UNIVERSITY OF SOUTHAMPTON

Intelligent Routing
in
Urban Vehicular Networks

by

Teodor Ivanescu

A thesis submitted in fulfillment for the
degree of Doctor of Philosophy

in the
Faculty of Engineering and Physical Sciences
School of Electronics and Computer Science

June 2023

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES
SCHOOL OF ELECTRONICS AND COMPUTER SCIENCE

Doctor of Philosophy

by Teodor Ivanescu

Future smart cities will rely on Vehicular Networks (VNs) to provide the communications capabilities needed for a wide range of safety, efficiency and entertainment urban applications. As multi-hop communications are employed to assure the coverage and throughput required by such applications, efficient routing design proves to be essential in VNs. However, significant challenges are encountered when large and dense urban VNs are considered. In such cases, existing communications systems cannot meet all quality-of-service (QoS) requirements of the large spectrum of VN applications and, as a consequence, new solutions are needed. This thesis addresses VN routing design and analysis.

A characterization of VNs is provided both from a radio-frequency propagation perspective as well as from a mobility evaluation perspective. Based on this, a network simulation environment is built, namely using a merge of MATLAB and Simulation of Urban Mobility (SUMO) through the TraCI4Matlab package found within SUMO. The simulator is used to first evaluate the effect of road-network structure size and complexity on the induced overhead.

Then, a framework for route lifetime analysis is provided based on an exhaustive search routing technique to set an upper bound of the route lifetime as well as a shortest-path routing technique, as a routing example. The route lifetime is measured in order to further reveal the trade-off between the structure and dimension of the road-network and performance requirements as a fundamental research baseline for investigating and developing sophisticated routing models for vehicular networks. Results reveal that, on average, the shortest-path route lifetime is sub-optimal 11.56% of the time compared to the upper bound route lifetime. Then, a trade-off between the road-network dimensions and the QoS requirements is provided, where it is demonstrated that wireless channel fading has significant effect on the route lifetime and that, on average, 7 times higher route lifetime could be achieved in a LOS scenario compared to its NLOS counterpart.

Additionally, a Q-learning-based routing algorithm is proposed, namely Infrastructure-aided Traffic-Aware Routing (I-TAR), which introduces and leverages the static wired RSU infrastructure for packet forwarding. Then, the focus shifts towards a multi-source, multi-destination problem and the effect this imposes on node availability, as nodes also participate in other communications paths. This motivates the use of a hybrid routing approach, namely Hybrid Infrastructure-aided Traffic Aware Routing (HI-TAR) that aims to select the best vehicle-to-vehicle/infrastructure (V2V/I) route by also considering Vehicle-to-Vehicle (V2V) only connections when an available RSU is not found and thus, vehicle-to-infrastructure (V2I) links are not available. Results demonstrate that I-TAR can achieve up to 19% higher average packet-delivery-ratio (APDR) compared to the state-of-the-art. Additionally, the hybrid approach improves the APDR and average end-to-end delay (AEED) performances of I-TAR by 4% and about 8%, respectively. Under a more realistic scenario, where node availability is considered, a decline of up to 51% decline in APDR performance is observed, whereas the proposed HI-TAR can increase the APDR performance by up to 50% compared to both I-TAR and the state-of-the-art. Finally, when multiple source-destination vehicle pairs are considered simultaneously, all the schemes that model and consider node availability, i.e. limited-availability, achieve from 72.2% to 82.3% lower APDR, when compared to those that do not, i.e. assuming full-availability. However, HI-TAR still provides 34.6% better APDR performance than I-TAR, and 40% more than the state-of-the-art.

Acknowledgements

To Dr. Mohammed El-Hajjar and Dr. Geo Merrett, Dr. Halil Yetgin, Dr. Satyanarayana Katla, all of my friends, both from the University of Southampton and outside of it, and, last but most importantly, to my family.

I would like to express my deep gratitude and appreciation to each and every one of you who has supported me throughout my journey in completing my PhD journey. Your invaluable guidance, encouragement, and unwavering support have been instrumental in helping me reach this milestone.

To my supervisors, Dr. Mohammed El-Hajjar and Dr. Geo V. Merrett, I am deeply grateful for your exceptional mentorship and guidance, which have played a pivotal role in shaping my research, and for instilling in me the values of academic rigor and excellence.

To my good friend and main collaborator, Dr. Halil Yetgin, I am grateful for your friendship, insightful contributions and unwavering commitment to our joint research endeavors. Your dedication and support have been invaluable, and I could not have accomplished this feat without you.

To my family, including my mother, father and my brother, Bogdan, I am forever indebted to your unwavering love, support and encouragement throughout my academic journey. Your belief in me has been a constant source of motivation and inspiration.

To my first PhD colleague, Dr. Satyanarayana Katla, I thank you for opening the path towards my research journey and, more importantly, for your friendship and support. Your presence has been a source of strength, and I am grateful for your camaraderie.

To all of my friends, both from the university and outside of it, thank you for your unwavering support, encouragement, and for the countless moments of laughter and camaraderie that have made this journey all the more memorable.

Completing my PhD in Wireless Communications as part of the Electronic and Electrical Engineering degree at the University of Southampton has been a transformative experience and I could not have done it without each and every one of you. I am truly grateful and look forward to continuing to build on this journey with you all.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Sharing information anytime and anywhere is a key element for existing communications systems as they have connected more than 5 billion people in the past 25 years [9]. Hence, considering upcoming intelligent transportation systems, vehicles can be seen as mobile data centers as a consequence of boosting their environmental awareness through different sensor technology. Moreover, by sharing their sensor data with other network participants, vehicles can improve this awareness even more, transforming the \connected car" into a means towards safer, more enjoyable and more efficient driving and eventually towards fully automated driving [10].

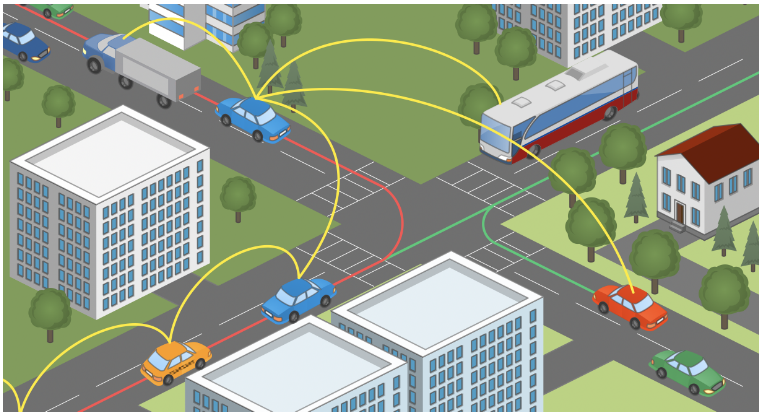


Figure 1.1: An example of multi-hop communications in VNs.

Unfortunately, existing communications systems are not able to achieve the adequate coverage, long-lasting stability and high throughput required by such smart city applications due to their highly dynamic and complex environments [11]. In that sense, cooperative communications approaches promise significant spatial diversity gain at the expense of bandwidth by routing the signal through intermediate nodes. By employing routing techniques with the aim to guide packets through optimum routes, Vehicular Networks (VNs) can rely on multi-hop communications to and thus achieve the required data rate and coverage [6], [12]. Figure 1.1 illustrates a potential urban VN model where the vehicles communicate between each other through vehicle-to-vehicle (V2V) wireless links. As buildings induce blockage on the communications links, multi-hop routes are provided instead with the aim to successfully assure transmissions between the source node and the destination node. Moreover, efficient routing design can lead to better bandwidth utilization, increased robustness and provide thus adaptability for VNs [13]. Unfortunately, in urban VNs, the high mobility of vehicles along roads as well as the complex environment pose major challenges to the existing routing approaches. Therefore, the design of efficient and robust routing algorithms is fundamental to meeting the quality-of-service (QoS) in VNs. However, efficient routing remains a significant challenge in the context of VNs and has attracted a lot of research attention due to its critical role in achieving successful communications [10].

1.1 Research Justification

Due to their uncontrolled and unpredictable nature, efficient routing design presents many challenges in mobile networks, which become even more severe in the case of highly dynamic, dense VNs [13], [14]. Therefore, even though multi-hop approaches can lead to increased stability, throughput and network coverage, further efforts towards efficient routing design are required with the aim to achieve Ultra Reliable Low Latency Communications (URLLC) [11]. Considering the continuously increasing demand for the enabling of VNs applications, solutions are required. However, the reviewed work has neglected some significant aspects of efficient VNs routing design as follows.

To start with, in order to efficiently evaluate VNs, the movement patterns of the partici-pant vehicles and how they are affected by both internal/external factors on the available road-network structures need to be properly estimated and modelled [15], [16]. Thus, in order to obtain results as close as possible to real-life scenarios, simulation methodology as well as some standardized bookmarks and test mobility models are needed. Then, based on the constructed mobility models, the movement of the participant nodes can be properly looked into in order to characterize what their effect is on the performance of VNs.

Then, considering accurate mobility and radio frequency propagation models, cross-layer traffic-aware routing approaches were proposed as a promising solution for meeting QoS requirements of VNs applications such as stability, throughput and coverage, while diminishing the produced overhead [14], [17], [18]. However, because they have such an uncontrolled and unpredictable nature, mobile networks suffer from transient connectiv-ity, which becomes even more obvious in the case of the highly dynamic VNs [16], [19]. As the high mobility of the nodes produces rapid changes in their underlying connectiv-ity capabilities, the routing information gathered becomes outdated and the established communication routes become invalid in a short time. This leads to substantial performance issues as the communication links get disconnected very often. The resulting disruption in the flow of information can cause significant delays and as routes require reconstruction, significant amount of additional network resources are consumed [20], [21]. Therefore, considering that in cooperative communications, the stability of a route depends on the links within itself and is determined by the performance of its weakest link, the criterion for the stability of a link is the time for which the link is up requires further investigation as it proves critical within VNs.

Infrastructure-aided routing was shown to be to be another performance enhancer for efficient VNs routing design, as they can enhance network coverage, by providing alternative routes when nodes cannot easily communicate with other nodes placed on different road segments due to NLOS conditions [14]. Thus, RSUs are considered in urban implementations, such as [17], [19], [22] to assist when the 'coverage hole' issue is encountered. However, such approaches can only handle a specific set of circumstances, they have their own advantages and challenges and as a consequence, each should be considered separately. On the other hand, a hybrid approach can improve the performance by providing the VNs routing method with flexibility.

Unfortunately, the state-of-the-art techniques still prove inefficient and unreliable as they cannot learn and adapt to the highly dynamic nature of the VNs. Thus, routing design was shown to further benefit from the use of reinforcement learning techniques, which can combat the challenges imposed by the highly dynamic environment of VNs [14]. Many routing protocols based on reinforcement learning (RL) have been proposed in recent years, where, owing to the learning ability of the algorithm, after a specific time during which the learning is completed, RL-aided routing is shown to perform better than the underlying geographic routing algorithms [14], [17], [23], [24], [25]. However, as VNs intend to serve multiple applications with a wide range of QoS requirements, it is critical that efficient VNs routing design is achieved. As the existing methodology proves not to be effective in that sense, there is a need for VNs routing design to address the beforementioned problems, which is the aim in this thesis.

1.2 Research Questions

Following the above discussion, as the state-of-the-art approaches to routing in VN still present the aforementioned challenges, a new series of new efforts is required in order to enable efficient VNs communications. Therefore, this thesis aims to answer the following research questions related to VNs routing:

Q-1. How can the effective and realistic estimation, modelling and simulation of VNs become possible? Additionally, how do the size and complexity of the considered road-network structure affect the performance of VNs communications?

Q-2. How do VNs applications' QoS requirements affect the duration of communications sessions? More generally, what is the trade-off between the considered link QoS requirements and route lifetime performance? Finally, how can the route lifetime be used when designing future routing algorithms?

Q-3. What is the effect of queuing phenomena and channel fading on the performance of the VNs routing approaches? How can such effects be mitigated through hybrid approaches for more efficient communications in VNs? How can infrastructure-aided cross-layer traffic-aware techniques be additionally improved through the use of RL-aided routing schemes?

1.3 Research Contributions

The contributions of the research presented in this thesis are as enumerated below:

C-1. A study of the accurate modelling, simulation and evaluation of VNs was performed. A VNs simulation platform was built, i.e. that allows the the extraction of simulation data from realistic urban mobility scenarios. A classification of urban VNs mobility models is detailed based on multiple performance-influencing parameters (e.g. the road-network structure and its dimensions, vehicle density). Moreover, based on such variables, the implementation complexity of each mobility model is studied based on the simulation overhead.

C-2. A route lifetime simulation framework is provided, i.e. that first sets an upper bound for route lifetime through an exhaustive search routing algorithm. This upper bound is then compared against the route lifetime given by the shortest-path forwarding mechanism based on Global State Routing (GSR) as a routing example. Considering signal-to-noise ratio (SNR) as the VN application requirement, an evaluation of route lifetime is presented for the studied mobility models while considering multiple factor variations such as the road-network dimensions and complexity, vehicle density, signal-to-noise ratio requirements (SNR_{req}) and channel fading conditions.

C-3. An infrastructure based traffic aware routing algorithm (I-TAR) was proposed based on reinforcement learning approaches, where the static infrastructure used for relaying messages through the network is wire-connected such that the vehicular routing problem is simplified by means of leveraging the interconnected RSUs infrastructure. Additionally, a multi-source, multi-destination scenario is employed to highlight the effects of the queuing phenomena in such conditions. Hence, the availability of the nodes is modelled based on their queue occupancy, as they take part of multiple communica-tions paths at the same time for a more realistic network modelling. Consequently, the effect of node availability on the communication performance was studied.

C-4. As an extension to contribution C-3, a hybrid infrastructure based traffic aware routing algorithm (HI-TAR) is proposed, as a new hybrid routing technique that chooses the optimum V2V/I path to the destination in terms of delay, link quality and route lifetime, accordingly. More specifically, unlike I-TAR and QTAR, HI-TAR does not always prioritise traffic through the RSUs but also takes other vehicles as potential next-hop candidates during the routing process. The performance analysis of the proposed hybrid routing scheme, HI-TAR, was provided and compared with I-TAR and QTAR, while varying the number of participant vehicles.

Software Contributions:

The MATLAB/SUMO VN Simulator as well as the algorithms presented throughout this thesis, namely Alg. 1, Alg. 2, Alg. 3, Alg. 4, are available at the following url address: https://github.com/TeodorIvanescu/VNs-MATLAB-Simulator

1.4 Publications

P-1. Teodor Ivanescu, Halil Yetgin, Mohammed El-Hajjar, and Geoff V Merrett. \Route lifetime analysis for vehicular networks". In: 2021 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS). (Accepted/In press.)

P-2. Teodor Ivanescu, Halil Yetgin, Geoff V Merrett, and Mohammed El-Hajjar. \Multi-Source Multi-Destination Hybrid Infrastructure-aided Traffic Aware Routing in V2V/I Networks". In: IEEE Access. (Accepted/In press.)

1.5 Thesis Organization

The reminder of this thesis is organized as follows:

Chapter 2 first provides an overview of VNs and their use cases in Section 2.1 and Section 2.2. Next, in Section 2.3, the existing communications systems and their key requirements within VNs are provided. Then, a classification of the existing routing methods is provided in Section 2.4 based on their routing mechanism and based on their considered routing target-metric. Then, the existing approaches to routing in VNs are detailed in Sections 2.4 - 2.6 from an evolutionary perspective, as they are encountered within the literature. Finally, Section 2.7 concludes the chapter and provides a discussion with the aim of appreciating the current trends against the contributions provided in this thesis.

Chapter 3 is structured as follows. In Section 3.1, a short review of the various already existing software for VN evaluation in a comparative manner based on their current features. Then, Section 3.2.2 introduces a VN simulator design. In more details, Section 3.2.1 provides a discussion of the employed modelling and evaluation tools. Then, in Section 3.2.2.2 several mobility models are designed while their detailed configurations are provided. Finally, Section 3.3 provides a discussion of the chapter.

Chapter 4 focuses on the evaluation of route lifetime within VNs, besides studying the effect of urban mobility on routing performance. In more details, the route lifetime is measured in order to reveal the trade-off between the structure and dimension of the road-network and performance requirements as a fundamental research baseline for investigating and developing sophisticated routing models for vehicular networks. In Section 4.1, the network model is discussed followed by the route lifetime evaluation process. In Section 4.2, a description of the simulation environment is provided, followed by the simulation results and their discussions. Section 4.3 concludes and discusses the chapter.

Chapter 5 is organized as follows. In that sense, the rest of this chapter is organized as follows. The considered network model is described in Section 5.1, followed by the description of QTAR, as the chosen benchmark algorithm. Then, in section 5.2, the newly proposed algorithm, ITAR, is discussed, as well as the approach for modelling node availability and the hybrid routing algorithm, namely HI-TAR. The simulation environment in Section 5.3, which also provides the simulations' results and their discussions. Section 5.4 concludes the chapter.

Chapter 6 concludes this thesis while providing a summary of the key contributions within. Additionally, as an extension of this work, future work directions are given.

Chapter 2

Routing Techniques in Vehicular Networks

This chapter provides a background and a detailed review of the existing approaches to routing in Vehicular Networks (VNs). Unfortunately, existing communications systems are not able to achieve the adequate coverage, long-lasting stability and large throughput required by smart city applications due to the highly dynamic and complex environments of VNs [11]. Thus, intelligent VNs rely on multi-hop communications to achieve increased data transmission and coverage [6]. As a consequence, efficient routing algorithm design has attracted a lot of research attention due to its critical role in achieving successful communications in VNs. However, due to their uncontrolled and unpredictable nature, VNs routing has many challenges [13].

This chapter first provides an overview of VNs and their use cases in Section 2.1 and Section 2.2. Next, in Section 2.3, the existing communications systems and their key requirements within VNs are provided. Then, a classification of the existing routing methods is provided in Section 2.4 based on their routing mechanism and based on their considered routing target-metric. Then, the existing approaches to routing in VNs are detailed in Sections 2.4 - 2.6 from an evolutionary perspective, as they are encountered within the literature. Finally, Section 2.7 concludes the chapter and provides a discussion with the aim of appreciating the current trends against the contributions provided in this thesis.

2.1 Vehicular Networks

VNs are high mobility networks constituted of moving vehicles which interact with each other through wireless links. In most words, VNs are similar to Mobile Ad-Hoc Networks (MANETs) in the sense that nodes are roaming randomly, but in VNs, the nodes travel following some fixed pathways such as urban/rural roads and highways. Moreover, VNs are highly dynamic, due the fast and continuous movement of the topology which implies several adverse effects on communications performance. However, unlike MANETs, VNs are not energy constrained, as vehicles are assumed to have considerably large batteries. Therefore, VNs are constructed as a subclass of MANETs because of their difficult additional characteristics as described in Table 2.1 [6].

Parameter	VNs	MANETs
Network size	Large	Medium
Node mobility	High	Low
Movement pattern	Restricted	Random
Energy limitation	Very low	High

Table 2.1: VNs vs MANETs Comparison [6].

Initially, due to their increased sizes, multi-hop communications techniques were considered to address the network coverage issue. Thus, routing techniques were employed with the purpose of efficiently obtaining successful transmission routes that assure communications across large distances in VNs. However, in addition to solving the coverage hole issue, multi-hop transmissions suffer additionally in such an environment as a consequence of the highly dynamic topology of VNs [13]. As a consequence, in order to achieve such reliable and flexible routing, VNs have to be properly studied and characterized. In that sense, table 2.1 provides a comparison between VNs and traditional MANETs based on their main differences as a motivation for their separate consideration. Moreover, a list of the main factors that need to be considered separately in VNs routing is presented as follows.

Parameters such as road-network structure dimensions as well as the considered number of lanes and the lane direction affect the connectivity of VNs and hence are critical during the routing design process from the perspective of successful protocol operation. For example, radio interference from other lanes can affect the performance of wireless links. In addition, the traffic behavior on each lane can be affected due to the intersections, which act as a bottlenecks for traffic. Moreover, traffic patterns vary based on road type which is, in general, divided into three main categories: rural, urban and highway [15].

Considering the complex environments of urban VNs, where buildings impose blockage on most signals, and the excess Doppler shift phenomena is experienced due to the high mobility of the vehicles, the Radio Frequency (RF) propagation conditions become critical for accurate routing design [26]. Moreover, traffic conditions, such as the vehicle density, can vary depending on the time during the day, week or even month. There are some peak times, such as rush hours, weekends, holidays or special events when traffic density can be heterogeneous. For example, in a traffic jam scenario, once a successful route is found, the chance for it to be interrupted due to vehicle movement is really low, as vehicles are clustering together. However, such a scenario can suffer from heavy interference which can implicitly affect existing communications sessions. Hence, the conditions of traffic on the available road-network structure is of high importance when designing routing for VNs. Finally, both static and dynamic obstacles (neighboring vehicles and pedestrians) have to be included in the routing process design process, as they can often lead to blockage which, in turn, often leads to interrupted connectivity of VNs [27].

Moreover, the drivers' behaviour is another distinctive factor as they interact directly with their surroundings, which can include both static and dynamic objects. Thus, routing design should take into account the mutual interactions between vehicles and other participants in the network, such as vehicle overtaking, traffic jams as well as preventive actions when confronted to pedestrians. Another important factor is represented by the acceleration and deceleration state of vehicles and it should be carefully taken into account [10].

2.2 VNs Use Cases

Following the discussion in Section 2.1, VNs can collect and process such information from the environment such as vehicle status (locations, velocities and trajectories among others), traffic status, weather conditions and available roadway and then share it fur-ther through various communications methods in order to obtain a more efficient and accident-free traffic [9]. Therefore, when encountering a traffic issue, an early triggered notification can guide the driver towards a safer, faster and more enjoyable journey to destination. As a result, the main existing and proposed use cases for VNs are:

Safety Applications - Extended Sensors - The main aim of vehicular communications is a safer, accident-free traffic. Exchanging data gathered by sensors provides the system with increased coverage, a projection of the surrounding map and the ability of antic-ipating future events. As a consequence, accidents could drop by 70% and even using traffic signs or police officers to guide traffic might become unnecessary [28].

Efficiency Applications - Vehicle Platooning - Vehicles can get together and travel as a group, at really small distances from one another. Thus, platoon operations are helpful with increasing the efficiency of the available roadway. Moreover, road congestion management applications provide drivers with the ideal path to the desired destination, improving the traffic flow, hence, avoiding the creation of traffic jams.

Comfort Applications and Interactive Entertainment - Users could be offered access to applications such as web browsing, file sharing, music and various games. Moreover, drivers can be provided with information about the gas stations/restaurants in the area, weather, parking information. Remote driving could also become possible, where an operator can remotely control a vehicle.

The use of sensors such as video cameras, Radars and Lidars become more common in the Vehicular Industry. This increasing number of on-vehicle sensors produces a huge amount of data that needs to be processed and then transmitted to other vehicles in the network. Table 2.2 shows the potential uses and compares the requirements of the sensor types mentioned above [10]. It can be observed that video transmissions require a lot of bandwidth. Moreover, applications such as Extended Sensors are expected to require up to thousands of megabytes-per-second [8]. Therefore, high data-rate access is critical in VNs communications.

Sensor Type	Uses uses	Data rate
Radar	target detection/vehicle estimation	<1 Mb/s
Camera	virtual mirrors	100-700 Mb/s - raw images 10-90 Mb/s - compressed images
Lidar	target detection recognition velocity estimation	10-100 Mb/s

Table 2.2: Sensor Classification [7], [8].

Table 2.2 shows the performance requirements for VNs use cases in terms of reliability, end-to-end latency, communication range and required data-rate provided by the 3rd Generation Partnership Project (3GPP) [7]. It is clear that the safety operations proposed are reliability dependent as well as delay sensitive. That is because a lower delay and hence, an earlier alert improves the reaction of the driver when he has to execute a maneuver. The lower the allowed delay is, the higher the expected reliability. For example, the Extended Sensors application can require up to 99.99% reliability and in terms of end-to-end latency as low as 3 ms for transmitting safety messages between vehicles unlike comfort applications that do tolerate certain delays [8].

Scenario	Max end-to-end latency	Reliability	Data Rate
Vehicles Platooning	20 ms	90-99.99%	50-65 Mbps
Advanced Driving	3-100 ms	99.99%	10-53 Mbps
Extended Sensors	3-100 ms	99.99%	10-1000 Mbps
Remote Driving	5 ms	99.99%	1-25 Mbps

Table 2.3: Sensor Requirements [8].

Furthermore, VNs also have a set of functional requirements in order to successfully serve the use cases presented above. For example, message prioritization, connection management and congestion control among others [20], [29]. In addition, depending on the use case, different routing dissemination modes can be used, such as unicast, broadcast, multicast and geocast transmission modes as discussed later, in Section 2.4. However, before deciding on the routing method, an accurate evaluation and representation of the VNs is required from the transmission process perspective. In that sense, Section 2.3 provides a classification of the most influencing parameters to radio frequency (RF) propagation in VNs.

2.3 Radio Frequency Propagation Model

In terms of propagation mechanisms, modelling aspects such as high path-loss, increased Doppler shift and fading caused by both static and mobile objects is difficult in an environment such as VNs. Therefore, for an accurate modelling of VNs radio frequency (RF) propagation the problem is split as follows.

Ideally, VNs communications systems should be able to share information between all participants on the road-network structure. Thus, transmission links can be divided, considering the source-destination pair they serve, into V2V (vehicle-to-vehicle), V2I (vehicle-to-infrastructure), V2P (vehicle-to-pedestrian), I2V (infrastructure-to-vehicle) and I2I (infrastructure-to-infrastructure) [9]. In more details, unlike V2V links, which serve only vehicles, V2I links assure transmission between vehicles and the road-side units placed along the road-network structure. Note that such equipment is used to improve the capacity and the coverage of the network. Therefore, I2V links are designed to allow transmission between road-side units and vehicles, while I2I links serve transmissions between multiple road-side units. Finally, V2P links aim to reduce the thousands of fatalities/injuries that take place every year by using a filter to identify pedestrians in order to trigger the right action, if needed [30]. It is important to note that the link type imposes changes on the communications QoS. For example, V2V and I2V links can differ in terms of provided QoS considering the different transmission rates of vehicles against those of the infrastructure's.

Based on the location where VNs operate, the transmission environment can be classified into the following three main categories: highway, rural and urban [31]. These are constructed based on specific environment-specific transmission-influencing factors such as the high speeds of vehicles in highway transmissions and the crowded surroundings in large cities. For example, speeds averaging more than 100 km/h on highways might represent a challenge for VNs. Moreover, considering the attenuation and reflection of the signal in different environment types is of vital importance. The presence of buildings, trees and other objects leads to path loss and shadowing effects hardening the transmission process, especially in city environments. Reports of highly variable and often contradicting path loss exponents were provided in several studies found in the literature. Values range between 1.6 - 2.9 in highway environments, 2.3 - 3.5 in suburban environments, and 1.8 - 3.4 in urban environments [32], [33]. Similarly, mean delay spreads values vary between 140 - 400 ns on highways, 80 - 104 ns for suburban scenarios, and 150 - 370 ns for urban scenarios [34], [35]. Also, special scenarios such as tunnels, bridges, covered and multilevel-ed roads have to also be taken into account.

Following the above discussion, RF propagation models can be classified as follows [26], [27], [31], [36]. Large-scale fading propagation models characterize the mean signal strength as a result of the attenuation produced during signal propagation over large distances. Diffraction around large objects is also considered. The most commonly used large-scale model is the Log-distance path loss model which is mainly used to predict the propagation loss over multiple environments such as inside buildings and densely populated areas [36]. Small-scale fading propagation models characterize the rapid variations that affect signal propagation in addition to large-scale fading and hence, are used to estimate the performance of the wireless channel over small distances or short time duration. Moreover, the available RF propagation models, can be further classified as encountered in the literature as follows [31]. Non-geometry-based stochastic (NGS) models are based on information extracted from a particular environment and therefore, they are usually used for a restricted propagation channel. As a consequence, such a model would not be suitable for a highly mobile environment where the topology is highly dynamic and, as a consequence, all the parameters are continuously changing. Geometry-based deterministic (GDB) models are used to evaluate the link level performance and they can be divided into link-level models, that focus on small-scale fading, and system-level models, that abstract it and focus on the large-scale fading [27].

Furthermore, a simplified geometry-based model can be designed; i.e. one that consid-ers the geometric properties of the surroundings while taking into account some channel characteristics from measurements/simulations. Ray-tracing models are the most commonly used models in the literature as they are able to provide an adequate means to model the multi-path propagation of the RF signal. However, they require a detailed description of the surroundings in order to achieve accurate calculation of the channel [27]. Therefore, in order to achieve realistic modelling of VNs, communications systems should take into consideration as many transmission-influencing parameters as possible, i.e. the nature and directionality of communications links, the available bandwidth, the traffic density as well as the blockage conditions among others. A classification of the main communications systems proposed for VN applications is provided below.

2.3.1 Communications Systems in VNs

In VNs the communication protocols used for data transmission are similar to those used in other wireless ad-hoc networks. For example, TCP/IP is the most commonly used protocol suite for communication in VNs, as it is in most other computer networks [37]. The TCP/IP protocol stack provides end-to-end communication services, including routing, data transmission, and error recovery. The application layer uses protocols such as HTTP, FTP, and SMTP to communicate with other nodes over the network. The transport layer uses protocols such as TCP and UDP to provide reliable or unreliable data delivery, depending on the application requirements. The network layer uses protocols such as IP and ICMP to route the data packets between nodes. And the data link layer uses protocols such as Ethernet or IEEE 802.11p to provide a physical link between the nodes.

However, in addition to TCP/IP, VNs may use specific protocols and standards, such as IEEE 802.11p or DSRC, to provide reliable communication services in the vehicular environment, where the network topology is highly dynamic and the signal quality is frequently affected by interference and obstacles. These protocols are designed to meet the unique requirements of vehicular communication, such as low latency, high data rate, and reliable transmission. The following are some of the common communication protocols used in VNs:

1. IEEE 802.11p: This protocol is a standard for wireless communication in vehicular environments. It is based on the IEEE 802.11 standard (Wi-Fi) and operates in the 5.9 GHz band. It provides a high data rate of up to 27 Mbps, low latency, and supports both unicast and multicast transmissions [38].

2. Dedicated Short-Range Communications (DSRC): Also identified as IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) is a communication technology designed specifically for VNs to operate at 5.9 GHz [39]. It is created as an extension of the WLAN IEEE.802.p standard for vehicular communications to function in highly dense networks [39]. The system supports vehicle speeds up to 200 km/h and a maximum transmission range of 1000m. Unfortunately, it can provide only up to 27 Mbps maximum data rate and therefore, it cannot support most of the bandwidth hungry VN applications on its own [40]. However, the DSRC protocol is able to provide insight on adapting the IEEE 802.11ad standard to vehicular communications as shown in the following discussion. Note that DSRC supports both unicast and multicast transmissions.

3. Cellular-based protocols: These protocols use cellular networks to provide communication services in VNs. They leverage existing cellular infrastructure to provide connectivity between vehicles and the Internet. Examples of cellular-based protocols include Long-Term Evolution (LTE) and 5G [41].

The mm-Wave spectrum, placed between 30 and 300 GHz (corresponding wavelength between 1-10 mm), presents huge potential towards achieving high data-rate transmissions in VNs [42]. Besides the highly unused and hence, available bandwidth, mm-Wave Communications use higher order modulations as well as multiple-input-multiple-output (MIMO) and Beamforming techniques to enhance the spectral efficiency of the transmission and achieve higher data-rates than the state-of-the-art wireless communications systems that operate below 6GHz [39]. Moreover, the same small-sized antennas that allow building large MIMO antenna arrays could be easily installed on vehicles without affecting the space efficiency. However, due to the rapid and uncontrolled mm-Wave channel variations caused by the high mobility of vehicles, transmission is subject to frequent handover and association events.

Additionally, Visible Light Communications (VLC) is an optical wireless communication system that uses modulated optical radiation from the visible light spectrum situated between 400nm – 700nm [43]. It represents a potential alternative to Radio Frequency as communications links can be formed between vehicles using only LED lights, photo diodes and some processing circuitry. Such systems reuse some of the existing infrastructure as LEDs are already in use in the automotive lighting industry and hence, manufacturing costs can be lowered. However, VLC systems are greatly affected by severe weather conditions such as rain or heavy fog. Also, sunlight has the potential to saturate the photo diodes used as receivers. An illustration example of VLC is provided in Figure 2.1 below.

