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Packet Delivery Delay and Throughput Optimization for Vehicular Networks

by

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A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Computer Science and Engineering in the School of Computing Sciences and Informatics of the College of Engineering of the UNIVERSITY OF CINCINNATI, OHIO

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Abstract

Vehicular networking is a new emerging wireless technology concept that supports communication amongst various nearby vehicles themselves and enables vehicles to have access to the Internet. This networking technology provides vehicles with endless possibilities of applications, including safety, convenience, and entertainment. Examples for these applications are safety messaging exchange, real-time traffic information sharing, route condition updates, besides a general purpose Internet access. The goal of vehicular networks is to provide an efficient, safe, and convenient environment for vehicles on the road.

In vehicular networking technology, vehicles connect either through other vehicles in an ad hoc multi-hop fashion or through road side units (infrastructure) which connects them to the Internet. These approaches have their own advantages and disadvantages. However, one of the main objectives of vehicular networking is to achieve a minimal delay for message delivery, and encourage potential continuous connectivity among vehicles.

This dissertation introduces a novel hybrid communication paradigm for achieving seamless connectivity as Vehicular Ad Hoc NETworks (VANETs), wherein connectivity is often affected by changes in vehicles’ speed, dynamic topology, as well as traffic density. Our proposed technique —named QoS-oriented Hybrid Vehicular Communications Protocol (QoSHVCP)— exploits both existing network infrastructure through a Vehicle-to-Infrastructure (V2I) protocol, as well as a traditional Vehicle-to-Vehicle (V2V), that satisfies Quality-of-Service requirements. We analyze time delay as a performance metric, and determine delay propagation rates when vehicles are tran-
mitting high priority messages via QoSHVCP.

Focusing on V2V communication, we propose a reliable and low-collision packet-forwarding scheme, based on a novel concept of probabilistic rebroadcasting. Our proposed scheme, called Collision-Aware REliable FORwarding (CAREFOR), works in a distributed fashion where each vehicle receiving a packet rebroadcasts based on a predefined probability. The success of rebroadcast is determined based on allowing the message to travel the furthest possible distance with the least amount of packet collisions.

We also present a QoS-Aware node Selection Algorithm (QASA) for VANET routing protocols. Our algorithm is focused on selecting the vehicle to forward the message, where vehicles on the east (west) select from the west (east), and is achieved by exploiting a useful notion of the bridging approach. The QoS metrics that are being optimized include the throughput in the network and end-to-end delay for the packets.

Finally, we exploit the use of autonomous vehicles in order to optimize the end-to-end packet delivery delay. Our protocol introduces a dynamic metric that depends on the vehicular density on the highway in order to control the inter-vehicle distance.

Our results show a great promise for their future use in the area of vehicular technology.
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Chapter 1

Introduction

The concept of vehicular technology has emerged due to advancements in wireless sensor networks as well as ad hoc networks. The progress in these fields has allowed sensors placed at different location within the vehicles to communicate with each other wirelessly. Ad hoc networks technology has allowed vehicles to communicate with other vehicles in its surrounding area. The combination of sensing and communication enables the vehicles to respond to different request and provide many useful services. For example, the vehicle brakes can respond when the vehicle senses that there is a vehicle at a very close proximity or that the conditions of the road cannot sustain the vehicle speed. Another example would be for the air bags and pre-tension safety belts to be activated when detecting a potential for an accident. Traffic conditions on the road ahead can be communicated to the vehicles and provide an alternative route that could shorten the length and duration of a trip. Internet can be accessible to the vehicle occupants through the communication ability of well-placed road side units. The Internet access can either be used for safety, or can be utilized for entertainment purpose such as streaming movies or browsing the Internet.
Figure 1.1 depicts different services that can be provided to the vehicle through the vehicular network technology.

![Diagram of vehicular network technology](image)

Figure 1.1: Figure depicting applications available to vehicle through the vehicular network technology

1.1 Scope of Applications

Vehicles have started playing an important role in peoples lives, and hence, enhancing them with software and hardware based intelligence would drastically improve the passengers quality of life and experience [5]. To elaborate on the importance of vehicular networks, it is worth mentioning that more than half of the accidents each year
in the US result from the drivers’ factors [1]. Figure 1.2 depicts the breakdown of the reasons that caused accidents in 1985 in both United States and Britain. Texas Transportation Institute also estimated that in 2000, “the 75 largest metropolitan areas experienced 3.6 billion vehicle-hours of delay, resulting in 5.7 billion U.S. gallons (21.6 billion liters) in wasted fuel and 67.5 billion dollars in lost productivity, or about 0.7 percent of the nation’s GDP” [6]. VANETs have the potential to provide solutions and answers to many of these problems.

![Figure 1.2: Breakdown of American and British Traffic Causes in 1985](image)

However, new technologies typically require applications that can benefit from them in order to be commercially deployed. Vehicular networks are no different, and since the development of the vehicular networks, the main emphasis has been to increase the traffic safety [7]. With increasing traffic safety, the number of accidents will decrease, and the number of lives affected and financial cost of accidents would be minimized. Under the umbrella of traffic safety, two main categories of applications have been the focus in the past few years: public safety, and vehicular traffic
coordination. An example for public safety applications would be collision avoidance, while others that allow coordination of vehicles movement with each other would be an example for vehicular traffic coordination [7].

Considerable work has also been done to introduce and address usefulness that relate to road traffic management, as well as those that are for added comfort. Road traffic management purpose helps resolve issues such as traffic congestion. This decreases the number of accidents during such congestions as well as aids in decreasing the travel time. On the other hand, comfort applications provide entertainment and relaxing experience to the drivers (viz., information from road-side units) and to the accompanying passengers (such as Internet access or video-on-demand).

Vehicular networks are still in the phase of research, and hence, they are not yet to be widely deployed. Many specific utilizations that are being considered in this field are speculative and can be challenged [8]. Different initiatives lead to distinct set of applications as their primary focus. However, there are three main categories for use of vehicular network technologies:

1. Vehicle safety related applications: These focus on the safety of vehicles and passengers. Collision avoidance are considered one of the most important applications in this category.

2. Traffic conditions: These are aimed at improving the traveling experience by helping the vehicle avoid traffic congested area or by providing useful traffic information that helps in selecting an effective routing.

3. Comfort applications: The goal is to provide comfort to the driver and the vehicle passengers. This can be achieved through applications that allow the user to communicate with the Internet, or allows for video streaming or mobile
office applications.

1.1.1 Application Requirements

Each one of the three application categories has different requirements based on the importance and required Quality of Service (QoS). The main goal of safety applications is to provide a safe environment for the occupants of the vehicle, the neighboring vehicles, the pedestrians, and the environment. This is usually achieved through creating a connectivity mechanism between the neighboring vehicles that ensures safety by avoiding any collision. In these types of endeavours, end-to-end message propagation delay ought to be minimized. Messages that can not achieve this delay requirement are discarded because of their irrelevance.

Traffic and congestion control applications aim to minimize the trip duration and avoid congested areas on the highway or on the roadway. The data for such applications are gathered from different vehicles throughout the area of interest. This data is not safety-sensitive; hence, the delay requirement can be slightly relaxed than the data in the safety applications.

Finally, the internet and multimedia applications are those that allow the vehicle occupants to have access to different context for the purpose of information and entertainment. These applications require access to the infrastructure that can connect them to the Internet. One of the main problems with this approach is the connectivity between the infrastructure and the vehicles, i.e., the last mile problem.

Moreover, some of the underlying applications require only one hop communication (i.e., each vehicle needs to relay the information to the next hop only). However, other applications require multi-hop communication (i.e., the information needs to be relayed from the source in multiple hops). An example could be changing lane for
collision avoidance. In a lane changing step, each vehicle needs to inform only the nearby vehicles merging from another lane and those are within its communication range. However, for the collision avoidance applications, one of the worst accident categories on the highway is that involves many vehicles rear-ending each other due to significant reduction in speed of the first vehicle. In this case, if the first vehicle could notify all multi-hop vehicles behind it of the sudden reduction in its speed, this could help avoid the sequence of any potential read-ending crash.

1.2 Vehicular Networking Technology

A vehicular network is composed of two main components: sensing and communication. The sensor part has the capability of understanding the environment, the vehicles, and the occupants of the vehicles. On the other hand, the communication entity has the facility of relying this understanding to other vehicles or to infrastructure on the side of the road (road side units).

The nature of vehicular networks is different than any other previously existing wireless network due to the nature of the nodes that form the network. The difference is that the current communication technologies are not applicable to a vehicular environment. Hence, new strategies are being introduced such as Wireless Access for Vehicular Environment (WAVE) and Dedicated Short-Range Communication (DSRC). These technologies are discussed in more detail in Chapter 2.

1.3 Vehicular Networking Initiatives

Due to the importance of the vehicular network and the potential impact of its applications, many initiatives and projects have been undertaken all around the world
by the Government and the private sector. In the US, the Department of Transport (USDOT) has introduced the IntelliDrive, which aims to leverage the communication and sensing capabilities of vehicles in providing a safe and smart road transportation service \[9\]. In Japan, a similar project has been introduced, namely Smartway, where the goal is to expand on existing usefulness and introduce innovative ones, such as navigation, safety, electronic automated toll payment, vehicle diagnostics, and others.

Other projects have been established such as E-ENOVA, Car-2-Car, PREVENT, PATH, WATCH-OVER \[10–14\]. These projects cover diverse topics such as pedestrian security, intersection safety, and development of hardware specific infrastructure targeted for risk-free vehicular network applications.

### 1.4 Problem Specification

Vehicular networks have emerged as a new paradigm that share some similarities but differ greatly with other existing wireless networks. One of the main networks that resemble the vehicular is the ad hoc networks. However, one of the fundamental difference is the very high mobility of the vehicles. In the following subsections, we will discuss different scenarios and the network connectivity for a vehicular network environment.

#### 1.4.1 Vehicular Networking Scenarios

A vehicular network scenario is constrained by real-life models with traveling vehicles on the roads and on the highways. These models are partitioned into either: highway model, or city model. In the highway model, vehicles travel in a near straight path with an almost constant speed which can best be characterized by the freeway
model [15]. Vehicles are highly mobile in this model with their average speed varying between 45 mph to 80 mph.

In the city or urban model, the movement represents vehicles within the city and can be best represented by a Manhattan city model [15]. The vehicle speed in the model average between 20 mph to 45 mph.

In both these models, the vehicles movements are constrained by the roadways and highways. These constraints are available through the map system such as GPS. Figures 1.3 and 1.4 represent the highway and the city model for vehicular networks respectively.

Figure 1.3: Highway model of a vehicular network

Figure 1.4: City model of a vehicular network
1.4.2 Network Connectivity

Current communication systems such as WiFi, Bluetooth, and cellular networks cannot support the necessities of a vehicular network primarily due to the associated high latency. The vehicular networks demand least possible latency to respond to very high mobility of the components.

Currently, there are communication technologies under development that could be catered to the vehicular networks. One main technology is the Dedicated Short Range Communication (DSRC) which is based on the 802.11 IEEE protocol [16]. Due to highly mobile nature of vehicles, chances of communication is very limited because of their mobility, vehicles remain in each others’ communication range for a very short duration of time. The advantage of DSRC is the connectivity it provides connectivity with a very low latency, which is adequate for the vehicles to communicate, even in such an environment.

1.5 Contributions

In this dissertation, we have made several important contributions that affect packet delay and improve the throughput in vehicular networks. The main contributions are:

1. We introduce a hybrid approach of vehicular communication that has been facilitated by utilizing both Vehicle-to-Vehicle (V2V) communication as well as Vehicle-to-Infrastructure (V2I). We present an effective mechanism for such a hybrid approach. An appropriate load balancing scheme has also been described an infrastructure overload might occur.

2. We analyze delay in delivery of messages within a vehicular network environ-
ment on a highway. We have attempted to present a fairly complex model for this delay in terms of many factors that affect and influence this delay. Initially, we present an analytical model that incorporates different connectivity phases of the vehicle communication during a typical trip on the highway. This leads to a realistic approach that resembles real-life connectivity among the vehicles. Our goal is to utilize this analytical model so that the vehicles can make real-time decisions for routing of its messages on the highway.

3. We simulate QoSHVCP protocol in a VANET scenario, and demonstrate the relationship between message delivery delay and the vehicular density on the highway. We also present the effect of an infrastructure overload on the message delivery delay, as well as discuss ways of improvements by incorporating a load balancing mechanism.

4. We introduce probabilistic routing protocol (CAREFOR) that judiciously combines multi-hop retransmission forecast with collision-aware constraints so that the end-to-end packet delivery delay for V2V communications can be optimized in vehicular networks. We present an analytical model for the rebroadcast probability, as well as simulation results showing better values from our protocol as compared with other existing approaches.

5. In order to address the optimal vehicle selection in the bridging approach (V2B), we present the QASA algorithm that improves the throughput of the VANET and optimizes the packet delivery delay with the focus on V2B communication (vehicles on the east lane of the highway communicating with vehicles on the west lane, and vice-versa). We present an analytical model as well as simulation results to demonstrate the effectiveness of our approach.
6. We utilize autonomous vehicles in order to improve end-to-end packet delivery delay and vehicle trip duration. By controlling the speed of the autonomous vehicles, we can manipulate the distribution of vehicles on the highway. Simulation results are presented to demonstrate the improvements by our protocol.

Table 1.1 summarizes the different aspects of our research. Briefly speaking, the scope of this research is to analyze and present a sophisticated model for message propagation delay in a VANET and introduce new approaches (overload balancing mechanism, routing mechanism, handoff criterion, etc.) in order to reduce this delay, as well as improve other QoS metrics.

Table 1.1: Specific Research Contributions.

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<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid Communication Protocol for vehicles on the highway and overload balancing mechanism &amp; Chapter 3</td>
<td>Chapter 3</td>
</tr>
<tr>
<td>An analytical model that accounts for different connectivity phases for the vehicle on the highway &amp; Chapter 3</td>
<td>Chapter 3</td>
</tr>
<tr>
<td>Simulation to compare the performance of the hybrid approach versus V2V model and to evaluate load balancing mechanism &amp; Chapter 3</td>
<td>Chapter 3</td>
</tr>
<tr>
<td>CAREFOR algorithm with probabilistic routing in VANET &amp; Chapter 4</td>
<td>Chapter 4</td>
</tr>
<tr>
<td>QASA algorithm for vehicle selection in V2B approach &amp; Chapter 5</td>
<td>Chapter 5</td>
</tr>
<tr>
<td>Utilizing autonomous vehicles in end-to-end packet delivery optimization &amp; Chapter 6</td>
<td>Chapter 6</td>
</tr>
<tr>
<td>Summary and Future work &amp; Chapter 7</td>
<td></td>
</tr>
</tbody>
</table>
1.6 Research Scenario

The research presented in this dissertation addresses the message delivery delay in a highway scenario, where vehicles transmit their messages from the beginning of the highway, and the messages propagate forward till they reach the end of the highway. Note that the results presented in this research can be generalized for messages propagating forward or backward on the highway. Since highways are composed of two direction lanes moving in opposite direction, messages propagating forward for one direction is considered propagating backward for the opposite direction. The focus of this research is to calculate the message delivery delay and provide solutions for minimizing this delay. However, this delay needs to be clearly expressed in terms of what are the factors behind this, and then, present appropriate approaches that could effectively address it. This requires us to look into an analytical model that helps us identify different components contributing to such a delay. Later on, this model can be used as a real-time metric that could let the vehicles decide the route to be taken in propagating the message throughout the highway. Following that, we focus on developing different effective routing protocols, and potential approaches for reducing this delay.

A typical scenario used in this dissertation is a highway in a rural area, covered by Wireless LAN units at different locations of the highway (i.e., Wireless LAN units from the restaurants, homes on the side of the highway). However, most of these Wireless LAN services may not be connected to the Internet or to a satellite system. As it is a delay tolerant application, the messages and the data can permit some delays in message delivery. In order for vehicles and Wireless LAN networks to be connected to the Internet, they have to transmit their messages to a cellular network located along the highway.


1.7 Dissertation Outline

The remainder of this dissertation is organized as follows:

- Chapter 2 presents different aspects of the vehicular network. It covers the concept of Intelligent Transportation Systems (ITS) and the vision for the vehicular networks in the future. The difference between a VANET and a cellular network as well as a MANET is presented. Inter-dependency between the architecture, communication systems, applications are also discussed.

- Chapter 3 introduces the QoSHVCP, discusses related work in the vehicular network research and delay tolerant networks. It also describes the effect of overload on the infrastructure network, presents a theoretical model for the rate of message delivery time, and performance results for simulation of different communication models.

- Chapter 4 presents the CAREFOR algorithm and the analytical probabilistic rebroadcast model that attempts to minimize the number of packet collisions in the network, as well as optimize end-to-end packet delivery delay. Simulation results demonstrate the effectiveness of CAREFOR.

- Chapter 5 presents the QASA protocol that focuses on vehicle selection in V2B approach with an objective to optimize throughput between the vehicles, and minimize end-to-end packet delivery delay.

- Chapter 6 introduces utilization of autonomous vehicles in optimizing end-to-end packet delivery delay and the vehicle trip duration on the highway. Simulation results indicate the effectiveness of our approach.
• Chapter 7 concludes the dissertation with a summary of the contributions and ideas for future research.
Chapter 2

Vehicular Networking

In this Chapter, we introduce different technologies that are used within the scope of vehicular networks. The chapter starts with a brief introduction of the concept of Intelligent Transportation System (ITS). Following that, we present characteristics of a VANET, and difference between a VANET, a cellular network, and a MANET. We also discuss different aspects and technologies that form a real life vehicular network. Finally, potential applications and current initiatives for the vehicle networks are covered.

2.1 Intelligent Transportation System

Information and communication technology applicable to vehicles and transport infrastructure are referred to as Intelligent Transportation System [17]. Tools encompassed in ITS include: concepts of traffic engineering, software, hardware, and telecommunication technologies. These tools are integrated together in order to provide services that improve the efficiency and safety of transportation services and vehicles. These services include: traffic management, commercial vehicle operations,
transit management, and information access to travelers. ITS applications have the potential to provide solutions for many problems caused by vehicles and transportation systems. For example, ITS can improve the traffic flows by avoiding and reducing the congestion of traffic. It can help enhance the air quality by reducing the pollution created by the exhaust system by simply minimizing the traffic delay. The overall safety of the vehicle, operator, and the environment can be improved by utilizing an advance warning system that can be activated in case of a crash, or by minimizing the environmental, road, or highway effects that cause a crash. Economic efficiencies can also be achieved through ITS by reducing the fuel consumption, and avoiding the dire expense due to traffic collision and potential accident [18].

2.2 Characteristics of VANETs

VANET is a type of Ad Hoc Network with some unique characteristics, and requirements. In the following, we discuss unique features of VANETs. Some of these main qualities are [5]:

- Computing Power and Battery Life: Vehicles have much higher reserve power and computing capability than a typical cell-phone or a mobile computer.

- Node Size and Weight: Vehicles have significantly larger size and weight, and hence, can support complex sensor applications with significant computing component.

- Vehicle Speeds: Vehicles travel at speeds up to hundred miles per hours, which results in the lack of continuous coherent communication links and could have frequently changing topology.
- Vehicle Grid: Vehicles in the grid are few hops away from a Road Side Unit (RSU) or the infrastructure.

## 2.3 VANET and Cellular Networks

Cellular networks provide many advantages for wireless communications. Some of the main advantages include:

- Always-on connectivity,
- Rich multimedia services, and
- Provides exclusive bandwidth for users which help relieve associated congestion.

These advantages are important for vehicular communications and coverage. However, VANET is better than cellular services (viz., 3G) services in a vehicular environment. This is mainly due to:

1. Vehicles are highly mobile, and many applications in the vehicular environment require transmission of a large volume of data. 3G cannot support such massive data due its bandwidth limitations.

