protocols for application in a sparse network environment where end-to-end communication between vehicles does not exist. As the performance of DTN is influenced by the routing protocol and buffer management, Chapter 4 explores both these in greater detail.

Chapter 4 Performance Evaluation of DTN Routing Protocols and Buffer Management Policies

Objectives

- Present an overview of DTN routing protocols
- Discuss the categorization of five DTN routing protocols
- Test and compare five DTN routing protocols using the ONE Simulator
- Present an overview of buffer management
- Discuss the categorization of six dropping buffer management policies
- Test the impact of TTL value on the six dropping policies
- Summarize the chapter

CHAPTER 4 PERFORMANCE EVALUATION OF DTN ROUTING PROTOCOLS AND BUFFER MANAGEMENT POLICIES

4.1 Introduction

DTN is a promising technique that can transmit data in challenging environments where the end-to-end path is not accessible. The link between the pair of nodes in DTN environments is frequently disrupted due to the rapid mobility of nodes, the nature of the dissemination, and power outages. DTN is characterized by intermittent connectivity, long delays, and high error rates [135]. A number of routing protocols have been utilized to serve a range of scenarios and topologies [108]. However, due to the random shifts in topology and the absence of an end-to-end route, routing is considered one of the major issues that impact the performance of DTN networks in terms of data delivery and resource consumption [49]. Therefore, effective routing in DTN that can direct the messages from one node to another is required. The main aim of this chapter is to study the performance of routing protocols in resource-constrained opportunistic networks. This is achieved by analyzing the performance of five DTN routing protocols that represent different DTN routing protocol classes: Epidemic, Spray&Wait, PRoPHET, MaxProp, and Rapid against changes in the network density and the buffer capacity using two different movement models. The main aim of this comparison is to offer an enhanced understanding of the behaviour of different DTN routing protocols in terms of delivery probability, overhead ratio, latency, and hop counts. Furthermore, the performance of these DTN routing protocols is modelled using the ONE simulator and a number of simulation models. The outcomes of this simulation

reveal that the MaxProp routing protocol provides the optimum performance of the five DTN routing protocols in terms of the delivery ratio in both the Shortest Path-Based Movement Model and Cluster Model.

To obtain high data delivery, the DTNs employ the innovation of the SCF technique that enables data transmission to successfully proceed to the destination despite the absence of continuous end-to-end paths [135]. However, various issues arise when using this technique such as buffer congestion and message drop, which result due to the growing number of carried messages in restricted network resources. Therefore, buffer management techniques are required to manage the buffer capacity of the nodes by determining how to effectively and precisely drop the messages and schedule the messages in the node's buffer. Therefore, this chapter also aims to study the impact of TTL on different drop policies for DTN routing protocols, with the performance of six buffer management policies evaluated, namely, First-In-First-Out (FIFO), Last-In-First-Out (LIFO), Drop Largest (DL), Drop Youngest (DY), Evict Shortest Lifetime First (SHLI) and Evict Most Forwarded First (MOFO), with the MaxProp and Spray&Wait routing protocols under variable message TTL values (60–300 min, with a step-change of 60 min). Moreover, this study utilizes the ONE simulator to evaluate the performance of the dropping policies, where five performance metrics are considered: delivery ratio, overhead ratio, average latency, hop count, and message drop. The evaluation results of each buffer management policy are briefly explained by these metrics.

4.2 Overview of DTN

A communication network capable of storing messages temporarily in intermediate nodes until the time that an end-to-end route is re-established is known as a DTN or disruption-tolerant network. DTN is defined as intermittently and sparsely connected (wireless) network, where the end-to-end connectivity between the source and destination nodes is not guaranteed. DTN can perform in challenging environments where a conventional network fails due to the absence of end-to-end communication [16, 136-138]. Examples of such challenging environments include animal habitat monitoring and network sensors for wildlife tracking [139], deep space communication sensors, underwater communications [140], disaster environments [141], and VDTN applications [142].

4.2.1 *Characteristics of DTN*

DTN has features that distinguish it from other networks such as long latency, unstable network topology, limited network resources, and disturbance of the end-to-end communication (intermittent connection) between nodes [135, 143]. Consequently, the routing protocol is the main issue in DTN, whose characteristics can be described as follows:

1. *Limited Resources:* In DTN, the nodes have limited resources such as bandwidth, energy, and buffer capacity. Therefore, the messages should be stored in the node's buffer in order to transmit them to the next node when the path is available. Nevertheless, since when a new message is received buffer

space is required to store the collected data, the data buffering will be restricted by limited memory capacity [144].

2. *Intermittent Connectivity:* Due to the node mobility and energy limitation, which are compounded by the continuous network topology change, the DTN is repeatedly disconnected (intermittent network) and an end-to-end path is unavailable [144].
3. *High Delay, Low Data Rate*: The intermittent connection in DTN causes a high delay and a low data rate. Due to the periods of disconnection, the message is stored in the node's buffer until an inter-node connection becomes available [144].

4.2.2 *Comparison Between the Conventional and DTN Routing Protocols*

As a comparison, the conventional routing protocols aim to create an end-to-end path between the source and the target nodes. While in the DTN, the main goal is to establish a pathway to enable the messages to arrive at their target node. Furthermore, with the traditional routing protocols, the delay will be shorter than that seen with the DTN routing protocol because, with traditional routing protocols, the routes are pre-defined when the packet leaves the source node. On the other hand, in order to maximize the delivery ratio, the DTN must exploit the possible contact among the intermediate nodes, source node, and destination node. Moreover, the use of the intermediate node's storage devices should be managed by the routing protocols [11]. **Figure 4-1** and **Figure 4-2** help to illuminate the

difference between the traditional and DTN routing strategies, respectively. To clarify, **Figure 4-1** depicts the scenario whereby the source vehicle sends a message to an intermediate vehicle, which receives the message but does not have any other node to forward the message. Therefore, a message drop will result.

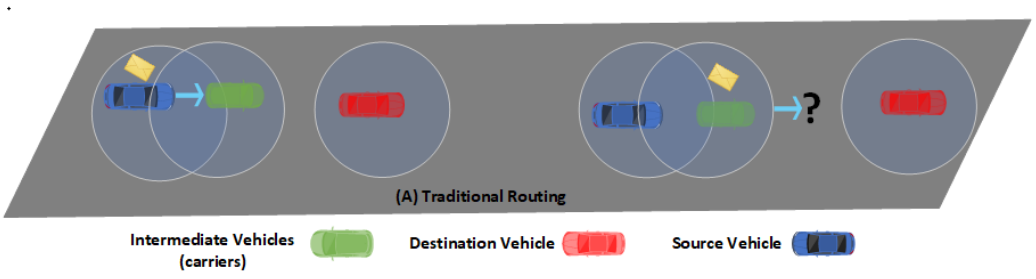


Figure 4-1: The strategies of traditional routing protocols

Meanwhile, as seen in **Figure 4-2**, when the intermediate node (vehicle) receives the message and there are no neighbours to forward it to, the intermediate vehicle will employ the SCF strategy to store the message in its buffer rather than drop the message. This message will be stored until the intermediate node meets with the destination or another neighbour's (carrier) node and is thus able to forward the message.

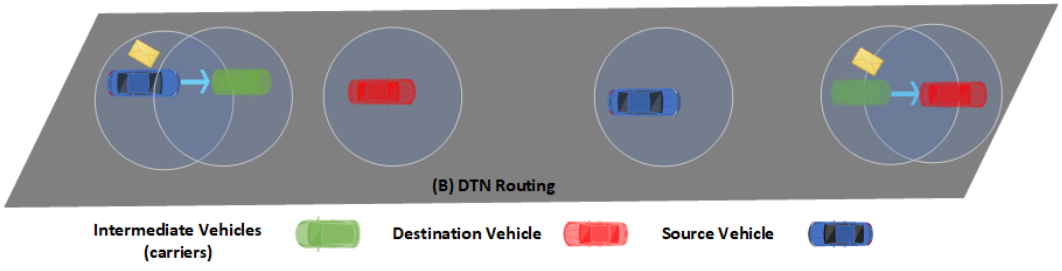


Figure 4-2: The strategies of DTN routing protocols

4.2.3 *Store-Carry-Forward Mechanism in DTN*

As mentioned previously, the SCF technique is the mechanism employed in the DTN routing protocol and is presented in **Figure 4-3**, starting on the left side of the figure. When the source (S) node has a message to send to the destination node (D), the (S) node initially saves the message in its buffer. Then, the (S) node carries the message while moving and forwards it to the intermediate node (I) when both (S) and (I) nodes are within the same communication range. After the (I) node receives the message, this will be saved in its buffer and carried out until it connects to the (D) node. Finally, the message is delivered to the (D) node from node (I) utilizing unprincipled contact, as discussed by Lee, *et al*. [145]. Every node in DTN stores the messages in a device referred to as persistent storage, which holds messages for a long period of time either when the next node is unavailable, or if the rate of incoming messages is higher than that of the outgoing messages [11, 134]. Therefore, additional space is required to buffer the message waiting for the availability of the next node to ensure that it exists for further forwarding. Despite the benefits of using the SCF mechanism, it may cause a transmission date delay because the source vehicle (sender node) is responsible for selecting the next appropriate intermediate vehicle (carrier node) that can deliver the message to the destination vehicle (target node). In addition, due to the short duration of contact between the nodes and the limited available bandwidth, a node may be unable to transmit all the messages that are stored in the buffer. Therefore, buffer

management policies are essential in order to manage and arrange the messages in the buffers of the nodes and enhance the network performance.

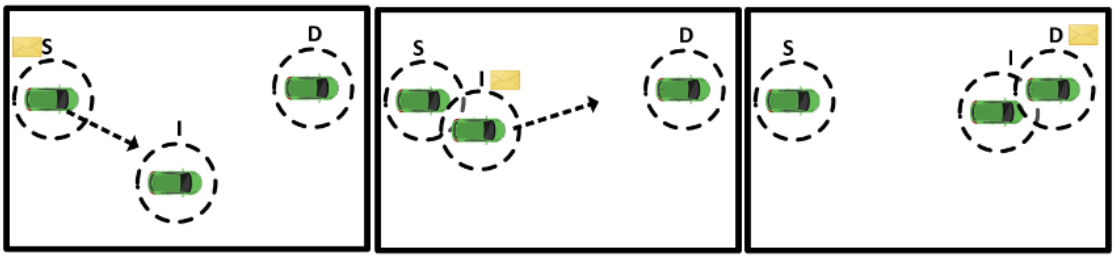


Figure 4-3: The mechanisms of SCF approach

4.3 Delay-Tolerant Routing Protocols

To clarify, the DTN routing protocol and buffer management are the primary aspects that affect network performance. Therefore, this chapter includes further details of both the DTN routing protocol and buffer management, with simulation results also provided.

The main goal behind routing protocols is to determine the appropriate paths between the network nodes that can successfully transmit the messages between them. Effective routing protocols should maximize the PDR while minimizing access delay and bandwidth consumption [135, 146]. The routing protocols are simply defined as the set of rules that determine the technique of inter-node connection and how the data messages are distributed through these nodes [81, 84]. Routing in ad hoc networks has received considerable attention in the literature. However, due to the unique properties such as high-speed mobility and sparse topology, traditional ad hoc routing protocols may not be suitable for VANET,

especially in rural where there is frequent intermittent connectivity [12]. As a result, VANETs are more likely to be characterized by low delivery probability, high error rates, and extended delivery times. Moreover, these challenges present barriers to the execution of common ad hoc routing protocols such as DSR and AODV [13, 14]. For this reason, the DTN routing protocol is required to resolve the issue of communication in challenging environments via the SCF mechanism.

In fact, different approaches can be employed to classify the DTN routing protocols. Some studies classified DTN into unicast and multi-cast based on the number of nodes involved in the sending and reception of the message [18, 147], while others classified DTN into a single copy and multi-copy depending on the number of messages replicated [147, 148]. Furthermore, the DTN routing protocols have been classified into flooding-based and forwarding-based algorithms according to the message-forwarding approach [149]. The DTN routing protocols can also be categorized according to the routing approach into prediction, message ferry, and opportunity routing techniques [150]. Considerable investigations have been conducted into DTN routing protocols' ability to handle frequent disconnections, high latency, limited resources, and long queuing delays [122, 149, 151, 152]. The difference between DTN routing protocols is the amount of available information that can help to facilitate the forwarding decision [153, 154]. For example, some protocols do not employ any information in delivering message decisions, but rather send all the messages to all the neighbouring nodes, such as the Epidemic (flood)

protocol [155]. Meanwhile, in terms of the decision to forward the message to a certain destination, the other protocols employ the past encounters of nodes to predict their future suitability. Moreover, these protocols differ in the replication strategies that determine how many copies of the messages are created, as well as the queue management strategies that can be utilized to determine which messages are forwarded first or which are deleted if the message queue is full [32, 122, 148, 149]. Some protocols only create a single copy such as the direct delivery and the first delivery protocols [148], while other protocols such as Spray&Wait have limited copies of the message [122, 155-157]. Meanwhile, protocols such as Epidemic generate an unlimited number of messages. According to the authors in ref. [122], there is no ideal routing scheme. Hence, here we conduct simulations and modelling to analyze and comprehend the applications of DTN routing protocols. As mentioned earlier, DTN routing protocols are employed when the connectivity of the network is unavailable, whereby the SCF technique is utilized with opportunistic contacts to successfully transmit a message to the destination node.

Although many DTN routing protocols have been studied [146, 148, 149, 158], in this section five routing protocols that represent different categories of DTN routing protocols are considered, as shown in **Figure 4-4**, with a brief overview of these protocols are presented.

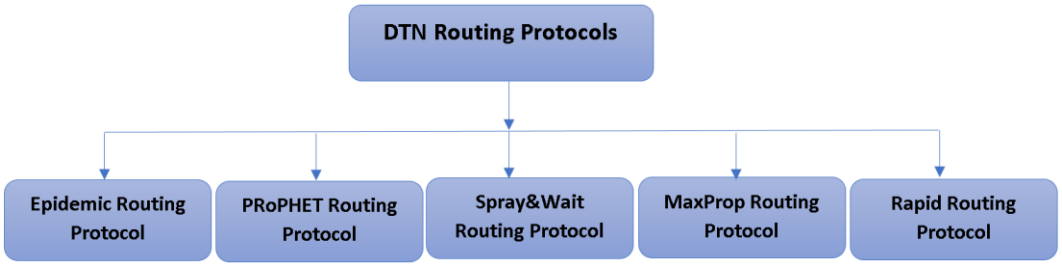


Figure 4-4: The different DTN routing protocols [158]

1. *Epidemic Routing Protocol*

Essentially, Epidemic is the most straightforward DTN routing protocol that depends on the flooding algorithm. Epidemic routing utilizes the concept of message replication, whereby when every node meets another node it exchanges all messages in its buffers because Epidemic assumes that every node has infinite bandwidth and buffer size [159]. Therefore, a high delivery probability can be achieved, and message delivery to the destination node is guaranteed. However, a huge amount of resource consumption results such as buffer space, bandwidth, and energy. Furthermore, the delay ratio and overhead ratio will be very high due to the unlimited message replication and limited DTN network resources [149, 160]. These properties render Epidemic routing a practical approach only in the case of very sparse networks and small message sizes. Due to the limited DTN network resources and unlimited message replicas disseminated through the network, Epidemic routing is less suited to congested traffic networks due to dropped messages and high overhead.

2. *Spray&Wait Routing Protocol*

The Spray&Wait routing protocol is one of the quota based DTN routing protocols that limit the message copies in order to achieve optimum performance. As the name suggests, there are two stages: the spray stage and the wait stage. First, in the spray stage, a node will begin to flood (spray) a message created from the node itself up to L copied messages. Then, when the spray stage is complete, the protocol shifts to the waiting stage, where every node retains its messages in the buffer until its destination is reached or the TTL is expired [160]. **Figure 4-5** visually depicts the operation of Spray&Wait, which is further explained as follows.

First, the source node generates a message and determines the initial value of the variable L, where in this example L=4 copies. When the source node encounters the other neighbouring nodes, the source must retain L/2 copies and transmit the remaining L/2. Hence, the source node and its encountered node will hold two copies. Then, node 1 encounters node 3, and the same process will be repeated. Now, as both node 1 and node 3 have only one copy, they will shift into a waiting phase. Therefore, at time T3, despite node 1 being connected with encountering node 2 and node 4, no copy of the message will be forwarded to them. Node 1 will continue to carry the message and not forward it to any encounter nodes except the destination node (D), as seen at time T4.

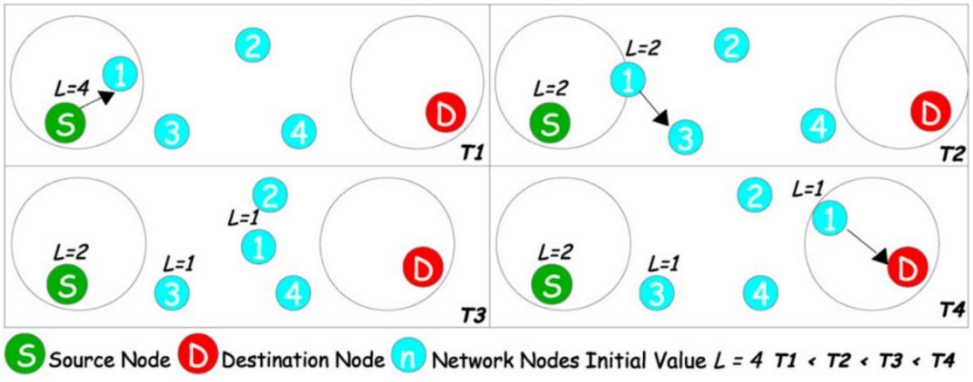


Figure 4-5: Mechanism of the Spray&Wait operation [114]

The advantage of the Spray&Wait protocol is lowering the overhead and buffer overflow by reducing excessive packet forwarding in networks that exist in flooding routing protocols such as Epidemic. The characteristics of Spray&Wait are high delivery probability, high scalability, and simple protocol operation. Nevertheless, despite Spray&Wait being a resource-friendly protocol, the messages may not be delivered if the destination is in a different area of the source node.

3. *PROPHET Routing Protocol*

The PROPHET is one of the early generations of DTN protocols employed to estimate a probability referred to as 'delivery predictability, depending on a node's history of previous encounters with the neighbouring nodes. At the contact time, the nodes exchange vectors containing information regarding the delivery predictability, with the vector updating after every contact. Despite the PROPHET routing protocol being dependent upon a vector that assists in selecting a message with a high probability of reaching the destination, it is not particularly effective in

DTN networks that feature unpredictable moving nodes [156, 160, 161]. Moreover, PROPHET necessitates certain overhead in order to keep track of the delivery probability estimates [162]. The PROPHET routing protocol is proposed to overcome the Epidemic's challenges through improvement in the delivery probability and a reduction in the poor usage of network resources. If the source encounters many nodes with high delivery probability, the overhead will be high as the messages are flooded through the network. Nevertheless, the forwarding strategy in PROPHET is more complicated than conventional routing protocols that base the forwarding decision on certain elementary metrics such as the shortest path and low cost. Furthermore, when a node encounters a neighbour with low delivery predictability, there is no guarantee that it will encounter another node with a higher delivery predictability value during the message lifetime, and therefore the messages may never leave the source node.

4. *MaxProp Routing Protocol*

MaxProp is another DTN routing protocol that depends on the same principles as PROPHET [11, 152]. MaxProp is designed to deliver the message in an urban environment. Every node's buffer is divided into two sections, as demonstrated in **Figure 4-6**. One section is utilized to store the messages that have been ordered depending on the hop count (from low to high). This section occupies the head (front) of the buffer, while the other section occupies the tail (end) of the buffer where the messages have been ordered from low to high cost [11]. Moreover,

Dijkstra's algorithm is employed to calculate the cost of the path from the source to the destination node [163]. The MaxProp protocol achieves superior performance through high delivery rates and low latency. However, a high overhead may result, as well as the consumption of resources in a restricted resources network [18].

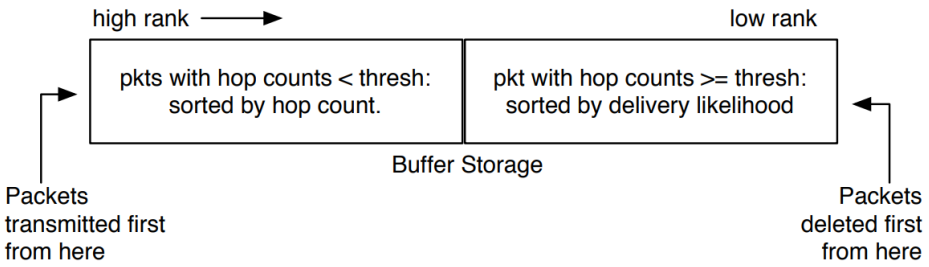


Figure 4-6: The node's buffer in the MaxProp routing protocol [11]

In terms of the calculation of the path costs, MaxProp can be described as shown in **Figure 4-7**, where the network has five nodes: A, B, C, D, and E. MaxProp calculates the cost of each possible path based on an **equation (4-1)**:

$$Cost(i, i+1, \dots, d) = \sum_{x=i}^{d-1} [1 - f_{x+1}^{x}] \tag{4-1}$$

In this example, cost (i,i+1,……,d) is calculated. We assume that A is the source node to generate a message that is delivered to the destination D. Hence, the most cost-effective path must be determined, which is found to be ACD.

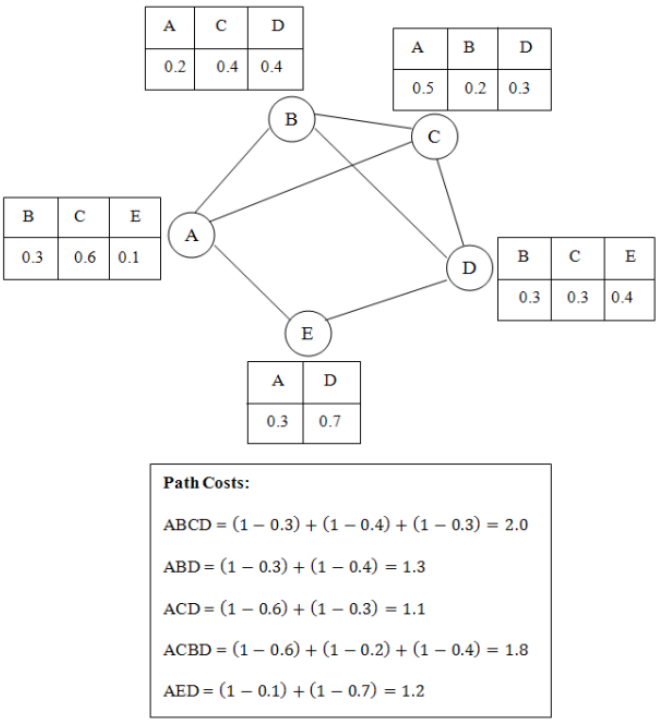


Figure 4-7: An example of MaxProp calculating the cost of the paths [114]

5. *Rapid Routing Protocol*

Rapid is the first protocol to consider buffer and bandwidth limits. Each message is assigned a utility by the protocol, which replicates messages that lead to the highest increase in utility [20]. One major drawback of the Rapid protocol is that replica information must be flooded throughout the network in order to derive the utility of messages, which leads to high overhead. Furthermore, the information disseminated may be outdated when it reaches the destination node due to delays [114]. The Rapid routing protocol was evaluated by Balasubramanian, *et al*. [20] through 40 buses, whereby the protocol provided superior performance in terms of

the average delay, delivery, and maximum delay. However, the number of nodes was only n=40, and therefore the results may differ when the number of nodes is increased.

4.3.1 *Simulation Tools*

In this study, the ONE simulator is utilized, which is the most suitable simulator to evaluate the performance of DTN routing protocols [122, 148]. The ONE simulator is a powerful tool that enables the generation of mobility traces running the DTN message, the visualization of the simulation, and the presentation of the results on completion. The ONE simulator is open-source software that allows the model to be modified and developed based on DTN routing protocols.

4.3.2 *Simulation Parameters*

The number of nodes and the network density impact the full network performance. The simulation parameters utilized to analyze the DTN routing protocols for the current work are summarised in **Table 4-1**. According to Keränen, *et al*. [122], the ideal routing scheme has not been created, which was also confirmed by the authors in ref. [51, 150]. Therefore, this research employs a different network density and buffer capacity with two different models to implement, test, and analyze five DTN routing protocols and determine their benefits and weaknesses.

Table 4-1: Parameters used to simulate five DTN routing protocols

No.	Parameter	Value
1.	Total Simulation Time	12 hours
2.	World Size	4500 X 3400 m
3.	Movement Model	Shortest Path-Based Movement Model, Cluster Model
4.	DTN Routing Protocol	Epidemic, Spray&Wait, PRoPHET, MaxProp, and Rapid
5.	Buffer Size	5 MB, 10 MB, 15 MB
6.	No. of Nodes	20, 30, 40, 50, 60, 70, 80
7.	Interface Transmit Speed	2 Mbps
8.	Interface Transmit Range	10 meters
9.	Message TTL	60 minutes
10.	Node Movement Speed	Min=0.5 m/s, Max=1.5 m/s
11.	Message Creation Rate	One message per 25–35 s
12.	Message Size	500 KB to 1 MB

4.3.3 *Performance of Employed Metrics*

The various evaluation matrices have been listed and explained in Chapter 2. To remind the reader, in this section four metrics, are considered: the delivery ratio, the overhead ratio, the latency average, and the hop count.

4.3.4 *Acquired Simulation Results and Discussion*

The acquired results and discussion are presented in this section, which is classified into the Shortest Path-Based Movement Model and Cluster Model sub-sections.

A. Shortest Path-Based Movement Model

According to the Shortest Path-Based Movement Model, the mobile nodes move following the shortest mobility model. This model is a sub-class of MapBasedMovement that utilizes Dijkstra's algorithm to select the shortest paths [122, 164]. Moreover, the impact of this mobility model was evaluated on five DTN routing protocols and their performance was compared by varying the network density, as shown in **Figure 4-8**, while the variations of the buffer capacity are depicted in **Figure 4-9**.

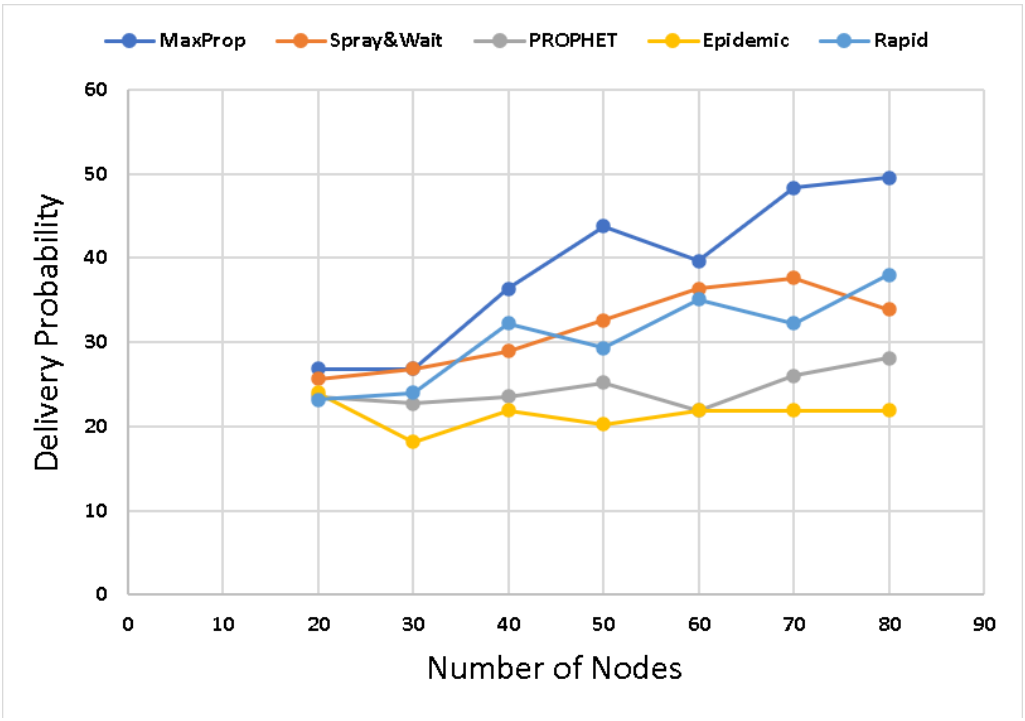
1. Variation of the number of nodes

Figure 4-8 (A) shows the results obtained using the delivery probability metric. The MaxProp protocol provides the optimum delivery probabilities as it orders the message to transmit and drop from the node's buffer. Moreover, MaxProp uses the acknowledgment to confirm that the message has been successfully delivered, which can help to delete the additional copies and provide an opportunity for the other messages to be delivered. On the other hand, Epidemic is the most inferior protocol with the lowest delivery probability value since the uncontrolled flooding inherent in such a strategy reduces the successful reception of messages due to the blind replication of the message. As previously indicated, the Epidemic protocol obtains 100% delivery probability with an infinite buffer size. However, due to the limited buffer size in our simulation, the Epidemic loses its performance.

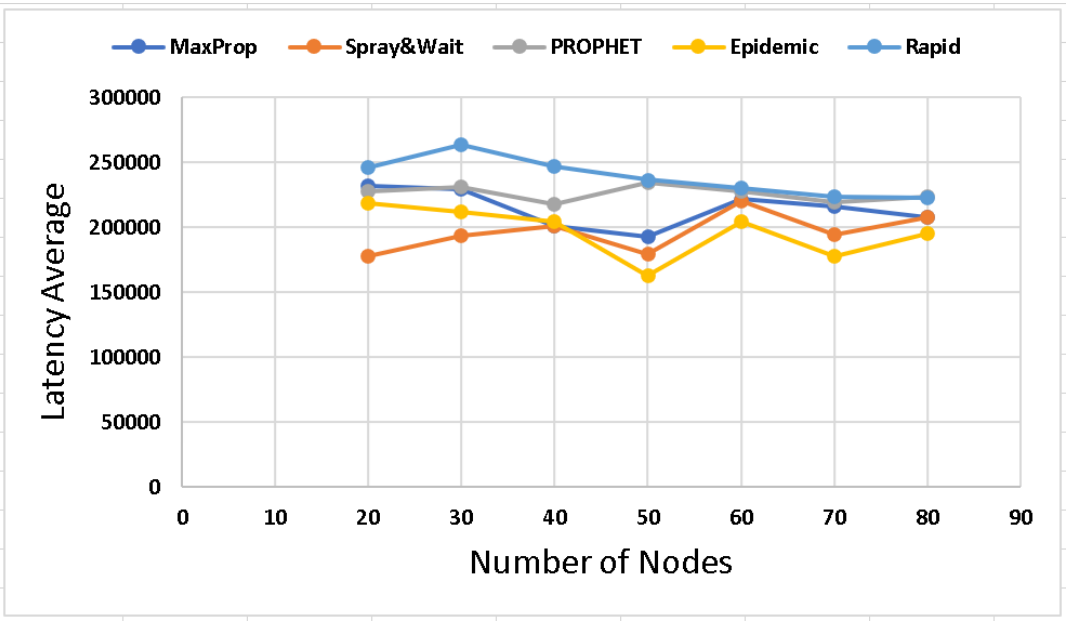
Figure 4-8 (B) presents the value of the latency average of the five DTN routing protocols, where in the Rapid protocol the latency average decreases gradually when the number of nodes increases. The optimum result is achieved by the Epidemic protocol when compared to the other four protocols.

Figure 4-8 (C) illustrates the achieved results of the hop count average for the five DTN routing protocols. Compared with the other protocols, Spray&Wait provides the optimum result as it does not consume network resources by limiting the copying of the message. Meanwhile, the Rapid and Epidemic protocols have the highest hop count, which is considered the inferior result compared with the other three protocols.

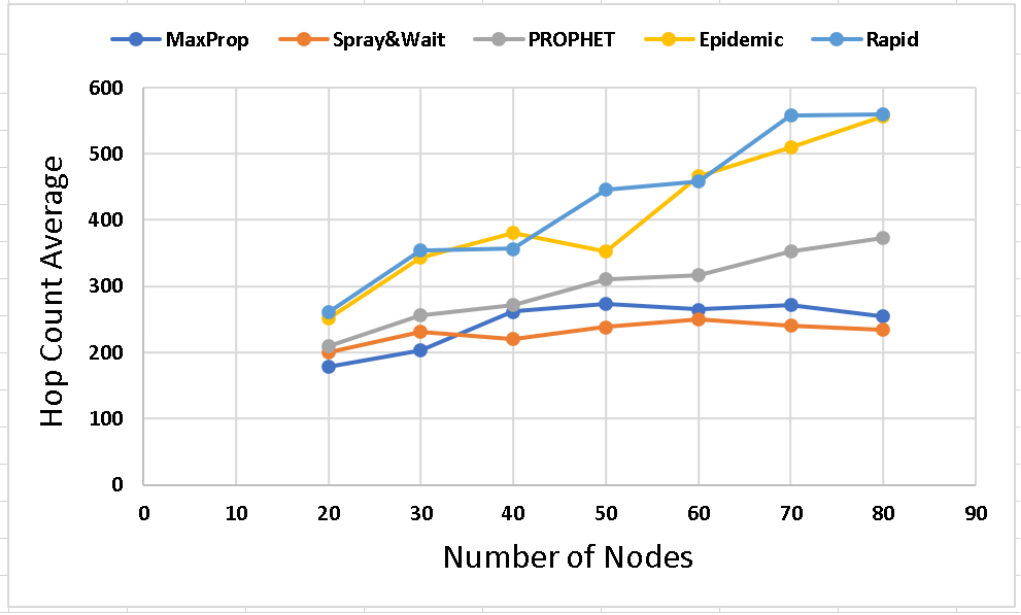
It can be seen from **Figure 4-8** (D) that as the number of nodes increases, the overhead rate also increases for all DTN protocols except for Spray&Wait, where the overhead rate remains stable and represents the lowest overhead rate because the protocol creates a limited number of copies that can optimize the network resource usage. Furthermore, it can be noted that the Epidemic protocol provides the highest overhead rate due to the elevated consumption of network resources due to the default replication of the message. Then, the medium overhead ratio of MaxProp, PROPHET, and Rapid are very close to each other. To validate the current model, in comparison with previous studies we found that the Spray&Wait protocol presented by [165] provides the optimum performance in terms of the overhead ratio and our modelling, with our results in agreement with their findings.


MaxProp
Spray&Wait
PROPHET
Epidemic
Rapid
Delivery Probability
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90
Number of Nodes

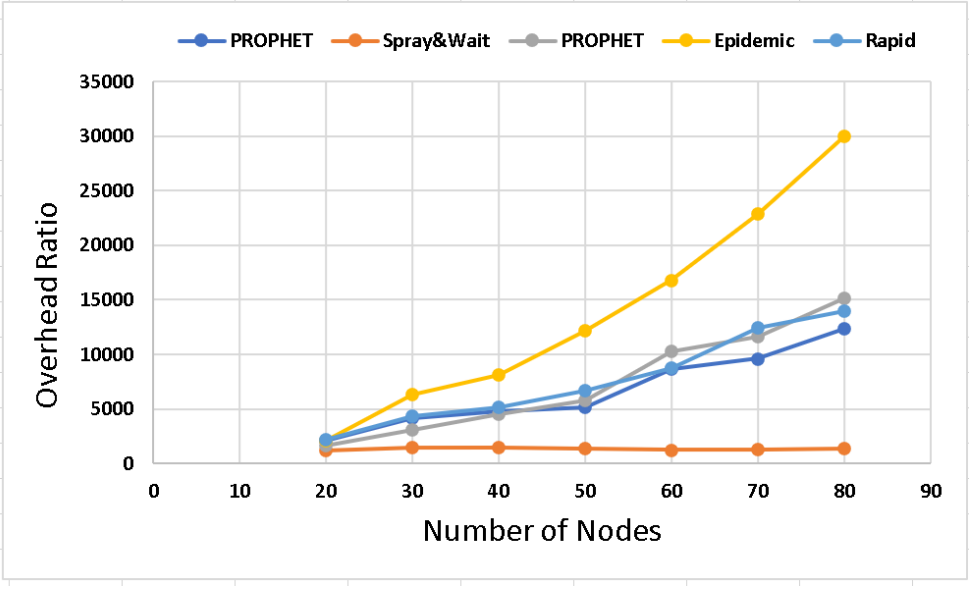
(A)


MaxProp
Spray&Wait
PROPHET
Epidemic
Rapid
Latency Average
0
50000
100000
150000
200000
250000
300000
0
10
20
30
40
50
60
70
80
90
Number of Nodes

(B)



(C)



(D)

Figure 4-8: The performance of different DTN routing protocols in the shortest path-based movement model with different numbers of nodes

2. Variation of buffer size

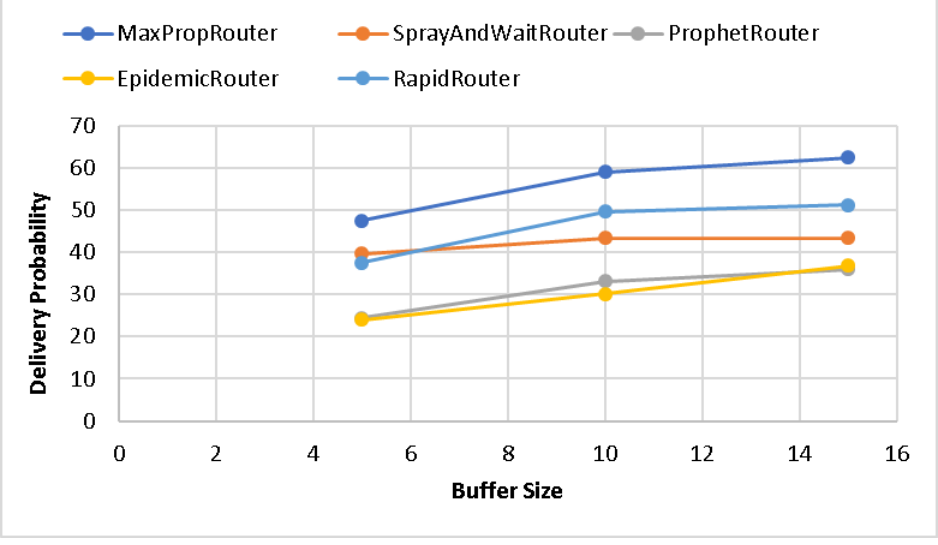
We varied the buffer size from 5 MB to 15 MB, with a step change of 5 MB.

Figure 4-9 (A) highlights that when the buffer size increases, the delivery ratio for all DTN protocols increases accordingly. The reason behind this is that as the buffer size increases, more messages will be stored in the buffer and will thus have a higher probability of being delivered. It can be observed that the MaxProp routing protocol provides a superior result since it uses buffer management and acknowledgement mechanisms to efficiently manage the node's buffer.

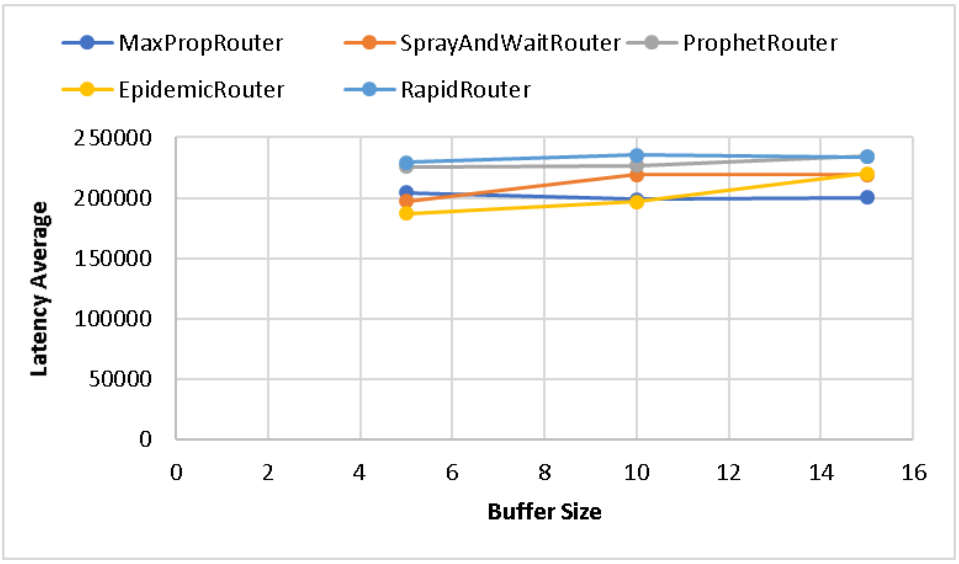
Figure 4-9 (B) illustrates that the highest latency average of the five DTN routing protocols was achieved by Rapid, followed by the PROPHET routing protocol. Meanwhile, the lowest latency average was achieved by the MaxProp protocol. Moreover, it can be seen that the Epidemic routing protocol has the smallest latency average at buffer size 5, which then increases gradually to be higher than the MaxProp latency average when the buffer size is increased. Meanwhile, the performance of MaxProp is not impacted by an increase in the buffer size, as this protocol employs its buffer management technique and also utilizes the delivered acknowledgement that can help to efficiently manage the node's buffer. That is, the MaxProp protocol includes both efficient buffer management and high-quality routing task and is unaffected by the buffer size.