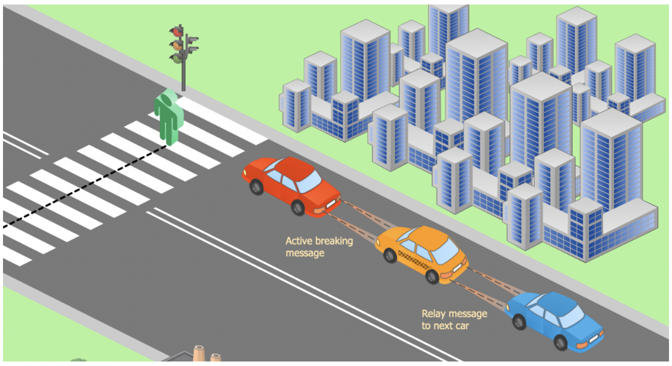


Figure 2.1: An illustration of Visible Light Communications (VLC).

In terms of how the data is generated, incorporated into packets, and sent from one node to another in VNs, the process involves the following steps [44],[38]:

1. Data generation: The data is generated by an application running on a node. The data can be anything from simple text messages to sensor data from various sources such as cameras, GPS, and accelerometers.

2. Packet formation: The data is divided into smaller units called packets, which are formatted according to the communication protocol being used. The packets contain the source and destination addresses, packet type, and payload data.

3. Packet transmission: The packets are transmitted over the wireless medium using the communication protocol being used. The packets are broadcasted or unicast to the destination node depending on the routing protocol and the network topology.

4. Packet forwarding: In a multi-hop network, the intermediate nodes receive the packets and forward them towards the destination node. The forwarding decision is based on the routing protocol and the information stored in the routing table.

5. Packet reception: The destination node receives the packets and reassembles them to form the original data.

Overall, the communication protocols and the process of generating, incorporating, and transmitting data packets in VNs are similar to those used in other wireless ad-hoc networks, with the addition of vehicular-specific protocols and considerations.

For example, it is shown in the literature that if two vehicles are blocked by obstacles such as other bigger vehicles (trucks/busses), buildings and so on, the probability for the packets to get lost on their way to destination increases [45]. As a consequence, the LOS condition is also of high importance for the transmission process. However, note that due to the great impact of blockage on the line-of-sight (LOS) condition of RF propagation, the LOS and non-line-of-sight (NLOS) conditions are considered separately when modelling large- and small-scale fading properties as follows.

2.3.2 Urban VNs Blockage

There is a large variety of automobile types available in the industry and they do not all share the same propagation characteristics. Thus, in order to lower their impact on the propagation channel, distinct characteristics of each type must be taken into consideration when designing the channel model. For example, LOS blockage caused by a large truck could produce around 20 dB increase in attenuation, compared to personal vehicles [1], [7]. In addition, it is shown in the literature that if two vehicles are blocked by obstacles such as other bigger vehicles (trucks/busses), buildings and so on, the probability for the packets to get lost on their way to destination increases [45]. Therefore, knowing the LOS condition of a communications link could permit the allocation of resources to those participants that provide good links with their pair. As a consequence, the LOS condition is critical for the transmission process. Note that sensor generated LOS conditions can, therefore, be a significant factor for route performance as they are good approximations for real RF LOS/NLOS. [36]. Thus, the time and space evolution of the LOS condition needs to be thoroughly analyzed based on the position of the vehicles as well as the data gathered from their surroundings.

A three-state Markov chain is proposed in [46] that defines the LOS condition using three states; i.e. LOS / NLOS-buildings (b) / NLOS-vehicles (v). Here, it is shown that due to the high mobility of the participating vehicles, in NLOS-v scenarios, the transmission suffers from different path-loss and shadowing effects when it is blocked by mobile objects (in VNs, other vehicles or mobile base-stations) compared to those induced by the static objects (NLOS-v). Moreover, if the LOS is blocked by both vehicles and buildings/trees, only NLOS-b is considered, as it represents the dominant factor.

Mobility data is then incorporated into the calculation of LOS and transition probability. In that sense, the received signal strength (RSS) at the receiver side proves to be revealing factor concerning LOS condition. Therefore, following the before-mentioned discussion and considering two nodes, N_i and N_j, that are communicating in a VNs environment, the received signal power (P_r) at the receiver side, namely at node N_j, can be characterized in dB as follows [47].

$$P_r^{N_j} = P_t^{N_i} - PL_{N_i;N_j}; \qquad (2.1)$$

where $P_t^{N_i}$ is the transmission power of node N_i, $PL_{N_i;N_j}$ is the path-loss from N_i to N_j defined in Equation (2.2) as follows:

$$PL_{N_i;N_j} = 20\log_{10}\frac{4\pi d_{N_i;N_j}}{\lambda} + G; \qquad (2.2)$$

where G represents the channel gain and λ is the corresponding wavelength.

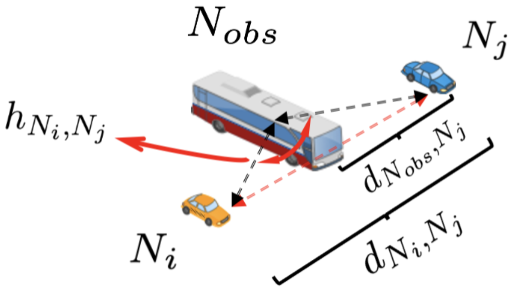


Figure 2.2: An example of vehicle induced blockage [1].

However, such P_r evaluations only characterize large-scale fading. In order to correctly estimate the LOS condition, all types of blockage must be considered. In addition, considering NLOS-v scenarios, it is shown that vehicle density has a major impact on the LOS condition [1]. This is caused by the small heights of the used antennas and it proves that different density values must be considered for a correct evaluation and modelling of the VNs. Therefore, the authors of [1] borrow the concept of fingerprint from localization techniques. More specifically, by using the appropriate channel-state-information (CSI), the RSS at the received side can be estimated for multiple locations and time-slots during the day, stored and used later during the routing process. Figure 2.2 provides an example scenario of how vehicle-induced blockage is produced following a source vehicle's (V_s) position with regards to a destination vehicle (V_d) it attempts to communicate with. Thus, if N_{obs} is considered to be an obstructing vehicle node as shown in Figure 2.2, the additional attenuation produced by other vehicles can be evaluated as follows:

$$A_{N_i;N_j} = 6.9 + 20\log_{10}\left[\sqrt{(v_{N_i;N_j} - 0.1)^2 + 1} + v_{N_i;N_j} - 0.1\right]; \quad \forall v > -0.7 \qquad (2.3)$$

$$v_{N_i;N_j} = \sqrt{\frac{2\,h_{N_i;N_j}}{r_f}} \qquad (2.4)$$

where $h_{N_i;N_j}$ represents the obstacle height, i.e. the distance between the line joining the RSU and the transmitting vehicle and its highest point, as depicted in Figure 2.2. Note that if $v <\ 0{:}7$ the attenuation is reduced to 0. Finally, r_f is the Fresnel ellipsoid radius expressed given by Equation (2.5) below.

$$r_f = \sqrt{\frac{d_{N_i;N_j}\ \ d_{N_{obs};N_j}\ (d_{N_i;N_j} \qquad d_{N_{obs};N_j})}{d_{N_i;N_j}}}; \tag{2.5}$$

where is the wavelength, $d_{N_i;N_j}$ is the distance between the transmitting vehicle and its intended destination, while $d_{N_{obs};N_j}$ is the distance between the obstacle and the V_d. As a result, the total received power at the receiver vehicle after considering both the channel induced path loss as well as the attenuation imposed by obstacles on signal transmission becomes:

$$P_r^{N_j} = P_t^{N_i} \quad PL_{N_i;N_j} \quad A_{N_i;N_j}: \tag{2.6}$$

As a consequence of knowing the LOS condition of a communications link, the allocation of resources to those participants that have good links with their pair could be permit-ted. Note that sensor generated LOS conditions can, therefore, be a significant factor for route performance as they are good approximations for real radio frequency LOS/n-LOS. [36]. Following the before-mentioned classification of communications links, one other main performance-influencing element that is analyzed and characterized for efficient transmissions in VNs is the considered transmission channel. Next, in Section 2.3.1 a comparison between some of the communication systems that are available for VNs is provided.

Thus, a realistic network model can be achieved by taking into account information from all previously described factors, assuming that they can be accurately estimated and processed for routing purposes. Next, Section 2.4 provides a classification of the existing single-layer routing protocols in an evolving way.

2.4 Single-Layer VNs Routing

Once all the necessary network information has been gathered, the routing process is employed. More specifically, a scoring function can be used to predict the weights and ranks of the available directions forwarding options, with the aim of finding optimal paths through various routing techniques [36], [48]. However, a large variety of routing techniques exists and therefore, a classification of the traditional single-layer routing techniques is provided next, as described in Figure 2.3.

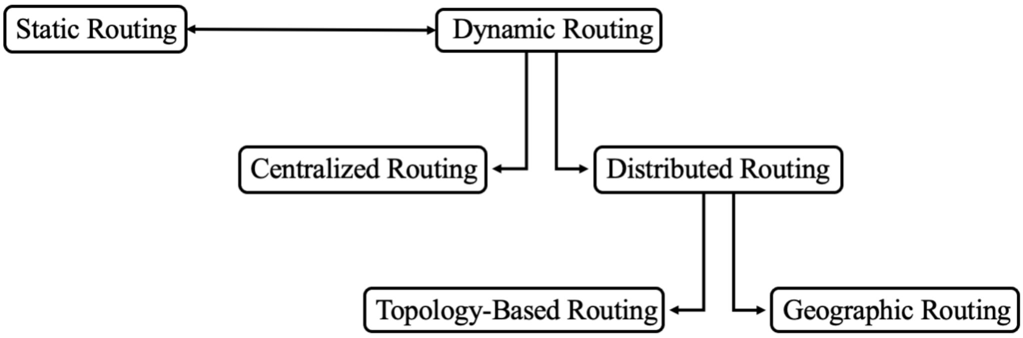


Figure 2.3: Existing VN Simulation Software [2].

Based on their adaptability to changes, traditional single-layer routing protocols can be split into static and dynamic routing algorithms [48]. In static routing a network manager is assigned to pre-configure static routing tables. However, this process is inefficient when placed in dynamic environments such as the VNs, where the routing information becomes outdated quickly. In dynamic routing, routing tables are built, updated and shared between neighbors regularly and automatically. Hence, VN applications require dynamic routing protocols as they can keep track of the continuously changing topology. However, in order to do so, complex algorithms are required which might impose large control overhead on the transmission.

Thus, dynamic routing can further be split into two main categories, namely centralized protocols and distributed protocols [48]. In centralized routing, a central node is designated to gather information towards an overall view of the system, acting similar to a global database. Following this approach, the central node is able to calculate the optimal paths, which he can distribute afterwards under the form of routing tables. In spite of this, the high chance of network failures or overloads leads to a complicated and costly maintenance and recovery process. On the other hand, in distributed routing, each node shares system-related information with other nodes in its vicinity in order to perform individual routing. As a result, each vehicle is able to build and maintain routing tables individually based on the last routing information received. Such a technique reduces dependencies between nodes and lowers the cost and complexity of the maintenance and recovery process and thus, it is optimal for VNs. However, single-layer routing protocols prove not to be flexible enough for such routing requirements of VNs. Even though they do improve the system in terms of QoS performance, they do not consider several important factors that allow transmission in VNs. Hence, the two main challenges faced by single-layer routing are congestion formation and interference, as presented in [6]. Congestion is formed in highly dense networks, where multiple data packets are sent from several nodes. This usually leads to frequent collision and thus, packets might get lost on-route [49]. Moreover, if multiple routes make use of the same node the buffer space at the receiver is exceeded and data packets might not be stored over the whole processing time resulting in additional packet-loss and a need for re-transmission requests. Interference usually happens when the transmitted signal gets mixed up with other unwanted signals on the way to the destination node. The problem can be split into intra-flow interference, where the nodes that interfere with each other are part of the same path and inter-flow interference, also called path coupling, where the interference takes place between close-by nodes on different paths [50]. For example, inter-flow interference can strongly affect VNs, especially in high traffic density scenarios, when nodes are crowded within the road-network structure. Thus, traditional single-layer routing protocols find themselves inefficient in the context of VNs as they fail to assure the required coverage and reliability needed for such systems. However, by also utilizing vehicle movement information, an accurate mobility model can be computed in order to efficiently localize and track the vehicles that are part of the network. Both static and mobility information can be obtained directly from sensorial data, as well as BSMs received through regular DSRC transmissions. Therefore, cross-layer routing has been proposed in the literature as a solution for routing in VNs as discussed next, in Section 2.5.

2.5 Cross-Layer Traffic-Aware VNs Routing

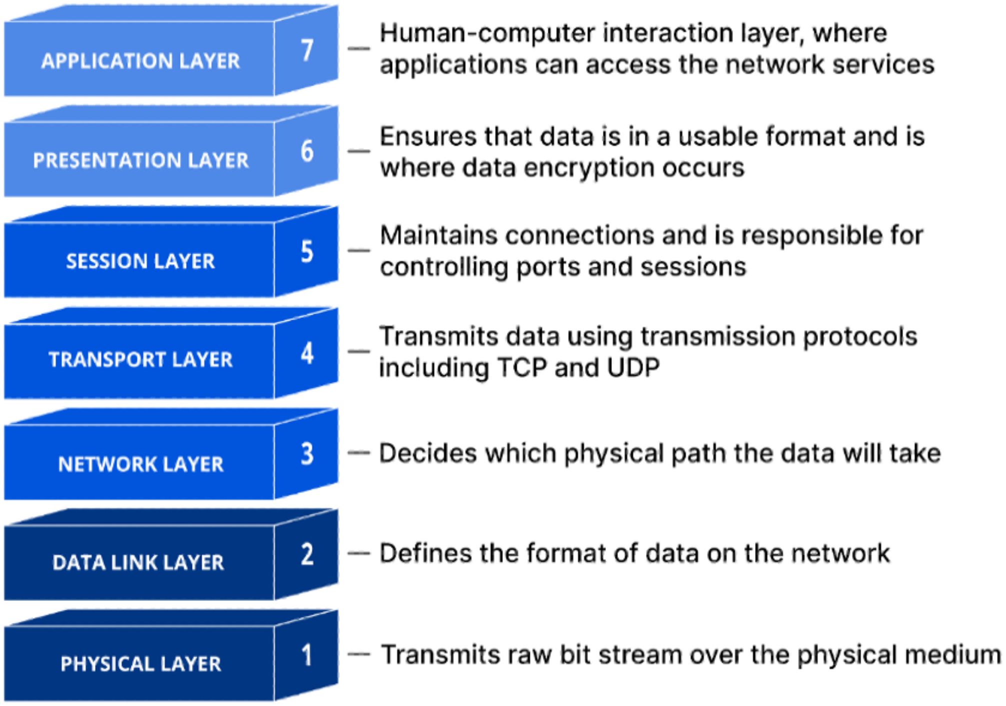


Figure 2.4: Open Systems Interconnection (OSI)-Layered View of a Communications System [3].

Traditionally, following the Open Systems Interconnection (OSI) model both the network layer (Layer 3) and data-link layer (DLL) (Layer 2) are involved in the routing decision process [51], [6], [3]. In more details, at the network layer of the OSI model, the routing decision is made based on the network address contained in the packet's header. The router examines the destination IP address and looks up its routing table to determine the next hop for the packet. Moreover, at the data-link layer, routers use medium-access-control (MAC) addresses to forward packets within a local network. When a router receives a packet on an interface, it looks up the MAC address of the next hop and forwards the packet to that MAC address. In a cross-layer system, however, multiple layers of the OSI model work together to make routing decisions.

More specifically, cross-layer systems are designed to optimize network performance by allowing communication between different layers and sharing information across those layers. For example, a cross-layer system may allow the physical (PHY) layer (Layer 1) to inform the network layer about the quality of the wireless link. The network layer can then adjust its routing decisions to favour paths with better link quality. Similarly, a cross-layer system may allow the transport layer (Layer 4) to provide feedback to the network layer regarding congestion on the network [52]. The network layer can then use this feedback to make routing decisions that avoid congested paths. In general, cross-layer systems can improve network performance by allowing different layers to work together and share information. However, cross-layer systems can also be more complex to design and implement, and they may require tighter coupling between different layers, which can make the system less flexible and less inter-operable with other networks.

Therefore, by sharing information among well-chosen neighbour vehicles and infrastructure, a virtual map of the environment can be build, expanding the individual sensing range of the VNs environment. More specifically, besides using only relative contextual information obtained by sensors from the surrounding environment, additional information can be attained at each node through lower frequency communications systems such as DSRC [53], [54]. Hence, following the OSI model, a functional split between the PHY layer, the MAC layer (as a sub-layer of the DLL), the network layer and the transport layer is proposed in the literature with the aim of achieving reliable and efficient routing [36], [53], [54], [55].

More specifically, unlike the traditional single-layered approach, cross-layer routing protocols can exploit the dependency between protocol layers by allowing nodes to exchange additional information, in order to achieve higher performance gains. For example, in [55], the authors propose a cross-layer mechanism, namely Channel State Information (CSI) and Queue State Information (QSI). CSI is provided by the PHY layer in order to indicate transmission opportunities whereas QSI reflects the presence of the congestion phenomena as part of the transport layer. However, the range of parameters that can help in VN applications is quite large.

Therefore, by assuring the inter-operability of the first four layers of the OSI model, routing algorithms become more robust against issues such as congestion and interference [56]. In addition, the throughput can be significantly improved while also saving energy, if transmissions are only scheduled to take place in favorable conditions. For example, interference effects can be captured and characterized by analyzing properties of the channel such as SINR, available at the physical layer. Moreover, by taking into account QSI available at the transport layer, the encounter of the congestion phenomena along communications paths can be avoided.

Within this context, in [57], a Situational Aware QoS Routing Algorithm is proposed with the aim of computing the best possible routes between communicating vehicles. Here, the authors employ a Situational Awareness (SA) concept as well as an ant colony system (ACS) which work together towards a situation-aware multi-constrained QoS (Quality of Service) routing. ACS promises to be an effective technique for calculating and managing the multi-constrained paths produced in VNs, as it offers several benefits: they are fully-distributed and self-organized. In other words, they grant increased ro-bustness and high tolerance to errors. However, it is still unknown to what extent they can be aid VNs and therefore, a further study of such techniques must be undertaken. Situational awareness (SA) represents the ability to extract information directly from the environment or through BSMs. Thus, if this data is combined with existing internal information, each vehicle could project an image of its immediate surroundings and thus, anticipate some of the upcoming events. As a consequence, the right countermeasures can be prepared and applied in order to manage the possible risks efficiently. SA con-cepts propose a different approach to the traditional QoS-based methods used in VNs by considering routing to be a continuous process. Thus, the chosen algorithm can find the best available paths, maintain them and prepare countermeasures in case of failure, i.e. backup/new routes. The four levels of the proposed SA model are discussed below [57].

- Perception - With the aim of determining the current state of the network, nodes can exchange sensorial data, as well as internal information such as position, speed or driver behavior. This can be done initially through BSMs transmitted technolo-gies such as DSRC, until the transmission has been established. However, due to the huge amount of information in the VNs, a multitude of available parameters can be extracted from their environments and choosing the right ones can also represent a challenge.
- Comprehension - The previously acquired data can then be synthesized and analyzed in order to properly characterize the network.
- Projection - In order to efficiently forecast the upcoming events in the network, the model needs to predict how reliable a link is and whether and when it might fail satisfying the constraints. Such information is then fed into the next level in order

for the best decisions to be made. One example is calculating the link lifetime between two nodes by taking into account the appropriate parameters generated during the previous SA stages.

- Resolution - Once the possible future events are predicted, the routing algorithm can proceed to find the optimal path, as required by VN applications, as well as prepare countermeasures that can be used in case of link failures. Note that the VNs environment is highly mobile and participants can access and exit the network at any point in time. Having that in mind, there are several potential countermeasures such as preparing backup routes as well as recalculating the new optimal path based on the obtained data.

Thus, distributed routing can be again delimited into two categories, namely topology-based and geographic-based routing. Topology based routing protocols compute and obtain the best route by using link information obtained through control data packets before the transmission. Unfortunately, the topology approach is not optimal for VNs as it offers degraded network performance and thus [6]. More specifically, in the case of large VNs, the overhead produced during the route discovery process is too high proving that such methods are more suitable for less dense and smaller scale networks. How-ever, considering the vehicle movement, the environment is indeed highly dynamic but, at the same time, restrictioned by the road-network structure. Therefore, besides chan-nel information, positional information becomes also relevant for routing, as it can be extracted, evaluated and utilized during the decision-making stage of the process. Hence, geographic routing protocols can use geographical information in order to compute the optimal route. A classification in terms of routing mechanism and geographic metric used is provided next. First, based on the routing mechanism employed, geographic routing can be categorized as follows [6].

- Beacon-based protocols update neighbors through frequent basic-safety-messages (BSMs) in order to enable transmitting nodes to take instantaneous decisions. They can also be characterized as sender-based protocols where the sender can select the best destination node in its vicinity as he already knows all of his neighbors.

- Beacon-less routing protocols, also known as receiver-based routing protocols, do not relay any BSMs messages. Instead, receiving nodes decide whether to take part in the process or not based on two main aspects, namely the forwarding phase and the waiting phase criteria. In more details, during the forwarding phase, nodes decide whether they will join the transmission and only once this condition is satisfied, they become forwarders themselves.

- Proactive routing protocols find and maintain the ideal path by storing routing information under table form (low latency, occupies major part of the bandwidth).

Tables are then shared with neighboring vehicles in order to be updated when any network change occurs. Unfortunately, in order to maintain the unused routes, major part of the bandwidth is occupied, although it assures low latency transmissions. Moreover, VNs suffer from frequent link failures and this mechanism cannot handle them well, making it inefficient [58], [59].

- Reactive routing protocols determine the best routing path on requirement and maintains only the paths in use. Therefore, less memory and bandwidth are required. However, they also result in high latency, which is really bad for most of the Vehicular Applications [58], [59].
- Hybrid approaches combine proactive and reactive routing in order to minimize the routing overhead and delay. Unfortunately, they perform poorly in highly mobile environments as they provide poor route convergence as well as low throughput [58], [59].

Based on the geographic metric considered, routing protocols can be further classified into location-based and traffic-aware approaches [6]. In location-based protocols, every node knows the location coordinates of its own, its neighboring nodes and maybe that of the destination vehicle. Furthermore, due to the high mobility experienced by VNs, using only static information might not be efficient enough and thus, traffic-aware routing was introduced, where the mobility aspects of the network have to be considered.

As a result, it becomes evident how important it is to extract the appropriate data from each layer with the purpose of using it during routing. Typical contextual-information such as position speed, direction, acceleration, weather conditions are useful parameters to take into account [7], [36]. However, separation distance impacts V2V performance limitedly, allowing transmission for most of the vehicular applications if it does not exceed 500m [45]. It is shown in [7] that high-level contextual information such as traffic density, channel gain prediction and previous antenna configuration must also be taken into account. For example, in the case of highly dense networks, the same message might be transmitted multiple times, which can be avoided if only a group of selected participants is allowed to send such messages. Moreover, in case of low-density networks, the dissemination method might need to be changed to a store-and-forward transmission mode and thus, based on the processed information, a hybrid routing approach can be employed. However, several parameters present additional interest to routing design due to their critical effect in VNs. For example, phenomena like network partitioning as well as queuing and their effects have to be considered separately, especially as VNs are scaled up in size and complexity, increasing thus, the randomness in the network. Therefore, the review of route lifetime in the context of VNs is provided next, in Section 2.5.1, followed by a discussion on the queuing phenomena and its effects on VNs routing in Section 2.5.2.

2.5.1 Route Lifetime

In VNs, frequent network partitions can be caused by the uneven distribution of vehicles. Thus, if the established routes suffer from premature disruptions, route reconstructions will be necessary more often. In addition, there is no guarantee for the new route not to die immediately or very shortly after its establishment. For an established route to become unusable, it is sufficient that a single link within the route to break. In the case where one link might be used within multiple routes, multiple route reconstructions would be necessary at the same time leading to an increased corresponding overhead and thus, increased delay [21]. This series of successive route reconstructions is called \ping-pong" behavior. The authors in [60] underline that VNs experience a significantly limited network diameter due to the high number of routes that fail before they can be utilized. The same behavior was observed in [61], where the authors looked at practical implementations of typical MANETs protocols. Thus, another routing parameter of great importance is the lifetime of communications links and implicitly of the routes they form.

There are multiple definitions of network and route lifetime within the context of wireless communications networks. In [62], they define the lifetime to be the time period during which the network/route continuously satisfies the application requirements. In [63], a parametric lifetime definition, including factors such as node availability, coverage, connectivity, service disruption tolerance and so on, is provided. Moreover, due to the fact that the required objective can include or discard from the formulation of the lifetime definition any such QoS considerations, this lifetime metric definition can be useful for most of their target use cases. In cooperative communications, the stability of a multi-hop route depends on all of the links composed within and is determined by the strength of the weakest link. The criterion for the stability of a link is the time for which the link is up. Such an ‘affinity’ parameter has been proposed in [64] which characterizes the strength and stability of the communications link between two nodes and is hence, a prediction of the lifetime of that link. They define the affinity as the time taken by one node to move out of the range of another node [65]. However, the above scheme totally disregards the path length while choosing the route through which the data transmission will take place [66]. However, other existing work using the time derivative of the link quality metric (affinity-based schemes, such as [67], [68]) implicitly assumes that any link in an improving phase is more reliable than a link in a deteriorating phase. This is not true as the link reliability also depends on the peak value of the RSS as well as on the relative speed between the nodes [69]. In [70], authors propose the use and distribution of GPS data for the calculation of expected connection duration and demonstrate that significant performance enhancement was achieved when the routing process takes the lifetime concept into account [69]. Several other definitions are presented as follows as they were discussed in [71], [72], [73], [74], [75], [76], [77]. Based on the QoS requirements of VN applications, lifetime is defined in the literature as the time duration until any

QoS requirement does not satisfy the desired threshold anymore, such as the coverage or the packet delivery ratio (PDR), the number of operational nodes in the network or the amount of transmitted information. Such a definition of lifetime could be useful in the context of VNs due to the high mobility of vehicles and the fact that they can always move apart from each other. Other definitions of lifetime are found in the literature, such as those based on the battery consumption. More specifically, ... define lifetime as the time until all/any of the nodes consume their battery. However, in the case of VNs, these definitions are redundant, as vehicles do not suffer from energy limitation issues.

Finally, it is critical to note that a path or network that cannot cope well with the highly mobile environment in VNs will face low route lifetime. Therefore, a path/network is considered stable only if it has an increased probability that link failures will be avoided. Thus, by considering factors such as the channel characteristics, the network topology, the resource limitations, the interference management, and other quality of service (QoS) requirements, the duration of the network's adequate operation can play a substantial role in determining optimum long-lasting routes through VNs, as required by their use cases. Next, in Section 2.5.2 the focus is on the queuing aspect of successful communications in VNs.

2.5.2 Queue State Information

Within VNs, the nodes employ store-and-forward mechanisms with the aim to solve the effects of frequent encounters of the coverage hole issue. More specifically, each node has to store and carry the packets until forwarding them once a successful transmis-sion link is provided with that purpose. In that sense, each node is equipped with an on-board-unit (OBU) which is responsible for functionalities such as sensing, processing and transmitting. Within sensing, the relevant contextual information is captured from the environment before being passed to the processing unit. Then, the data is processed and prepared to be propagated throughout the VNs. In general, the queue structure of OBUs follows a buffer-type model, where nodes gather packets as they arrive during each communications session and store them in the appropriate order, while waiting to be forwarded again, following the adopted IEEE 802.11p standard [78]. More speci-fically, once a reliable communications session is established, multiple nodes will attempt to join it for packet forwarding. Thus, nodes end up managing separately multiple communications flows at a time. However, as the packets arrive at each node, they can be backlogged and thus, large queuing delay can be experienced. In addition, the available size of the buffers is limited at each node which can affect the performance of VNs. For example, as nodes get involved in multiple communications sessions they can encounter queuing issues and thus, they become unavailable for a new communications sessions. Note that the dimensions of the node's buffer size differs as it reflects its ability to store additional packets.

As the need for sharing information among the nodes is considerably high, especially in highly complex and dense VNs, mechanisms that are capable of handling queuing aspects have to be considered in order to optimize the routing design process. Thus, it becomes critical to consider the queue state inside the next-hop decision stage of routing in order to achieve low end-to-end delay and avoid packet-loss caused by queue overflowing. For example, a multi-hop approach is employed in [79] where the buffer size is treated as a metric within the next-hop decision process. Moreover, in [80], the Multi-Hop Cross-Layer Decision Based (MHCLD) algorithm is proposed, where the neighbor selection criteria is based on SINR data extracted from the PHI layer, as well as queuing information from the MAC layer. A new variable is introduced, namely channel quality factor (CQI) in order to select the appropriate neighbors. Transmission is then modeled based on queuing information. This protocol manages to reduce the number of hops but it performs badly in highly dynamic environments because their frequent changes are not considered. The approach was improved in Cross-Layer Decision Based (CLDB) [81] where each link is associated with an individual channel-rate and the next hop is based on the highest achievable rate. However, both methods perform badly in sparse VNs conditions, due to the lack of available communications links. Thus, even though they do improve the system in terms of QoS performance, they do not consider several important factors that allow transmission in VNs. Additionally, similarly to [36], the authors in [48] propose a model where each vehicle creates its own utility function, balancing classical CSI and QSI with contextual mobility information. As a consequence, congestion can be avoided as well as the implicit additional end-to-end delay while also satisfying other VN applications requirements. Thus, in the context of VNs, a hybrid approach is desirable; i.e. one that takes into account the appropriate contextual information from all three layers, namely PHI, MAC, and network. In that sense, Section 2.5.3 provides a summary of the existing traffic-aware routing strategies.

2.5.3 Traffic-Aware Routing

Following the discussion in Section 2.4, traditional geographical routing methods can provide design simplicity and scalability [82], [83], [84]. For example, [85] proposed a traditional position-based routing approach called Greedy Perimeter Stateless Routing (GPSR) which leverages position information as it transmits packets. Although the method provides the adaptability required by VNs, the coverage issue is encountered. Therefore, such techniques are unable to achieve the acceptable performance required in VNs. However, routing can be further improved by considering real-time road traffic information [14] as obtaining knowledge of the neighboring vehicles' mobility has been shown to be beneficial for routing performance in both sparse and dense VNs. [86]. Therefore, to further remedy such limitations, techniques such as traffic-aware routing have been introduced as they prove to be the most promising forwarding strategy in the urban VNs [17]. Numerous traffic-aware routing protocols have been proposed that make routing decisions by considering multiple traffic awareness-related metrics and as a result, they significantly reduced the failure probability of successful communica-tions [14], [17], [18], [24], [87], [88].

A comparison between the existing cross-layer traffic-aware techniques is provided next based on the shared contextual information used during the routing process as they were encountered in the literature. A-STAR [18], for example, is a Global State Routing (GSR) based routing algorithm that relies on the information collected from bus routes to estimate probabilities for each road segment to provide sufficient coverage and implicitly a successful communication session. Unfortunately, such anchor vehicles only cover the road-network partly, which often leads to network partitioning and to extended end-to-end delay (EED). On the other hand, GyTAR [87] is a cross-layer geographical routing protocol that aims to find robust routes by also taking into account information about vehicles speeds and directions since as it considers realistic urban environment with multi lanes and double direction roads.

However, collecting real-time traffic information can prove to be difficult, mostly due to the network partitioning phenomena. Cross-Layer Weighted Position-Based Routing (CLWPR) is a unicast, multi-hop routing technique which extracts and processes information available at the PHY and MAC layers as well as sensor positional information in order to choose the next hop. Thus, by periodically exchanging node information such as positions, velocities, direction, road IDs as well as MAC frame-error rate under the form of BSMs, the weight of the available next hop can be computed. Moreover, SINR is extracted from the PHI layer and recorded once BSMs reach their destination and fed back to the source in order to characterize the quality of the links with the aim to achieve end-to-end delay [89].