2. Cellular networks are designed primarily for continuous coverage and everywhere availability to users at all the time. In order to establish a cellular network specifically for a VANET, this could come with a very high cost that exceeds hundreds of millions of dollars [19]. On the other hand, VANETs do not require any extra cost for infrastructure besides the network interface cards installed on each vehicle.
3. Current cellular networks cannot sustain an additional volume of data exchange on their networks. This is particularly evident in the case of existing cellular networks. Especially after the introduction of smartphones, these networks have become increasingly overloaded. An example would be AT&T in which, “the net result is dropped calls, spotty service, delayed text and voice messages and glacial download speeds as AT&T’s cellular network strains to meet the demand” [20]. This basically causes introduction of a new type of data category to an already overloaded network that is less practical and almost infeasible.

Constant connectivity is not a requirement in many VANET applications. For example, email, transfer of files, bulk downloads, etc. can sustain continuous disruptions in the connectivity of the network. In other words, VANET is basically a Delay Tolerant Network (DTN).

2.4 VANET versus MANET

Another technology that is typically very similar to a VANET is the Mobile Ad Hoc Network (MANET). VANET is typically considered a special category of a MANET in which the mobile nodes are vehicles. However, there are differences between the two technologies that don’t allow the adoption of the MANET technology directly to VANET. Some of the main dissimilarities are:

1. Very high mobility speed: Vehicles in VANET move with a speed up to 100 m/s, and hence, there is a frequent change in the topology of the network. Moreover, vehicles only get a very slim window in order to communicate with each other. This results in a continuously disconnected and a highly dynamic network topology.
2. Number of nodes in VANET: A VANET address a scenario where it is expected that many vehicles will be equipped with the VANET interface card, and hence, the node density is usually very large. Any VANET algorithm needs to be salable to a very large number of nodes.

Table 2.1 provides a brief comparison between VANET and MANET [21]. These differences result in a unique set of problems in the VANET, which need to be addressed with new problem formulations, protocols, and algorithms.

<table>
<thead>
<tr>
<th>Characteristic &amp; MANET</th>
<th>VANET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of production</td>
<td>Cheap</td>
</tr>
<tr>
<td>Change in network topology</td>
<td>Slow</td>
</tr>
<tr>
<td>Mobility</td>
<td>Low</td>
</tr>
<tr>
<td>Node density</td>
<td>Sparse</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Hundreds of kbps</td>
</tr>
<tr>
<td>Range</td>
<td>Up to 100 m</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Depends on power source</td>
</tr>
<tr>
<td>Multi-hop routing</td>
<td>Available</td>
</tr>
<tr>
<td>Moving pattern of nodes</td>
<td>Random</td>
</tr>
<tr>
<td>Position acquisition</td>
<td>Using ultrasonic</td>
</tr>
</tbody>
</table>

2.5 Vehicular Network Hardware

In order to achieve the goals and the vision of ITS, the vehicles and highways are equipped with different types of software and hardware. The hardware falls under two main categories: sensors and communication systems. In the next subsections, we will be giving a brief introduction to these categories.
2.5.1 Sensor Network

Sensors play a major role in vehicular technology since they provide the means of understanding the environment, the vehicle, and the vehicle operator. Many sensors are equipped within the vehicle, and along the road or highway. Vehicles also can act as sensors themselves. Examples for the sensors that can be equipped in the car include: Tire Pressure Monitoring Systems (TPMS), Vehicle Speed Sensor (VSS), Traction Control System (TCS), Electronic Stability Control Systems (ESC), Automated Collision Avoidance Systems (ACAS) and many more [22]. Vehicle manufacturers are already including many sensors such as those mentioned previously and more in the assembly of vehicles. Honda is introducing a Blind Spot Information (BSI) sensor that informs the vehicle operator in case there are any neighboring vehicle in his/her blind spot [23]. Ford has begun developing a heart rate monitoring seat in its vehicles. The information gathered by the heart rate sensors is analyzed by an on-board computer system and provides real-time health information or alerts the vehicle operator [24]. Figure 2.1 presents examples of different types of sensors in a vehicle.

Aside from on-board vehicle sensors, the vehicles themselves can be used as mobile sensors. Applications that can utilize such approach include real-time update of traffic speeds, or updating digital road maps by utilizing GPS traces [25]. One example for using vehicles as sensors is the OPTIS project implemented in Sweden [26]. In order for the city to validate data gathered from cameras/loop detector systems, 220 vehicles reported their real-time speeds using cellular GPRS modems [26].
2.5.2 Communication Systems

In order to communicate the data gathered from on-board sensors, vehicles are also required to be equipped with communication tools. IEEE has defined the standards for communication amongst vehicles for Wireless Access in a Vehicular Environment (WAVE) and the Dedicated Short-Range Communications (DSRC) standards. WAVE standard manages the network layers from the network layer up to the application layer. The physical and data link layers are managed by the DSRC standard. Figure 2.2 presents different layers managed by each standard.

Table 2.2 provides a comparison between the DSRC and other wireless technologies. As shown in the table, the main advantage for the DSRC wireless technology is the very low latency as compared to other network technologies.
2.5.3 Sensor and Communication Applications

There are many applications that depend solely on the sensors in the vehicle and do not require any information exchange with other entities (i.e., other vehicles or the Internet), while such exchange are desirable for other uses. Examples for both kinds of application are given in Table 2.3.

In this dissertation, we are not concerned with any sensor applications. Our focus is only on communication aspect in a VANET, the feasibility of connection to a vehicle as well as delay in the message delivery.

2.6 Vehicular Network Model

As mentioned earlier, vehicles are equipped with both sensors and communication devices. After sensor nodes sense data, it is expected to communicate this data to other vehicles and the surrounding infrastructure. In other instances, vehicles are
required to retrieve data from other vehicles, from the infrastructure, or from the Internet. Vehicles themselves are considered as nodes in a large network. Due to the nature of the vehicular network, these nodes are highly mobile. When vehicles travel on the highway or in the city, they come in close proximity (within the communication connectivity range) with other vehicles or with road side units (infrastructure). Hence, we can assume that the communication infrastructure of vehicular networks is one of three main models: Vehicle-to-Vehicle, Vehicle-to-Infrastructure, and Hybrid models. Figure 2.3 presents different models in a vehicular network scenario.

![Image of different communication models in a Vehicular network scenario](image)

Figure 2.3: The different communication models in a Vehicular network scenario  [4]

### 2.6.1 Vehicle-to-Vehicle

In vehicle-to-vehicle (V2V) model, vehicles communicate with each other in an ad hoc fashion. Vehicles that are in close proximity with each other, communicate directly. Vehicles outside of this range communicate in a multi-hop fashion. One of
the main disadvantages of this model is that it depends heavily on the density of vehicles on the road or a highway. When the vehicle density is high, vehicles can communicate with each other in a multi-hop fashion. However, when the vehicle density is low, this type of communication is not feasible. This model also overcomes conventional centralized approach and avoids any fixed network size, or end-to-end delay. End-to-end delay depends mainly on availability of intermediate vehicles that can be used as hops to communicate or propagate the data.

2.6.2 Vehicle-to-Infrastructure

Vehicle-to-Infrastructure (V2I) model is when vehicles connect with an infrastructure-based communication system. An infrastructure-based system is also referred to as Road Side Unit (RSU) [27]. They can be cellular, WiMax, or 802.11 networks. The advantage of these networks is that they are centralized and enable a vehicle access to the Internet. One of the main disadvantages of this model is that the communication infrastructure network could be easily overloaded, while the cost of using the network could be substantially high.

2.6.3 Hybrid Model

The hybrid model combines the advantages of both the vehicle-to-vehicle model and the vehicle-to-infrastructure model. In this hybrid model, vehicles communicate by using either of the two models depending on a specific criteria and availability. If other vehicles are absent in the vicinity, vehicles can communicate through the infrastructure.
2.7 V2V versus V2I

It is a common expectation that a vehicular network should rely entirely on "free" V2V communications without any dependence on the Infrastructure [5]. However, due to connectivity limitations of the vehicles in a V2V mode, an existing infrastructure can be used as a complementary charged access service in case an application requires a guaranteed service, or minimal delay. There are many types of infrastructure that can be used such as cellular networks and WiFi. The main disadvantage for cellular networks is that they are already overloaded, are not free, while their throughput is relatively low. However, they have the advantage of covering almost all the highways and the cities. On the other hand, WiFi has very small coverage area, while having a very high throughput.

Another solution would be to install a totally new infrastructure system. This is proposed by the Intelligence Transportation System (ITS) of the Department of Transportation (DoT) [28]. The total cost for such an establishment is approximated by 251 million dollars. Yet, this investment will not be adequate to cover all the highways where V2V communications is still desirable. Therefore, this dissertation calls for installation of infrastructure only at few key areas such as busy intersections, urban locations, and interstate highways.

It is worth mentioning that according to the Department of Transportation (DoT), V2V system helps avoid 79 percent of all vehicle crashes, while V2I systems could help only 26 percent of the crashes. These two systems combined could address up to 81 percent of the crashes [29].
2.8 Vehicular Networking Initiatives

Many initiatives have been undertaken around the world in order to develop the vehicular networking technology. In Japan, Smartway is an initiative that creates a platform to deploy infrastructure on the roads and enables vehicles to communicate with the environment [30].

In Europe, many organizations have emerged with the goal of enhancing the Intelligent Transportation System. Some of these organizations are: E-ENOVA, Car-2-Car Communication Consortium, PREVENT, and PATH [10–12,14].

In the United States, the U.S. Department of Transportation (USDOT) has introduced a comprehensive initiative that aims to enable a safe, wireless network that continuously connects vehicles [31]. Under this initiative, many research goals have been presented that utilize ITS, and are discussed in the following paragraphs.

2.8.1 Congestion Initiative

Paying Toll, Transition, Telecommuting, and Technology are four synergistic strategies presented by the congestion initiative in order to minimize any urban accumulation.

2.8.2 Next Generation 9-1-1

The goal of the NG9-1-1 initiative is to enable the Public Safety Answering Point (PSAPs) and emergency responder networks to incorporate voice, data, and video transmission from different communication devices.
2.8.3 Cooperative Intersection Collision Avoidance System

The Cooperative Intersection Collision Avoidance System aimed to find solutions for intersection crash problems caused by stop sign movements, stop sign violations, traffic signal violations, and unprotected signalized left turn movements.

2.8.4 Clarus

This initiative delivers timely and reliable weather and road condition information by integrating a wide variety of weather observing, forecasting, and data management systems.

2.8.5 Mobility Services for All Americans

The main drawback of the public services is that they are fragmented, inefficient and unreliable. MSAA initiative attempts to provide the basic need of transportation for the many Americans that use the public transportation services.

2.8.6 Rural Safety

The main goal of Rural Safety Innovation Program is to improve the rural road safety. In order to achieve that, the Rural Safety initiative assists rural communities in addressing highway safety problems, increasing interest in rural safety issues, and promoting the benefits of rural safety countermeasures that could reduce rural accidents.
2.9 Summary

In this chapter, we presented different aspects of the vehicular technology. The concept of Intelligent Transportation Systems (ITS) has been introduced. Following that, we have discussed different hardware functionalities that is needed for the vehicular network. Vehicle-to-Vehicle, Vehicle-to-Infrastructure, and the Hybrid communication models have been presented as the scenarios for the vehicle network. We also indicate some advantages and disadvantages for each model. Finally, we cover some of the recent initiative in the vehicular networking realm.

<table>
<thead>
<tr>
<th>Sensor Applications</th>
<th>Communication Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blind Spot Indicator (BSI)</td>
<td>Traffic Optimization</td>
</tr>
<tr>
<td>Tire Pressure Monitoring Systems (TPMS)</td>
<td>Cooperative Driving</td>
</tr>
<tr>
<td>Vehicle Speed Sensor (VSS)</td>
<td>Collision Avoidance</td>
</tr>
<tr>
<td>Traction Control System (TCS)</td>
<td>Internet Coverage (Email)</td>
</tr>
<tr>
<td>Front/Rear Parking Sensors</td>
<td>Multimedia Streaming</td>
</tr>
<tr>
<td>Object Detection Sensors</td>
<td>Parking Availability</td>
</tr>
</tbody>
</table>
Table 2.2: A comparison between the different wireless technologies and the DSRC technology [3]

<table>
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<tbody>
<tr>
<td><strong>Capabilities</strong></td>
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<tr>
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<td>4-6 km</td>
<td>10 m</td>
<td>40 km</td>
<td>120 km</td>
<td>1000 m</td>
<td>300-400 km</td>
<td>2 km</td>
<td>30 m</td>
<td>30-50 km</td>
<td>US 48 states</td>
<td>30-50 km</td>
<td>NA</td>
</tr>
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<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
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<td>X</td>
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<tr>
<td>One-way from vehicle</td>
<td>X</td>
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<td></td>
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<td>X</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Point-to-multipoint</td>
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<td>?</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>?</td>
</tr>
<tr>
<td>Latency</td>
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<td>1.5-3.5 sec</td>
<td>3.4 sec</td>
<td>10-30 sec</td>
<td>3.5 sec</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>10-20 sec</td>
<td>10-20 sec</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 micro sec</td>
<td>1.5-3.5 sec</td>
<td>3.4 sec</td>
<td>10-30 sec</td>
<td>3.5 sec</td>
<td>NA</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>10-20 sec</td>
<td>10-20 sec</td>
<td>?</td>
</tr>
</tbody>
</table>


Chapter 3

QoSHVCP: QoS-oriented Hybrid Vehicular Communications Protocol

3.1 Related Work

Many factors can characterize a VANET topology and its dynamic behavior. Traffic density (i.e., well-connected, sparsely connected, and totally disconnected neighborhood), vehicles’ speed (i.e., low, medium, and high) and the heterogeneous network environment (i.e., technologies of wireless networks around the VANET and their deployment) are the main aspects depicting a VANET. The fast mobility of vehicles make most traditional MANETs routing protocols inefficient for VANETs applications, mainly due to lack of any topology maintenance.

This section presents related work in specific areas of vehicular networking that this dissertation expands on. Each subsection presents only one aspect. The first
subsection presents the concept of delay tolerant networks and its relation to vehicular networks as well as the research done in this area. The following subsections include research findings in broadcasting techniques for vehicular network, vehicle-to-infrastructure communication model, and the hybrid model. Finally, we present analytical models developed for data delivery rates in vehicular network, followed by research findings in load sharing and balancing in vehicular networks.

3.1.1 Delay Tolerant Networks

Delay Tolerant Networks (DTNs) are networks that are composed of nodes that are either static or dynamic and the network may not be connected at all times. The DTN concept was initially introduced for the networks such as Military Ad-Hoc Networks and Sensor and Sensor/Actuator Networks [32]. The main characteristic of these networks is the frequent disconnection of the network. In sensor networks, this is caused by limitations on the battery life of the sensor nodes which cause many of them to be turned off before they become dead. On the other hand, in vehicular networks, this is caused by the high mobility of the vehicles.

In order to overcome the problem of connectivity, an approach called opportunistic forwarding has been presented [33]. This approach is also extended to VANETs in achieving connectivity between vehicles via V2V and opportunistically disseminate useful information. It provides message propagation through building the links dynamically as a bridging technique, where any vehicle can be used as the next hop temporary storage element and subsequently rebroadcast to forward the message to the final destination whenever feasible. In [34], the authors define an opportunistic forwarding technique in VANETs as an advanced information dissemination communication pattern, which has an objective to disseminate information among the vehi-
cles and enduring for a certain amount of time. Traditionally, schemes for advanced information dissemination use single-hop broadcasts or store-and-forward technique, and forward messages multiple times to all those vehicles unreachable because of an existing network partitioning.

DTNs have the ability to tolerate a given amount of delay in delivering the message to the destination. Many applications in VANET can accept such a delay, such as traffic information, email downloading, and many others. However, being an inherent nature of a VANET, the scope of our research is to minimize the delay in the message delivery so as to provide a better service to the users. Also, there are some applications that require an upper limit of the delay, or else the information will be irrelevant within a few seconds.

3.1.2 Broadcasting Techniques

Message and time delay propagation in a VANET via opportunistic networking have been largely investigated in the literature, and different broadcasting techniques have been proposed, many of which can be classified by distance, location, probability and topology-based [35]. These methods are effective only with V2V for dense traffic scenario. But, their use is very limited when vehicles constitute a low density neighbourhood.

Distance and Location Based Approaches

The distance and location based approaches simply exploit the inter-vehicular distance and the vehicles’ positions by GPS devices in order to select the next hop to forward a message further within the area. Beacon messages are implemented in many location-based approaches, where vehicle’s position information is embedded either
through GPS or a-priori calculations. In [36], each vehicle has the knowledge of its neighbors in term of both the numbers of neighbors and their relative positions. The next hop selection involves the furthest vehicle within its communication range from the source vehicle. In [37], a fast multi-hop broadcast technique has been proposed. It estimates vehicles’ distance and provides a reduction on the number of needed hops and associated delay required to forward a broadcast message throughout the area. It is well known that a non-optimal number of hops, experienced by a message to be forwarded to a destination vehicle, causes higher delays due to associated parameters such as queuing delays, link quality, etc. and the network performance can be drastically affected. However, the major drawback of position-based broadcasting approach is the need for global information concerning the vehicular network topology, as well as the geographical characteristics of the vehicular scenario. A huge quantity of data information is needed which can be exchanged only by a dedicated logical channel.

**Probability Based Approaches**

In the probability-based broadcasting technique, probability of collision reduction and hence, a decrease in required number of transmitted messages is assumed. Upon message reception, each vehicle retransmits with a probability depending on the distance from the source vehicle [38]. It follows that greater the vehicle’s distance is from the source (but within its communication range), higher will be the retransmission probability. In [39], Resta et al. deal with multi-hop emergency message dissemination through a probabilistic approach and derive lower bounds on the probability that a vehicle can correctly receives a message within a fixed time interval. Similarly, in [40], Jiang et al. introduce an efficient alarm message broadcast routing protocol and estimate the receipt probability of alarm messages sent to the vehicles.
3.1.3 **Vehicle-to-Infrastructure**

Road-side infrastructure could represent a viable solution to extend the vehicular connectivity support in scenarios where V2V fail which is only effective in dense vehicle scenario. However, they are dysfunctional in a low density area. Many authors investigated novel techniques in order to allow vehicles to be seamlessly connected. Such approaches rely on using portions of both V2V as well as V2I techniques. Such a combination is commonly referenced as QoS oriented Hybrid Vehicular Communications Protocol (QoSHVCP).

V2V and V2I communication technologies have been developed as a part of the Vehicle Infrastructure Integration (VII) initiative [41]. The use of a vehicular grid along with an opportunistic infrastructure placed on the roads, can guarantee seamless connectivity in a dynamic vehicular scenario, as described in [42, 43]. In [44], the authors propose a Cooperative Infrastructure Discovery Protocol, called CIDP, which allows vehicles to gather information about encountered RSUs through direct communication with the network infrastructure, and subsequent message exchanges with neighboring vehicles via V2V. The authors show the effectiveness of their approach. But, it seems to be limited to the message exchange about the infrastructure discovery. In [45], Wedel et al. use QoSHVCP communications for an enhanced navigation system which intelligently help drivers to circumnavigate congested roads and avoid traffic roadblocks. Their contribution highlights the advantages of QoSHVCP communication protocols for numerous safety applications.

3.1.4 **Hybrid Model**

Finally, Seo et al. [46] analyze the performances of a general hybrid communication protocol, based on the IEEE 802.11p WAVE (Wireless Access in Vehicular Environ-
ments) system. The authors focus on packet error rates for the proposed method, while connectivity issues and reliability of vehicles have not been incorporated.

### 3.1.5 Analytical Models for Data Delivery Rates

Several studies have introduced analytical models for the data delivery rates and delay time within vehicular networks. Some works have addressed propagation delay for safety critical warning messages in a vehicular environment [47–49]. In [47], the authors develop an analytical model that evaluates the message delivery delay in critical safety applications and its relation to the buffering and switching mechanism within the WAVE protocol. The same problem has been considered in [48] by the authors. However, they observe the tradeoff between the message delivery delay versus the cluster size used by the vehicles travelling on the highway. Finally, in [49] the authors present an analytical model and its dependence on vehicular density on the highway. Our work concentrates on a different aspect of the VANET that represents a more realistic view of such networks. We present an analytical model when the vehicular network appears as a partitioned network that incorporates different connectivity phases a vehicle encounters during its trip on the highway.