It is evident from **Figure 4-9** (C) that the Spray&Wait protocol has a small number of hops due to controlling the number of messages replicated. In contrast, the

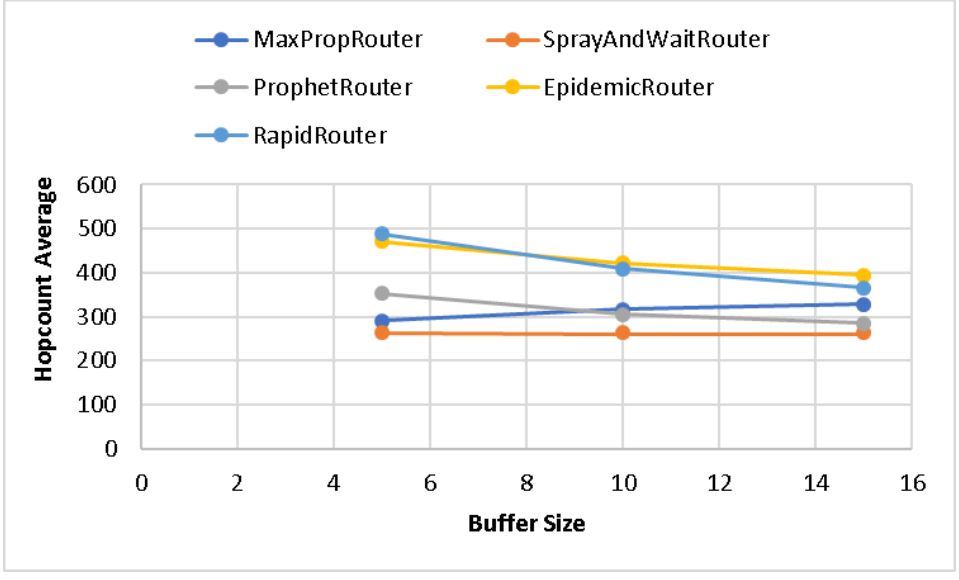
Epidemic protocol features the highest number of hops, followed by the Rapid protocol. Increasing the buffer size does not affect the hop count metrics in Spray&Wait because the protocol depends on a limited number of copied messages. **Figure 4-9** (D) presents the overhead ratio for the five DTN protocols according to the different buffer sizes. It can be observed that the highest overhead ratio is achieved by the Epidemic protocol while the lowest is achieved by Spray&Wait, thus indicating that the latter provides the optimum performance of all the routing protocols in terms of the overhead ratio since Spray&Wait limits the number of copies of a message. Increasing the buffer size does not affect the overhead in Spray&Wait. Meanwhile, the other three protocols feature the same impact, whereby when the buffer size increases, the overhead gradually decreases.



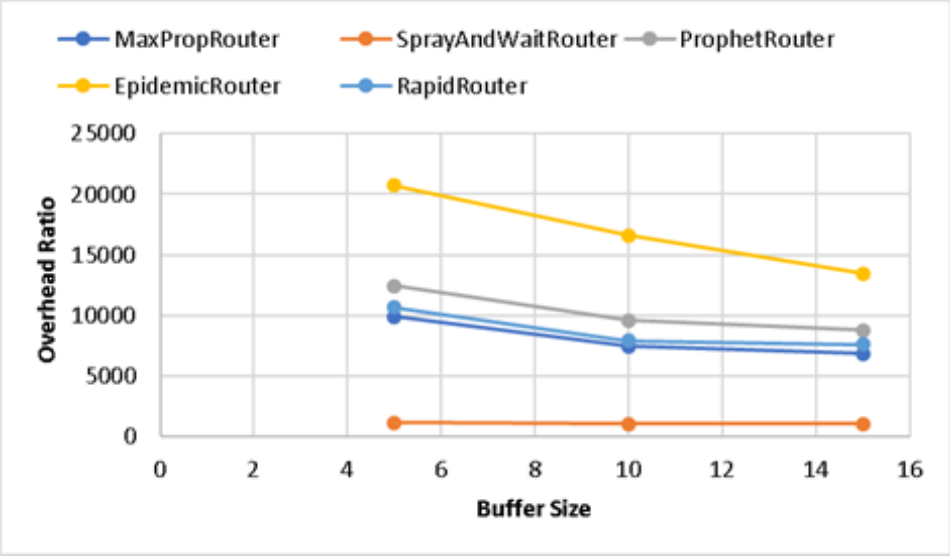
(A)


MaxPropRouter
SprayAndWaitRouter
ProphetRouter
EpidemicRouter
RapidRouter
Latency Average
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
12
14
16
Buffer Size

(B)


MaxPropRouter
SprayAndWaitRouter
ProphetRouter
EpidemicRouter
RapidRouter
Hopcount Average
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
Buffer Size

(C)



(D)

Figure 4-9: The performance of different DTN routing protocols in the shortest path-based movement model with different buffer sizes

B. Cluster Model

1. Variation of the number of nodes

Figure 4-10 (A) presents the results obtained using the delivery probability metric. It can be noted that the MaxProp and Rapid protocols offer the same results, which are considered optimum compared with the other three protocols because the former feature a buffer management mechanism. In contrast, the PROPHET and Epidemic protocols achieve very similar results, which represent the most inferior delivery probability as PROPHET depends on calculating the probability that is time-consuming and can cause message loss due to the expiration of the TTL prior to its

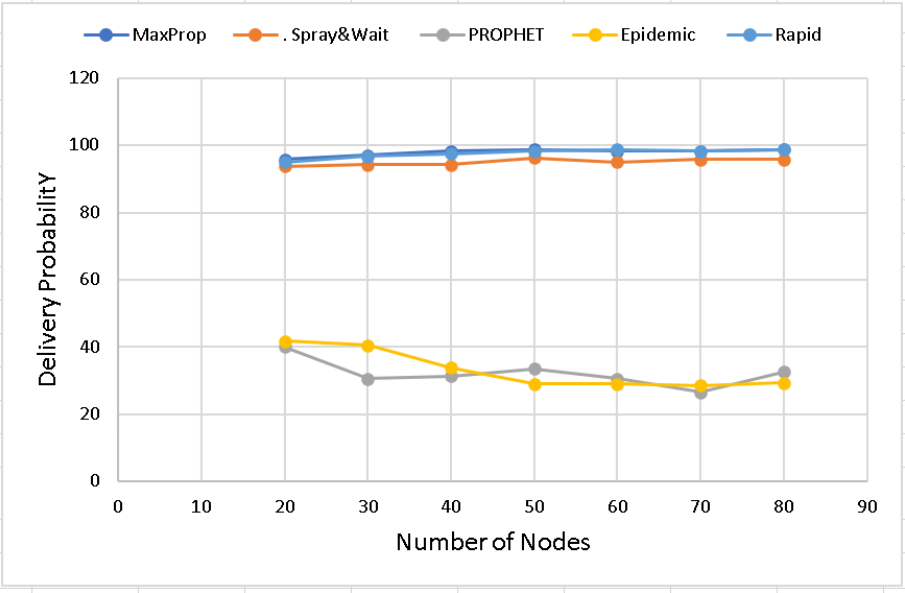
transmission, while Epidemic provides low delivery probability because the protocol creates an unlimited number of messages with restricted buffer size.

Figure 4-10 (B) presents the value of the latency average of the five DTN routing protocols. It can be seen that the latency average of the MaxProp and Rapid protocols decreases exponentially when the number of nodes is increased. Meanwhile, for the other three protocols, the latency average is inconsistent, and the performance cannot be clearly described.

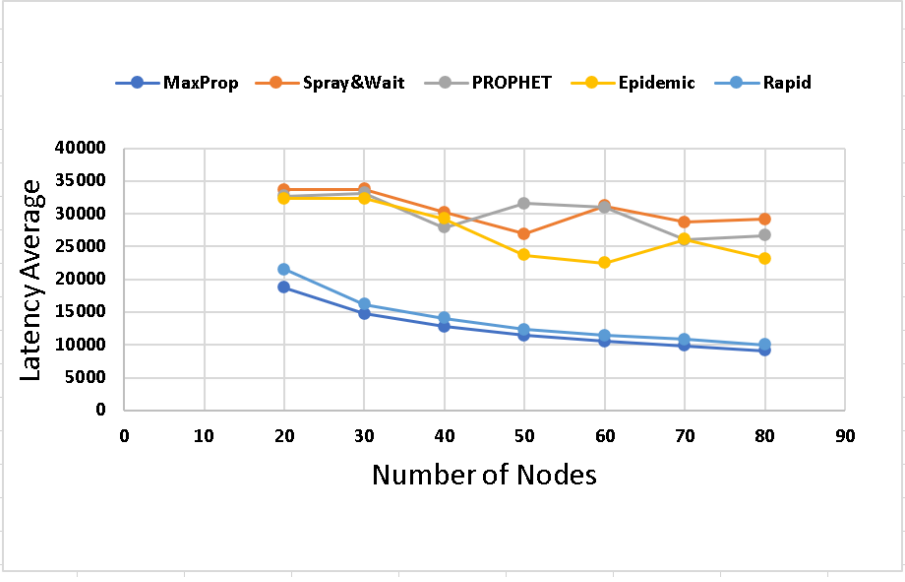
Figure 4-10 (C) presents the hop count, where the acquired results of the hop count average for the five DTN routing protocols are varied based on the type of routing protocol. Spray&Wait is stable and does not affect the variation of the number of nodes because the protocol employs limited copies of the messages to prevent blind flooding in the network while also preventing congestion from the aforementioned blind flooding. In contrast, the Epidemic protocol achieves the highest hop count, which represents the most inferior routing protocol performance, followed by the PROPHET protocol. Meanwhile, the Rapid and MaxProp protocols provide approximately the same results, which are slightly superior to the PROPHET protocol.

Figure 4-10 (D) illustrates that the highest overhead rate is achieved by the Epidemic protocol, followed by PROPHET, whereas the optimal result is achieved by Spray&Wait, whereby when the mobile nodes increase, the overall overhead ratio also increases since more messages are transmitted than are delivered. In

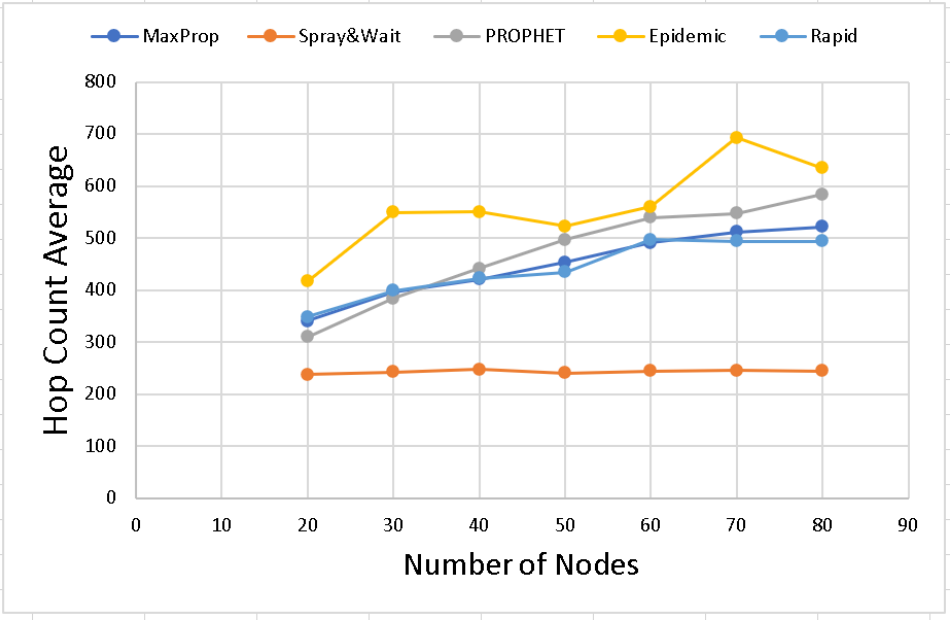
addition, delivery latency increases as the number of nodes in the network grow, with each node spending more time processing data.



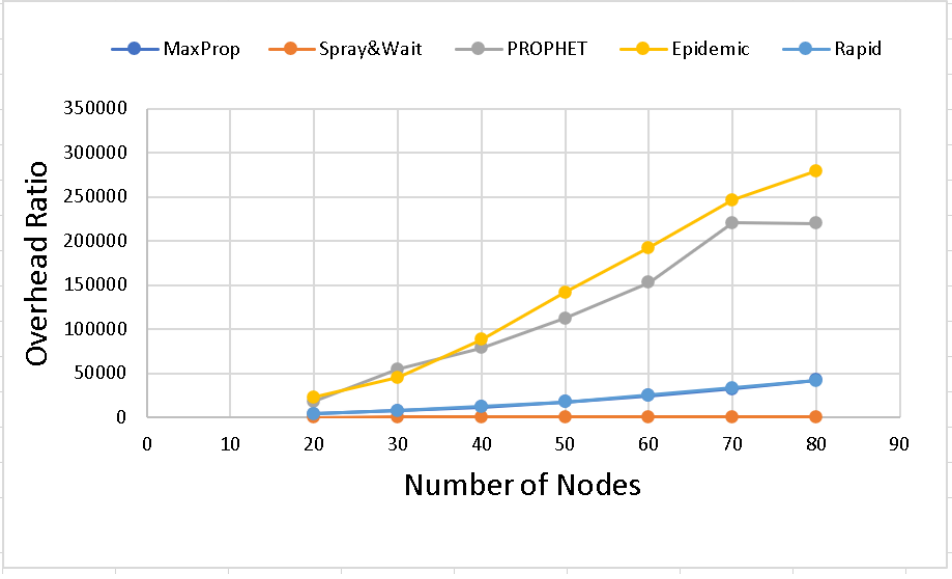
(A)



(B)



(C)



(D)

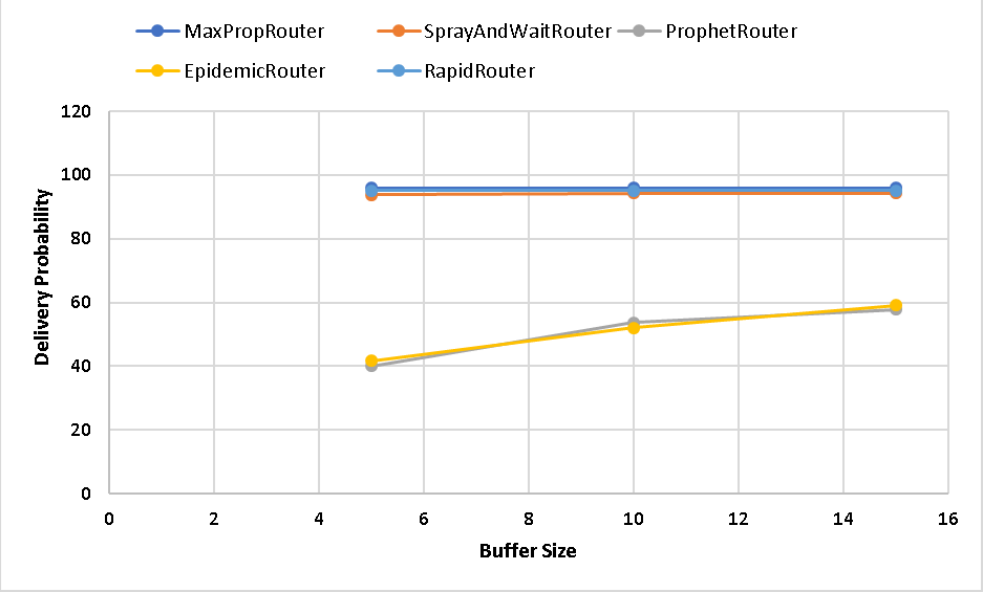
Figure 4-10: The performance of different DTN routing protocols in the cluster model with different numbers of nodes

2. Variation of buffer size

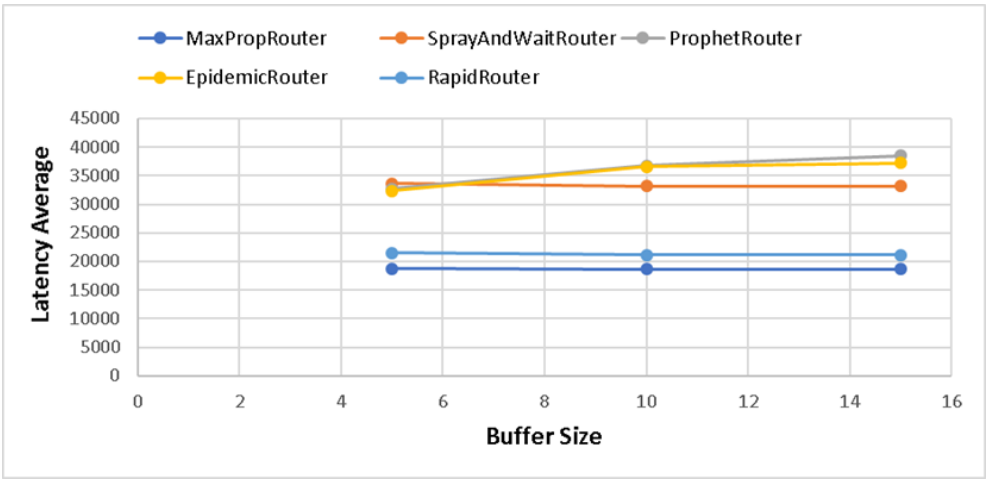
Figure 4-11 (A) clearly shows that when the buffer size increases, the delivery ratio also increases for the Epidemic and PROPHET protocols, while for the MaxProp and the Rapid protocols, the results are the same high delivery probability, followed very closely by Spray&Wait. **Figure 4-11** (B) illustrates the latency average of the five DTN routing protocols, where it can be observed that when the buffer size increases, the latency average of both the PROPHET and Epidemic protocols also increases. Meanwhile, in terms of the remaining protocols, the latency average remains stable even when the buffer size increases, with the MaxProp protocol providing the lowest latency average due to its effective buffer management scheme.

Figure 4-11 (C) highlights that the buffer size does not impact the performance of the MaxProp, Rapid, and Spray&Wait protocols. However, the hop count average of the Epidemic and PROPHET protocols decreases gradually with the increase of the buffer size to 10 MB. **Figure 4-11** (D) presents the overhead ratio for the five DTN protocols according to the different buffer sizes, where it can be observed that the highest overhead ratio is achieved by the Epidemic protocol, followed by the PROPHET protocol. The reason for this is that Epidemic sends messages to all possible nodes, while for PROPHET an unlimited number of replicas can be generated which causes an increase in the overhead ratio. On the other hand, the lowest overhead ratio is achieved by Spray&Wait. Moreover, we noted that

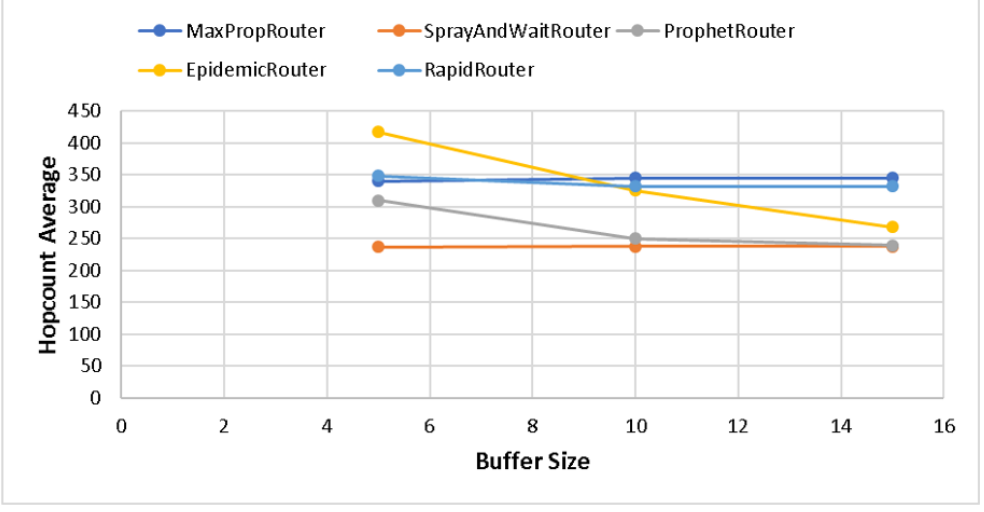
increasing the buffer size does not affect the overhead ratio in Spray&Wait because it is dependent on a limited number of copied messages, which is independent of the buffer capacity. The MaxProp and Rapid protocols have the same overhead ratio, even when the buffer size is increased due to these two protocols' use of buffer management.



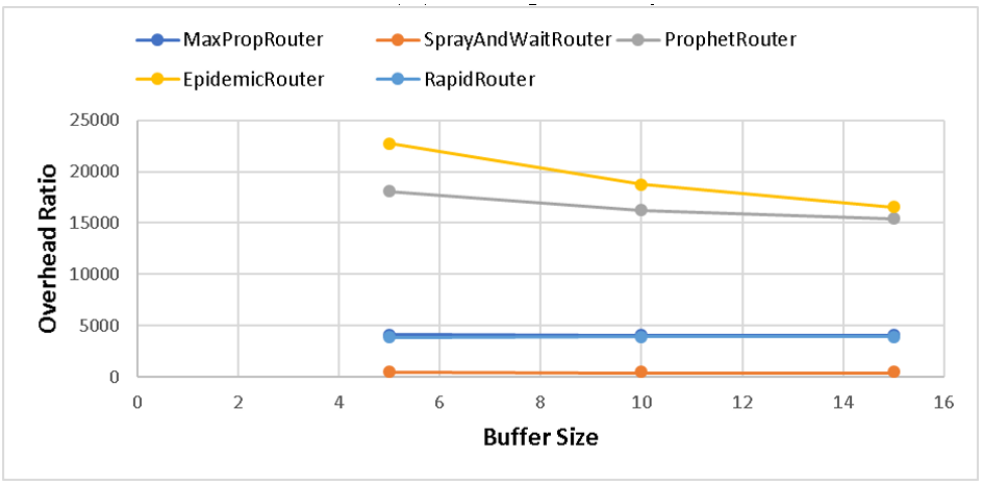
(A)


MaxPropRouter
SprayAndWaitRouter
ProphetRouter
EpidemicRouter
RapidRouter
Latency Average
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
14
16
Buffer Size

(B)


MaxPropRouter
SprayAndWaitRouter
ProphetRouter
EpidemicRouter
RapidRouter
Hopcount Average
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Buffer Size

(C)



(D)

Figure 4-11: The performance of different DTN routing protocols in the cluster model with different buffer sizes

Eventually, as the MaxProp and Spray&Wait achieved the best and the second-best performance, we selected these protocols as benchmark protocols for implementing the six dropping policies in the next sections.

4.4 Buffer Management Policies

The performance of routing protocols in DTN is heavily influenced by buffer management techniques [25, 166]. As mentioned previously, the SCF mechanism can be employed in DTN to forward messages between the nodes, although the duration between encountered nodes can be rather long. Hence, nodes must be able to store messages in their buffers for extended periods that may cause congestion in the node's buffer. As a result, some messages may be dropped due to limitations in the available buffer size. Therefore, the buffer management policy is essential to

manage the buffers of the nodes, avoid message drops, and improve routing performance. This can be confirmed by previous investigations that were presented in [49, 167, 168]. The buffer management in DTN includes both (i) dropping policies, which can be employed to determine which message is to be dropped in case of buffer overflow; and (ii) scheduling policies, which are utilized to determine which message has to be forwarded first when a meeting occurs between nodes [113, 169]. Hence, in the remainder of this chapter, the performance of the FIFO, LIFO, DL, DY, Evict SHLI and Evict MOFO buffer management techniques are evaluated with the MaxProp and Spray&Wait routing protocols under variable TTL values. Moreover, various metrics are selected for the evaluation of these techniques.

4.4.1 *Dropping Buffer Management Policies*

The dropping policies are one part of the buffer management that can be employed to determine which message is to be dropped in the case of buffer overflow.

In DTNs, the messages do not discard of the node's buffer unless the TTL of these messages is expired (TTL=0) [138]. As a result, when the node's buffer is full, it is important to ensure that an effective mechanism exists to determine which messages will be dropped in order to free up space in the node's buffer so that new incoming messages can be accommodated [170]. According to these aspects, in subsection 4.4.5 the performance of six buffer management policies is evaluated. Furthermore, their impact on the two different DTN routing protocols is analyzed

based on the overhead ratio, delivery probability, latency, hop count average, and message drop metrics. The six policies that are considered in this study: FIFO, LIFO, DL, DY, SHLI, and MOFO are explained as follows:

1. First-In First-Out

The FIFO policy is also referred to as the Drop-Front policy. With the FIFO buffer management technique, the message in the buffer that entered the queue first will be selected to be dropped first [113, 170]. The FIFO policy is the simplest dropping policy since it does not consider any particular message attributes during the selection process for the message to drop, with the choice based solely on the order in which messages arrive or reside in the buffer, leading to the achievement of a high delivery ratio. However, the messages in the tail may be deleted prior to having any opportunity to be delivered.

2. Last-In First-Out

The LIFO policy is also known as the Drop-Tail or Drop-Last policy. LIFO drops the newly arrived message, which means that the message that arrives last will be the first to be dropped [117, 170]. LIFO is a simple dropping scheme, which performs poorly when the buffer is congested as it simply rejects any incoming messages when a node's buffer overflows [171].

3. Drop Largest

The message in the buffer that has the largest size will be chosen to be dropped first when the buffer overflows occur. To free more space to accommodate incoming

messages, the DL aims to drop large-size messages rather than drop several small-size messages. Dropping the largest size message will thus create more free space for new incoming messages. However, the largest-size message's destination node may be the next node [117, 172].

4. Drop Youngest

When using this policy, the youngest message (i.e. the one with the longest remaining TTL) is the first message to be discarded from the node's buffer when the buffer overflows manifests [173, 174]. Although the benefit of dropping such messages is to reduce the overhead, the technique will drastically reduce the probability of delivery [175].

5. Shortest Life Time First

Each message in the DTN architecture has a timeout value (TTL) that specifics when the message is no longer useful in the network and should be discarded [174]. When employing the SHLI policy, the message with the smallest TTL is discarded first. The benefit of SHLI is dropping those messages that will shortly be discarded anyway due to their TTL reaching zero (expired message) [175]. However, it is possible for a message to be dropped that is about to be delivered.

6. Evict Most Forwarded First

The MOFO drop policy requires the routing agent to keep track of how many times each message has been forwarded. Then, if the node's buffer is congested, the message that has been forwarded the most times will be selected first for discard

[174]. MOFO ensures that the dropped messages are those that have been disseminated around the network the most by dropping messages that have previously been sent to numerous other nodes. This explains the satisfactory performance obtained by MOFO since it reduces the risk that a message is dropped without being forwarded at least once [32].

4.4.2 *Simulation Works*

The performance of various buffer management policies with the MaxProp and Spray&Wait routing protocols is analyzed through simulation via the ONE simulator.

4.4.3 *Simulation Scenario Parameters*

In this sub-section, we establish various TTL values. We increased the messages' TTL value from 60 to 300 min, with a step-change of 60 min, to realize the impact of the different TTL values on the different dropping policies. Here, we retain the node density constant (200) nodes and fix the buffer size of 5 MB. We compare the six dropping policies for the MaxProp and Spray&Wait routing protocols only, with the simulation configuration utilized for this study summarized in **Table 4-2**.

Table 4-2: Elements of modelling works

No.	Parameter	Value
1.	Total Simulation Time	12 hours
2.	World Size (meter)	4500 X 3400 m
3.	DTN Routing Protocol	MaxProp and Spray&Wait
4.	Buffer Size	5 MB
5.	Number of Nodes	200 (-)
6.	Interface Transmit Speed	2 Mbps
7.	Message TTL	60, 120, 180, 240, and 300 minutes
8.	Node Movement Speed	Min=0.5 m/s, Max=1.5 m/s
9.	Message Creation Rate	One message per 25–35 seconds
10.	Message Size	500 KB to 1 MB
11.	Buffer Management Policies	FIFO, LIFO, DL, DY, SHLI, MOFO

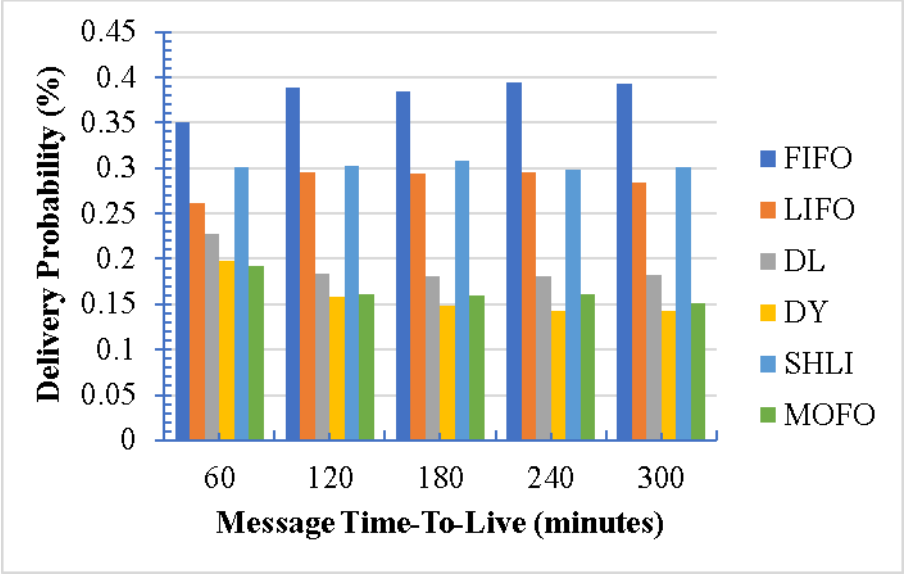
4.4.4 *Metrics for Performance Evaluation*

We employed six policies in our simulation, with five metrics utilized as explained in detail in Chapter 2 (i.e. delivery probability, overhead ratio, average latency, hop count average, and messages drop). The definition of the evaluation metrics was explained and defined in Chapter 2, specifically in subsection 2.4.

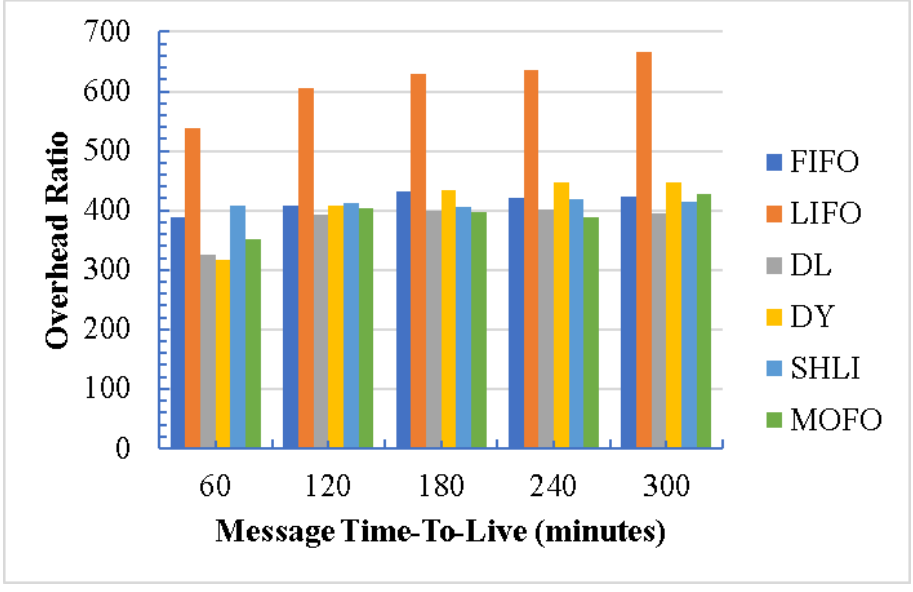
4.4.5 *Performance Analysis and Discussion of the Results*

1. Impact of Varying the Messages' TTL values on the MaxProp Routing Protocol with Different Drop Policies

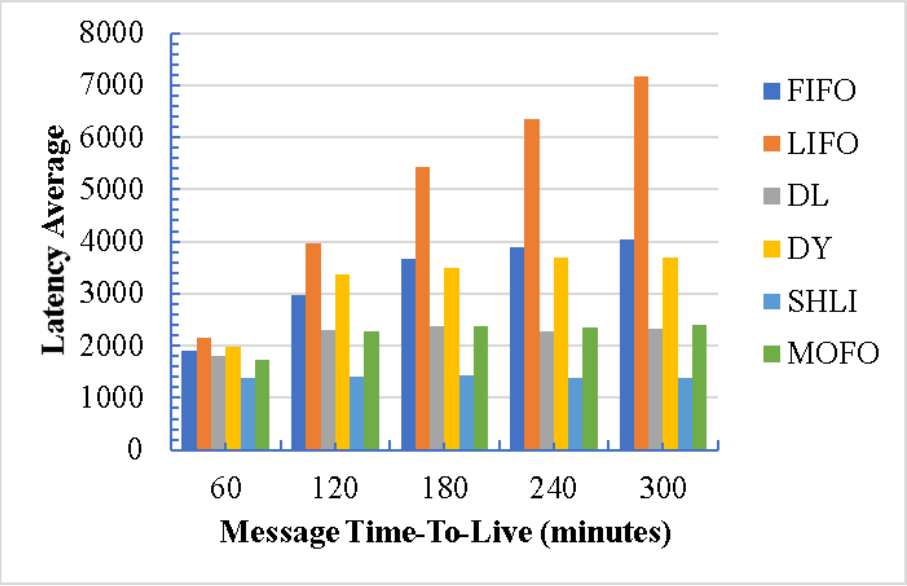
The effect of the six aforementioned policies was implemented on the MaxProp routing protocol, with the acquired results analyzed based on the different performance metrics, as shown in **Figure 4-12**.



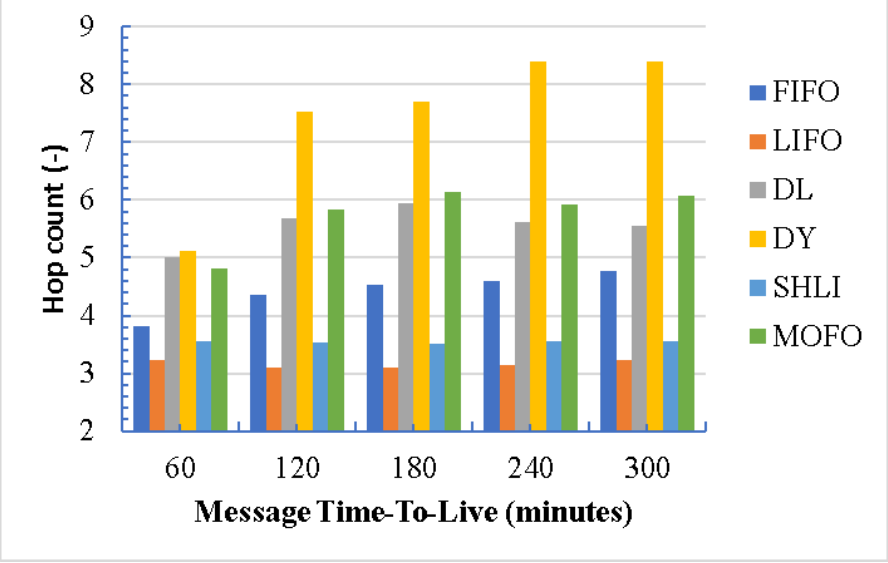
(A) Message Delivery Probability



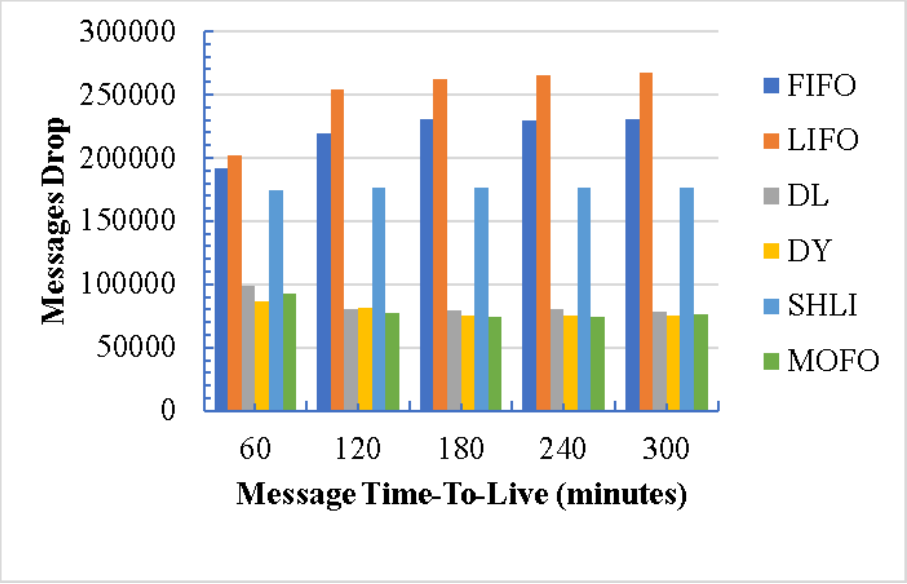
(B) Overhead Ratio



(C) Latency Average



(D) Hop Count



(E) Messages Drop

Figure 4-12: The performance of various drop policies in the MaxProp routing protocol with different TTL values

A. Delivery Probability

The change in the delivery ratio is illustrated in **Figure 4-12** (A) when the TTL value is between 60 and 300 min. As can be noted, the highest delivery ratio is achieved by the FIFO policy, followed by SHLI which depends on the remaining TTL value. The reason for this is that the messages with FIFO and SHLI are stored longer in the buffer, which leads to an increase in the potential for delivery. Therefore, dropping such messages will not affect the delivery ratio as these messages will soon become expired and be dropped anyway. The results of SHLI and LIFO are roughly the same at the start of the TTL=120 min and above, while the most inferior delivery ratio is by DY, with MOFO joining it when TTL=300

min. The delivery ratio of DY is low because it is negatively affected by dropping the message that has the longest TTL.

B. Overhead Ratio

Figure 4-12 (B) shows that the overhead ratio increases gradually with an increase in the TTL values. This is because when the TTL for the messages is high, this will increase the possibility of duplicating the same messages and saving all the messages for a long period of time, even though they do not receive any chance of being transmitted. The LIFO policy gives the highest overhead ratio because when the node's buffer overflows, LIFO only rejects the incoming messages without deleting any buffered message. This result is considered the most inferior compared to the other five dropping policies.

C. Latency Average

The change in the average latency when the TTL value is between 60 and 300 min can be illustrated in **Figure 4-12** (C), where the latency average increases in accordance with the increase in the TTL values for FIFO and LIFO policies. There is no effect of the TTL on the SHLI because the basis of SHLI is dropping messages with the lowest TTL, and thus by increasing or decreasing the TTL, the SHLI will follow the same base principle. SHLI achieves the lowest latency (the optimum result) compared with the other policies, whereby the latency average with MOFO and DL remains stable at TTL=120 min and above. On the other hand, the highest

average latency is by LIFO as when congestion occurs, LIFO only drops recently received messages.