A modified version of the Ad-Hoc On-Demand Distance Vector routing protocol (AODV) was proposed, namely Portable Fuzzy Constraints Q-learning AODV (PFQ-AODV) [88], which benefits from considering the direction of each vehicle along with communication channel estimations. On the other hand, due to the use of AODV, the ’broadcast storm’ phenomena is experienced often, which leads to lower EED performance. A receiver based routing protocol is proposed in [90] in order to provide the system with the ability of selecting the next relay on the fly. Moreover, in order to avoid the highly probable multi-path formation at the receiver, an effective forwarding zone with a predefined angle of 60° is used. Then, the eligible nodes can apply for forwarding after waiting for a period of time. The waiting time is chosen based on the geographical progress of the node towards destination. However, the system analyzes different velocities and traffic densities without taking into account the environment where the transmission takes place. The authors in [91] proposed Adaptive Geographic Routing Protocol based on Quality of Transmission (AGQOT) for urban environments. Here, they introduced a metric, namely quality-of-transmission (QOT) which jointly considers the transmission PDR as well as the link connectivity in order to select and reflect the performance of the next road segment in a hop-by-hop manner. Moreover, every vehicle is capable of knowing its position and speed through GPS technology and thus, the source vehicle can localize the destination vehicle.

iCar-II investigates an intersection-based traffic-aware routing protocol which aims to increase the packet-delivery-ratio (PDR), while trying to minimise the end-to-end-delay (EED) [19]. To further improve the PDR and the EED performance, the authors in PIRP and HQVR verify if the pre-existing routes at a defined time interval [92], [93]. That way, they make sure that the freshest path is always considered. However, in order to avoid any negative effects on the available bandwidth, the control packets have to be properly managed. Note that, unlike PFQ-AODV, PIRP and Q-LBR employ broadcast-storm mitigation techniques. The broadcast storm phenomena affects the performance of the routing scheme as it translates into increased poorly bandwidth usage. However, only reactive routing protocols encounter a high probability for such issues. Furthermore, QGRID [24] relies on collecting and using taxi data based on Shanghai's traffic, which, unfortunately, only suits a specific region. Table 2.4 presents a timeline-based comparison between the most popular traffic-aware routing schemes encountered based on their innovative idea, for a better understanding of how routing design has evolved in VNs.

Table 2.4: Timeline of main contributions to traffic-aware routing design in VNs based on their innovative ideas.

2004	A-STAR [18] - estimates the coverage probability for each road segment based on information collected from bus routes.
2006	GyTAR [87] - gathers traffic data, such as the node density between intersections to improve routing decisions.
2013	PFQ-AODV [88] - implements a communication channel measurement technique based on the bandwidth, the quality of the communications link, and the movement criteria of the vehicles along with the direction.
2015	PP-AODV [94] - uses bandwidth, delay, and packet collision probability as the selection parameters of the next-hop decision.
2020	DBDR [95] - proposes a distance-weighted back-pressure dynamic routing (DBDR) technique that considers queue-state information (QSI) and node coordinates to prioritise vehicles closer to the destination when making next-hop decisions.
2020	[96] - aims to lower the network overhead by considering queue-state-information (QSI) within the next-hop decision metric.
2020	QTAR [17] - adapts geographic routing to acquire the traffic conditions at each intersection and chooses the next-hop based on end-to-end delay (EED), the link quality (LQ) and the estimated link expiration time (LET).

2021	HERO [97] - a heuristic routing for vehicular networks (HERO) approach is proposed which considers vehicle mobility data aiming at three goals, namely increasing the packet-delivery ratio (PDR) and reducing the EED as well as the network overhead.

Next, in Section 2.5.4, the review of infrastructure-aided routing is provided as a further enhancement of VNs communications.

2.5.4 Infrastructure-Aided Routing

Initially, intersection-based routing was shown to be another performance enhancer for routing in VNs [14]. The main reason behind this is that network congestion and interference issues are encountered more often at intersections, mostly due to their relatively increased vehicle density [98]. Moreover, nodes cannot easily communicate with other nodes placed on different road segments due to NLOS conditions. As a consequence, as seen in [17], routing algorithm performance can also be improved significantly by considering intersection data in the next-hop decision process. For example, [87] dynamically chooses intersections to forward packets towards, one at a time based on a pre-configured map. In addition, RSUs are considered in urban implementations, such as [19], [17], [22], [99], [100], [101] and can be placed around intersections and assist whenever the 'coverage hole' issue is encountered. An RSU placement strategy is provided in [102] with the aim to harmonize the combined use of the infrastructure and the VNs by minimizing additional overhead.

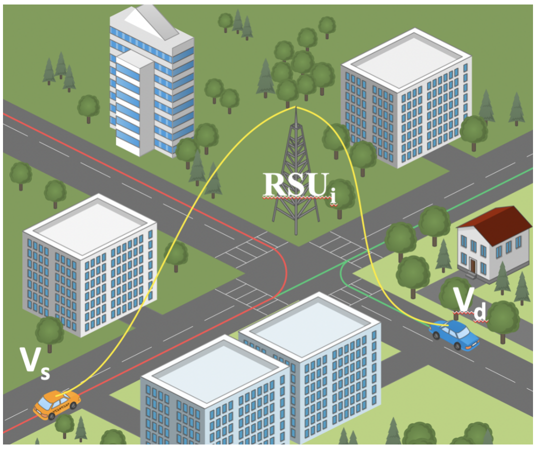


Figure 2.5: An example scenario of infrastructure-aided VN [4].

Generally, there are two main benefits from introducing RSUs in VNs. Firstly, the higher heights of RSUs can provide V2I and I2V communications with higher transmission ranges as well as improved reliability [103]. Additionally, the RSU infrastructure can be connected to backbone networks that permit access and communications across the road-network structure. Note that, in such scenarios, RSUs can also be considered part of separate network that aids VNs communications by providing improved range and reliability of transmissions. Figure 2.5 provides an example scenario of an urban VN where the source vehicle (V_s) cannot transmit directly to the destination vehicle (V_d) and therefore, the infrastructure placed at the intersection, namely RSU_i, is used as an extra hop. Moreover, a review of several notable studies that explore the insertion of RSUs as part of VNs is provided as folows.

For example, the authors of [104] investigate the performance of VNs, as RSUs are installed, with the aim to support the transmission process. Moreover, a cooperative traffic-aware approach is considered where the RSUs are used in the early deployment stage of the network. Additionally, a genetic algorithm is proposed with the purpose of localising RSUs across the network.

An urban scenario is considered in [105] with the aim of achieving optimal RSU deployment. Thus, the connectivity increases across the network is shown to increase by increasing the number of informed vehicles. In [106], RSUs are placed at the intersections with the aim of optimizing transmission by using them as relay and broadcast stations. Moreover, a subset of the main roads in the road-network structure is created, following the placement of the RSUs, which can be used to prioritize transmissions.

In [107], the availability of V2V links is contested, as they might not always satisfy transmission requirements. Thus, a store-and-forward routing mechanism is employed that prioritises vehicles travelling through the RSUs in order to increase the chance of finding such links. Moreover, [17] relies on the intersection-based geographic routing protocol that leverages fixed RSUs placed at the intersections to deliver the packets to the destination node. However, RSUs can easily transform into bottlenecks as they become unavailable due queuing issues. Such events should be taken into account when designing the recovery policy of the algorithm. V2I communications systems are also considered in [108], [109], [110]. However, the focus in these studies is on providing vehicles with access to the Internet rather than on improving VNs routing techniques.

Hybrid V2V and V2I techniques were also encountered in the literature. For example, a hybrid approach was proposed [111], namely Infrastructure Enhanced Geographic Routing Protocol (IEGRP), where both V2V and V2I unicast routing are considered with the aim to maximise PDR. Moreover, a geographic routing approach is proposed in [111], which benefits from both V2V-only communications, as well as hybrid V2V/I communications. Additionally, in [99], the link duration is studied while employing a hybrid infrastructure-aided routing approach. Table 2.5 provides a timeline-based overview of the main infrastructure-aided routing techniques based on their innovative idea.

Table 2.5: Timeline of main contributions to infrastructure-aided routing design in VNs based on their innovative ideas.

2013	IEGRP [111] - investigates a hybrid infrastructure-aided traffic-aware routing protocol which employs both V2V and V2I unicast routing with the aim to maximise packet-delivery-ratio (PDR).
2014	[99] - proposes a hybrid infrastructure-aided routing approach and investigates the duration of communication links and.
2017	[100] - employs a routing approach which relies on the deployment of an information network infrastructure that consists of Road Side Units (RSUs).
2016	iCar-II [19] - investigates an intersection-based traffic-aware routing protocol which aims to increase the PDR, while trying to minimise the end-to-end-delay (EED).
2020	[101] motivate the use of sensors, mounted on the existing infrastructure mounted sensors to aid establishing and maintaining mm-Wave communication links.
2020	QTAR [17] - considers traffic conditions at each intersection, while modelling separate routing techniques for vehicles and for RSUs.
2021	[101] - investigates the association of RSUs with the aerial drones while considering contextual-information to improve routing performance.

Unfortunately, the above-surveyed techniques are unable to provide efficient and highly reliable communications, since they cannot 'learn' and adapt to the highly dynamic nature of the VNs. Therefore, as a subset of Machine Learning approaches, namely Reinforcement Learning (RL) techniques present a huge potential in that sense for efficient communications within VNs. Therefore, an overview of RL-aided routing is provided in Section 2.6.

2.6 Reinforcement-Learning Aided VNs Routing

Considering the highly dynamic nature of traffic in VNs, RL algorithms can be used to effectively explore, learn and map the environment as well as to keep track of the frequent topology changes. As a consequence,

For example, the Q-learning algorithm allows network participants to map their set of possible actions to a set of environment states. Then, Q-learning attempts to maximise the current state's reward for interacting with the environment towards the goal state [112], [113], [114], [115], [116]. More explicitly, the nodes explore their surroundings by frequently transmitting packets into the network and thus attain and update the latest state of the environment, which gradually and intelligently enables the learning of the dynamic environment. In the context of VNs, each packet sent into the network can be modelled as an agent. If the current node (N_c) is considered to be the current state of the agent, then the pool of available states it can interact with takes the form of N_c's neighbors. Hence, the Q-table takes the form of a two-dimensional array, where rows represent states while the columns represent their set of neighbors. More explicitly, after initialising the Q-table to 0, N_c updates it through regular exchange of BSM packets with its neighbors [117]. The Q-value evaluation upon receiving an update from N_i can be formulated as follows [118].

$$\underbrace{Q_{N_c;N_i}}_{\text{New Q-Value}} = \underbrace{Q_{N_c;N_i}}_{\text{Current Q-Value}} + \underbrace{\alpha}_{\text{Learning rate}} \Big[\underbrace{R_{N_c;N_i}}_{\text{Reward}} + \underbrace{\gamma}_{\text{Discount rate}} \overbrace{\max Q_{N'_c;N'_i}}^{\text{Maximum predicted reward, given new state and all possible actions}} - Q_{N_c;N_i} \Big] \tag{2.7}$$

where $R_{N_c;N_i}$ is the obtained reward of N_c from the action of packet forwarding to N_i for V2V Q-learning. The learning rate, , serves as a Q-value update rate at each step of the learning process, which determines the ability of the learning algorithm to adapt to the changes in the environment. For example, if is too small, the algorithm cannot keep up with changes in the network. On the other hand, a large value of will lead to large fluctuations in the Q-values even when changes in the environment are insignificant. The discount factor, , establishes how relevant rewards in the distant future are, considering changes in the environment in the immediate future. In more detail, a larger is favorable in a static environment, while in a highly dynamic one, i.e, a VN, a smaller value is preferred.

Therefore, VNs can be further improved through RL approaches that search through the most likely to be successful links by exploiting different types of information extracted from the environment, namely the vehicle densities and their behaviour patterns and the topology of the available roadway, CSI and QSI among others. In that sense, Q-learning is a RL technique that Many routing protocols based on reinforcement learning have been proposed in recent years [17], [14], [23], [24], [25]. The most notable are presented below, as encountered within the literature.

In [88], communications links are evaluated based on the Q-learning algorithm. More specifically, the approach aims to choose the optimal next-hop, while considering per-link bandwidth, quality as well as changes in the node's speed and direction. However, the learning process and the route discovery process are performed simultaneously, and thus the rapid changes in the environment cannot be managed properly, leading to additional EED. Furthermore, in [24], a grid-based protocol is proposed which uses historical information to learn the environment in an offline manner in order to choose the next optimal grid. Unfortunately, the protocol performs poorly in a highly dynamic environment, as the offline populated Q-table can become outdated quickly.

[96] and [119] optimise the reward propagation mechanism used in the Q-learning algorithm by configuring each intermediary vehicle to store the Q-values. In hierarchical routing schemes on the other hand, vehicles are grouped into clusters while only the cluster-heads (CHs) are considered agent and participate in the learning process. On the other hand, the main drawback experienced by both methods lays in feeding the reward values backwards towards the V_{d} [120], [121]. Furthermore, in [23], a RL-aided routing technique was designed for high mobility scenarios, where the algorithm predicts vehicular and link-state information using the Q-learning approach. However, these schemes use a centralised routing approach, which does not suit VNs well.

Finally, QTAR [17] uses different Q-learning techniques for V2V/I connections than for I2V/I connections with the aim to to learn traffic conditions at each intersection, which leads to better overall routing performance than previously studied geographic routing protocols. More specifically, owing to the learning ability of the algorithm, after a specific time during which the learning is completed, QTAR is shown to perform better than the underlying geographic routing algorithms. Therefore, in Chapter 5.2, QTAR is used as a benchmark that helps highlight the proposed contributions. Table 2.6 provides an overview of the most recent RL-aided routing design trends based on their novel features.

Table 2.6: Timeline of main contributions to RL-aided routing design in VNs based on their innovative ideas.

2010	QL-AODV [23] - predicts the vehicular and link-state information using a centralised Q-learning-based routing approach.
2013	PFQ-AODV [88] - implements a Q-learning approach based on bandwidth, the quality of the communications link and the movement of vehicles.
2014	QGRID [24] - uses historical data generated by taxis in Shanghai to train the RL model and optimise the grid forwarding technique using Q-learning and greedy forwarding within the grid.
2015	PP-AODV [94] - uses bandwidth, delay, and packet collision probability as the selection parameters of the RL-aided algorithm for choosing an intermediary hop to the destination.
2020	Q-LBR [96] - introduces a Q-learning based load balancing routing (Q-LBR) approach based on three key objectives; i.e. lowering the network overhead by considering queue-state-information (QSI) as well as the convergence time of the Q-learning technique employed.

2020	[122] - introduces a novel machine learning architecture that uses a deep reinforcement learning (DRL) approach to predict the movement of vehicles and to improve the capacity of found routes.
2020	RLRC [123] proposes a RL-aided protocol for clustered vehicles, to evaluate decision rewards while considering the available bandwidth and the vehicles’ movement.
2020	[124] - uses a Q-learning-based approach to optimise next-hop selection while considering the quality of neighbor nodes’ information as well as the coordinates of the destination node.
2020	QTAR [17] - adapts RL-aided geographic routing to learn traffic conditions at each intersection, while modelling separate Q-learning techniques for vehicles and for road-side units (RSUs).
2022	[116] - proposes a DRL-aided routing approach to further optimise the decision making process of the next-hop selection.

2.7 Discussion

The increased demand for reliable and robust communications in VNs has brought routing design into the attention of recent research. More specifically, in order to provide access to the range of existing VN applications, routing techniques must be able to combat the challenges caused by attempting to transmit through such a highly dynamic environment. However, based on this chapter’s overview on VNs, state-of-the-art routing approaches are yet to satisfy VN applications’ QoS requirements and thus, further evaluation of VNs routing is required with the aim of achieving higher performance communications systems.

Following the discussion in Section 2.3 and in Section 2.5, routing relies on contextual information extracted from the environment. Moreover, by exploiting the nonrandom behavior of vehicles’ mobility patterns VNs can efficiently construct long-lived, stable routes and avoid the frequent disruptions of communications links. Thus, a realistic representation of VNs is required that permits the accurate extraction of such information. In that sense, in Chapter 3, a summary of the existing mobility and network simulator software is initially presented. In addition, an outline of the VNs applications process employed in this thesis is included along with the generated road-network structures and a discussion on their characteristics.

Considering the highly dynamic nature of VNs, successful communications sessions are often interrupted due to the continuous movement of vehicles, as they can leave each other’s communications range at any time. As a consequence, the network partition phenomena represents a great challenge for overhead-efficient routing design in VNs. Thus, as long-lasting routes are desirable in this context considering Section 2.5.1, the study of lifetime in VNs demands further efforts. In that sense, Chapter 4 provides an evaluation of route lifetime in VNs. More specifically, measurements of route lifetime are provided with the aim of revealing existing trade-offs between road-network structure and routing performance requirements in both fading and no fading.

For a realistic representation of VNs, both sparse and dense environments have to be considered during routing design. Thus, following the discussion in Section 2.5.4, Chapter 5 considers an infrastructure-aided VN, where RSUs can help combat the ’coverage hole’ problem by assuring connectivity across VNs. In addition, considering that queuing phenomena generated issues, discussed in Section 2.5.2, are encounter often, especially in dense VNs, its effects on the availability of nodes to participate in further communica-tions sessions is also studied in Chapter 5. As a consequence, a hybrid routing approach is proposed, that chooses between the optimum V2V or V2V/I communications paths during its routing process. Moreover, it was shown in Section 2.6 that, by employing a RL aided traffic-aware routing approaches, the required contextual information can be successfully extracted and then monitored from VNs environments and, as a consequence, routing performance can be enhanced. In that sense, Chapter 5 also studies the performance of RL-aided traffic-aware routing in urban VNs.

Chapter 3

Modelling and Evaluation Tools for Urban VNs

The simulation of VNs allows the study of network performance through repeatable evaluations that are conducted under a controlled environment where various parameters can be isolated and varied [20] as required by vehicular use cases, as discussed in Sec-tion 2.2. The goal is for such analysis to be conveyed in scenarios as realistic as possible in order for the extracted results to be close to real-life. Thus, in this chapter, the focus is on the employed approach to model VNs with the aim of gathering data. Against the aforementioned points this chapter's contributions can be highlighted as follows.

Contributions:

- A review of the existing software available for the construction, modelling and evaluation of VNs is presented in a comparative way based on their particular features.
- A VN simulation platform is achieved by allowing SUMO and MATLAB to communicate with each other through TraCI4Matlab.
- A classication of VNs mobility models is given in an evolving way based on their particular features while detailing the mobility models considered in throughout this thesis as example.

The rest of this chapter is structure as follows. Next, in Section 3.1, a short review of the various already existing software for VN evaluation in a comparative manner based on their current features. Then, Section 3.2.2 introduces a VN simulator design. In more details, Section 3.2.1 provides a discussion of the employed modelling and evaluation tools. Then, in Section 3.2.2.2 several mobility models are designed while their detailed congurations are provided. Finally, Section 3.3 provides a discussion of the chapter.

3.1 Existing Simulation Software

To start with, the more geographic, sociological as well as external factors are considered during the VNs evaluation the more accurate mobility patterns of vehicles can be determined [125]. Thus, simulating VNs are most often unreasonable because of mobility models that do not take into account sufficient traffic scenario characteristics. The authors in [2] can categorize traffic models based on the granularity, transport and travel patterns as follows. The macroscopic models, like METACOR [126], represent vehicle movement at a huge scale. Macroscopic models occupy characterise mobility on a segment by segment basis instead of tracking specific vehicles. Examples of macro-mobility features include street topology and road characteristics, limits on vehicular speed, number of lanes, traffic signs etc. [127]. Such models have significantly less effect on network conditions as compared to the microscopic models because they do not have the ability to interpret developments as the microscopic models do. On the contrary, microscopic mobility models refer more to the movement of vehicles which affects road traffic unpredictably and uncontrollable because of variables such as drivers' behaviour. Other examples are vehicles roaming with different velocities in diverse traffic conditions, while accelerating or decelerating, or even in scenarios such as overtaking. Such unpre-dicted events can affect the road traffic significantly [127]. Finally, mesoscopic mobility models take into account both the features of macro-mobility and micro-mobility sim-ulation models. For example, CONTRAM (Continuous Traffic Assignment Model) [128].

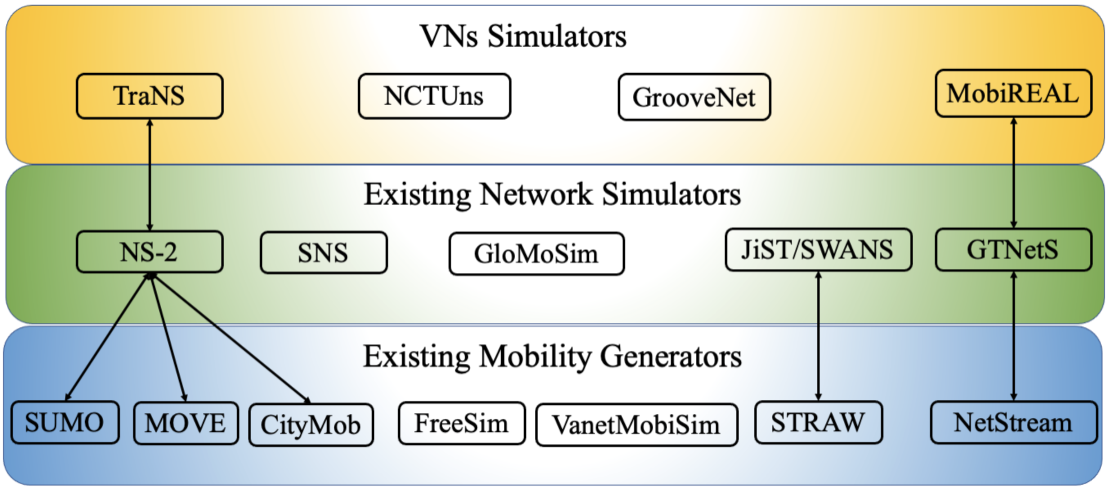


Figure 3.1: Existing VN Simulation Software [2].

Note that it would be appropriate for macro and micro-mobility factors to be implemented together in the development of a mobility model in order to achieve an appropriate level of details and achieve precise results from the simulation of VNs [127]. Additionally, the level of authenticity of modelling and simulating VNs can be enhanced though by using realistic vehicular mobility generators as well as capable network simulators.

Considering the discussion above, two main components are critical for the simulation of VNs, namely a vehicular traffic simulator, capable of providing a mobility model as close as possible to real-life scenarios for the nodes of a VN to follow, and a network simulator, for simulating the network's behaviour from a wireless communications perspective. There are several available simulators that make research work within VNs possible [2], [129], [130] ,[131], [132], [133]. A classification of the existing software for VNs simulation within three distinct classes has been done, namely, vehicular mobility generators, network simulators and VN simulators following Figure 3.1 above.

3.1.1 Vehicular Mobility Generators

Initially, the road structure, as well as the mobility-related factors for various traffic conditions can be considered altogether as inputs for the mobility model generator. The output of such generators includes the coordinates of each vehicle at each time-step throughout the whole simulation session. Several examples of Mobility Generators are MOVE [134], STRAW [135], SUMO [136], VNMobiSim [137], FreeSim [133], CityMob [138], and Netstream [139]. Table 3.2 displays a review of the examined vehicular mobility generators based on their most important features [2].

3.1.2 Network Simulators

Besides the modelling of vehicular mobility, building wireless connections and node interactions in real-time conditions is a challenging task within VNs. As a consequence, multiple platforms were created with the purpose of carrying out such tasks. A few examples are NS-2, NS-3, OMNET++, GloMoSiM, SNS, JiST/SWANS, and many more. Table 3.1 presents a comparison between the existing Network Simulators found in the literature [2]. It can be concluded that NS3 and OMNET++ provide several advantages over other simulators due to their ability to work competently in congested traffic areas [140], [141].

3.1.3 VN Simulators

Lastly, more complex VN simulators are available that offer the collaboration of both network and mobility simulators, such as MobiREAL [21], NCTUns [22], and GrooveNet [23], TraNS [10]. Table 3.3 shows a list of commonly used network simulators in VN environment and their comparison [2].

Parameters	Reviewed Network Simulators					
	NS-2	NS-3	GloMoSim	SNS	JiST	OMNET++
1. Software features						
i) Open Source	Yes	Yes	No	Yes	Yes	Yes
ii) Console	Yes	Yes	Yes	Yes	Yes	Yes
iii) Continuous development	Yes	Yes	No	No	Yes	Yes
iv) Portability	Yes	No	Yes	Yes	Yes	Yes
v) Available examples	Yes	Yes	Yes	Yes	Yes	Yes
vi) Freeware	Yes	Yes	Yes	Yes	Yes	Yes
vii) GUI	Yes	Yes	Yes	Yes	Yes	Yes
viii) Scalability	Poor	High	High	High	High	High
ix) Ease of setup	Hard	Easy	Moderate	Easy	Hard	Easy
x) Ease of use	Hard	Easy	Hard	Hard	Hard	Easy
3. VNs						
i) 802.11p	Only after NS-2.33	Yes	No	No	No	Yes
ii) Obstacles	No	Yes	No	No	No	-
iii) Vehicular traffic flow model iv)	No	Yes	No	No	No	Yes
Sensors	Yes	Yes	-	Yes		Yes
v) LTE	Yes No	Yes	No	No	No	Yes

Table 3.1: A Comparison Between Reviewed Network Simulators.

Parameters	Reviewed Mobility Generators					
	CityMob	FreeSim	MOVE	SUMO	STRAW	VNMobiSim
1. Software features						
i) Open Source	Yes	Yes	Yes	Yes	Yes	Yes
ii) Portability	Yes	Yes	Yes	Yes	Yes	Yes
iii) Freeware	Yes	No	Yes	Yes	Yes	Yes
iv) Console	Yes	Yes	Yes	Yes	-	Yes
v) Available examples	No	Yes	Yes	Yes	-	Yes
vi) Continuous development	Yes	-	No	Yes	No	No
vii) Ease of setup	Easy	Easy	Easy	Moderate	Moderate	Moderate
viii) Ease of use	Easy	Easy	Moderate	Hard	Moderate	Moderate
2. Map Types						
i) User defined ii)	No	No	Yes	Yes	-	Yes
Real	No	Yes	Yes	Yes	Yes	Yes
iii) Random	Yes	No	Yes	Yes	No	Yes
3. Mobility Models						
i) Downtown traffic models	Yes	No	No	No	No	No
ii) Random way point	Yes	No	Yes	Yes	No	Yes
iii) Multi lane roads	Yes	-	Yes	Yes	Yes	Yes
iv) Speed constraints	Yes	Yes	Yes	Yes	Yes	Yes
v) Microscopic	Yes	Yes	Yes	Yes	Yes	Yes
vi) Macroscopic	No	Yes	No	No	No	No
vii) Lane changing	Yes	-	Yes	Yes	Yes	Yes
viii) Collision free movement	Yes	-	Yes	Yes	-	-
ix) Intersections management	No	-	Yes	Yes	-	Yes
x) Route Calculations	No	Yes	Yes	Yes	Yes	Yes
4. Traces setup						
i) QualNet support	No	No	Yes	No	No	Yes
ii) NS-2 trace support	Yes	No	Yes	No	No	Yes
iii) SWANS support	No	No	No	No	Yes	No
iv) GloMoSim support	No	No	Yes	No	No	Yes
v) XML-based support	No	No	No	No	No	Yes

Table 3.2: A Comparison Between Reviewed Mobility Generators.

Parameters	Reviewed VN Simulators			
	GrooveNet	MobiReal	TraNS	NCTUns
1. Mobility models	Random waypoint	Probabilistic rule based	Random and manual routes	Random and manual routes
2. Mobility generator	GrooveNet	MobiReal	SUMO	NCTUns
3. Speed models	Uniform street speed	Street speed	Street speed	Random
4. Network Simulator	-	Based on GTNets	NS-2	-
5. Traffic lights	Manually defined	Manually defined	Manually defined	Automatically generated on intersections
6. Trip Model	Dijkstra	Manually defined	Random & Manually defined	Manually defined
7. Road topology	Any	Any	Any	User defined
8. Ease of setup	Moderate	Easy	Moderate	Hard
9. Ease of use	Hard	Hard	Moderate	Hard

Table 3.3: A Comparison Between Existing VN Simulators.

3.2 VN Simulation Platform

A new VN simulation platform is achieved by allowing SUMO and MATLAB to communicate with each other through TraCI4Matlab as explained further in this section. Initially, SUMO is used to generate movement traces for vehicles and form mobility models which are then used as data for routing protocol evaluation in MATLAB. Using the commands within TraCI4Matlab, vehicle features such as position, speed, acceleration, vehicle length, vehicle colour, etc. can be transmitted to MATLAB, where the performance of the employed routing approaches can be computed and evaluated based on the target application requirement [4]. Moreover, TraCI4Matlab is also used to send vehicle-controlling commands from MATLAB to SUMO such as rerouting vehicles once they reach the previously SUMO-generated destination within the road-network structure with the aim of achieving continuous movement of the nodes until the end of the simulation.

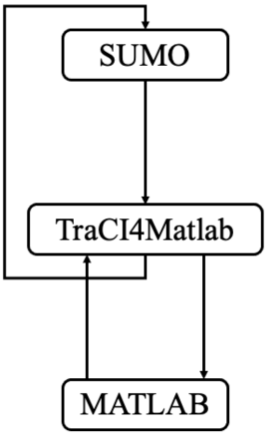


Figure 3.2: An block-diagram illustration of the introduced VN simulator.

3.2.1 Modelling tools

An overview of how the Simulation of Urban MObility (SUMO), TraCI4Matlab and MATLAB software are used together in order to achieve the network simulation platform introduced in this chapter is provided next, in Section 3.2.1.1 and Section 3.2.1.2 below [4]. Additionally, Figure 3.2 provides a description of the relationship between the three software mentioned above.

3.2.1.1 SUMO

SUMO is an open source traffic simulation environment available since 2001 which al-lows the modelling of vehicular traffic structures such as vehicles, public transport and pedestrians [4]. SUMO has evolved within the past decades into a full featured simulation environment and now incorporates a multitude of tools that support the creation, execution and evaluation of traffic simulations which is why it was chosen for the pur-pose of building realistic mobility models. Among its functionalities one can find the ability of route calculation, visualization as well as calculation of emissions. Moreover, its utilities include a road network importer capable of reading different source formats. An example is provided in Figure 3.3 below, where a road structure of Burgess Road in Southampton UK, was downloaded directly from Open Street Map (OSM). This can simplify the process of developing mobility models [142].

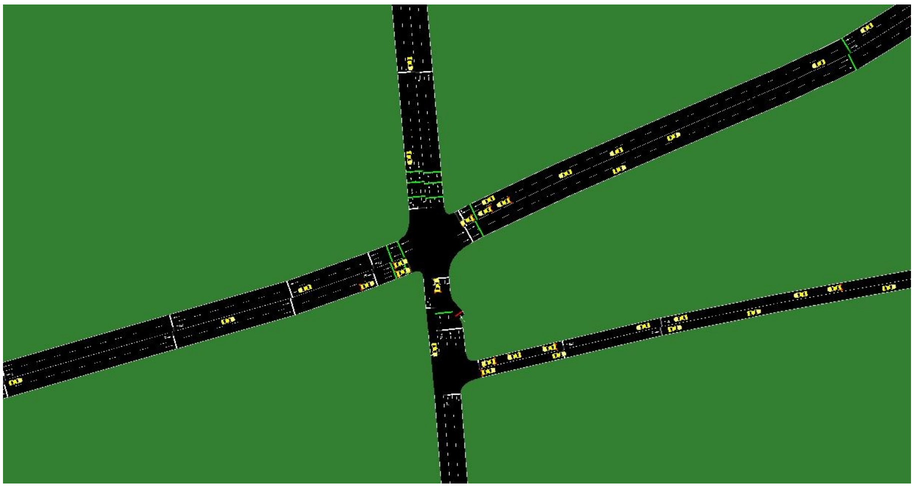


Figure 3.3: Burgess Road - An example of a road structure downloaded directly from OSM.

However, custom models can also be constructed and modelled through SUMO and various application programming interfaces (APIs) are provided to remotely control the simulation as discussed in Sections 3.2.1.2 and 3.2.2. In more details, the `<input>` of the configuration file includes the network file and route file, where the first one reads and visualizes the route connections in SUMO and the latter contains the generated vehicles' traces. Moreover, within the same configuration file, users are allowed to choose which time frame should be used within the simulation by varying the <time> variable. The simulation starts at 0s and stops as soon as all vehicles have reached their destination and left the road-network. The default step length in SUMO simulations is set at 1s, while the value for <step length> can be reduced down to a minimum time-step of 1ms if a smooth simulation flow is desired. Also, the maximum supported scenario duration is bound to 49 days [143]. The employed setup uses a Time-Step of 1s, thus, updating the data matrices stored within the VN MATLAB simulator at each second of the simulation time in order to avoid inducing too much complexity. Moreover, the maximum simulation time is set to 100000 simulation time-steps. This is particularly useful in cases where the link/route between nodes would not break and the simulation would continue for an infinite amount of time-steps. In such cases, the links between nodes would be always successful as vehicles would either get stuck travelling behind each other because of setting up a communications range too large or because they cannot overtake each other while following the lane restrictions, thus, being forced to cluster and travel together.

All nodes are assigned rerouting devices, in order to keep them from leaving the simulation once they reach their pre-assigned destination on the road-network structure. Thus, once they reach the last part of their trip, vehicles are assigned another destination from the edges available in the road-network structure and keep moving. Note that the new destination must be possible to reach. For example, if a two-way street is considered, the vehicles can reach any of the lanes going in the opposite direction if and only if it is possible for them to turn around, just like in real life scenarios.