Another work [50] has also developed an analytical model for the message delivery delay in a VANET by exploring queuing theory in studying the vehicular connectivity when the traffic follows a unidirectional model. We generalize this by extending to bidirectional traffic on the highway in a typical dynamic network.

Finally, the authors in [51] derive an analytical model that characterizes the connectivity of the VANET on a unidirectional road. We compute an expected delay for the message delivery rather than simply considering the network connectivity aspect only in a unidirectional traffic scenario.
To our knowledge, our work is the first to introduce an analytical model that includes delay from V2I communication as well as V2V.

### 3.1.6 Load Sharing and Balancing

In order to provide a more efficient resource management and in an attempt to satisfy soft real-time requirements in a distributed system, there has been a significant number of works that looked at how to implement load sharing and load balancing mechanism in a distributed system [52]. Most of the work focus on the distribution and/or migration of the workload among many different servers [53, 54]. Some even go as far as adapting the functionality of the clients in the system [55]. When there is an option of re-distribution, load balancing could also be obtained by distributing the traffic generated among multiple paths and servers [56, 57]. However, such load balancing mechanisms might not provide optimal resource management in a VANET scenario due to the fact that there is often a lack of multiple resources, or routing options are limited. In many cases, cars would be limited to either go through the route using the infrastructure, or to use the formed ad hoc network.
3.2 Our QoSHVCP Approach

Network connectivity is one of the main challenges in the vehicular environment. In this chapter, we investigate a hybrid approach for enhancing the connectivity among vehicles. Our approach of a hybrid vehicular protocol, i.e. QoSHVCP, appropriate switching is provided from V2V to V2I and relying on a vehicular grid with a neighboring network infrastructure. The protocol switching enables seamless connectivity and expected to be effective independent of any specific traffic scenarios or vehicle speeds. It consists of a handover procedure from V2V to V2I (and vice versa), resulting in improving the opportunistic connectivity with respect to the traditional inter-vehicle communications. Our QoSHVCP also has a load balancing component that considers two different classes of message priorities. It allows the network to gracefully degrade, while still maintaining good performance for high priority messages.

3.2.1 QoSHVCP Scheme

QoSHVCP scheme is a hybrid approach that provides a link between both vehicles (i.e., V2V) and from vehicles to the infrastructure (i.e., V2I) communications. The cooperation and coexistence of these two different methods can assure a good connectivity in a VANET scenario, especially in sparsely connected neighborhoods where V2V communications are not always feasible.

QoSHVCP is a broadcast protocol that reduces the time required by a message to propagate from a source vehicle to the farthest vehicle within the communication range inside a certain strip-shaped area-of-interest. QoSHVCP represents a smart and realistic communication protocol, since vehicles can establish opportunistically
both V2V and V2I communications and reduce the message delivery time, as well as avoid disconnections due to changed vehicle density that cause dynamic topological changes.

Based on the estimation of the *link utilization time* (i.e., the message delivery time for one hop) of vehicles, QoSHVCP is then used to reduce the amount of hops needed to deliver the message. In a previous version of QoSHVCP [58], we assumed a known and constant transmission range of vehicles. But, this limits the protocol resulting in an unrealistic implementation of the algorithm. In this dissertation, we adapt QoSHVCP to be a more pragmatic broadcast protocol where vehicles’ actual transmission data rates are subjected to continuous changes due to physical obstacles, vehicle density, speed, network overload, etc.

Apart from achieving seamless connectivity to a VANET through dynamic protocol switching, our proposed technique also guarantees message delivery with smaller delay, specially for HP (high priority) messages. In particular, QoSHVCP reserves HP messages (e.g., warning, safety, and soft-real time messages) to be forwarded via V2I; while LP messages (e.g., delay-tolerant) via V2V. The main scope of QoSHVCP is to exploit the connectivity with the network infrastructure for HP messages whenever available, as RSU (Road Side Unit) can forward a message to the next RSU, resulting in quicker message propagation inside the vehicular grid.

In the following Subsection 3.2.2, we describe the QoSHVCP protocol switching mechanism, while in Subsection 3.2.3 we introduce the QoS prioritization adopted in QoSHVCP.
3.2.2 Delay-based Protocol Switching Mechanism in QoSHVCP

Let us consider the vehicular scenario depicted in Figure 3.1. Several RSUs of different wireless technologies are deployed, partially covering a given area. The local information —assumed as global— comprises the key data defining the network scenario, since the traffic density is directly inter-related to the vehicles density. Each vehicle continuously monitors its local connectivity by storing their periodic HELLO broadcast messages with piggyback information about neighbors. It is then able to determine if it is within a group of vehicles called a cluster or is travelling alone on the road. A vehicle will be aware of neighbouring wireless networks on the basis of broadcast signalling messages sent by the Road Side Units (RSUs).

![Figure 3.1: Vehicular grid with an overlapping heterogeneous wireless network infrastructure.](image)

The knowledge of RSUs’ presence in the range is indicated by a routing parameter, defined as *Infrastructure Connectivity* (*IC*). This parameter gives information about the ability of a vehicle to be directly connected with one or more RSUs. The *IC*
assumes two values, i.e., $IC = \{0, 1\}$, respectively corresponding to no RSU, and one or more available RSUs. For instance, when a vehicle has $IC = 1$, it means that it is driving inside the radio coverage of a wireless cell of an RSU and is potentially able to directly connect to that RSU associated with the neighbouring wireless cell. Otherwise, the value of $IC$ is 0 when no wireless cell is available for such an access.

Let us consider a cluster $C$ comprised of a set $S$ of vehicles (i.e., $S = \{1, 2, \ldots, n\}$). Then, $m$ RSUs (i.e., $m < n$) are displaced in the network scenario as depicted in Figure 3.1. Each vehicle is able to communicate with all the other vehicles around it via V2V. At the same time, we assume that only a limited subset of vehicles in the cluster $C$, (i.e., $S' = \{1, 2, \ldots, l\} \subset S$, with $l < n$), is able to connect to an RSU via V2I. For example, not all the vehicles might have an appropriate network interface card, and/or are not in the range of connectivity of an RSU. Analogously, we assume that only $k$ RSUs (i.e., $k = \{1, 2, \ldots, h\}$ with $h < m$) are available to V2I communications.

For the connectivity link from the $i$-th to the $j$-th vehicle, we define link utilization time $q_{(i,j)}$ [s] as the time needed to transmit a message of length $L$ [bit] from the $i$-th to the $j$-th vehicle, at an actual data rate $f_{(i,j)}$ [Mbit/s]. This is given by:

$$q_{(i,j)} = \frac{L}{f_{(i,j)}}. \quad (3.1)$$

For a direct link between $i$-th vehicle and $k$-th RSU, the data rate is computed by the nominal data rate $\tilde{f}_{(i,k)}$ by applying a Data Rate Reduction (DRR) factor (i.e., $\rho_{(i,k)}$) that depends on the distance from the vehicle to the RSU, namely $f_{(i,k)} = \rho_{(i,k)}\tilde{f}_{(i,k)}$. The DRR factor increases when a vehicle is located within the bound of a wireless cell corresponding to an RSU.

Let us define a path from $i$-th vehicle to $k$-th RSU, comprising of a sequence of
$M$ hops, where a single hop represents a link between two neighboring vehicles. The path length represents the number of hops $M$ for a single path. It follows that the maximum number of directed links from a vehicle to an RSU is $\alpha = l \cdot h$, while the maximum number of different paths that can connect $i$-th vehicle to $k$-th RSU is $n \cdot \alpha$.

From the definition of a path, we define the path utilization time $Q_{(i,k)}$ [s] from the $i$-th vehicle to the $k$-th RSU as the sum of single link utilization time parameters (i.e., $q_{(i,j)}$), for each hop that constitutes the path as:

$$Q_{(i,k)} = q_{(i,j)} + q_{(j,x)} + \ldots + q_{(x,k)} = L \sum_{i=1}^{n} \sum_{x \in S} f_{(i,x)}^{-1}. \tag{3.2}$$

Among all possible paths, the optimal path will be the one with the minimized time required by a path and can be given by:

$$\min_{s=1,2,\ldots,n\alpha} Q_{(s,i,k)} = L \cdot \min_{s=1,2,\ldots,n\alpha} \sum_{i=1}^{n} \sum_{x \in S} f_{(i,x)}^{-1}. \tag{3.3}$$

Equation (3.3) is compared with the link utilization times in V2V communications in order to detect the most appropriate transmission path.

### 3.2.3 Load Balancing Mechanism in QoSHVCP

QoSHVCP aims to guarantee connections either through V2V or through V2I on the basis of minimizing path required time. However, in a VANET, various applications require different communication modes and QoS levels. For instance, two most important safety applications are the Extended Emergency Brake Light (EEBL), and the Cooperative Intersection Collision Avoidance System (CICAS) [59]. EEBL is based on V2V communications, while CICAS exploits V2I mode [59]. Leveraging on such consideration, we assume that two sets of vehicles are respectively transmitting
EEBL and CICAS safety messages. EEBL and CICAS messages are classified to have Low and High Priority, respectively. QoSHVCP forces HP messages to be transmitted via V2I, while LP messages are directed towards V2V.

As presented in the simulation results of section 3.5, when the traffic density increases, the message propagation delay decreases due to enhanced connectivity of the vehicles and possibly larger size cluster. However, this is somehow unrealistic due to the fact that when the traffic density increases, the overload on the network infrastructure also increases. This results in a decrease in the bandwidth available for each vehicle, which could mean increased message propagation delays.

In order to avoid this traffic overload in the network infrastructure, a load balancing mechanism can be employed. We define the channel utilization, i.e., $\rho(\nu)$, as the percentage of the traffic load in a wireless network, where $\nu$ is the number of vehicles connected to the RSU inside a wireless cell. The channel utilization is expressed as:

$$\rho(\nu) = \begin{cases} \exp\left[\frac{\nu - \nu_{\text{max}}}{\nu_{\text{max}}}\right], & \text{for } \nu \leq \nu_{\text{max}} \\ 1, & \text{otherwise} \end{cases}$$

where $\nu_{\text{max}}$ is the maximum number of vehicles which can be served by the RSU. When $\nu > \nu_{\text{max}}$ the traffic load in the wireless cell will be maximum and new HP messages cannot be served with success.

The analytical variation in the channel utilization is depicted in Figure 3.2. Notice that $\nu_{\text{max}}$ is a threshold which strictly depends on particular wireless network technology. It needs to be updated constantly and is expressed as $\nu_{\text{max}} \propto (r, B)$, where $r$ [m] is the wireless radio coverage, and $B$ [b/s] is the the bandwidth of a particular wireless network.

The load balancing mechanism is enabled once the overload on the network infras-
structure exceeds a given threshold $\nu_{\text{max}}$. Before overload on the network exceeds this threshold, any High Priority packets are routed via V2I communications \(^1\), and any Low Priority packets are routed using V2V. Once the overload exceeds the threshold, regardless of their priority, any new packets are forced to communicate using V2V, until the overload is reduced below the threshold.

\(^1\)Due to minimal delay and guaranteed service V2I provides
3.3 Message Delivery Time Rates

In this section, we investigate the message delivery time delay that propagates in a VANET within the network infrastructure. We breakdown the message propagation delay according to the connectivity sequence of the vehicles. After we formulate the message propagation delay within each phase, we can obtain the probability of the vehicle being in that phase. Finally, we present a theorem that provides an average message reception delay that incorporates all message propagated to the destination vehicles using different technologies and possibly passing through alternate phases.

3.3.1 Delay in Vehicle-to-Vehicle Communication

It is important to note that RSUs are connected together using land-line as they are placed at pre-defined physical locations. As depicted in Figure 3.1, vehicles move in clusters in two separated lanes (i.e., left and right lanes), where north (i.e., N), and south (i.e., S) respectively represent the directions of the left and the right lanes. The message propagation is based on the number of vehicles involved in forwarding and assumed to be N and vehicles are traveling at a constant speed \( c \) [m/s].

The time delay for a message propagating within a cluster \( C \) is \( d \) [s] which is defined as the difference between the time-stamps of message reception (i.e., \( t_{Rx} \)) and transmission rate (i.e., \( t_{Tx} \)), respectively:

\[
d = t_{Rx} - t_{Tx}.
\]  

(3.5)

For a successful transmission of a message of length \( L \) [bit] between a couple of vehicles \( (i, j) \), equation (3.5) can be also expressed as the link utilization time, i.e., \( d_{(i,j)} \) [s], where \( i \)-th vehicle transmits a message to \( j \)-th vehicle at a transmission rate
\( f_{(i,j)} \) [Mbps], such as:

\[
d_{(i,j)} = \frac{L}{f_{(i,j)}}. \tag{3.6}
\]

We assume that the cluster \( C \) comprises of a set of vehicles connected with each other using \( h \) hops (i.e. \( h = \{1, 2, \ldots, H\} \)), the average propagation time delay within a cluster (i.e., \( d \) [s]) is addition of delay contributed by each single link \((i, j)\) such as:

\[
d = \sum_{i,j} d_{(i,j)} = L \sum_{i,j} \frac{1}{f_{(i,j)}} \tag{3.7}
\]

We can define message delivery time for V2V communications (i.e., \( d_{V2V} \) [s]), as:

\[
d_{V2V} = d + \Delta T, \tag{3.8}
\]

where \( d \) [s] is the propagation time delay within a cluster, as defined by (3.7), and \( \Delta T \) [s] is the minimum time interval necessary to connect a couple of vehicles traveling at speed \( c \) [m/s] and separated by a distance \( \Delta x \) [m]. \( \Delta T \) is defined as

\[
\Delta T = \frac{\Delta x}{c}. \tag{3.9}
\]

Notice that when no connectivity is present (i.e., a vehicle is traveling alone), the propagation time delay is equal to \( \Delta T \) [s]. In V2V communications, the message delivery time delay drastically increases for low traffic density scenario.
3.4 Delay in Vehicle-to-Infrastructure Communication

Analogous to (3.6), let us consider $d_{\text{RSU}}$ [s] as the propagation time delay through the network infrastructure to the destination as:

$$d_{\text{RSU}} = \frac{L}{f_{\text{RSU}}},$$  \hspace{1cm} (3.10)

which is defined for the link between the $m$-th and $(m+1)$-th RSU as the ratio between the message length $L$ [Bit], and the effective data rate $f_{\text{RSU}}$ [b/s]. It represents the time necessary to forward a message of length $L$ between two consecutive RSUs at rate $f_{\text{RSU}}$ [b/s]. Equation (3.10) represents the time delay propagation rate within the preexisting network infrastructure.

Each RSU works as a relay node and forwards the message to vehicles crossing its wireless cell. According to Figure 3.1, we shall also consider the propagation time delay in uplink (downlink), when a vehicle sends a message to an RSU (and vice versa), such as:

$$d_{\text{UP}} = \frac{L}{g(i,m)}, \quad d_{\text{DOWN}} = \frac{L}{g(m,i)},$$  \hspace{1cm} (3.11)

where $g(i,m)$ and $g(m,i)$ are the effective transmission data rate for the link $(i,m)$ (uplink), and $(m,i)$ (downlink), respectively.

From relations (3.10) and (3.11), it follows that the propagation time delay consists of propagation $d_{\text{V2I}}$ [s] for communication between vehicles and RSUs via V2I depends only on the effective transmission data rates in uplink and downlink (i.e., $d_{\text{UP}}$ and $d_{\text{DOWN}}$, respectively) and on the effective data rate for intra-RSU communications.
\(i.e., d_{RSU}\) given by:

\[
d_{V2I} = d_{UP} + d_{RSU} + d_{DOWN} = L\left(\frac{1}{g_{(i,m)}} + \frac{1}{f_{RSU}} + \frac{1}{g_{(m,i)}}\right).
\] (3.12)

3.4.1 Connectivity Phases

Using a generic vision, we can model the overall system as an alternating renewal process where vehicular connectivity structure alternates between three phases as follows:

1. **Phase 1** (*No connectivity*): A vehicle is traveling alone in the vehicular grid. It represents a typical totally-disconnected traffic scenario where no connectivity via V2V is available. Moreover, we assume that no connectivity via V2I is assumed to be present during this phase (no network infrastructure).

2. **Phase 2** (*Short-range connectivity*): A vehicle is traveling and forming a cluster with other vehicles. V2V connectivity is available within the transmission range of the sender/forwarder. No connectivity via V2I is assumed to be available during this phase.

3. **Phase 3** (*Long-range connectivity*): A vehicle is traveling and forming a cluster with other vehicles. It enters a wireless cell and can connect with the associated RSU via V2I. No connectivity via V2V is assumed to be available during this phase. Vehicles are connected with an accessible network infrastructure.
Each phase is described as follows. During **Phase 1**, the vehicles are completely disconnected due to very low vehicle density and no available network infrastructure. Data packets are cached within a vehicle and traverse the network once a connectivity link becomes available. Minimum time needed for a vehicle to get connected with a neighbouring vehicle is $\Delta T \ [s]$, which depends on the inter-vehicle distance $\Delta x \ [m]$ and the vehicle speed $c \ [m/s]$, as expressed by (3.9).

When a vehicle is in **Phase 2**, the messages propagate in a multihop fashion via V2V within the cluster. The transmission time delay to forward a message within a cluster is $d \ [s]$, which depends on the effective transmission data rates for each hop within the cluster, as defined by (3.7).

We assume that a traditional opportunistic networking in a VANET depends on exploiting connectivity in both Phase 1 and Phase 2. In order to avoid disconnections, the bridging technique connecting vehicles separated in Phase 1 from those in Phase 2. It follows that the message delivery time delay via V2V ($i.e., d_{V2V} \ [s]$) respectively comprises of both two components from Phase 1 ($i.e., \Delta T \ [s]$), and Phase 2 ($i.e., d \ [s]$).

Finally, in **Phase 3**, time period necessary for a vehicle to transmit a message via V2I to an RSU is $d_{UP} \ [s]$, which depends on the RSU’s wireless technology. End-to-end time delay between two separated vehicles for communications via V2I comprises of the uplink ($i.e., d_{UP}$), the inter-RSU link ($i.e., d_{RSU}$), and the downlink ($i.e., d_{DOWN}$) time delays.

By utilizing such assumptions, we shall define the **average data transmission delivery time delay** ($i.e. \ d_{avg} \ [s]$) as the average time delay necessary to propagate a message in a vehicular network, where vehicles are able to opportunistically communicate either via V2V and/or V2I. Basically, the average time delay alternates between
(i) the time delay occurring in Phase 1 \( (i.e., \Delta T \text{ [s]} \), (ii) the multihop time delay in Phase 2 \( (i.e., d \text{ [s]} \), and (iii) the time delay in Phase 3 via V2I \( (i.e., d_{V2I} \text{ [s]} \), respectively. Let us denote \( T^{(n)}_\tau \) with \( \tau = \{1, 2, 3\} \) the random amounts of time a vehicle spends in one of the three phases during the \( n \)-th cycle. \( T^{(n)}_\tau \) are independent and identically distributed (i.i.d.) variable, due to the memory-less assumption on the inter-vehicular distances, and the expected time spent in the \( \tau \)-th phase is \( E \left[ T^{(n)}_\tau \right] \).

It follows that the long-run fraction of time spent in each of these phases is:

\[
p_\tau = \frac{E \left[ T_\tau \right]}{\sum_\tau E \left[ T_\tau \right]},
\]

(3.13)

where \( E \left[ T_\tau \right] \) has been assumed to approximate \( E \left[ T^{(n)}_\tau \right] \).

We are now able to compute the average propagation time delay \( d_{avg} \), which occurs in a vehicular scenario, where connectivity is alternating between three main phases:

\[
d_{avg} = p_{(\tau=1)} \Delta T + p_{(\tau=2)} d + p_{(\tau=3)} d_{V2I}.
\]

(3.14)

Each term in relation (3.14) represents the effective delivery time delay which occurs each time a vehicle is in a given connectivity phase, \( i.e., \) for \( \tau = \{1, 2, 3\} \). The probability that a vehicle lays in one of the three phases can be expressed as the probability that a vehicle is not connected, connected with neighbors and RSUs, respectively.