D. Hop Count Average

The hop count of all the drop policies is the minimum at TTL=60 min and the maximum at TTL=300 min. From **Figure 4-12** (D), the hop count of the DY policy is the maximum when compared to the other five drop policies, while the lowest hop count is by LIFO followed by SHLI. The hop count with DL increases gradually until TTL=180 minutes and then starts to drop at TTL=240 min and above.

E. Messages Drop

From **Figure 4-12** (E), it can be seen that the LIFO policy drops the highest amount of dropped messages, followed by the FIFO and SHLI policies, respectively. The other three policies (DL, DY, and MOFO), on the other hand, approximately drop the same amount of messages, which commence with a high drop amount at 60 min, start to drop gradually at 120 min, and then remain stable even when the TTL value increases, as they do not rely on the lifetime for dropping the messages.

2. Impact of Varying the Messages' TTL on the Spray&Wait Routing Protocol with Different Drop Policies

To observe the impact of varying the packet's TTL values on the Spray&Wait routing protocol, we increase the TTL value up to 300 min from an initial value of 60 min, with a step change of 60 min. The effect of the six previously mentioned

policies was investigated on Spray&Wait, with the results analyzed based on the different performance metrics, as shown in **Figure 4-13** and discussed as follows:

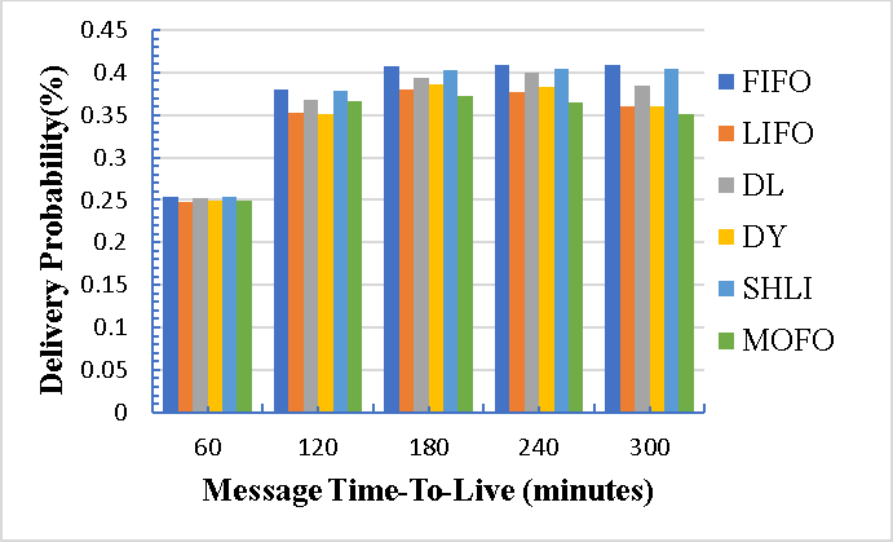
A. Delivery Probability

We first evaluate each policy in terms of delivery probability and show their comparison in **Figure 4-13** (A). All the dropping policies commence with the same delivery probability at TTL=60 min of 0.25, and then the delivery probability increases with all the policies when the TTL value is 120 min. As we can note, the Spray&Wait protocol provides a good delivery probability, and this rate is positively impacted by the increase in the TTL value. The reason behind this is that the Spray&Wait routing protocol limits the copying of the message and does not consume network resources. Furthermore, the delivery rate is increased because it takes advantage of the restricted copying of messages forwarded. The highest delivery ratio is attained with FIFO and SHLI, followed by DL. Meanwhile, the lowest delivery probability is given by the MOFO policy. The LIFO, DY, and MOFO policies continue to increase with the increase of the TTL until TTL=240, min when the delivery probability starts to decrease.

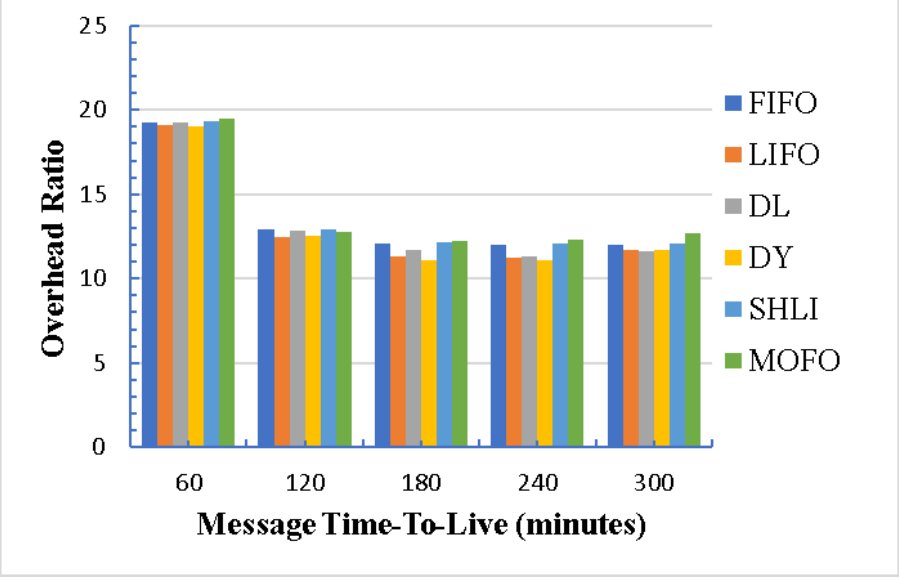
B. Overhead Ratio

The overhead ratio of Spray&Wait continues to decrease with the increase of TTL. **Figure 4-13** (B) presents the overhead ratio of the six dropping policies impacted positively by increasing the TTL value, which starts to become high at TTL=60 min, and then decreases until TTL=120 min. The overhead ratio is approximately

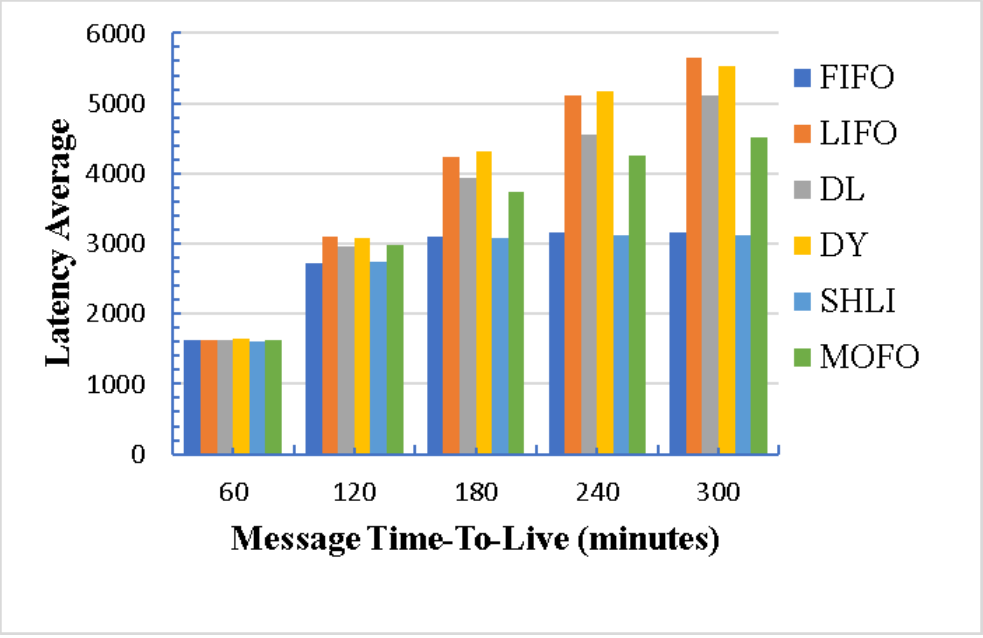
equal to SHLI and FIFO, regardless of the TTL value. The DY policy provides slightly less overhead ratio than the other five policies. The Spray&Wait protocol lowers the overhead and buffer overflow by reducing excessive packet forwarding.



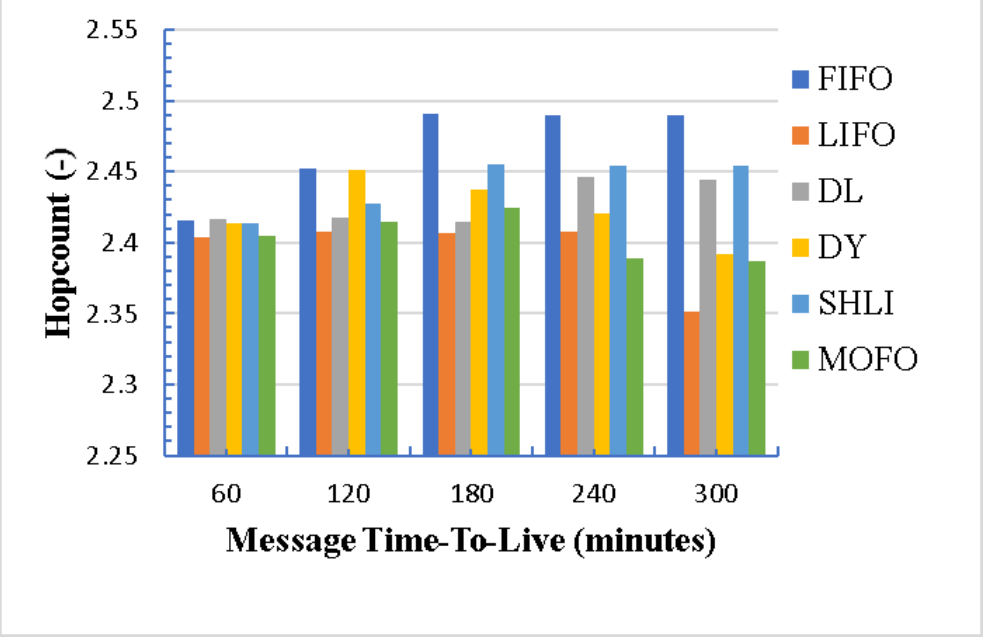
(A) Message Delivery Probability



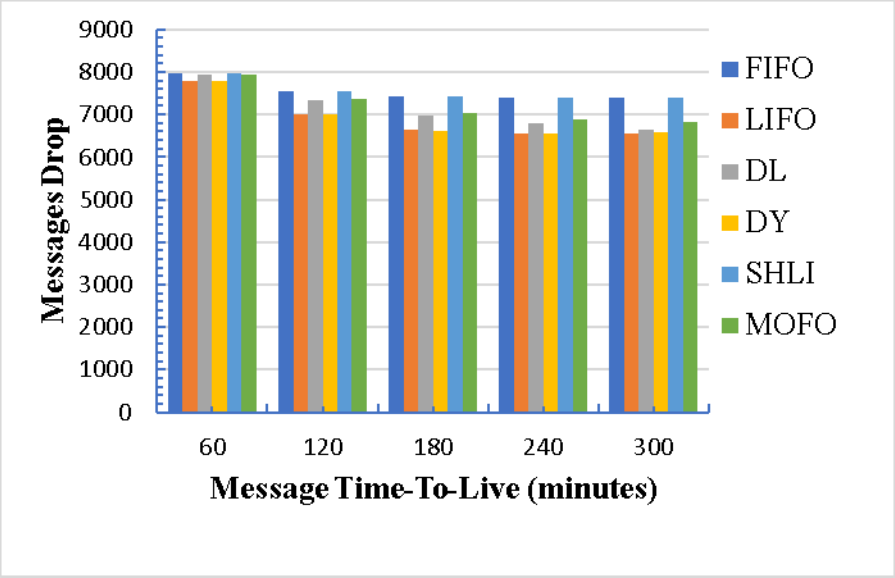
(B) Overhead Ratio



(C) Latency Average



(D) Hop Count



(E) Messages Drop

Figure 4-13: The performance of various drop policies in the Spray&Wait routing protocol with different TTL values

C. Latency Average

Figure 4-13 (C) presents the comparison of the six policies in terms of latency average, where it can be seen that the latency average ratio increases with increasing TTL value in all the dropping policies that commence with the same latency average at TTL=60 min. Therefore, the latency average is negatively impacted by increasing the TTL, because the store time for the messages will be longer and cause high latency, as well as the dropping of messages. The latency average of the SHLI and FIFO policies is markedly lower than the other four policies that remain virtually unchanged near 1500 s regardless of the TTL value. Moreover, we can note that

LIFO and DY provide the same latency average, which is considered to be the highest (i.e. the most inferior result) compared with the other four dropping policies.

D. Hop Count Average

It can be observed from **Figure 4-13** (D) that the hop count for the FIFO and SHLI policies is increased at TTL=180 min, and then remains without any change at higher TTL values. FIFO and SHLI feature the highest and second-highest hop count, as these policies allow the messages to remain in the node's buffer for longer periods of time. Meanwhile, LIFO stays stable until TTL=240 min, and then the hop count decreases when the TTL increases to 300 min. The best result is obtained by LIFO at TTL=300 min, while FIFO features the most inferior result at TTL=180 min and above. With DY, the hop count decreases gradually at TTL=180 min and above.

E. Messages Drop

In **Figure 4-13** (E), it can be seen that at TTL=60 min all the policies provide the same extent of message drop, which then start to gradually reduce for all the policies. Therefore, the messages drop metrics are positively impacted by increasing TTL, as the storage time for the messages will be longer and fewer messages will be dropped. Furthermore, the potential for the message to be delivered to the destination is high when the TTL is large. The DY drops the least number of messages forwarded by LIFO, while FIFO and SHLI drop the highest number of messages, followed by MOFO and DL, respectively.

4.5 Challenges and Open Issues in DTN

Since DTN routing protocols are not effective to meet every traffic situation as the scenarios will differ, designing an effective routing protocol has attracted significant attention from researchers. Nevertheless, numerous research challenges are presented in this study, since an effective routing protocol must be able to (i) work efficiently in sending messages to all nodes with minimum overhead, collision, and duplication by adaptive reliable broadcast and multi-cast transmission; and (ii) improve network throughput and PDR, minimize bandwidth consumption, reduce the delivery delay, and guarantee optimal paths between nodes. Therefore, as our topic is extensive and includes various sub-topics, the challenges are explained in the following subsections:

4.5.1 *The Challenges and Open Issues in DTN Routing Protocols*

In terms of the challenges and open issues in DTN routing protocols, after presenting the comparison and review of the DTN routing protocols, it is concluded that several research issues remain to be addressed, and thus require further investigation. These issues are listed as follows [11, 29, 176]:

1. There is no clear approach to determining the number of nodes to forward the messages. We found that a large number of nodes increases the opportunities to deliver messages to the destination. However, this could lead to the ineffective use of bandwidth and buffer space, and consequential

increases in cost. Therefore, the resource friendly DTN routing protocol is required.

2. There is no proper metric performance to determine the efficiency of the DTN routing protocol, in terms of whether the overhead ratio, delivery probability, average latency, hop account, or other metric is utilized. Therefore, an effective method is required in order to define the system capacity during the intermittent case.
3. There is no way to determine the number of suitable copies. For example, the copies in the Spray&Wait protocol can be divided until the last node maintains the final copy, which will not be delivered to any spare node except the destination node. Moreover, unnecessary copies must be deleted to minimize buffer occupancy. This is one of the issues that will be overcome in this thesis by proposing a novel dynamic number of replicas techniques.
4. An effective approach is required to schedule messages in the node's buffer based on the properties of prioritized transmission.
5. Vehicles can evolve in both congested and sparse traffic areas. Therefore, the ideal DTN routing protocols must work perfectly in both scenarios.
6. The lifetime for a message is defined whereby the period that the message remains stored in a buffer should be lower than the lifetime. If the stored time for the message has expired, then the message should be deleted from

the buffer. The limitation of this is that the message could be discarded prior to reaching the destination node. Moreover, we do not know how long the message will be stored in this case, which is the main issue.

7. The notification of a received message at the destination is required since copies will remain in the network after the message reaches its destination. These messages are stored in the intermediate nodes, which will result in the inefficient use of buffer storage and other network resources. Therefore, we need to establish techniques to predict when the message will arrive at the destination, after which, the surplus copies should be deleted.
8. Due to high mobility, frequent disruption, and the unpredictability of contacts, the DTN is not suitable for all vehicular applications because some of these such as accident awareness and emergency feature severe delay constraints.

4.5.2 *Challenges and Limitations of Buffer Management*

It can be observed from the literature review and from our performance analysis and acquired results in this chapter that there are gaps in the area of buffer management in DTN routing protocols. The main challenges and limitations in buffer management policies can be summarised as follows:

1- Various buffer management policies depend on solely computing a single metric to drop the message [32, 170, 177, 178]. However, a serious

weakness in this argument is that a fair selection of which message to drop cannot be achieved by a single metric.

2- Every message has its particular level of resource consumption. For instance, an emergency message might remain in the buffer for a long period of time even if it has already been delivered to the destination node. Similarly, other message types might have been carried by other nodes and have consumed more network resources such as bandwidth, energy, and buffer without getting the opportunity to be delivered. Therefore, dropping such messages may not affect the network performance. Hence, defining a drop metric that drops the message according to the message type is required.

3- Due to messages with the highest TTL obtaining more opportunities to transmit, the TTL has a direct impact on message delivery in the DTN. The DTN defines a time limit for the transmission of message copies [179, 180], whereby the message is automatically removed from all the nodes if it is unable to reach its destination within the TTL. Nevertheless, the TTL based on certain buffer management policies does not keep track of the lifetime of the message in the node's buffer. Therefore, in order to improve performance and avoid network congestion it is pertinent to remove those messages that no longer have any transmission opportunity.

4- Another issue with the existing buffer management is maintaining the replication of the message until the TTL has expired without providing any method to compute how many copies have been transmitted thus far. Hence, the benefits of the threshold limit are valuable to enable the messages that have been transmitted a greater number of times than the threshold value to be dropped.

5- Continuing carrying and saving the messages in the node's buffer even if these have already been delivered to their destination causes buffer congestion and reduces the probability of the other messages being delivered. Therefore, employing an acknowledgement mechanism that leads to the reservation of the node's buffer is pertinent and required.

4.6 Summary

The DTN routing protocol and buffer management are the main aspects that affect network performance. This chapter presented two parts. In the first part, DTN routing protocols were found to be responsible for delivering data messages to the destination in an intermittent network where end-to-end communication is not available. In this chapter, various types of DTN routing protocols that represent different classes of DTN were discussed in detail to facilitate an understanding of the mechanism of DTN routing protocols. In addition, this chapter compared five DTN routing protocols via different network models in order to establish the impact of the network density and buffer capacity in such a DTN environment. From this

analysis, it became evident that the highest delivery ratio with two models (Shortest Path-Based Movement Model and Cluster Model) is achieved by the MaxProp protocol, followed by Spray&Wait.

Lastly, we employed the ONE simulator to assess the DTN routing protocols in order to consistently select the most efficient routing protocols and utilize them as our benchmark. Since MaxProp and Spray&Wait were the two protocols that achieved the optimum results, they were selected as our benchmark protocols after reviewing the DTN routing protocols. This also motivated us to continue working on these two protocols for further enhancements. Therefore, in part two of this chapter, we studied and evaluated the performance of six buffer management policies, namely FIFO, LIFO, DL, DY, SHLI, and MOFO, with the MaxProp and Spray&Wait routing protocols under variable message TTL values. The acquired results highlighted the clear benefits of increasing the TTL value for delivery probability and overhead ratio in the Spray&Wait routing protocol. This implies that Spray&Wait is positively impacted by the increase of the TTL value and offers improved delivery probability and overhead ratio with the six policies compared to the MaxProp routing protocol. We conclude this chapter by asserting that the forwarding techniques in DTNs can be classified into flooding- and quota-based strategies. The first forwarding technique is the flooding-based strategy where the nodes may flood messages to every encountered node. However, this strategy causes congestion and consumes network resources (i.e. bandwidth and buffer

storage). The second forwarding technique is the quota-based strategy which is limited to disseminating the number of replica messages through the network to resolve the problems caused by the flooding strategy. However, the quota-based strategy suffers from a low delivery ratio. In Chapter 5, a novel technique will be proposed to improve the performance of DTN routing protocols.

Chapter 5 Novel Enhanced Message Replication Technique for DTN Routing Protocols

Objectives

- Review and clarify the limitation in the related work
- Provide an overview of the proposed EMRT
- Explain the details of the EMRT algorithm
- Summarise the chapter

CHAPTER 5 NOVEL ENHANCED MESSAGE REPLICATION TECHNIQUE FOR DTN ROUTING PROTOCOLS

5.1 Introduction

DTN is intermittently connected (wireless) networks, whereby there is no guaranteed end-to-end connectivity between the source and destination nodes [14-16, 181]. These networks can be disrupted by factors such as node mobility, density, and limited radio range, leading to frequent disconnections. As a result, traditional TCP/IP cannot be used, and instead, a SCF approach is employed to allow data transmission to continue despite the lack of a continuous path [16, 182]. Nevertheless, this routing approach can cause issues such as buffer congestion and inefficient use of network resources due to the dissemination of multiple copies of a message across the network [16, 18, 19].

There are several routing techniques [20-29] available for addressing the routing problem in DTN, which can be divided into two categories: flooding-based and quota-based [30, 31]. Flooding-based protocols allow nodes to replicate messages indefinitely, which can lead to good network performance when resources are not limited. However, they may have a low delivery ratio, high overhead, and high delay when resources are limited [32, 33]. Quota-based protocols, on the other hand, set a maximum number of replicas for each message, unlike flooding-based protocols where the number of copies is determined by the number of encounters [34]. These protocols are resource-efficient and perform well but may experience low delivery rates and long delays when resources are insufficient. Additionally, the number of replicas is fixed for all messages and is not affected by network

capacities, such as node buffer size, energy, TTL values, and encounter rate [32, 33]. The limitations of both flooding-based and quota-based routing protocols in DTNs have led us to propose the EMRT. EMRT dynamically adjusts the number of message replicas based on a node's ability to quickly disseminate the message, taking into consideration various parameters such as existing connections, encounter history, buffer size history, energy, and TTL values. This can improve the delivery ratio and enhance network resource utilization.

5.2 Review and Clarification of the Limitations in the Related Work

5.2.1 *Flooding-based Protocols*

A common DTN flooding protocol is the Epidemic routing protocol that was proposed by Vahdat and Becker [159]. The Epidemic protocol transmits the messages between the nodes in the network without any restriction. Due to the limited DTN network resources and unlimited message replicas disseminated through the network, the Epidemic routing protocol has shown less efficiency in the congested traffic network leading to dropped messages and high overhead.

To address the issues associated with the Epidemic routing protocol, Matsuda and Takine proposed the (p - q) epidemic algorithm with a vaccination routing protocol (PQERPV) [183]. The q probability indicates the probability of receiving a message from the source while the p probability indicates the probability of receiving a message from other nodes. The performance of the PQERPV protocol is influenced

by the value of q and the p-values, which can impact the protocol's performance. Lower p-values can lead to a low rate of message dissemination.

In [184], the two-hop forwarding protocol was proposed by Grossglauser, *et al*. In this routing protocol, the sender nodes exchange bundles with arbitrarily encountered nodes that will forward these messages only to the destination node. The overhead of this protocol is lower than the overhead of pure Epidemic since the message will be sent across two hops only. However, if the destination node is not reachable via two hops, the messages may fail to be delivered to the destination node. Furthermore, due to the low dissemination rate, the message may suffer from a large delay. Additionally, various DTN protocols that select the next hop node based on encounters history, have been proposed to decrease the network overhead issue of flooding protocols. One example of these protocols is PROPHET, which was presented by Lindgren, *et al*. [185]. PROPHET utilizes the delivery predictability parameter to estimate the probability of delivering the messages to their destination. In PROPHET, the delivery predictability parameter will be updated after each node's encounter. However, when a node encounters a neighbour node with low delivery predictability, there is no guarantee that it will encounter another node with a higher delivery predictability value during the message lifetime, and therefore the messages may never leave the source node. On the other hand, if the source encounters many nodes with high delivery probability, the overhead will be high because the messages are flooded through the network.

MaxProp is another example of a flooding-based routing protocol, which achieves better performance in terms of high delivery rates and low latency averages as was reported by Burgess, *et al.* [9]. However, the MaxProp approach may produce a high overhead on the restricted resource network [18]. Moreover, in the Rapid protocol approach, the messages are ordered using a utility function [20]. Each message is assigned a utility by the Rapid protocol. Rapid replicates messages can lead to an increase in utility [20]. However, one major drawback of Rapid is that replica information must be flooded throughout the network to derive the utility of messages. Therefore, this may cause high overhead and high delivery delays. Also, the information disseminated may be outdated when it reaches the nodes because of delays.

Another technique is PREP, which is a prioritized Epidemic routing protocol where the messages have been assigned with priority based on both cost to the destination and the expiration time. This assigned priority is used to determine which messages should be sent or dropped when the buffer or bandwidth are both limited.

Erramilli and Crovella proposed techniques to utilize the properties of nodes to make forwarding decisions by selecting the optimum node to forward messages based on utility value [186]. However, this technique causes flooding when many encountered nodes have high utility values. Moreover, the messages may never leave the source nodes when many of the encountered nodes have low utility values.

Based on the above analysis, the issue with flooding-based protocols is the high consumption of the network resources such as bandwidth, buffer, and energy. Therefore, to mitigate the waste in network resources, quote-based protocols can be utilized.

5.2.2 *Quota-based protocols*

One example of a quota-based protocol is the single copy scheme proposed by Spyropoulos, *et al*. [187], in which the source delivers messages directly to the destination node. However, this protocol can be redundant if the destination is located far from the source node and the messages may never be delivered.

To address this issue, Spyropoulos, *et al.* [26] proposed the Spray&Wait routing protocol, which is a multi-copy two-hop scheme. In the Spray&Wait protocol, the number of replicas is fixed at the time of message creation. The protocol consists of two phases that are the spray phase and the waiting phase. The former in which message replicas are disseminated, and the latter, in which the node waits with only one copy message to meet the destination and deliver the message directly to it. The Spray&Wait protocol is resource-efficient, but it may still fail to deliver messages if the destination is in a different area than the source node. To address this issue, Spyropoulos proposed the binary Spray&Wait routing protocol, in which the node forwards half of the message's replicas during each contact.

Cui, *et al*. [188] proposed the adaptive Spray&Wait (QoN-ASW) routing algorithm, which adaptively allocates the number of message copies between encountered

nodes based on the Quality of Node (QoN) metric during the spray phase. In the waiting phase, a forwarding scheme is implemented to increase flexibility. Unlike the direct transmission approach, the QoN-ASW strategy makes use of encounter opportunities and, when a node is left with only one copy, it forwards the copy to a suitable candidate node with higher improved delivery predictability instead of waiting for the destination to be encountered. While the QoN-ASW algorithm improves network performance in terms of delivery rate and average delay, it has a slightly higher overhead than the Spray&Wait protocol.

Another example of a quota-based protocol is Spray & Focus, which was proposed by Spyropoulos, *et al*. [27]. This protocol uses a timer-based utility value to track the intervals between nodes' encounters and assumes that nodes with similar mobility patterns have short intervals between encounters. Spray & Focus also has two phases: the spray phase and the focus phase, in which a single copy is forwarded to maximize a utility function. Both Spray&Wait and Spray&Focus aim to reduce the high overhead caused by flooding-based protocols but have low delivery ratios due to low message dissemination [114].

Bulut, *et al*. [189] proposed an algorithm for transmitting replicas over various periods, in which the source node forwards n copies to the first n encountered nodes and waits for an acknowledgement to confirm successful delivery. If delivery fails, more copies are injected into the network in subsequent periods to increase the delivery probability. However, if a message is successfully delivered, the source

node's acknowledgement may not be received on time due to the significant delays in DTN, leading to the forwarding of many replicas to nodes and causing buffer congestion and dropped messages. Dhurandher, *et al*. [190] proposed the Encounter and Distance based Routing (EDR) protocol for DTN, which uses a forward parameter to select the next hop based on the number of encounters and distance to the destination. However, EDR assumes that all nodes have sufficient energy, which may not be the case and was not evaluated in terms of delivery ratio, a crucial evaluation metric in DTN.

In ref. [191], the Adaptive Message Replication Technique (AMRT) was proposed for use with quota protocols. AMRT controls network traffic by assigning different numbers of replicas for each generated message based on network conditions (such as congestion among the sender's neighbours) using historical traffic information as an estimate of future capacity. AMRT was implemented and evaluated with various quota routing protocols, improving the delivery ratio and reducing the delivery delay.

Another work in the field of quota-based routing protocols is Encounter-Based Routing (EBR), proposed by Nelson, *et al*. [32]. EBR creates a limited number of replicas for each message based on the history of a node's encounters. In EBR, nodes that have encountered each other frequently, have the best chance of successfully transmitting messages to the destination. However, a destination may

never receive transmitted messages if it has low encounter rates in a low-density network.

To address this issue, Iranmanesh, *et al*. [33] proposed the Destination Based Routing Protocol (DBRP). DBRP assigns weights to nodes based on the rate of encounters with the destination and other nodes, with nodes that have encountered the destination receiving higher weights. In networks with limited node buffer space, DBRP has been shown to perform better than other quota routing protocols such as Spray&Wait and EBR. However, DBRP does not consider a node's capability in determining the appropriate number of replicas, which can lead to either buffer congestion due to lack of space or inefficient use of network resources when a small number of replicas are transmitted by a node with sufficient resources. Both EBR and DBRP have been shown to have good performance through simulation, but blindly forwarding replicas to nodes with high encounter rates without considering their capability can lead to delivery delays, message drops, and inefficient resource utilization.

In [192], a novel method was proposed to address the issue of resource consumption caused by message replication. This method determines the dissemination of DTN data based on the expected path of a node, transmitting duplicates to nodes that are close to the destination. The method was evaluated by comparing the number of arrived data to the number of generated data for both the proposed method and an existing method and was found to achieve a higher message arrival rate. However,

this method focuses on where duplicated messages should be sent but do not consider how many replicas of each message should be sent to encountered nodes. Although quota-based protocols are more resource-friendly than flooding-based protocols, they still suffer from low delivery ratios and high delivery delays. To address this issue, we propose the EMRT, a dynamic quota-based technique that considers not only encounter-based routing metrics, but also network congestion and capacity to minimize overhead, maximize delivery ratio, and efficiently utilize network resources. **Table 5-1** provides a summary of the features and characteristics of DTN routing protocols [108]. The table includes details on both flooding-based and quota-based DTN routing protocols.

Table 5-1: Comparison of the various DTN strategies

Protocols	Category	Decision Criteria	Advantages	Limitations	Delivery Ratio	Average Delay	Overhead
Epidemic [147] (2000)	Flooding	None	- Simple, no prior knowledge required	- High drop ratio - High overhead ratio	High if resources unlimited	Low if resources unlimited	High
(p,q)-Epidemic [182] (2008)	Flooding	None	- Recovery process to clear unnecessary messages. - No prior knowledge is Required	- High drop ratio with limited resources -High power consumption	High if resources unlimited	Low if resources unlimited	High
PROPHET [184] (2003)	Flooding	History	- Universal and based on the delivery probability	- High drop ratio. - Acts like Epidemic - Low delivery probability	High if resources unlimited	Low if resources unlimited	High
MaxProp [185] (2006)	Flooding	History	- Fewer messages traffic	- High drop ratio limited. -High power consumption	High if resources unlimited	Low if resources unlimited	High
Spray&Wait [26] (2005)	Quota	None	- Simple and resources friendly	-High drop ratio if resources are limited. -High power consumption	High if resources unlimited	Low if resources unlimited	Medium
QoN-ASW [188] (2019)	Quota	History	- Resources friendly	-High drop ratio if resources are limited. -High power consumption	High if resources unlimited	Low if resources unlimited	High
Spray and Focus [27] (2007)	Quota	History	- Simple and resources friendly	-High drop ratio if resources are limited. -High power consumption	High if resources unlimited	Low if resources unlimited	Medium
Bulut et al [189] (2010)	Quota	None	- Simple, no prior knowledge required	-High drop ratio if resources are limited. -High power consumption	High if resources unlimited	Low if resources unlimited	Medium
AMRT [191] (2018)	Quota	History	- Resources friendly	- High drop ratio -High power consumption	High if resources unlimited	Low if resources unlimited	Low
EBR [32] (2009)	Quota	History	- Resources friendly	- High drop ratio -High power consumption	High if resources unlimited	Low if resources unlimited	Low
DBRP [33] (2012)	Quota	History	- Resources friendly	-High drop - High power consumption	High if resources unlimited	Low if resources unlimited	Low

5.3 Enhanced Message Replication Technique

As the main objective of DTN routing protocols is to achieve high delivery ratios, low delivery delay, and low overhead [190]. Based on the literature review, quota-based protocols suffer from trial-and-error values for the parameters of the algorithm. In this section, we propose the EMRT technique to set the maximum initial number of replicas for each generated message dynamically based on the network circumstances such as density, buffer availability, energy, and TTL values. To define each of the criteria above, we assume that each node has an Encounter Value (EV) which indicates the history of the rate of encounters. This implies that the past rate of encounters can be used to predict the future encounter rate. Let us briefly explain how EVs are calculated. Every node should maintain a Current Window Counter (CWC) that counts the number of encounters in the last time interval. Let's say each time interval duration is 30 seconds. Accordingly, the EV of a source node ***s*** is updated as follows:

$$EV_s(\text{updated}) = \alpha \times CWC + (1 - \alpha) \times EV_s(\text{old}) \qquad (5\text{-}1)$$

Where $\alpha \in (0,1)$ i.e., 0.85. When the interval has ended, CWC is reset to zero, and EV is updated. In order to evaluate whether an encountered node is likely to be located in a high-density area, we will use the criterion of EV. Based on this information, the initial number of replicas for a new message can be appropriately determined for the node. In addition to the encounter rate, we have also defined other criteria to consider when determining the initial number of replicas.

An average buffer of nodes, that the source node has encountered, is another criterion which is represented by B_{avg}. The information or the criterion (B_{avg}) can be used to evaluate the space capacity of the nodes that the source will likely see them again in the future. If their storages have enough space, more replicas will be created. Otherwise, a less initial number of replicas will be generated to reduce the rate of dropped messages.

TTL_i is another criterion that represents the amount of time that a generated message i can remain in the network. If the TTL expires, the message will be dropped. Hence, if the TTL is short, the dissemination should be more. Consequently, the maximum initial number of replicas should be increased.

Lastly, E_s represents the available energy of the source node. If the remaining energy is small and the node is about to die, a message generated by that node cannot live for a long time at the source node. So, it should be disseminated to other encountered nodes. As a result, if E_s is small, the maximum initial number of replicas should be increased.

Based on the above definitions, after normalization, the maximum initial number of replicas for each generated message i is calculated as follows:

$$M_i = m_{init} \times \frac{EV_s + B_{avg}}{TTL_i + E_s} \tag{5-2}$$

Where m_{init} is the initial number of message replicas that the existing quota-based routing protocols use. As a result, M_i will be the new maximum initial number of replicas for the quota-based protocol.

Algorithm 1 shows how each source node produces a different number of initial replicas for each generated message. As mentioned above, each node is responsible for maintaining the encounter value, which is used to predict future encounter rates (Line 2 in Algorithm 1 below). CWC is used to count the number of encounters in the current time interval. So, when the update interval expires, the CWC will be set to zero (line 3). For each generated message the maximum initial number of replicas is calculated based on **equation (5-2)** (line 7). This is while m_{init} is dependent on the routing protocol used. For example, EBR uses $m_{init} = 11$, Spray&Wait uses $m_{init} = 8$. Consider the numerical example in **Figure 5-1**. Let us assume the routing protocol used is EBR. Node A with $EV_s = 20$, $B_{avg} = 25$, $TTL_i = 8$, $E_s = 11$, and m_{init}=11. M_i for node A is $M_i = 11 \times \left\lfloor \frac{20+25}{8+11} \right\rfloor = 22$. While node B with $EV_s = 12$, $B_{avg} = 20$, $TTL_i = 20$, $E_s = 30$, and m_{init}=11. M_i for node B is $M_i = 11 \times \left\lfloor \frac{12+20}{20+30} \right\rfloor = 4$.

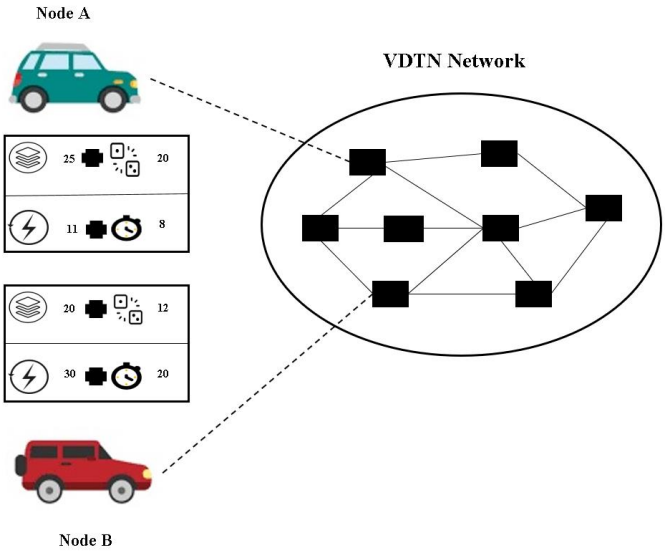


Figure 5-1: Network's circumstances from each node's perspective

Algorithm 1: EMRT

1: ***if*** $time \geq nextUpdate$ ***then***

2: $EV \leftarrow \alpha * CWC + (1 - \alpha) * EV$

3: $CWC \leftarrow 0$

4: $nextUpdate \leftarrow time + Wi$

5: ***end if***

6: ***for*** $every\ new\ messages\ i$ ***do***

7: $M_i \leftarrow m_{init} \times \left\lfloor \frac{EV_s + B_i}{TTL_M + E_s} \right\rfloor$

8: ***end for***

5.4 Summary

This chapter introduces EMRT, a novel message replication technique for Quota-based DTN protocols that enables the number of replicas to be dynamic based on

nodes' capabilities. EMRT is designed to generate the optimal number of replicas for newly generated messages by considering the history of encounters, as well as the buffer availability, energy, and TTL values of nodes. As a result, EMRT improves the performance of quota protocols and more effectively utilizes network resources. To evaluate the performance of EMRT, three quota protocols (Spray&Wait, EBR, and DBRP) were considered. The results show that EMRT significantly improves the delivery ratio (up to 13%, 8%, and 10% for Spray&Wait, EBR, and DBRP, respectively) and reduces the latency average (by 51%, 14%, and 13% for Spray&Wait, EBR, and DBRP, respectively) compared to the original quota protocols. The implementation and evaluation of EMRT will be explained in more detail in Chapter 6.

Chapter 6 Implementation, Evaluation, and Validation of Results

Objectives

- Justify the use of the ONE Simulator
- Present the simulation metrics and results
- Present the validity and performance of the proposed technique
- Discuss and analyze the results
- Summarize the chapter

CHAPTER 6 IMPLEMENTATION, EVALUATION, AND VALIDATION OF RESULTS

6.1 Introduction

There are many network simulation tools available to implement the proposed technique. Since most of the research in DTN has been implemented using ONE simulator that it is designed especially for simulating and evaluating DTN, we are in the same manner using ONE simulator [122]. ONE simulator can be used to evaluate DTN protocols across many scenarios and requires suitable simulation tools. It provides a framework for developing routing and application protocols and enables users to build scenarios based on various synthetic movement models and real-world traces. This chapter, therefore, implements and simulates the proposed EMRT using ONE simulator.

6.2 The Evaluation of EMRT

EMRT has been tested using the ONE simulator, which is a Java-based, open-source tool for evaluating and implementing routing protocols, particularly for DTN [122]. The performance of EMRT was evaluated against the original form of Spray&Wait, EBR, and DBRP. The experiments were conducted based on the benchmark simulation settings available in the ONE simulator as listed in

Table 6-1.