Additionally, the vehicles' default colour is yellow, but it can be changed to blue, red and green respectively. This can be helpful in VNs' research as such features that allow users to change vehicle's physical properties can be used to differentiate vehicles that present more interest. For example, they can allow them to keep track of the transmission process without losing track of the source and destination nodes [127]. Moreover, [54] suggests a separation between emergency vehicles and regular vehicles. Due to the risks they are exposed to, it is critical that emergency vehicles have access to the exchange of sensor data as fast as possible. Based on this, they build the motivation for prioritization requirement. However, so far, in the employed models, only default colours are considered as vehicles can be tracked directly within the network simulator. In addition, the vehicle type component has not been taken into account in this thesis and thus, SUMO is set to generate random vehicle types as defaulted. This can be useful once blockage is be included in the VNs applications process as different types of vehicles produce different types of blockage, as discussed in Section 2.3.2.

Table 3.2.1.1 above provides the set of parameters SUMO provides, that can be used within the modelling of VNs. In the next section, a detailed discussion regarding how the

SUMO parameters	Value
Number of Vehicles	V
Time-step	1 s
Maximum simulation time	100000 s
Maximum speed	0-13,84 m/s [4]
Vehicle type	regular/ bus/ taxi
Vehicle color	yellow - default
Rerouting device	X
Traffic lights	X

SUMO simulation can be controlled through the MATLAB and TraCI4Matlab software for evaluation purposes.

3.2.1.2 TraCI4Matlab Network Simulator

Although there are numerous network simulators available for research within VNs, not all of them enable users to do calculation or enable controls over SUMO simulations. Moreover, using only the SUMO software on its own is not sufficient as it does not offer algorithm computation features. Hence, the Traffic Control Interface for MATLAB (TraCI4Matlab) is introduced to SUMO simulations in order to enable both protocol and algorithm computation within MATLAB. Having these in mind, a software tool was developed, which is later adopted in this work, for the purpose of modelling and analysing the area of Wireless Communications within VNs.

MATLAB was chosen as it provides its users with a multi-paradigm numerical computing environment that can perform matrix calculation, compute and implement algorithms, plot different functions or data, or even create custom user interfaces that can coop-erate with programs written in other languages making it a good alternative for the simulation and evaluation of vehicular network operations [144]. Moreover, MathWorks offers some VN scenarios that are open to public [144]. In more details, because of its high computational power, matrix manipulation capabilities as well as the possibility to communicate directly to the SUMO simulation through TraCI4Matlab, MATLAB is the ideal candidate environment chosen to build the VNs network simulator in. Thus, all the data extracted from SUMO can be extracted from SUMO, such as inter-vehicles' distance, velocities, accelerations, etc. and perform the targeted operations on them. As a consequence, the performance of all links between nodes can then be estimated. Note that the node information updates at each time-step.

TraCI is the short term for "Traffic Control Interface" and it allows users to retrieve values of simulated objects and to manipulate their behaviour by giving access to a running road traffic simulation. In more details, TraCI4Matlab is an application programming interface (API) that allows communication between MATLAB and SUMO. As MATLAB allows users to perform matrix calculation or algorithm computation, linking it with SUMO also enables control over vehicles that are moving in SUMO [4]. TraCI4Matlab allows users to specify what SUMO configuration to load, control the vehicles, traffic lights, etc, and enabling applications such as traffic light signalization and dynamic route assignments in SUMO [127]. Therefore, MATLAB is given the permission to access and modify the simulation settings of the server, SUMO. Within the introduced VN simulator, TraCI4Matlab is used for a multitude of tasks as presented below.

- Simulation control-related commands
  - Initiating and closing the connection with the SUMO server - In more details, in order to start the simulation, the ‘`traci.start()`’ command needs to be specified. Also, if the user uses TraCI4Matlab, the –`end` option within the SUMO configuration file is ignored and the simulation can be ended by using the ’`traci.close()`’ command. In addition, reloading the simulation with a new list of arguments is also possible by using the load-command.
  - Performing a simulation step – As MATLAB takes over absolute control of the SUMO generated scenario, ’`traci.step()`’ is used in order to model how the simulation advances from one time-point to another.
- Value Retrieval
  - Simulation Value Retrieval - Commands such as ‘`traci.simulation.getTime()`’, ‘`traci.simulation.getLoadedIDList()`’ and ‘`traci.simulation.getDeltaT()`’ are used in order to obtain the current simulation time and time-step length as well as the current number of loaded vehicles.
  - Vehicle Value Retrieval - Through the ‘`traci.vehicle.getPosition()`’ command TraCI can provide the coordinates of all vehicles present in the network which can in turn be used later in the analysis of communications link quality. Moreover, when doing rerouting, ‘`traci.vehicle.getRoute()`’ is used to obtain the remaining route of a travelling node and ‘`traci.vehicle.getRoadID()`’ to check the current location of that node within the route it follows.
  - Route Value Retrieval - ‘`traci.route.getIDList()`’ returns all available travel routes in the network.
  - Edge Value Retrieval - ’`traci.edge.getIDList()`’ returns all available edges in the network. This is useful as it provides the pool of all potential new destinations which can be assigned during the rerouting process of the participant vehicles.
- State Changing
  - Change Vehicle State - ‘`traci.vehicle.changeTarget()`’ is used during the rerouting process, in order to assign each vehicle a new destination once they

reach their previously generated destination to assure a continuous flow of the simulation from a mobility perspective.

- Change Route State - TraCI permits the addition of new routes based on a given ID and a set of given edges that the route will follow using the 'traci.route.add()' command.
- Change Simulation State - The simulation state can be saved at each time-step through the 'traci.simulation.saveState('fileName')' command.

Node No.	1	2	3	4	5	6	7	8	9	10
1	0	25.478	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
2	25.478	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
3	Inf	Inf	0	Inf	Inf	29.755	Inf	Inf	Inf	Inf
4	Inf	Inf	Inf	0	Inf	Inf	inf	inf	9.332	inf
5	Inf	Inf	Inf	Inf	0	Inf	Inf	47.1341	Inf	Inf
6	Inf	Inf	29.755	Inf	Inf	0	Inf	Inf	Inf	Inf
7	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf
8	Inf	Inf	Inf	Int	47.1341	Inf	Int	0	Inf	Inf
9	Inf	Inf	Inf	9.332	Inf	Inf	Inf	Inf	0	Inf
10	Inf	Inf	Int	Inf	Inf	Inf	Inf	Inf	Inf	0

Table 3.4: A MATLAB Routing Table example at a Random Simulation Time-Step

Therefore, the simulator allows the manipulation of mobility models and the extraction of data, i.e. contextual information, that can be used within the employed routing approach. Table 3.4 shows an example of a routing table for a 10 node VN, as a hollow symmetric matrix, where the main diagonal has all zeroes, representing self-node connections, while the upper triangle and lower triangle are "equal". For example, both values in positions $(n; n+1)$ and $(n+1; n)$ represent the incoming connection from a node n towards node $n+1$. Moreover, if the link between such two vehicles does not satisfy the desired QoS application requirements, the routing tables will maintain a value of Inf and, as a consequence, the corresponding link will be ignored by the routing algorithm. Then, once all the calculations are done, MATLAB's plotting competency can be exploited to analyse the results in an adequate format. In the next section, a discussion on the considered SUMO-generated mobility models is provided.

3.2.2 Urban VNs Mobility Model

In this section, the VN mobility models created for use within this thesis are presented and discussed, based on the evolution of their individual characteristics. More specifically, urban mobility models are described first considering their individual characteristics. Then, a discussion regarding the considered mobility models is provided.

3.2.2.1 Individual Characteristics of Mobility Models

Due to their complexity, urban VNs applications should take into account several critical parameters, that can directly affect the QoS of VN applications. A classification of the important particular characteristics of VNs that should thus, be considered during the mobility modelling process is presented as follows.

Based on the allowed direction of travel, road-network structures can be categorised into one-way roads and two-ways roads. In more details, one way roads permit vehicle movement in one direction only and such scenarios should be treated separately from the urban model evaluation introduced in this chapter. Therefore, two-way streets have been included when constructing the road-network structure, as shown in Figure 3.4, which allows vehicles to move in both directions while placed on the same street, simi-lar to most grid-based road-networks. Note that this is critical in order to successfully model realistic urban road-network structures that follow the Manhattan Grid rules.

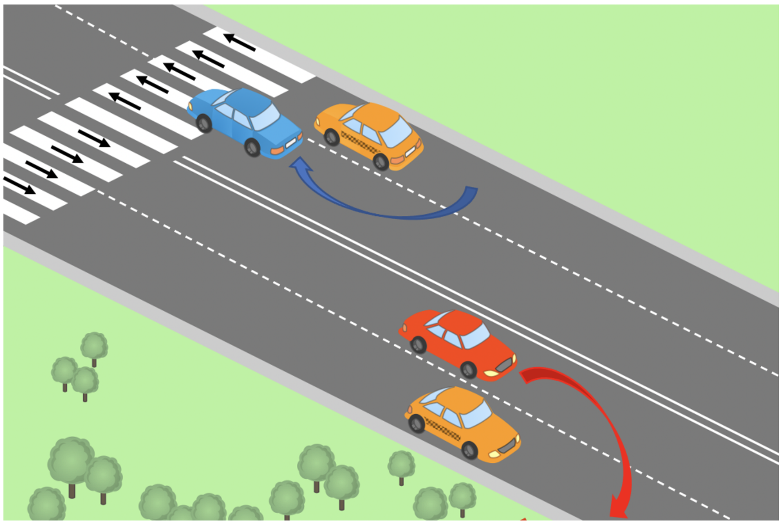


Figure 3.4: An example of a two-ways, two-lanes road.

Based on their number of lanes, road-network structures can be further divided into one-lane and multiple-lanes models. In one lane scenarios, vehicles are not allowed to overtake each other, and thus, they can easily end up getting stuck behind each other once they catch up with the car in front. This can lead to the creation of a ‘never-ending’ connection between nodes and implicitly of communications paths that are maintained active until the vehicles are forced to move apart from each other by some other external factors. For example, one such factor is represented by the channel fading phenomena which can have a great effect on the quality of the wireless links as shown in Section 2.3.2. Once again, best practice urges that such cases have to be treated as isolated scenarios for a more realistic evaluation of VNs. Contrary to the above-mentioned case, in sce-narios that provide multiple lanes for the movement of vehicles, traffic participants can overtake once they reach the car in front, following the example in Figure 3.4 above. As a direct consequence, the never-ending links issue is avoided, and the eect of free movement along the road-network can be tracked and evaluated. In more details, once a vehicle approaches another, it can now change lanes and move past the obstacle-vehicle that would have otherwise obstructed its movement pattern. From a communications performance perspective, the link between a pair of such vehicle nodes becomes more stable as they approach and then destabilizes once again as they move apart. Note that, following the discussion in Section 2.3.2 this link behaviour is caused due to the direct dependency between the decreasing distance between nodes and path loss. Thus, when building mobility models for this thesis, only two-lane roads were considered, following the lane evolution example provided in Figure 3.5.

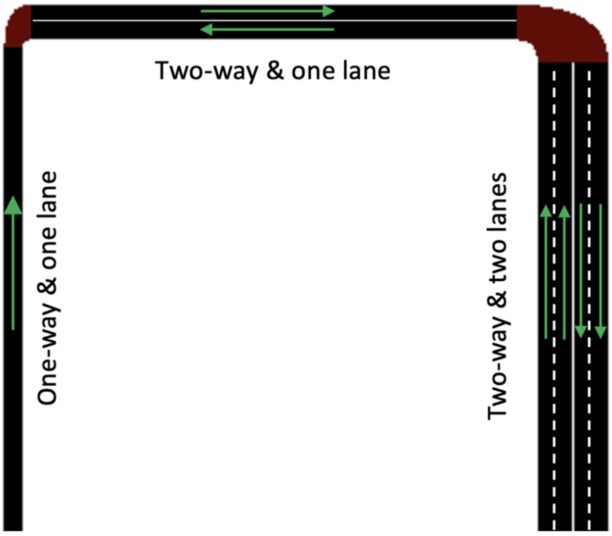


Figure 3.5: Evolution of lane characteristics.

By increasing the road-network structure dimensions, moving vehicles can spread over larger areas and, as a consequence, the distance between them increases on average. This can lead to less successful links available to choose from in the routing process as such links exceed the communications range of the nodes which, in turn, can be translated to less packets that can successfully reach their intended destination. Thus, the aim by doing so is to analyze the dependency between link/route performance as well as computational complexity and the dimensions of roads.

Intersections play a vital role in the realistic representations of VNs. Moreover, considering the discussion in Section 2.5.2, they can also provide aid with the emplyed routing approach. Therefore, in this thesis, the aim is to analyse how the QoS of communications links, and implicitly routes, varies with the number of junctions modelled into the scenario. Note that whenever a vehicle approaches a junction/turning point, it adapts its velocity as adequate. To be more specific, as in real-life scenarios, vehicles tend to break and lower their velocity as they approach such a point along their pre-established SUMO trace followed by accelerating again up to the maximum allowed speed after they have passed it. Thus, such behaviour has to be modelled to achieve realistic evaluation of VNs. An example of a two-way, two-lane urban intersection scenario is illustrated in Figure 3.6 below.

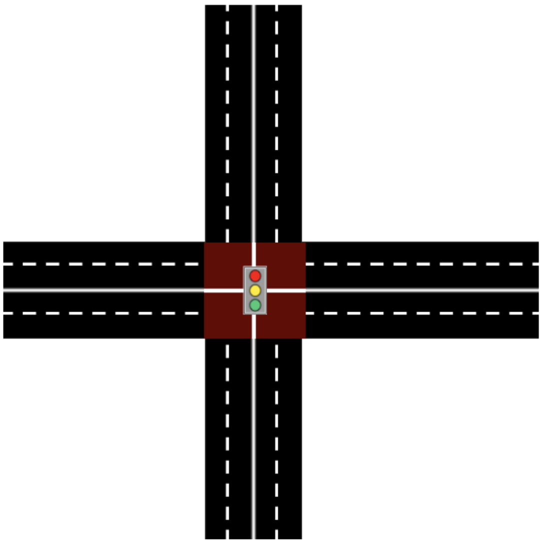


Figure 3.6: An illustration of a traffic-light aided intersection and two-ways, two-lane roads.

Traffic lights are generated within this VN simulator with the aim of strengthening the realistic representation of urban traffic as their introduction into the VNs design changes nature of vehicular movement towards realistic urban VNs. Therefore, each intersection can be equipped with a traffic-light and, as a direct consequence, the movement of vehicles around junctions is only permitted based on the following green traffic-light phases:

- green phase for moving straight
- green phase for turning left
- a straight green phase for the direction orthogonal to the first one
- a left-turning green phase for the direction direction orthogonal to the first one (only if there is a dedicated left-turn lane)

Note that, green traffic-light phases have a duration of 31s, as defaulted by SUMO [4].

Moreover, road-side units (RSUs) can be employed within the road-network structure. As discussed in Section 2.5.4 by placing RSUs at each existing intersection, connectivity accross the network can be assured. Moreover, RSUs can be integrated in both wired and wireless data transmission into the modelling of VNs. In more details, by employing a separate wired RSUs infrastructure, its resources can be accessed at any point in order to assure that the QoS requirements are met accross the VNs. Note that, in such scenarios, the vehicles communicate wirelessly, using V2V links between each other, the static RSUs are reached through V2I links, while the RSUs infrastructure can be considered as a separate wired network based on I2I links, where the nodes have global knowledge regarding all other RSU nodes as a direct consequence [145].

Considering the discussion in Section 2.3, VNs applications can finally be categorised based on the radio-frequency (RF) propagation model considered. More specifically, large-scale fading is employed, with the aim of representing realistic signal attenuation caused by urban VNs propagation.

Note that, if the channel propagation conditions are not modelled, it is only the movement of nodes that affect the QoS of existing wireless links. More specifically, in the absence of fading, the effect of path-loss (PL) on the quality of packet transmission is dependant only on how the distances between nodes changes. Thus, in such scenarios, the aim is to analyze how the mobility affects the performance of the communications link quality on its own, while avoiding the effects of the fading phenomena. However, for an accurate representation of VNs, the modelling process has to also consider the effect of the RF propagation environment on the signal. Therefore, channel fading is included into the analysis to show its effect on communications links/routes. More specifically, by modelling the channel conditions into the mobility models, additional randomness is introduced which imitates transmissions in real-life scenarios. Note that, due to the existence of such additional random variations, an early network shortage might be pro-duced. By doing so, the aim is to be able to characterize which has a greater effect on the link/route quality, namely node movement or the channel conditions, and therefore, what is the predominant reason behind the numerous disconnections between nodes in VNs. Note that these models can be further developed by also considering line-of-sight (LOS) blockage from obstacles, such as pedestrians and pedestrian crossings, public transport and bus stops as well as traffic lights and traffic signs.

Following the discussion above, different mixes of all factors mentioned have been employed for the construction of several mobility models for the purpose of evaluation in the context of VNs. Therefore, the next section provides a classification of the mobility models constructed and evaluated in this thesis.

3.2.2.2 An Evolution of the Considered Mobility Models

In this thesis, several urban road-network structure scenarios where a simplified Manhattan-grid was considered. The Manhattan road-structure model is a generated-map-based model introduced by the authors in [146] with the aim of simulating urban scenarios.

The road-network is formed of vertical and horizontal two-lane roads that allow overtaking as well as the motion in the two directions, as illustrated in Figure 3.7 below [147].

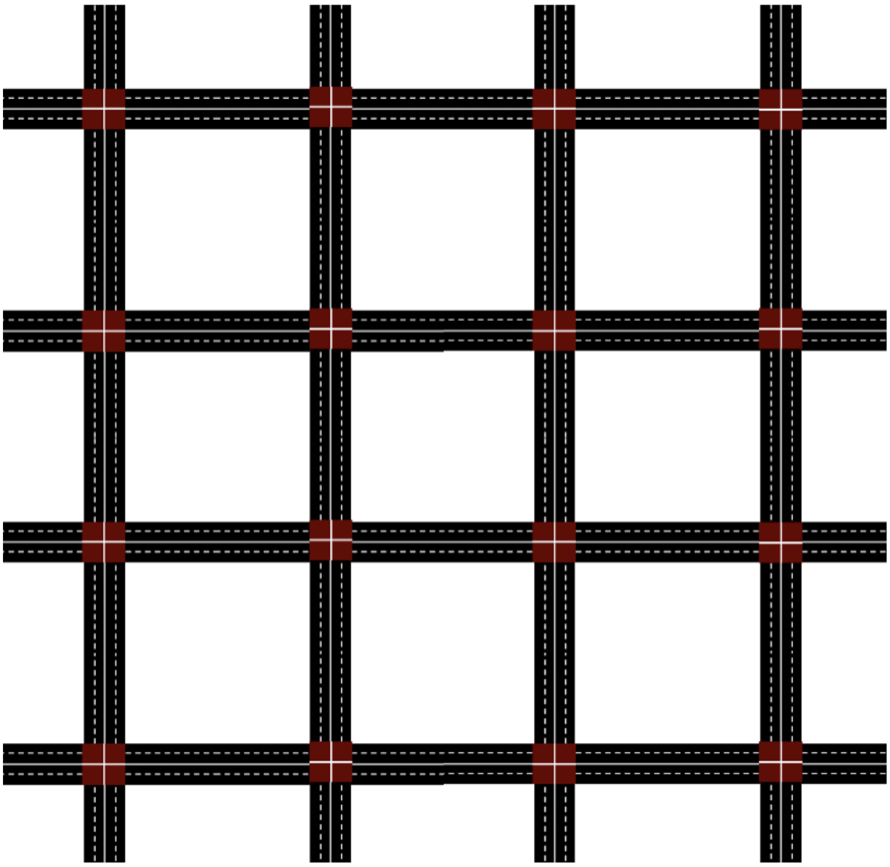


Figure 3.7: An illustration example of the Manhattan-grid road-network structure.

Thus, following the above-presented model, a grid as simple as a one square structure is initially considered and then evolved by increasing its dimensions and by adding junctions, additional lanes as well as traffic lights for a more realistic urban scenario modelling. The reasoning behind this is that the aim of this evaluation was to start from simpler and theoretical mobility models and then move towards more real life-like scenarios by adjusting the available variable parameters. By doing so, the scenario configuration effects become tractable and thus, easier to observe the performance effect produced by increasing the road dimension or by adding more intersections or lanes.

Considering the complexity of VNs mobility models, the aim in this thesis was to start from low-complexity models and evolve them by increasing their dimensions, as well as adding more intersections and traffic lights. Following that approach the effect of such conditions can be isolated and evaluated in the context of VNs routing performance. Therefore, an evolution of the considered mobility models is provided as follows. It is important to remind that each mobility model is specific to its scenario configuration due to their highly dynamic nature [148]. For example, in scenarios such as traffic jams, vehicles stop moving and as a consequence, the wireless links established between them always stay active. Thus, several traffic states are excluded that need to be considered separately. Therefore, only two-ways, two-lanes roads are considered, which makes vehicle overtaking possible in order to avoid traffic jams for the vehicle density ranges evaluated in Chapter 4 and Chapter 5.

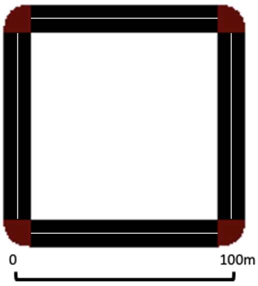


Figure 3.8: One-Square (OS) 100100 Road Structure.

One-Square (OS) 100100 was introduced first as the most simplified Manhattan-grid. More specifically, a road network structure following the shape of a square with the side-length of 100m is built. In some ways, this structure is similar to a never ending road where cars have to slow down when they turn left or right. Figure 3.8 describes the presented model.

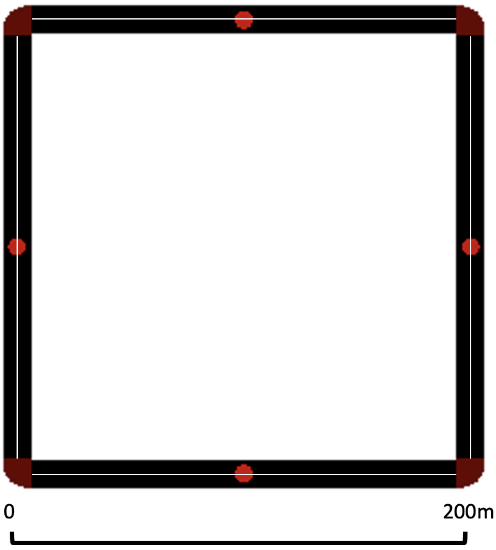


Figure 3.9: One-Square (OS) 200200 Road Structure.

Then, the One-Square (OS) 200200 was constructed based on the previous one but while considering double the side-length of the square; up to 200m to be more specific as shown in Figure 3.9. Thus, when compared to its predecessor, namely OS 100100, the effect of increased road-network structure dimensions can be isolated and evaluated in the urban VNs routing context.

The mobility model was then evolved once more, in One-Square-Junctions (OSJ) 200200, by adding junctions at 100m from each other, on top of the OS 200200 model, as illustrated in Figure 3.10. As a consequence of this upgrade, the effect of junctions on the

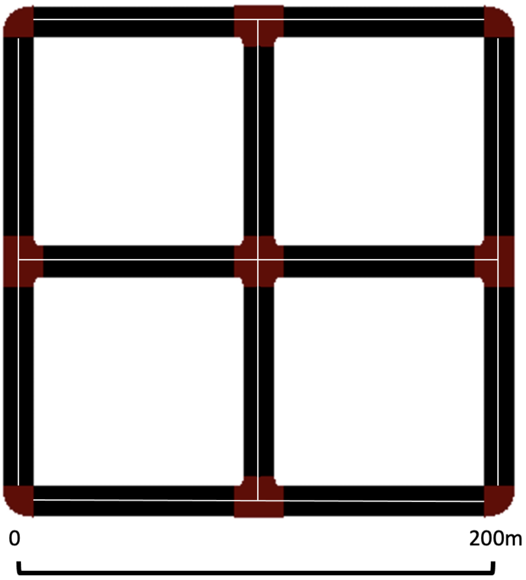


Figure 3.10: One-Square-Junctions (OSJ) 200200 Road Structure.

movement of vehicles and implicitly on the QoS of communications links/paths can be isolated and studied for urban VNs routing purposes.

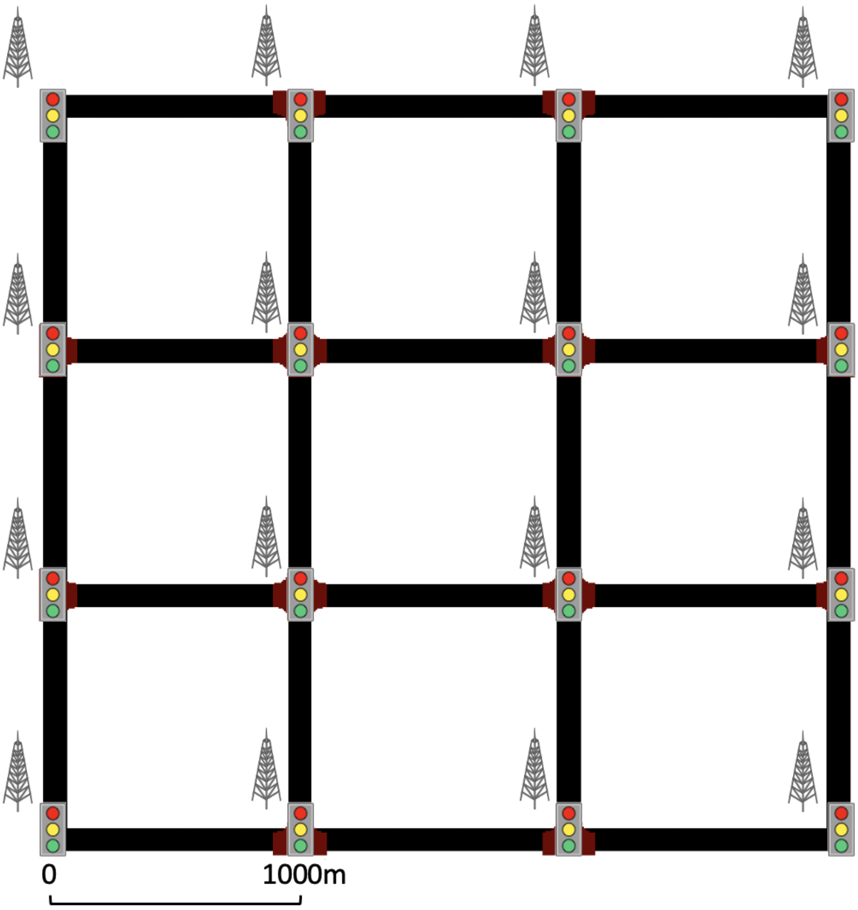


Figure 3.11: One-Square-Junctions (OSJ) 30003000 Road Structure.

Finally, for the purpose of realistic modelling of VNs, a larger more complex mobility model is produced, i.e. One-Square-Junctions (OSJ) 30003000. More specifically, a 3000m 3000m Manhattan-grid based road-network structure is modelled which is then divided into nine 1000m 1000m smaller grids by placing intersections at 1000m from each other as shown in Figure 3.11 above. Additionally, traffic lights are placed at each intersection in the road-network for a more realistic traffic flow and, implicitly, modelling of the scenario. Moreover, based on the discussion in Section 2.5.4, RSUs are considered at each intersection in the grid leading to a total of 16 RSUs, with the aim of extending network coverage.

3.3 Discussion

This chapter provided an overview of urban VNs applications, considering its importance for efficient routing that can construct long-lived, stable routes and avoid the frequent disruptions of communications links. Following the discussion provided in Sections 2.3 - 2.5, as efficient routing approaches rely on extracting contextual information from the environment, by evaluating the nonrandom behavior of vehicular mobility patterns, a realistic representation of urban VNs can be attained. Moreover, besides vehicular mobility, other characteristics of VNs mobility models have to be accurately considered, namely the road-network structure dimensions and their complexity (for example, factors such as intersections, buildings, trees, among others) as they can impose great challenges especially in urban VNs. Therefore, considering the importance of accurately estimating, modelling and evaluating VNs for efficient routing design, a summary of the existing mobility and network simulator software was initially presented. Following, a VNs simulation environment is introduced, namely using a merge of MATLAB and Simulation of Urban Mobility (SUMO) through the TraCI4Matlab package found within SUMO. A characterization of the introduced VNs simulation platform is provided next both from a radio-frequency propagation perspective as well as from a mobility evaluation perspective. Furthermore, several urban VNs scenarios are detailed. Next, the VN simulator introduced in this chapter as well as the discussed mobility models, are employed as a simulation platform in both Chapter 4 and Chapter 5. More specifically, the simulator is used to first evaluate the effect of road-network structure size and com-plexity on the induced overhead and then to evaluate routing performance for urban VN applications.

Chapter 4

Route Lifetime Analysis in Urban VNs Routing

The continuously changing topology of urban VNs has a multitude of adverse effects on the efficiency of existing communications systems as discussed in Section 2.5. One such example is represented by the effect of the rapid changes in the position of the vehicles on node to node connectivity. More specifically, in realistic urban VNs scenar-ios, as vehicles move around the road-network structure, they can leave the network or reach their destination at any time. As a direct consequence of such behavior, their connectivity capabilities are affected as they move inside and outside of each other's range of communications. Moreover, the gathered routing information becomes outdated and the established communication routes become invalid within a short time. Consequently, as the established routes suffer from premature disruptions, mechanisms such as route reconstruction are required which can lean to increased overhead and latency [21]. Therefore, in this chapter, besides studying the effect of mobility on routing performance, the focus is on the evaluation of the duration of established communications sessions within VNs. More specifically, considering the various lifetime definitions discussed in Section 2.5.1, a route lifetime evaluation is introduced with the aim of revealing the duration of established communications routes, based on the performance and duration of each link within. In that sense, as state-of-the-art routing techniques such as [69], [149], [150] are shown to often lead to sub-optimal routes from a route lifetime perspective, previous research has shown that route lifetime is a vital factor for enhancing the performance of VNs as discussed in section 2.5.1. Hence, given the above background, route lifetime in VNs needs thorough investigation. Therefore, in this chapter, the route lifetime is measured in order to reveal the trade-off between the structure and dimension of the road-network and the performance requirements as a fundamental research baseline for investigating and developing sophisticated routing models for vehicular networks. Moreover, such route lifetime estimations can be later used at optimising routing algorithms' decision process. In more details, by evaluating the route lifetime utilizing the dynamic nature of VNs, the aim is to further develop a method that produces a link lifetime-related metric capable of capturing the remaining lifetime of a VN communications link accurately enough so that it can be used as within the route construction stage of the routing protocol. For example, in [70], [96], [121], the authors consider the distribution of positioning data for calculating the expected connection duration between nodes and demonstrate that significant performance enhancement is achieved when the route lifetime is taken into account within the routing design. However, such a metric needs to go beyond describing the tendency of the future quality of targeted links and be capable of capturing the remaining route lifetime as accurately as possible due to the critical importance of extending the duration of successful communications links in VNs.

Contributions:

Considering the above discussion, the VN route lifetime has to be thoroughly examined as it has a significant effect on the performance of routing protocols and their develop-ment. Thus, in this chapter, the route lifetime is evaluated, while utilizing the dynamic nature of VNs. The goal behind this work is to develop a method that produces a link-lifetime-related metric capable of capturing the remaining lifetime of a link in the VNs context accurately enough to be used as a route construction metric within the next-hop stage of VNs routing protocols. Against this background, this chapter's contributions can be summarized as follows:

- A route lifetime simulation framework is provided, that first sets an upper bound for route lifetime through an exhaustive search routing algorithm.
- This upper bound is then compared against the route lifetime given by the shortest-path forwarding mechanism based on global state routing (GSR) revealing that the latter is sub-optimal 11.56% of the time given the dynamic environment of VNs. Note that the choice of routing technique is to provide an example and thus, the framework can be applied to other routing schemes.
- The route lifetime of the signal-to-noise ratio requirement (SNR_{req}) based shortest-path route is evaluated when varying the modelled quality-of-service (QoS) requirements defined by the per-link SNR_{req}, road-network structure and dimensions as well as the number of participating vehicles. This analysis reveals a trade-off between the road-network dimensions and the performance requirements.
- Besides mobility, channel fading is demonstrated to have a great effect on the route lifetime performance. Moreover, 7 times greater mean route lifetime and data transfer could be achieved in a line-of-sight (LOS) scenario compared to its non-line-of-sight (NLOS) counterpart.

The rest of this chapter is organized as follows. In Section 4.1, the network model is detailed, while discussing the road-network structure, considered QoS requirements as well as the route lifetime evaluation process. In Section 4.2, a description of the simulation environment is provided, along with the simulation results and their discussions. Section 4.3 concludes the chapter.