In order to determine the probability that a vehicle is connected with other vehicles traveling in the same or opposing direction, it is useful to assume that vehicular grid is discretized in terms of a number of cells, that is, the gap between two vehicles is equivalent to \( N \) cells. Basically, we consider two bounds for the cell size, \( i.e., \) \( R \) an upper bound, and \( R/2 \) a lower bound.
Figure 3.3 depicts how the vehicular grid is assumed to be composed of cells. Each cell has a size $l$ [m]. We consider a cell to be occupied if one or more vehicles are positioned within that cell.

![Vehicular Grid Diagram](image)

Figure 3.3: Vehicular grid comprised of $l$-size virtual cells. The probability that a vehicle is connected via V2V and V2I depends on the cells occupancy by the vehicles.

For a vehicle traveling alone on the eastbound (westbound), the probability that it will be connected in **Phase 1** via multi-hop with a next vehicle on the eastbound (westbound) depends on whether each of the $N$ eastbound (westbound) cells within the gap is occupied by at least one vehicle given by:

$$
(p_{e,w})^N = (1 - \exp(-\lambda_{e,w}R))^N,
$$

(3.15)

where $\lambda_{e,w}$ is the traffic density distribution on eastbound (westbound). In this case, the number of cell is $N = 1$ since the gap equals the minimum inter-vehicle distance, i.e., $G = R$ [m]. Equation (5.2) becomes

$$
pe,w = (1 - \exp(-\lambda_{e,w}R)).
$$

(3.16)
Again, in **Phase 2** the vehicles along eastbound (westbound) are connected via V2V if each of the \( N \) westbound (eastbound) cells in the gap is occupied by at least one vehicle. This is an event which occurs with the probability expressed by (5.2). But, the number of cell \( N \) is equal to:

\[
N = \left\lfloor \frac{G}{R} \right\rfloor, \tag{3.17}
\]

where \( G \) [m] is the gap between two separated vehicles. However, in the event that not all of the \( N \) cells in the westbound direction are occupied, the vehicles along eastbound are deemed to be disconnected. A message is then buffered in the vehicle’s cache until connectivity is again re-established.

Finally, in the **Phase 3**, probability that a vehicle traveling in the westbound (eastbound) will be connected via V2I with a westbound (eastbound) next vehicle depends on if each of the \( N \) westbound (eastbound) cells in the gap is occupied by at least one RSU, such as:

\[
(p_{w,e})^N = (1 - \exp (-\lambda_{w,e}R))^N, \tag{3.18}
\]

where the number of cell \( N \) is:

\[
N = \left\lfloor \frac{G}{K \cdot R} \right\rfloor, \tag{3.19}
\]

Since we assumed the wireless networks have a larger cell size than that in the vehicular grid, \( i.e., l = K \cdot R \) [m], with \( K > 0 \).
3.4.2 Average Propagation Time Delay

We can now introduce the following Theorem:

**Theorem 5.1 (Average Propagation Time Delay):** The average time delay necessary for a vehicle, being driven in a vehicular grid partially covered by a wireless network, to forward a message of length $L$ is:

$$d_{avg} = p_{e,w} ([N = 1]) \cdot \Delta T + p_{e,w} (N = \lfloor G/R \rceil) \cdot d + p_{w,e} (N = \lfloor G/(K R) \rceil) \cdot d_{V2I}.$$  

(3.20)

As we introduced, two bounds for the cell size (i.e., the upper and lower one, for $l = R$ and $l = R/2$, respectively), the average propagation time delay in relation (3.20) will have a lower and an upper bound.

3.5 Simulation Results

In order to properly authenticate our theoretical model, we performed an extensive simulation. In this section, we compare the delay propagation rates in a VANET scenario using different communication method as defined by the three phases of connectivity previously described in Subsection 3.3. We also evaluate the performance of the load balancing mechanism and observe the improvements in the message delivery delay.

The following Subsections 3.5.1 and 3.5.2 respectively introduce the simulation setup and the obtained results.
3.5.1 Simulation setup

We developed our own simulator, written using Java, which includes the highway model scenario with 4 different car speeds. The simulator measures the data delivery delay as the main performance metric. We considered both asymmetric and symmetric bidirectional traffic flows, where the traffic density on respective eastbound and westbound traffic is different and assumed equal. However, in this dissertation, we assume a symmetric traffic flow, that is a typical configuration, illustrating the propagation behavior and message delivery performance when cars follow all the three connectivity phases.

We simulated two typical safety applications, i.e., the Extended Emergency Brake Light (EEBL), and the Cooperative Intersection Collision Avoidance System (CI-CAS), corresponding to Low and High Priority messages, respectively. All messages are being propagated in the vehicular grid. A large number of simulations have been performed so as to decrease any random fluctuation. We assumed an idealistic perfect conditions, assuming no dropped packets while contention or interference occurrence are present. This ideal situation represents the first scenario to simulate in order to understand how delay is affected in the best case. The vehicle density on highways is varied from as low as 1 vehicle per kilometer, up to 100 vehicles per kilometer, and speed ranges from 15 up to 35 [m/s]. These values represent a typical highway condition of a sparse, medium and heavy traffic conditions on the roadways.

The vehicular traffic has been generated using a random exponential distribution which created the inter-vehicle distances on the highway. The exponential distribution has been largely shown to be in a good agreement with real vehicular traces for uncongested traffic conditions, i.e., up to 1000 vehicles per hour. The inter-arrival time of vehicles is calculated based on the vehicle density and the speed of vehicle over
the highway. For these reasons, the network connectivity is not always guaranteed. Consequently, at any given time, there is a non-zero possibility that a partition may exist in the network.

For each scenario, the simulation has been run for 10,000 seconds, and the average delay has been calculated from 200 different iterations to account for the randomness of the simulation. Distance between RSUs is 500 [meters] and they are distributed uniformly.

Following these parameters, the QoSHVCP technique has been simulated. Firstly, the effect of overload and the resulting channel utilization are considered in the traffic scenario. Packets introduced to the system are randomly assigned either High Priority (HP) or Low Priority (LP). The fraction of HP packets of the total packets in the system is controlled. This fraction is varied from 10% up to 40% of the total number of messages.

Finally, the load balancing mechanism is included in the system. The message reception delays for HP packets before and after the introduction of the load balancing are analyzed and compared. Complete details about the simulation setup are presented in Table 3.1.

Table 3.1: Parameter setup used in simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of simulation</td>
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</tr>
<tr>
<td>Number of runs</td>
<td>200</td>
</tr>
<tr>
<td>Estimated Vehicular Tx Range</td>
<td>[0, 200] meter</td>
</tr>
<tr>
<td>Infrastructure Tx Range</td>
<td>500 meter</td>
</tr>
<tr>
<td>Packet size</td>
<td>400 bytes</td>
</tr>
<tr>
<td>Vehicle speeds</td>
<td>15 to 35 meter/s</td>
</tr>
<tr>
<td>Vehicle density</td>
<td>1 to 100 veh/km</td>
</tr>
<tr>
<td>Load balancing threshold</td>
<td>40 veh</td>
</tr>
</tbody>
</table>
3.5.2 Simulation results

In this subsection, we begin by presenting the simulation results of the message reception delay without any load balancing technique. This presents the propagation delay rates versus different factors such as connectivity phase, vehicle speed, and RSU throughput. The following subsection includes results that indicate the effect of overload on the message reception delay and the improvement after implementing our overload balancing technique.

Propagation Delay vs Connectivity Phases

We compared the delay reception rates in three different connectivity phases for typical safety applications (e.g. EEBL and CICAS) in VANETs. However, to better understand and validate our simulator, we also included a “limited” Phase 2 that allows transmission of a single direction only. So, the message propagates strictly in an \textit{ad-hoc} hop-to-hop fashion from vehicle to vehicle in a single direction of the highway. This allows results to be analyzed in the light of (i) no connectivity; (ii) limited one-directional communication; (iii) vehicle communication that allows transmissions to both directions through bridging; and finally (iv) our hybrid QoSHVCP model in which a message can propagate using all possible transmission means. This may be in \textit{ad-hoc} mode or through an infrastructure, whenever available.

We use the following legends in the graphs: “V2V” represents the single-direction message propagation; “V2V Bridged” represents \textbf{Phase 2}; and “QoSHVCP” our hybrid model.

The results in Figure 3.4 (a) show that as the vehicle density increases, the delay decreases. The delay also decreases as the vehicle speed increases. The graph represents a typical behavior anticipated in \textbf{Phase 1}. The delay in the no connectivity
Figure 3.4: (a) Average message propagation delay for increasing vehicle density, and speed for Phase 1 (no connectivity) at different speeds (i.e., 15, 20, 25 and 35 m/s). (b) Average message propagation delay for increasing the vehicle density at different traffic speeds using V2V communication.
phase is the ratio of physical distance covered over the vehicle speed. Thus, the delay is significantly large as compared to Phases 2 and 3. Notice that the reception time delay in this phase does not depend on vehicles’ density, since no connectivity is assumed.

Propagation delay also depends on the vehicles’ speed. To better understand correlation between the delay and the vehicle speed, we have simulated vehicular movement and the delay at four different speeds, relying solely on a single-direction of communication. The simulation results unambiguously show that the delay reduces with an increase in the vehicle speed as illustrated in Figure 3.4 (b). As a consequence, Figure 3.5 (a) depicts the average time delay propagation for a message traveling at the vehicle speed, and the vehicle density is low. The time delay results in an average delay smaller than that of Phase 1 with no connectivity. Moreover, by varying the speeds of the vehicles, the maximum time delay also changes. As the vehicle density increases, the average delay decreases. This is because when the probability of connectivity among vehicles increases, the message travels faster than the vehicle speed.

Figure 3.5 (a) shows that in a low density situation, the average delay follows an increasing order. This is clearly expected and reaffirms correctness of our simulator. The results show that under high density conditions, majority of the vehicles are inter-connected and the message travels at the radio speed. Beyond this level, the effect of increasing vehicle density does not seem beneficial. Obviously, as vehicle density increases, more and more vehicles are connected and majority of time, the message can travel at the radio speed in ad-hoc mode.

In Figure 3.5 (b), we compare the message delivery delay for pure infrastructure communications only, since it reflects the best and worst cases of delivery time delay.
As a matter of fact, infrastructure communication performance is not affected by the vehicle density since it does not rely on any multihop vehicle communications. It is only affected by variations in the uplink and downlink data rates of the network infrastructure. The transmission rates used are a combination of the maximum uplink and downlink rates for the infrastructure in order to demonstrate the impact of different thresholds. The uplink data rate ranges from 0.2 Mbps to 2.7 Mbps, and the downlink from 5 Mbps to 12.2 Mbps. Notice that infrastructure communication shows the best (i.e., 5 s) and the worst (i.e., 48 s) time delays respectively for low (i.e., uplink 0.2 Mbps and downlink 5 Mbps) and high (i.e., uplink 2.7 Mbps and downlink 12.2 Mbps) values of data rates.

Comparing Figure 3.5 (a) and (b), we are able to establish thresholds for handover between a purely infrastructure-based connection to any of the other options.

**Propagation Delay and Overload Balancing**

The performance of the V2V and the V2I, after incorporating the overload factor on the network, is presented in Figure 3.6. As shown, V2V is not affected by the overload of the network. This is due to the increased connectivity coverage due to increase in the vehicle density.

In Figure 3.7, we compare the message propagation delays for HP and LP messages versus different vehicle densities. As expected, when the probability of HP messages increases, the message propagation delay increases for higher vehicle densities. Figure 3.8 compares the message propagation delays for the same case after introducing the load balancing mechanism. Figures 3.9, 3.10, and 3.11 present the number of packets that experience different message delivery delays in both schemes.

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2We ignored the collision and contention due to increased number of packets
Figure 3.5: (a) Average message propagation delay for increasing vehicle density for V2V, V2V Bridged and QoSHVCP at a fixed speed. (b) Average message propagation delay for increasing vehicle density in pure infrastructure communications at different uplink and downlink rates.
Figure 3.6: The effect of the network overload on both V2V and V2I.
Figure 3.7: Message propagation delay for High and Low Priority messages with different probabilities of High Priority without load balancing mechanism.
Figure 3.8: Message propagation delay for High and Low Priority messages with different probabilities of High Priority with our load balancing mechanism.
Figure 3.9: Number of packets experiencing different message propagation delays at the vehicle density of 65 [veh/km] and HP message probability of 0.2.
with and without load balancing mechanism. These message delivery delays are at
the vehicle density of 65 [veh/km]. They primarily represent high priority packets
with probability 0.2, 0.3, and 0.4, respectively.

Figure 3.10: Number of packets experiencing different message propagation delays at
the vehicle density of 65 [veh/km] and high priority message probability of 0.3.

3.6 Summary

In this chapter, we have investigated QoSHCVP, a Hybrid Vehicular Communica-
tion Protocol with QoS prioritization, combining both V2V and V2I approaches. In
order to avoid disconnections and maintain a seamless connectivity, vehicles should
exploit any available connectivity link that may be present in the vehicular grid.
Figure 3.11: Number of packets experiencing different message propagation delays at the vehicle density of 65 [veh/km] and high priority message probability of 0.4.
Based on a delay-based decision criterion, our approach represents a *handover* mechanism between V2V and V2I.

We have illustrated the effectiveness of such technique in terms of message delivery time delay rates. Simulation results confirm our analytical work on how hybrid approach enhances the connectivity support, specially in high mobility and low density vehicle scenarios as compared to traditional opportunistic V2V techniques for dense areas.

The effect of traffic overload on the message propagation delay has also been presented. The failure of achieving QoS requirements has been addressed with our novel *load balancing mechanism* that decreases the message propagation delay of high priority packets regardless of the network overload.

The main contributions presented in this chapter can be summarized as follows:

- **A Hybrid protocol for vehicle communication on highway:** We presented a hybrid protocol that utilizes both vehicle-to-vehicle communication as well as vehicle-to-infrastructure communication in order to achieve a low message delivery delay.

- **An analytical model that formulates the end-to-end message propagation delay:** In order to get this formula, we analyzed the vehicle connectivity as one of three possible scenarios: vehicle travelling alone, vehicle travelling along with other vehicles on the highway, and vehicle travelling within the coverage of road side units (infrastructure). The average delay formula accounts for different connectivity scenarios with the probability of the vehicle being in each scenario.

- **Infrastructure load analysis and a load balancing mechanism:** We in-
roduced the effect of increasing the load on the throughput of infrastructure. We presented the impact of this overload on the end-to-end message delivery delay. A load balancing mechanism was introduced to minimize the effect of this overload.

- **Simulation results:** We presented simulation results that analyzed end-to-end message propagation delay versus the vehicle density in a highway scenario. We simulated the effect of the infrastructure overload on the message delivery delay. We finally simulated the performance of our load balancing mechanism.
Chapter 4

CAREFOR for VANET

In this chapter, we introduce a novel reliable and low-collision packet-forwarding scheme for vehicular ad hoc networks, based on a probabilistic rebroadcasting. Our proposed scheme, called Collision-Aware REliable FORwarding (CAREFOR) works in a distributed fashion where each vehicle receiving a packet, rebroadcasts it based on a predefined probability. This probability is manipulated by different physical factors derived from the vehicular environment, including density of the vehicles in the vicinity, distance between transmitting and receiving vehicles, and finally, transmission range of the next-hop. All these factors are combined into one probability that enables each vehicle to evaluate whether there is another vehicle that ought to be receiving this message and could be feasible if the message is rebroadcasted. The success of rebroadcast is determined based on allowing the message to travel the furthest possible distance with the least amount of packet rebroadcast collision.

CAREFOR is different from other existing techniques as it accounts for the effect of the next-hop transmission in the rebroadcast decision. Simulation results show the effectiveness of our approach in terms of limited number of rebroadcasts needed with
low collision probability as compared to existing techniques. Two and three-hops message retransmissions are also considered.

4.1 Introduction

Frequent topological changes of a VANET makes it not very efficient to rely on existing MANET protocols. Rebroadcasting packets by multiple vehicles causes an increase in redundant data, which leads to wasted bandwidth and misuse of radio channels in the network. One of the main objectives of packet rebroadcasting in a VANET is to minimize this redundancy while still guaranteeing packet delivery to all relevant vehicles.

Due to these unique features of a VANET, several types of routing protocols have been introduced in the literature [60]. These protocols are mainly defined taking certain attributes of the VANET into account, such as (i) connectivity-based, (ii) mobility-based, (iii) infrastructure-based, (iv) location-based, and (v) probability-based routing protocols. Later on, many techniques are used to exploit probability theory in systems’ dynamic, representing the likelihood of certain events, such as the probability of link breakage at a given transmission power. Many such routing protocols utilize a probability model to indicate the state of a wireless communication link between two adjacent nodes, while using many different parameters (e.g., link lifetime in the network) as a major routing parameter.

In this research, we propose a probability-based multi-hop broadcast protocol, called Collision-Aware RELiable FORwarding (CAREFOR) with an objective of reducing the number of rebroadcasts in the network. This minimizes the number of packets in the system which leads to a lower collision probability and eventually im-
proved throughput. CAREFOR achieves this by allowing the vehicles to compute the probability of their successful transmission in case they are selected to rebroadcast the packet if there exists no better candidate for rebroadcast. A better candidate would be a vehicle that has a chance of delivering the packet for a larger number of uncovered vehicles with fewer number of retransmissions and with minimum packet collisions. Hence, the CAREFOR algorithm relies both on collision avoidance and reliable forwarding mechanism. By using both, CAREFOR is able to limit the number of retransmissions while maintaining lower collision value.

The rest of this chapter is organized as follows. Subsection 4.2 discusses some recent research on routing protocols for VANETs. We mainly highlight the work of [61], which is the foundation of our CAREFOR technique. In Subsection 4.3, we describe CAREFOR algorithm with details mainly covering the theoretical analysis of the next-hop vehicle election probability, and the collision probability estimation. Considerations on the use of two vs. three hops forward prediction are also investigated in order to determine the optimal approach. The simulation results demonstrates the effectiveness of our technique and is presented in Subsection 4.4. Finally, conclusion and future work are drawn in the last subsection.

4.2 Related Work

Many categories of routing protocols in VANETs have been described in the literature over the past few years. One of these schemes is the probability-based routing protocol that avoids flooding of the network with duplicates of the same packet by assessing availability of the links and reachability of the packet to the destination through a given multi-hop route. Clearly, the advantage of such technique is to reduce
the overall required number of packets in the system that improves the performance by minimizing the number of collisions. If each vehicle rebroadcasts probabilistically, the number of duplicate packets could be considerably lowered in the system. This type of routing protocols have been used in many papers. These techniques opportunistically select the next hop based on a given specific criteria. The most common rule is the ability to retransmit the packet successfully. This is affected by different physical factors of the environment and the network. Examples for these physical factors include: transmission power, received signal strength, vehicle density, vehicle speed, etc.

In [62], authors presented a ticket-based technique as a routing protocol. These tickets are control packets transmitted on selected links which is based on the metrics of stability, delay and cost. Ticket-based systems were initially introduced in MANETs [63] with the objective of identifying a reliable route based on multiple links that are selectively probed.

Jiang et al. [64] presented a routing algorithm defined as REAR, which considers the reception probability of the alarm message and analyzes similar to a real wireless channel model in a VANET. Particularly, the probability model takes into account physical parameters, such as the received signal strength, the path loss as well as the diffraction loss factor. The receipt probability is computed by using the relationship between the packet loss rate and the received signal strength. The links with highest reception probability of additional vehicles are then selected for routing.

Sun et al. [65] proposed GVGrid algorithm to find a reliable routing path that meets a given delay requirement. By assuming an equally spaced inter-vehicle gap and a normally distributed vehicle speed, GVGrid computes the probability of link lifetime as a function of link reliability. The proposed technique will select that path
with the highest reliability, and relatively smaller link delay as the routing path.

Common to all previous techniques, physical parameters play an important role for the rebroadcast probability and the link selection. In [66], the authors present a rebroadcast probability that is based on the inter-vehicle distance. This probability is directly proportional to the distance from the transmitter. The larger the distance is, higher will be the rebroadcast probability.

From [66], the rebroadcast probability is a function of inter-vehicle distance and can be expressed as:

$$p = \frac{d}{z},$$  \hspace{1cm} (4.1)

where \(d\) is the distance between receiving and transmitting vehicles, and \(z\) is the transmission range. The rebroadcast probability follows a linear dependence that increases with the distance.