Table 6-1: Parameters of the simulation works

No.	Parameter	Value
1.	Total Simulation Time	12 hours
2.	World Size	Helsinki Finland 5 X 3 km^2
3.	Movement Model	Map-based Model
4.	DTN Routing Protocol	Spray&Wait, EBR, and DBRP
5.	Speed of Nodes (m/s)	Tram: U [7, 10] Vehicle: U [2.7: 13.9] Pedestrian: U [0.5: 1.5]
6.	Buffer Size	20 MB
7.	Number of Nodes	50, 100, 150, 200, 250
8.	Data Rate	54 Mbps
9.	Interface Transmit Range	140 meters
10.	Message TTL	60 minutes
11.	Node Movement Speed	Min=0.5 m/s, Max=1.5 m/s
12.	Message Creation Rate	One message per 25–35 seconds
13.	Message Size	100 KB

6.2.1 *Metrics Performance*

The goal of the experiments is to test the impact of EMRT on the Spray&Wait, EBR, and DBRP quota protocols by comparing the results with the original versions of these protocols. This means that the performance of these protocols was not compared to each other, but rather, the performance of the protocols with and without EMRT was compared in order to validate the effectiveness of EMRT. Six metrics, as defined in ref. [191], were used in the analysis. The three conventional metrics of delivery ratio, overhead ratio, and latency average were explained in detail in Chapter 2. However, to remind the reader, a brief definition is provided in this sub-section. The delivery ratio is a key metric used to evaluate the performance of a network. It is calculated as the ratio of the number of delivered messages to the number of generated messages; latency average, measured in seconds, is the average time it takes for messages to be delivered to their destination in the network; while the overhead is defined as the ratio of the number of delivered messages to the number of relay nodes. In order to account for the trade-off between different metrics and penalize protocols that unfairly optimize a single metric, three composite metrics, DL, DO, and DLO, are used to compare the delivery probability and conventional metrics as ratios. These metrics, which were introduced in [190, 191], are defined below:

DL is a composite metric that is used to adjust the performance of a protocol if it is optimized for delivery ratio but has poor latency. DL is a ratio of the Delivery Ratio (DR) to the Latency Average (LA), and it can be calculated using **equation (6-1)**:

$$\mathrm{DL}=\mathrm{DR}\times\frac{1}{\mathrm{LA}} \tag{6-1}$$

As defined in **equation (6-2)**. DO combines the DR and the Overhead Ratio (OR) to capture the trade-off between these two metrics.

$$\mathrm{DO}=\mathrm{DR}\times\frac{1}{\mathrm{OR}} \tag{6-2}$$

Finally, the trade-off between DR, LA, and OR is captured by DLO in **equation (6-3)**:

$$\mathrm{DLO}=\mathrm{DR}\times\frac{1}{\mathrm{LA}}\times\frac{1}{\mathrm{OR}} \tag{6-3}$$

6.2.2 *Simulation Results*

The performance of EMRT was analyzed by varying the node density (number of nodes). The results of the impact of EMRT on Spray&Wait, EBR, and DBRP at various node densities are shown in **Figure 6-1**, **Figure 6-2**, and **Figure 6-3**. To clarify, "Spray&Wait-EMRT", "EBR-EMRT", and "DBRP-EMRT" refer to the application of the proposed EMRT on the original Spray&Wait, EBR, and DBRP quota routing protocols, respectively. The performance of Spray&Wait-EMRT, EBR-EMRT, and DBRP-EMRT is improved by EMRT when the number of nodes exceeds 50. This is because the source node adaptively adjusts the initial maximum

number of message replicas according to its own buffer size, allowing it to generate the appropriate number of copies for each message rather than relying on a fixed limited number of copies for all generated messages.

Figure 6-1 shows the relationship between node density and message delivery ratio for different quota protocols. The delivery ratio for all protocols (the original Spray&Wait, EBR, and DBRP, as well as the enhanced Spray&Wait-EMRT, EBR-EMRT, and DBRP-EMRT version) increases significantly as the number of nodes increases. This is because when there are more nodes, more of them are involved in delivering messages and the number of replicas also increases, increasing the chance of the messages being delivered. In addition, **Figure 6-1** shows a significant improvement when the proposed EMRT technique is applied to Spray&Wait, with results showing up to a 13% improvement compared to the original Spray&Wait. This is because Spray&Wait relies on a fixed number of replicas for all messages, while Spray&Wait-EMRT uses a dynamic number of replicas based on the node's ability to carry the messages without causing congestion or wasting network resources. As a result, EMRT reduces the number of copies of newly generated messages when the source's neighbours experience message congestion. The EBR-EMRT protocol also shows improvement when EMRT is applied, with the delivery ratio increasing by up to 8% compared to the original EBR. This is because, in addition to directing replicas towards high-density areas, EBR-EMRT controls the

number of replicas based on the capability of the node, taking advantage of the available size of the node buffer to carry and store more copies of the message until a good forwarding opportunity arises. Finally, the DBRP-EMRT also achieves up to a 10% improvement compared to the original DBRP by controlling the level of congestion in the network to improve the delivery ratio by ensuring that the number of replicas is appropriate for the available network resources.

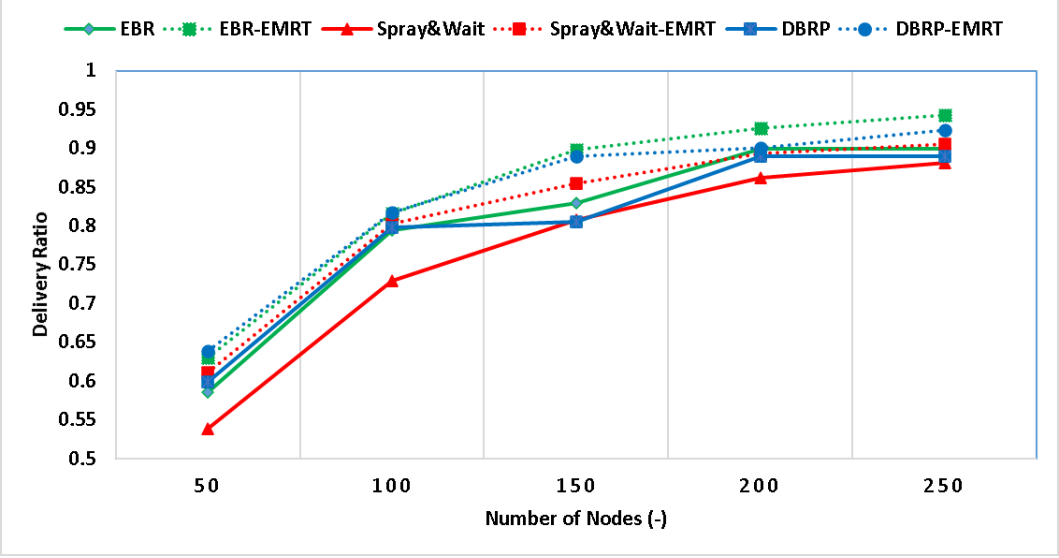


Figure 6-1: The delivery ratio in different node densities

Figure 6-2 shows the relationship between the overhead ratio and node density. As the node density increases, the overhead ratio decreases for all protocols, because these quota protocols rely on a small number of message copies, so they are not greatly affected by the increasing number of nodes. At the same time, the figure also shows the results of applying EMRT to Spray&Wait, EBR, and DBRP in terms of the overhead ratio. There is not a significant reduction in the overhead ratio of

DBRP-EMRT, while the overhead ratio of Spray&Wait-EMRT and EBR-EMRT protocols are reduced by up to 9%, and 6%, respectively, compared to Spray&Wait and EBR. This is because the network resources are controlled and congestion is reduced by relaying messages based on the rate of encounter and the level of network congestion (available network resources), resulting in a low overhead ratio. This means that when a node has sufficient resources such as free buffer space and energy, the number of replicas for newly generated messages will be increased. Otherwise, the number of copies of newly generated messages will be decreased.

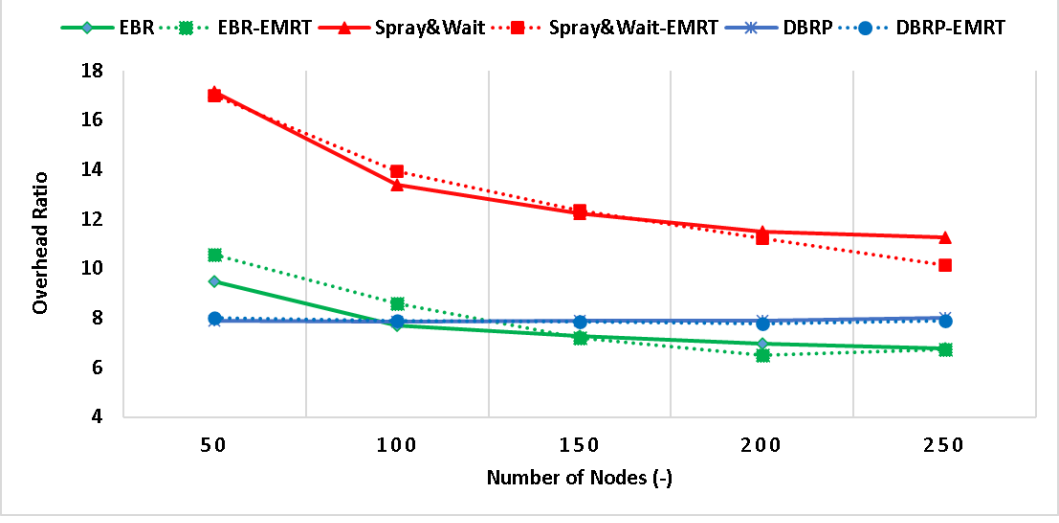


Figure 6-2: The overhead ratio in different node densities

Figure 6-3 shows the relationship between latency average and node density, where it is clear that the latency average increases as the number of nodes increases. This is because more nodes become involved, leading to congestion in the network, and information processing at each node takes time, resulting in an overall increase in

latency. In addition, buffering messages at a node causes delays in message delivery. The figure also shows the results of applying EMRT to Spray&Wait, EBR, and DBRP in terms of latency average. The increased latency average at higher densities with the original protocols is due to more nodes sending copies of the message, leading to a delay in message delivery. It can be seen that the latency average of the Spray&Wait-EMRT, EBR-EMRT, and DBRP-EMRT protocols is reduced by up to 51%, 14%, and 13%, respectively. This is because the rate of dropping messages is controlled by selecting a number of replicas appropriate for the available network resources. An uncontrolled number of replicas can lead to buffer congestion or inefficient use of network resources. By reducing congestion, the rate of message drops is reduced, resulting in a decrease in latency average.

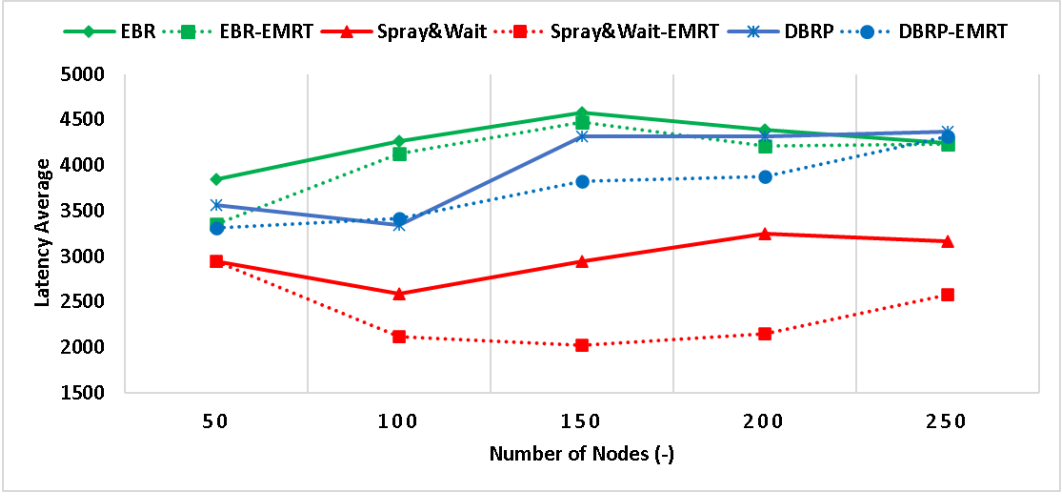


Figure 6-3: The latency average in different node densities

Figure 6-4 shows the composite metric combining delivery ratio and latency average. The results show that applying EMRT to Spray&Wait can improve both the delivery ratio and latency average by up to 60%. This is due to the individual improvements in each of these metrics, as explained in **Figure 6-1** and **Figure 6-3**. Additionally, there is up to a 25% improvement in this composite metric for EBR and DBRP. These improvements are less compared to Spray&Wait, and this is due to the more targeted forwarding strategy used in these protocols.

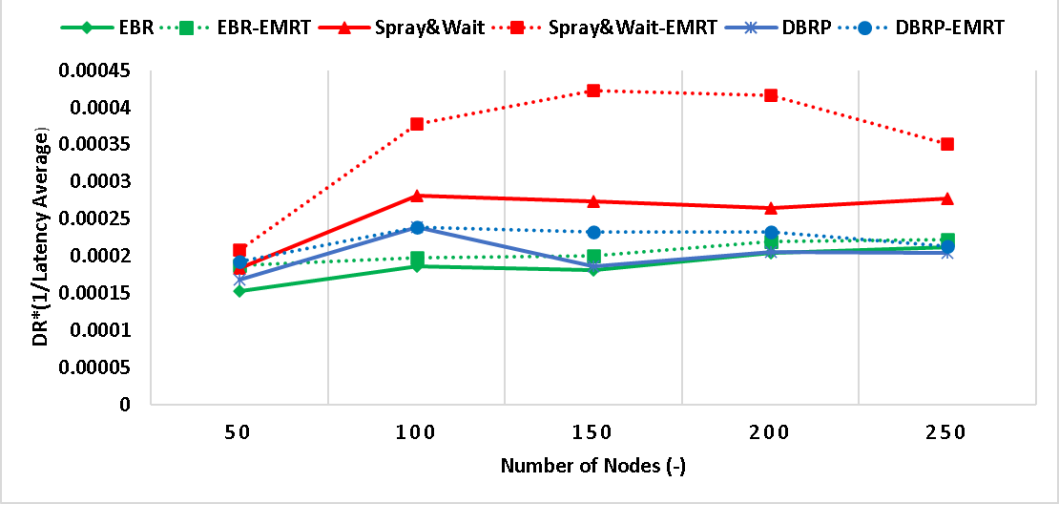


Figure 6-4: The Delivery/Latency composite metric

The composite metric **Figure 6-5**, which evaluates both delivery ratio and overhead, shows up to a 14% improvement for all considered protocols when EMRT is applied. EMRT increases the number of replicas when there are sufficient resources, leading to an expected increase in overhead. However, when there are

insufficient resources, the number of replicas decreases. Therefore, EMRT is not expected to lead to a significant improvement in the overhead ratio. However, the high dissemination rate resulting from the production of more replicas increases the delivery ratio, leading to the impact shown in **Figure 6-5**. This trade-off between overhead and delivery ratio is why EMRT has an impact on these composite metrics.

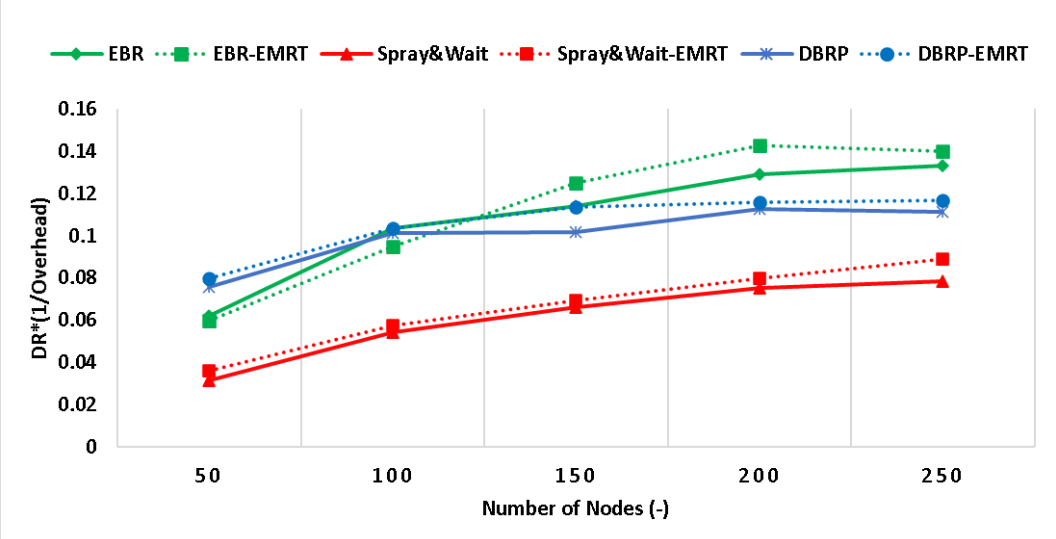


Figure 6-5: The Delivery/Overhead composite metric

Finally, **Figure 6-6** shows a clear image of the performance of EMRT when applied to the considered protocols and all delivery ratios, average latency, and overhead are combined. The results for all protocols show up to a 72% improvement. This is because the improvement of applying EMRT can be seen in all individual metrics as well. The EMRT results show that making the number of replicas adaptive increases the overall performance of the routing protocol. This is because the

number of copies is not dependent on the number of encounters and remains fixed for each generated message.

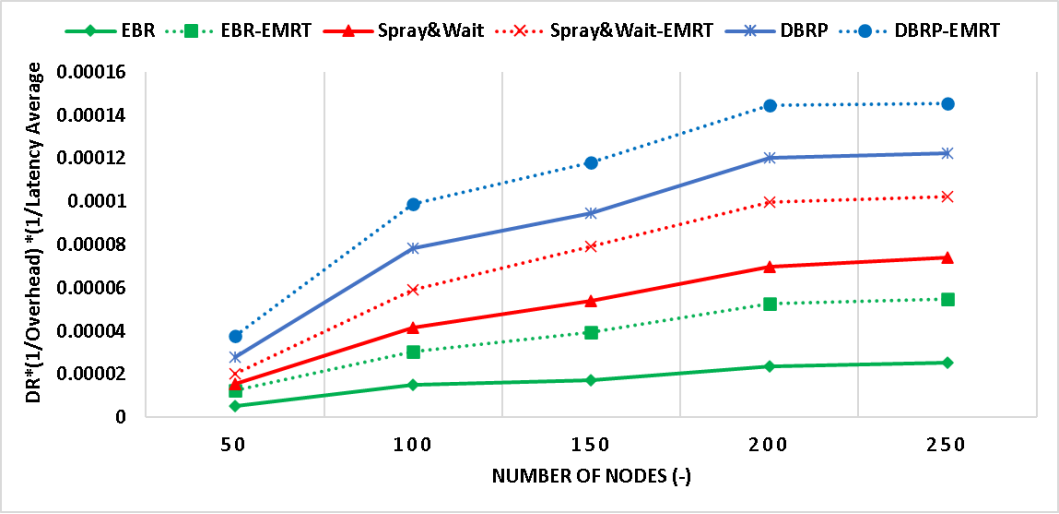


Figure 6-6: The Delivery/Latency/Overhead composite metric

6.3 Summary

In this chapter, the implementation of EMRT was explained, with the results clearly presented to validate the performance of EMRT. As a result of EMRT, the quota-based protocols' performance improved, with the network resources more effectively utilized. To evaluate the performance of the EMRT technique, the Spray&Wait, EBR, and DBRP quota-based protocols were considered, with the proposed EMRT achieving an improvement in terms of the delivery ratio of up to 13%, 8%, and 10%, respectively, compared to the original protocols. Moreover, the latency average was reduced by 51%, 14%, and 13%, respectively.

Chapter 7 Conclusion, Recommendations, and Future Works

Objectives

- Provide a conclusion to the research
- Discuss the research contributions
- Present the potential for future works
- Summarize the chapter

CHAPTER 7 CONCLUSION, RECOMMENDATIONS, AND FUTURE WORK

The purpose of this chapter is to conclude, summarize, and discuss the project's contributions while presenting the implications for future study of the various issues explored in this thesis. The chapter concludes by pointing out some open issues and possible directions for further research related to Vehicular Ad-hoc Network (VANET), Delay Tolerant Network (DTN), and Vehicular Delay Tolerant Network (VDTN), in order to complete the aim of this project.

7.1 Conclusion

As has been pointed out, the present research aimed to improve the position-based routing protocol to reduce road traffic accidents and increase safety. This section presents a summary of the thesis, alongside the potential for further work. A VANET is a sub-class of Mobile Ad-hoc Networks (MANETs) that enables vehicles to exchange different types of information with each other. In VANET, the vehicles are equipped with wireless devices to collect data from the environment and share road safety and traffic information with in-range vehicles, roadside units, and other connected objects. Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure, and Vehicle-to-Everything (V2X) communications are the terms of these functions. The nodes in VANET are vehicles that can act as servers or clients for the exchange the information via their shared radio transmission range to facilitate V2V and V2I communications. However, due to the rapidly changing topology and fast node mobility, the existing routing protocols in VANET still have limitations that require

further investigation to allow improvements to be realized, especially in contexts where end-to-end communication is not available. Therefore, in this thesis, the DTN routing protocols were considered.

DTN is defined as intermittently connected (wireless) networks, where there is no guaranteed end-to-end connectivity between the source and destination nodes. Frequent disconnections are experienced due to node mobility, node density, limited radio range, and power constraints. Due to such frequent disconnectivity, Transmission Control protocols/Internet Protocols are not suitable. Hence, the Store-Carry-Forward (SCF) approach becomes pertinent, which allows data transmission to successfully proceed despite the absence of continuous end-to-end paths. However, various issues arise in this DTN routing approach such as buffer congestion and the inefficient utilization of network resources due to the dissemination of multiple copies of a message across the network.

One of the more significant findings to emerge from this study is that the topic of improving road safety and avoiding road traffic accidents through using the position-based routing protocol requires further investigation since safety in VANET remains a crucial issue. The most significant objective of a DTN routing protocol is to increase the probability of message delivery and avoid message drop. With the help of SCF techniques, we can overcome the challenges of a high error rate, the lack of a direct or indirect route from the source to the destination and no

predetermined/fixed connectivity. DTN is employed to deal with this unpredictable environment for data communication, where the messages need to be stored in the node in the absence of any suitable forwarder. Therefore, the node carries messages until it locates a suitable forward node.

The SCF mechanism is utilized by nodes in DTN networks to transmit messages. Moreover, such networks employ message replication as a means of improving the potential for messages to reach their destination. Since buffer congestion can occur as a result of message replication, determining the proper number of replicas can help to improve the delivery ratio and enhance the utilization of network resources. Therefore, this thesis conducted an extensive review of the literature on VANET, focusing on the position routing protocol in general, and DTN routing protocols in particular, as well as the contemporary routing protocols and buffer management policies considered to avoid buffer congestion and message drop issues. We can conclude that the routing protocols for safety applications in VANET play an important role due to their responsibility for delivering data messages to the destination through the optimum route and in a timely manner. Therefore, the routing protocols must be effective, with a strong emphasis on successful delivery and low delay. In this thesis, we proposed an Enhanced Message Replication Technique (EMRT) to improve the network performance by preventing the nodes from excessive resource utilization. EMRT fits into quota-based protocols to render

the number of replicas dynamic based on the capability of the nodes for quick dissemination. The performance of the EMRT technique was validated using simulation in a resource-constrained network, with the simulation results demonstrating the efficiency of EMRT with different quota-based protocols. According to our simulations, applying EMRT to the three selected protocols improved the delivery ratio, overhead ratio, and latency average. As a result of EMRT combined with Spray&Wait, Encounter Based Routing (EBR), and Destination Based Routing Protocol (DBRP), the delivery ratio improved by 13%, 8%, and 10%, respectively, while the latency average was reduced by 51%, 14%, and 13%, respectively. On the other hand, there is no significant reduction in the overhead ratio with DBRP-EMRT, but the overhead ratio of the Spray&Wait-EMRT and EBR-EMRT protocols are reduced by up to 9% and 6%, respectively.

7.2 Research Contributions

VANET has a range of applications such as traffic management, security, congestion control, and safety. However, this project focused on the safety field in VANET, which aims to contribute towards saving lives by avoiding road traffic accidents and improving road safety. Safety is a critical topic in VANET that still requires further investigation to minimize the fatalities caused by serious road traffic accidents. Therefore, to achieve this aim, we focused on transmitting the message efficiently in the network, reducing the buffer congestion, avoiding

message drop, enhancing the utilization of network resources, and controlling the number of replicas to help increase the delivery ratio, reduce the delay, and minimize the overhead.

The major contributions of the thesis are summarised as follows:

1. Conducted an extensive performance evaluation of state-of-the-art routing protocols for DTNs with different buffer management policies, giving insight into the impact of these policies on DTN routing protocol performance. The empirical study gave insight into the strengths and limitations of the existing protocols and also enabled the selection of the benchmark protocols utilized in evaluating the new proposed Enhanced Message Replication Technique (EMRT) scheme.
2. A novel EMRT is proposed that improves the efficiency of message transmission in DTNs thus enhancing vehicular safety; EMRT is a dynamic quota-based technique that considers not only encounter-based routing metrics, but also network congestion and capacity, to minimize overhead, maximize delivery ratio, and efficiently utilize network resources.
3. An in-depth evaluation of the EMRT approach via extensive experiments with conventional metrics and composite metrics, giving insight into the performance of EMRT and its capacity to enhance the state-of-the-art DTN routing protocols.

7.3 Future Works

This final section draws the chapter to a close, while underscoring the potential for further work. Albeit that VANET has been a hot topic, its limitation and challenges have also been highlighted due to the high mobility and speed of vehicles active in a highly dynamic network topology with short contact duration [1, 43, 193]. Therefore, the vehicles may find that establishing and maintaining an end-to-end path between the source and destination is difficult (e.g., topology partitioning and intermittent connectivity). To overcome these challenges, the DTN is utilized since DTN is not sensitive to delay, as opposed to the conventional VANET which requires a full connectivity path between the source and destination. The DTN is more flexible and a good candidate for the resilience of the delay and overcoming the interruption of the network due to the features of SCF techniques. In conducting this work, the new optimization and investigation of the DTN routing protocol were presented, along with the potential for using a novel technique to control the number of replicas and reduce network resource consumption. Therefore, some directions for future research are identified in this section as follows:

- In Chapter 3, we worked on a random area of Leicester city. In the future, we plan to work on an urban scenario as a portion of central Leicester. Furthermore, the highway scenario will be considered. In addition. in future work, we are interested in adding the obstacle channel model to obtain more

realistic simulation results to prevent road accidents. Also, making the vehicles run on the network from the specific sources to the destination in a two-lane system will be considered in the future.

- To optimize the DTN routing protocols that provide the optimum performance, such as MaxProp and Spray&Wait. The routing protocols need to be effective, with a strong emphasis on delivery and a low delivery ratio delay. However, the existing DTN routing protocols still experience limitations that need to be resolved [49]. Therefore, further investigation will be carried out to investigate the five DTN routings mentioned in Chapter 4 in terms of congestion control and energy consumption in the network.
- Practically, buffer management includes two parts, the scheduling and dropping policies, in order to manage the messages optimally and improve the routing performance. However, in Chapter 4 only one part of the buffer management was considered (i.e., dropping policies), while the scheduling part was neglected. Therefore, in future work, both scheduling and dropping parts will be considered as a single entity to improve the overall network's performance.
- As the DTN performance is influenced by both the routing and buffer management, in the future the routing protocol and buffer management will

be considered as a single entity to enhance the performance of DTN. The routing protocol will be used to transmit the messages between the nodes while the buffer management will be used to order the message in the node's buffer perfectly according to the specific scenario to be ready for transmission during the limited duration time or for dropping during the buffer is congested.

- Finally, the adaptive number of replicas is determined based on the network capacity such as the encounter rate and buffer availability leading to improving the delivery ratio and minimizing delay. However, as the performance of any network is superior with a higher delivery ratio, further investigation is still required to achieve additional improvements and increase the delivery ratio as high as possible. Moreover, only three conventional metrics were tested, with only the quota-based routing protocols considered for our investigation. Therefore, in the future, both flood- and quota-based routing protocols will be considered. Moreover, extensive simulation work will be conducted, and additional evaluation metrics will be considered.
- One drawback of the EMRT is that the message type is neglected during deciding the number of replicas, which may lead to dropping important messages (emergency messages) due to not having enough space in the

node's buffer to carry copies of such significant messages. In the future, the safety message will be treated as a specific case to avoid it being dropped or neglected.

CHAPTER 7 CONCLUSION, RECOMMENDATIONS, AND FUTURE WORK

List of Author's Publications

Poster

[1] S. Hasan and A. H. Al-Bayatti, "Improving Road Safety for Vulnerable Road Users (Children)", 21 March 2019, Posted at De Montfort University in Leicester/UK.

Published papers presented during the period of this research:

[1] S. Hasan, A. H. Al-Bayatti and S. Khan, "Critically Analysing Routing Protocols in a Vehicular Ad-hoc Network". Proceedings of the 4th International Symposium on Computer Science and Intelligent Control (ISCSIC), November 2020, Article No: 28, Pages 1–7, Newcastle University, UK.

[2] S. Hasan, A. H. Al-Bayatti and S. Khan, " Investigating the Effectiveness of Delay-Tolerant Networking Routing Protocols: An Extensive Comparison", Hindawi Publishing Corporation, the Scientific World Journal, 26 April 2021.

[3] S. Hasan, M. Sharifib, S. Iranmanesh, A. H. Al-Bayatti, S. Khan and R. Raad, " Enhanced Message Replication Technique for DTN Routing Protocols". Sensors 2023, vol. 23, no. 2, p. 922. https://doi.org/10.3390/s23020922.

CHAPTER 7 CONCLUSION, RECOMMENDATIONS, AND FUTURE WORK

Post Graduate Research Conference at De Montfort University

[1] S. Hasan, A. H. Al-Bayatti and S. Khan, "Development of a Reliable Delay Tolerant Routing Protocol for Preventing Road Accidents in Vehicular Ad Hoc Network", The 1st Post Graduate Research (PGR) Student Conference, 23rd of June 2021, De Montford University.

[2] S. Hasan, A. H. Al-Bayatti and S. Khan, " Study and Analysis of the Impact of Time to Leave on Different Drop Policies for Different DTN Routing Protocols", Post Graduate Research Conference, 7th September 2022, De Montford University.

Under Review Papers

[1] S. Hasan, A. H. Al-Bayatti and S. Khan, "Study and Analysis of the Impact of Time to Leave on Different Drop Policies for Different DTN Routing Protocols".

[2] S. Hasan, A. H. Al-Bayatti and S. Khan, "Extensive Survey and Taxonomy of Vehicular Delay-Tolerant Networks".

References

[1] A. Cherif, "Design and Assessment of Routing Protocols For Vehicular Delay Tolerant Networks," PhD Thesis, Universite Abou-Bekr Belkaid – Tlemcen, 2018.

[2] F. Arena, G. Pau, A, and Severino, "A review on IEEE 802.11 p for intelligent transportation systems,". Sensor and Actuator Network, 2020, vol. 9, no. 2, p. 22. https://doi.org/10.3390/jsan9020022.

[3] A. Aldegheishem , H. Yasmeen, H. Maryam, M. Shah, A. Mehmood, N. Alrajeh and H. Song. "Smart Road Traffic Accidents Reduction Strategy Based on Intelligent Transportation Systems (TARS)". Sensors, 2018; vol 18, no. 7, p.1983, https://doi.org/10.3390/s18071983.

[4] J. Katuka, A. Latiff, and M. Shafie, "VANETs and its related issues: an extensive survey," 2014, vol. 66, no. 1.

[5] J. Jakubiak and Y. Koucheryavy, "State of the art and research challenges for VANETs,".In Consumer communications and networking conference, 5th IEEE, 2008, pp. 912-916, doi: 10.1109/ccnc08.2007.212.

[6] Y. Toor, P. Muhlethaler, A. Laouiti, and A. De La Fortelle, "Vehicle ad hoc networks: Applications and related technical issues," IEEE communications surveys & tutorials 2008, vol. 10, no. 3, pp. 74-88.

[7] M. Ghori, A. Sadiq, and A. Ghani, " VANET Routing Protocols: Review, Implementation, and Analysis,". In Journal of Physics: Conference Series, 2018, vol. 1049, no. 1, p. 012064, dol: 10.1088/1742-6596/1049/1/012064.

[8] A. Ullah, X. Yao, S. Shaheen, and H. Ning, "Advances in Position Based Routing Towards ITS Enabled FoG-Oriented VANET-A Survey,". IEEE Transactions on Intelligent Transportation Systems, 2019, vol. 21, no. 2, pp. 828-840, doi: 10.1109/TITS.2019.2893067.

[9] T. Taleb, E. Sakhaee, A. Jamalipour, K. Hashimoto, N. Kato, and Y. Nemoto, "A stable routing protocol to support ITS services in VANET networks,". IEEE Transactions on Vehicular Technology, 2007, vol. 56, no. 6, pp. 3337-3347, doi: 10.1109/TVT.2007.906873.

[10] K. Lee, U. Lee, and M. Gerla, "Survey of routing protocols in vehicular ad hoc networks,". In Advances in vehicular ad-hoc networks: Developments and challenges: IGI Global, 2010, pp. 149-170, doi: 10.4018/978-1-61520-913-2.ch008.

[11] J. Gonçalves Filho, A. Patel, B. Batista and J. Júnior, "A systematic technical survey of DTN and VDTN routing protocols,". Computer Standards & Interfaces, 2016, vol. 48, pp. 139-159, https://doi.org/10.1016/j.csi.2016.06.004.

REFERENCES

[12] D. Yu and Y. Ko, "FFRDV: fastest-ferry routing in DTN-enabled vehicular ad hoc networks,". In 11th International Conference on Advanced Communication Technology, 2009, vol. 2, pp. 1410-1414.

[13] S. Tornell, C. Calafate, J. Cano and P. Manzoni, "DTN protocols for vehicular networks: An application-oriented overview,", IEEE communications surveys & tutorials, 2014, vol. 17, no. 2, pp. 868-887, doi: 10.1109/COMST.2014.2375340.

[14] T. Spyropoulos, R. Rais, T. Turletti, K. Obraczka, and A. Vasilakos, "Routing for disruption tolerant networks: taxonomy and design,", Wireless networks, 2010 vol. 16, no. 8, pp. 2349-2370, https://doi.org/10.1007/s11276-010-0276-9.

[15] Z. Zhang, S. Chen, and J. Ren "Opportunistic routing in mobile ad hoc delay-tolerant networks (DTNs),". In Advances in Delay-Tolerant Networks (DTNs), 2015, pp. 159-172.

[16] A. Verma and S. Kumar, "Routing protocols in delay tolerant networks: Comparative and empirical analysis", Wireless Personal Communications, 2021 vol. 118, no. 1, pp. 551-574, https://doi.org/10.1007/s11277-020-08032-4.

[17] A. Singh and R. Pamula, "An efficient and intelligent routing strategy for vehicular delay tolerant networks," Wireless Networks, 2021, vol. 27, no. 1, pp. 383-400, https://doi.org/10.1007/s11276-020-02458-1.

[18] N. Mehta and M. Shah, "Performance of efficient routing protocol in delay tolerant network: A comparative survey,", International Journal of Future Generation Communication and Networking, 2014, vol.7,no 1, pp.151-158.

[19] H. Kim and I. Yeom, "Minimizing the impact of buffer overflow in dtn,". In proceedings international conference on future internet technologies (CFI), 2008, p. 20.

[20] A. Balasubramanian, B. Levine, and A. Venkataramani, "DTN routing as a resource allocation problem,". In Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communications, 2007, vol. 37, no. 4, pp. 373-384, https://doi.org/10.1145/1282380.1282422.

[21] J . Burgess, B. Gallagher, D. Jensen, and B. Levine, "MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks,". In Proc. IEEE Infocom, Spain, 2006, vol. 6.

[22] V. Erramilli and M. Crovella, "Forwarding in opportunistic networks with resource constraints,". In Proceedings of the third ACM workshop on Challenged networks, 2008, pp. 41-48, doi: 10.1145/1409985.

[23] S. Farrell, V. Cahill, D. Geraghty and I. Humphreys, "When TCP breaks: Delay-and disruption-tolerant networking", IEEE Internet Computing, 2006, vol. 10, no. 4, pp. 72-78, doi: 10.1109/MIC.2006.91.

REFERENCES

[24] A. Lindgren, A. Doria, O. Schelén. "Probabilistic routing in intermittently connected networks,", ACM SIGMOBILE Mobile Computing, 2003, vol. 7, no. 3, pp. 19-20, https://doi.org/10.1145/961268.961272.

[25] R. Ramanathan, R. Hansen, P. Basu, R. Rosales-Hain, and R. Krishnan, "Prioritized epidemic routing for opportunistic networks,". In Proceedings of the 1st international MobiSys workshop on Mobile opportunistic networking, 2007, pp. 62-66, https://doi.org/10.1145/1247694.1247707.

[26] T. Spyropoulos, K. Psounis, and C. Raghavendra, "Spray and wait: an efficient routing scheme for intermittently connected mobile networks,". In Proceedings of the ACM SIGCOMM workshop on Delay-tolerant networking, 2005, pp. 252-259, doi: 10.1145/1080139.

[27] T. Spyropoulos, K. Psounis, and C. Raghavendra, "Spray and focus Efficient mobility-assisted routing for heterogeneous and correlated mobility,". In Fifth Annual IEEE International Conference on Pervasive Computing and Communications Workshops, 2007, pp. 79-85, doi: 10.1109/PERCOMW.2007.108.

[28] B. Walker, J. Glenn, and T. Clancy, "Analysis of simple counting protocols for delay-tolerant networks,". In Proceedings of the second ACM workshop on Challenged networks, 2007, pp. 19-26, doi: 10.1145/1287791.

[29] Z. Zhang, "Routing in intermittently connected mobile ad hoc networks and delay tolerant networks: overview and challenges", IEEE Communications Surveys & Tutorials, 2006, vol. 8, no. 1, pp. 24-37, doi: 10.1109/COMST.2006.323440

[30] Z. Jiao, R. Tian, B. Zhang and C. Li. "DTN routing with back-pressure based replica distribution", Journal of Communications and Networks, 2014, vol. 16, no. 4, pp. 378-384.

[31] S. Iranmanesh and M. Saadati, "A Novel Congestion Control Technique in Delay Tolerant Networks,". International Journal of Interdisciplinary Telecommunications and Networking (IJITN), 2018, vol. 10, no. 1, pp. 20-35, doi: 10.4018/IJITN.2018010102.

[32] A. Lindgren and K. Phanse, "Evaluation of queueing policies and forwarding strategies for routing in intermittently connected networks," in 1st International Conference on Communication Systems Software & Middleware, 2006, pp. 1-10, doi: 10.1109/COMSWA.2006.1665196.

[33] S. Iranmanesh, R. Raad, and K. Chin, "A novel destination-based routing protocol (DBRP) in DTNs". In International Symposium on Communications and Information Technologies (ISCIT), 2012, pp. 325-330, doi: 10.1109/ISCIT.2012.6380915.

[34] S. Iranmanesh, R. Raad, M. Raheel, F. Tubbal, and T. Jan, "Novel DTN mobility-driven routing in autonomous drone logistics networks,", in IEEE

REFERENCES

Access, 2019, vol. 8, pp. 13661-13673, doi: 10.1109/ACCESS.2019.2959275.

[35] A. Elwhishi, P.-H. Ho, K. Naik and B. Shihada, "A novel message scheduling framework for delay tolerant networks routing,", in IEEE Transactions on Parallel and Distributed Systems, 2012, vol. 24, no. 5, pp. 871-880, doi: 10.1109/TPDS.2012.197.

[36] C. Suthaputchakun and Z. Sun, "Routing protocol in intervehicle communication systems: a survey,". IEEE Communications Magazine, 2011, vol. 49, no. 12, pp. 150-156, doi: 10.1109/MCOM.2011.6094020.

[37] A. Santamaria, C. Sottile, F. De Rango, and M. Voznak, "Road safety alerting system with radar and GPS cooperation in a VANET environment,". In Wireless Sensing, Localization, and Processing IX, 2014, vol. 9103, p. 91030G, https://doi.org/10.1117/12.2053299.