4.1 Network Model

This chapter's network model is provided in this section. More specically, an urban VN composed of V vehicles is modelled where the participants communicate in a wire-less fashion through vehicle-to-vehicle (V2V) transmission links following the example model given in Figure 4.1. During the deployment of the simulation, the vehicles are randomly and uniformly spatially-distributed over the road-network structure before starting to move from their randomly allocated positions with varying velocities follow-ing the Random Waypoint Mobility Model (RWP). Note that, once the destination is reached, vehicle can choose new destinations and continue their movement through the VN.

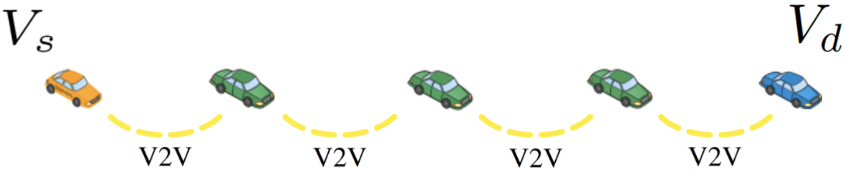


Figure 4.1: An example of V2V communications.

Before beginning each routing session, a source vehicle (V_s) and a destination vehi-cle (V_d) are selected while the rest of the vehicles act as relays to assure connectivity across the VN for the V_s - V_d pair. Considering each vehicle is quipped with a pre-installed Global Positioning System (GPS), their coordinates can be accessed and used for the improvement of routing decisions. Moreover, through the regular exchange of basic-safety-messaged (BSMs), all vehicles are assumed capable of gathering and stor-ing contextual information about any change in the distance to all other nodes in the network, as well as other mobility data such as velocities and accelerations, which they can then use during the next-hop decision stage of the routing process.

In that sense, considering an urban model, an approach for evaluating the communications duration within VNs is introduced in this chapter. Note that, at most one V_s-V_d pair can be activated at a time and the information is being generated by the assigned V_s solely. Moreover, as the V_s may have numerous alternative routes for delivering the data and is also capable of directly transmitting to the V_d, provided that a link exists

Table 4.1: The list of the considered symbols and their notations.

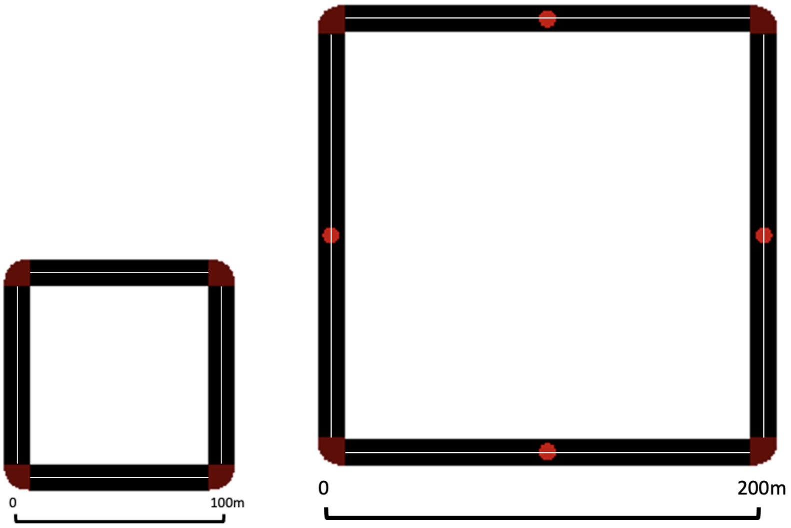
Symbols	Definitions
V	Number of Vehicles ($v \in \{1; \ldots; V\}$)
V_s	Source Vehicle
V_d	Destination Vehicle
V_c	Current Node
V_i	Any node but the current node
$dist_{V_c;V_i}$	Distance between nodes V_c and V_i
c	Speed of Light
Ps	Packet size
Tr	Transmission rate
Cr	Wireless transmission range
SNR_{req}	Signal-to-Noise Ratio Requirement

between them. Additionally, all nodes are assumed to transmit at the same transmit power while considering perfect encoding and decoding. Moreover, it is assumed that there is no interference between communicating nodes in the VN and no retransmission aspects of any nature are considered at the medium access control (MAC) layer. By following such assumptions, this analysis provides an upper bound of the route lifetime. A list of all symbols used within this chapter is provided in Table 4.1 along with their definitions. The considered road-network structure mobility model is discussed next.

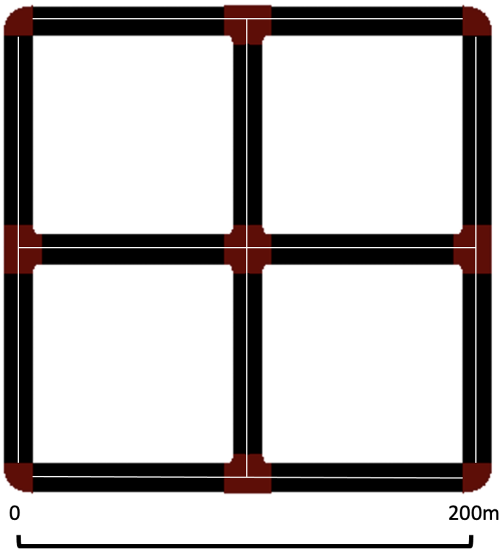
4.1.1 Road-Network Model

With the intention of modeling urban VNs, a simple Manhattan grid-based road-network structure is considered in this chapter, i.e. a structure composed of vertical and horizontal two-lane roads. This allows the motion in the two directions following a simplified Manhattan grid and then evolves towards various dimensions and additional junctions, as portrayed in Figure 4.2. The reason for using multiple grids is that the aim of this study is to start from simpler and theoretical mobility models and then move towards more real life-like scenarios by adjusting the available variable parameters. By doing so, the scenario configuration effects become tractable and thus, easier to observe the performance effect produced by increasing the road dimension or by adding more intersections or lanes. A classification of the considered network mobility models is presented below based on their characteristics. Initially, One-Square (OS) 100100 was modelled as a grid as simple as a square structure with a side-length of 100m, as shown in Figure 4.2(a). Then, the model was evolved by increasing the dimensions of the road-network structure side-length to 200m in One-Square (OS) 200200 and, additionally, by adding junctions in One-Square-Junctions (OSJ) 200200. The two models are portrayed in Figure 4.2(b) and Figure 4.2(c) respectively.

Each vehicle can accelerate or decelerate and has a maximum achievable speed chosen randomly from a distribution within 0 - 13.89 m/s, as described in Chapter 3. Also,



(a) One-Square 100100 (b) One-Square (OS) 200200



(c) One-Square-Junctions (OSJ) 200200

Figure 4.2: One-Square (OS) 100100, One-Square (OS) 200200 and One-Square-Junctions (OSJ) 200200 as the considered road-network structures.

note that the vehicles can change direction when they reach a junction based on a previously computed/assigned trace during their insertion/rerouting process. It is important to specify that each mobility model is specific to its scenario configuration due to their highly dynamic nature [148]. Note that there are several traffic states that need to be excluded. For example events such as traffic jams should be considered separately. In such scenarios, vehicles stop moving and, as a consequence, the wireless links between them may never break. This often leads to infinite route lifetime results which are incon-clusive for this analysis. Thus, only two-lane road-network structures were considered in order to allow vehicle overtaking, and thus avoid traffic jams. Note that each mobility model is scenario specific due to their highly dynamic nature. The routing aspects of this work are described next.

4.1.2 Routing Problem Description

Due to the uncontrolled high mobility of urban VNs, one major issue faced by efficient routing is that the available routes tend to break prematurely as vehicles move throughout the network. Additionally, this can lead to the repetition of the routing process and implicitly to significant overhead. Moreover, it is important to note that by considering an increased number of vehicles, following realistic urban VNs mobility models, it is expected to achieve exponentially increasing complexity and, implicitly, overhead, as the VNs resources are limited and the number of participants trying to access them increases.

A V2V communication link can be established between a pair of vehicles whenever they are within communications range of each other and they satisfy the desired QoS requirements. More specifically, when the current vehicle $(V_c \ 2 \ (1:::V))$ transmits packets towards any other vehicle $(V_i \ 2 \ (1:::V); V_c = V_i)$ which is able to successfully receive the signal, a communications link is created between the V_c - V_i pair only if the considered QoS requirements are satisfied. Following the same process, active links can become inactive as they stop satisfying such requirements.

Therefore, with the aim of studying such behaviour of urban VNs, this chapter considers the route lifetime (L_r) to be the total amount of time a route is active and thus, available for routing consideration in a VNs environment. However, such a route from V_s to V_d consists of multiple links chained in series, and thus, its performance depends on the performance of each wireless link between adjacent vehicle nodes. Therefore, in this chapter, L_r represents the duration all component links within a route satisfy the considered QoS requirements.

As a consequence, VNs' QoS applications' requirements such as the channel characteristics [151], [152], [153], network topology [154], [155], [156], resource limits, interference management [73], [157], [158], bit error ratio (BER) and other quality of service (QoS) requirements play a significant role in determining the duration of the successful communications routes in VNs. In that sense, the following section details the considered QoS requirements for the modelled VN.

4.1.2.1 Optimized QoS Performance Metrics

This study considers employing a fixed capacity achieving system, where perfect encod-ing and decoding are assumed, allowing the focus of the presented work to be on setting an upper bound of the L_r. Then, the L_r performance is studied considering different wireless channel characteristics and different mobility network topologies, while maintaining the desired QoS requirements. Therefore, considering its ability to reflect the collaborative impact of both the vehicle movement patterns as well as the effect of RF propagation within VNs, in this chapter, the routing focus is on the effect of the per-link SNR requirement (SNR_{req}), as a realistic urban VNs application QoS requirement. Therefore, the stability of a route, which depends on the quality of the wireless links within that specific route, is determined by the strength of the weakest link and the duration it maintains the required SNR_{req}. If fixed noise power N_0 is considered at the receiver, the SNR of any link between vehicles V_c and V_i can be computed, for a given bandwidth B and transmit power P_t, as follows.

$$SNR_{V_c;V_i} = \frac{P_t \quad H \quad \overline{4dist}\,\overline{\qquad}_{V_c;V_i}^{\;2}}{N_0 \quad B}; \qquad (4.1)$$

$$= \frac{c}{f}(4.2)^{c}$$

where P_t is the transmit power, H is the channel gain, $d_{V_c;V_i}$ is the distance between nodes V_c and V_i, c represent the speed of light and f_c is the carrier frequency.

Target BER	SNR requirement [dB]	Corresponding range in no fading conditions [m]	
0.4465	-20	150	50
0.1079	0	30	20
0.01421	7		
0.001334	14		

Table 4.2: SNR as a VN applications Requirement based on BER - SNR Look-up Table.

Additionally, for the routing performance metric validation, this evaluation relies on a BER-SNR look-up table (LUT) which specifies the particular SNR requirements to be satisfied for the sake of maintaining a given target BER, as shown in Table 4.2. Note that no interference is considered in this VN model. Note that the extracted SNR samples are related to large-scale path loss, where random variations on the received power level are treated as noise. Note that the extracted SNR samples are related to large-scale path loss, where random variations on the received power level are treated as noise.

The analysis is done for a Rician channel with a K factor of 4 and BPSK modulation. More specifically, given the mobile vehicular nodes, small-scale Rician fading is considered, where the Rician K factor is defined as the ratio of the energy of the specular part r^2, the so-called LOS component, and the diffuse part, namely NLOS, denominator 2^2

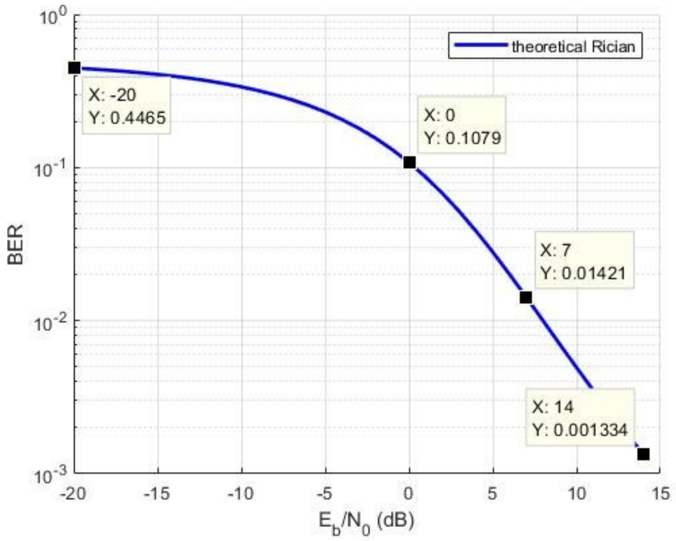


Figure 4.3: Theoretical bit-error-rate (BER) vs signal-to-noise ratio (SNR) evaluation of Rician channel, K = 4.

of the received signal and is given by,

$$K = \frac{r^2}{2\,{}^2}; \tag{4.3}$$

where r is the amplitude of the dominant path, and represents the standard deviation of all other weak path amplitudes [159]. Thus, the corresponding channel impulse response is given by,

$$H_{Rician} = \sqrt{\frac{K}{K+1}}\,H_{LOS} + \sqrt{\frac{1}{K+1}}\,H_{NLOS}; \tag{4.4}$$

where H_{LOS} and H_{NLOS} are the LOS and NLOS channel impulse responses given by,

$$H_{LOS} = \cos + j\ \sin;\ H_{NLOS} = (1 + j)\ ; \tag{4.5}$$

where is the transmission antenna angle of departure and CN(0; 1) is a complex-valued Gaussian random variable, whose amplitude and phase are Rayleigh and uni-formly distributed, respectively [159]. Additionally, this study considers half-duplex communication over the same shared wireless channel.

Therefore, following the above discussion, in this chapter, a route, and implicitly link, is considered to be successful/stable when the chosen QoS requirement, namely the SNR_{req} in this case, is satisfied as both the mobility effects and the channel effects on the L_r can be observed. Note that, if no channel fading conditions are assumed, the SNR-based metric performance follows the changes of the distance between the vehicle nodes as shown in Table 4.2. Next, a discussion of the employed approach to evaluate Lr is provided.

4.1.3 Route Lifetime Evaluation Algorithm

Initially, an upper bound for L_r is set by employing the following approach based on an exhaustive search routing algorithm. It is considered that, once all available routes are found, they can then be monitored for as long as they satisfy the QoS requirements. To be more specific, each active route is observed until the SNR_{req} is broken by at least one link within. Note that, if there is no fading considered, the SNR mainly depends on the distance between the said nodes and so does the L_r. More specifically, once the nodes move out of each other's radio transmission range, the route/link breaks. When all found routes get disconnected, the L_r performance of the last active one is saved. Thus, the best L_r route in the network is found in an exhaustive manner. Then, the routing process starts again until all samples are collected as seen in Algorithm 1.

Algorithm 1 Route Lifetime Measurement Technique.

```
Input: V, sampleSize, $SNR_{req}$, $V_s$, $V_d$
s   0; i   0; routes   inactive;
i++;
while s  sampleSize do
    !   update routingTable(i) against $SNR_{req}$;

    if routes = inactive then
        !   DO routing ) active routes
        Lifetime(all active routes)   1;
        routes = active;
    else
        for all active routes do
            !   check links against $SNR_{req}$;
            if all links are still active then
                Lifetime(route)++;
            else
                !   record Lifetime(route);
                !   routeStatus(route) = inactive;
            end
        end
        if all routeStatus = inactive then
            !   routes = inactive;
            !   s++;
            !   upperBound(s) = max(Lifetime);
        end
    end
end
```

Then, the L_r performance is analysed when employing a simple GSR-based routing approach based on Dijkstra's shortest-path algorithm with the aim of finding the optimal single shortest-path available in the network. Therefore, unlike in the before-mentioned approach, this time the focus is on the performance of the shortest-path route only

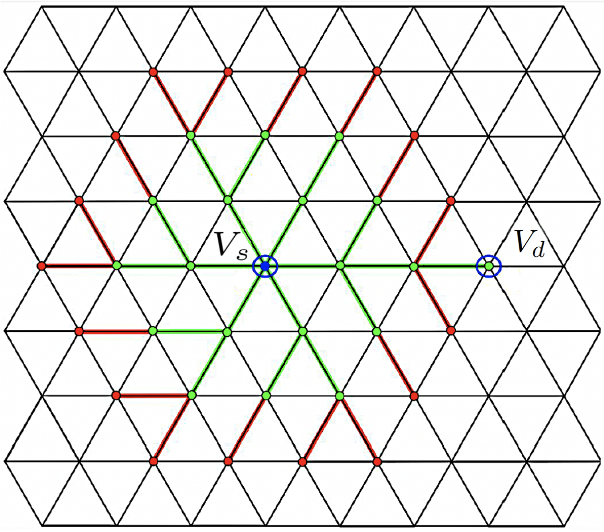


Figure 4.4: Best case of a Dijkstra's shortest path algorithm in a tri-hexagonal grid where the reached nodes are depicted in red and settled nodes in green [5].

instead of following all available routes in the network. The shortest-path algorithm begins by reaching all of the V_s's neighbours and proceeds to settling all concentric reached nodes that have the same tentative distance, until finally, reaching all nodes in the network. Note that, if there is a known pair of nodes such as V_s and V_d, the shortest-path algorithm can be considered a heuristic search, similar to a greedy search. This means that the algorithm will look for the optimum solution and try to optimize it at each stage. To be more specific, the algorithm reduces the travelling cost and chooses the appropriate path from the V_s to V_d as portrayed in Figure 4.4.

However, under a given mobility model, the shortest-path algorithm might not provide the best application-level performance and more sophisticated routing should be considered. Therefore, it is important to specify that Dijkstra's shortest-path algorithm is one routing example, while the framework can be applied to other routing techniques. This choice of algorithm is merely due to its low computational complexity but this serves as motivation for further improvement both in terms of routing algorithm choice as well as QoS metric considered.

Therefore, considering the approaches detailed above, the route between the V_s and the V_d can be selected for evaluation. Note that the RL computations are based on 1 second time-steps so as to maintain up-to-date routing tables without producing excessive over-head, according to [4]. More specifically, at each time-step, the routing table is updated according to the SNR_{req}. Note that the aim is to evaluate both the average L_r as well as the L_r distribution.

4.2 Simulation Results

In this section, the simulation environment is first described. Then, the route lifetime performance of the GSR based shortest-path forwarding mechanism is compared against the upper bound route lifetime of the network. Finally, an analysis of the shortest-path L_r, while varying the QoS requirements, the mobility scenario and the wireless channel fading is provided.

4.2.1 Simulation Environment

For the purpose of realistic evaluation in terms of both communications and mobility, a VN platform is simulated by allowing Simulation of Urban MObility (SUMO) and MATLAB to communicate with each other through Traffic Control Interface for MATLAB (TraCI4Matlab) [160]. SUMO is used to generate movement traces for vehicles and form mobility models which are then used as data for routing performance evaluations in MATLAB. Thus, a simple Manhattan grid model is considered and evolved in terms of dimensions and complexity following the discussion in Section 3.2.2.2. Fi-nally, vehicles are randomly and uniformly distributed over the available road-network. Each vehicle can decelerate to 0 m=s and accelerate to 13:89 m=s as defined by the urban speed limit. Note that velocities are normally distributed with a standard deviation of 0.1, as defaulted by SUMO [4]. The number of participant vehicles generated on the road-network structure varies from 2 to 20 with a step of 2. Furthermore, the shortest-path simulations are averaged over 4000 route lifetime samples for each set of vehicles considered in order to obtain a more accurate evaluation of the considered models. This simulation also takes into account communications factors and hence, the most relevant fixed parameters considered for the simulation environment are provided in Table 5.3, as extracted from [17], [14], [161], [162], [163].

The performance of the proposed route lifetime benchmark is studied in the following section under different simulation parameters such as the mobility model configurations, the number of vehicles and the fading conditions. Initially, fading scenarios are ignored in order to focus on how the mobility and the per-link SNR_{req} affect route lifetime performance. Then, Rician fading (RF) scenarios are employed in order to reveal the impact of fading on the route lifetime performance.

4.2.2 Route Lifetime Analysis

In terms of QoS metric, utilizing information related to the quality of the radio link to construct reliable routes offers an immediate way to exploit the direct coupling of physical layer operations to the network topology. Thus, the use of the received power

Table 4.3: Fixed Simulation Parameters.

Fixed Parameters	Value
Number of nodes	2:2:20
Target SNR requirement [dB]	-20, 0, 7, 14
Channel model	Rician
Path loss exponent, n_p	3
Noise power, N_0 [W/Hz]	$10\ ^{15}$
Transmit power, P_t [W]	0.2
Carrier frequency, f_c [Hz]	$5{:}9\ 10^{9}$
Bandwidth, B [Hz]	$10\ 10^{6}$
Vehicular transmit rate [bps]	$10\ 10^{6}$
Urban speed range [m/s]	0 - 13.89

or SNR as a metric for the targeted wireless links might be successful in providing an informed choice for the succesful transmission between a V_s-V_d pair. However, such a criterion focuses more on the past observations without extrapolating in the future. More specifically, by exploiting such metrics, a routing algorithm only looks for a momentarily stable grouping of the nodes which may not always lead to optimum L_r performance. Furthermore, temporal dependence of the link quality is not linear, as it is dictated by both the path loss exponent as well as the high mobility of the vehicles as shown this chapter. Thus, because of the VNs challenging propagation environment, using the link quality's instantaneous rate to predict the future of the wireless links may lead to erroneous estimations. Therefore, the aim in this section is to show that although SNR is a strong indicator of the instantaneous link quality and may thus, under certain conditions, imply larger momentary throughput, utilizing the SNR as a metric for route construction does not necessarily lead to the longest living routes.

Having that in mind, the L_r of the shortest-path based on the chosen SNR_{req} metric was compared against the upper-bound L_r provided through analysing all available routes in the VN exhaustively. Figure 4.5 presents the performance gap of the shortest-path L_r to the upper-bound L_r, where each circle represents one L_r sample per trial. In 11.56% of the trials, the shortest-path L_r is lower than the upper bound available L_r in the VN. Shortest-path may achieve the best possible result at some trials, but as pointed by the circles, there are performance gaps below the benchmark set by the upper bound L_r at different trials, which indicates sub-optimal characteristics of the shortest-path life-time algorithm. The findings reveal that the shortest-path is not optimal for obtaining the best L_r solutions and that an intelligent selection of the best candidate vehicles is required when establishing a route. Note that in some vehicle-scarce trials, there may be only one route available due to the unsatisfied path QoS requirements, and hence

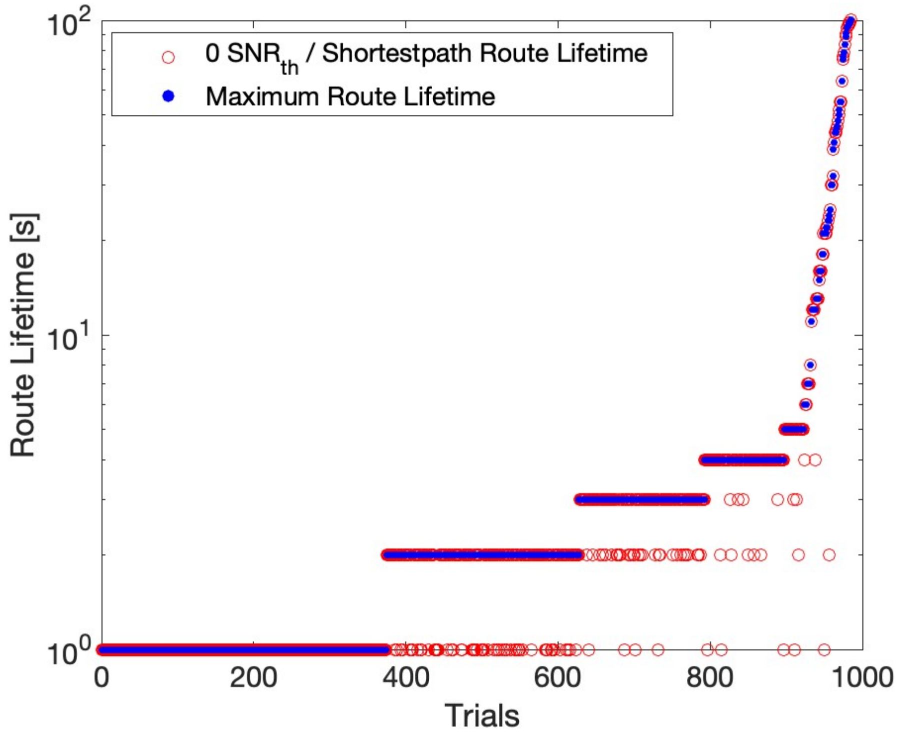


Figure 4.5: Shortest-path route lifetime vs. upper bound route lifetime for OS 100100 scenario with no fading (NF) and per-link signal-to-noise ratio requirement (SNR_{req}) 0dB.

shortest-path L_r becomes equal to the upper bound L_r. Next, the L_r of the shortest-path algorithm is evaluated while adjusting several critical factors. More specifically, the L_r performance is studied while varying the SNR_{req}, the road-network structure configuration as well as the channel conditions.

4.2.2.1 SNR Requirement Analysis

Figure 4.6 presents the mean route lifetime against the number of vehicles present in the network, while varying the SNR_{req} and considering different road-network models when no-fading is considered. It can be observed that, for the same road-network model once the requirement is decreased, the mean route lifetime increases. This confirms the expectations that the QoS requirements have a direct influence on the route lifetime. In Figure 4.6, it can be observed that OSJ 200200 has lower lifetime in comparison to OS 200200. For a SNR_{req} of 0dB, OS 200200 is able to achieve a mean route life-time value up to 8.5s whereas in the 14dB SNR_{req} case it solely reaches 6s on average. Therefore, considering a vehicular transmit rate of 10 10^6 bps a data transfer of size 10.62MB and 7.5MB, respectively, can be achieved.

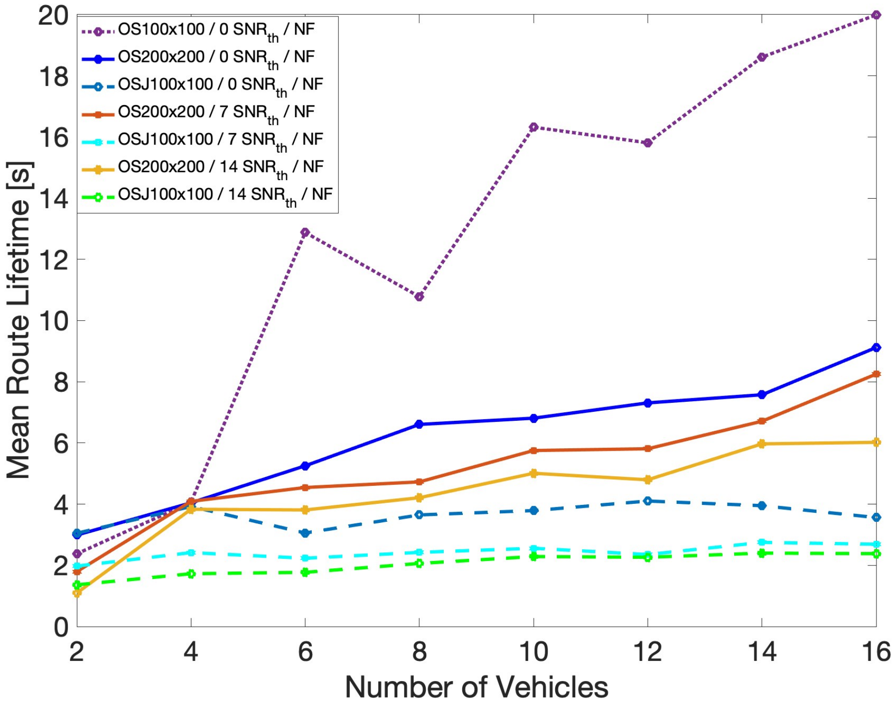


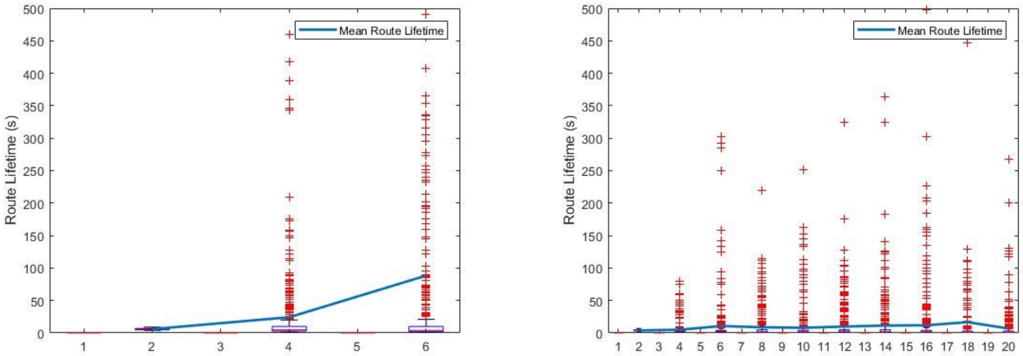
Figure 4.6: Mean route lifetime for different road-network models considering various per-link signal-to-noise ratio requirement (SNR_{req}) values and no fading (NF).

4.2.2.2 Mobility Analysis

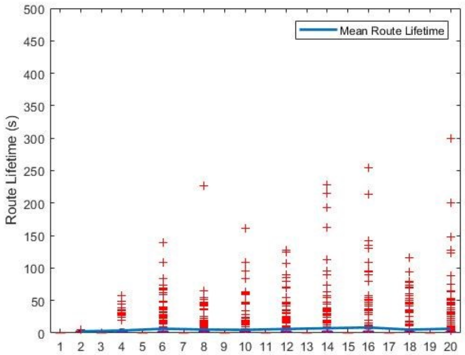
Figure 4.6 also reveals the trade-off between road-network structure and dimensions (mobility patterns) and SNR_{req}. For an SNR_{req} of 0dB, it can be observed that, in OS 100100, the mean route lifetime increases steeply to 20s, whereas in all other scenarios it stays below 8.5s corresponding to data transfer of size 25MB and 10.62MB, respectively. This is mainly because the equivalent communications range is 50 meters in no-fading scenarios. Therefore, for OS 100100 scenario, the likelihood of a route to stay connected for a prolonged duration is large, since the connectivity can be provided throughout the given dimensions. It is also important to note that in smaller, denser structures, the probability of congestion is higher and thus, traffic jams might appear. As a consequence, the route lifetime tends to increase uncontrollably as the vehicles stop moving away from each other and start clustering.

Figure 4.7, Figure 4.8, and Figure 4.9 provide the L_r distributions for the OS 100100, OS 200200 and OSJ 200200 scenarios respectively. It can be observed that once the SNR_{req} is decreased and thus, the communications range increased, the mean L_r increases. This confirms the expectations that the application QoS requirements, to be more specific the SNR_{req} metric, has a direct effect on the L_r. Also, it is important to notice how the L_r increases on average when the number of vehicles on the road network increases.

For the OS 100100 scenario, the road-network structure is small and agglomerated, making it much easier for the vehicles to remain within range of each other for longer time. Therefore, it can be observed in Figure 4.7 that, for a SNR_{req} of 0dB, once the number of vehicles reaches 6, the L_r starts increasing significantly. The approach was employed again for 8 vehicles and, as a result, the simulation eventually found a route that would not break leading to a L_r equal to infinity. The reasoning behind this is that the road-network structure is small enough for the vehicles to eventually remain within range for a very long time. Moreover, considering a vehicular transmit rate of $10 10^6$ bps, transmissions up to 300Mb, 1500Mb and 4000Mb respectively were achieved achieved.



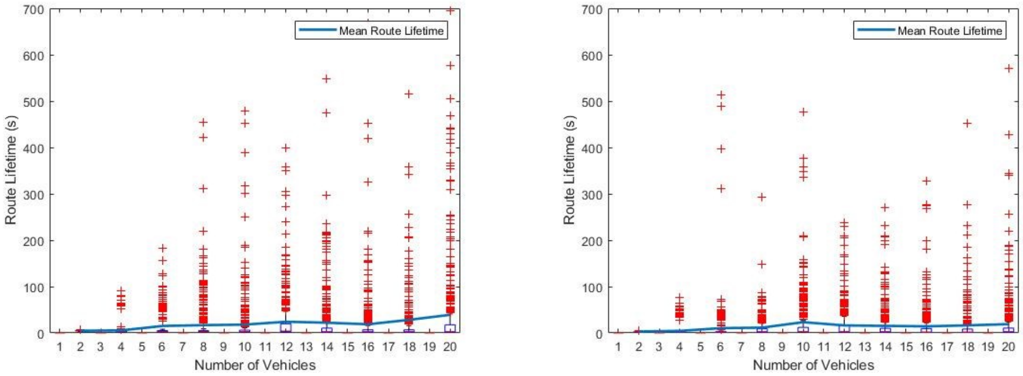
(a) SNR_{req} = 0dB (b) SNR_{req} = 7dB



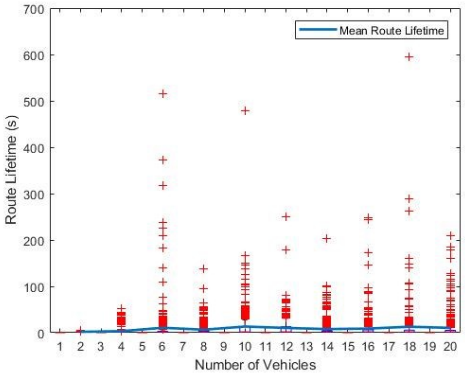
(c) SNR_{req} = 14dB

Figure 4.7: Route Lifetime Distribution in the One-Square (OS) 100100 with no fading.