Based on this technique, the authors in [61] present a protocol named Irresponsible Forwarding (IF) which accounts for both the signal strength, as well as the statistical distribution of the vehicles. The main idea behind IF is that each vehicle evaluates the presence of other vehicles within the transmission range of the source vehicle. If the receiving vehicle evaluation results in the likeliness of the presence of another vehicle that is better qualified to rebroadcast the packet, the vehicle decides irresponsibly to refrain from rebroadcasting the packet. A more qualified vehicle is the one that will be able to cover a longer distance with one hop transmission if it is allowed to rebroadcast the packet.

Therefore, a vehicle that receives a packet, should rebroadcast it only if the probability of finding a better qualified vehicle in the transmission range is very low. If the probability is very low, then the vehicle should avoid rebroadcasting the packet. In [61], the authors define the rebroadcast probability for a receiving vehicle as:
where $d$ is the inter-vehicle distance between the receiving and the transmitting vehicles, $\rho$ is the exponentially distributed inter-vehicle spacing [veh/m] with mean value $1/\rho$, and $c \leq 1$ is a coefficient which can be selected to shape the rebroadcast probability (as a function of $d$).

It is clear from the equation that the larger the value of $c$, higher will be the rebroadcast probability will be at any value of $d$. In the case that $c = 1$, the rebroadcast probability is reduced to the probability of no vehicles in the range of $(z - d)$.

The IF protocol is a very effective approach in order to limit the number of rebroadcasts in the system. However, it has one major limitation as it fails to account for packet collision from the vehicle that rebroadcasts. Since IF is a probabilistic approach, more than one vehicle may decide to rebroadcast the message, which will cause packet collision, and hence, the loss of the packet. In order to overcome this limitation, the authors in [67] leveraged the assumption that vehicles travel on the highway within the cluster with high probability. The authors present a protocol in which a cluster-head is elected within each cluster which is responsible for rebroadcasting the packet, while other vehicles in the cluster refrain from rebroadcasting. This avoids the occurrence of packet collisions within the cluster, and minimizes the number of rebroadcasts in the network.

The main disadvantage of the cluster-based approach is that it is a centralized protocol. While this can be feasible in MANETs, it is difficult to generalize for a VANET. The high mobility of a VANET makes creating clusters very difficult on the highway, since different vehicles are added and others leave the cluster within a very short span of time. Moreover, cluster-based approach entails different security
weaknesses and adds to the existence of malicious nodes in the cluster.

Finally, the IF approach [61] relies mainly on the coverage range of the transmitting vehicle, i.e., \( z \) [m]. IF only accounts for the probability of another vehicle being present in the range \((z - d)\) [m] at a distance \( d \) [m] from the transmitting vehicle. If this probability yields to absence or a low chance of having any other vehicles in this range, the vehicle will rebroadcast the packet. IF relies on the assumption that all the vehicles have the same transmission range. Hence, the vehicle density metric within the transmission range of any vehicle is dependent only on the distribution of the vehicles on the highway. This assumption does not always hold good in a real life scenario. In case this assumption is not true, this will result in a different vehicle density within the transmission range of every vehicle. This vehicle density will not only depend on the vehicle distribution, but on the transmission range of the vehicle as well. Another limitation in the IF protocol is the assumption of a collision-free environment, which is not true in a VANET and ought to be relaxed in a realistic protocol.

In this research, we consider IF approach as the foundation for our novel probability-based protocol that minimizes the redundancy caused by the packet retransmission. Moreover, this protocol aims to reduce the packet collisions in the system. The main focus of CAREFOR is to enhance the performance, as observed by the simulation results. We also present a thorough theoretical analysis, and investigate the effect of including two and three-hops information as factors in computing the rebroadcast probability.
4.3 Collision-Aware REliable FORwarding

In this section, we introduce the CAREFOR technique, and discuss the main rationale behind it, reliable forwarding and collision probability. The CAREFOR protocol particularly exploits twofold probabilistic analysis, aiming (i) to limit the number of packet collisions, and (ii) to select potential vehicle forwarder. CAREFOR takes into consideration reduction in the packet collision probability by estimating and selecting the next-hop forwarder for every single transmission as a method for packet rebroadcasting. One of the main improvements of the CAREFOR algorithm over other traditional approaches is that it accounts for more than one-hop neighbor information as the traditional approaches do. CAREFOR relies on the probability obtained from information extended to the next hop(s) (i.e., from two to three hops).

We discuss the reliable forwarding and the collision probability in Subsection 4.3.1 and Subsection 4.3.2, respectively. An analytical model for message rebroadcast probability has been developed in Subsection 4.3.3. In Subsection 4.3.4, the main features of CAREFOR are presented in an algorithmic form. Finally, in Subsection 4.3.5 we investigate the benefits of CAREFOR technique based on information from two and three hops.

4.3.1 Reliable Forwarding

Before we introduce our proposed technique, we present an example that elaborates on the reason for considering two-hop (prediction) information in order to compute the rebroadcast probability instead of the traditional one-hop method.

Consider Figure 4.1, with the vehicle has a transmission range of $z \text{ [m]}$. We make a basic assumption that each vehicle has the knowledge of its exact location
using a Global Positioning System (GPS), and that this location is piggybacked along with the data packets to other vehicles in the vicinity. As shown in this example, there are two vehicles (i.e., the dark (i.e., \(v_1\)) and light colored (i.e., \(v_2\)) vehicle in Figure 4.1), within the transmission range of the source vehicle (i.e., \(v_0\)). Both vehicles are at a distance \(d' \) [meter] and \(d'' \) [meter] respectively, where \(d'' > d'\). Following the traditional IF protocol [61], the rebroadcast probability for vehicle \(v_2\) is higher than that for vehicle \(v_1\) since the probability is directly proportional to the distance from the source vehicle \(v_0\). From this example, it is clear that the IF limits the rebroadcast probability to control the one-hop transmission and reflect the inter-vehicle distance.

In the IF protocol, it is assumed that each vehicle has the same transmission range. This assumption may not be true in real life and the transmission range could vary from vehicle to vehicle due to different factors, including the transmission power, as well as signal effects such as multipath or fading. A practical algorithm should incorporate these factors in computing the rebroadcast probability, since the objective of a selected forwarding vehicle is to be able to forward the packet as fast as possible, and hence, minimize the number of required packet rebroadcasts in order to reach all the vehicles in the group.

Since the objective of any routing algorithm is to forward the packet to the destination through the most efficient route, a successful forwarder should not be considered based on the performance from only the one-hop transmission point of view. If possible, the effect of the hops following, beyond the first hop ought to be considered when selecting the first forwarder. In other words, the best routing protocol would be able to aggregate the effect of every hop from the source to the destination, and select the first forwarder based on which one will provide the best overall coverage. In our work, we investigate the effect of relying on information from two hops as well
Figure 4.1: Schematic of RF approach in a vehicular network. The vehicle $v_0$ is a source transmitting a packet to potential forwarding vehicles within its transmission range (i.e., $z$). The basic assumption is that vehicles may have different transmission ranges (i.e., $z'' < z' < z$), which affect the next-hop rebroadcast probability.

as three hops by piggybacking in the process of selecting the first hop vehicle. The effect of these factors can be included in the IF probability as:

$$p = \exp \left[ -\rho \cdot \frac{(z - d)}{c} \cdot \frac{z}{z_i} \right].$$  \hspace{1cm} (4.3)

It may be noted that such a new IF probability would include the difference in the two-hops transmission ranges, i.e., $z$ and $z_i$ [m] are the transmission ranges of the source, and of the $i$-th receiving vehicle, respectively. The ratio $z/z_i$, with $z \neq z_i$, is useful as we assume each vehicle has a different transmission range.

If we consider the example of Figure 4.1, ($i = 2$) vehicles are candidate for potential retransmission; the dark $v_1$ vehicle has a transmission range of $z_{(i=1)} = z' = 150$ m, the light $v_2$ vehicle has a range $z_{(i=2)} = z'' = 50$ m, and the source vehicle has a

\footnote{Notice that this work considers up to two hops, and investigate the use of three hops. The reason that an aggregate for all hops from source to destination cannot be considered in VANETs is due to the dynamically changing topology of the network. It will be shown later via simulation that the improvement from three hop information from two hop information is not very useful in a vehicular environment.}
transmission range \( z = 200 \) m. As mentioned earlier, the traditional IF rebroadcast probability is based on the distance between the source and the receiving vehicle, as well as the vehicular density. Hence, based on (4.2), assuming that \( \rho = 0.02 \), \( c = 2 \) and \( d'' = 150 \) m, the traditional IF rebroadcast probability for the green vehicle will be 0.6. If we assume that \( d' = 100 \) m, the IF rebroadcast probability for the \( v_1 \) dark vehicle will be 0.36. Hence, the \( v_2 \) light vehicle will be selected based on the higher rebroadcast probability, while \( v_1 \) will not rebroadcast.

If we relax the assumption that vehicles have the same transmission range, and if we note that the objective of the routing protocol is to eventually transmit the packet to the longest distance with the least number of rebroadcasts along the route, then the vehicle that provides an overall largest aggregate transmission distance should be selected. In this case, the \( v_1 \) vehicle should be selected, since its next-hop transmission range is larger than that of \( v_2 \) vehicle (i.e., \( z' > z'' \)), resulting as the most efficient rebroadcaster. This allows the packet to potentially reach a larger number of vehicles in a fewer number of rebroadcasts, and hence reducing the span of time. The RF probability for the dark vehicle is 0.26, while for the light vehicle it is 0.13.

Allowing the vehicles to estimate the potential for future second hops vehicles shifts the paradigm of the protocol from being irresponsible forwarding to be a stable and reliable protocol. Hence, the new probability metric is named Reliable Forwarding (RF). The behavior of the RF probability for two-hop forward transmission versus different transmission ranges is depicted in Figure 4.2. It may be noticed from the figure that the RF probability depends on the distance between the source and the destination as well as the transmission range. The main advantage for RF over IF, is that IF only considers one hop rebroadcast, while the RF introduced here considers the two hops rebroadcast as well. It also can be observed from (4.3) that when the
transmission range of the receiving vehicle is equal to that of the source vehicle \((i.e., z' = z)\), the value of the RF probability is equal to that of the IF probability.

As it is shown in Figure 4.2, the RF probability allows a vehicle with a larger transmission range to have a higher value for the RF probability. This results in better chances of rebroadcasting the message and allowing the packet to reach an increased number of vehicles due to the transmission range covering a larger distance. The main disadvantage is that the larger the covered area, higher will be the number of vehicles in the transmission range, which could result in a higher packet collision probability. Hence, we address this issue in the following section.

4.3.2 Collision Probability

The authors in [68] define the collision probability as the probability that more than one vehicle is transmitting at the same time. In order to model this probability, \(P_{\text{coll}}\), we initially need to analyze the probability that there is at least one vehicle transmitting in the current time slot, \(P_{\text{busy}}\). This can be defined by:

\[
P_{\text{busy}} = 1 - (1 - p)^{(n-1)},
\]

where \(p\) is the RF probability from (4.3), which is the probability that the vehicle will decide to rebroadcast the packet in this instance, and \(n\) is the number of other vehicles interfering with this transmission. As we assume that \(N\) is the number of vehicles interfering in every hop, and our RF probability considers only two hops, the total number of interfering vehicles will be \(n = 2N\).

Based on \(P_{\text{busy}}\), we can define another probability \(P_t\), which is the probability that there is only one vehicle using in the channel at this time. The probability can be
given by:

\[ P_t = \frac{p \cdot (1 - p)^{n-1}}{P_{busy}}. \]  \hspace{1cm} (4.5)

Based on (4.4) and (4.5), we can define the collision probability \( P_{coll} \), which is the probability that more than one vehicle is transmitting, causing the collision. Hence, \( P_{coll} \) is:

\[ P_{coll} = P_{busy} \cdot (1 - P_t). \]  \hspace{1cm} (4.6)

In Figure 4.3 \( (a) \), we observe collision probabilities for different next-hop transmission ranges \( i.e., \) \( z_i \in \{100, 200, 400\} \) m, in a forward packet transmission v/s the transmission range of the source \( i.e., \) \( z = 200 \) m. As expected, we can notice that a larger next hop transmission range results in a higher collision probability. However, this result is obtained against the RF probability, as depicted in Figure 4.2, since for high next-hop transmission range, the RF probability increases for growing distance from the source.

In order to decide which vehicle should be allowed to forward the packet due to experiencing a low collision probability versus which vehicles are experiencing a high collision probability, we need to define a threshold. This threshold is based on different physical factors in the network, such as the next-hop transmission range \( i.e., \) \( z_i \) [m], and the number of vehicles—the vehicle density \( i.e., \) \( \rho \) [veh/m]. We define the collision threshold as:

\[ Th_{coll} = 1 - \exp (\rho z_i). \]  \hspace{1cm} (4.7)

In Figure 4.3 \( (a) \), this threshold is presented by the horizontal line at 0.4. Note
that the threshold varies for different transmission ranges. As shown in the figure, for transmission ranges of \([100, 200, 400]\) m, the collision threshold of (\(i.e., 0.4\)) is at distances \([172, 143, 86]\) m respectively from the source. This means that any vehicle with a transmission range of 100 m, and is at a distance smaller than 172 m from the source, should be able to satisfy the collision probability threshold. The smaller the transmission range, the higher the distance from the transmitter can be, hence, more vehicles will have a collision probability lower than the threshold.

For a fixed source transmission range (\(i.e., z = \{100, 200, 400\}\) m), Figure 4.3 \((b)\) presents the behavior of the threshold for the collision versus the vehicle density. Notice that if the vehicle density is fixed, the collision threshold is indirectly proportional with the transmission range.

### 4.3.3 Analytical Model

Let us consider the scenario where an information packet propagates forward from a source vehicle, as previously depicted in Figure 4.1. The message direction is the same as that of the vehicle speed, and we assume vehicles are being driven along the lane following a Poisson distribution.

In such a scenario, we consider the average number of packets collectively being rebroadcasted by the vehicles in the network. More specifically, we need to distinguish how many packets are retransmitted by the other vehicles for each hop in the vehicular network. This coincides with the average number of vehicles that rebroadcast the packet transmitted by the source vehicle which experiences a low collision probability. Obviously, we implicitly assume each vehicle rebroadcasts only one copy of each received packet and then no more copies of the same packet need to be retransmitted within the network.
As shown in Figure 4.1, following a Poisson distribution with parameter \( \lambda \) we assume there are \( N_z \) vehicles in the transmission range \( z \) of the source vehicle. Each vehicle in the range \((0, z)\) can rebroadcast a packet based on its RF probability and this event can be represented by the following Bernoulli random variable:

\[
V_i = \begin{cases} 
1, & \text{if } i\text{-th vehicle rebroadcasts} \\
0, & \text{otherwise},
\end{cases}
\]  

(4.8)

with \( i = 1, 2, \ldots, N_z \), as the \( i \)-th candidate vehicle for rebroadcasting. It follows that the average number of vehicles in \((0, z)\) which can rebroadcast the packet, is represented by means of a random variable \( M_z \), as follows:

\[
E[M_z] = \sum_{i=1}^{N_z} V_i.
\]

(4.9)

Since \( N_z \) follows a Poisson distribution with parameter \( \lambda z \), by applying the law of total probability and observing that

\[
E[M_z | N_z = 0] = 0.
\]

(4.10)

Then, the average number in (4.9) can be rewritten as follows:

\[
E[M_z] = \sum_{n=1}^{\infty} E[M_z | N_z = n] P\{N_z = n\} = \sum_{n=1}^{\infty} E\left[\sum_{i=1}^{N_z} V_i | N_z = n\right] P\{N_z = n\} = \\
= \sum_{n=1}^{\infty} \sum_{i=1}^{n} E[V_i | N_z = n] P\{N_z = n\} = \sum_{n=1}^{\infty} e^{(-\lambda z)}(\lambda z)^n n! \sum_{i=1}^{n} E[V_i],
\]

(4.11)

Based on Bernoulli behavior of \( V_i \) random variable, we can obtain the average number
of rebroadcasting vehicles based on the corresponding RF probability:

$$E[V_i] = P \{ V_i = 1 \},$$

(4.12)

where $P \{ V_i = 1 \}$ is the probability of rebroadcasting for the $i$-th vehicle (i.e., RF probability). As per (4.3), this probability depends on both the distance $d_i = \tau$ of the $i$-th vehicle from the source vehicle, as well as on the transmission range $z_i = \delta$ of the $i$-th vehicle:

$$P \{ V_i = 1 | d_i = \tau, z_i = \delta \} = \exp \left[ -\frac{\rho \cdot (z - \tau)}{c} \cdot \frac{z}{\delta} \right].$$

(4.13)

By applying the total probability theorem, (4.13) can be written as:

$$P \{ V_i = 1 \} = \int_0^\infty P \{ V_i = 1 | d_i = \tau, z_i = \delta \} f_{d_i}(\tau) f_{z_i}(\delta) \, d\tau \, d\delta =$$

$$= \int_0^z \int_0^\delta \exp \left[ -\frac{\rho \cdot (z - \tau)}{c} \cdot \frac{z}{\delta} \right] f_{d_i}(\tau) f_{z_i}(\delta) \, d\tau \, d\delta,$$

(4.14)

where $f_{d_i}(\cdot)$ and $f_{z_i}(\cdot)$ are respectively the probability density functions (pdf) of the distance $d_i$ [m] and the transmission range $z_i$ [m] of the $i$-th vehicle.

Assuming that each vehicle is traveling along with a Poisson distribution within the transmission range, following a linear path, then the distance $d_i$ can be expressed as the sum of the distances of the vehicles behind the $i$-th vehicle in the range $(0, z)$, such as:

$$d_i = \sum_{j=1}^{i-1} y_j,$$

(4.15)

\footnote{We assume that the vehicles from 1 to $N_z$ are in an increasing order of distance from the origin.}
where \( y_j \), with \( j = i - 1 \), is the distance from the \( j \)-th vehicle to the \( i \)-th vehicle. Assuming the variables \( y_j \) are randomly independent and identically distributed (i.i.d.) with exponential distribution with mean value \( 1/\rho \), then \( d_i \) follows Erlang distribution with parameters \( i \) and \( \rho \) as:

\[
f_{d_i - \text{Erlang}}(\tau) = \frac{\rho e^{-\rho \tau} (\rho \tau)^{i-1}}{(i-1)!} U(\tau),
\]

where \( U(\tau) \) is the unit-step function, limited to be lower than \( z \). The pdf of the distance \( d_i \) from the source vehicle can be written as:

\[
f_{d_i}(\tau) = f_{d_i - \text{Erlang}}(\tau | d_i \leq z) = \begin{cases} f_{d_i - \text{Erlang}}(\tau) & \text{if } 0 < d_i \leq z \vspace{1mm} \\ 0 & \text{otherwise} \end{cases},
\]

where \( F_{D_i - \text{Erlang}}(z) \) is the cumulative distribution function (CDF) of an Erlang pdf with parameters \( i \) and \( \rho \). In particular, it can be shown that

\[
F_{D_i - \text{Erlang}}(z) = \frac{\gamma(i, \rho z)}{(i-1)!},
\]

where \( \gamma \) is the lower incomplete gamma function:

\[
\gamma(i, \rho z) = \int_0^{\rho z} t^{i-1} e^{-t} dt.
\]

Finally, (4.17) becomes

\[
f_{d_i}(\tau) = \frac{\rho e^{-\rho \tau} (\rho \tau)^{i-1}}{\gamma(1, \rho z)} [U(\tau) - U(\tau - z)].
\]

Similar substitutions can be done for the \( f_{z_i}(\cdot) \) pdf of the transmission range \( z_i \).
for the $i$-th vehicle. We distinguish two cases, i.e., (i) for $z_i = z$, and (ii) for $z_i > z$.