[38] P. Jing, W. Huang, and L. Chen, "Car-to-pedestrian communication safety system based on the vehicular ad-hoc network environment: A systematic review," Information, 2017, vol. 8, no. 4, p. 127, https://doi.org/10.3390/info8040127.

[39] L. Jackson and R. Cracknell, "Road Accident Casualties in Britain and the World,". House of Commons Library: London, UK, 2018.

[40] P. Sewalkar and J. Seitz, "Vehicle-to-pedestrian communication for vulnerable road users: survey, design considerations, and challenges,". Sensors, 2019, vol. 19, no. 2, p. 358, https://doi.org/10.3390/s19020358.

[41] World Health Organization (2015), Global Status Report on Road Safety 2015, World Health Organization, ISBN 978 92. 4 156506 6, Italy.

[42] D. Schrank, B. Eisele, T. Lomax, and J. Bak, "urban mobility scorecard," The Texas A&M Transportation Institute and INRIX, August 2015.

[43] A. Hamza-Cherif, K. Boussetta, G. Diaz, and F. Lahfa, "Performance evaluation and comparative study of main VDTN routing protocols under small-and large-scale scenarios,", 2018, vol. 81, pp. 122-142, https://doi.org/10.1016/j.adhoc.2018.07.008.

[44] https://www.itf-oecd.org/sites/default/files/docs/irtad-road-safety-annual-report-2020_0.pdfInternational Transport Forum, 2020 "Road safety annual report 2020", Accessed on: 18/09/2021.

[45] World Health and Organization, "Global status report on road safety: summary,". World Health Organization 2018.

[46] World Health and Organization,"Global status report on road safety 2013: supporting a decade of action: summary," World Health Organization".

[47] (WHO Road Traffic Injuries, World Health Organization. available at :https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries, accessed [29/08/2021].

REFERENCES

[48] ANONYMOUS. (2013). List of countries by traffic-related death rate. last accessed 18/09/2023. at the link: https://wikimili.com/en/List_of_countries_by_traffic-related_death_rate.

[49] C. Sobin, V. Raychoudhury, G. Marfia, A. Singla, and C. Applications, "A survey of routing and data dissemination in delay tolerant networks,", Journal of Network and Computer Applications, 2016, vol. 67, pp. 128-146, https://doi.org/10.1016/j.jnca.2016.01.002.

[50] J. Kurhinen and J. Janatuinen. "Delay tolerant routing in sparse vehicular ad hoc networks,", Acta Electrotechnica et Informatica, 2008, vol. 8, no. 3, pp. 7-13.

[51] N. Er, K. Singh, C. Couturier, and J. Bonnin. "Towards A Simple and Efficient VDTN Routing Protocol for Data Collection in Smart Cities,", Computer Science, Cornell University, 2021, https://doi.org/10.48550/arXiv.2108.09044.

[52] E. Onwuka, A. Folaponmile, and M. Ahmed, "MANET: A reliable network in disaster areas,". 2011, vol. 9, no. 2, pp. 105-113.

[53] A. Bakshi, A. Sharma, and A. Mishra, "Significance of mobile AD-HOC networks (MANETS),". International Journal of Innovative Technology and Exploring Engineering (IJITEE), 2013, vol. 2, no. 4, pp. 1-5.

[54] R. Balmahoon and R. Peplow, "Vehicular Ad-Hoc Networks: An Introduction to Privacy,". In Southern African Telecommunication Networks and Applications Conference (SATNAC), 2012, vol. 2.

[55] D. Chadha and Reena, "Vehicular Ad hoc Network (VANETs): A Review,", International Journal of Innovative Research in Computer and Communication Engineering, 2015, vol. 3, no. 3, pp. 2339-2346.

[56] R. Dutta and R. Thalore, "A Review of Various Routing Protocols in VANET," International Journal of Advanced Engineering Research and Science, 2017, vol. 4, no. 4, https://dx.doi.org/10.22161/ijaers.4.4.34.

[57] E. Singh, "Overview of Challenges in VANET,". International Journal of Innovative Research in Science and Engineering, 2016, Vol. 2, Issue.08, pp. 389-394.

[58] B. Nguyen, D. Ngo, N. Tran, M. Dao, and H. Vu, "Dynamic V2I/V2V cooperative scheme for connectivity and throughput enhancement,", in IEEE Transactions on Intelligent Transportation Systems, 2020, vol. 23, no. 2, pp. 1236-1246, doi: 10.1109/TITS.2020.3023708.

[59] F. Cunha, L. Villas, A. Boukerche, G. Maia, A. Viana, R. Mini and A. Loureiro, "Data communication in VANETs: Protocols, applications, and challenges", Ad Hoc Networks, 2016, vol. 44, pp. 90-103, https://doi.org/10.1016/j.adhoc.2016.02.017.

[60] S. Shah, A. Malik, A. Rahman, S. Iqbal, and S. Khan, "Time Barrier-Based Emergency Message Dissemination in Vehicular Ad-hoc Networks,". IEEE

Access, 2019, vol. 7, pp. 16494-16503 , doi: 10.1109/ACCESS.2019.2895114.

[61] R. Raw and S. Das, "Performance comparison of Position based routing Protocols in vehicle-to-vehicle (V2V) Communication," International Journal of Engineering Science and Technology (IJEST), 2011, vol. 3, no. 1, pp. 435-444.

[62] C. Ksouri, I. Jemili, M. Mosbah, A. Belghith and C. Practice, "Towards general Internet of Vehicles networking: routing protocols survey,", Concurrency and Computation Practice and Experience, 2022, vol. 34, no. 7, p. e5994, https://doi.org/10.1002/cpe.5994.

[63] S. Al-Sultan, M. Al-Doori, A. Al-Bayatti, and H. Zedan, "A comprehensive survey on vehicular ad hoc network,". Journal of network and computer applications, 2014, vol. 37, pp. 380-392, https://doi.org/10.1016/j.jnca.2013.02.036.

[64] P. Singh, and S. Nandi, "A tutorial survey on vehicular communication state of the art, and future research directions", Vehicular Communications, 2019, vol. 18, p. 100164, https://doi.org/10.1016/j.vehcom.2019.100164.

[65] S. Hasan, A. H. Al-Bayatti, and S. Khan, "Critically Analysing Routing Protocols in a Vehicular Ad-hoc Network," in *Proceedings of the 4th International Symposium on Computer Science and Intelligent Control*, 2020, pp. 1-7. https://doi.org/10.1145/3440084.3441204.

[66] R. Barskar and M. Chawla, "Vehicular ad hoc networks and its applications in diversified fields", International Journal of Computer Applications, 2015, vol. 123, no. 10.

[67] K. Alodadi, A. H. Al-Bayatti, and N. Alalwan, "Cooperative volunteer protocol to detect non-line of sight nodes in vehicular ad hoc networks," Vehicular Communications, 2017, vol. 9, pp. 72-82, https://doi.org/10.1016/j.vehcom.2017.03.001.

[68] M. Weigle and S. Olariu, "Vehicular networks: from theory to practice". Chapman and Hall/CRC, 2009, doi: https://doi.org/10.1201/9781420085891.

[69] C. Ksouri, I. Jemili, M. Mosbah, and A. Belghith, "Hybrid routing for safety data with intermittent V2I connectivity,", Vehicular Communications, 2022, vol. 38, p. 100519, https://doi.org/10.1016/j.vehcom.2022.100519.

[70] K. Mehta, L. Malik, and P. Bajaj, "VANET: Challenges, issues and solutions,", 6th International Conference on Emerging Trends in Engineering and Technology, 2013, pp. 78-79.

[71] M. Sheikh, J. Liang, and M. Computing, "A Comprehensive Survey on VANET Security Services in Traffic Management System,", Wireless Communications and Mobile Computing, 2019, https://doi.org/10.1155/2019/2423915.

REFERENCES

[72] F. Arena and G. Pau, "An overview of vehicular communications,", Future Internet, 2019, vol. 11, no. 2, p. 27, https://doi.org/10.3390/fi11020027.

[73] G. Naik, B. Choudhury, and J. Park, "IEEE 802.11 bd & 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications,", in IEEE access, 2019, vol. 7, pp. 70169-70184, doi: 10.1109/access.2019.2919489.

[74] E. Ben Hamida, H. Noura, and W. Znaidi, "Security of cooperative intelligent transport systems: Standards, threats analysis and cryptographic countermeasures,", Electronics, 2015, vol. 4, no. 3, pp. 380-423, https://doi.org/10.3390/electronics4030380.

[75] S. Malik and P. Shahu, "A comparative study on routing protocols for VANETs,", Heliyon, 2019, vol. 5, no. 8, p. e02340, https://doi.org/10.1016/j.heliyon.2019.e02340.

[76] V. Jindal and P. Bedi, "Vehicular ad-hoc networks: introduction, standards, routing protocols and challenges,", International Journal of Computer Science Issues (IJCSI), 2016, vol. 13, no. 2, p. 44.

[77] H. Miller, S. Shaw, and A. Shaw, "Geographic Information Systems for Transportation: Principles and Applications". Oxford University Press, 2001.

[78] M. Anwer, C. Guy, "A survey of VANET technologies,", Journal of Emerging Trends in Computing and Information Sciences, 2014, vol. 5, no. 9, pp. 661-671.

[79] D. Jiang and L. Delgrossi, "IEEE 802.11 p: Towards an international standard for wireless access in vehicular environments,". In VTC Spring IEEE Vehicular Technology Conference, 2008, pp. 2036-2040, doi: 10.1109/VETECS.2008.458.

[80] A. Awang, K. Husain, N. Kamel, and S. Aïssa, "Routing in vehicular ad-hoc networks: A survey on single-and cross-layer design techniques, and perspectives", IEEE Access, 2017, vol. 5, pp. 9497-9517, doi: 10.1109/access.2017.2692240.

[81] F. Aadil, S. Rizwan, and A. Akram, "Vehicular Ad Hoc Networks (VANETs), Past Present and Future: A survey,", In Seventh International Open Conference HET-NETs 2013 (IFIP)'Performance and Security Modelling & Evaluation of Cooperative Heterogeneous Networks, 2011, pp. 1-12.

[82] S. Yousefi, M. Mousavi, and M. Fathy, "Vehicular ad hoc networks (VANETs): challenges and perspectives,". In 6th international conference on ITS telecommunications, 2006, pp. 761-766, , doi: 10.1109/ITST.2006.289012.

REFERENCES

[83] A. Vegni, M. Biagi, and R. Cusani, "Smart vehicles, technologies and main applications in vehicular ad hoc networks,". In Vehicular Technologies-Deployment and Applications, 2013, pp. 3-20.

[84] A. Abdalla, S. Salamah, Network, and S. Sciences, "Performance Comparison between Delay-Tolerant and Non-Delay-Tolerant Position-Based Routing Protocols in VANETs,", International Journal of Communications, Network and System Sciences, 2022, vol. 15, no. 1, pp. 1-14, doi: 10.4236/ijcns.2022.151001.

[85] C. Tripp-Barba, A. Zaldívar-Colado, L. Urquiza-Aguiar, and J. A. Aguilar-Calderón, "Survey on Routing Protocols for Vehicular Ad Hoc Networks Based on Multimetrics," , Electronics, 2019, vol. 8, no. 10, p. 1177, https://doi.org/10.3390/electronics8101177.

[86] H. Shahwani, B. Mugabarigira, Y. Shen, J. Jeong, and J. Shin, "DAPF: Delay-aware packet forwarding for driving safety and efficiency in vehicular networks,", 2020, vol. 14, no. 9, pp. 1404-1411, https://doi.org/10.1049/iet-com.2019.0427.

[87] S. Ahmad and M. Shcherbakov, "A Survey on Routing Protocols in Vehicular Adhoc Networks,". In 9th International Conference on Information, Intelligence, Systems, and Applications (IISA), 2018, pp. 1-8, doi: 10.1109/IISA.2018.8633700.

[88] M. Al-Doori, F. Siewe, and A. Al-Bayatti, "VSHDRP: Vehicle second heading direction routing protocol in VANET,". International Journal of Computer Theory and Engineering, 2012, vol. 4, no. 5, p. 851.

[89] J. Skiles, "Adaptive Routing Protocols for Vanet," PhD thesis, Florida Atlantic University, Skiles, Joanne,2017.

[90] S. Bhoi and P. Khilar, "Vehicular communication: a survey," IET Networks, 2014 vol. 3, no. 3, pp. 204-217, https://doi.org/10.1049/iet-net.2013.0065.

[91] A. Devangavi and R. Gupta, "Routing protocols in VANET — A survey,".In International Conference On Smart Technologies For Smart Nation (SmartTechCon), 2017, pp. 163-167, doi 10.1109/SmartTechCon.2017.8358362.

[92] H. Kaur, "Analysis of VANET geographic routing protocols on real city map,". In 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT), 2017, pp. 895-899, doi: 10.1109/RTEICT.2017.8256727.

[93] R. Brendha and V. Prakash, "A survey on routing protocols for vehicular Ad Hoc networks,".In 4th International Conference on Advanced Computing and Communication Systems (ICACCS), 2017, pp. 1-7, doi: 10.1109/ICACCS.2017.8014615.

[94] A. Saggu and K. Pandey, "Comparative Analysis of Position-Based Routing Protocols for VANETs,". In IEEE 8th International Advance Computing

Conference (IACC), 2018, pp. 119-125 , doi: 10.1109/IADCC.2018.8692111.

[95] Y. Sharma and D. Mukherjee, "A Contemporary Proportional Exploration of Numerous Routing Protocol in VANET," International Journal of Computer Applications, 2012, vol. 50, no. 21, pp. 14-21.

[96] B. Paul and M. Islam, "Survey over VANET routing protocols for a vehicle to vehicle communication," IOSR Journal of Computer Engineering (IOSRJCE), 2012, vol. 7, no. 5, pp. 1-9.

[97] O. Abedi, M. Fathy, and J. Taghiloo, "Enhancing AODV routing protocol using mobility parameters in VANET,". In IEEE/ACS International Conference on Computer Systems and Applications, 2008, pp. 229-235, doi: 10.1109/AICCSA.2008.4493539.

[98] N. Chandel and M. Gupta, "Review of Routing Protocols Routing Protocols Routing Protocols for VANET," IJRIT International Journal of Research in Information Technology, 2014, Vol. 2, Issue 4, pp. 625- 632.

[99] R. Kaur and S. Rana, "Overview of Routing Protocols in VANET," IRJET, 2015, vol. 2, no. 3, pp. 1333-1337.

[100] S. Smiri, A. Boushaba, R. Abbou, and A. Zahi, "Geographic and topology based routing protocols in vehicular ad-hoc networks: Performance evaluation and QoS analysis,". In International Conference on Intelligent Systems and Computer Vision (ISCV), 2018, pp. 1-8, doi: 10.1109/ISACV.2018.8354070.

[101] E. Khoza, C. Tu, and P. Owolawi, "Comparative Study on Routing Protocols for Vehicular Ad-Hoc Networks (VANETs),". In International Conference on Advances in Big Data, Computing and Data Communication Systems (icABCD), 2018, pp. 1-6, doi: 10.1109/ICABCD.2018.8465434.

[102] A. Touil and F. Ghadi, "Efficient dissemination based on passive approach and dynamic clustering for VANET,", Procedia Computer Science, 2018, vol. 127, pp. 369-378, https://doi.org/10.1016/j.procs.2018.01.134.

[103] M. Alowish, Y. Takano, Y. Shiraishi, and M. Morii, "Performance Evaluation of a Cluster Based Routing Protocol for VANETs," Journal of Communications, 2017, vol. 12, no. 2, pp. 137-144.

[104] M. Altayeb and I. Mahgoub, "A survey of vehicular ad hoc networks routing protocols,". International Journal of Innovation and Applied Studies, 2013, vol. 3, no. 3, pp. 829-846.

[105] A. Srivastava, A. Prakash, and R.Tripathi, "Location-based routing protocols in VANET: Issues and existing solutions,", Vehicular Communications, 2020, vol. 23, p. 100231, https://doi.org/10.1016/j.vehcom.2020.100231.

[106] A. Dhiman and R. Kumar, "A comparative study of position-based routing protocols in VANETs,".In International Conference on Intelligent

Sustainable Systems (ICISS), 2019, pp. 306-311 , doi: 10.1109/ISS1.2019.8908065.

[107] J. Liu, J. Wan, Q. Wang, P. Deng, K. Zhou, and Y.Qiao, "A survey on position-based routing for vehicular ad hoc networks,", Telecommunication Systems, 2016, vol. 62, no. 1, pp. 15-30.

[108] M. Madni, S. Iranmanesh, and R. Raad, "DTN and Non-DTN routing protocols for inter-CubeSat communications: A comprehensive survey,", Electronics, 2020, vol. 9, no. 3, p. 482.

[109] T. Darwish, K. Bakar, and K. Haseeb, "Reliable intersection-based traffic aware routing protocol for urban areas vehicular ad hoc networks,", IEEE Intelligent Transportation Systems Magazine, 2018, vol. 10, no. 1, pp. 60-73, vol. 10, no. 1, pp. 60-73, Spring 2018, doi: 10.1109/MITS.2017.2776161.

[110] W. Fan, Y. Shi, S. Chen, and L. Zou, "A mobility metrics based dynamic clustering algorithm for VANETs,", IET International Conference on Communication Technology and Application (ICCTA), 2011, doi: 10.1049/cp.2011.0769.

[111] E. Wang, Y. Yang, J. Wu and W. Liu, "A buffer scheduling method based on message priority in delay tolerant networks,", Journal of Computer Science and Technology, 2016, vol. 31, no. 6, pp. 1228-1245, https://doi.org/10.1007/s11390-016-1694-7.

[112] M. Shahid, "Fixed Cluster Based Cluster Head Selection Algorithm in Vehicular Adhoc Network," Master thesis, 2019.

[113] A. Rani, S. Rani, and H. Bindra, "Performance evaluation of MOFO buffer management technique with different routing protocols in DTN under variable message buffer size,", International Journal of Research in Engineering and Technology, 2014, vol. 3, no. 3, pp. 82-86.

[114] S. Iranmanesh, "Data management in delay tolerant networks " PhD thesis, University of Wollongong, 2014.

[115] F. AL-Dhief, N. Sabri, M. Salim, S. Fouad, and S. Aljunid, "MANET routing protocols evaluation: AODV, DSR, and DSDV perspective,". In MATEC web of conferences, 2018, vol. 150, p. 06024 https://doi.org/10.1051/matecconf/201815006024.

[116] N. Alobaidi, "A scenario-based performance analysis of VANET protocols," Master Thesis, Unitec Institute of Technology, 2017.

[117] Y. Harrati and A. Abdali, "MaxHopCount: DTN congestion control algorithm under MaxProp routing,", International Journal of Computer Science and Network Security, 2017 vol. 17, no. 5, p. 206.

[118] T. Sivakumar and R. Manoharan, "SRP: A Stable Routing Protocol for VANETs,", International Journal of Applied Engineering Research, 2016, vol. 11, no. 5, pp. 3499-3504.

REFERENCES

[119] I. Abdel-Halim and H. Fahmy, "Prediction-based protocols for vehicular Ad Hoc Networks: Survey and taxonomy,", Computer Networks, 2018, vol. 130, pp. 34-50, https://doi.org/10.1016/j.comnet.2017.10.009.

[120] H. Hasrouny, A. Samhat, C. Bassil, and A. Laouiti, "VANet security challenges and solutions: A survey,", Vehicular Communications, 2017, vol. 7, pp. 7-20, https://doi.org/10.1016/j.vehcom.2017.01.002.

[121] H. Hartenstein and K. Laberteaux, "VANET: vehicular applications and inter-networking technologies". John Wiley & Sons, 2009.

[122] A. Keränen, J. Ott, and T. Kärkkäinen, "The ONE simulator for DTN protocol evaluation," in Proceedings of the 2nd international conference on simulation tools and techniques, 2009, pp. 1-10, https://doi.org/10.4108/ICST.SIMUTOOLS2009.5674.

[123] F. Martinez, C. Toh, J. Cano, C. Calafate, and P. Manzoni, "A survey and comparative study of simulators for vehicular ad hoc networks (VANETs),", Wireless Communications and Mobile Computing, 2011, vol. 11, no. 7, pp. 813-8281, https://doi.org/10.1002/wcm.859.

[124] OMNet++, User guide version 5.5, available at: https://doc.omnetpp.org/omnetpp/UserGuide.pdf [accessed: 02/12/2019].

[125] M. Amoozadeh, B. Ching, C. Chuah, D. Ghosal, and H. Zhang, "VENTOS: Vehicular network open simulator with hardware-in-the-loop support,", Procedia Computer Science, 2019, vol. 151, pp. 61-68 https://doi.org/10.1016/j.procs.2019.04.012.

[126] D. Krajzewicz, J. Erdmann, M. Behrisch, L. Bieker, and Measurements, "Recent development and applications of SUMO-Simulation of Urban MObility,", International journal on advances in systems and measurements, 2012, vol. 5, no. 3&4.

[127] C. Sommer, R. German, and F. Dressler, "Bidirectionally coupled network and road traffic simulation for improved IVC analysis,". IEEE Transactions on mobile computing, 2011, vol. 10, no. 1, pp. 3-15, doi: 10.1109/TMC.2010.133.

[128] D. Hs. "Vehicle safety communications project: Task 3 final report: identify intelligent vehicle safety applications enabled by DSRC,". National Highway Traffic Safety Administration, Washington, 2005.

[129] C. Sommer, Z. Yao, R. German, and F. Dressler, "Simulating the influence of IVC on road traffic using bidirectionally coupled simulators,". In IEEE INFOCOM Workshops 2008, pp. 1-6 , doi: 10.1109/INFOCOM.2008.4544655.

[130] A. Wegener, M. Piórkowski, M. Raya, H. Hellbrück, S. Fischer, and J.-P. Hubaux, "TraCI: an interface for coupling road traffic and network simulators," in Proceedings of the 11th communications and networking

simulation symposium, 2008, pp. 155-163, https://doi.org/10.1145/1400713.1400740.

[131] OpenStreetMap, available at https://www.openstreetmap.org/#map=15/52.6342/-1.1332, accessed [15/09/2021].

[132] A. Keränen, T. Kärkkäinen, and J. Ott, "Simulating Mobility and DTNs with the ONE," , Journal Of Communications, 2010,vol. 5, no. 2, pp. 92-105.

[133] A. Haris, "A DTN study analysis of implementations and tools," Master's thesis, Informaatio- ja luonnontieteiden tiedekunta, Tietokoneverkot, Aalto University, 2010.

[134] R. Sachdeva and A. Dev, "Review of opportunistic network: Assessing past, present, and future,", International Journal of Communication Systems p. e4860, 2021, vol. 34, no. 11, https://doi.org/10.1002/dac.4860.

[135] J. Rodrigues and V. Soares, "An introduction to delay and disruption tolerant networks (DTNs)," in Advances in Delay-Tolerant Networks (DTNs), 2015, pp. 1-20, https://doi.org/10.1533/9780857098467.1.

[136] T. Le, H. Kalantarian, and M. Gerla, "A dtn routing and buffer management strategy for message delivery delay optimization,". In 8th IFIP Wireless and Mobile Networking Conference (WMNC), 2015, pp. 32-39 , doi: 10.1109/WMNC.2015.11.

[137] H. Zhu, S. Du, Z. Gao, M. Dong, and Z. Cao, "A probabilistic misbehavior detection scheme toward efficient trust establishment in delay-tolerant networks," IEEE Transactions on parallel and distributed systems, 2013, vol. 25, no. 1, pp. 22-32, doi: 10.1109/TPDS.2013.36.

[138] H. Wang, H. Wang, G. Feng, and H. Lv, "NWBBMP: a novel weight-based buffer management policy for DTN routing protocols,", Peer-to-Peer Networking and Applications, 2018, vol. 11, no. 5, pp. 917-923, https://doi.org/10.1007/s12083-017-0597-x.

[139] E. Ayele, N. Meratnia, and P. Havinga, "An asynchronous dual radio opportunistic beacon network protocol for wildlife monitoring system,". In 10th IFIP International Conference on New Technologies, Mobility and Security (NTMS), 2019, pp. 1-7, doi: 10.1109/NTMS.2019.8763854.

[140] N. Rajpoot and R. Kushwah, "An improved PROPHET routing protocol for underwater communication,". In 2015 International Conference on Communication Networks (ICCN), 2015, pp. 27-32 , doi: 10.1109/ICCN.2015.6.

[141] K. Hazra et al., "A novel network architecture for resource-constrained post-disaster environments,". In 11th International Conference on Communication Systems & Networks (COMSNETS), 2019, pp. 328-335 , doi: 10.1109/COMSNETS.2019.8711166.

REFERENCES

[142] P. Liu, C. Wang, T. Fu, and Y. Ding, "Exploiting opportunistic coding in throw box-based multicast in vehicular delay tolerant networks,", in IEEE Access, 2019, vol. 7, pp. 48459-48469 , doi: 10.1109/access.2019.2910244.

[143] J. Zhang, G. Wang, C. Liu, F. Zhao, and X. Zhang, "Delay Tolerant Network and the Algorithms of DTN Routing,". In Journal of Physics: Conference Series, 2019, vol. 1169, no. 1, p. 012058, doi:10.1088/1742-6596/1169/1/012058.

[144] N. Benamar, K. Singh, M. Benamar, D. El Ouadghiri, and J.Bonnin, "Routing protocols in vehicular delay tolerant networks: A comprehensive survey,", 2014, vol. 48, pp. 141-158, https://doi.org/10.1016/j.comcom.2014.03.024.

[145] E. Lee, D. Seo, and Y.Chung, "An efficient routing protocol using the history of delivery predictability in opportunistic networks,", Applied Sciences, 2018, vol. 8, no. 11, p. 2215, https://doi.org/10.3390/app8112215.

[146] E. Alaoui, S. Agoujil, M. Hajar, and Y.Qaraai, "The performance of DTN routing protocols: a comparative study,", WSEAS Transactions on Communications, 2015, vol. 14, pp. 121-130.

[147] F. Warthman, "Delay-and disruption-tolerant networks (DTNs),", Interplanetary Internet Special Interest Group, 2012, pp. 5-9.

[148] K. Massri, A. Vitaletti, A. Vernata and I. Chatzigiannakis, "Routing protocols for delay tolerant networks: a reference architecture and a thorough quantitative evaluation,", Journal of Sensor and Actuator Networks, 2016, vol. 5, no. 2, p. 6 https://doi.org/10.3390/jsan5020006.

[149] H. Zekkori and S. Agoujil, "Hybrid delay tolerant network routing protocol for heterogeneous networks,", Journal of Network and Computer Applications, 2019, vol. 148, p. 102456 https://doi.org/10.1016/j.jnca.2019.102456.

[150] K. Ahmed, M. Omar, and S. Hassan, "Survey and comparison of operating concept for routing protocols in dtn,", Journal of Computer Science, 2016, vol. 12, no. 3, pp. 141-152, http://doi.org/10.3844/jcssp.2016.141.152.

[151] Y. Mao, C. Zhou, Y. Ling, and J. Lloret, "An optimized probabilistic delay tolerant network (DTN) routing protocol based on scheduling mechanism for internet of things (IoT),", Sensors, 2019, vol. 19, no. 2, p. 243 https://doi.org/10.3390/s19020243.

[152] L. Pelusi, A. Passarella, and M. Conti, "Opportunistic networking: data forwarding in disconnected mobile ad hoc networks,", in IEEE Communications Magazine, 2006, vol. 44, no. 11, pp. 134-141 , doi: 10.1109/MCOM.2006.248176.

[153] J. Karvo and J. Ott, "Time scales and delay-tolerant routing protocols," in Proceedings of the third ACM workshop on Challenged networks, In

Proceedings of the third ACM workshop on Challenged networks, 2008, pp. 33-40 https://doi.org/10.1145/1409985.1409993.

[154] S. Iranmanesh and R. Raad, "A novel data forwarding strategy for a drone delay tolerant network with range extension,", Electronics, 2019, vol. 8, no. 6, p. 659, doi: 10.3390/electronics8060659.

[155] A. Vahdat and D. Becker, "Epidemic routing for partially connected ad hoc networks," Technical Report CS-200006; Duke University: Durham, NC, USA, 2000.

[156] A. Lindgren, A. Doria, and O. Schelen, "Probabilistic routing in intermittently connected networks,", Springer, 2004, pp. 239-254.

[157] J. Leguay, T. Friedman, and V. Conan, "Evaluating mobility pattern space routing for DTNs,", arXiv preprint cs/0511102, 2006. doi: 10.1109/INFOCOM.2006.299.

[158] S. Hasan, A. H. Al-Bayatti, and S. Khan, "Investigating the Effectiveness of Delay-Tolerant Networking Routing Protocols: An Extensive Comparison,", An Extensive Comparison, 2021.

[159] M. Artimy, W. Robertson, and W. Phillips, "Connectivity in inter-vehicle ad hoc networks," IEEE in Canadian Conference on Electrical and Computer Engineering, 2004, vol. 1, pp. 293-298. doi: 10.1109/CCECE.2004.1345014.

[160] M. Seki, K. Ogura, Y. Yamasaki, and H. Ohsaki, "Performance comparison of geographic DTN routing algorithms," in IEEE 39th Annual Computer Software and Applications Conference, 2015, vol. 3, pp. 617-620 , doi: 10.1109/COMPSAC.2015.148.

[161] Z. Du, C. Wu, T. Yoshinaga, and Y. Ji, "A prophet-based DTN protocol for VANETs,". In IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation, 2018, pp. 1876-1879, doi: 10.1109/SmartWorld.2018.00315.

[162] P. Pereira, A. Casaca, J. Rodrigues, V. Soares, J. Triay and C. Cervello-Pastor."From Delay-Tolerant Networks to Vehicular Delay-Tolerant Networks,". In IEEE Communications Surveys & Tutorials, 2012, vol. 14, no. 4, pp. 1166-1182, doi: 10.1109/SURV.2011.081611.00102.

[163] G. Blokdyk, "Dijkstra's Algorithm: End-to-end Data Analysis." CreateSpace Independent Publishing Platform, 2017. ISBN: 1979932034.

[164] M. Wazid, AK. Das, N. Kumar, V. Odelu and AG. Reddy "Design of Lightweight Authentication and Key Agreement Protocol for Vehicular Ad Hoc Networks,". IEEE Access, 2017, vol. 5, pp. 14966-14980 , doi: 10.1109/Access.2017.2723265.

[165] A. El Arbi ABDELLAOUI, C. Koumétio, A. Gallais, and S. Agoujil, "Towards a DTN protocol for the Internet of Things,". In Global

Information Infrastructure and Networking Symposium (GIIS), 2019, pp. 1-6 doi: 10.1109/GIIS48668.2019.9044962.

[166] X. Zhang, G. Neglia, J. Kurose, and D. Towsley, "Performance modeling of epidemic routing,", 2007, vol. 51, no. 10, pp. 2867-2891.

[167] K. Shin and S. Kim, "Enhanced buffer management policy that utilizes message properties for delay-tolerant networks,", IET communications, 2011, vol. 5, no. 6, pp. 753-759, doi: 10.1049/iet-com.2010.0422.

[168] O. Rahman, I Abbasi, H.Hashem, K.Saeed, M. Majeed and S. Ali. "SS-Drop: A Novel Message Drop Policy to Enhance Buffer Management in Delay Tolerant Networks," Wireless Communications and Mobile Computing, 2021, https://doi.org/10.1155/2021/9773402.

[169] S. Jain and M. Chawla, "Survey of buffer management policies for delay tolerant networks,", the Journal of Engineering, 2014, vol., no. 3, pp. 117-123.

[170] S. Rashid, Q. Ayub, M. Zahid, and A. Abdullah, "E-drop: An effective drop buffer management policy for DTN routing protocols,", International Journal of Computer Applications, 2011, pp. 118-121.

[171] L. Leela-Amornsin and H. Esaki, "Heuristic congestion control for message deletion in delay tolerant network," in Smart spaces and next generation wired/wireless networking: Springer, 2010, pp. 287-298.

[172] S. Rashid, Q. Ayub, M.Zahid, and A. H.Abdullah, "Impact of mobility models on DLA (drop largest) optimized DTN epidemic routing protocol,", International Journal of Computer Applications, 2011, vol. 18, no. 5, pp. 1-7.

[173] S. Rashid, Q. Ayub, and N. Security, "Efficient buffer management policy DLA for DTN routing protocols under congestion,", International Journal of Computer and Network Security, 2010, vol. 2, no. 9, pp. 118-121.

[174] A. Krifa, C. Barakat, and T. Spyropoulos, "Optimal buffer management policies for delay tolerant networks," in 5th annual IEEE communications society conference on sensor, mesh and ad hoc communications and networks, 2008, pp. 260-268, doi: 10.1109/SAHCN.2008.40.

[175] M. Moetesum, F. Hadi, M. Imran, A.Minhas, and A. Vasilakos, "An adaptive and efficient buffer management scheme for resource-constrained delay tolerant networks,", Wireless networks, 2016, vol. 22, no. 7, pp. 2189-2201.

[176] V. Soares, J. Rodrigues, and F. Farahmand, "Impact analysis of the shortest path movement model on routing strategies for VDTNs in a Rural region,". In 7th Conference on Telecommunications, 2009.

[177] S. Rashid, A. Abdullah, Q. Ayub, M. Zahid, and C. Applications, "Dynamic Prediction based Multi Queue (DPMQ) drop policy for probabilistic routing protocols of delay tolerant network,", Journal of Network and Computer

Applications, 2013, vol. 36, no. 5, pp. 1395-1402 https://doi.org/10.1016/j.jnca.2013.02.030.

[178] A. Prodhan, R. Das, H. Kabir and G. Shoja. "TTL-based routing in opportunistic networks,", Journal of Network and Computer Applications, 2011, vol. 34, no. 5, pp. 1660-1670,https://doi.org/10.1016/j.jnca.2011.05.005.

[179] Q. Ayub, A. Ngadi, S. Rashid, and H. Habib, "Priority queue based reactive buffer management policy for delay tolerant network under city based environments,", PLOS ONE, 2018, vol. 13, no. 2, p. e0191580,https://doi.org/10.1371/journal.pone.0191580.

[180] J. Lakkakorpi, M. Pitkänen, and J. Ott, "Adaptive routing in mobile opportunistic networks,". In Proceedings of the 13th ACM international conference on Modeling, analysis, and Simulation of Wireless and mobile systems, 2010, pp. 101-109, https://doi.org/10.1145/1868521.1868539.

[181] R. Udroiu, A. Deaconu, and C.-S.Nanau, "Data Delivery in a Disaster or Quarantined Area Divided into Triangles Using DTN-Based Algorithms for Unmanned Aerial Vehicles,", Sensors, 2021, vol. 21, no. 11, p. 3572 https://doi.org/10.3390/s21113572.

[182] A. Singh and R. Pamula, "An efficient and intelligent routing strategy for vehicular delay tolerant networks,", Wireless Networks, 2021, vol. 27, no. 1, pp. 383-400.

[183] T. Matsuda and T.Takine, "(p, q)-Epidemic routing for sparsely populated mobile ad hoc networks,", in IEEE Journal on Selected Areas in Communications, 2008, vol. 26, no. 5, pp. 783-793, doi: 10.1109/JSAC.2008.080605.

[184] M. Grossglauser and D. Tse, "Mobility increases the capacity of ad hoc wireless networks,", IEEE/ACM transactions on networking, 2002, vol. 10, no. 4, pp. 477-486, doi: 10.1109/TNET.2002.801403.

[185] A. Lindgren, A. Doria, and O. Schelen, "Probabilistic routing in intermittently connected networks,". ACM SIGMOBILE Mobile Computing and Communications Review, 2003. vol. 7 https://doi.org/10.1145/961268.961272.

[186] Y. Wang and H. Wu, "Delay/fault-tolerant mobile sensor network (dft-msn): A new paradigm for pervasive information gathering," IEEE Transactions on Mobile Computing, 2007, vol. 6, no. 9, pp. 1021-1034, doi: 10.1109/TMC.2007.1006.

[187] T. Spyropoulos, K. Psounis, and C. Raghavendra."Single-copy routing in intermittently connected mobile networks,". In First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks. 2004, pp. 235-244 , doi: 10.1109/SAHCN.2004.1381922.

REFERENCES

[188] J. Cui, S. Cao, Y. Chang, L. Wu, D. Liu, and Y. Yang, "An adaptive spray and wait routing algorithm based on the quality of node in delay tolerant network,", IEEE Access, 2019, vol. 7, pp. 35274-35286, doi: 10.1109/ACCESS.2019.2904750.

[189] E. Bulut, Z. Wang, and B. Szymanski, "Cost-effective multiperiod spraying for routing in delay-tolerant networks,", IEEE/ACM Transactions On Networking, 2010, vol. 18, no. 5, pp. 1530-1543, doi: 10.1109/TNET.2010.2043744.

[190] S. Dhurandher, S. Borah, I. Woungang, D. Sharma, K. Arora, and D. Agarwal, "EDR: an encounter and distance-based routing protocol for opportunistic networks,". In IEEE 30th International Conference on Advanced Information Networking and Applications (AINA), 2016, pp. 297-302, doi: 10.1109/AINA.2016.15.

[191] S. Iranmanesh, M.Saadati, and Networking, "A novel congestion control technique in delay tolerant networks,", International Journal of Interdisciplinary Telecommunications and Networking (IJITN), 2018, vol. 10, no. 1, pp. 20-35, doi: 10.4018/IJITN.2018010102.

[192] K. Ueda, "DTN Routing Method Based on Node Movement Prediction and Message Deliverability,". The 25th International Conference on Network-Based Information Systems, 2022, pp. 267-278.

[193] E. ETSI. "Intelligent transport systems (ITS), communications architecture," 2010, pp.1-44.

[194] M. Amin, A. Khan, S. Haq, and I. Rasool, "A survey of routing protocols for delay tolerant networks in VANETs,", Science International, 2016, vol. 28, no. 2.

[195] J. Harri, P. Cheng, J. Weng, L. Tung, M. Gerla, and K. Lee, "GeoDTN+ Nav: a hybrid geographic and DTN routing with navigation assistance in urban vehicular networks,". In Proceedings of the First Annual International Symposium on Vehicular Computing Systems, Dublin, Ireland, 2008.

[196] A. Khan, D. Kum, J. Nam, and Y. Cho, "Minimum delay routing protocol for DTN-enabled VANETs,".In 18th Asia-Pacific Conference on Communications (APCC), 2012, pp. 534-538 doi: 10.1109/APCC.2012.6388251.

[197] I. Leontiadis and C. Mascolo, "GeOpps: Geographical opportunistic routing for vehicular networks,".In IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, 2007, pp. 1-6, doi: 10.1109/WOWMOM.2007.4351688.

[198] A. Cherif, K. Boussetta, G. Diaz, and D. Fedoua, "Improving the performances of geographic VDTN routing protocols,".In 16th Annual Mediterranean Ad Hoc Networking Workshop, 2017, pp. 1-5, doi: 10.1109/MedHocNet.2017.8001641.

REFERENCES

[199] V. Soares, J. Rodrigues, and F. Farahmand, "GeoSpray: A geographic routing protocol for vehicular delay-tolerant networks,", Information Fusion , 2014, vol. 15, pp. 102-113, https://doi.org/10.1016/j.inffus.2011.11.003.

[200] J. Zhao and G. Cao, "VADD: Vehicle-assisted data delivery in vehicular ad hoc networks,", IEEE Transactions on vehicular technology, 2008, vol. 57, no. 3, pp. 1910-1922, doi: 10.1109/TVT.2007.901869.

[201] A. Ali and S. Raazi, "Survey on low delay message propagation in vehicular ad hoc network,".In International Conference on Energy Systems and Policies (ICESP), 2014, pp. 1-5.

[202] P. Cheng, K. Lee, M. Gerla and J. Härri, "GeoDTN+ Nav: geographic DTN routing with navigator prediction for urban vehicular environments,", Mobile Networks and Applications, 2010, vol. 15, no. 1, pp. 61-82, https://doi.org/10.1007/s11036-009-0181-6.

[203] J. Skiles, "Adaptive Routing Protocols for VANET", PhD Thesis, Florida Atlantic University, 2017.

[204] A. Bitorika, M. Robin, M. Huggard, and C. Mc Goldrick, "A comparative study of active queue management schemes,".In Proc. of ICC, 2004.