Additionally, in the OS 200200 scenario, the maximum achievable L_r values vary between 800s, 1000s and 1200s for a SNR_{req} of 14dB, 7dB and 0dB respectively as it can be seen in Figure 4.8. Thus, it can be said that, following the data-rate chosen, in each case the best route can be used for the transmission of up to 800Mb, 1000Mb and 1200Mb respectively until it gets disconnected and a new route is required. However, it is important to note that the maximum values are not realistic L_r values as, on average,



(a) SNR_{req} = 0dB (b) SNR_{req} = 7dB

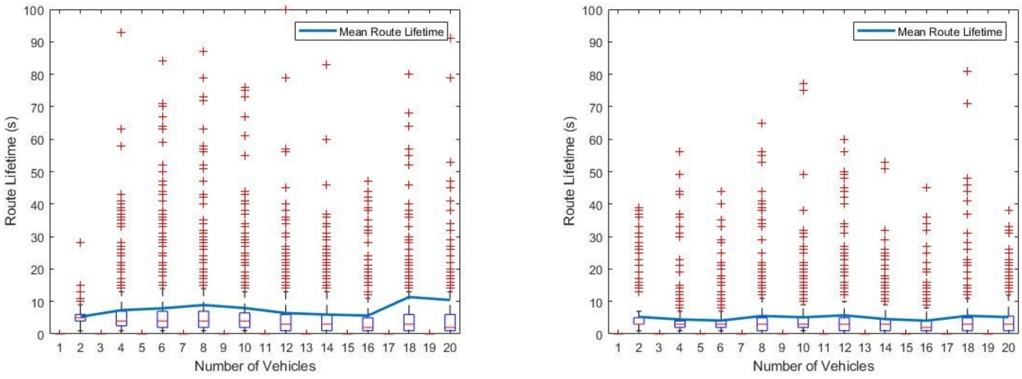


(c) SNR_{req} = 14dB

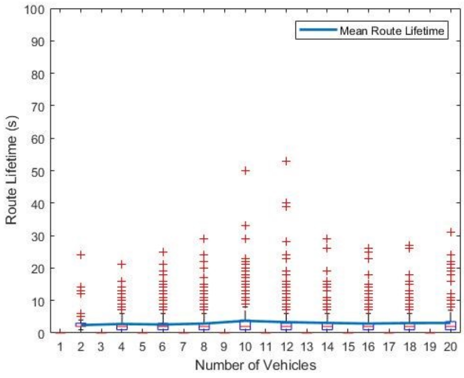
Figure 4.8: Route Lifetime Distribution in the One-Square (OS) 200200 scenario with no fading.

L_r varies between 2-10s, 3-17s, 5-40s for each considered value of the SNR_{req}. This corresponds to an average of just as much data transmitted, which is significantly lower.

Finally, in the OSJ 200200 scenario, the maximum L_r values vary between 55s, 120s and 800s for a SNR_{req} of 14dB, 7dB and 0dB respectively as it can be seen in Fig-ure 4.9. Thus, it can be said, following the data-rate chosen, in each case one route can be used for the transmission of up to 55Mb, 120Mb and 800Mb respectively until the active route gets disconnected and a new route is required. However, the correspondent average L_r vary between 2:5s; 5s; 6 11s for each considered SNR_{req}. This corresponds to an average of just as much data transmitted, which is significantly lower. The lower L_r values are caused in this case compared to the previous ones due to the addition of a junction and implicitly more turning points and roads. Thus, in some cases, instead of continuing their movement together towards the same direction, vehicles can now change direction and move apart from each other more often. Therefore, by adding more junctions in scenarios where connectivity/coverage is limited (for higher SNR_{req} requirement requirements/large road-network dimensions) increases the chance for vehicles to move away from each other, and thus lowers the route lifetime on average. As



(a) SNR_{req} = 0dB (b) SNR_{req} = 7dB



(c) SNR_{req} = 14dB

Figure 4.9: Route Lifetime Distribution in the One-Square-Junctions (OSJ) 200200 scenario with no fading.

a consequence, in OSJ 200200, only up to 3.125MB of data transfer could be achieved on average, corresponding to a maximum mean route lifetime of 2.5s. Note that if the range is sufficiently increased, the addition of more junctions would have no effect on the route lifetime performance as changing direction does not necessarily mean exceeding communications range. When the SNR_{req} is small, on the other hand, adding junctions can be seen as a higher chance for the vehicles to move away from each other thus, breaking their wireless communications link.

4.2.2.3 Fading Analysis

Figure 4.10 shows a mean route lifetime comparison between scenarios with and without fading based on OS 200200 and considering 7dB and 14dB SNR_{req}. A Rician K factor of 4 is considered. It can be readily observed that the fading scenarios are not able to achieve more than 3.5s lifetime and 4.375MB data transfer, which is significantly lower in comparison to no-fading scenarios.

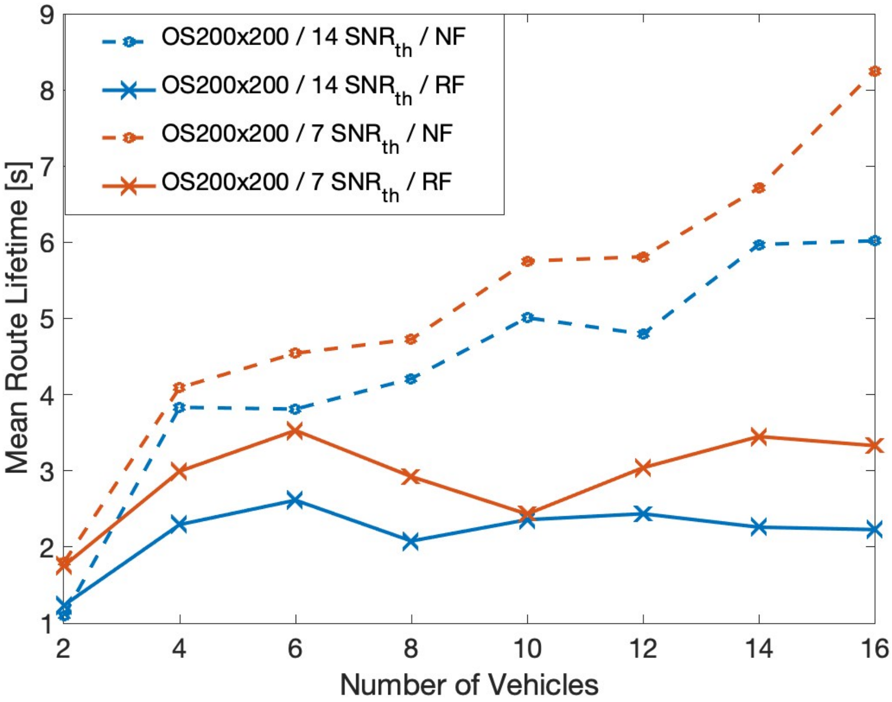


Figure 4.10: Rician fading (RF) effect against no fading (NF) for One-Square (OS) 200200 scenario considering per-link signal-to-noise ratio requirement (SNR_{req}) 14dB and 7db.

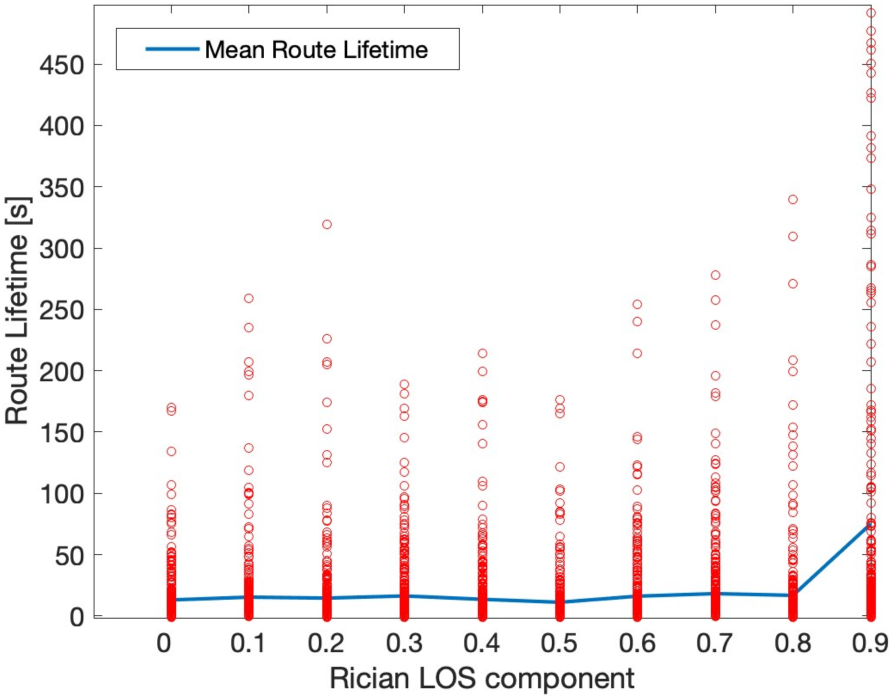


Figure 4.11: Route lifetime distribution versus Rician LOS component, which is related to the K factor using Equation (4.3), in One-Square (OS) 100100.

Then, in order to analyse the effect of fading, the aim is to eliminate the effect of the mobility component on the quality of wireless communications links. Thus, all vehicles are forced to be within communications range by switching the metric from SNR_{req} to a distance requirement (d_{req} = 150 meters (m)). More specifically, since a d_{req} of 150m is always greater than the maximum distance any two nodes can reach within the OS 100100 model, then all nodes should be able to establish successful communication links with all the other vehicles present in the network. As a consequence, considering fading under these circumstances reveals the sole effect of wireless channel fading on the route lifetime performance. The following Rician K values are considered: 0.1/0.9, 0.2/0.8, 0.3/0.7, 0.4/0.6, 0.5/0.5, 0.6/0.4, 0.7/0.3, 0.8/0.2, 0.9/0.1, whose associated route lifetime distributions are provided in Figure 4.11, which illustrates that until a ratio of 9 is maintained, the mean route lifetime always stays below 13.5s, thus always achieving less than 16.8MB of data transfer. However, for a K factor of 9, the mean route lifetime jumps to 75s corresponding to a data transfer of size of 93.75MB. This means that in the latter case, a communications system could achieve on average 7 times more data transfer than in scenarios where NLOS is more dominant. Then, when the LOS factor is increased to 1, because the distance requirement is high enough for all vehicles present on the OS 100100 road-network model to be within range of each other, the route lifetime will increase indefinitely. Therefore, a conclusion can be drawn, that besides the mobility of nodes, channel impairments play a critical role in route lifetime performance since instead of having nodes clustered together and achieving high route lifetime, the communication links break due to the detrimental fading effect.

4.2.3 Overhead Analysis based on Use Case Requirements

Besides the L_r, this section aims to evaluate how the effect of the road-network structure size and topology on the computational complexity of VNs' simulations based on each of the considered mobility models. Thus, it reveals how many simulation time-steps encountered no available paths when searching for a successful route by introducing a new variable, called 'nopathsfound', which is evaluated against the total simulation time. To be more specific, what is the probability for a routing algorithm not to find an available path that provides the desired performance?

For this evaluation, the two mobility models which present the most differences are considered, namely OS 100100 and OSJ 200200. These models differ in terms of both road-size dimensions, as well as the number of junctions. Note that both road structures assume two-lane road structures in order to allow vehicles to overtake and drive-by each other. In addition, the effect the SNR_{req} on the simulation overhead is also studied. With that goal, 7dB and 14 dB SNR_{req} performance requirements were considered. Note that, no channel effects were considered in this evaluation as the focus was on the vehicle mobility characteristics and their effects and therefore, the SNR_{req} is equivalent to d_{req} in this case as shown in Table 4.2. Again, a varying number of vehicles is generated; from 2 to 20 with a step of 2 to be more specific. This evaluation is run in parallel with the one in Section 4.2.2 as the number of 'nopathsfound' is counted until a number of 4000 successful routing samples are gathered. Figure 4.12 describes how the computational complexity of the OS 100100 and the OSJ 200200 scenarios depend on their dimensions, number of vehicles present and QoS requirements.

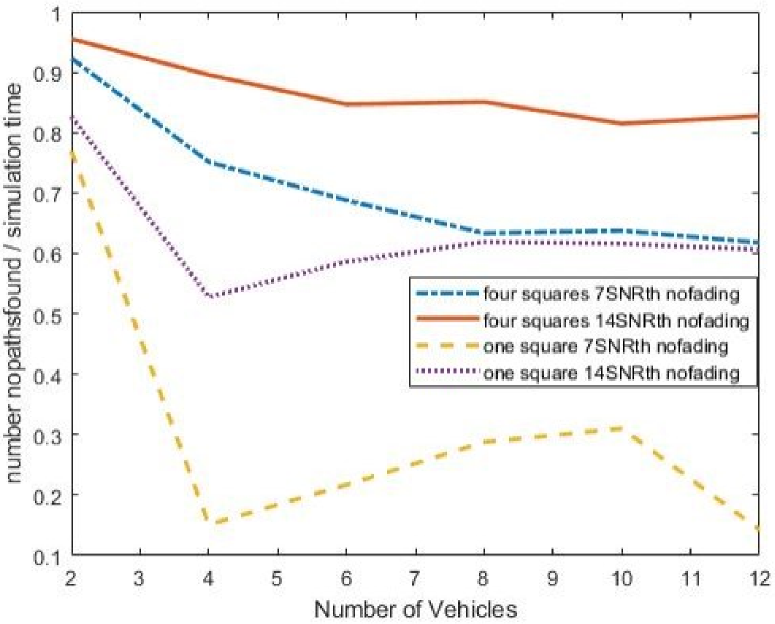


Figure 4.12: Simulation Complexity Analysis under dierent mobility scenarios and performance requirements.

It can be observed that the number of 'nopathsfound' decreases as the number of vehicles increases in all scenarios. If the case where only two vehicles are considered is considered, the 'nopathsfound'/simulation time ratio is always greater than 0.75 in all cases whereas, in the one square model it can reach as low as 0.15 for an SNR requirement of 7dB and 20 vehicles. This proves that the number of available or successful communications paths increases with the number of vehicles on the available road network. This is however expected as more crowded roads network means less distance between neighbor vehicles and thus more vehicles within range of each other.

On the contrary, when the road dimensions are increased, from one square to four squares, the vehicles are distributed in a sparser way, and thus, they have a higher chance to be out of range of each other. This leads to a smaller number of available paths and implicitly an increased simulation overhead. More exactly, the number of 'nopathsfound' against simulation time is much higher in both OSJ 200200 scenarios achieving values as low as 60% and up to more than 90% . Finally, when the SNR requirement is increased, therefore decreasing the communications range, the issue of increased overhead and smaller path availability is once again encountered. In the OSJ 200200 model, the 'nopathsfound'/simulation time ratio varies between 0.95 and 0.85 for a requirement of 14dB while for 7dB it takes values between 0.93 and 0.62 as the number of vehicles increases.

4.3 Discussion

This chapter initially sets an upper bound of the route lifetime by exhaustively evaluating all available paths in the VN. Then, the shortest-path L_r is compared with this upper bound where a signal-to-noise ratio requirement (SNR_{req}) focused shortest-path forwarding mechanism based on GSR was chosen as a routing example. It was observed that the SNR_{req} based shortest-path is not optimal which motivates the need for an intelligent vehicle selection algorithm for constituting a route with the goal of an extended and uninterrupted data transmission, which is improved upon in Chapter 5. The effect of the SNR_{req}, the road-network structure dimensions and topology (based on realistic urban mobility models) and the channel fading on the L_r performance of VNs were then studied. Following, a trade-off between the QoS requirements described by the chosen SNR_{req} and the road-network structure dimensions and topology. Additionally, it is observed that, fading significantly influences the L_r performance. Moreover, better L_r and data transfer performances could be achieved in a LOS scenario compared to its NLOS counterpart. Thus, this chapter shows that the quality of the communications links does not vary linearly with the distance separating the vehicles involved, but the channel fading has a significant effect on the respective rate of change and, as a conse-quence, it has to be carefully taken into account when designing the routing algorithm. Finally, the complexity of the chosen algorithms is studied under different scenarios, revealing that the evolution of the road-network structures as well as the increase in QoS requirements leads to increased overhead.

Chapter 5

Reinforcement Learning Aided Traffic-Aware Routing

Due to their uncontrolled and unpredictable nature, routing in mobile networks has many challenges, which become even more severe in the case of VNs [13]. For exam-ple, the frequent network topology changes as well as the non-uniformity of the vehicle spread on the available road infrastructure can often lead to frequent network parti-tions and implicitly to low communications performance. Such nature of VNs prevents network designers to realize applications with a wide range of quality of service (QoS) requirements, such as high throughput and low delay [164].

A variety of conventional routing techniques have been proposed. Traditional geographical routing techniques, for example, provide design simplicity and scalability [82], [83], [84]. However, these techniques do not work in VNs, as they do not consider real-time road traffic information and thus, are unable to achieve the required QoS requirements of urban VNs [14]. To remedy such limitations, techniques such as cross-layer traffic-aware routing and infrastructure-aided routing have been introduced [17].

Traffic-aware routing protocols are believed to be the most promising forwarding strat-egy in the urban VNs. Obtaining knowledge of the neighboring vehicles in the net-work has also been shown to be beneficial for routing performance in both sparse and dense environments [86]. Many traffic-aware routing protocols have been proposed that make routing decisions by considering multiple traffic awareness-related metrics and as a result, they significantly reduced the failure probability of successful communica-tions [14], [17], [18], [24], [87], [88].

Intersection-based routing was shown to be another performance enhancer for routing in [14]. The main reason behind this is that network congestion and interference issues are encountered more often at intersections, mostly due to their relatively increased vehicle density [98]. Moreover, nodes cannot easily communicate with other nodes placed on different road segments due to NLOS conditions. As a consequence, as seen in QTAR, routing algorithm performance can also be improved significantly by considering intersection data in the next-hop decision process [17]. Moreover, RSUs are considered and placed around intersections in urban implementations of VNs, such as [19], [17], [22] and can assist when the 'coverage hole' issue is encountered and provide VNs with the desired connectivity.

Additionally, as the above-surveyed techniques cannot learn and adapt to the highly dynamic nature of VNs, they are are unable to provide efficient and highly reliable communications. Presented as a potential solution in that sense within the literature, Reinforcement Learning (RL) is a type of machine learning that involves training an agent to make decisions based on the feedback it receives from its environment [14], [17], [23], [24], [25]. Therefore, in the context of urban VNs where each node acts as an agent, RL can be used within a routing algorithm to assure multi-hop communications between vehicles and infrastructure placed on the roadside. However, in order to integrate RL as part of the routing algorithm, a set of actions that the agents can take needs to be defined initially, as well as a reward function that reflects the quality of the communications links between the source and destination nodes. For example, in the case of VNs, the actions can vary between selecting a relay node, adjusting the transmission power, or changing the frequency. The reward function can be based on QoS-based factors such as the signal-to-noise ratio (SNR), estimated link lifetime and packet loss rate, or end-to-end delay. Consequently, once the action space and reward function are defined, the RL agent can be trained using techniques such as Q-learning. During the training phase, the agent learns to select actions that maximize the expected reward, based on the current state of the environment (e.g., location of vehicles and relays, channel conditions, etc.). Once the RL agent is trained, the routing algorithm can make decisions dynamically while keeping track of the current network conditions. For example, the quality of the communication link can be periodically evaluated and the decision whether to switch to a different relay node or adjust the transmission power to improve the link quality. Overall, RL can be a powerful tool for designing efficient and adaptive routing algorithms in urban VNs, by allowing each node to learn and adapt to changing network conditions in real-time.

Additionally, Deep Reinforcement Learning (DRL) is a type of RL that uses deep neural networks to represent the policy or value function, instead of the traditional lookup tables used in Q-learning-based RL [165], [166]. Therefore, in the context of VNs, DRL can also be used within a routing algorithm to assure multi-hop communications between vehicles and infrastructure placed on the roadside. The main difference between DRL and Q-learning RL lies in the way they represent the policy or value function. For example, Q-learning uses a lookup table to represent the Q-function, which maps states and actions to their corresponding Q-values. In contrast, DRL uses a deep neural network to represent the policy or value function, which allows it to learn complex, non-linear relationships between states and actions. Thus, DRL does not need to handcraft features or state representations which can potentially lead to better performance than the before mentioned Q-learning alternative, which requires a manually defined state space and action space. However, this thesis does not tackle DRL algorithms, but focuses on the optimisation of routing techniques through Q-learning, leaving room for further developments in that sense.

Thus, many routing protocols based on RL have been proposed in recent years [14], [17], [23], [24], [25]. Considering the before-mentioned approaches to efficient urban VNs rout-ing, QTAR [17] uses different Q-learning techniques for Vehicle-to-Vehicle/Infrastructure (V2V/I) connections and Infrastructure-to-Vehicle/ Infrastructure (I2V/I) connections to learn traffic conditions at each intersection, which leads to better routing performance than traditional routing protocols. Moreover, QTAR relies on an intersection-based geographic routing protocol that leverages fixed RSUs placed at the intersections to assure connectivity and deliver the packets to the destination node. Owing to the learning ability of the algorithm, after a specific time during which the learning is completed, QTAR is shown to perform better than the underlying traditional routing algorithms. Therefore, in this chapter, QTAR is used as a benchmark.

However, considering the large number of nodes in urban VNs, the queuing phenomena can lead to increased processing overhead as multiple attempts to use a node as a next hop are made, and thus, become harmful to the routing approach's efficiency, as discussed in Section 2.5.2. This is even more evident when RSUs are considered within the VNs since they can easily transform into bottlenecks as their queues overflow due to high demand from other nodes and they become unavailable. Against the above discussion, the contributions in Chapter 5 can be highlighted as follows.

Contributions:

As the state-of-the-art approaches to routing in VN still presents the aforementioned challenges, a hybrid routing algorithm is proposed for urban VNs, which relies on the static wired infrastructure to relay packets, while also considering vehicles as next-hop relays whenever the RSUs experience queue overflow and become unavailable for participation in additional communications sessions. In addition, the main novelty points tackled in this chapter are highlighted in Table 5.1, on the following page, for a bet-ter understanding of how routing design was improved. Against this background, this chapter's contributions can be summarized as follows:

- A new infrastructure based traffic aware routing algorithm (I-TAR) is proposed for VNs, where the static infrastructure used for relaying messages through the network is wire-connected. It is shown that a 19% higher APDR can be achieved compared to the considered benchmark, QTAR, while maintaining the same quality-of-service (QoS) requirements.

- The availability of the nodes is modelled, based on their participation within multiple communications paths at the same time in a multi-source, multi-destination scenario for a more realistic network modelling. Then, QTAR as well as the proposed scheme, I-TAR, are shown to provide more than 50% less APDR, when the more-realistic limited-availability (LA) scenario, which considers the availability of nodes based on their queue state, is employed.
- Therefore, hybrid infrastructure based traffic aware routing algorithm (HI-TAR) is proposed, as a new hybrid routing technique that chooses the best V2V/I path to the destination accordingly. As a consequence, HI-TAR is shown to improve the APDR by up to 50% when compared to I-TAR as well as QTAR.
- The performance analysis of the proposed hybrid routing scheme, HI-TAR, is provided and compared with I-TAR and QTAR, while varying the number of participant vehicles as well as the total number of source-destination vehicle (V_s-V_d) pairs. This shows that for the LA scenario, HI-TAR still provides 34.6% better APDR performance than its previous version, I-TAR, and around 40% more than the QTAR. Additionally, the effect of channel fading on APDR is highlighted within the hybrid approach.

This chapter's contributions are highlighted against the state-of-the-art in Table 5.1. In that sense, the rest of this chapter is organized as follows. The considered network model is described in Section 5.1, followed by the description of QTAR, as the chosen benchmark algorithm. Then, in section 5.2, the proposed algorithm, ITAR, is discussed, as well as the approach for modelling the queue state of the nodes and implicitly their availability status and the hybrid routing algorithm, namely HI-TAR. The simulation environment in Section 5.3, which also provides the simulations' results and their discussions. Section 5.4 concludes the chapter.

5.1 Network Model

This chapter's network model is provided in this section. More specifically, an urban infrastructure-aided VN composed of V vehicles and 16 RSUs is modelled where the participants can communicate in a multi-hop fashion through the aid of reinforcement-learning (RL) aided routing techniques and vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) transmission links following the example model given in Figure 4.1. During the deployment stages of the simulation, the vehicles are randomly and uniformly spatially-distributed over the road-network structure, before starting to move from their randomly allocated positions with varying velocities, while the static RSUs are fixed at the intersections as depicted in Figure 5.1. More specifically, vehicles are generated at random starting coordinates and then choose a

Table 5.1: An overview of the main novelty points.

Themes of Contributions	Geographic routing	No global knowledge	Traffic-aware routing	RSU-based routing	Separate wired infrastructure	RL-aided routing	QoS optimization	No dependency on RSUs	Consider QSI effect on node availability
HI-TAR	X	X	X	X	X	X	X	X	X
I-TAR	X	X	X	X	X	X	X		
QTAR [17]	X	X	X	X		X	X		
iCar-II [19]	X		X	X			X	X	
PP-AODV [94]	X		X			X	X	X	
QGRID [24]	X		X			X	X	X	
PFQ-AODV [88]	X		X			X	X	X	
QL-AODV [23]	X		X				X	X	
GyTAR [87]	X		X				X		
A-STAR [18]	X		X				X		

Table 5.2: The list of symbols and notations.

Symbols	Definitions
V	Number of Vehicles $(v \in \{1, \ldots, V\})$
N	Number of Nodes $(i \in \{1, \ldots, N\})$
V_s	Source Vehicle
V_d	Destination Vehicle
N_c	Current node
dist	Distance
c	Speed of Light
Ps	Packet size
Tr	Transmission rate
Cr	Wireless transmission range
K	Optimal normalized distance position with respect to Cr
v_{N_c}	Velocity of node N_c
$_{N_c}$	Velocity angle of node N_c
x_{N_c}, y_{N_c}	Coordinates of node N_c
v_{N_i}	Velocity of node N_i
$_{N_i}$ x_{N_i},	Velocity angle of node N_i
y_{N_i} Q	Coordinates of node N_i
R	Q-value
	Obtained Reward
	Learning Rate
	Discount Factor

target destination position. Then they start to move around the road-network structure towards the designated destination with a random uniformly distributed speeds following the Random Waypoint Mobility Model (RWP) [167]. Note that, once the destination is reached, the vehicle chooses a new destination while this position becomes the new starting point.

Before beginning each routing session, a V_s and a V_d are selected while the rest of the nodes (both vehicles and RSUs) act as relays to assure connectivity across the VN for the V_s - V_d pair. Each node is aware of its own coordinates through the use of a pre-installed Global Positioning System (GPS) [14]. Moreover, considering the regular exchange of basic-safety-messaged (BSMs), all nodes are assumed capable of gathering and storing contextual information about any change in the distance to all other nodes in the network, as well as other mobility data such as velocities and accelerations, which they can then use during the next-hop decision stage of the considered RL-aided routing process.

Additionally, all nodes are assumed to transmit at the same transmit power while considering perfect encoding and decoding. Moreover, it is assumed that there is no interference between communicating nodes in the VN and no retransmission aspects of any nature are considered at the medium access control (MAC) layer. A list of all symbols used is provided in Table 5.2 along with their definitions. The considered road-network structure is discussed next.

5.1.1 Road-Network Model

This chapter evaluates different routing approaches in realistic, large and dense urban VN environments. Therefore, similarly to the road-network structures studied in Chap-ter 4, a Manhattan grid-based road-network structure is considered in this chapter, composed of vertical and horizontal two-lane roads which allows movement in two directions. It is important to specify that each mobility model is specific to its scenario configuration due to their highly dynamic nature [148]. Therefore, with the aim to model more realistic urban scenario, a larger and denser VN is introduced in this chapter. In more details, in this analysis, a fixed 3000m 3000m Manhattan grid structure is considered and modelled as portrayed in Figure 5.5 [145]. Note that traffic lights were shown to alter traffic movement towards more realistic urban patterns and thus, they are placed at each intersection in the road-network structure for a more realistic urban traf-fic. As vehicles move along the road-network structure, they can accelerate or decelerate and have a maximum achievable speed chosen randomly from a distribution within 0 -13.89 m=s, as described in Chapter 3. Also, note that the vehicles can change direction when they reach a junction based on a previously computed/assigned trace during their insertion/rerouting process. Additionally, with the aim of extending network coverage, RSUs are considered at each intersection in the grid. Note that only the vehicles are required to communicate wirelessly. More specifically, the static RSUs are assumed to be connected through wires to the local infrastructure, as shown in Figure 5.1, which it can access at any time.

It is important to specify that each mobility model is specific to its scenario configuration due to their highly dynamic nature [148]. Note that there are several traffic states that need to be excluded. For example events such as traffic jams should be considered separately. In such scenarios, vehicles stop moving and, as a consequence, the wireless links between them may never break. This often leads to infinite route lifetime results which are inconclusive for this analysis. Thus, only two-lane road-network structures were considered in order to allow vehicle overtaking, and thus avoid traffic jams. The routing aspects of this work are described next.

5.1.2 Routing Problem Description

Considering highly dynamic nature of urban VNs, the ability to ’learn’ the environment provided through RL-aided techniques can be highly beneficial to efficient routing design. This allows each node to record and update a classification of the available communi-cations links in Q-tables based on their performance given the chosen VN applications

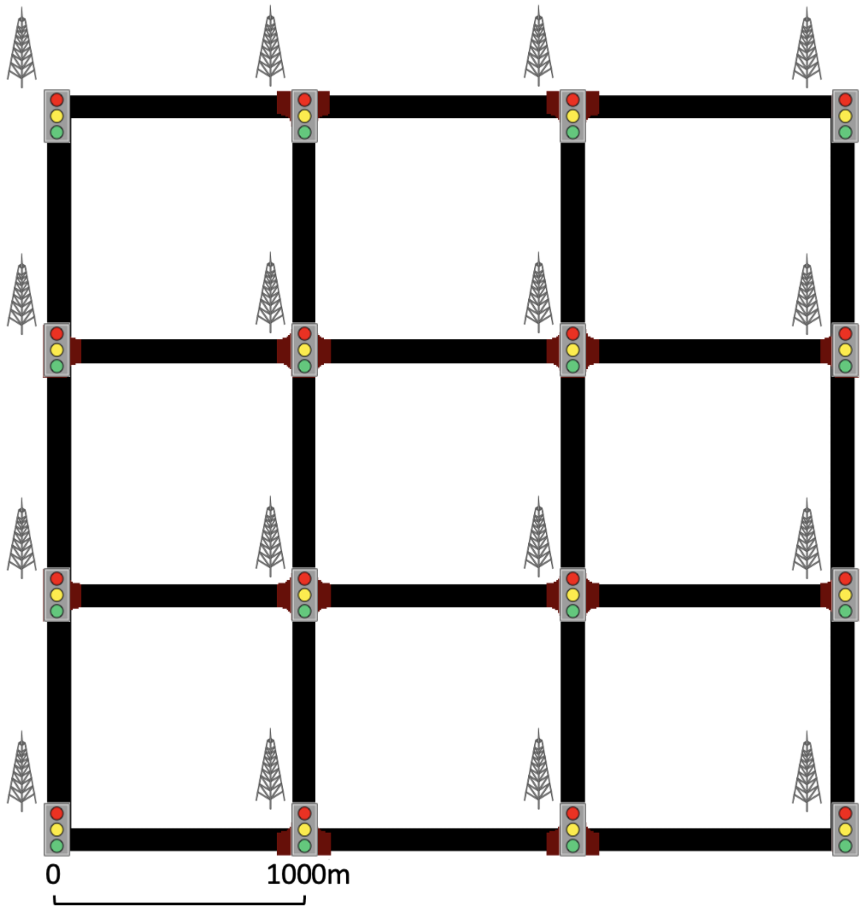


Figure 5.1: One-Square-Junctions (OSJ) 3000×3000 as the considered road-network structure.