In the former case, we can write

$$z_i = z = \sum_{j=1}^{N_z} y_j,$$  \hspace{1cm} (4.21)

and that follows:

$$f_{z_i \sim \text{Erlang}}(\delta) = \frac{\rho e^{-\rho \delta} (\rho \delta)^{i-1}}{(i-1)!} U(\delta),$$  \hspace{1cm} (4.22)

with $i = N_z$. The pdf of the transmission range $f_{z_i}(\cdot)$ can be expressed as:

$$f_{z_i}(\delta) = f_{z_i \sim \text{Erlang}}(z_i | \delta \leq z) = \begin{cases} \frac{f_{z_i \sim \text{Erlang}}(z_i)}{F_{z \sim \text{Erlang}}(z)}, & \text{if } 0 < z_i \leq z \\ 0, & \text{otherwise} \end{cases},$$  \hspace{1cm} (4.23)

It follows as:

$$f_{z_i}(\delta | z_i = z) = \frac{\rho e^{-\rho \delta} (\rho \delta)^{i-1}}{\gamma(1, \rho z)} [U(\delta) - U(\delta - z)].$$  \hspace{1cm} (4.24)

In the second case, for $z_i > z$, we can write:

$$z_i = z + \Delta z = \sum_{i=1}^{N_z} y_i^{(z)} + \sum_{j=1}^{N_{\Delta z}} y_j^{(\Delta z)},$$  \hspace{1cm} (4.25)

$$f_{z_i}(\delta) = f_{z_i \sim \text{Erlang}}(z_i | \delta > z) = \begin{cases} \frac{f_{z_i \sim \text{Erlang}}(z_i)}{F_{z \sim \text{Erlang}}(z)}, & \text{if } z_i > z \\ 0, & \text{otherwise} \end{cases},$$  \hspace{1cm} (4.26)

and then,

$$f_{z_i}(\delta | z_i > z) = \frac{\rho e^{(-\rho \delta)} (\rho \delta)^{N_{z_i} - 1}}{(N_{z_i} - 1)!} U(z).$$  \hspace{1cm} (4.27)

By using (4.17) and (4.24) into (4.14), the RF probability becomes:
\[ P \{ V_i = 1 \} = \int_0^\infty \int_z^\delta \exp \left[ -\rho \frac{(z - \tau) z}{c} \frac{\rho \exp [-\rho \tau] (\rho \tau)^{i-1}}{\gamma(i, \rho z)} \cdot \frac{\rho \exp [-\rho \delta] (\rho \delta)^{i-1}}{\gamma(i, \rho z)} \right] d\tau d\delta = \]

\[ = \frac{\rho^2}{\gamma^2(i, \rho z)} \int_0^\infty \int_z^\delta \exp \left[ -\rho \frac{(z - \tau) z}{c} \frac{\rho \exp [-\rho \tau] (\rho \tau)^{i-1}}{\gamma(i, \rho z)} \cdot \frac{\rho \exp [-\rho \delta] (\rho \delta)^{i-1}}{\gamma(i, \rho z)} \right] d\tau d\delta = \]

\[ = \frac{\rho^2}{\gamma^2(i, \rho z)} \int_0^\infty \int_z^\delta \exp \left[ -\rho \frac{z^2 + \tau z - c\delta \tau - c\delta^2}{c\delta} \right] (\rho \tau)^{i-1} \cdot (\rho \delta)^{i-1} d\tau d\delta. \quad (4.28) \]

### 4.3.4 CAREFOR algorithm

In this subsection, we present the details of how the CAREFOR protocol can actually work in a VANET environment. As mentioned earlier, the protocol includes two main phases: (i) Collision probability estimation, and (ii) Reliable forwarding.

CAREFOR considers a contention resolution procedure necessary for each vehicle to estimate the collision threshold associated with the vehicle density and the actual transmission ranges. The procedure follows in several steps which can be described as follows:

- **RTB transmission**: In this step, the source vehicle broadcasts a Request-to-Broadcast (RTB) control message to all the vehicles in its vicinity. The RTB message is a MAC-broadcast packet which includes the GPS information of the source node, the vehicle density around the source node (which can be found out by ping messages), and finally, the transmission power level.

Notice that, since the transmission ranges are relatively short (i.e., lower than 400 meter), we assume that the local vehicular density can approximate the global vehicular density within the transmission range. Moreover, the transmis-
sion power level is used as a factor indicating the source’s transmission range (i.e., $z \ [\text{m}]$).

- **Collision Assessment**: Once the RTB transmission is received, each vehicle utilizes the information in the RTB packet in order to compute the collision threshold as identified in 5.8. Once the threshold is determined, the vehicle finds its own collision probability using equation 4.6. Once both values are obtained, the vehicle identifies whether it qualifies for the next phase of RF probability computation, or not and hence will refrain from retransmission. This phase acts as the first filtering phase in order to eliminate the vehicles that are non-qualified as rebroadcasters, and only a subset of vehicles are selected as potential message forwarders.

- **CTB transmission**: Once a vehicle is qualified to enter the RF probability computation phase, it sends a Clear-to-Broadcast (CTB) packet to the source. This CTB message includes the vehicle ID, the GPS location of the qualified vehicle (see Table 4.1). The CTB packets are used to inform the source of the qualified rebroadcast forwarders.

The phase of collision probability estimation is combined with the transmission of valid CTB packets. The main aim of *Collision Assessment* process is to identify those vehicles within a transmission range that are able to rebroadcast the packet with a low collision probability. This phase represents the initialization process to guarantee the next packet retransmission phase with minimum collisions.

The *Reliable forwarding* process is controlled by each vehicle with a low collision probability; the message is rebroadcasted initially by vehicles with a higher RF probability, then the lower probabilities. In order to achieve that, a waiting time, (i.e.
Table 4.1: Message exchanged classification and content.

<table>
<thead>
<tr>
<th>Message</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTB</td>
<td>– Source node’s position</td>
</tr>
<tr>
<td></td>
<td>– Vehicular density</td>
</tr>
<tr>
<td></td>
<td>– Transmission power level</td>
</tr>
<tr>
<td>CTB</td>
<td>– Vehicle’s ID and position</td>
</tr>
</tbody>
</table>

Table 4.2: Simulation Parameters.

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Runs</td>
<td>100</td>
</tr>
<tr>
<td>Simulation Duration</td>
<td>50 s</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>[100, 250] m</td>
</tr>
<tr>
<td>Vehicle Density</td>
<td>[10, 60] veh/km</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Message Size</td>
<td>1 KB</td>
</tr>
<tr>
<td>Message Generation Rate</td>
<td>10 packets/s</td>
</tr>
</tbody>
</table>

\[ T_w \text{ [s]} \] — a backoff time — is computed as follows:

\[
T_w = [CW_{\text{min}} + (CW_{\text{max}} - CW_{\text{min}}) (1 - p)] \cdot t_{\text{slot}}, \tag{4.29}
\]

where \( p \) is the RF probability, \( t_{\text{slot}} \) is the number of time slots, and \( CW_{\text{max}} \) and \( CW_{\text{min}} \) are respectively the maximum and minimum contention window sizes. By using (4.29), the vehicles that experience a higher RF probability will transmit before the vehicles with a lower one. Based on the CSMA/CA of IEEE 802.11, the backoff time is decremented by 1 at each idle slot, and frozen in case the medium becomes busy.
4.3.5 CAREFOR as two hop vs. three hop algorithm

We further investigated the performance of the CAREFOR algorithm in a scenario that takes into consideration information from three hops instead of only two. Currently, the CAREFOR algorithm relies on the information from vehicles one hop away from the source in order to indicate which vehicles pass the threshold for reliable forwarding, and also relies on the second hop information in order to indicate which of these vehicles has a low chance of collision when the packet is being forwarded. In the three hop scenario, we considered one step further in which the collision probability of the two hop vehicle is taken into consideration, which is considered as the three hop information obtained from piggybacking. The collision probability of the third hop is averaged with the collision probability of the second hop, and both are taken in consideration when making a decision whether the vehicle passes the collision threshold requirement or not.

Feasibility of gathering three hops information in a VANET is rather tedious. This is because of the rapid movement of the vehicles in such a scenario. Information is only valid for a very short period of time. Hence, for the locality and collision data to propagate and be processed after the delay introduced by three hops will cease to be valid quite frequently even though piggybacking can be used, in principal. A detailed analysis on the comparison between two and three hops prediction in CAREFOR is investigated in Subsection 4.4.2. This will show whether a three-hop approach provides a major improvement over the current CAREFOR algorithm or not.
4.4 Simulation Results

In this section, we present results of extensive simulation to illustrate the performance and the advantage of the CAREFOR over the previous IF algorithm. In Subsection 4.4.1, we compare the collision probability, the percentage of successful transmissions, and the total throughput in the system in the case of CAREFOR versus the IF protocol. In Subsection 4.4.2, we show that for a two-hops prediction, CAREFOR works efficiently and extending to a three-hops prediction does not provide any effective improvement.

For these results, we used our own simulator that we have developed before for our previous work [69]. Each vehicle is assumed to be equipped with GPS device, as well as a IEEE 802.11b network interface card. Vehicles move at a constant speed of 20 m/s. Different parameters used in the simulation are given in Table 6.1. The simulation starts when a given source vehicle transmits a message to neighbors within its own transmission range.

4.4.1 CAREFOR v/s IF

In our simulations, we have compared the performance of the CAREFOR algorithm with the IF to demonstrate the advantage of our algorithm. Intuitively, the performance of the CAREFOR algorithm is expected to be better than IF, since CAREFOR adds two extra filtering factors in order to select the best rebroadcasting vehicle. This results in a lower number of overall packets in the system in the case of CAREFOR as compared to IF (due to the lower number of rebroadcasters). Furthermore, CAREFOR minimizes the number of rebroadcasts in the route to the destination, since its selection algorithm elects the rebroadcasters that are able to
deliver the packet to a further location in a two-hop transmission with the least number of rebroadcasts. Hence, it is expected that CAREFOR will outperform the IF technique. In order to compare both algorithms, both have been simulated after considering the collisions in the case of CAREFOR since the IF algorithm does not consider collisions.

In Figure 4.4, we compare the collision probability for CAREFOR and IF. We calculated the collision probability as the percentage of collisions in the duration of the simulation compared to the number of total attempted transmissions in the system. As it is clear from the figure, CAREFOR performs better than IF at all vehicle densities since CAREFOR considers minimizing the collision chances as part of the algorithm. As expected, collision probability increases as the vehicle density increases since more vehicles are present in the system.

We show the throughput for the CAREFOR and IF algorithms in Figure 4.5. We compute the throughput as the percentage of packets that have been received at the destination, compared to the total number of packets in the system which includes the collided packets, the packets just generated in the vehicle buffer, and the packets being transmitted through the system. Figure 4.5 illustrates the behaviour and the decreasing slope as the vehicle density increases. This is expected since as the vehicle density increase, the rate of increase in the number of the total packets in the system is larger than the rate of receiving the packets at the destination. With regards to the throughput in the system, it is expected that CAREFOR can perform better than IF since CAREFOR minimizes the number of total packets in the system as well as collisions by limiting the number of rebroadcasters, which is contrary to the IF.

Finally, in Figure 4.6, we compare the total number of successful transmissions for both CAREFOR and IF. Again, the number of successful transmissions are compared
to the total number of vehicles in the system. As it is shown, CAREFOR performs better than IF. Based on the previous results, it is clear that the CAREFOR algorithm improves the throughput, minimizes the collisions, and increases the number of successful transmissions as compared to the traditional IF. It is also worth mentioning that these improvements are achieved using CAREFOR in minimum latency since all one round trip for the control messages additional time is required.

### 4.4.2 Two vs. Three Hops Prediction

In order to validate the performance on CAREFOR further, we simulated the performance of the algorithm in case it considers three-hop information instead of just two-hops. First of all, feasibility of gathering three-hop information in VANET is difficult using a piggybacking scheme. This is because rapid movement of the vehicles in the vehicular scenario, which has a short-lived connectivity links and causes fast changes in the network. It follows that such information is valid only for few seconds. Data and collision information have to be propagated and processed, as additional delay is introduced by obtaining three-hop prediction and may make it to be invalid by the time it is done, or it maybe at least highly questionable.

However, we investigated the improvement introduced by three-hop information in order to validate the effectiveness of the CAREFOR algorithm. Figure 4.7 depicts the collision probability using the CAREFOR algorithm for two cases of two hop and three hop information. Figure 4.8 and Figure 4.9 present respectively the throughput and the percentage of successful transmission in both the scenarios. As it is expected, including three hop information yields only marginal improvement. However, as the simulation results show, this improvement is considerably small as compared to the benefits from one hop information (i.e., IF) to two hop information (i.e., CAREFOR).
Hence, using two hop information algorithm in CAREFOR is more cost efficient (in terms of delay, and validity of data) than utilizing three-hop algorithm.

4.5 Summary

In this chapter, we presented a novel algorithm, Collision-Aware Reliable Forwarding (CAREFOR), which is probabilistic rebroadcast scheme for VANETs. CAREFOR aims to improve the overall performance of the VANET system by minimizing the number of rebroadcasts required in order for a packet to reach a destination. It also relies on reducing the number of collisions using a distributed algorithm. CAREFOR is composed of two phases, a collision probability estimation phase, followed by a reliable forwarding phase.

We tested our system, and compared CAREFOR to an already existing Irresponsible Forwarding (IF) algorithm, [61]. Our simulation results demonstrate superiority of CAREFOR as compared to IF. This is clear from the performance of collision probability, the throughput, and the percentage of successful transmissions. Considerations about how many hops are necessary in CAREFOR for rebroadcast probability estimation have been also investigated, given that an end-to-end multi-hop approach is not suitable in vehicular networks.

As a future work, we will address validation of CAREFOR in real urban traffic scenarios, also assuming the deployment of road side units (e.g., WiFi access points, or base stations), as potential fixed nodes to forward messages.
Figure 4.2: RF rebroadcast probability as a function of the distance between the receiver vehicle and the transmitter. (a) Dependence on different values of \( c \), and \( \rho \). The solid lines are for \( z/z_i = 2 \), while dotted lines are for \( z/z_i = 0.5 \) m; (b) dependence on increasing next-hop transmission ranges i.e., \( z_i = 100, 200, 400 \) m, given \( c = 2 \), \( z = 200 \) m, and \( \rho = 0.02 \).
Figure 4.3: Analytical trends of (a) collision probability experienced by vehicles within a $z = 200$ m source's transmission range, and (b) collision probability threshold, vs. the vehicle density; for different next-hop transmission ranges, $n = 2$, $\rho = 0.04$ and $c = 5$. 
Figure 4.4: Comparison between IF and CAREFOR, in terms of collision probability, as a percentage of the collisions part of the total number of messages in the system, vs. the vehicular density. Notice that the collision reduction is provided by CAREFOR.

Figure 4.5: Comparison between CAREFOR and IF in terms of throughput, as a percentage of messages arrived to a vehicle receiver and relative to the total number of messages exchanged in the system, vs. the vehicular density. The high performance with CAREFOR is due to the high reduction of broadcast messages.
Figure 4.6: Comparison between CAREFOR and IF in terms of the percentage of successful transmissions vs. the vehicular density, w.r.t. the total number of transmissions including the collided attempts.

Figure 4.7: Collision Probability, as a percentage of the collisions part of the total number of messages in the system, in both three and two hops CAREFOR algorithm. A small increase of performance is provided by three hop CAREFOR approach.
Figure 4.8: Throughput, as a percentage of messages arrived to a vehicle receiver and relative to the total number of messages exchanged in the system, in both three- and two-hops CAREFOR algorithm. Minor improvement is provided with the three-hop prediction.
Figure 4.9: Percentage of successful transmissions compared to the total number of transmissions including the collided attempts, in both three- and two-hops CARE-FOR algorithm. Minor improvement is provided with the three-hop prediction.
Chapter 5

QASA: QoS-Aware Node Selection Algorithm

In this chapter, we present a QoS-Aware node Selection Algorithm (QASA) for routing protocols to be suitable for a particular class of opportunistic networks, i.e., the vehicular ad hoc networks. Our algorithm is focused on selecting the vehicle to communicate with and is achieved by exploiting the bridging approach for message forwarding (i.e., vehicles on the east (west) select from west (east)). The QoS metrics that are being optimized are the throughput in the network, as well as end-to-end delay for packets. In order to provide the best network performance, our algorithm utilizes a probabilistic rebroadcasting scheme that is based on different network parameters including vehicle density, inter-vehicle distance, and the transmission range for the vehicles. Moreover, QASA utilizes a transmission range based metric that can be changed as per application requirements, whether it is high throughput or minimum end-to-end delay. Simulation results show the effectiveness of our approach in terms of improved QoS metrics in different VANET scenarios.
5.1 Introduction

Opportunistic networking techniques allow mobile devices to exchange messages by having knowledge of the mobility patterns and accordingly explore the use of store-carry-and-forward approach. Following this technique, a message can be stored in a node and then forwarded using available wireless link to other nodes, as soon as a connection opportunity becomes feasible with a neighbouring device. Such occasionally used next-hop forwards information towards a desired destination.

In opportunistic networks, the assumption of a complete path between a source and a destination is relaxed, allowing mobile nodes to communicate with each other even if a route connecting them may not currently exist or may break frequently. Messages are cached in the network, and wait for an end-to-end path to be available. Thus, additional delays in message delivery can occur. For this reason, opportunistic networks belong to the class of Delay Tolerant Networks (DTN), since connectivity is provided despite long link delays or frequent link breakage due to nodes moving out of the range, or the environmental changes, or interference from other devices, etc.

Vehicular Ad hoc NETworks (VANETs) are a special kind of Mobile Ad hoc NETworks (MANETs) in which packets are exchanged between mobile devices (vehicles) travelling on constrained paths, in case of Vehicle-to-Vehicle (V2V) communications, and between vehicles and road-side access points, i.e., Road-Side Units (RSUs), in case of Vehicle-to-Infrastructure (V2I) communication.

Opportunistic forwarding is the main technique adopted in DTN [70], and has also been extended in VANETs to achieve connectivity between vehicles via V2V so as to disseminate traffic information [39, 71, 72]. In particular, the authors in [72] assume a bidirectional road, where vehicles’ clusters formed in one direction of the highway come in intermittent contact with other clusters traveling in the opposite
direction. Such contacts can be opportunistically exploited as a bridging technique, linking the partitioning that exists between clusters traveling in the same direction of the roadway. As a result, the connectivity can be maintained along the road.

On the other hand, exploitation of RSUs together with inter-vehicle communications represents a viable solution to extend connectivity support in those scenarios where vehicles are not able to directly communicate with each others. The use of V2I communications can bridge the inherent network fragmentation that exists in any multi-hop network in existing network infrastructure [73, 74]. As an analogy, a vehicular grid together with an opportunistic infrastructure deployed on the roads, can be a good solution to guarantee seamless connectivity in a dynamic vehicular scenario [75, 76], as well as hybrid vehicular communication paradigm with intermittent connectivity. In such an approach, connectivity can be provided by both existing network infrastructure (i.e., RSUs) through a V2I protocol, and traditional V2V networking [44, 45]. Such a combination is commonly referred to as V2X; the cooperation and coexistence of V2V and V2I methods can ensure a good connectivity for a VANET.

Based on the concept of bridging in a VANET, an open issue is the fact that any vehicle traveling along one direction (e.g., east) can select any of the multiple vehicles on the opposite side (e.g., west) of the roadway to carry the message. How to choose a next-hop forwarder is a real challenge, as an optimum choice should consider numerous factors such as the longest inter-vehicle distance, link connectivity time, mobility pattern, and so on.

This research addresses the best way to select the next-hop forwarder node assuming the use of bridging approach not only when (i) there is no connectivity link along one direction, but also when (ii) the network performance (i.e., link connec-
tivity time, and throughput) ought to be improved. Based on the Quality-of-Service (QoS) requirement of a given application, we propose a routing protocol, which relies on choosing an opportunistic node, named as QoS-Aware Node Selection Algorithm (QASA).

This chapter is organized as follows. In Section 5.2, we provide a background on existing routing protocols for vehicular networks which exploit opportunistic networking. Then, in Section 5.3 we introduce our proposed QASA protocol, and describe the main aspects through an analytical model, as well as the algorithm, respectively in Subsections 5.3.1 and 5.3.2. The effectiveness of QASA has been illustrated with simulation results, as covered in Section 5.4, specifically expressed in terms of throughput and time delay. Finally, conclusions are drawn at the end of this chapter.