[205] G. Fathima and R. Wahidabanu, "A new queuing policy for delay tolerant networks,", International Journal of Computer Applications, 2010, vol. 1, no. 20, pp. 56-60.

[206] B. Burns, O. Brock, and B.Levine, "MORA routing and capacity building in disruption-tolerant networks,", Ad hoc networks, 2008, vol. 6, no. 4, pp. 600-620 https://doi.org/10.1016/j.adhoc.2007.05.002 Get rights and content.

[207] J. Naves, I. Moraes, and C. Albuquerque, "LPS and LRF: Efficient buffer management policies for delay and disruption tolerant networks,".In 37th Annual IEEE Conference on Local Computer Networks, 2012, pp. 368-375 , doi: 10.1109/LCN.2012.6423649.

[208] Y. Li, M. Qian, D. Jin, L. Su, and L. Zeng, "Adaptive optimal buffer management policies for realistic DTN," in GLOBECOM IEEE Global Telecommunications Conference, 2009, pp. 1-5 , doi: 10.1109/GLOCOM.2009.5426161.

[209] G. Fathima, R. Wahidabanu, and M. Networks. "Buffer management for preferential delivery in opportunistic delay tolerant networks,", International Journal of Wireless & Mobile Networks 2011, vol. 3, no. 5, p. 15, doi : 10.5121/ijwmn.2011.3502

Appendices

Appendix A: Description of a Simple Wireless Network

In this appendix, the developed network has two cars, where one car will send a UDP data stream wirelessly to the other car. The aim is to make a simple module. There are two ways to represent the network: either in a graph or by writing code under the Network Description (NED) source file of the network, as seen in **Table A-1**.

Besides the two cars, there are additional important components that should be included in the project such as visualization, configuring the IP layer, and modelling the physical radio channel. We use generic hosts (*standeredHost*) to represent the cars that have protocol components such as TCP, IP, and UDP; a slot for plugging in the application models; and various Network Interfaces (NICs). The wireless is considered a standard host that is configured for wireless scenarios.

The basic communication in the network is to define the IP address and the MAC address. Here in this module, the IP address is assigned by the *Ipv4NetworkConfigurator* module. While the MAC address is used. *GlobalArp* modules instant of real ARP.

The procedure to generate a UDP packet to be sent from car A to car B is that car A is configured to have a *UDPBasicApp* module, which enables the generation of 1000-byte UDP messages at random intervals with the meantime 12 ms. Therefore, the model will generate 100 Kbyte/s (800 Kbps) UDP traffic. Meanwhile, car B has a *Udpsink* application that is employed to discard the received messages.

Physical layer modeling

All wireless simulations in INET require a radio medium module to represent the standard physical medium. This module is responsible for taking the physical phenomena into account (e.g. interface, attenuation, and signal propagation). The

simplest example of the radio medium model is *UnitDiskRaioMedium*. This module implements a variation of unit disc radio, which means that the communication range is specified in meters and the signal attenuation is ignored. Furthermore, a number of modules are considered optional such as modeling collision and interface range.

In the *omnetpp.ini* file, in this model, the physical layer model was chosen as *UnitDiskradioMedium* and *UnitDiskRadio*, where the communication range is set to 500 m, but the modeling for packet losses due to collision is turned off and the radio data rates are set to 1 Mbps. Finally, the simple MAC layer is chosen.

Mac layer

MultipleAccessMac is implemented in this model, where *AckingWirelessInterface* is configured. This will provide encapsulation/decapsulation. Moreover, the acknowledgment mechanism is turned off.

Discussion of the results

To conclude what occurs after we run the simulation: first, car A's *UdpBasicApp* generates UDP messages at a random interval. Then, these created messages are sent down via UDP and IPV4 to the network interface for transmission. After that, the network interface queues messages and transmits these, as shown in **Figure A-1**.

Table A-1: The NED source code and *.ini* files of the network

WirelessA.ned

`import inet.network layer.configurator.ipv4.Ipv4NetworkConfigurator;`
`import inet.node.inet.INetworkNode;`
`import inet.physical layer.unit disk.UnitDiskRadioMedium;`
`import inet.visualizer.contract.IIntegratedVisualizer;`

```
network wireless

{

    @display("bgb=847,400");

    submodules:

        visualizer:

<default(firstAvailableOrEmpty("IntegratedCanvasVisualizer"))>    like

IIntegratedVisualizer if type name != "" {

            @display("p=783,182");

        }

        configurator: Ipv4NetworkConfigurator {

            @display("p=783,309");

        }

        radioMedium: UnitDiskRadioMedium {

            @display("p=783,66");

        }

        carA: <default("WirelessHost")> like INetworkNode {

            @display("p=50,325;i=misc/car2");

        }

        carB: <default("WirelessHost")> like INetworkNode {

            @display("p=276.575,324.44376;i=misc/car2");

        }

}
```

WirelessA.ini

```
[General]

network = WirelessA

sim-time-limit = 20s

*.car*.ipv4.arp.type name = "GlobalArp"

*.carA.numApps = 1

*.carA.app[0].type name = "UdpBasicApp"

*.carA.app[0].destAddresses = "carB"

*.carA.app[0].destPort = 5000

*.carA.app[0].messageLength = 1000B

*.carA.app[0].send interval = exponential(12ms)

*.carA.app[0].packet name = "UDPData"


*.carB.numApps = 1

*.carB.app[0].typename = "UdpSink"

*.carB.app[0].localPort = 5000


*.car*.wlan[0].typename = "AckingWirelessInterface"

*.car*.wlan[0].mac.useAck = false

*.car*.wlan[0].mac.fullDuplex = false

*.car*.wlan[0].radio.transmitter.communicationRange = 500m

*.car*.wlan[0].radio.receiver.ignoreInterference = true

*.car*.wlan[0].mac.headerLength = 23B


*.car*.**.bitrate = 1Mbps
```

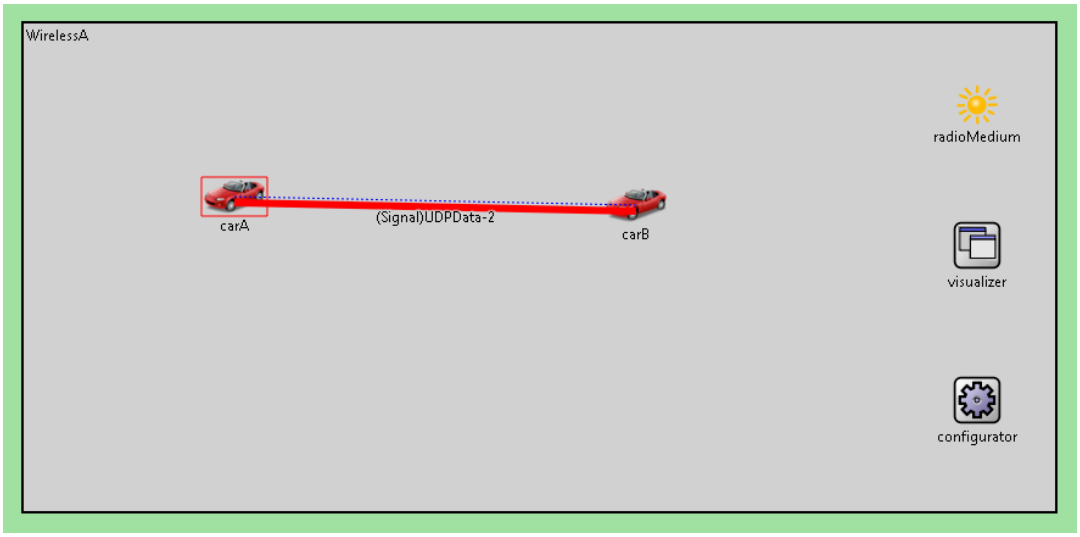


Figure A-1: A simple wireless network

As we monitor the simulation run time, we conclude that the number of messages sent was 1596, and the number of messages received was 1595, because as mentioned previously, this is a simple network and there is direct communication between the two nodes (i.e. there are no interface and obstacles in the signal between the nodes). Therefore, there are no lost messages.

Appendix B: How to Install GatcomSUMO to Import Real Map

1) Download GatcomSUMO

First, download GatcomSUMO, as shown in **Figure B-1**.

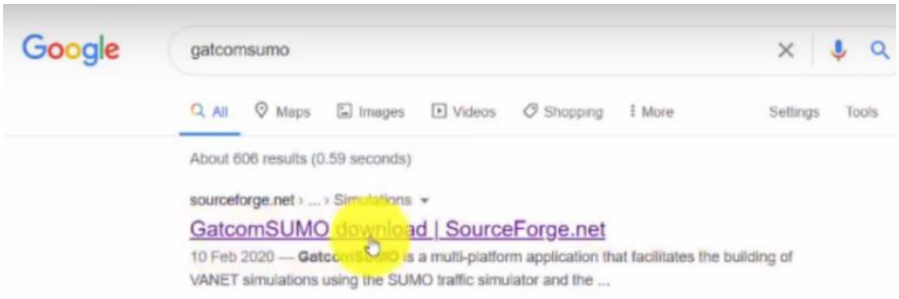


Figure B-1: Download GatcomSUMO

The screen shown in **Figure B-2** is then displayed:

Figure B-2: Use the Download option to start the installation

Click Download and select the fourth option, as shown in **Figure B-3**. Then select the file with the name:

Released/v1.04/GatcomSUMO-src-1.04.zip

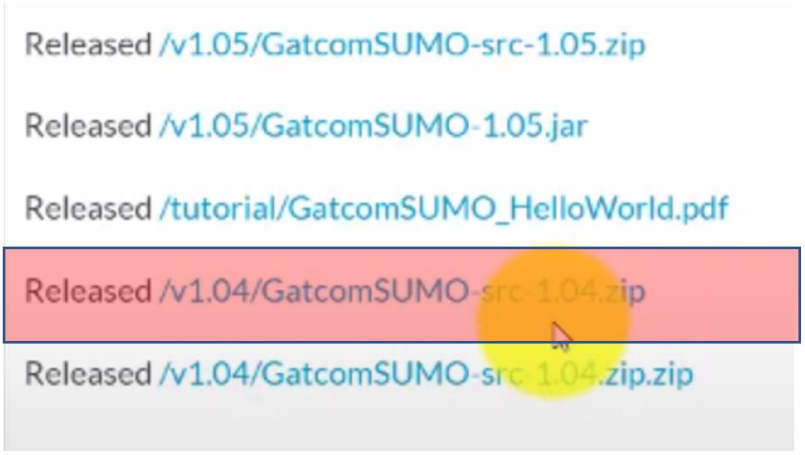


Figure B-3: The proper option to start the download of GatcomSUMO

Then, wait for the download to complete and go to the download folder and copy the downloaded *GatcomSUMO.zip* file. Next, create a new folder on the desktop named *GatcomSUMO* and copy the *GatcomSUMO.zip* file from the download folder and paste it into this new folder. Finally, extract the file as shown in **Figure B-4**.

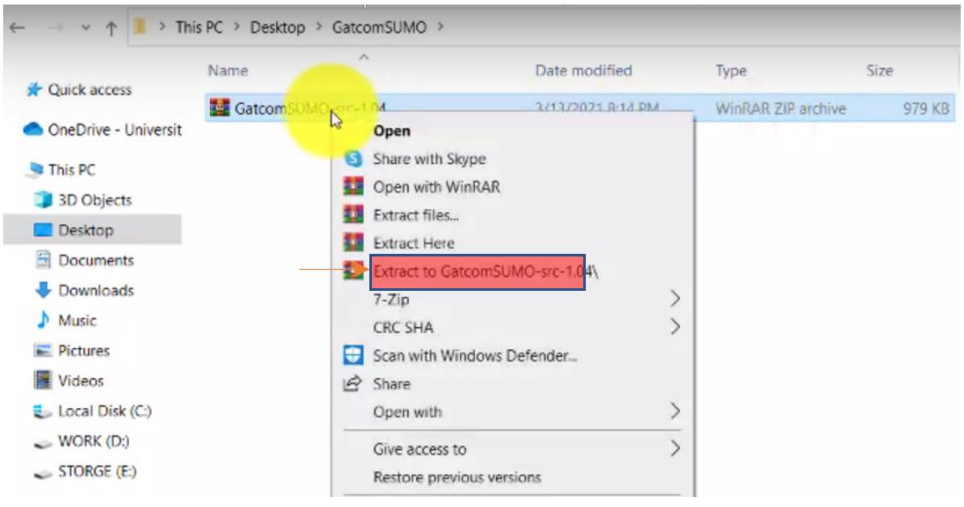


Figure B-4: Extract the GatcomSUMO file

After unzipping the GatcomSUMO file, the *Proyecto NetBeans* folder will be created, as seen in **Figure B-5**.

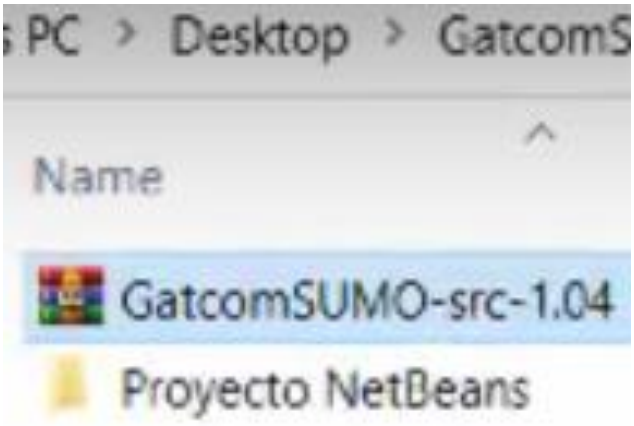


Figure B-5: Folder generated from the extracted GatcomSUMO file

The *Proyecto NetBeans* folder contains all the required folders and files, as seen in **Figure B-6**.

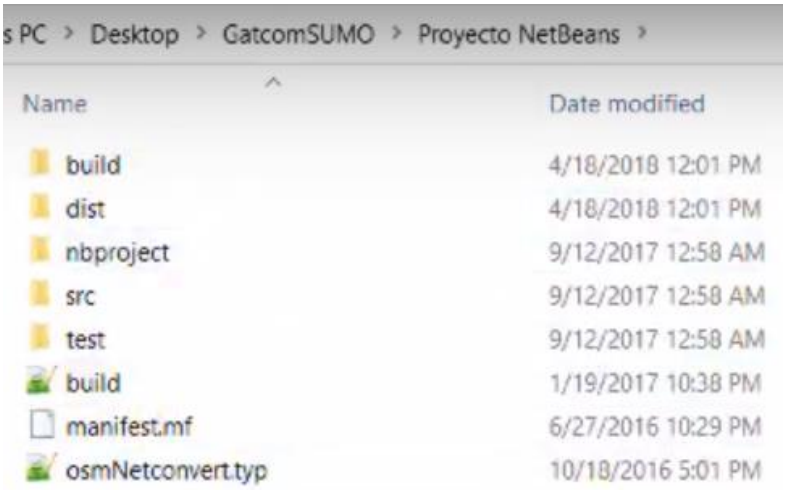


Figure B-6: The extracted folders and files inside the Proyecto NetBeans folder

Next, open the *dist* folder to reveal the files shown in **Figure B-7**.

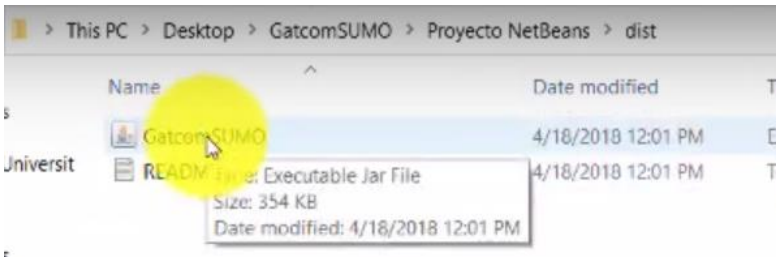


Figure B-7: The Java application inside the *dist* folder

Click on the *GatcomSUMO* application file. If you see a GUI similar to that shown in **Figure B-8**, then the application is ready to use.

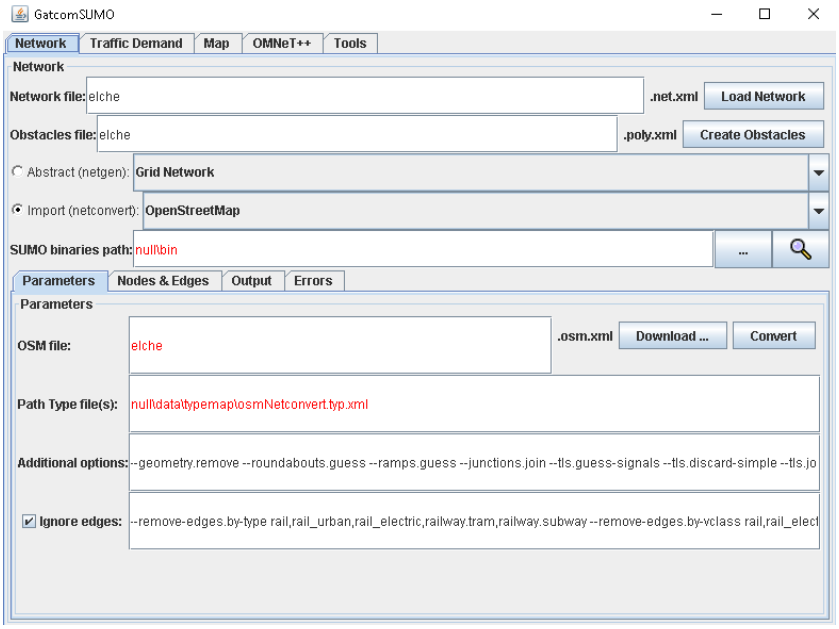


Figure B-8: Installation completed successfully

2) Example to Extract Leicester Map

1- First, create a new folder on the desktop, which we will call the Leicester Project.

2- Then, copy the GatcomSUMO application seen in **Figure B-9** and paste it into the folder created in step 1.

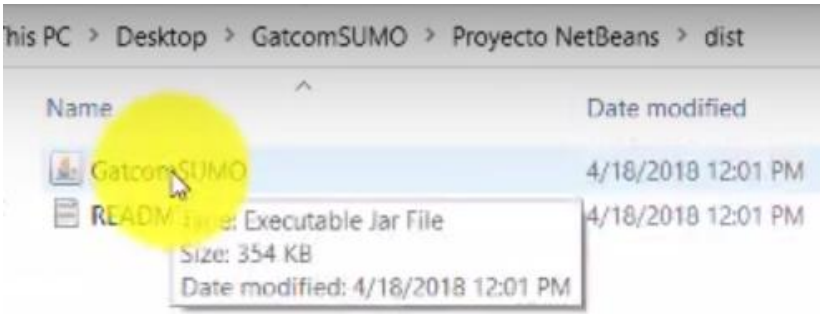


Figure B-9: Creating the Leicester map

3- ***Note***: Ensure that the SUMO is downloaded into an easily accessible file path such as C: or D: and avoid a long pathway to ensure the work remains simple, as seen in **Figure B-10**.

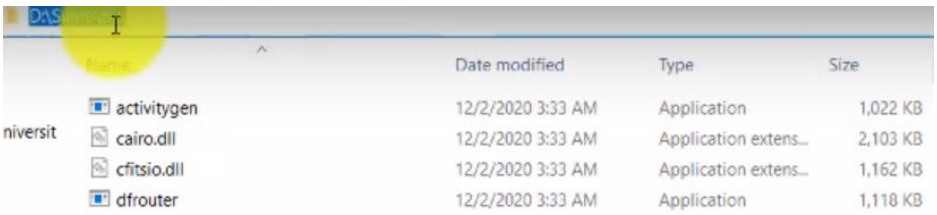


Figure B-10: Select D:/ as a direct direction for *SUMO/bin*

4- Go to the GatcomSUMO application and click on the three dots on the right-hand side, as shown in **Figure B-11**, and select the *sumo.bin* folder path for the bin folder; this will appear automatically in the Folder name, as shown in **Figure B-11**. Then, in the next pane select *Open*.

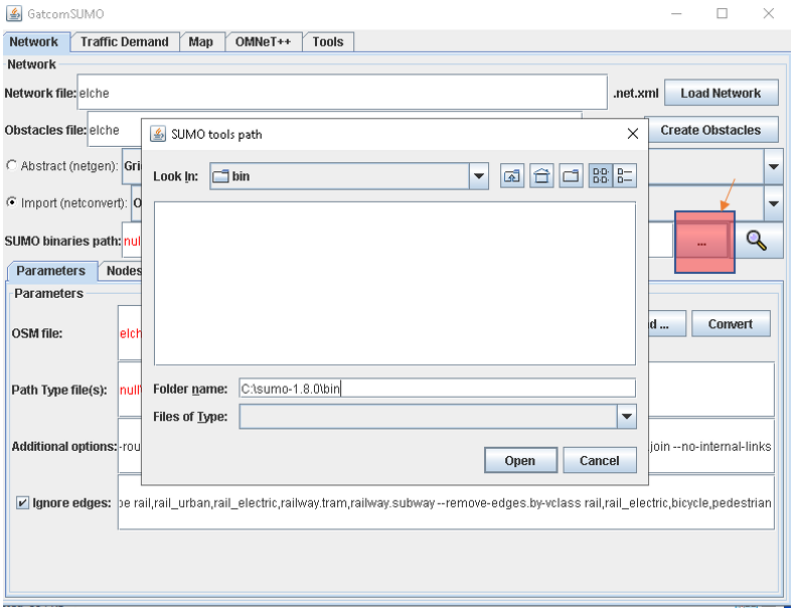


Figure B-11: The three-dot icon that helps to select the correct SUMO path

Now, start to download the Leicester map by clicking the *Download* button, after entering the name *Leicester* in the OSM file field, as shown in **Figure B-12**.

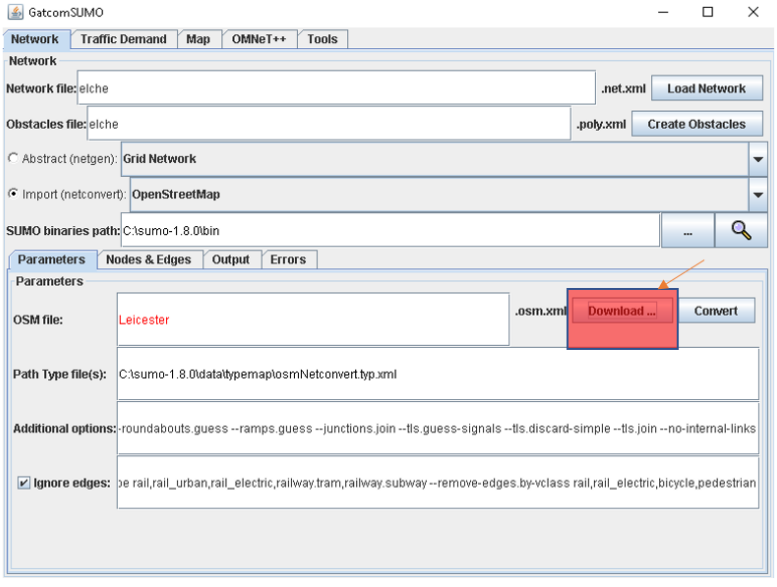


Figure B-12: Download the Leicester map

We will now see a new GUI (**Figure B-13**) to select the area of the Leicester map. To apply that, Open Street Map from Google, search for Leicester and select the area that you want to work on.

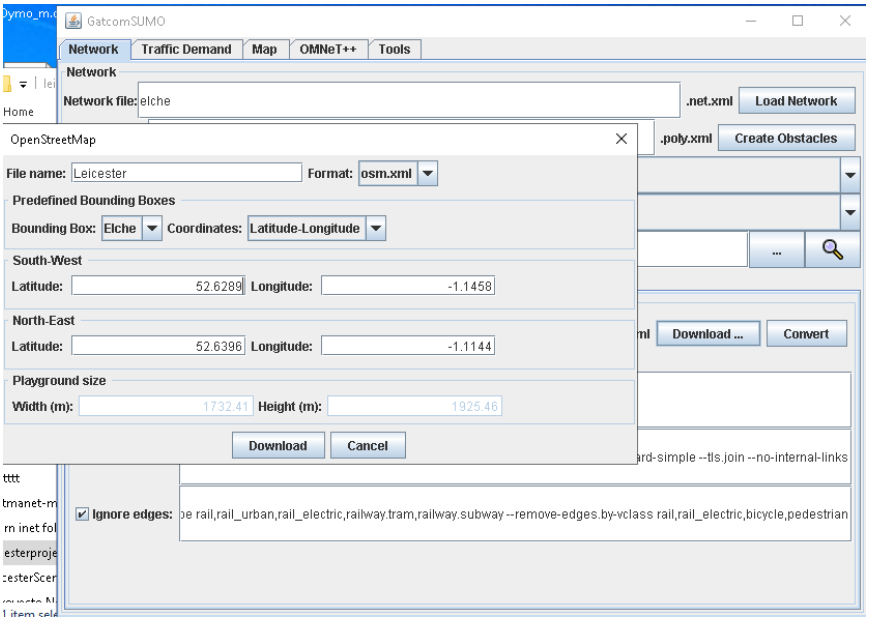


Figure B-13: Determine the area of the Leicester map

Two files (*Leicester.osm* and *Leicester_bbox*) will appear in the *Leicester project* folder that was created in step 1, as shown in **Figure B-14**.

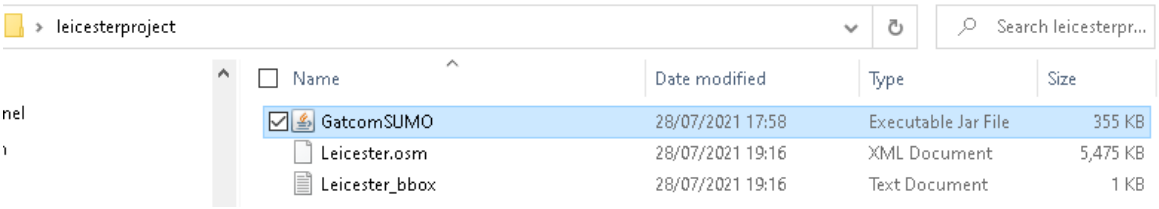


Figure B-14: Two new files appear in the created folder

Then, as shown in **Figure B-15**, convert the Leicester map from *.osm* to *a network SUMO file* by selecting the Convert option, but first, choose a name for the network file (e.g. *Leicester.net.xml*).

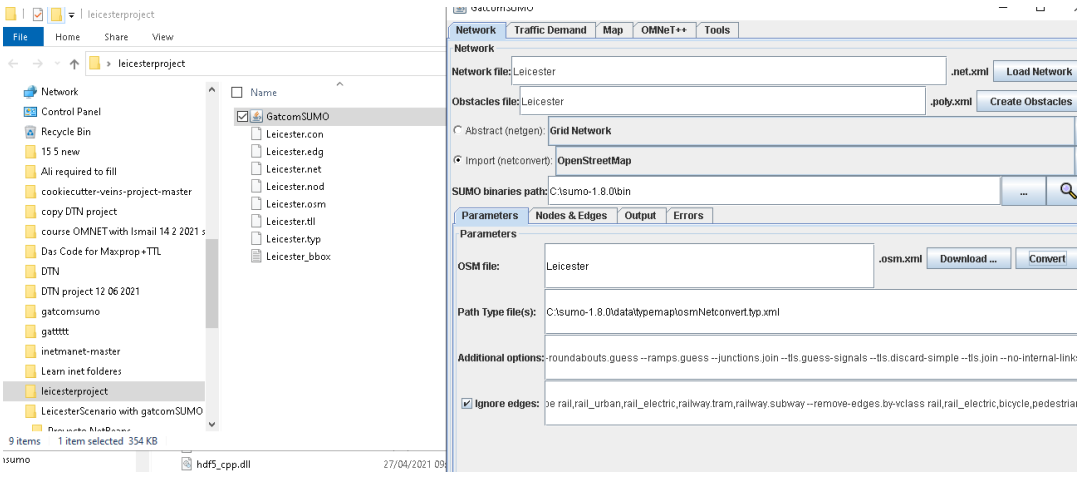


Figure B-15: Convert the *.osm* file to a network file

Then, click the Load Network button to be able to see the map when we click on the Map tab, as shown in **Figure B-16**.

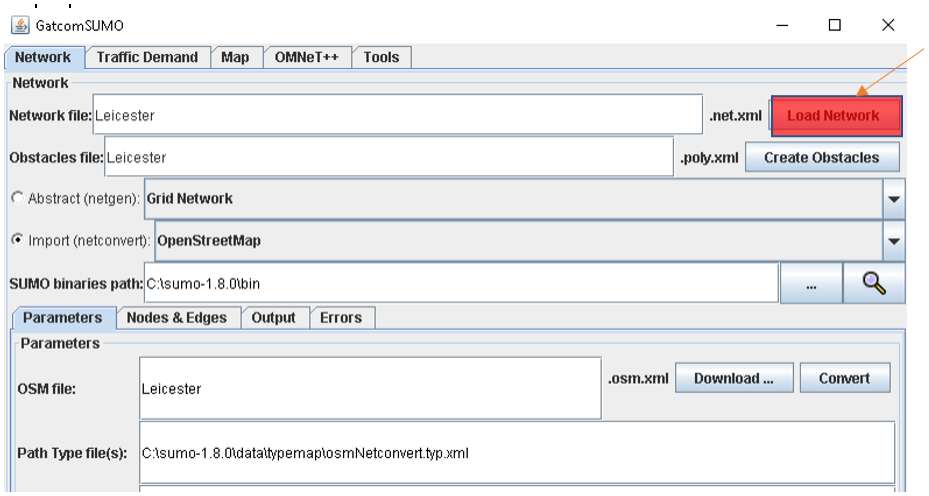


Figure B-16: Loading the converted network

Now, click the Map tab and you will see that the map is converted to a road network that is understood by SUMO, as shown in **Figure B-17**.

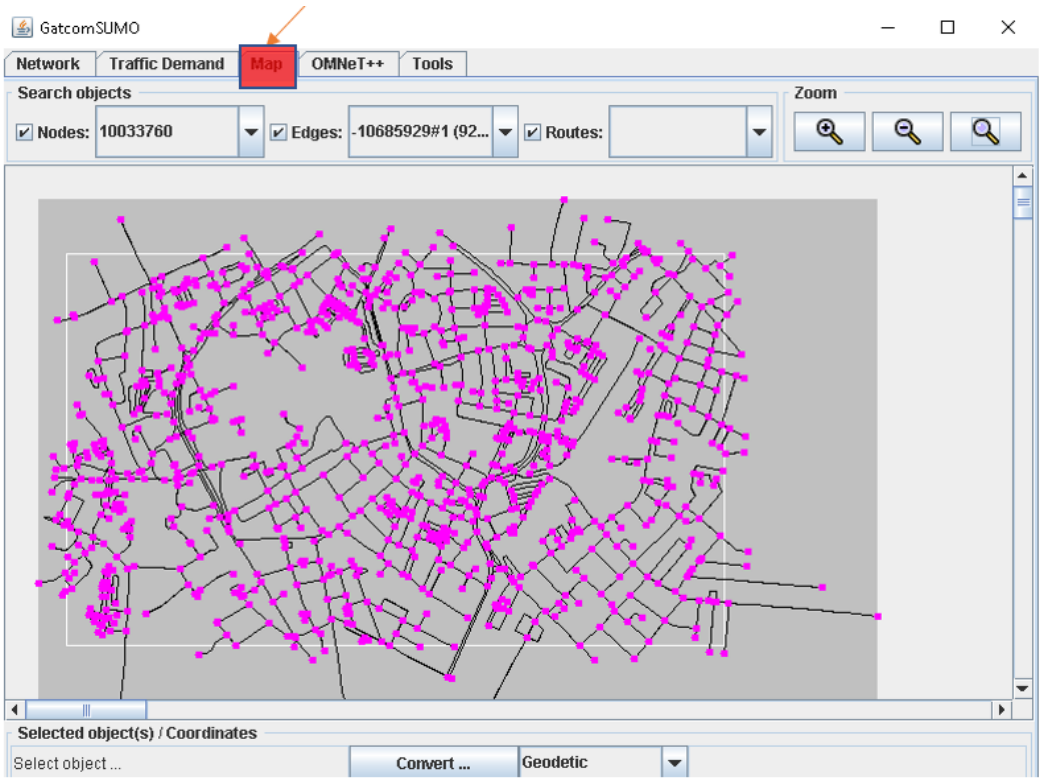


Figure B-17: Leicester map converted to a road network

Now traffic demand is required. Start by selecting the Traffic Demand tab and choose the Trips details, as shown in **Figure B-18**. Then, click the Generates trips button to confirm the trip's details.

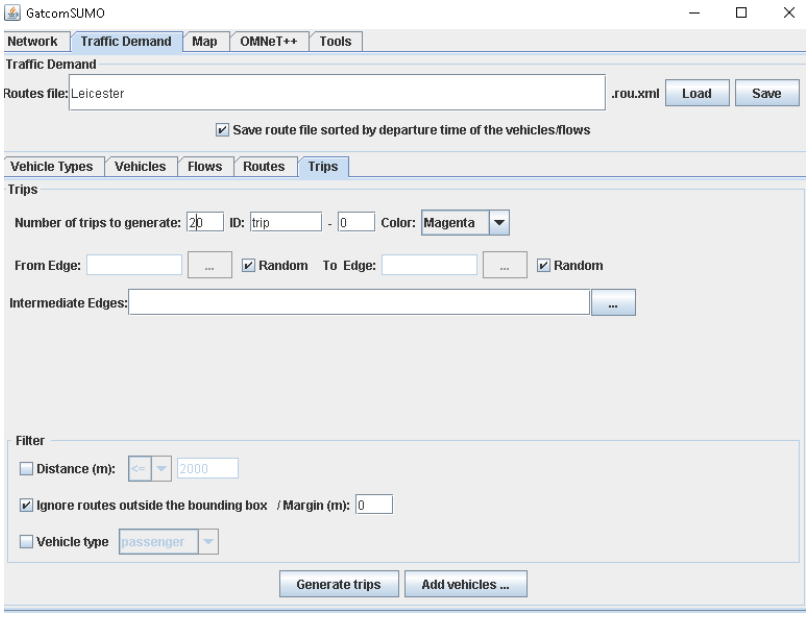


Figure B-18: Preparing the traffic demand

The panel seen in **Figure B-19** confirms that the routes have been generated successfully.

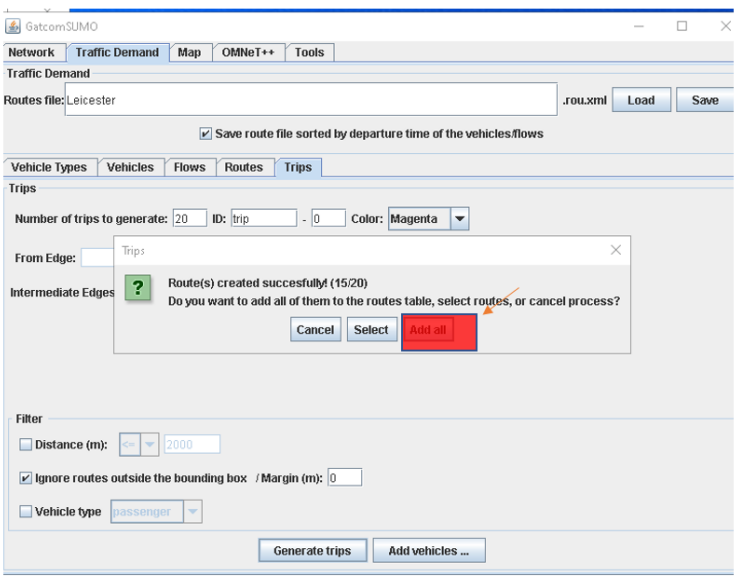


Figure B-19: The routes have been created successfully

Click the Add all button in the next pane, then click OK, as shown in **Figure B-20**.

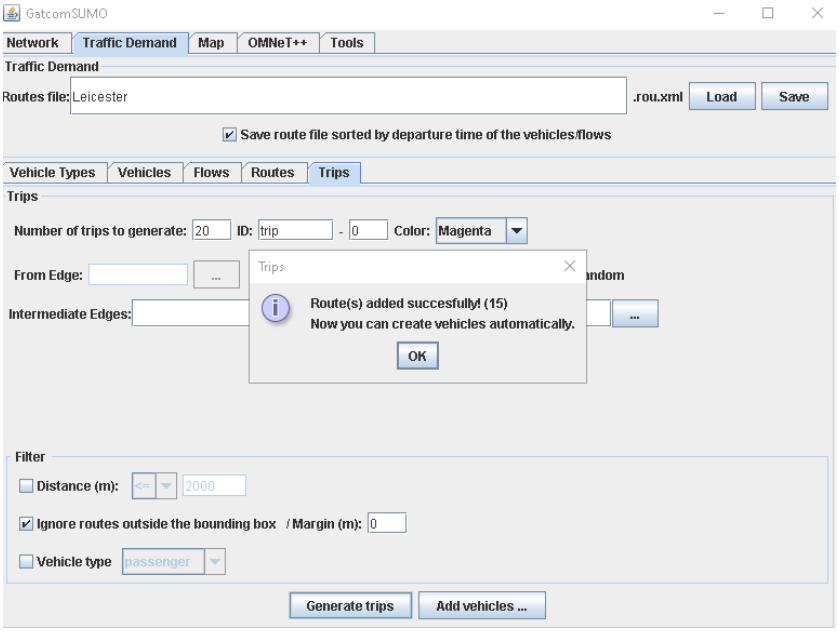


Figure B-20: The routes have been added successfully

After that, vehicles and their attributes can be added by clicking the Add vehicles option at the bottom of the panel and then selecting Save to create the *.rou* file. Now that the network and traffic demand have been created, select the OMNeT++ tab to show the required files for OMNeT++, as presented in **Figure B-21**.

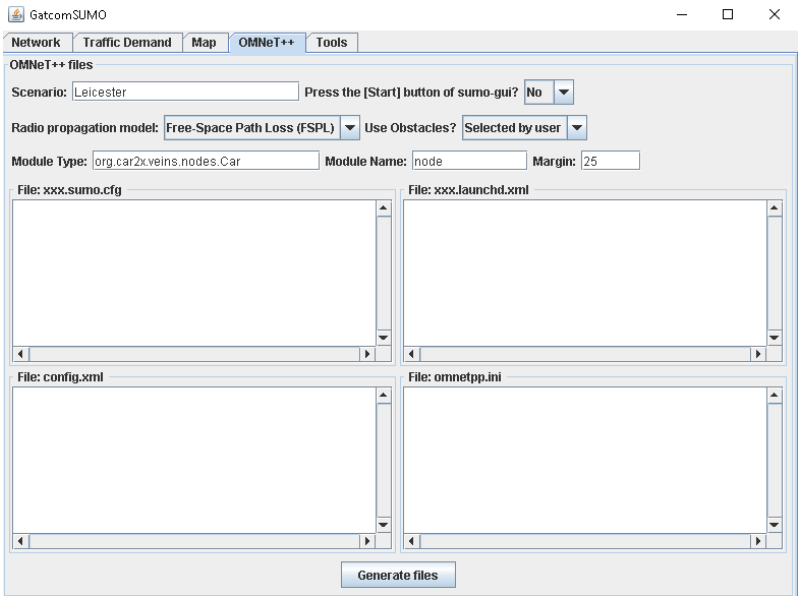


Figure B-21: The four important files For OMNeT++

Next, click the Generate files button to generate these files and make them ready for use in OMNeT++; a confirm pane will be shown, as seen in **Figure B-22**.