QoS requirements. Thus, based on these Q-tables, the next-hop decision process can improve its ability to find optimal source-destination communications paths. In more detail, vehicles record a Q-table for successful communications links with both other vehicles and the RSUs while the RSUs can maintain two Q-tables each, one for links with vehicles (I2V) and one for links with RSUs (I2I), as part of the separte wied infrastructure. Note that the source vehicle (V_s) may have numerous alternative routes for delivering the data and is also capable of directly transmitting to the destination vehicle (V_d), without requiring help from the fixed infrastructure, provided that a successful communications link exists between them.

A successful communications link can be established between a pair of nodes whenever they are within communications range of each other, their queues are not filled and they satisfy the desired VN application QoS requirements. More specifically, when a current node ($N_c \in (1, \ldots, (V + 16))$) transmits packets towards any other node ($n_i \in (1, \ldots, (V + 16)); N_c = N_i$) which is able to successfully receive the signal, a communications link is created between the N_c - N_i pair only if the considered QoS requirements are satisfied. Considering the high QoS requirements of urban VN applications in large and dense realistic scenarios, routing protocols aim to optimize different performance aspects of a communications system. Thus, ensuring that the QoS requirements are met remains the most critical purpose behind the routing algorithm design [112], [168]. The following section describes the considered QoS metrics for the purpose of evaluating the performance of proposed routing approaches in urban VNs.

5.1.2.1 Optimized QoS Performance Metrics

The chosen QoS targeted requirements considered in this chapter's approach to routing design are elaborated in this section, namely end-to-end delay (EED), link quality (LQ) and link expiration time (LET). Note that many other general performance factors, such as the variation of mobility, loop avoidance, node degree, multipath information and others have been considered by the literature [14]. However, by choosing the above-mentioned performance-revealing factors, VN challenges such as the link-stability, the overhead as well as the extension the duration of communications sessions can be solved.

End-to-end delay represents the amount of time it takes for a packet of data to travel from the source device to the destination device over a network [169], [170]. This includes the time it takes for the packet to be transmitted over the network, as well as the time it takes for the packet to be processed at each intermediate network node and the destination device. The end-to-end delay can be affected by various factors, such as the distance between the source and destination, the network congestion, the processing delay at intermediate nodes, and the speed of the devices themselves. It is typically measured in milliseconds or microseconds. In communication networks, minimizing end-to-end delay is important because it can affect the quality of real-time applications, such as voice and video calls, which require low latency to ensure smooth and uninterrupted communication. Thus, by optimizing the EED, a routing protocol aims to achieve successful transmission between the N_s and N_d in the shortest time possible [169]. For example, such techniques are used in both QTAR and PP-AODV. There are various types of delay, namely caused by propagation, queuing and internal processing. Additionally, once a reliable connection (route) is established, multiple nodes will attempt to use it for packet forwarding, leading to the apparition of the queuing phenomena which in turn leads to increased overhead. Therefore, the considered per-link EED metric calculation can be evaluated as follows [169].

$$EED_{N_c;N_i} = \frac{dist_{N_c;N_i}}{c} + \frac{Ps}{Tr} \tag{5.1}$$

where $dist_{N_c;N_i}$ represents the distance between the current vehicle, N_c, and another vehicle node, N_i. c is the speed of electromagnetic radiation propagation in free space, while Ps is the packet size and Tr represents the available transmission rate. Note that the transmission rates for V2V/I links differ from that of I2I links as the RSUs are assumed to be part of the wire-connected infrastructure [171], [148].

Connection reliability refers to the ability of a network connection to consistently transmit data between two devices without interruption or errors [17],[172]. A reliable connection ensures that data is delivered successfully, without any loss or corruption. Connection reliability can be affected by various factors, such as network congestion, signal interference, distance between devices, and hardware or software failures. A reliable connection is essential for many applications, such as real-time communication, online gaming, and financial transactions, where data loss or delay can have significant consequences. Thus, connection reliability is another factor shown to be of great importance when it comes to successfully routing packets throughout the network. Hence, protocols such as QTAR and PFQ-AODV estimate and ensure the reliability of a link between two nodes before considering it for packet forwarding. Unfortunately, in order to verify the reliability of a link, the two nodes defining it are required to exchange an increased num-ber of control packets, which can implicitly lead to additional overhead. Equation (5.2) below describes the calculation of the connection reliability metric [17]:

$$LQ_{N_c;N_i} = 1 - \mathrm{abs}\left(\frac{dist_{N_c;N_i}}{Cr} - K\right); \tag{5.2}$$

where $dist_{N_c;N_i}$ represents the two-dimensional Euclidean distance between the current node, N_c, and any other node in the VN, N_i. Cr represents the wireless transmission range while the parameter K represents the optimal normalized distance position with respect to Cr.

Finally, considering the discussion in Chapter 4 on the route lifetime, the next-hop decision on the most stable link is optimised based on the computation of the link expiration time (LET) of each path. More specifically, each receiving intermediate node can then use the information received from its neighbors as well as its own local mobility information to calculate the LET of each communications link [173]. Note that, in this chapter, the path with the maximum LET is considered to be the most stable. The LET can be calculated as provided below [174].

$$LET_{N_c;N_i} = \begin{cases} \infty; & a = 0 \,\&\, b = 0 \\ \min(\infty; \tau); & a = 0 \mid b = 0 \end{cases}; \tag{5.3}$$

where

$$\begin{aligned} \tau &= \frac{-(ab + cd) + \sqrt{(a^2 + c^2)\,Cr^2 - (ad - bc)^2}}{a^2 + c^2}; \\ a &= v_{N_c} \cos\theta_{N_c} - v_{N_i} \cos\theta_{N_i}; \\ b &= x_{N_c} - x_{N_i}; \\ c &= v_{N_c} \sin\theta_{N_c} - v_{N_i} \sin\theta_{N_i}; \\ d &= y_{N_c} - y_{N_i}; \end{aligned} \tag{5.4}$$

in which v_{N_c} and v_{N_i} represent the velocities of nodes N_c and N_i with the velocity angles of θ_{N_c} and θ_{N_i} and the coordinates x_{N_c}, y_{N_c} and x_{N_i}, y_{N_i}, respectively.

5.1.2.2 Traffic-Aware Routing Based on Reinforcement Learning for Urban VNs

Following the successfully extraction and processing of the contextual information as well as the desired QoS requirements, the Q-learning-based RL-aided routing approach can be employed for an optimisation of the next-hop decision. Considering the discussion provided in Section 2.6, Q-learning is a RL technique that attempts to maximise the current state's reward for interacting with it environment towards the goal state [112], [113], [114], [115], [175]. In the context of urban VNs, each packet sent into the network can be modelled as an agent. More specifically, if the current node (N_c) is considered to be the current state of the agent, then the pool of available states it can interact with takes the form of N_c's neighbors. Hence, the Q-table takes the form of a two-dimensional array, where rows represent states while the columns represent their set of neighbors. More explicitly, after initialising the Q-table to 0, N_c updates it through regular exchange of BSMs with its neighbors [117]. The Q-value evaluation upon receiving an update from N_i can be formulated as follows [118].

$$\underbrace{Q_{N_c,N_i}}_{\substack{\text{New}\\ \text{Q-Value}}} = \underbrace{Q_{N_c,N_i}}_{\substack{\text{Current}\\ \text{Q-Value}}} + \underbrace{\alpha}_{\substack{\text{Learning}\\ \text{rate}}} \Big[\underbrace{R_{N_c,N_i}}_{\text{Reward}} + \underbrace{\gamma}_{\substack{\text{Discount}\\ \text{rate}}} \overbrace{\max Q_{N'_c,N'_i}}^{\substack{\text{Maximum predicted reward, given}\\ \text{new state and all possible actions}}} - Q_{N_c,N_i} \Big], \tag{5.5}$$

where R_{N_c,N_i} is the obtained reward of N_c from the action of packet forwarding to N_i for V2V Q-learning, which can be evaluated as Equation (5.7) below.

$$R_{N_c,N_i} = w_1 \, LQ_{N_c,N_i} + w_2 \, LET_{N_c,N_i} + w_3 \, EDD_{N_c,N_i}, \tag{5.6}$$

where w_1, w_2 and w_3 are weight factors that correspond to the QoS metrics, namely link quality (LQ), link expiration time (LET) and end-to-end delay (EED), respectively, as defined in [17]. Note that $w_1 + w_2 + w_3 = 1$, while w_1, w_2 and w_3 can be adjusted in order to represent different QoS requirements for different use cases. Moreover, α serves as a Q-value update rate while γ is the discount factor.

5.1.2.3 QTAR - a benchmark algorithm

Following the review of the state-of-the-art approaches to VNs cross-layer traffic-aware routing provided in Section 2.5, QTAR proves to be the most promising as it considers a mixture of the proposed solutions with the aim of achieving low-latency, high-quality and long-lasting communications for VNs. In more details, in QTAR [17], an infrastructure-based VN model is proposed, where RSUs are placed at each intersection to assist with assuring the required coverage across the network. Moreover, a RL-aided routing technique in employed, that prioritises the RSUs during the next-hop decision process. If a vehicle V_i generates or receives a packet Pk to send towards the destination, it employs V2V/I Q-learning until Pk can reach V_d. Moreover, RSUs act as static vehicular nodes intelligently placed at each intersection with higher priority during the routing process to guide the resulted route towards the intended destination as illustrated in Figure 5.2. Note that, in QTAR, a route can occasionally consist of vehicles alone if and only if any two vehicular nodes along the resulted route are within range and the use of one or mutiple RSUs is not required. Thus, intersections are dynamically selected using V2I Q-learning while the next-hop vehicle nodes are chosen using V2V Q-learning, as routes can pass through both vehicles and the RSUs.

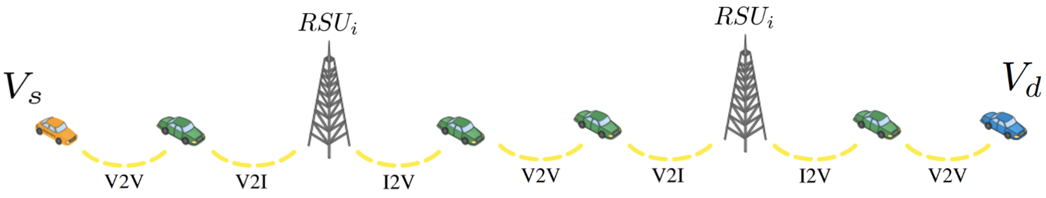


Figure 5.2: An example of V2V/I communications as introduced by QTAR.

Unfortunately, there are several drawbacks to be dealt with in QTAR. Firstly, the hypothesis that prioritising traffic through the RSUs does not always guarantee the optimal routing solution is presented. This happens especially when the packets try to reach an RSU even if a better V2V path is available for use. Secondly, as multiple V_s-V_d pairs intend to communicate simultaneously at each time instant, nodes get involved multiple communications sessions and, as a consequence, they encounter queuing issues which can lead to congestion and make them unavailable for a additional communications sessions and, implicitly, routing attempts [17]. This shows that QTAR did not touch upon the QSI-based availability metric of nodes, when making the next-hop decision which often leads to non-existing routes and implicitly to low PDRs. Therefore, in addition to traffic condition, routing techniques should also consider the availability of both vehicular nodes and the RSUs. Hence, in this work, the traditional state-of-the-art intersection-aware routing approach is contested and a new hybrid routing technique that chooses the best V2V/I route is proposed. Moreover, a separated wired I2I infrastructure is implemented, which can off-load vehicular nodes, while also considering the QSI at each node once it takes part in an active communication link in order to establish their availability for routing sessions. The following section provides descriptions and discussion for the proposed techniques.

5.2 Hybrid Infrastructure-aided Traffic-aware Routing

In this section, the proposed hybrid intersection-aided routing approach is explained . More specifically, the novel functionalities of the proposed network model are explained first, i.e. those of I-TAR. This is followed by the queue state modelling approach and finally, the proposed hybrid routing technique, HI-TAR.

5.2.1 Infrastructure-aided Traffic-aware Routing (I-TAR)

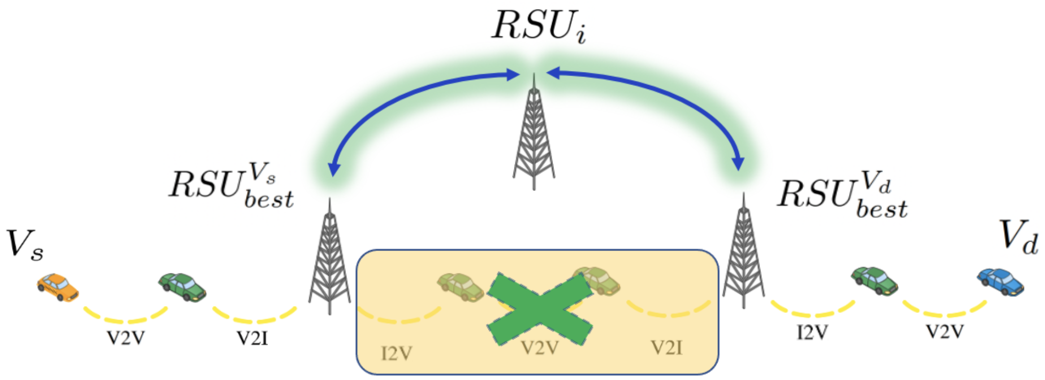


Figure 5.3: An illustration of ITAR generated routes.

There are several studies in the available literature that suggest that RSU-assisted networks can prove superior to traditional V2V-only routing protocols in terms of overall performance [176], [177], [178], [179], [180], [181]. Thus, in the first proposed scheme, namely I-TAR, RSUs are placed in critical positions, namely at each intersection, with the purpose of integrating them into both wireless and wired data transmission, following the state-of-the-art approach. Thus, vehicles that have data to send towards the destination can do so using both V2V wireless links to reach other vehicles or V2I wireless links to connect to the static infrastructure. However, the wired-infrastructure can act as a separate network which can take packets across the VN without using a high number of additional vehicles and thus, avoiding the multitude of drawbacks imposed by their high mobility. Note that, additionally, wired networks can achieve better reliability and transmission speeds over longer distances through I2I wired links when compared to its unstable wireless counterpart [145], [181]. Hence, the RSUs can be always connected as well as aware of all other RSUs in the network, due to periodic signaling exchange using the wired network. Moreover, given the static nature of the RSUs, there is no motivation for using RL-aided techniques for routing the traffic. Hence, a simple GSR-based shortest-path algorithm is employed initially for generating the routes that traverse the wired I2I infrastructure which are then stored in lookup tables (LUTs) at each of the RSUs such that they can be accessed at any time. As a consequence, RSUs are prioritised in the next-hop decision process of the vehicles in order to permit the exploitation the reliable and fast wired connections inside the static infrastructure.

An example of I-TAR generated routes is illustrated in Figure 5.3, which highlights the main improvement it provides against the state-of-the-art. In more details, in I-TAR, if a vehicle V_i has a packet Pk to send towards the destination, it employs V2V/I Q-learning until Pk reaches the optimal RSU of V_i, $RSU_{best}^{V_i}$, or its final destination vehicle, V_d. Each vehicle knows the location and status of every RSU within the road network. Therefore, $RSU_{best}^{V_i}$ denotes the best next-hop available RSU for vehicle V_i based on the employed QoS performance metric. Then, $RSU_{best}^{V_i}$ reroutes Pk through the wired infrastructure until the best RSU for V_d is found, namely $RSU_{best}^{V_d}$ [182]. Once the packet has arrived at $RSU_{best}^{V_d}$, V2V/I Q-learning is employed once again to reach V_d. On the other hand, once the static infrastructure is reached, the data is taken towards V_d over a separate infrastructure-to-infrastructure (I2I) wired channel until $RSU_{best}^{V_d}$ is reached. Finally, $RSU_{best}^{V_d}$ transmits the data to V_d through infrastructure-to-vehicle (I2V) and V2V wireless channels. Hence, drivers can acquire the services they need by accessing the network at any time. In addition, the pseudo-code of the I-TAR forwarding process at each node is given in Algorithm 2 above.

In other words, when a vehicle V_i has data to send, the routing problem can be simplified to the extent of just achieving successful communication with the local wired infrastructure, by reaching their optimal RSU, $RSU_{best}^{V_i}$, rather than doing routing inefficiently among all nodes in the network towards the destination vehicle, V_d.

5.2.2 Modelling Queue State for Multiple V_s-V_d Pairs

In realistic urban VNs scenarios, multiple source nodes may need to communicate with multiple destination nodes simultaneously. As a store-and-forward mechanism is employed, the packets are stored at each node along the route until a successful communication route is provided. This requires an efficient routing protocol that can handle the complexity of routing in such a dynamic and highly congested urban environment. Furthermore, under such scenario considerations, it is possible that multiple nodes may use the same path to communicate with their respective destinations simultaneously which can lead to congestion and reduce the overall network performance.

Algorithm 2 I-TAR Next-Hop Routing Decision.

```
Requirements:
!   $Pk$ : A packet that is transmitting in the network.
!   $V_i$: A vehicle node.
!   $V_d$: The destination vehicle of $Pk$.
!   $V_c$: The current vehicle that is processing $Pk$.
!   $NB_{V_i}$: The set of neighbor nodes of $V_i$:
!   $RSU_i$ : An RSU node.
!   $RSU_c$: The current RSU that is processing $Pk$.
!   $NB_{RSU_i}$: The set of neighbor nodes of $RSU_i$.

Upon $V_i$ having a packet $Pk$ to forward to $V_d$:
!   $V_c$   $V_i$;
!   Select $RSU^{V_s}_{best}$, the best available intermediary destination intersection of $V_c$;

!   Next-hop decision:
if $V_c = V_d$ then
    $Pk$ has reached its destination;
else if $V_d$ 2 $NB_{V_i}$ then
    Send $Pk$ directly to $V_d$;
else if $RSU^{V_s}_{best}$ 2 $NB_{V_i}$ then
    Send $Pk$ directly to $RSU^{V_s}_{best}$;
else
    Forward $Pk$ to $RSU^{V_s}_{best}$ using V2V/I RL-aided routing;
end

Upon $RSU_i$ having a packet $Pk$ to forward to $V_d$:
!   $RSU_c$     $RSU_i$ ;
!   Select $RSU^{V_d}_{best}$, the best available intermediary destination intersection of $V_d$;

!   Next-hop decision:
if $RSU_c = RSU^{V_d}_{best}$ then
    Send $Pk$ to $V_d$ using V2V/I Q-learning routing;
else if $V_d$ 2 $NB_{RSU_i}$ then
    Send $Pk$ directly to $V_d$;
else
    Forward $Pk$ to $RSU^{V_d}_{best}$ using pre-configured $LUT$ using a simple I2I GSR-based
    routing;
end

!   Output: $PATH$
```

In general, there is no fixed limit on the number of communication paths that a node can be part of in urban VNs. More specifically, a node can be part of multiple communication paths as long as it has sufficient communication range to reach all of the other nodes in the paths. However, the number of paths that a node can be part of may be limited by its processing capacity and available resources. For example, when considering a multi-source, multi-destination scenario, the number of communication paths that a node can be part of depends on several factors, including its location, its communication range, the density of other nodes in the network as well the number of packets it can store in its queue [183], [184], [185]. The queue size determines how many packets can be stored at each node before they are transmitted to the next node in a communication path. Consequently, a larger queue size can help to reduce packet loss caused by the congestion phenomena, but it can also increase latency and delay. Note that the queue size at each node in a multi-source, multi-destination communication setup within urban VNs depends on multiple factors, such as the traffic load, the channel capacity and the packet size.

Additionally, when RSUs are also considered, they can be part of an increased number of communication paths simultaneously, serving as communication gateways and relays between vehicles and the Internet or other external networks, especially since they are typically stationary and have a wider communication range than vehicles [176], [177], [178], [179], [180], [181]. Therefore, within the existing literature, RSUs are prioritised within the next-hop decision stage of the routing process and thus, their queue states fill considerably faster than those of other vehicle-nodes. It is important to also note that the number of paths that an RSU can be part of will depend on its placement and density, as well as its processing capacity and available resources.

Thus, the design of an efficient routing protocol and queue management scheme should take into account these factors and be optimized to provide the best possible network performance. In a cross-layer system, the transport layer can provide a solution by sending feedback to the network layer about congestion on the network. For example, the transport layer may detect packet loss or long delays and assume that the network is congested. The transport layer can then send this feedback to the network layer, which can adjust its routing decisions to avoid congested paths. Therefore, one way the network layer can avoid congested paths is by using a routing protocol that takes into account network congestion. More specifically, some routing protocols, such as the GSR-based shortest-path algorithm, can use a metric that takes into account network congestion, among other factors, to determine the best path for a packet.

Therefore, packet queue state information (QSI) at each node is critical for delay-sensitive message dissemination in VNs, especially when multiple sources and destinations attempt to communicate in urban scenarios with complex street conditions and high traffic demand [184],[185]. With that purpose, as part of the transport layer feed-back, a metric consisting of a queue size of two (thus permitting two active connections

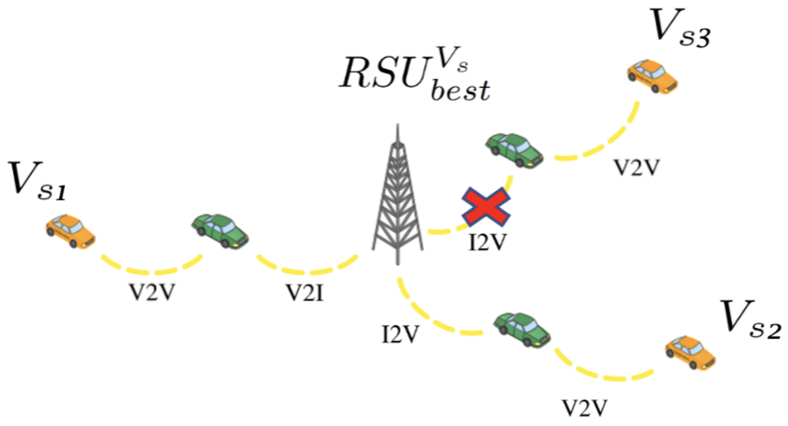


Figure 5.4: An example illustration of the effect of queuing phenomena on the availability of nodes for new generated routes.

at once) is considered within this chapter for simulation purposes. Further developments in this direction could be made by also considering an extended queue size value or even a variable one, depending on the demand at each of the nodes.

In more details, as multiple V_s-V_d pairs attempt to communicate at the same time, the queue overflowing phenomena can be encountered at several nodes along the way, which, implicitly, imposes additional delay on the communications performance or even leads to congested paths. It is important to remember that a connection is considered successful only if the information is not out-dated on arrival at the V_d or otherwise, the packet is dropped. As a consequence, in this chapter, some nodes experience limited-availability (LA) as they take part in more than two active communications links and, consequently, their queues capacities are filled and they are required to prioritise already received packets against new incoming connections. An example scenario is given in Figure 5.4 below, where, considering that $\mathrm{RSU}^{best}_{V_s}$ only allows up to two V2V/I connections at once, only vehicles V_1 and V_2 are able to access the infrastructure resources while V_3 cannot. Moreover, the I-TAR section in Figure 5.5 also describes an LA scenario example, as the pair of red vehicles are already involved in a communication path, and hence they are not available for future routing sessions. Therefore, the wired infrastructure is employed to assure connectivity between V_s and V_d.

Therefore, in this chapter, a new variable is introduced, namely the QSI-based node availability, with the aim of separating LA scenarios from their full-availability (FA) counterparts by modelling the problem induced by the packet queuing phenomena. The availability status of a node is thus defined based on whether its maximum queue capacity was reached or not. More specifically, as nodes take part in several different communication paths at a time, once the queue limit is reached, they become overloaded for the other transmission attempts. Thus, nodes suffering from LA cannot provide successful

Algorithm 3 Node Availability Modelling.

```
! Initialise all nodes as available:
$nodes_{av}$ = ones(1:NumberOfNodes);
! Verify that all nodes in $PATH$ are available:
if sum($nodes_{av}$($PATH$)) < length($PATH$) then
    $PATH$ is unsuccessful ! $P_k$ is dropped;
else
    $PATH$ is successful ! $P_k$ has reached $V_d$;
end
! Update $nodes_{av}$ after each routing attempt:

if $PATH$ is successful then
    $nodes_{av}(PATH) = nodes_{av}(PATH)$ 1
end
```

communications and, as a consequence, considering the queue state at each node proves of critical importance during the next-hop selection process. Algorithm 3 above presents the approach considered in this chapter for keeping track of QSI-based node availability at each time-step as several V_s-V_d pairs attempt to communicate. In more details, ini-tially, all nodes are assumed to be available for incoming communications sessions. Note that at the end of each routing session, each route is validated based on the availability of the nodes within. Then, once routing is performed and that nodes are engaged in a successful route, become unavailable for future routing sessions.

5.2.3 Hybrid Infrastructure-aided Traffic-aware Routing (HI-TAR)

HI-TAR is proposed as an extension of I-TAR which takes into account the availability, i.e. the LA/FA condition, based on the QSI at the nodes as they take part in multiple communications paths, as discussed in Section 5.2.2. To elaborate further, when RSUs are prioritised for packet forwarding, their queues reach maximum capacity and they become unavailable faster than other nodes on average. Eventually, this leads to network congestion, due to the low number of available RSUs still under demand. Therefore, it is vitally important to optimise the decision on whether the data should be relayed to the RSU or not, based on their QSI.

An example urban VNs scenario is illustrated in Figure 5.5, for the One-Square-Junctions (OSJ) 30003000 road-network structure, while also considering the use of RSUs at each intersection to show the evolution from I-TAR to HI-TAR.

First, at the top left section of Figure 5.5, the benefits of I-TAR can be observed where the yellow vehicle is generated as a source node and the blue vehicle as the destination. If full availability of all nodes is assumed, the packets are initially sent to the closest RSU so the yellow vehicle, then taken over the wired infrastructure until the closest RSU to the blue vehicle is reached. Finally, this RSU sends it through to the blue vehicle and

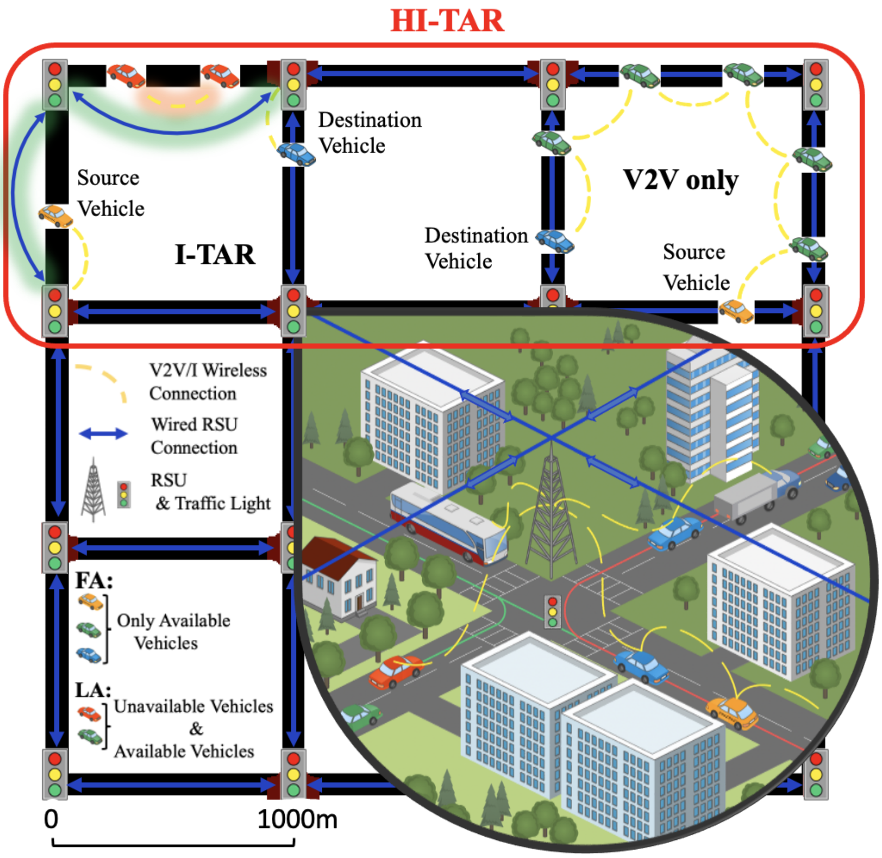


Figure 5.5: An illustration of HI-TAR as a combination of I-TAR and V2V-only communications in One-Square-Junctions (OSJ) 30003000

thus, the destination is reached. Therefore, as discussed in Sec. 5.2.1 this method can provide better overall performance than using V2V links only.

However, as realistic queuing is considered, the chance of congestion is increased in the case of RSUs, especially if such an approach is employed, as discussed in Sec. 5.2.2. In such a scenario, the available V2V links, similar to the one between the red vehicles, can provide an alternative path to the destination node, avoiding the occurrence of the congestion phenomena. Thus, within the top right section of Figure 5.5, the case where all RSUs have exceeded their queues and, consequently, have become unavailable to be used within the next-hop decision process is portrayed, leading to a V2V only path. Hence, HI-TAR is an integration of the two solutions described above, which tries to provide routing alternatives by incorporating both V2V/I and I2I routes, hence, taking advantage of the high number of available vehicles spread across the VN as well as the wired infrastructure.

In the Algorithm 4 provided above, the hybrid technique is introduced, i.e. one that does not always prioritise the RSUs but also considers the best V2V path available as an alternative. As a consequence, it is not necessary to consider queuing at the RSUs alone anymore but at all nodes. Due to the increased number of nodes spread across the network, whenever an RSU is not available for a communication session, the nodes

Algorithm 4 HI-TAR.

```
! Do V2I2V Routing ! $Path_{V2I2V}$;
! Do V2V-only Routing ! $Path_{V2V}$;

if both $Path_{V2I2V}$ & $Path_{V2V}$ do not exist then
    ! $packets_{lost} = packets_{lost} + 1$;
else if $Path_{V2V}$ exists & $Path_{V2I2V}$ does not then
    ! $packets_{received} = packets_{received} + 1$;
    ! $PATH = Path_{V2V}$;
else if $Path_{V2I2V}$ exists & $Path_{V2V}$ does not then
    ! $packets_{received} = packets_{received} + 1$;
    ! $PATH = Path_{V2I2V}$;
else
    ! $packets_{received} = packets_{received} + 1$;
    ! measure whether $Path_{V2I2V}$ or $Path_{V2V}$ are better in terms of performance and
    choose the best one;
    if $Path_{V2I2V} <= Path_{V2V}$ then
        $PATH = Path_{V2I2V}$;
    else
        $PATH = Path_{V2V}$;
        end
    end
    end
end
```

can alternately use V2V links. the employed hybrid approach for HI-TAR is shown in Algorithm 4. More specifically, both V2V-only routing as well as I-TAR routing are employed. Then, based on the QSI at each node, the availability of the nodes is considered and thus, routes generate through the two above-mentioned techniques can be produced and validated. Finally, the optimum route (in terms of satisfying the chosen QoS requirements) is chosen, assuming such a route exists. Note that the scheme can be applied to other routing schemes that are RSU dependant such as QTAR. The following section first describes the simulation environment considered in this chapter and then provides the performance analysis of the aforementioned schemes.

5.3 Simulation results and discussions

In this section, the simulation environment is provided and described in more detail, then the routing performance analysis of I-TAR and HI-TAR are provided against the literature while varying several factors such as the number of vehicles and the number of V_s-V_d active pairs. Furthermore, for both variations, the schemes are compared under a more realistic scenario, namely while modelling and considering LA conditions on node availability.

5.3.1 Simulation environment

For the purpose of realistic evaluation in terms of both communications and mobility, a VN platform is simulated by allowing Simulation of Urban MObility (SUMO) and MATLAB to communicate with each other through Traffic Control Interface for MATLAB (TraCI4Matlab) [160]. SUMO is used to generate movement traces for vehicles and form mobility models which are then used as data for routing performance evaluations in MATLAB. Thus, a 3000m 3000m grid is considered and modelled, which is divided into nine smaller 1000m1000m grids by placing intersections at 1000m from each other as shown in Figure 5.5. Finally, vehicles are randomly and uniformly distributed over the available road-network. Each vehicle can decelerate to 0 m=s and accelerate to 13:89 m=s as defined by the urban speed limit. Note that velocities are normally distributed with a standard deviation of 0.1, as defaulted by SUMO [4]. The simulation also takes into account communications factors and hence, the most relevant fixed parameters considered for the simulation environment are provided in Table 5.3, [17], [14], [161], [162], [163].

Table 5.3: Fixed Simulation Parameters.