5.2 Related Work

For the past few years, routing protocols for vehicular networks have been a topic of interest in the literature. These protocols are classified into different categories, such as the probability-based routing protocol. Such a protocol rely on the algorithm that allows selection of specific vehicles to communicate with amongst many vehicles within the communication range of the source vehicle. As the main advantage, the use of probability in selecting a routing protocol is based on avoiding the flooding of the network with duplicates of the same packet. Clearly, this provides a significant improvement in the performance of the network, since it reduces the number of collisions, and hence improves the throughput, as well as reduces end-to-end delay.

Among various probabilistic routing protocols in the literature, we recall the ticket-based techniques [62, 63], where the vehicle is selected based on stability, delay and
cost metrics. Authors in [64] presented REAR algorithm which considers reception probability of the alarm messages and exploit physical parameters like received signal strength measurements, the path loss and diffraction loss factor, so that next-hop vehicles can be selected. Another solution is the GVGrid algorithm [65] that is used to find a reliable routing path satisfying specific delay requirement. The algorithm determines the link lifetime based on the link reliability.

In [66], rebroadcast probability is a function of inter-vehicle distance, signal strength and the statistical distribution of the vehicles [61, 77]. In [61], the authors introduce Irresponsible Forwarding (IF) algorithm, so that each vehicle will refrain from broadcasting whenever likelihood of other qualified vehicles is present to rebroadcast a packet. Whether a vehicle is better qualified in IF is decided based on whether the packet will travel for a longer distance in one hop or not. The main disadvantage for IF stems from being a probabilistic approach, which results in more than one vehicle rebroadcasting the packet.

In [77], the CAREFOR technique considers the vehicle selection based on the probability that at least two vehicles will be qualified as the next-hop forwarders. Basically, CAREFOR considers not only the rebroadcast probability for one hop, but extends this probability up to two next-hops. This approach represents a two-hops prediction in selecting a qualified vehicle as an effective next-hop forwarder.

All these techniques are driven by reducing the replica of a packet within the vehicular network. However, many applications have different QoS requirements, which routing protocol should also maximize [78]. For example, throughput optimization has been considered in the literature, specially when addressing the issue of content distribution. In [79], authors developed CodeTorrent protocol that employs a network coding based file swarming protocol. They also investigated the effect of the
vehicular density and mobility on the performance of network coding. Authors in [80] developed a similar collaborative content distribution approach, which used a multi-hop randomized network coding in a decentralized approach. At the same time, low end-to-end delay should be achieved for safety point of view (e.g. quick braking) [78].

In this research, we consider a QoS-oriented and probability-based routing protocol for vehicular network that maximizes the throughout while considering end-to-end delay. The routing protocol is developed by selecting a vehicle from opposite side of the highway. In other words, for vehicle on east side selects a vehicle on the west side to communicate with and vice-versa. We investigate the effectiveness of our algorithm in two different vehicular scenarios (i.e., urban and highway).

5.3 QoS-Aware Node Selection Algorithm

In this section, we introduce the QoS-Aware Node Selection (QASA) algorithm, and discuss the major aspects behind its usefulness. The reference scenario is a vehicular network comprised of two lanes (i.e., lane E and W), where vehicles are being driven in opposite directions, as depicted in Figure 5.1. Let us assume vehicles on lane E (W) being driven to the east (west) direction. We consider the vehicular network to have a highly dynamic topology due to different mobility patterns that form vehicles’ clusters. As an instance, vehicles traveling on the roadway, along the east and west directions, are characterized by frequent link breakages that strongly hinder stable and durable V2V communications. In particular, a cluster formed in one direction of the highway comes in intermittent contact with clusters of vehicles travelling in the opposite direction. Such contacts can be opportunistically exploited as a bridge, linking the partitions that exist between clusters travelling in the same
Figure 5.1: Schematic of a vehicular opportunistic network, with bridging approach. A source (blue) vehicle shall select a next-hop forwarder from the opposite lane, since the forward inter-vehicular gap is too large for allowing V2V communications (i.e., $r_i^{(Tx)} > \delta_{ij}$). The blue and black boxes represent the source’s transmission range and the cluster size, respectively.

direction of the roadway. This reflects typical bridging connectivity in a VANET.

In such a scenario, let us consider a source vehicle being driven on the E lane. V2V communications along the E lane cannot occur since the inter-vehicular gap among the $i$-th source vehicle and its $j$-th neighbours (i.e., $\delta_{ij}$ [m]) is so large that the source connectivity range (i.e., $r_i^{(Tx)}$ [m]) results in a very short time as compared to this (i.e., $r_i^{(Tx)} > \delta_{ij}$). Thus, the main aspect of QASA algorithm is to allow a source vehicle on east side to be able to select the best candidate to be a receiver from the opposite lane (i.e., the west side).
Figure 5.2: QASA technique main aspects. (a) Dividing the transmission range of a source vehicle (i.e., the white vehicle) into smaller circular transmission domains (i.e., with $C_1 > C_2 > C_3$) for next-hop selection. (b) The scenario explains the trade-off between time delay and throughput performance with QASA technique.

Consider Figure 5.2, when the vehicle on the east (i.e., vehicle v2) is getting ready to transmit a message to the west side of the highway, it will have two candidate
vehicles as receivers on the west side within its transmission range (i.e., vehicle v1, and v3). The best candidate would be able to offer the best QoS metrics in a VANET, specifically (i) the best throughput, and (ii) the least packet transmission delay. If vehicle v2 selects vehicle v1, the established connection will only last for a short time due to v1 moving out of vehicle v2’s transmission range.

However, if vehicle v2 ends up selecting vehicle v3 instead, this will allow for the connection to remain established for a longer period of time due to vehicle v3 being in v1’s transmission range for a longer period. The shorter the time the connection lasts a larger number of connections can be established within the same time duration. The disadvantage of establishing a new connection lies in the overhead for Clear To Broadcast (CTB)/ Ready To Broadcast (RTB) signals and backoff algorithm.

5.3.1 Analytical Model

In order to analyze selecting the best candidate vehicle, we divide the transmission range of the source vehicles into smaller circular domains. As demonstrated in Figure 5.2, the domains correspond to actual transmission range (i.e., the full transmission range, half the transmission range, and one quarter of the transmission range). These domains are the different ranges from which the source (east) vehicle can select a destination (west) vehicle. We investigate the performance of the VANET with regards to the different ranges for the vehicle selection.

Let us assume that $R_1$ is the radius for the circle $C_1$; $R_2$ for $C_2$; and $R_3$ for $C_3$. We develop an analytical model for the probability of the existence of a vehicle in each circular domain. Vehicles are distributed on the highway following a Poisson distribution model which is a common practice in the VANET literature [81].

---

1We assume each vehicle is equipped with an omnidirectional antenna.
The probability that a vehicle can be selected as a receiver depends on two events, 
\( i.e., (i) \) the vehicle is within the transmission range, and \( (ii) \) the vehicle is expected 
to have a large enough connectivity interval to guarantee enough time for packet 
transmission and relay. Both conditions should be satisfied in order to select a vehicle 
as the best packet forwarder. We express the probability that a vehicle will be a 
receiver \( (i.e., p_{rx}) \) as follows:

\[
p_{rx} = \Pr [d^* \leq R_i] \cup \Pr [\Delta T(R_i) > \tau], \tag{5.1}
\]

where \( d^* [m] \) is the inter-vehicular distance from a potential receiver to a source, 
\( \Delta T(R_i) [s] \) is the expected time interval the vehicle is within the coverage area \( R_i \), 
and \( \tau [s] \) is a given threshold to guarantee a larger connectivity time interval. Notice 
that \( \Delta T(R_i) \) depends on the radius \( R_i \) in a given coverage area, since this can be 
increased from the maximum distance between the source and the receiver within its 
transmission range.

Let us consider Figure 5.2. The probability that a vehicle is laying at distance 
\( d = d^* \) from a source vehicle follows the following equation:

\[
\Pr [d = d^*] = \frac{\lambda^{d^*} \cdot \exp (-\lambda)}{d^*!}, \tag{5.2}
\]

where \( \lambda [\text{veh/km}] \) is the traffic density distribution on the highway, following a Poisson 
distribution.

From (5.1), the probability that a vehicle, placed at distance \( d^* \) from a source 
node, is inside the \( i \)-th coverage area \( C_i \) with radius \( R_i \), for \( i \in \{1, 2, 3\} \), becomes:

\[
\Pr [d^* \leq R_i] = \frac{\Gamma([d^* + 1], \lambda)}{[d^*]!}, \tag{5.3}
\]
where $\Gamma$ is the incomplete Gamma function, and the operator $\lfloor \cdot \rfloor$ represents the floor function.

Again, from (5.1), the probability that a vehicle will experience a time interval $\Delta T$, within a given coverage area, higher than a threshold $\tau$ is as follows:

$$\Pr [\Delta T(R_i) > \tau] = 1 - \frac{\Gamma (\lfloor \tau + 1 \rfloor, \lambda)}{[\tau]!}, \quad (5.4)$$

where $\Delta T$ (also called coverage crossing time) can be expressed as the time difference between the entrance and exit instants of the coverage area (i.e., $t_{in}$ and $t_{out}$, respectively), such as:

$$\Delta T = t_{out} - t_{in}, \quad (5.5)$$

which becomes:

$$\Delta T = \frac{\Delta x}{\|v\|} = \frac{2R_i}{\|v\|} \cdot \cos \left[ \arctan \left( \frac{y_s - y_r}{x_s - x_r} \right) \right], \quad (5.6)$$

with $\|v\|$ [m/s] as the module of vehicle’s speed vector $v$, assumed to be constant for all the vehicles, and $\Delta x$ [m] is the expected distance traveled by the vehicle within a given coverage area. Figure 5.3 (b) depicts the schematic for $\Delta T$ calculation. Notice that the coordinates of the source and the receiver vehicles’ positions, respectively $(x_s, y_s)$ and $(x_r, y_r)$, are known since we assume each vehicle is equipped with a GPS device.

### 5.3.2 QASA Algorithm

As it will be evident from the simulation results, limiting the selection range to the farthest range provides improved throughput. But, it does perform badly in terms of
average time delay. However, QASA assumes that the closer the vehicle is, the worse will be the expected throughput, while it provides reduced time delay.

Consider the scenario in Figure 5.2 (b), if vehicle v2 on the east selects the furthest available vehicle in its transmission range on the west, QASA algorithm will select vehicle v1. As will be observed from simulation results, this leads to a smaller average time delay, but will result in a lower throughput. If vehicle v2 waits for a short anticipated time\(^2\), it will be able to select vehicle v3, which could result in a higher throughput, but in a slightly increased time delay. The choice between vehicles v1 and v3 can be decided by restricting the region from where the east vehicle selects a west vehicle. This restriction should be defined solely based on the type of application. Some vehicular network applications require minimum delay regardless of the throughput, while other applications require maximum throughput but are delay tolerant.

In order to overcome this trade-off, the algorithm needs to allow the vehicle to select the furthest possible vehicle available in a specific area within the transmission range. In the following subsection, we describe the QASA algorithm, which relies on the CAREFOR protocol [77].

The QASA is a probabilistic forwarding routing protocol that ensures selection of the farthest available vehicle in the transmission range that could forward the packet (i.e., the next-hop forwarder). This algorithm attempts to improve the QoS of routing protocols in a VANET by selecting the best candidates among the vehicles on the opposite direction (i.e., on the lane west) to act as bridges for communication between vehicles on the other side (i.e., the lane east). The QoS metrics of concern behind QASA are both (i) the throughput of the network, as well as (ii) the average

\(^2\)It is evident that vehicle v3 will enter the coverage area \(C_1\), in a short time.
time delay for packet transmission, with and without packet duplication.

Let us consider the scenario in Figure 5.2, where a source vehicle is being driven alone on the lane E. The algorithm works through different phases as follows:

- **Phase 1**: The source vehicle on the east evaluates the current vehicular density within its transmission range (i.e., $C_1$). Based on the vehicular density, it decides the appropriate radius of the circular region (i.e., $C_i$ with $i = 1, 2, 3$) in which the vehicles on the west lane can respond back to the source vehicle.

- **Phase 2**: The source vehicle broadcasts a Request-to-Broadcast (RTB) message to all vehicles in its transmission range. The RTB message is a broadcast message that includes the local vehicular density at the source node, the GPS location of the source node, and the radius computed from Phase 1.

- **Phase 3**: When all vehicles in the transmission range of the source node receive the RTB message, they check if their location matches the requirements provided by the message. If they do not qualify, they drop the packet. If they do qualify, they calculate the Reliable Forwarding (RF) probability, which is expressed as [77]:

\[
p = \exp \left[ -\frac{\rho \cdot (z - d)}{c \cdot z_i} \right],
\]

where $\rho$ [veh/m] is the vehicular density, $z$ and $z_i$ [m] are the transmission ranges for the source, to the $i$-th receiving vehicle, $c \leq 1$ is a coefficient which can be selected to influence the rebroadcast probability (as a function of $d$), and $d$ [m] is the inter-vehicle distance between the receiving and the transmitting vehicles.
Table 5.1: QASA message exchanged classification and content.

<table>
<thead>
<tr>
<th>Message</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTB</td>
<td>1) Source node’s position</td>
</tr>
<tr>
<td></td>
<td>2) Vehicular density</td>
</tr>
<tr>
<td></td>
<td>3) FRP</td>
</tr>
<tr>
<td></td>
<td>4) Transmission power level</td>
</tr>
<tr>
<td>CTB</td>
<td>1) Vehicle’s ID and position</td>
</tr>
</tbody>
</table>

The decision of packet retransmission is taken by each vehicle by comparing the RF probability to a transmission threshold (i.e., $Th_{coll}$). That means:

$$Th_{coll} = 1 - \left[\exp\left(-\rho z_i\right)\right],$$  \hspace{1cm} (5.8)

where $z_i$ [m] is the transmission range of the $i$-th vehicle, and $\rho$ [veh/m] is the vehicular density. If calculated RF value is larger than the threshold, then the vehicle broadcasts a CTB message. Otherwise, the vehicle refrains from any rebroadcasting. The CTB message includes the GPS location of the vehicle.

- **Phase 4:** Once the source vehicle receives the CTB messages, it determines which vehicle amongst those who responded is the furthest. Once that is decided, the source vehicle transmits the packet with a destination address to the vehicle selected from the west lanes. All vehicles which receive the packet, but do not have their vehicle ID as the destination, simply drop the packet.

An explanation of each control message used in the algorithm is presented in Table 5.1.

Different applications in vehicular networks can have varying QoS requirements. Some applications require minimum delay regardless of the throughput, while others
require the opposite, and some applications may need a balance between throughput and average time delay. In order for the algorithm to be functional for different applications, we introduce a Full Range Portion (FRP) parameter that restricts the performance of the network as per the QoS requirements.

The FRP parameter is a value larger than 0 but smaller or equal to 1, and represents the fraction of a full transmission range, from which a vehicle on the west side can be selected by a vehicle from the east side. For example, in Figure 5.2, $C_3$ is selected using a FRP factor equal to 0.25; $C_2$ using FRP equal to 0.5; while FRP is equal to 1 for $C_1$. The FRP factor is equal to 1 when the requirement is to provide the minimum average delay regardless of the throughput. The smaller the FRP variable is, better will be throughput the network experience, and the higher will be the average time delay. However, if the FRP parameter becomes too small, the region from which the west vehicle can be selected will be very restricted, and may cause failure in establishing any connection. Hence, FRP parameter depends mainly on the transmission range and the vehicle density in the network.

5.4 Simulation Results

In this section, we present simulation results for the QASA algorithm as well as results to illustrate improvements in QoS. The metrics used in this simulation are the throughput, total effective communication time, and the average time delay. The total effective communication time is measured after excluding any time used in setting up the connection or selecting the vehicles for communication. We use our own VANET simulator [77, 82]. Different parameters used in our simulation are presented in Table 6.1.
Table 5.2: Simulation Parameters.

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Runs</td>
<td>50</td>
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<td>Simulation Duration</td>
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</tr>
<tr>
<td>Transmission Range</td>
<td>400 m</td>
</tr>
<tr>
<td>Vehicle Density</td>
<td>[1, 65] veh/km</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Highway Length</td>
<td>3 km</td>
</tr>
<tr>
<td>Control Packet Size</td>
<td>2 KB</td>
</tr>
<tr>
<td>Message Size</td>
<td>32 KB</td>
</tr>
<tr>
<td>Message Generation Rate</td>
<td>20 packets/s</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MB/s</td>
</tr>
</tbody>
</table>

Figure 5.4 demonstrates the impact of the bridging approach on the vehicular network performance. When vehicles on either side of the highway are allowed to connect with vehicles on the opposite side of the highway, the overall network connectivity is enhanced. For sake of readiness, we identify the bridging approach as a “Vehicle-to-Bridge” (V2B), since a vehicle forms a bridge each time it communicates with another vehicle driving in the opposite direction.

We present results by varying the number of disconnected clusters at different vehicle densities with and without bridging (i.e., V2B used, and not used, respectively). As expected, allowing bridging reduces the number of disconnected clusters which enhances the connectivity between vehicles on the network, allows for enhanced throughput, and reduces the average time delay experienced in the network.

In Figure 5.5, we present the total time communicated during the simulation runs, which proves the effectiveness of the concept of limiting the region within the transmission area of the east vehicle from which a vehicle on the west can communicate.
The case where any vehicle on the west within the source vehicle’s transmission region can communicate with the east vehicle is demonstrated for full range of variations, and the diameter of the region are changed to 0.75, 0.5, and 0.25 respectively. We observe that dynamically varying the transmission ranges in different regions can provide an enhancement of connectivity within the network. Note that all these regions are located at the end of the transmission range. For example, in Figure 5.2, $C_3$ represents the 0.25 of full range $C_1$. Moreover, in Figure 5.6, we show the throughput analysis for the same region. Again, high performance are obtained with a reduction of transmission range (e.g., for 0.5 and 0.25 of full range we reach maximum values of throughput).

Figure 5.7 represents simulation results for throughput at a lower vehicular density for different ranges (i.e., full transmission range, half transmission range, and one quarter of the transmission range). Consider the scenario presented in Figure 5.2. If the system uses a smaller range (i.e., $C_3$ range) from which the west bridge vehicle can be selected, and as there is no vehicle in this range, no vehicle will be selected. Therefore, no connection will be established between the source vehicle and any other vehicle from the west lane of the highway.

However, with the assumption of a continuously moving highway scenario, even at lower vehicle densities, each vehicle on the east will get the chance to communicate with each vehicle on the west regardless of the communication range restriction. This is because QASA detects and selects a potential forwarder, based on both the transmission range, as well as the longest inter-vehicles distance (i.e., the furthest vehicle in a coverage area). In the light of such considerations, it can be easily understood why at lower vehicular densities, the throughput is the same for different values of the circular range.
As indicated earlier, QoS metrics for vehicular networks include more than just the throughput of the network. Another main metric is end-to-end time delay for a packet. In order to investigate the effectiveness of our algorithm, we simulated time delay performance for a packet to be communicated from the beginning of the highway till the end. In order to provide comprehensive results, we investigated cases where vehicles generate messages (i) only once during their trip on the highway, no packet regeneration, and (ii) periodically, with packet regeneration. We present each case separately.

In the case of no packet regeneration, we simulated the average time delay for packets to traverse through the whole length of the highway. Packets in this scenario are generated once by a source vehicle on the highway. Packets are forwarded via multi-hop through the highway and utilize vehicles connections on both sides of the highway. Figure 5.8 presents this average time delay for both the cases of (i) the vehicles on the east lane allowed to communicate with any vehicle within its communication range on the west lane, and (ii) the case where vehicles on the east are only allowed to communicate with vehicles on the west within a circular area of diameter one eighth of the source communication range. Basically, the first case corresponds to a traditional routing protocol based on source’s transmission range, while the second case is for QASA approach, where the routing task is accomplished based on bridging with a transmission range reduction, and furthest node selection.