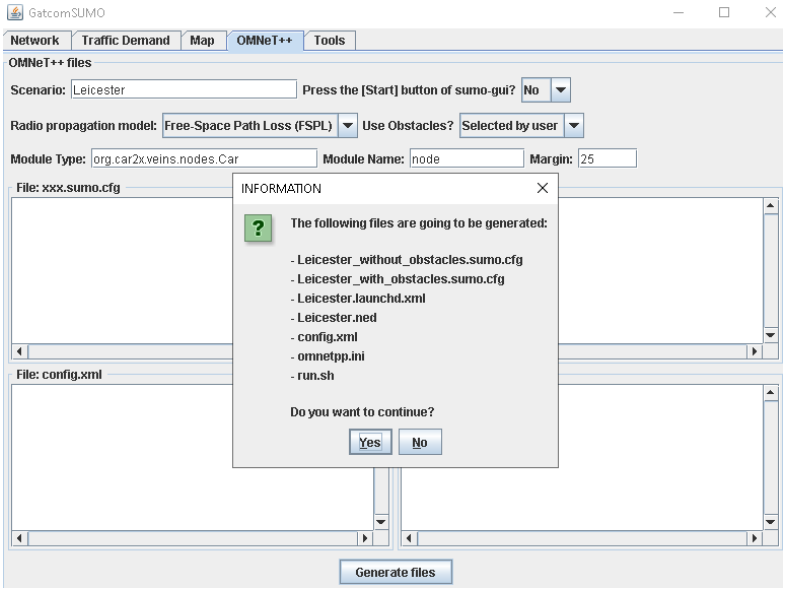


Figure B-22: Confirm the download of the OMNeT++ file

Click Yes, and these files will appear both on the screen and in the folder, as shown in **Figure B-23**.

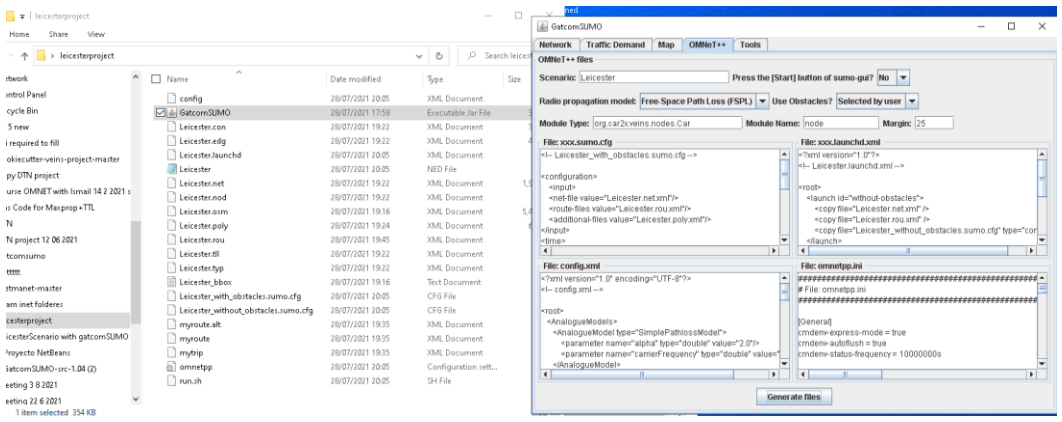


Figure B-23: Presenting the details of the prepared OMNeT files

Appendix C: Getting Started with GatcomSUMO, SUMO, VEINS, and OMNeT++

This appendix describes how the Leicester map is integrated into OMNeT++.

1. Open OMNeT++.
2. Go to *veins*, then *example*, then *veins*.
3. Right-click on the *omnetpp* folder (inside my folder) and open it with the NotePad application to copy the area for Leicester for x, y and z, and place them in the *.ini* file that exists in the *veins* folder.
4. In the folder copy the *config.xml* file and paste it into the *Veins folder*; a dialogue box will appear asking if you would like to overwrite. Select the Overwrite option, as shown in **Figure C-1**.

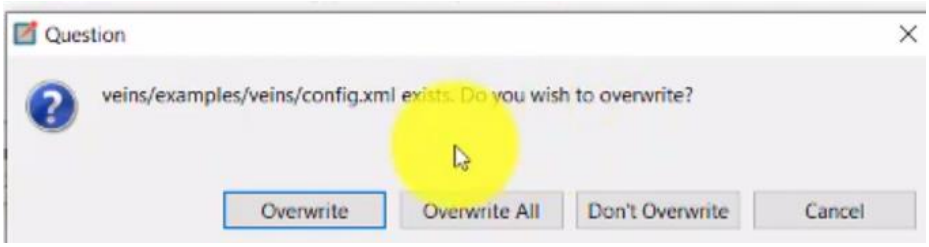


Figure C-1: Confirm to overwrite the existing configuration file in the veins example

Copy the *leicester.launched.xml* file and paste it into the *veins* folder as well.

Then, in the *initialise.ini* file, change the launched file name to your launched file name (i.e. *leicester.launched.xml*).

Open the Leicester launched file and remove the code with no obstacle and the root, as shown in **Figure C-2**.

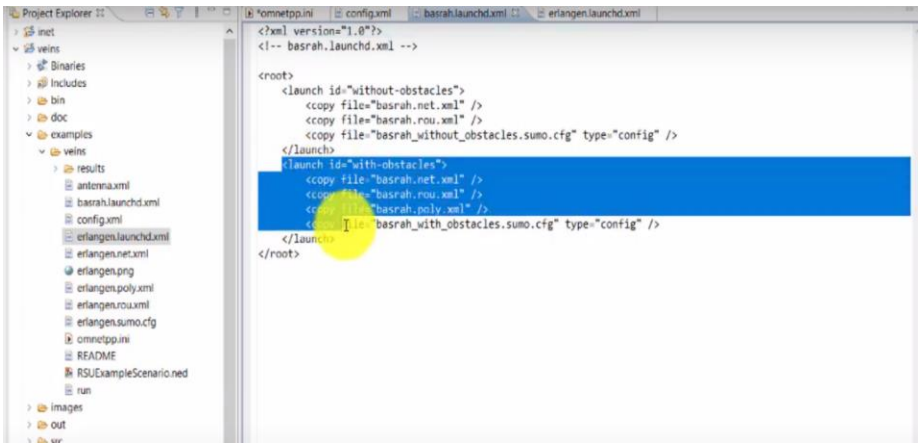


Figure C-2: Preparing the launched file for Leicester

The final configuration for the Leicester launched file will be seen in **Figure C-3**.

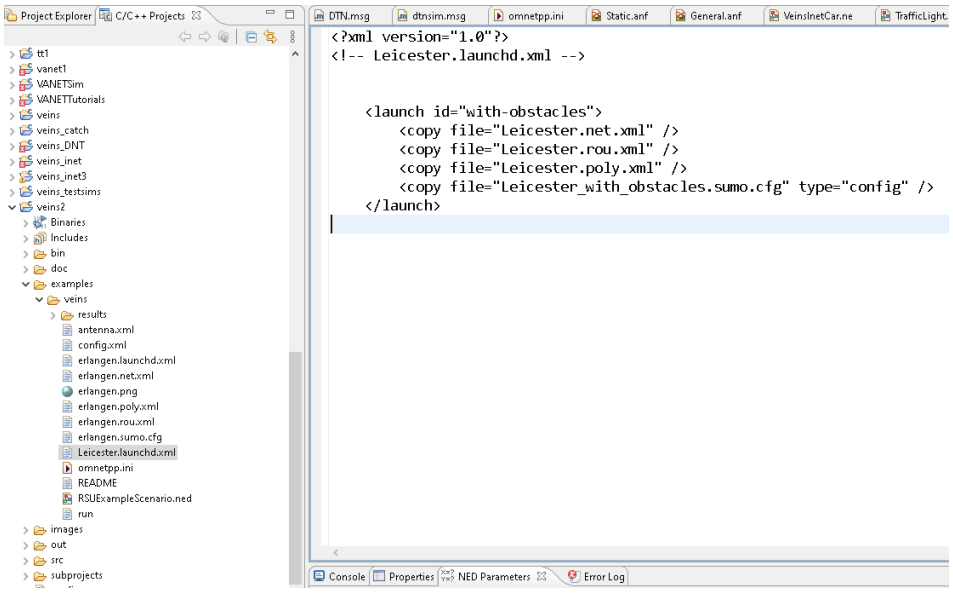


Figure C-3: The final launched file for Leicester

Next, as an important step, copy the four files highlighted in **Figure C-4**.

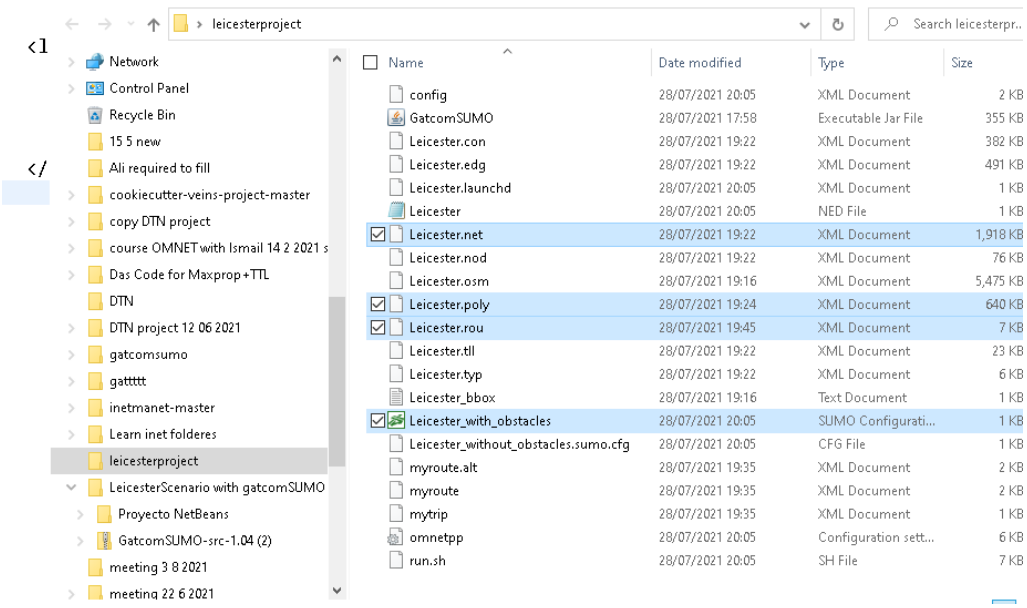


Figure C-4: The four files that should be copied to the veins example

Then, paste these into the *veins* folder. Before running the simulation, we should join SUMO with OMNeT++. In my work, we employ the following link to join SUMO and VEINS: *C:/omnetpp-5.6.2/samples/veins2/sumo-launchd.py -vv -c /C:/sumo-1.8.0/bin/sumo-gui.exe*. Finally, save and run the simulation.

After the simulation has completed the run process, the results seen in **Figure C-5** will be presented.

Figure C-5: The Leicester map in the SUMO and OMNeT environments

Cars will start to appear during the run time, as seen in **Figure C-6**.

Figure C-6: OMNeT and SUMO running in parallel to simulate the Leicester scenario in VEINS

Appendix D: Developed OMNeT ++ Project

- **The required steps to implement the OMNeT++ simulation**
- **Step 1: set up the project**

  To create a new project in OMNeT++:

  From the File menu select New, then select OMNeT++ project, and select Empty project, Finally, click Finish and an empty project will be created in the Project Explorer panel on the left.

- **Step 2: add the NED file**

  The NED file is an important file in OMNeT++ that can be utilized to define the network components and assemble these into the networks. To add the NED file to the project, right-click on the project directory in the Project Explorer panel on

the left, and then from the menu select New, and select Network Description File (NED). Enter the *selected name. ned* and click Finish.

- **Step 3: add the C++ files**

  The C++ files are employed to implement the functionality of the simple module in C++. To create a C++ file named *txc1.cc*, select New from the File menu, and then select Source File.

- **Step 4: Add the *omnetpp.ini* file**

  The *omnetpp.ini* file should be created as a mandatory file to run the simulation. Since the NED file may contain several networks, the *.ini* file is utilized to inform the simulation program which of these networks needs to be simulated. To create an *omnetpp.ini* file, select New from the File menu, then select the initialization file (INI).

  Now, the model is created and ready to compile and run.

1. Running the simulation

Once the project-creation steps are complete, the simulation can be run by selecting the *omnetpp.ini* file and clicking the Run button (as seen in **Figure D-1**), then the IDE will build the project automatically. If no compilation errors appear, the simulation will be ready to run.

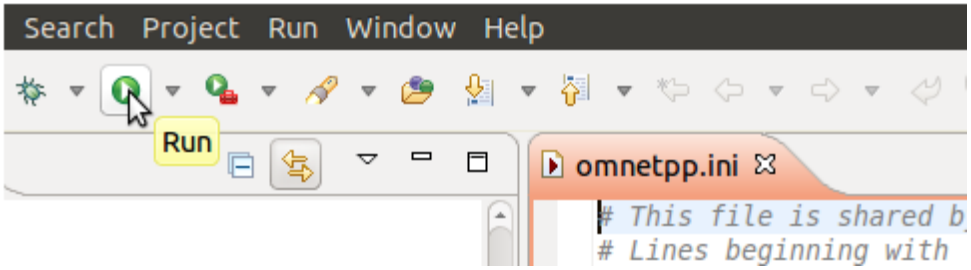


Figure D-1: OMNeT GUI to run

After the simulation run time is complete, a *result* folder will be created under the project folder, which will contain *.vec* and *.sca* files that store the results in vector and scalar form, respectively. Vectors record data values as a function of time, while scalars typically record aggregate values at the end of the simulation.

2. SUMO Simulator setup

This section describes the procedure for setting up a SUMO traffic simulation that is employed to simulate VANET. The SUMO Simulator is utilized to generate the traffic scenario, as shown in **Figure D-2**, where the Leicester map is downloaded with an *.osm* file extension.

Figure D-2: Leicester map network in SUMO

Then the *.osm* file is utilized to generate the other two important files: *.net.xml* and *.rou.xml*. These files are employed to feed SUMO to help generate *SUMO.cfg* files. Then, run the *SUMO.cfg* file to get the network on SUMO, as shown in **Figure D-3**.

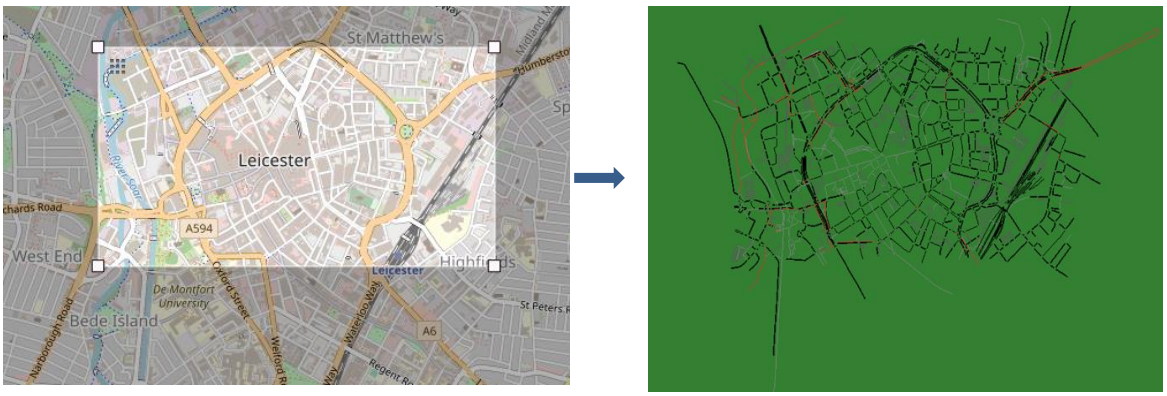


Figure D-3: Leicester map from OSM to SUMO

The *Leicester.net.xml* file can now be utilized to generate a *Trips* file using the *randomTrips* python script provided with the SUMO package, as shown in **Figure D-4**.

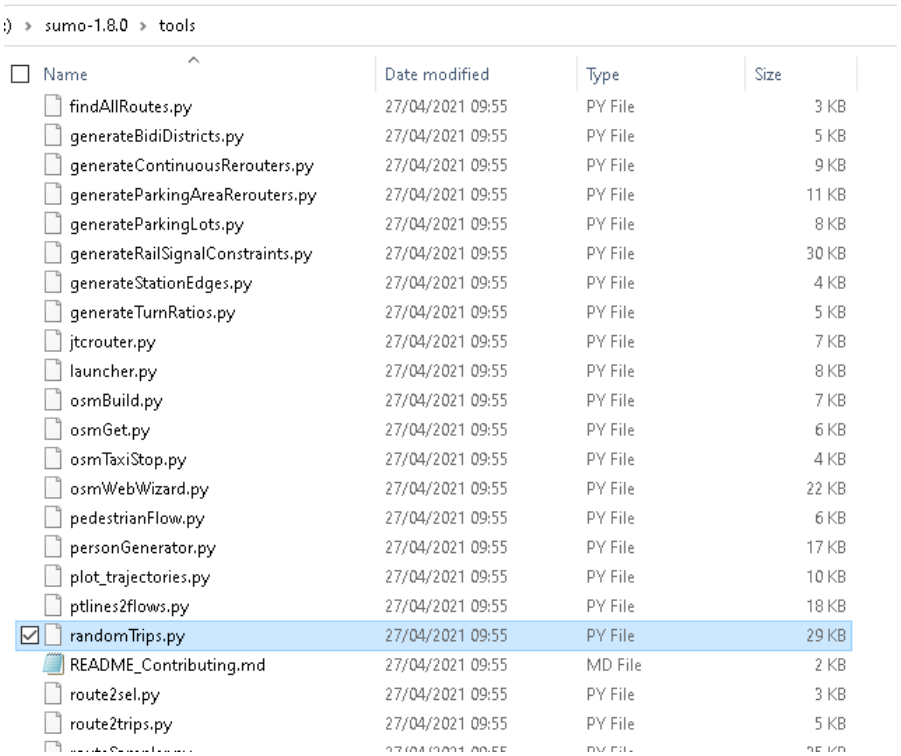


Figure D-4: Selecting the randomTrips file

Use the following command line:

Py C:\Users\sohe_\Desktop\Sumo_demo\OSM_RandomTrips\randomTrips.py -n Leicester.net.xml -r Leicester.rou.xml -e 50 -l

Finally, the SUMO configuration file needs to point to the corresponding *.net.xml* and *.rou.xml* files to determine the start and the end times of the simulation. In SUMO, every scenario has a file with the extension *.sumo.cfg*. In this work, the configuration file is created as follows:

Creating config file (sumo.cfg)

<configuration>

<input>

<net-file value="Leicester.net.xml"/>

<route-files value="Leicester.rou.xml"/>

</input>

<time>

<begin value="0"/>

<end value="2000"/>

</time>

</configuration>

Appendix E: Introductory Results of the First Test of a Novel EMRT

Delivery Ratio

Figure E-1 shows that the delivery ratio for all protocols (the original Spray&Wait and EBR, and the improved Spray&Wait-EMRT and EBR-EMRT versions) increases significantly when the number of nodes is increased. This is because when the number of nodes increases, more nodes are involved in delivering messages, and the number of replicas will also increase, thus raising the probability of the messages being delivered. In addition, we can note a significant improvement when the proposed technique is applied to Spray&Wait, where the results highlight up to 8% improvement compared to the original Spray&Wait. This is because Spray&Wait depends on a fixed number of replicas for all messages, while Spray&Wait-EMRT utilizes a dynamic number of replicas based on the node's

ability to carry the messages without causing congestion or the ineffective usage of network resources. As a result, EMRT decreases the number of copies for newly generated messages when the source's neighbours experience message congestion. Additionally, improvement can also be seen in the EBR-EMRT protocol, where the delivery ratio increases up to 13% compared to the original EBR. The reason is that besides sending the replicas toward high-density areas, the number of replicas is controlled based on the capability of the node in EBR-EMRT. Therefore, EBR-EMRT benefits from the available size of the node buffer, which leads to the carrying and storing of more copies of the message waiting for a good forwarding opportunity to be delivered.

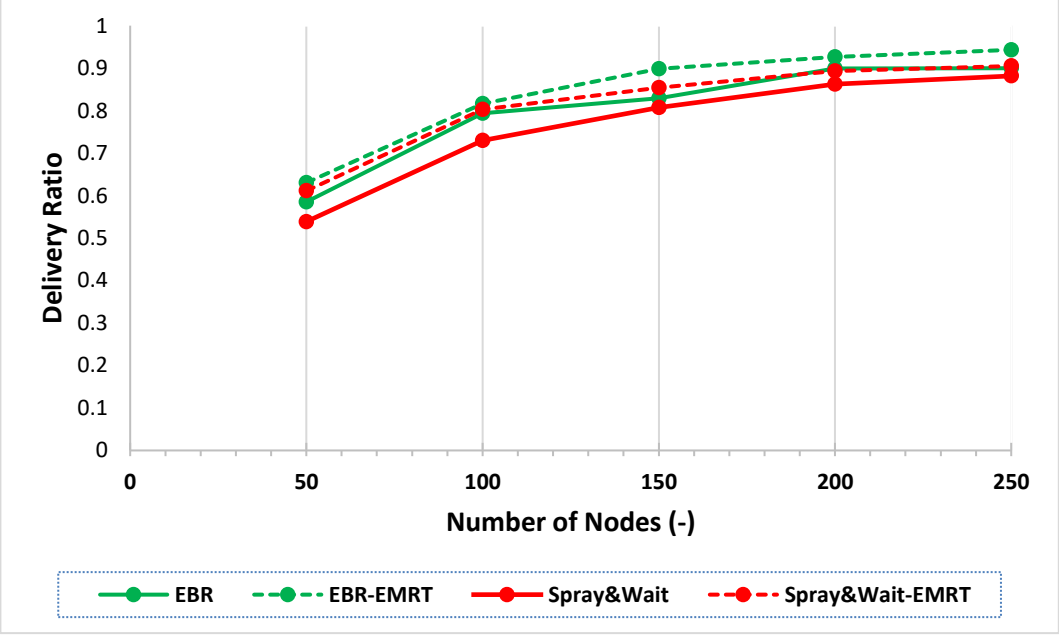


Figure E-1: The delivery ratio in different node densities

Overhead Ratio

Figure E-2 demonstrates the overhead ratio against the node density. It can be observed from the obtained results that when node density increases, the overhead ratio decreases with all protocols because as these quota-based protocols only relay a few message copies, this is not affected by the increasing number of nodes. At the same time, the improved results in terms of the overhead ratio can also be noted where EMRT is applied to Spray&Wait and EBR. Although there is no significant reduction in the overhead ratio, the overhead ratio of both the Spray&Wait-EMRT and EBR-EMRT protocols reduces by up to 9% and 6%, respectively, compared with the original protocol versions. This is because the network resources have been controlled and congestion is reduced by relaying messages based on the rate of encounter and network congestion (available network resources), leading to a low overhead ratio. Therefore, when the node has sufficient resources such as free buffer space and energy, the number of replicas of newly generated messages will be increased. Otherwise, the number of copies of newly generated messages will be decreased.

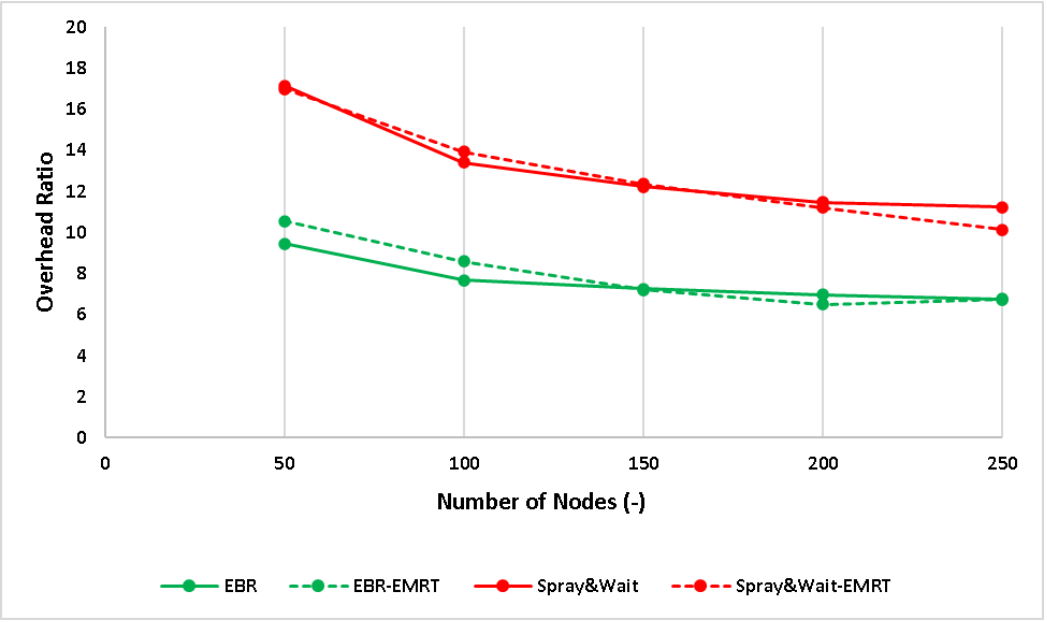


Figure E-2: The overhead ratio in different node densities

Delay Ratio

Figure E-3 demonstrates the delay ratio against the node density, where it is clear that the delay ratio increases as does the number of nodes. This is because more nodes become involved, which leads to congestion in the network. Therefore, the information processing at every node takes more time, and thus the overall delay is increased. Moreover, buffering the messages at the node causes delays in message delivery. The results in terms of delay ratio are shown, where EMRT is applied to Spray&Wait and EBR. It can be seen that the increased delay ratio at a higher density with the original protocols is because more nodes will send copies of the message, which leads to a delay in the delivery of the messages. We note that the delay ratio of the Spray&Wait and EBR protocols reduces by up to 51% and 14%,

respectively, Spray&Wait-EMRT and EBR-EMRT protocols. This is because the rate of dropping messages is controlled based on selecting an appropriate number of replicas given the buffer availability. Based on the fact that an uncontrolled number of replicas will lead to buffer congestion or inefficient use of the network resources, as we reduce the congestion, we also reduce the messages drop, which thus decreases the delay ratio.

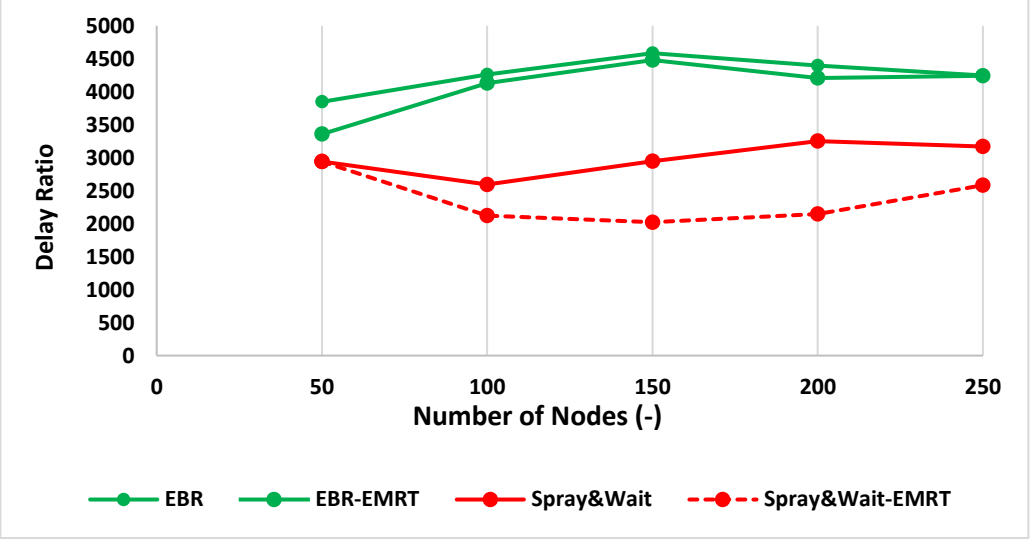


Figure E-3: The delay ratio at different node densities

Appendix F: Paper Ready for Submission

Extensive Survey and Taxonomy of Vehicular Delay-Tolerant Networks

1. Introduction

Due to the high mobility and rapid topology changes in the Vehicular Ad-hoc Network (VANET) environment, the links between vehicles may not exist. This intermittent connection in the networks causes packet losses and delays in delivering the messages to their destination, especially in a sparse environment. Therefore, to overcome the issues inherent in such challenging environments, the DTN routing protocol has been proposed to transmit the messages between vehicles by employing the SCF mechanism to carry the packet to the designated destination. However, the node may store a message for a long period of time until an appropriate forwarding opportunity arises. Furthermore, most DTN protocols rely on the replication of messages in the network to improve on-time delivery, Nevertheless, the benefit of replication is at the expense of more resource- and storage-intensive, thus leading to high overhead. Consequently, it is crucial to effectively manage the messages in the node's buffer in order to ensure effective usage of the network resources and reduce the delivery delay period, especially in safety applications. Recently, DTN studies have either focused on DTN routing protocols or buffer management policy. Additionally, the majority of the DTN

protocols degrade performance because they fail to take the resource constraints into account. Hence, this paper conducts an extensive and critical review of both the DTN routing protocol and buffer management.

2. **Routing Protocols for Vehicular DTN**

In VDTN, a range of routing approaches have been investigated, simulated, designed, and validated [89, 194-201]. In general, the VDTN routing protocols can be classified into (i) zero knowledge-based protocols, such as direct delivery, Epidemic, and Spray&Wait; and (ii) and knowledge-based protocols such as PRoPHET, GeoOpps, Geo DTN+Nav, VADD, and MOVE. Zero knowledge-based protocols do not need to collect any information during the running time. In vehicular situations, however, these protocols are less likely to succeed due to the Rapid topological changes. On the other hand, knowledge-based protocols are required to collect some information regarding the network such as the number of nodes and the buffer size, which may cause more delay than the zero knowledge-based protocols. In this section, the VDTN routing protocols are classified into three categories according to selecting the forwarding neighbour: distance-based routing protocols, delay-based routing protocols, and direction-based routing protocols, as shown in **Figure F-1.**

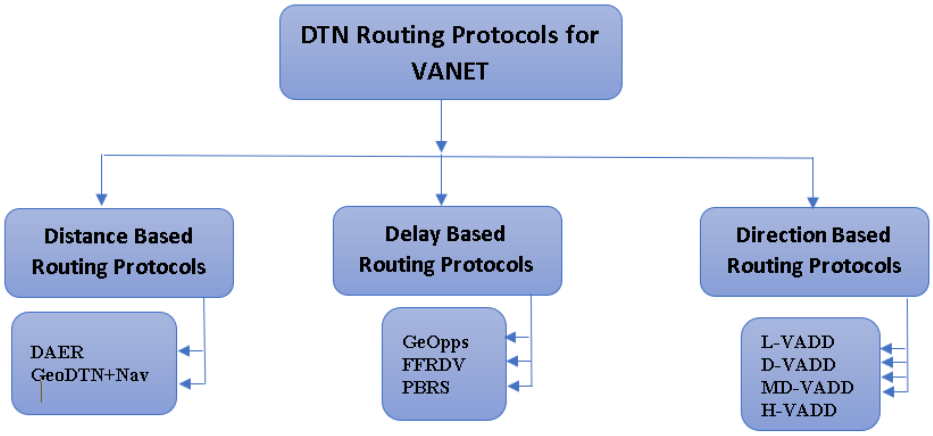


Figure F-1: The various DTN routing protocols for VANET

1- Distance-Based Routing Protocols

The protocols under this category exploit the greedy routing approach to forward the message between the source and the destination nodes. With a greedy strategy, the data packet is forwarded by selecting the nearest neighbour to the destination among all neighbours' nodes [194]. To clarify, **Figure F-2** presents the distance-based forwarding neighbour selection. The blue vehicle is the source vehicle, and the red vehicle is the destination vehicle, while the remaining vehicles are the intermediate vehicles between the source and destination that will be employed in this example as carrier vehicles. When the blue vehicle wants to send a data packet to the red vehicle, the distance between the red vehicle and all the intermediate vehicles will first be calculated. Then, the neighbour that offers the least distance will be chosen as a carrier vehicle. Therefore, in the presented example, the yellow vehicle is selected as a carrier vehicle because the distance between the yellow

vehicle and the red vehicle is a shorter route distance (3 m) than via the other neighbouring vehicles. Therefore, the blue (source) vehicle forwards the data messages to the yellow (carrier) vehicle, which will forward these messages to the red (destination) vehicle. GeoDTNS+Nav and Distance Aware Epidemic Routing (DAER) are good examples that fall under the distance-based routing protocols category.

As stated above, DAER is one example of a distance-based routing protocol that attempts to address certain issues that have not been considered in a conventional Epidemic routing protocol such as the absence of a priority mechanism for forwarding the message, inefficient use of resources, and geographic information not considered in the buffer replacement policy [194]. The DAER utilizes the message priority assignment strategy to prioritize messages that will be closer to their destination. However, the DAER depends on greedy distance forwarding to transmit the messages and does not take the speed or direction of the nodes into consideration.

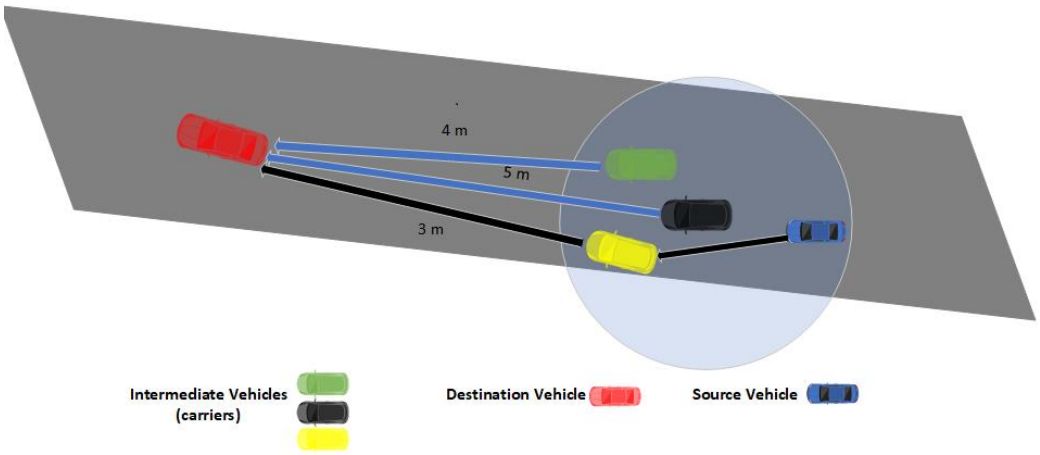


Figure F-2: The distance-based forwarding technique

Harri. *et al,* [195] proposed a hybrid geographic routing protocol (GeoDTNS+Nav) as another example of a distance-based routing protocol. Because the GeoDTNS+Nav routes messages by employing different modes (e.g., greedy, perimeter, and DTN), the routing protocol overcomes the Greedy Perimeter Stateless Routing (GPSR) and Greedy Perimeter Coordinator Routing (GPCR) that solely rely on the greedy procedure. Traditional protocols such as GPSR and GPCR can effectively transmit messages when the underlying network is fully connected [195]. A possible explanation for this might be that with GeoDTNS+Nav, the messages are initially transmitted in greedy mode. If this fails due to no neighbouring vehicle accepting the source vehicle, then the perimeter mode will be utilized. Finally, the DTN mode will be adopted when both the perimeter mode and the greedy mode fail [202]. The transition diagram between greedy, perimeter, and DTN modes is shown in **Figure F-3**. The choice of one of these modes will depend

on the cost function, the threshold related to network partition detection, and the quality of the node. These elements will allow proper selection between the greedy, perimeter, and DTN modes. According to the results achieved by Harri, *et al*. [195], the GeoDTNS+Nav improves the delivery ratio and enhances the graph reachability by employing the DTN strategy. However, the packet delivery delay increased due to the switching between the three modes, which represents the main weakness of this procedure.

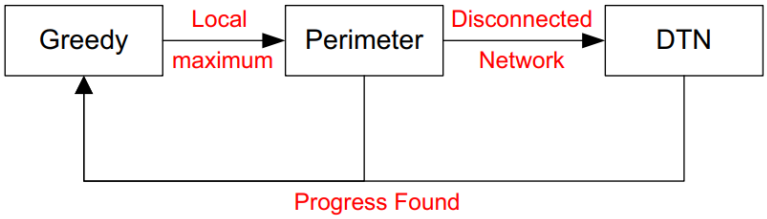


Figure F-3: The transition diagram between the three different modes

2- Delay-Based Routing Protocols

All protocols that fall under this category depend on the time to forward the data packet between vehicles. The data packet is forwarded by choosing a neighbour that can forward the message in the shortest time compared to the other neighbouring node. **Figure F-4** presents the delay-based forwarding neighbour selection process. As per the earlier example, the blue vehicle is the source vehicle, the red is the destination vehicle, and the remainder is the carrying vehicle. Hence, if the blue vehicle has a message that needs to be forwarded to the red vehicle, the delay time between the red and all the carrier vehicles will be determined first. Then, the

neighbouring vehicle with the shortest time delivery will be selected as a carrier vehicle. In this example, the yellow vehicle is chosen as a carrier because the delay time between yellow and red (3 s) is less than other carrier vehicles. The GeoOpps, Fastest-Ferry Routing in DTN enabled VANET (FFRDV), and PBRS are good examples that fall under the delay-based routing protocols category.

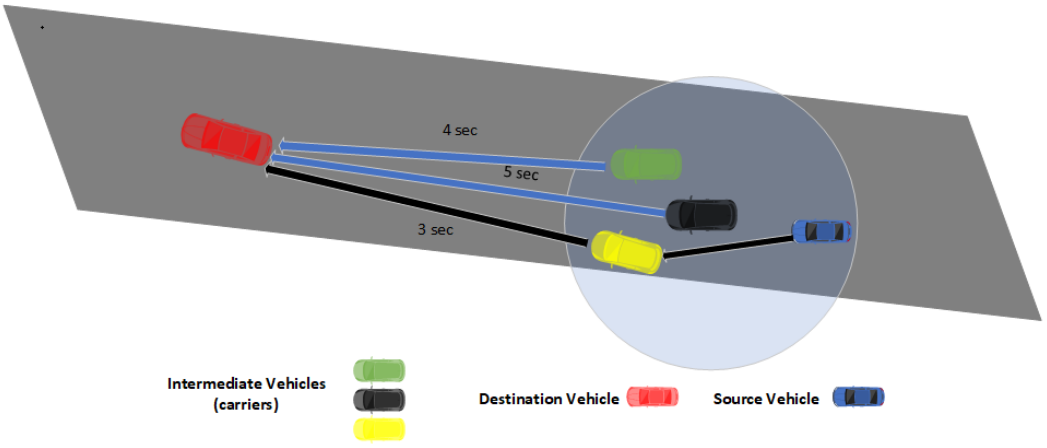


Figure F-4: Delay-based forwarding technique

FFRDV was proposed as a unicast routing scheme for the highway VANET environment, which has the benefit of utilizing a partitioned network that is caused due to the rapidly changing topology in VANET. In FFRDV, GPS is utilized to obtain the current location information for each vehicle. This geographic information is employed to divide the road into blocks, as shown in **Figure F-5.**

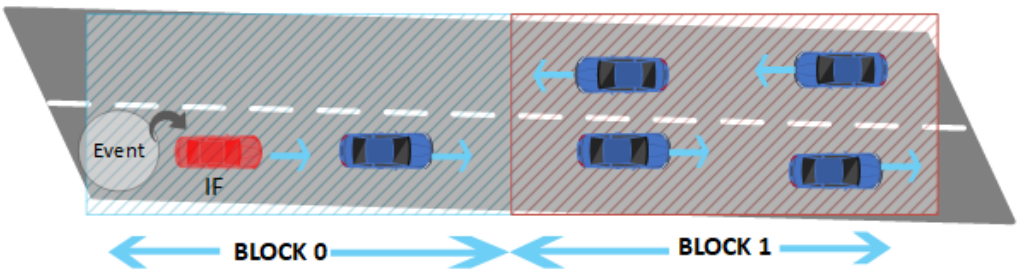


Figure F-5: Initial ferry sensing during an urgent event

FFRDF is utilized to transmit the packet by choosing a ferry vehicle that has the maximum velocity in the block. The FFRDV is implemented in two phases: (i) ferried selection, and (ii) message forwarding. The ferried selection commences when there is an event on the road and the event source is sensed by the neighbour's vehicles. Then, the selection is based on the request/response mechanism, whereby the first response vehicle will be the Initial Ferry (IF). The IF is responsible for selecting the next ferry based on speed priority. The next ferry could be any vehicle (node); when the vehicle carries the data it will be referred to as a ferry, otherwise, it will be called a normal vehicle [9]. In each block, the priority of vehicle selection is decided by maximum velocity. In other words, every vehicle in a block can be chosen as the IF provided that it has the maximum velocity compared to the velocity of the other vehicles in the same block. Therefore, the fastest vehicle will be chosen for the next ferry. The ferry selection process is then repeated block by block until the packet reaches the destination. Moreover, when IF is moving to a new block, as

shown in **Figure F-6**, it will broadcast a hello message and require a status report from the neighbouring vehicle to obtain information regarding its velocity.

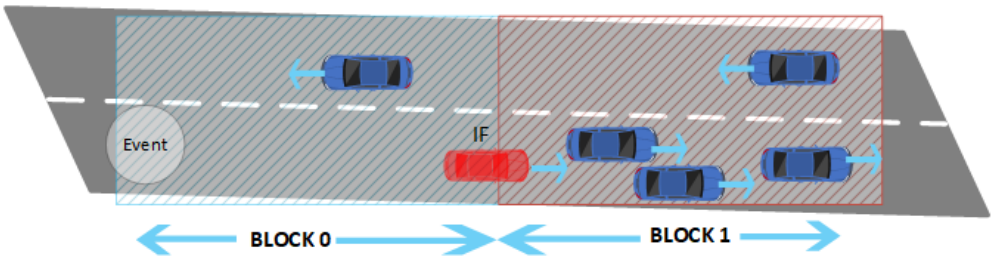


Figure F-6: Initial ferry entering a new block and broadcasting hello messages in the network

Next, the IF will start to compare its velocity with that of its neighbours. If any neighbour has a velocity higher than the IF, this neighbour will change to become a ferry vehicle. After this procedure, the IF will send the packet to the new ferry and wait to obtain a response from the new ferry that will confirm the packet has been received. Finally, the IF will either discard this packet (if successfully received) or continue to carry the packet (if unsuccessfully received). FFRDV was implemented and evaluated using the NS-2 network simulator, where the results show that FFRDV provides superior performance in terms of delivery ratio compared with DAER which is dependent on the greedy scheme to forward the data packet. Therefore, the FFRDV approach clearly offers advantages. However, it would be useful if the simulation works by Yu and Ko [12] considered other metrics such as overhead, latency, and EED. Furthermore, different comparisons with

different DTN protocols are required to improve the FFRDV protocol's performance.

The Minimum Delay Routing Protocol (MDRP) was introduced by Khan, *et al*. [196] to determine the delivery delay for intermediate vehicles, where this protocol employs the velocity and distance from the destination of the neighbouring vehicles. In addition, the MDRP scheme for VANETs is utilized to calculate the packet delivery delay from each neighbour's vehicle to the destination. Then, the carrier vehicle with the shortest delivery time delay is chosen to transport the messages to their destination. Lastly, the NS-2 simulator was employed to verify the performance of the MDRP scheme and compared it with the FFRDV scheme which depends solely on the velocity to select the next carrier vehicle. The FFRDV scheme may have a negative impact by exceeding the time delivery delay. According to the simulation results, MDRP provides superior results to FFRDV in terms of the average inter-meeting time and EED. Nevertheless, it would be useful if the author in ref. [196] added the direction of the neighbour's vehicles to decrease the overhead and the time delivery delay that may result due to sending messages to irrelevant vehicles that are traveling away from the destination. Therefore, more simulation results are still required to ensure the credibility of MDRP.

Leontiadis and Mascolo [197] discussed the GeoOpps routing protocol that can route the packet between nodes in the VANET environment. GeoOpps is geographic delay tolerant and can deliver to a specific location by utilizing a

Navigation System (NS). GeoOpps exploits the navigation information obtained by NS to route the message to the correct location (specific location). NS helps in the selection of a suitable vehicle to carry the packet close to the destination position. The node with the minimum delivery time will be selected by GeoOpps as a suitable node to forward the message as reported by Leontiadis and Mascolo [197]. All the vehicles in GeoOpps periodically broadcast the destinations of the messages that they have stored. Then, all the neighbouring nodes will start to calculate the Minimum Estimated Time of Delivery (METD) for the packet using **equation (F-1)**:

$$METD_{mD}^{V_1} = ETA\left(V \rightarrow N_{m_D}^{V}\right) + ETA(N_{m_D}^{V} \rightarrow D) \quad \text{(F-1)}$$

Where V, V_1 are vehicles, m_D carries a message, $ETA\left(V \rightarrow N_{m_D}^{V}\right)$ means that vehicle V can estimate its time of arrival to the nearest point in its trajectory $N_{m_D}^{V}$ to the destination node, and $ETA(N_{m_D}^{V} \rightarrow D)$ is the estimated time that the packet would take from the nearest point $N_{m_D}^{V}$ to the destination node D. These calculations will be sent to the source vehicle. Finally, the source vehicle will compare the METD values, whereby the vehicle with the smallest METD value will be chosen as a carrier vehicle that can deliver the message faster than any of the other neighbouring vehicles. This implies that either the carrier vehicle decides to retain the packet if its METD value is the lowest, or it will forward the data packet to a neighbouring vehicle that has the lowest value, to thus become a new carrier. This

process will be periodically repeated until the packet arrives at the destination, or the packet time has expired. The advantage of GeoOpps is that it has a high delivery ratio because the delivery ratio depends on the road topology and mobility patterns, rather than the network density. However, navigation information is detected in all nodes in the network environment, raising security concerns. Another limitation is that GeoOpps' single copy technique restricts the benefits of discovering multiple paths to the target, even if some of them may be a faster option. The OMNeT++ simulator was utilized by Leontiadis and Mascolo [197] to evaluate the performance of GeoOpps and compare the results with other works.

Another example of VDTN is the Geographic Vehicular DTN routing protocol, which is based on multiple forwarding metrics (GeoVDM) and was proposed by Cherif, et al. [198]. GeoVDM is a VDTN protocol that takes advantage of the GeoOpp [197] and GeoSpray [199] geographic routing protocols. Furthermore, the benefits of integrating custody and multi-copies strategies were analyzed to design GeoVDM. In GeoVDM, the routing distance between the nearest point and the message destination (Dist) is introduced as a second metric. Therefore, the GeoVDM depends on two different forwarding metrics: (i) METD, which is utilized to select the quickest forwarding node; and (ii) Dist, which is employed to select the closest forwarder node to the destination [198]. Finally, the performance of GeoVDM was tested using OMNeT++, SUMO, and VEINS. In addition, according to the obtained results, GeoVDM improved the delivery ratio and

provided a low delay compared with GeoSpray. However, GeoVDM has an inferior overhead ratio compared with GeoSpray because the former does not employ a limited multi-copy scheme to control the copies of the messages.

3- Direction-Based Routing Protocols

The protocols under this category exploit the direction of the vehicles to forward the data packet between the source and the destination. The data packet is forwarded by selecting the neighbouring vehicles that are closest to the carrier vehicle and moving toward the direction of the destination vehicle. As per the earlier example, the blue vehicle is the source vehicle, the red vehicle is the destination, and the remainder of the vehicles are the intermediates that can facilitate the transfer of messages from the source to the destination. In **Figure F-7**, despite the green vehicle being the closest to the destination vehicle, the yellow vehicle is chosen as a suitable carrier due to its direction being the same as that of the red vehicle. To simplify, Vehicle-Assisted Data Delivery (VADD) is a good example that is categorized under the direction-based routing protocols. To address the issue of efficient data delivery in VANET, some techniques were proposed by Zhao and Cao [200] to efficiently route the packet with reasonable delay. The fundamental requirements in VANET are that propagating the messages efficiently leads to increased reliability and decreased data delay in the network. To achieve these objectives, the VADD protocols were presented in [200, 201]. The benefit of VADD is the ability to select a path with the smallest expected delivery delay by

utilizing three features: knowledge regarding the road topology, the maximum speed of each road, and traffic density. For instance, when the source node has a message to deliver to the destination and there is no direct connection between them, the node will send the message to the road that has a higher speed and higher density to carry the messages faster. In general, the VADD protocol follows the basic principle of transmitting as many as data messages through the wireless channel as possible.

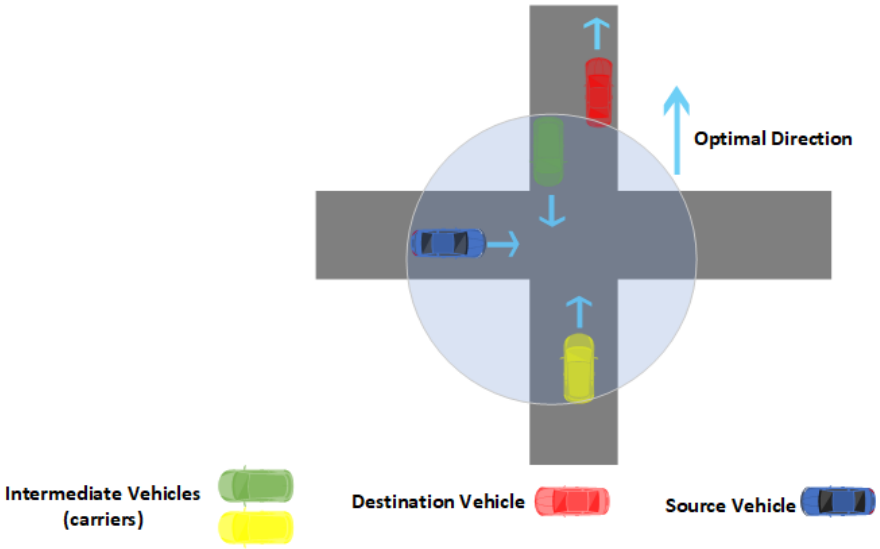


Figure F-7: Direction-based forwarding technique

The next principle is that the messages must be carried through multiple roads, where the highest-speed road will be selected. The final principle is a dynamic path selection, which should be implemented constantly through the packet forwarding process [203]. The VADD protocol is classified into the Location-VADD (L-

VADD), Direction-VADD (D-VADD), and Hybrid-VADD (H-VADD) protocols [201]. In L-VADD, the message will be sent to the closest vehicle to the destination, although the weakness of the protocol is the network loop issues. On the other hand, the D-VADD overcomes this loop problem, but the message delivery period is very high, thus degrading the network direction to choose the next hop. Finally, the H-VADD is proposed to overcome the disadvantages of both L-VADD and D-VADD by delivering the message without a loop and with less delay. The advantages of VADD are that the protocol has the desirable feature of multi-hop data delivery and a high delivery ratio. However, one major drawback of this approach is that VADD causes large delays due to traffic density and changes in topology. Moreover, with VADD the sparse network is neglected. It would therefore be useful if the spray network were taken into consideration.

To conclude, with all the VDTN routing protocols, the nodes may have to buffer messages for a long period of time, which may lead to congestion issues if the nodes have insufficient opportunities to forward all the buffered messages. To address this concern, the node needs to determine the messages that should be dropped when their buffer is out of capacity and to order the buffered messages at each forwarding opportunity. However, dropping messages randomly may cause failure in message delivery. In addition, the nodes/vehicles may have a short contact duration that prevents these nodes from exchanging all the messages. Hence, the nodes must determine which messages to forward first. Therefore, the nodes need to prioritize

their respective messages to be ready to transmit in a short time duration in order to maximize the important message delivery ratio. In summary, an efficient scheduling/dropping policy is necessary to determine the optimum messages to exchange. Therefore, in the next section, different buffer management techniques are considered.

3. Critical Analysis of Buffer Management Policies

As mentioned previously, the buffer management policies define which messages need to be forwarded when the encounter occurs, or which should be dropped if the buffer of a DTN node is full and a new message needs to be accommodated [174]. Existing buffer management policies are based on one or more parameters such as the message age, size, TTL, and replication count. There is no efficient approach available for prioritizing emergency messages. Therefore, in this section, various existing buffer management schemes are discussed. The traditional buffer management schemes for DTN such as LIFO, FIFO, Drop Oldest (DO), and Drop Randomly were considered in [204]. These policies rely on the order in which messages arrive or reside in the node's buffer. LIFO depends on the message's arrival time and selects the most recently arrived message to drop first. In contrast, the messages in the head of the queue are selected to be dropped first in FIFO, which is the most suitable policy when the contact duration is sufficient to transmit all messages. A short contact period, however, renders the FIFO strategy ineffective because it does not provide any mechanism to deliver or store high-priority

messages. Drop Randomly drops the messages of the node's buffer without considering any particular message attribute to select the message. These traditional schemes are simple and may perform better in infrequently connected networks [175]. However, these schemes may not be suitable for frequently disconnected (intermittently connected) networks. Therefore, these schemes perform poorly in the DTN environment. Furthermore, these traditional buffer management and other schemes such as DO and DY do not consider the priority of messages to transmit important messages over others [205]. Moreover, these policies depend on only a single metric to drop the message. A serious weakness in this argument, however, is that a fair selection of the message to drop cannot be given or achieved by a single metric. For example, the impact of various dropping and scheduling policies on the performance of the VDTN was studied in [32]. These policies were FIFO, Random, and Remaining Lifetime Descending Order (RL-DESC), which are evaluated on the Epidemic and Spray&Wait routing schemes. By employing the FIFO policy, the messages are stored in order based on the received message. Meanwhile, in random scheduling policies, the messages are sorted by random order. Finally, in the RL-DESC policy, the messages are considered by determining their remaining TTL [32]. As a result, the messages with the longest remaining TTL are scheduled to be broadcast first, since they have an increased probability of reaching their destination. On the other hand, the head-dropping policy first drops the message that has been stored in the node's buffer for the longest period of time, while with a

random drop policy, the messages are randomly selected and discarded from the node's buffer. However, the RL-ASC dropping policy is dependent upon TTL to drop the messages, whereby those messages with the smallest TTL will be selected to drop first. Nevertheless, the message may have a small TTL but a high delivery probability. In this case, RL-ASC drops the message despite its high delivery probability. **Figure F-8** shows the use of these scheduling policies to illustrate the mechanism of the three policies for VDTN. The obtained results achieved in [32] indicate that with the Epidemic routing protocol, FIFO provides better performance than the random and the remaining lifetime in terms of the message delivery ratio and message delivery delay, while in terms of the Spray&Wait routing protocol, the remaining lifetime provides the best results compared with the FIFO and random policies.

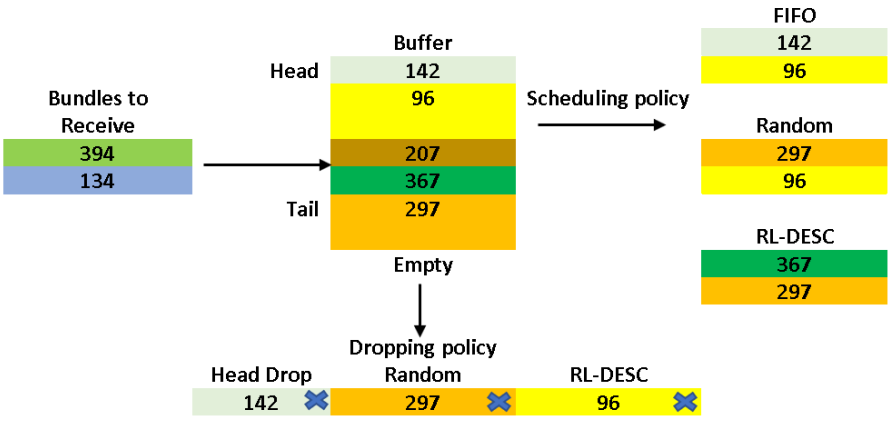


Figure F-8: Mechanisms of scheduling and dropping policies [32]

One of the limitations of this explanation is that all the messages were assumed to have the same size. But in fact, the messages may differ in size. It would have been more beneficial if the authors had taken into consideration the impact of variation in the message size with their buffer management policies. This is because the performance of message delivery and EED is influenced by the decision to drop one large message only or several small messages when congestion arises in the node's buffer. Furthermore, in the case of an emergency message, the message size should be considered an essential criterion since an emergency message may have a different size to a normal massage. Therefore, neglecting the size feature might negatively impact the performance of the buffer management policies.

Various scheduling and dropping policies were proposed in [30] to evaluate their impact on the Spray&Wait and Epidemic routing protocols. The combination of the scheduling and dropping policies was considered to measure the performance of the average delivery delay and the message delivery ratio. Drop Largest drops messages from the tail of the queue, Drop Front removes messages from the head and Drop randomly drops the messages from the node's buffer randomly. These traditional schemes are not complex and may perform better in infrequently connected networks [31]. These schemes may not be suitable for frequently disconnected networks (intermittently connected). Therefore, these schemes may perform poorly in the DTN environment. According to the results measured using the ONE Simulator, the integration of dropping and scheduling policies has good

performance in terms of both the delivery ratio and average delay. In addition, the lifetime DESC-lifetime-ASC policy that depends on the TTL only to schedule and drops the messages achieves the optimum results in terms of delivery rate and average delay compared with the other combination policies. Meanwhile, FIFO has the most inferior performance among these policies in both message delivery probability and message average delay, depending on the order of messages that arrives at the buffer in its scheduling and dropping of the messages.

In another work, Lindgren and Phanse [32] evaluated different buffer management policies: MOFO, DO, Most Favourable First, and Least Probable First. The MOFO policy drops the messages that are forwarded the most, the Most Favourable First policy drops the messages with the highest delivery probability, while the Least Probable First drops those messages that have the lowest delivery probability. The problem with the MOFO policy is that the MOFO message's lifetime is not considered in the dropping decision. Therefore, if a message has not been forwarded the most, it will not be dropped if the lifetime for delivery is insufficient. Burns, et al. [206] proposed a new scheme named Meets and Visit, which learns how frequently nodes meet and how these nodes often visit a certain region. Then, this information is utilized to rank the messages according to the probability of delivering them through a specific path. Nevertheless, many messages with the same destination may exit in a node's buffer. Hence, in this case, all of the messages

have the same priority to be forwarded, whereas their different TTL values can affect message delivery.

New buffer management was presented in [33], where the buffer management titled Message Drop Control Source Relay (MDC-SR) was employed to improve the MaxProp routing performance, especially in the case of small buffer size where MaxProp performs poorly. MDC-SR is buffer management whereby the source relay is utilized as the main mechanism. In addition, the MDC-SR employs Upper Bound (UB) as a threshold for the messages that a node will bring them. The UB value is employed with MDC-SR to accomplish efficient buffer management for the MaxProp routing protocol. The lower UB is calculated by dividing the buffer size by the probability of the largest message, while the division of buffer size by the potential of the smallest message is utilized to obtain the higher UB value. The performance of MDC-SR MaxProp was simulated and tested with the ONE simulator, where the results of MDC-SR MaxProp achieved a superior delivery probability than the original MaxProp with low buffer size and low density (5–20 nodes). Meanwhile, with a low buffer size and high nodes density (50), the MDC-SR MaxProp has a lower delivery probability than the original MaxProp due to the former's use of a small buffer size and UB setting that restricts the entry of messages and does not permit all message to enter the buffer. Furthermore, MDC-SR MaxProp improves the performance of the original MaxProp in terms of messages dropped and overhead ratio, although the latency average is higher than the

MaxProp [33]. Perhaps the most serious disadvantage of this method is that the MDC-SR still requires further improvements to decrease the average latency with lower UB, which is high due to the message waiting for a long period of time in the node's buffer before it is delivered to the destination. Moreover, the emergency or safety message was not taken into consideration [33] during the drop buffer management mechanism. This would be beneficial to consider, in order to avoid dropping an important message that could help to save lives.

Another dropping policy named MaxHopCount was proposed in ref. [34], which depends on the hop count, that is, how many nodes the message has passed through from the source node to the current node. The hop count metric is considered in the MaxHoupCount approach. Therefore, the message with the highest hop count is selected for dropping in order to avoid the buffer overflow problem. This will not impact the delivery ratio, because these highest-hop-count messages are widely replicated in the network. The performance of MaxHoupCount was evaluated using the ONE simulator, which achieved a superior delivery ratio than the other six dropping policies: FIFO, LIFO, DL, DY, SHLI, and MOFO. Furthermore, the overhead ratio with MaxHoupCount keeps decreasing while the TTL value is high, which is the opposite result of the other dropping policies that cause an increase in the overhead ratio when the TTL increases. However, other criteria and drop policy should be considered to avoid the issue when two messages have the same number of hops. Moreover, only the dropping policy was considered while the scheduling

policy was neglected, which could be problematic in cases where there is an emergency message, and during the short contact time, it is not scheduled to transmit first to avoid delay.

In [24] presented a new buffer management scheme to schedule and drop the messages from the node's buffer. This scheduling for message transfer and message drop is handled by the logical partitioning of the buffer based on the threshold of the hop count value. There are two cases: (i) if the hop counts are lower than the threshold, the messages will be stored according to their hop count to be transmitted first; and (ii) if the hop count is higher than the threshold, the messages will be stored according to their TTL value to be dropped first. However, in order to transmit the message, the one with the lowest hop count will be selected to transmit first. When dropping the message, the one that has lower TTL and hops count will be dropped first. The proposed buffer management was analyzed in [24] on the performance of the Epidemic routing protocol to evaluate the performance by applying various drop policies, where buffer various management schemes were compared. It is worth mentioning that ref. [24] claimed that the combination between forwarding strategy and queuing can significantly impact the DTN routing protocol, whereby the proper combination will enhance the performance.

[35] presented another buffer management policy for DTN. The effectiveness of the packet in the node's buffer was estimated using this method by evaluating how well it could reach the target node. In this approach, each packet in the network is given

a weight W_i. To ensure this buffer management is acceptable for both spray and density networks, two sections are considered for weighing the message. The first section considers the possibility that the packet will arrive at its destination directly, with the weight in the first part calculated via **equation (F-2)**:

$$Wd_i = 1 - e^{-\lambda T} \quad \text{(F-2)}$$

Where T is the message's remaining TTL and λ is the parameter linked with the inter-contact time between the nodes, which is exponentially distributed. The second section considers the possibility that the messages were relayed to intermediate nodes prior to reaching their final destination. Therefore, the weight is calculated using the information regarding how many copies of these messages were transmitted to the network by recording the number of copies of a packet through **equation (F-3)**. Every node keeps track of the number of copies i it has created as NC_i, and the total copy number of messages I as TC_i. Every node updates its TC_i using the encountered node's NC_i during an encounter opportunity.

$$Wi_i = \frac{NC_i - TC_i}{NC_i} \quad \text{(F-3)}$$

Lastly, **equation (F-4)** is employed to calculate the total weight for message i:

$$Wi = \propto Wd_i + \beta W_i \quad \text{(F-4)}$$

Thus, when the buffer is congested, the packet with the lowest W_i is the first to be dropped. Another work regarding drop/forward policies was proposed by Naves, *et al*. [207] exploring the Less Probable Spray (LPS) and Least Recent Forward (LRF)

policies that depend on local knowledge for forwarding and dropping a decision. For the dropping, the number of replicas and the delivery probability was considered. With LPS, the messages with the lowest delivery probability will only be dropped if the message has been disseminated in the minimum number of replicas. On the other hand, the LRF forwards a message that has not been forwarded over a certain period of time. However, the issue with the MOFO policy is that it disregards a message's lifetime, which means that a message that has not been forwarded the most will not be dropped if its lifetime is insufficient for delivery.

Various studies have depended on the size of the messages to investigate different buffer management policies for DTN. For example, the policies presented in [36-38] only depend on the message size metric for taking drop decisions when the buffer overflows. First, in [36] proposed the T-drop policy to prevent the buffer congestion issue by dropping the packet that is located within the predefined threshold range of the buffer, with the policy also depending on the size of messages during congestion. [37] focused on the message size, where an Equal drop (E-drop) policy is introduced to drop a packet that has the same size as an incoming packet size when the node's buffer is full. The benefit of the E-drop policy is that it enables the conservation of space by dropping multiple small messages to create room for a newly arriving packet. This is because when a smaller packet is dropped to make room for a new incoming packet, a lot of messages must also be dropped if the

space is insufficient to save the new incoming message. In [39], the mean drop policy was proposed, whereby the mean of the size of the messages in the congested node is calculated and then only those messages that have a size greater than or equal to the mean will be dropped.

In ref.[38] proposed another buffer management policy based on the message size metric, namely, the DL policy [38] that drops the message with the largest size when its buffer overflows, rather than dropping many small-sized messages. Another buffer management strategy specific to Epidemic routing was proposed by In [47], with the main aim of the proposed buffer management strategy to design an efficient dropping policy to prevent buffer congestion. In this policy, the number of times a message has been forwarded since its creation is tracked by every node in the network. Furthermore, every node calculates the threshold N as a function of its buffer size, whereby when the buffer size increases, so does the threshold N. When the buffer is full, every node begins to check the number of forwarding instances of each packet in the buffer. If all the messages in the buffer have a value less than N, then the packet at the tail of the buffer will be dropped. The N-drop policy outperformed the DL policy, where the messages at the tail of the buffer are dropped if buffer congestion occurs. However, the N-drop strategy degrades to DL when all the messages have their forward count less than N. Moreover, the blind forwarding of the Epidemic-based protocol is not controlled [47]. However, a single

metric can cause a huge drop in small-size messages to accommodate one large-size message.

In ref. [41] utilized the dedicated Message Ferry for DTN buffer management, where the dedicated node was named Message Ferry. The mechanism is that the Message Ferry will visit and collect the messages from the other nodes to deliver them to the destination node. Since the ferries' buffer is limited, the buffer management method is applied. This method is based on a max–min fairness model that allows the Message Ferry to accept information from the different source nodes and keeps a message in the buffer only if it has maximized the minimum data rate of any of the nodes [41]. Besides the buffer management method, the buffer effective routing method was proposed with a fair buffer allocation when the path chosen is based on the ferry transportation cost and route delay.

In ref. [19] proposed an Enhanced Buffer Management Policy (EBMP) to minimize the average delay and enhance the message delivery in DTN. The EBMP utilizes various message properties such as the message age, remaining TTL, and the number of replicas to calculate two utility functions of each message based on **equations (F-5)** and **(F-6)**:

$$EBMP_i^{delivery} = \frac{1}{ETR_i} + \frac{1}{\log(AGE_i)} \quad \text{(F-5)}$$

Where AGE_i is the age of message i, and $ETR_i$is the estimated total number of replicas of message i. To calculate the age of the message, the message creation

time is subtracted from the current time. While the $EBMP_i^{delay}$ can be determined by Kim, *et al.* [19]:

$$EBMP_i^{delay} = \frac{1}{ETR_i} + \log\left(RTTL_i\right) \quad \text{(F-6)}$$

Where $RTTL_i$ is the remaining TTL of the message i, and the log is employed to limit the impact on the utility value since the age and the remaining TTL are much larger than the replicant count. Every node employs these two equations to compute the utility value of every message in its buffer. The utility function (1)'s buffer management tends to remove those messages that have been copied several times, while the utility function (2)'s buffer management prefers to delete the oldest message (i.e. that with the shortest remaining TTL). These utility functions can help the EBMP to select the most suitable message to drop whenever the buffer is occupied. Therefore, the message with the smallest utility value will be deleted first when the buffer overflows. The EBMP provides better performance than traditional policies such as the History-Based Drop (HBD) [42], MOFO, and SHLI [43] in terms of message delivery and average delay. Nevertheless, the EBMP was only combined with the Epidemic algorithm, and thus it would interesting if the author in ref. [43] had combined the EBMP with another routing algorithm and implemented it in a real situation.

Balasubramanian, *et al*. [20] proposed a Rapid protocol that considers the bandwidth and buffers constraints. Rapid protocol assigns utility to all messages to

measure their expected contribution in maximizing a metric such as delay. Messages with the largest utility increases are replicated. However, in order to use messages, replica information must be spread widely throughout the network, which leads to high overhead and when the propagated information reaches nodes it may be obsolete. Rapid's second drawback is that it requires more bandwidth as traffic volume increases. Furthermore, Li, *et al.* [208] introduced a drop strategy that utilizes the control channel to assist vehicles in obtaining global network information such as the node meeting time and duration, and the transmission opportunities of messages. Nevertheless, this policy does not address the forwarding issue. Krifa. *et al*, [174] proposed a distributed algorithm that approximately calculates the number of replicas and nodes that have seen the message I since its formation. The estimated task depends on the number of buffered messages created prior to message i. As a result, the distributed method becomes dependent on the rate at which earlier messages are disseminated. However, the limitation of this study is that the change in topology was not considered, which may result in unreliable information, particularly in the case of newly created messages.

None of the above-mentioned studies considered the importance of the messages in the drop/forwarding decision. On the other hand, some investigations focused on the priority of scheduling and dropping the buffered messages; for example, the Priority Queue-Based Reactive (PQB-R) buffer management policy was proposed

in [40], which is a new policy that classifies the buffered messages into three queues of source, relay, and destination, as shown in **Figure F-9**. Moreover, through using the PQB-R buffer management policy, different drop metrics were applied to individual queues such as R-QDM, R-QRM, and R-QSM. Three methods were utilized to drop the messages from the queue in the node's buffer: in the first queue, R-QDM was employed for holding messages that are delivered to the destination and assigning the Time-To-Dead value for these messages, with a high drop priority given to messages with a minimum remaining value; in the second queue, R-QRM was used for holding the relay messages and the drop priority was computed via various parameters such as the message size, hop count, TTL, and the aggregation redundancy count; and in the third queue, R-QSM was employed to hold the source messages, with the drop priority dropped for those messages that remain in the node's buffer without achieving a transmission opportunity. In summary, the PQB-R buffer management policy was simulated with the ONE Simulator, and the results compared with other existing buffer management policies, showed that the PQB-R gave a superior performance in different performance metrics.

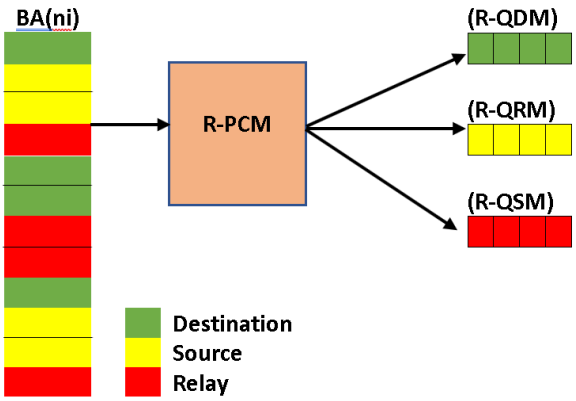


Figure F-9: Logical partition of queue priority computation module

Another buffer management policy is a routing scheme that estimates the remaining lifetime of the packet and delivery time while scheduling the messages based on their priority [44]. The message priority is classified according to various events into three categories: accidents, weather conditions, and traffic congestion. The highest priority is assigned for an emergency message, followed by a congestion message as a moderated priority, and finally, a general event is considered a low-priority message. To implement this algorithm, first, all the mobile nodes should have GPS to provide the vehicle's geographical information at any time. Second, the messages are created by the mobile or source node in response to the event. Setting the type of packet and providing the packet priorities initializes the algorithm. Third, when two nodes encounter, each node arranges its stored messages according to the packet priorities. The remaining lifetime and expected time for delivering these messages to the destination should then be checked prior to forwarding them. Fourth, the highest-priority messages are forwarded via the

controlled flooding approach. Medium- and low-priority messages, on the other hand, are forwarded with a limited number of copies based on a threshold value. Finally, when the buffer is full, this algorithm starts to drop messages based on their remaining lifetime and priority in ascending order. Although this algorithm achieved a superior delivery ratio compared with other DTN routing protocols such as Epidemic, PROPHET, and GeoSpray, the delivery latency was higher than the other approaches. Perhaps the most serious disadvantage of this approach is that the emergency messages are not removed from the buffer, even after the message has reached the destination node. Therefore, it would be useful to focus on an acknowledgement mechanism that would allow the removal of the residual emergency messages once they have been delivered to the destination to avoid any delays incurred by new emergency messages.

Fathima, *et al*. [209] proposed to classify messages based on three priorities: high, medium, and low. Then, when the node's buffer is congested, the messages with low priority will be dropped first, followed by the medium-priority messages. Furthermore, the TTL value of messages is considered during the dropping decision.

In ref. [45] investigated three different scheduling and drop policies that can be utilized to implement traffic differentiation: Priority Greedy (PG), Round Robin (RR), and Time Threshold (TT). This approach utilizes an indexing system to index incoming messages based on their priority class. The transmission priority is

specified to the highest priority classes. Thereby, in cases of buffer overflow, the lower priority (bulk) message is discarded first. Hence, this indexing system can be utilized by various scheduling policies to determine the outgoing message order. Meanwhile, the first PG scheduling policy accurately complied with the priority class sequence from high priority (expedited) to low priority (bulk) presented in [45]. Therefore, when contact occurs between nodes, the class messages with higher priority are always scheduled ahead of the class messages with low priority. Hence, the high-priority messages have the ability to exploit the network resources while the lower-priority message can be delayed. The second scheduling policy was RR, which served the priority classes equally. The policy is employed to ensure all priority classes have an equal opportunity to dispatch their messages by scanning the priority class indices in circular order and then serving one message from each class. The third scheduling policy was TT, which depends on the double criteria of the priority class of each message and their remaining TTL to order the messages to be forwarded at a contact opportunity by following the priority class sequence from high to low. However, at each priority class, only those messages with a remaining TTL greater than the predefined threshold will be selected. Then, the remainder of the messages will be scheduled to be sent later. Finally, evaluation of the effect and comparison of the performance of the three policies were carried out by using ONE simulator with different scenarios. The results were compared only in terms of delivery probability, and thus it would be helpful if the authors utilized

more performance metrics such as overhead or delivery delay in order to evaluate their investigation. Moreover, due to the TT algorithm giving absolute priority to messages with higher TTL remaining, the scheduling policy may not take into account the importance of sorting the indices of the priority classes. Therefore, further investigations are still required to minimize the delivery delay and maximize the delivery probability ratio.

To enable traffic differentiation at the message layer, network traffic must first be classified and marked via a method that establishes the traffic priority classes. Additionally, all network nodes are required to follow the buffer management and scheduling regulations, as well as the drop policies. [25] reported two different buffer approaches, as shown in **Figure F-10** and **Figure F-11**. In **Figure F-10**, the buffer management shows that all the messages share the same buffer space, with the drop policy selecting lower-priority messages to be dropped first in the case of buffer congestion.

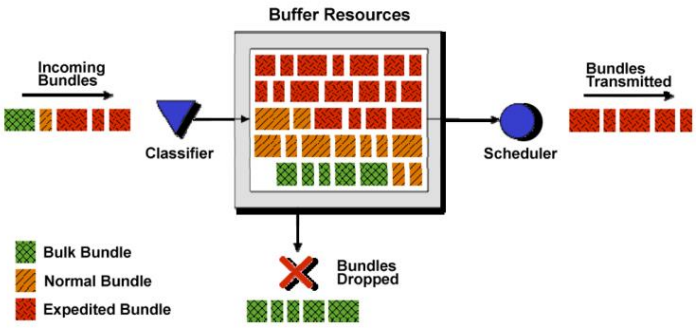


Figure F-10: All the priority classes share the buffer

Meanwhile, **Figure F-11** shows the other buffer management strategy, which proposes creating a distinct queue for each priority class. The drop policy only removes messages from the queue if a buffer congestion issue exists. The benefit of this approach is ensuring that network nodes can always store and carry messages of all priority classes, regardless of the storage restrictions.

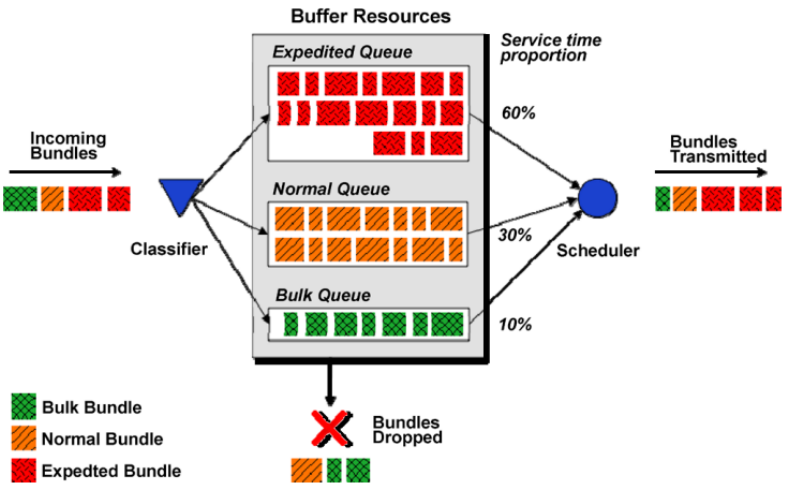


Figure F-11: Each priority class is separated into a specific queue

In addition, two other scheduling strategies: PG and Customs Service Time (CST), were applied. With the PG scheduling policy shown in **Figure F-10**, class messages with a higher priority are always scheduled ahead of those with lower priorities. Meanwhile, the CST scheduling policy assigns service time percentages to each of the priority classes, as shown in **Figure F-11**. The ONE simulator was employed to evaluate and compare the performance of the PG and CST under the ONE simulator by utilizing different node densities. However, since only the Spray&Wait routing

protocol was considered, it would be useful to consider the other DTN routing protocols and compare the results.

A novel buffer management policy for DTN routing protocols named Novel Weight-Based Buffer Management Policy (NWBBMP) was proposed in ref. [46], with a priority message queue, high-weight message queue, and low-weight message queue representing the three main queues that comprise the policy. The priority queue contains all the newest messages that are not allowed to be discarded when buffer overflow occurs. NWBBMP never deletes any messages from the priority queue when a node receives a new message and causes a buffer overflow; instead, it chooses which queue's messages (high weight or low weight) should be destroyed depending on whether the current node is the destination node of the new message. The message in the high-weight message queue is the only one to be deleted if the nodes with overflow are not the new message's destination node. However, if the node is the destination node, NWBBMP begins to discard the high-weight queue's messages. If there is still insufficient buffer space to hold incoming messages, discarding of the low-weight queue commences. According to the results, NWBBMP overcomes the traditional buffer management policies such as DY, DL, and DO in terms of delivery ratio and network overhead.

According to the literature review, the FIFO policy is the most suitable if the contact duration is sufficient to transmit all messages. In contrast, FIFO fails with limited contact duration because the policy does not provide any mechanism for the

preferential delivery of storing high-priority messages. Furthermore, traditional buffer managements such as FIFO, LIFO, DO, and DY do not consider the priority in order to prioritize the transmission of important messages over others. In addition, the MOFO policy does not consider the message's lifetime in the drop decision, which causes a problem whereby those messages with insufficient lifetime for delivery will not be dropped if the message has not been forwarded the most frequently [114]. On the other hand, various buffer management policies have ignored the influence of scheduling regulations, while buffer management is dependent on the type of message being broadcast. Moreover, no efficient policy was found in terms of the priority buffer management approach and thus a gap remains to be addressed.

To conclude, it can be observed from the literature review that a gap exists in the domain of buffer management in DTN routing protocols in terms of considering emergency messages in specific road traffic accident scenarios as the most important message that should be delivered on time by scheduling it with a higher priority. Moreover, when the mobile nodes increase, the overall overhead ratio also increases because more messages will be transferred in comparison to the delivered messages. Additionally, the delivery latency increases because the increase of nodes in the network consumes considerable time in processing information at each node.

4. Conclusion

APPENDICES

The Vehicular Delay Tolerant Network (VDTN) is one of the results of the current Vehicular Ad-hoc Network (VANET) research. Messages are sent through the network by nodes utilizing a Store-Carry-Forward technique in this mobile Delay Tolerant Network (DTN) application. Due to its high mobility, it frequently disconnects and is congested at the nodes, which causes message loss. Therefore, to increase the network's efficiency, an extensive survey and taxonomy of VDTN and buffer management policies are provided in this paper. This helps us to better understand the full scope of the DTN while contributing towards the achievement of further improvements and increasing the network's efficiency. In the future, a Priority scheduling and dropping Policy will be proposed to schedule the messages pending in the node's buffer that can help to transmit warning messages at an appropriate time. Furthermore, this study focuses on the techniques that will allow the removal of emergency messages once they have been successfully delivered.