The result was expected since vehicles carry the message at the entrance of the highway before they interact with any vehicle on the west lane of the highway. Because of this, both cases allow the vehicle on the east lane to communicate with the vehicle on the west side with the same time delay. This results in both cases yielding the same performance for the average time delay.
As presented for the case with no packet regeneration, the average time delay for QASA algorithm, as well as for the traditional forwarding case yields the same result. However, this does not hold when vehicles generate message repeatedly during their trip through the highway (i.e., *periodically packet regeneration*). With such an assumption, the average time delay for both the case of the vehicles on the east lane (i) are allowed to communicate with any vehicle within its communication range on the west lane—*i.e.*, $R$—, and (ii) are only allowed to communicate with vehicles on the west within a reduced circular area of diameter three fourth of the source communication range—*i.e.*, $3/4R$—, are presented in Figure 5.9.

To explain the result for the case vehicles regenerating packets, we consider the scenario in Figure 5.2 (b) representing the instance at which the source (v2) vehicle has just generated a new packet. At this instance, the vehicle will not be able to communicate with vehicle v1, if its communication range is restricted to half of the transmission range, and will also not be able to communicate with the vehicle v3, since it is not in its transmission range yet. This will result in vehicle v2 to wait till vehicle v3 enters its transmission range $C_2$, which causes the average time delay to increase in case of restricting the communication range at a low vehicle density.

As presented earlier, the use of FRP factor affects the QoS requirements for different applications of the VANET. Figure 5.10 and Figure 5.11 present the effect of the FRP factor on the total communication time in the network at different vehicle density. As expected, smaller the value of FRP, and higher the vehicular density, larger will be the communication time. Figure 5.12 presents the same results for the throughput in the network.
5.5 Summary

In this chapter, we have introduced QASA algorithm which is primarily a forwarding node selection algorithm for routing protocols in an opportunistic vehicular network. QASA allows vehicles on one side of the highway to successfully select a vehicle from the opposite side that improves the QoS metrics for the network. The QoS metrics used to analyze the algorithm are total communication time, throughput, and packet end-to-end time delay.

We tested our system by extensive simulation and verified the importance and usefulness of bridging in vehicular networks. Furthermore, we compared the performance of QASA with normal scenarios. The results have shown significant improvement by QASA in terms of throughput, and end-to-end packet delay. Finally, we presented an FRP parameter that will help provide better performance based on the QoS requirements for the VANET application.
Figure 5.3: Scheme for next-hop forwarder selection algorithm based on the coverage crossing time calculation, $\Delta T$ [s]. Assuming each vehicle has an omnidirectional coverage, with radius $R$ [m], (a) the red vehicle will experience longest time connection with the blue vehicle, respect to the green one, which is exiting the coverage area. (b) The coverage crossing time is calculated as a time interval (i.e., from $t_{in}$ to $t_{out}$ [s]).
Figure 5.4: Effect of bridging on the number of disconnected clusters on highway.
Figure 5.5: Total communication time analysis for algorithm with different regions.

Figure 5.6: Throughput analysis for algorithm with different regions.
Figure 5.7: Throughput for different ranges at lower traffic densities.

Figure 5.8: Average time delay vs. the vehicular density for different ranges.
Figure 5.9: Average time delay vs. the vehicular density for different ranges with a packet regeneration every 20 seconds.

Figure 5.10: Effect of FRP variable on total time communicated.
Figure 5.11: Effect of FRP variable on total time communicated.

Figure 5.12: Effect of FRP variable on throughput.
Chapter 6

QoS-Aware Routing for Autonomous Vehicles

In this chapter, we present a QoS-Aware routing protocol for autonomous (which are driverless or self-driving vehicles capable of doing what a human being does) vehicles on a highway. The ability to control the motion and location of autonomous vehicles provide endless possibilities for the improvement of the performance of vehicular networks. In this chapter, we focus on the end-to-end packet delivery delay in vehicle-to-vehicle communication, and minimizing this delay by reorganizing and controlling autonomous vehicles on highways. The scheme introduced is a dynamic protocol that depends mainly on the vehicle density on the highway, and controls the inter-vehicle distance. We investigate the performance of this protocol compared to normal VANET scenario. The side effects of this protocol are investigated mainly in terms of the effect on the vehicles trip travel time. A metric is introduced that is scenario dependent to control the trade-off between end-to-end delay, and the total vehicle travel time on the highway.
6.1 Introduction

Over the last decade, great progress in computational power in terms of hardware and software, as well as sensing capabilities have been achieved. These advancements have facilitated the introduction of autonomous vehicles. With the help of the computational power, vehicles are able to operate autonomously with a high degree of reliability in environments that exhibit high degrees of dynamicity as well as uncertainty. With deploying redundant sensitive sensors on the vehicle, it is able to understand with great reliability the environment around it. This allows the vehicle to respond accurately and in a timely fashion to environmental changes, such as the existence of another vehicle, or as basic as changes in the road conditions.

The concept of autonomous vehicles is no longer just a research subject. It is expected that in the next few years, autonomous vehicles may be introduced to be used widely in normal highways and cities. Many car manufacturers have already embarked on developing autonomous vehicles. BMW has started testing autonomous vehicles since the year 2005 [83]. In 2011, General Motors (GM) created the Electric Networked Vehicle (EN-V) in hope to have their autonomous vehicle in the market by the year 2018 [84]. In 2011, Audi was able to send an autonomous vehicle TTS to achieve close to race speeds at Pikes peak [85]. Many other manufacturers have been working on their own autonomous vehicle as well [86]. Moreover, several states have started to allow autonomous vehicles to be used on their roads. Nevada was the first state to grant Google a license to test their driverless vehicles on the roads [87]. On October 29, 2012, California was the second state to grant Google the same license [88]. More vehicle manufacturers are being granted similar license to test their vehicles [89]. It is anticipated that by the year 2040, vehicle operators may not be required to obtain a drivers license as the vehicles will be driven autonomously [90].
Many benefits are expected from a wider use of autonomous vehicles [86]. Those benefits can be summarized as:

- Fewer traffic collisions due to increased reliability of the vehicles in sensing and reacting to the environmental traffic changes [91].

- Reduced traffic congestion due to absence of traffic collisions, and required safety gaps [91], as well as the development of algorithms that selects the best possible path to the destination.

- Vehicles passengers no longer are required to drive and navigate the vehicle, and hence can perform other chores while inside the vehicle.

- Higher speed limits can be granted to autonomous vehicles [92].

- Lack of restrictions on the passengers such as age, vision, impaired or intoxication.

- Improved fuel efficiency [93].

With these benefits and advancements, vehicle operators will no longer be involved in the manipulation or in the control of the vehicle speed, location, or direction. Vehicle operators will only notify the vehicle of the destination they are heading to and the vehicle will determine the path, speed, and direction to be used in order to reach to the destination. Enabling the vehicle to autonomously select these variables opens endless possibilities for potential innovation of new algorithms that will provide the best possible experience for the vehicle passengers within limits of the surrounding environment.

This chapter introduces the concept of utilizing autonomous vehicles in order to improve end-to-end message delay which is achieved through intelligently adjusting
the inter-vehicle distance by controlling their speed and hence location. This chapter is organized as follows: first, related work regarding routing protocols to manipulate autonomous vehicles is introduced in Section 6.2. The effect of inter-vehicle distance on end-to-end packet delivery delay is introduced in Section 6.3. Section 6.4 introduces our algorithm and approach. Finally, Section 6.5 introduces our simulation results followed by the chapter summary.

6.2 Related Work

For many years, the problem of planning a path or a trajectory in a dynamic environment or that is cluttered by obstacles has been the object of many researches in the area of robotics and artificial intelligence [94]. Building on these research finding, different algorithms have tailored them to be applicable to autonomous vehicles in a VANET environment. The scope of those different algorithms have varied from collision avoidance, to path selection, to fuel economy optimization.

Authors in [95] have introduced a collision avoidance system for autonomous vehicles using cooperative motion control. The system introduced is composed of two systems: collision prediction and avoidance. Collision prediction is achieved through estimating the trajectory of objects, while collision avoidance is achieved through controlling the speed of the vehicle or through modifying the path of the vehicle. In [96], authors developed fuel-economy optimization system (FEOS), which gathers input data from the vehicle as well as the environment, and mathematically computes the optimum speed for the vehicle.

Many research publications focused specifically on path planning, or real-time motion planning. Authors in [97], proposed an autonomous real-time driving motion...
planner with trajectory optimization. The optimization is based on a set of cost functions. Moreover, their framework reduces the planning time by 52 percent. In [98], authors presented a method for vehicle guidance that is based on path relaxation to compute critical points using a-priori information and sensor data along a desirable path. The scope of this method is to provide a collision free path for the vehicle along the desirable route.

To our knowledge, none of the presented algorithms in literature regarding the control or manipulation of autonomous vehicles has had the goal of optimizing the end-to-end route delay. This delay has been the focus of other research in the literature that considered regular vehicles, rather than autonomous vehicles.

In [62], Yan et al. presented a ticket-based technique as a routing protocol. These tickets are control packets transmitted on selected links which indicate the metrics of stability, delay and cost. Ticket-based systems were initially introduced in MANETs [63] with the objective of identifying a reliable route based on multiple links that are selectively probed.

Sun et al. [65] proposed the GVGrid algorithm to find a reliable routing path that meets a given delay requirement. By assuming an equally spaced inter-vehicle gap, and a normally distributed vehicle speed, GVGrid computes the probability of link lifetime as the function of link reliability. The proposed technique can select a path with the highest reliability, and relatively smaller link delay as the selected route.

Common to all previous techniques, physical parameters play an important role for the rebroadcast probability and the link selection. In [66], the authors present a rebroadcast probability that is based on the inter-vehicle distance. This probability is directly proportional to the distance from the transmitter. The larger the distance is, higher will be the rebroadcast probability.
Table 6.1: Simulation Parameters.

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Runs</td>
<td>50</td>
</tr>
<tr>
<td>Simulation Duration</td>
<td>6000 s</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>200 m</td>
</tr>
<tr>
<td>Vehicle Density</td>
<td>[1, 65] veh/km</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Maximum Vehicle Speed</td>
<td>100 m/s</td>
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<td>Highway Length</td>
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<tr>
<td>Control Packet Size</td>
<td>2 KB</td>
</tr>
<tr>
<td>Message Size</td>
<td>32 KB</td>
</tr>
<tr>
<td>Message Generation Rate</td>
<td>40 packets/s</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MB/s</td>
</tr>
</tbody>
</table>

In this chapter, we present an algorithm that focuses on optimizing end-to-end delay that also reduces vehicles’ travel time. However, unlike previous work, attempts to control and manipulate the inter-vehicle distance rather than developing a routing protocol that uses these distances as an input variable.

6.3 Inter-vehicle Distance and Delay

In this section, we investigate the effect of the inter-vehicle distance on the end-to-end message delay. The simulator used is based on our own VANETs simulator [77, 82]. In these simulations, the inter-vehicle distance is presented as a percentage of the vehicle’s transmission range. Parameters used in the simulation are presented in Table 6.1.

Figure 6.1 presents the end-to-end delay performance for the different values of
Figure 6.1: 3D figure presenting end-to-end packet delay for the different values of r.

inter-vehicle distance. The inter-vehicle distances are presented as a percentage of the vehicle’s transmission range. As expected, as the vehicle density increases, the end-to-end packet delay decreases. However, it is noticeable that for each vehicle density, there is an optimum inter-vehicle distance value beyond which improvement in end-to-end delay is minimal. This can be easily seen in Figure 6.2.

Controlling the inter-vehicle distance and limiting this distance to be less than or equal to the transmission range improves the performance of the VANET as compared
Figure 6.2: 2D figure presenting end-to-end packet delay for the different values of \( r \).

to not controlling this distance. In Figure 6.3, we present this improvement. As presented in this figure, controlling the inter-vehicle distance always yields a smaller end-to-end delay than the case of not controlling it, except the case of high vehicle densities with the inter-vehicle distance being equal to 0.25 or lower. This explains that in the case of controlling the vehicle to very small inter-vehicle distance with a high vehicle density, yields the creation of different disconnected clusters on the highway that takes time to interconnect them together. This introduces an added delay than a regular scenario.
As is evident from Figure 6.2, forcing the inter-vehicle distance to be equal to 100 percent of the transmission range always yields the best performance for end-to-end delay. However, there is a trade-off, larger the distance between vehicles is, the longer will be the vehicle trip on the highway. In other words, it will take a vehicle longer to travel through the highway. This is presented in Figure 6.4, and can is clearly shown in Figure 6.5.

However, it is notable that in the case of controlling inter-vehicle distance, the vehicle travel time on the highway is lower than the case of not controlling the dis-
distance. In case of not controlling the inter-vehicle distance, the vehicle travel time is a constant value calculated according to the length of the highway divided by the vehicle speed, which in the case of this simulation is equal to 150 seconds.

### 6.4 Inter-vehicle Distance Manipulation for Autonomous Vehicles (ID-MAV)

Based on findings of the previous section, we present a routing protocol based on the ability to control the speed and location of vehicles on the highway. As illustrated in various figures, there is a trade-off between the inter-vehicle distance and the vehicle trip duration at different vehicle densities. In order to achieve a balance between both these values, the inter-vehicle distance ought to be changed according to the following
The protocol is presented in different phases:

- **Phase 1.** Each vehicle estimates the vehicle density on the highway through computing the density in its communication range using ping messages.

- **Phase 2.** The constant variable $c$ is pre-set according to the application require-
ments. If an application does not require end-to-end delay to be the minimum value, but requires the vehicle trip duration to be minimal, the variable $c$ can be relaxed. The effect of the $c$ value on the inter-vehicle distance versus the different vehicle densities is presented in Figure 6.6.

- **Phase 3.** Each vehicle computes the inter-vehicle distance required per equation 6.1.

- **Phase 4.** Once the inter-vehicle density is calculated, each vehicle increases or decreases its speed till it can be maintained at the inter-vehicle distance desirable on the highway from the vehicle ahead of it. Note that we utilize a maximum vehicle speed. This speed is the maximum speed any vehicle is allowed to use in case it would like to increase its speed. Once the vehicle reaches
required inter-vehicle distance, its speed ought to be immediately adjusted equal to the speed of the vehicle ahead of it.

6.5 Simulation Results

In this section, we present simulation results for the ID-MAV algorithm. We used the same simulation setup as that presented in Table 6.1. Also, value for the variable used in these results is set to 6.

The performance of our algorithm for end-to-end packet delay and the different inter-vehicle distance values are presented in Figure 6.7. The vehicle delay performance is presented in Figure 6.8.

Note that the vehicle trip duration is always set at a lower value regardless of the chosen inter-vehicle distance chosen as compared to conventional non-autonomous vehicles. The main reason is that controlling the inter-vehicle distance forces the vehicles to speed up till they reach required distance.

6.6 Summary

In this chapter, we have introduced ID-MAV algorithm which is a vehicle speed manipulation algorithm for autonomous vehicles. The goal of the vehicle speed control is to optimize end-to-end packet delivery delay. However, a downside of controlling the speed of the vehicles is the effect on the vehicle trip duration on the highway. Hence, the ID-MAV is a dynamic algorithm that changes QoS requirement of vehicle trip duration for different VANET applications of vehicle trip duration versus end-to-end message delivery delay.

We tested our algorithm by verifying the effect of inter-vehicle distance on both
end-to-end message delivery delay, and on vehicle trip duration. We presented the results of the ID-MAV algorithm and improvements on the VANET QoS.

Future work includes developing ID-MAV algorithm to deal with VANET scenarios that include both autonomous and non-autonomous vehicles, and optimizing the control of the autonomous vehicles to achieve QoS requirements in a hybrid VANET application.
Figure 6.8: Vehicle delay performance for c=6 vs the different inter-vehicle distance values.
Chapter 7

Summary & Future Research Directions

In this chapter, we present a summary of research contribution made in this dissertation. Following that, we present future research directions that stems from our findings and the results of this research.

7.1 Summary

In this dissertation, we addressed some important QoS issues in Vehicular Ad Hoc Networks (VANETs). An introduction to VANET technology with different aspects have also been given. Based on different communication schemes in a VANET, average total message propagation delay has been analytically determined. In order to optimize end-to-end message delivery delay, we presented a QoSHVCP hybrid communication protocol. Moreover, we introduced CAREFOR algorithm which is a probabilistic routing protocol for VANETs. In order to improve end-to-end message delivery delay and the throughput in the VANET, we introduced the QASA vehicle
selection algorithm. Finally, we utilized the ability to control speed of autonomous vehicles in order to manipulate the vehicle distribution on highway to minimize end-to-end message delivery delay. We can summarize our research contributions in this dissertation as follows:

- We introduced a hybrid approach for vehicular communication that utilizes both Vehicle-to-Vehicle as well as Vehicle-to-Infrastructure communications. We present simulation results to demonstrate end-to-end packet delivery delay based on each communication model separately. Based on these findings, we analyze the total average packet delivery delay using this protocol. Following that, we investigated the improvements presented by our hybrid approach by accounting for overloads in the infrastructure and the net effect on the delay of packet delivery. We present an analytical model for the delivery delay, and simulation results to demonstrate the effectiveness of our QoSHVCP protocol.

- We presented a probabilistic routing protocol (CAREFOR) that utilizes multi-hop retransmission forecast with collision-aware constraints in order to optimize end-to-end packet delivery delay for V2V communications in vehicular networks. CAREFOR allows each vehicle to compute a rebroadcast probability that decides whether the vehicle should be allowed to rebroadcast the packet, or refrain from rebroadcasting. Decreasing the number of rebroadcasters helps minimize the number of packet collisions due to smaller flooding of the network. The vehicle with a higher rebroadcast probability is selected as a vehicle which has a higher chance of forwarding the packet to the largest distance. We present an analytical model for the rebroadcast probability, as well as simulation results comparing our protocol to other existing approaches.
• We presented the QASA algorithm that considers improving the throughput of the VANET and optimizing the packet delivery delay. The algorithm is tailored specifically for vehicles communication using the V2B model. This model allows vehicles from the east lane to communicate with vehicles on the same lane through a bridge using vehicles from the opposite lane. The QASA algorithm allows vehicles on the east to select the vehicles from the west that will maximize the throughput. This introduces a trade-off with end-to-end packet delivery delay. We also presented a metric that is manipulated based on the application QoS requirements. We have also included simulation results to demonstrate the effectiveness of our approach.

• We investigated utilization of autonomous vehicles in order to improve end-to-end packet delivery delay and vehicle trip duration. The advantage presented by autonomous vehicles is that they are automatically controlled and the driver does not interfere or control the speed of the vehicle. By allowing the protocol to control the speed of the vehicle, we can manipulate the distribution of vehicles on the highway. This allows us to control the connectivity of vehicles on the highway, and hence control the end-to-end packet delivery delay. A trade-off is presented between the total time delay for the vehicle and vehicle speed manipulation to travel the highway length. We present a metric to control this trade-off depending on the requirement of the application utilizing the protocol. Simulation results are presented to demonstrate the improvements by our protocol.
7.2 Future Research Directions

In this dissertation, we have investigated different approaches to optimize end-to-end packet delivery delay as well as the throughput in the vehicular networks.

Many future research directions stem from the work presented in this dissertation. Some of specific directions include:

- **Routing Protocols:** In this dissertation, we presented routing protocols, as well as vehicle selection algorithms for vehicle-to-vehicle communication. However, throughout our analytical model and simulation, we assumed vehicles to travel at a constant speed. A future research direction could investigate the effect of vehicles having different speeds and the changes required in the different models and protocols.

- **Traffic Scenario:** In the research presented in this dissertation, we have assumed highway scenarios where vehicles travel in either one of two directions. A future research direction would include developing the different models and routing protocols for a city model, which includes road intersections, stop signs, different speed limits, etc.

- **Autonomous Vehicles:** In this dissertation, we presented the idea of the utilization of autonomous vehicles with the goal of minimizing end-to-end packet delivery delay. However, in our scenario, we assumed all the vehicles to be autonomous. In reality, this is not a practical assumption. Future research direction should include developing a model for end-to-end packet delivery delay for highways with hybrid vehicles (including both autonomous and regular cars). The percentage of autonomous vehicles on the highway can be manipulated, and a dynamic algorithm to manipulate the autonomous vehicle speed...
can be based on the percentage of these vehicles on the highway. Moreover, this problem can be modeled after adhoc networks that include both static and mobile nodes, where regular vehicles are considered relatively static, while autonomous vehicles can be considered as the mobile nodes.
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