Fixed Parameters	Value
Path loss exponent, n_p	3
Noise power, N_0 [W/Hz]	$10\;{}^{15}$
Transmit power, P_t [W]	0.2
Carrier frequency, f_c [Hz]	$5{:}9\;10^{9}$
Bandwidth, B [Hz]	$10\;10^{6}$
Vehicular transmit rate [bps]	$12\;10^{6}\;3$
RSU transmit rate [bps]	$10^{6}\,4096$
Packet size [bits]	0 - 13.89
Urban speed range [m/s]	0.7
K	350
C_r [m]	0.8
	0.9
$! = !_1 = !_2 = !_3$	0.33

The performance of the proposed HI-TAR algorithm is studied in the following section under different simulation parameters such as number of vehicles and number of V_s-V_d pairs against its bench-markers, namely I-TAR and Q-TAR. More specifically, at each time-step, a number of V_s-V_d pairs are selected randomly which then attempt to communicate with each other wirelessly. Generally, the simulation time is 1000 s, the maximum number of V_s-V_d pairs is set to 20 and the maxSpeed is set to 10 m/s. Moreover, the Q-learning parameters and are set to 0.8 and to 0.9, respectively.

5.3.2 APDR and AEED vs. the Number of Vehicles Analysis

Initially, this section provides an evaluation of how the proposed techniques, namely I-TAR and HI-TAR, perform against the literature while varying the number of vehicles in the VN. Then, the hybrid approach (provided in Algorithm 4) is also applied to QTAR, namely as Hybrid QTAR, to reveal how it can improve any RSU dependant routing technique by providing V2V-only alternatives.

The average packet-delivery-ratio (APDR) is a network performance metric that measures the percentage of packets that are successfully delivered to their destination out of all the packets transmitted. More specifically, it is a measure of the reliability of a network in terms of packet delivery by considering by comparing the number of paths found that are satisfy all QoS requirements against the total number of found paths. For example, a high average packet delivery ratio indicates that the network is reliable and efficient in delivering data packets, while a low ratio indicates that there may be issues such as network congestion, signal interference, or hardware or software failures that are causing packet loss. Thus, the APDR is an important performance metric for evaluating the quality and reliability of a network. It is often used in network optimization and troubleshooting to identify areas where packet loss is high and to improve the overall network performance.

On the other hand, the average end-to-end delay (AEED) represents the average time it takes for a packet of data to travel from the source device to the destination device over a network, including the time it takes for the packet to be transmitted and processed at each intermediate node. It is calculated by dividing the total end-to-end delay of all packets transmitted by the number of packets transmitted. In other words, in this chapter, the end-to-end delay of all paths found is averaged to obtain the AEED. This provides an overall measure of the network's performance in terms of delay. The aver-age end-to-end delay is an important metric for evaluating the performance of network protocols and applications. It is often used in network performance analysis and optimization to identify areas where delays are high and to improve the network's overall performance. Thus, reducing the average end-to-end delay can lead to improved network performance, better user experience, and increased efficiency in data transmission.

As a consequence, the APDR and AEED provided by the routing algorithms is analysed for up to 20 V_s-V_d active pairs while increasing the number of vehicles from 50 to 500. Moreover, the idealised case where the routing approach is indifferent to the QSI at each node and thus, the availability of the nodes is not modelled, is considered first. Then, the benefits of the proposed schemes are highlighted in the same scenario-setup considered by QTAR in [17]. The QSI is then studied and node availability is modelled as described in Algorithm 3 and, finally, it is shown how the before mentioned different schemes perform under a more realistic urban VN configuration.

5.3.2.0.1 Full-availability (FA)

With no node availability considerations, it is clear from Figure 5.6 that increasing the number of vehicles participating in the network from 50 to 500 leads to better APDR performance. This can be interpreted by the fact that the probability of network connectivity is directly proportional to the number of vehicles in the network. More specifically, as vehicles populate the network, the 'coverage hole' issue fades as there are more 'next-hop' options to choose from. Furthermore, it can be observed that I-TAR already provides a much better packet delivery performance, achieving up to 18.9% higher APDR than Q-TAR for 500 vehicles. This is mainly because in I-TAR, the routing problem is reduced to just being able to connect the V_s and V_d to any RSU. More specifically, once the packets reach an RSU, the wired infrastructure takes them over directly from the V_s side of the network towards the V_d without the need to route them through all other available vehicles. It is important to note that in this case packets also benefit from a more reliable path as the RSUs are static and thus, the links between them do not break due to mobility.

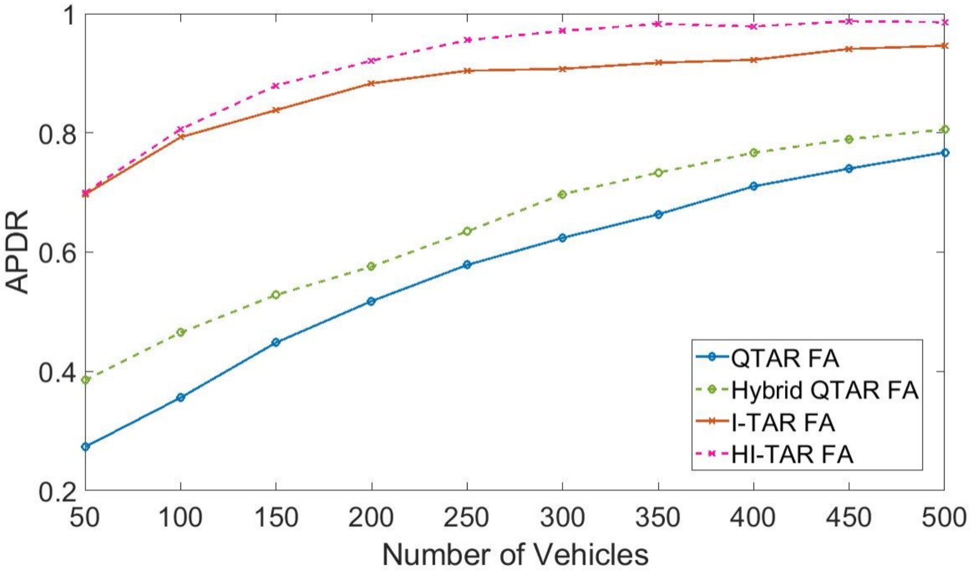


Figure 5.6: APDR vs. number of vehicles for FA scenario.

Then, it is shown that by using the hybrid approach, APDR can be improved further for both I-TAR and QTAR. To elaborate, hybrid QTAR achieved up to 4.7% higher APDR than QTAR while HI-TAR improved I-TAR's APDR performance by 4%. In this case, where the availability of the nodes is not considered, the performance is slightly better simply because nodes are provided with a backup option when the RSUs are unreachable. Figure 5.7 depicts the AEED for the 4 schemes presented above while varying the number of vehicles from 50 to 500 and maintaining the number of V_s-V_d pairs at 20. It can be observed that due to the use of the delay metric considered in the

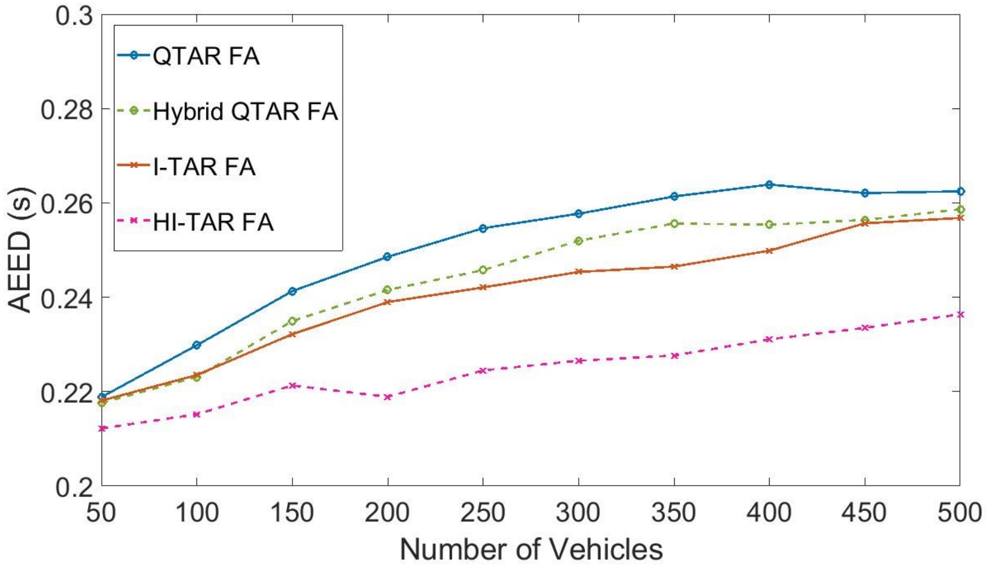


Figure 5.7: AEED vs. number of vehicles for FA scenario.

next-hop decision process, all 4 schemes provide good AEED performance, in the range of 0.21-0.27 s. However, the aim here is to highlight the comparison between QTAR and Hybrid QTAR and then between I-TAR and HI-TAR as the focus is on the effect of the hybrid approach. Thus, as both Hybrid QTAR and I-TAR can be seen as improvements of QTAR, it is expected that they will both outperform the benchmark described in Sec. 5.1.2.3. On average, I-TAR provides 2.4% lower EED than QTAR as less hops are used to reach the destination. Moreover, as all nodes are considered available, the hybrid scheme only provides a shorter path between the V_s and the infrastructure, and between the infrastructure and the V_d. More specifically, HI-TAR improves the AEED performance of I-TAR by 7.6% while applying the hybrid scheme improves the AEED performance of QTAR by 9.9%.

5.3.2.0.2 Limited-availability (LA)

In this study, different communication schemes were evaluated after simulating the availability of nodes based on their queue states, following a certain scenario. The simulations were performed for 20 pairs of source and destination vehicles, with the number of vehicles varying from 50 to 500. The results showed that the performance of the APDR metric significantly decreased, particularly for the I-TAR and QTAR schemes, due to their prioritization of infrastructure in the decision-making process. This caused queues at the RSUs to block other attempts to communicate through the network.

The results also revealed that in the LA scenario, HI-TAR, I-TAR, and QTAR had an APDR that was 18.2%, 50.7%, and 47.8% smaller than their FA counterparts. However, HI-TAR was able to achieve a higher APDR by offering an alternative to non-available infrastructure-based paths. HI-TAR achieved an APDR that was around 42.1% higher than I-TAR and around 49.6% higher than QTAR. Additionally, when availability was modeled, HI-TAR achieved 4.7% more APDR than the no-availability scenario of QTAR.

Following the FA scenario, the before mentioned schemes are evaluated, while modelling the node availability based on each node's queue state. Simulations are performed while varying the number of vehicles from 50 to 500 for 20 V_s-V_d pairs. It can be observed that the APDR performance drops significantly under such conditions especially in the case of I-TAR and QTAR. This is expected mainly because in both of these schemes, the infrastructure is always prioritised in the 'next-hop' decision process and, as a consequence, the queues at the RSUs end up chocking other attempts to communicate through the network. It can be observed from Figure 5.8 that, in LA scenarios, HI-TAR, I-TAR and QTAR provide a 18.2%, 50.7% and 47.8% smaller APDR than their FA counterparts. However, by being given an alternative to non-available infrastructure-based paths, HI-TAR manages to achieve an APDR around 42.1% higher than I-TAR and around 49.6% than QTAR. Moreover, when availability is modelled, HI-TAR achieves 4.7% more APDR than the no availability scenario of QTAR.

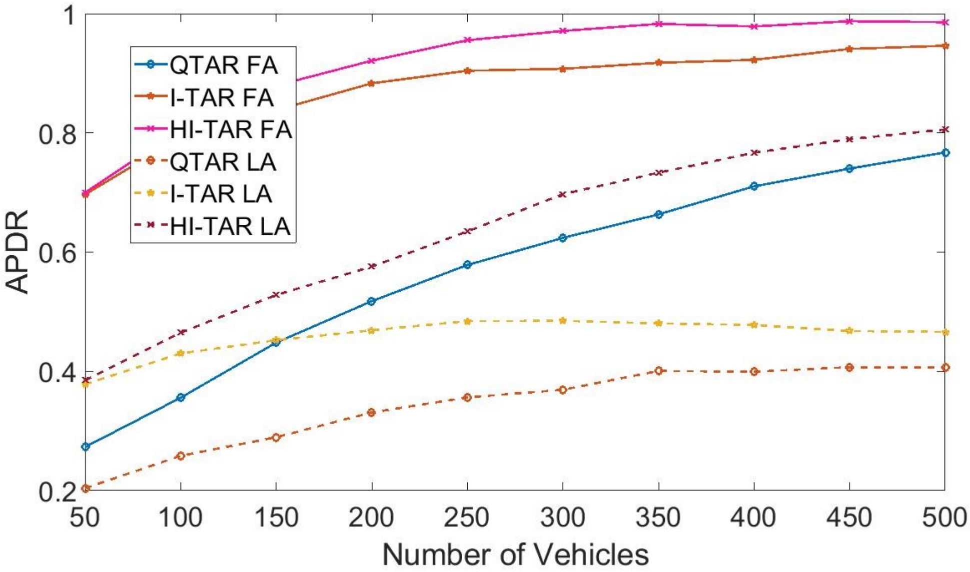


Figure 5.8: APDR vs. number of vehicles for FA scenario.

Furthermore, it can be seen from Figure 5.9 that the delay-focused metric provides a good overall AEED performance. Moreover, a trade-off is revealed, when analysing the LA scenarios. More explicitly, QTAR and I-TAR provide 6% and 11.5% lower delay than their full-availability counterparts. However, under LA conditions, HI-TAR provides 2.9% higher delay than its FA scenario. If the hybrid approach is not used, the packets are simply dropped when encountering an unavailable node while the targeted delay does not change for successful paths. However, the hybrid approach is able to

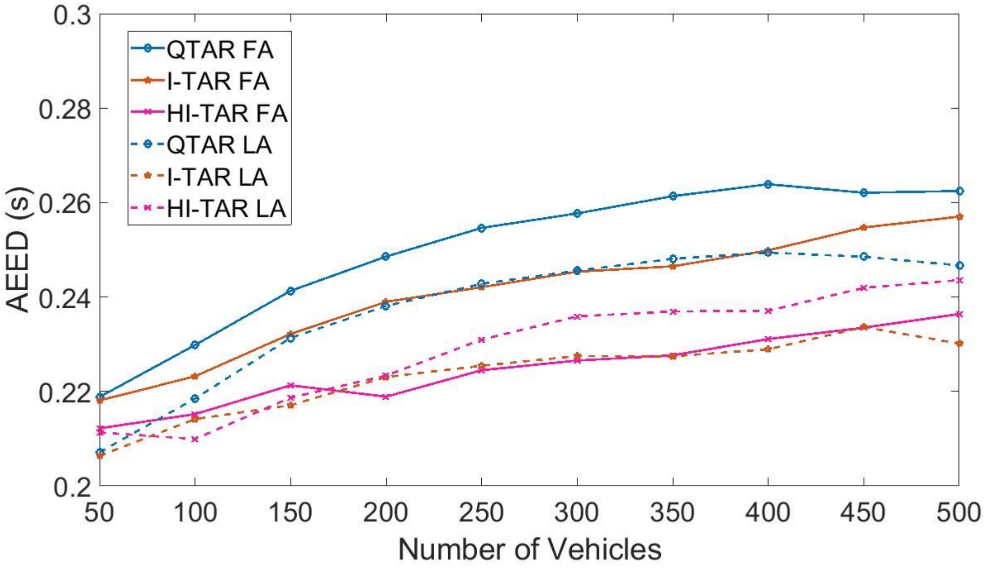


Figure 5.9: AEED vs. number of vehicles for FA and LA scenarios.

achieve a higher APDR at the cost of a small increase in AEED. More specifically, for hybrid scenarios, when a node is not available, the routing algorithm will look to work-around the said node by taking a longer alternative path. Hence, this eventually leads to a successfully transmitted packet but rather over a longer delay-induced path.

5.3.3 APDR and AEED vs the Number of V_s-V_d Pairs Analysis

Finally, the number of vehicles is fixed at 300 and the performance of the proposed schemes is analysed in both FA and LA scenarios while varying the number of V_s-V_d pairs attempting to communicate with each other at each time-step of the simulation. This analysis reveals the effect of multiple V_s-V_d pairs on node availability and implicitly on the routing performance. Initially, the FA scenarios are studied, where no availability is considered. As expected, there is no effect on routing performance as the number of V_s-V_d pairs is increased. Nodes are always available, which means they are always considered in the routing decision process as potential next-hops. However, the APDR of all schemes drops significantly for the limited-availability scenario. More specifically, nodes become involved in several communication sessions, making them unavailable for other communication paths. The more V_s-V_d pairs are considered, the less packets end up at the intended destination. It can be seen in Figure 5.10 that in LA scenarios, HI-TAR, I-TAR and QTAR achieve 72.2%, 82.3% and 81.9% less packets successfully delivered, respectively, when compared to their FA counterparts for 100 active V_s-V_d pairs. However, out of the three mentioned schemes, HI-TAR still provides the best APDR performance. More specifically, HI-TAR achieves 34.6% more packets successfully transmitted than its I-TAR counterpart, and around 39.6% more than QTAR. This proves that the hybrid approach helps when multiple sources attempt to connect to multiple destinations, as it provides alternative paths, in order to assure successful and reliable communications across the network.

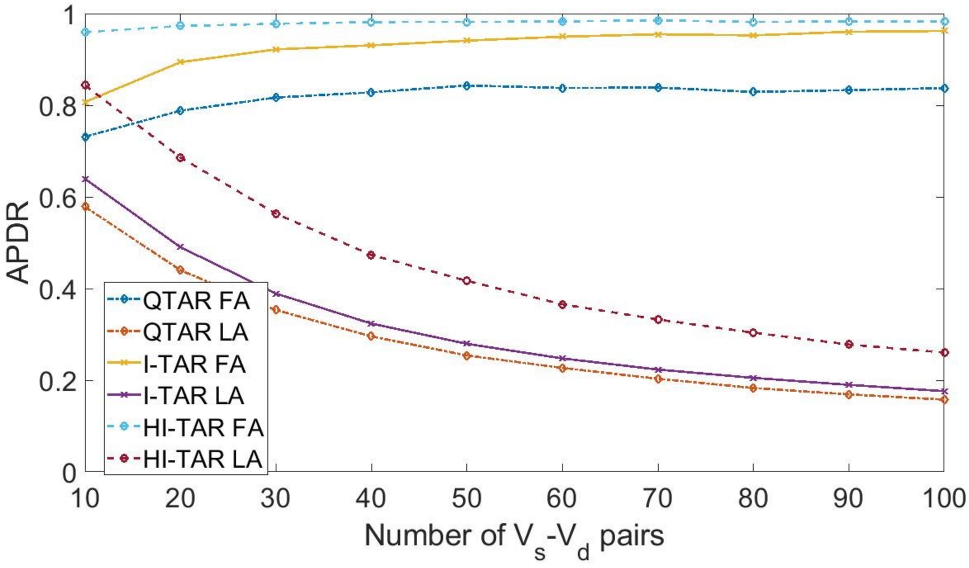


Figure 5.10: APDR vs. number of V_s-V_d pairs for FA and LA scenarios.

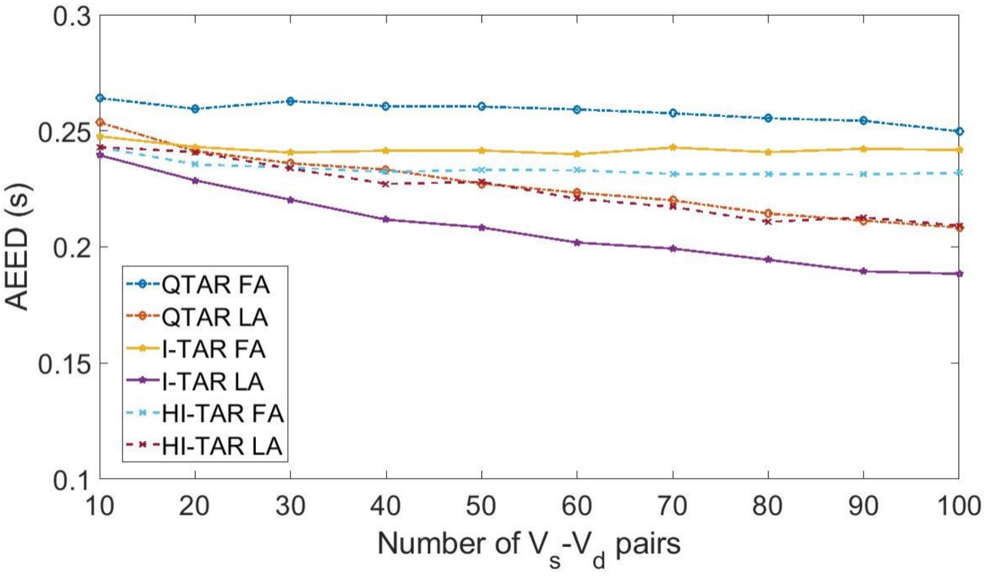


Figure 5.11: AEED vs. number of V_s-V_d pairs for FA and LA scenarios.

Figure 5.11 depicts the AEED for QTAR, I-TAR and HI-TAR for the same setup. Again, it can be observee that the effect of the delay-oriented metric used in the routing process as all three schemes perform well. To elaborate, among the full-availability scenarios, HI-TAR is able to achieve the lowest AEED, precisely 6.8% less than QTAR and 4.1%

less than I-TAR. The reasoning behind this stands again in the fact that the hybrid technique provides the algorithm with the freedom of choosing the best path based on the chosen metric rather than restricting traffic to always pass through the infrastructure. However, when node availability is considered, all three schemes perform better than in the previous scenarios. This is expected as most longer paths are dropped due to the unavailable participant nodes within. Note that the more hops a path has, the higher the chance to encounter an unavailable node is. Hence, longer paths, with higher EED implicitly, are considered unsuccessful which leads to a smaller delay overall at the cost of achieving significantly low PDR. Moreover, the trade-off between APDR and AEED for the hybrid approach is observable once more here. With availability modelled, I-TAR provides 13.4% lower AEED than in QTAR. However, for the same scenario, HI-TAR provides approximately the same AEED performance as QTAR, namely 13.5% higher AEED than I-TAR. More specifically, once the hybrid scheme is introduced, the delay increases slightly while the APDR increases.

5.3.4 APDR vs. Fading Analysis

Finally, the effect of channel fading was studied for a varying vehicle density of 50-500. More specifically, following the approach in Section 4.1.2.1, a Rician fading based channel model with a K-factor of 4 is employed along with a signal-to-noise ratio requirement (SNR_{req}) which is introduced within the RL-aided routing metric reward as follows.

$$R_{N_c;N_i} = w_1 \, LQ_{N_c;N_i} + w_2 \, LET_{N_c;N_i} + w_3 \, EDD_{N_c;N_i} + w_4 \, SNR_{req}{}^{N_c}; \qquad (5.7)$$

where w_1, w_2 and w_3 are weight factors that correspond to the QoS metrics. Considering that $w_1 + w_2 + w_3 + W_4 = 1$, the weights can be adjusted as $w_1 = w_2 = w_3 = w_4$.

It is important to remember that the SNR can reveal the effects of both the continuously changing distances between the nodes as well as the effects of radio-frequency propagation path-loss, which is why it was chosen for this analysis. Considering the above discussion, Figure 5.12 illustrates the effect of considering fading while employing the HI-TAR approach with that aim. It can be observed that, once channel fading is considered within the next-hop decision metric, HI-TAR achieves lower APDR. More specifically, the APDR is drops with 11.4%. Hence, the impact of channel fading on communications performance is highlighted again which motivates the further study of routing design from a propagation perspective.

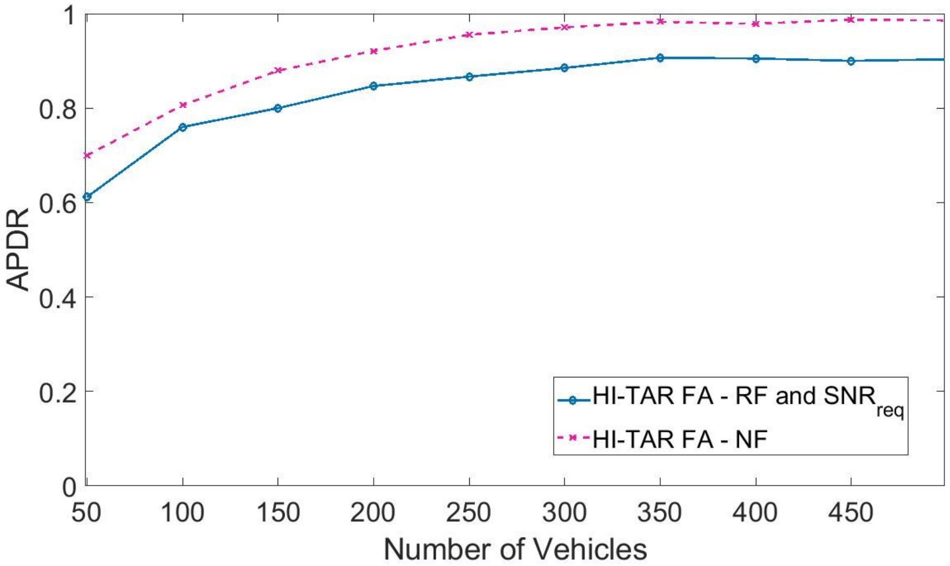


Figure 5.12: APDR vs. number of V_s-V_d pairs for HI-TAR in no-fading and Rician fading scenarios while also considering a SNR_{req} within the routing metric.

5.3.5 Processing Complexity Discussion

This subsection briefly discusses the processing complexity of routing in VNs at both node and network level based on the processing of the routing approach employed. Therefore, since the most processing power is needed during the decision making stage of the transmission process this discussion aims to consider the total number of RL-aided routing processing against the total number of transmission links in a benchmark route. However, as discussed in Section 5.2.1, RL-aided routing is only needed for V2V, V2I and I2V transmissions while wired I2I transmissions become negligible in that sense as the road-side infrastructure is static and each RSU is assumed to already have pre-calculated lookup tables (LUT) which store the ideal I2I routes to all other RSUs in the VN. Thus, as vehicles are reached by packets, they will always perform RL-based routing when attempting to find a next-hop node to transmit them towards. On the other hand, the RSUs only do so when they transmit the packets to other vehicles but not to other RSUs as I2I transmissions are performed by the separate wired I2I infrastructure.

Having that in mind, the following processing complexity comparison between HI-TAR and its predecessors, I-TAR and QTAR, is provided, based on a few route examples as presented in Figure 5.13. In QTAR all nodes perform V2V/I RL-based routing all the time, as there is no separate wired I2I infrastructure to rely on. As a consequence, for a given 5 nodes QTAR route, the first 4 nodes have to process the packets and decide on a next-hop through RL-aided routing, similarly to a V2V-only route. On the contrary, I-TAR takes advantage of the wired I2I infrastructure and thus, the RL-aided routing processing is only required at the vehicles, until the I2I infrastructure is reached, namely

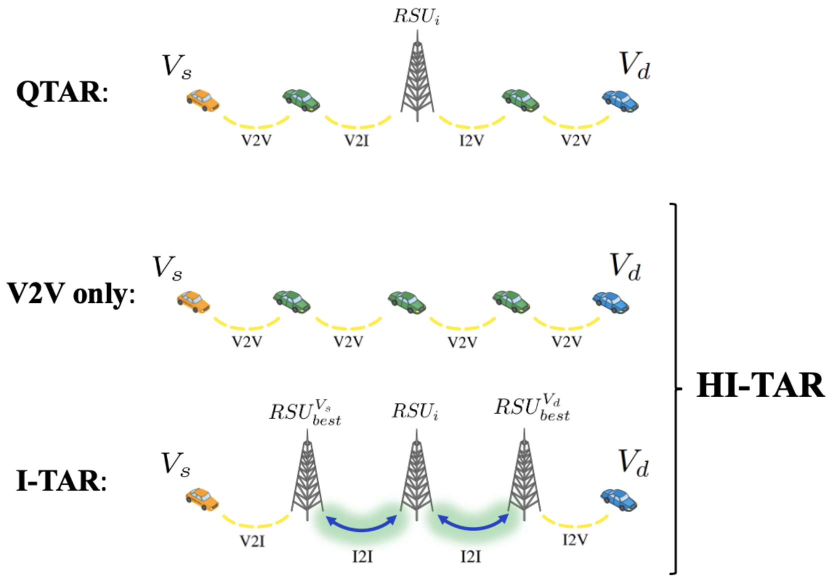


Figure 5.13: Example of 5 node routes generated through HI-TAR, I-TAR, QTAR and pure V2V routing techniques.

RSU$^{best}_{V_s}$, and once again at RSU$^{best}_{V_d}$, where the packets leave the I2I wired infrastructure and are forwarded through vehicle next-hop nodes as they try to reach V_d. Thus, for a given 5 node route, the processing complexity an I-TAR route can be as low as 2, as only two V2V/I links are required while the wired RSU infrastructure can assure network connectivity and is thus employed with that aim. Note that, in I-TAR, occasionally, if V_s is closer to V_d than to RSU^{best}$_{V_s}$the wired I2I infrastructure is not needed, and I-TAR will produce some short-hopped V2V-only paths and thus, similar processing complexity to QTAR or V2V-only routing approaches. However, in most cases, especially as the dimensions and the complexity of the road-network structure are scaled up following realistic urban VN scenarios, the wired I2I infrastructure becomes critical as there is a much higher chance that V_s-V_d will not reach each other without making use of the RSUs. Finally, as depicted in Figure 5.13, in HI-TAR, some of the successful routes are gathered through V2V-only RL-based routing while some are similar to I-TAR, as both options are provided through the hybrid technique. As a consequence, V2V-only routing can be considered the processing complexity lower-bound for HI-TAR while I-TAR provides its upper bound. Therefore, considering a 5 node V2V/I route is required to assure connectivity between V_s and V_d, HI-TAR can achieve a processing complexity up to 4, for 4 V2V/I links, but it can go to as low as 2, for 2 V2V/I links, as provided by I-TAR. Moreover, V2V/I paths are found to be a lot longer than I-TAR generated routes in terms of number of hops as the infrastructure assures coverage across the VN and hence, a multitude of V2V/I links is not needed. For example, let us assume that V_s requires a 100 links V2V/I route to reach V_d across the proposed VN while using QTAR or V2V-only routing. I-TAR, on the other hand, could lower the processing complexity to as little as 2. More specifically, in the idealised scenario presented above, the RL-processing is required for 2 V2V/I links only as V_s is within range of $\text{RSU}^{\text{best}}_{V_s}$ and $\text{RSU}^{\text{best}}_{V_d}$ is within range of V_d. In more details, in such a scenario, the only two RL-based routing processes are performed between V_s and $\text{RSU}^{\text{best}}_{V_s}$ and between $\text{RSU}^{\text{best}}_{V_d}$ and V_d as shown in Figure 5.13 while the processing of the I2I links can be ignored as it relies on pre-configured static routing.

5.4 Discussion

In this chapter, a new vehicular routing algorithm is first proposed, named Infrastructure-aided Traffic Aware Routing (I-TAR) which uses the static wired RSU infrastructure for packet forwarding. A new hybrid approach is also proposed, namely, Hybrid Infrastructure-aided Traffic Aware Routing (HI-TAR), which aims to solve the multi-source, multi-destination problem and the effect this imposes on node availability. Moreover, the hybrid approach is applied to the state-of-the-art algorithms and it is shown how RSU dependent routing algorithms can be improved through its use. Against these adaptations, the effect of varying several critical parameters for the routing performance of VNs is then examined. More specifically, an evaluation of the APDR and AEED performance of the routing algorithms is provided while varying the number of vehicles in the network, as well as the number of active V_s-V_d pairs to better reveal the challenges imposed on node availability. Additionally, the effect of channel fading is highlighted on the APDR of HI-TAR. The effectiveness of the hybrid approach in terms of APDR and AEED performances is approved through extensive simulations. Finally, a discussion regarding processing complexity is provided for both node and network levels.

Chapter 6

Conclusions and Future Work

This chapter presents the conclusions of this thesis and provides the potential future research directions.

6.1 Conclusions

As established in this thesis, in urban VNs, the design of efficient and robust routing algorithms is fundamental to meeting the quality-of-service (QoS) demanded by the wide range of applications proposed for VNs. However, the high mobility of vehicles along the road-network structures as well as their complex environment pose major challenges to the existing routing approaches. Considering this thesis's the review of existing VNs routing approaches, as detailed in Chapter 2, state-of-the-art routing approaches are yet to satisfy VNs applications' QoS requirements and thus, further evaluation of VNs routing is required with the aim of achieving higher performance communications systems. To address such issues, several contributions were made in this thesis and their conclusion is presented as follows.

Considering the dependency between efficient routing design and the extraction of contextual information from the VNs environment, as discussed in Sections 2.3 - 2.5, accurately estimating, modelling and evaluating VNs is critical for efficient routing design in such environments. By exploiting the data such as the nonrandom movement of vehicles and the road-network structure dimensions and their complexity (intersections, buildings, trees, among others), VNs can efficiently construct long-lived, stable routes that provide the QoS required by VNs applications. Thus, in Chapter 3 a realistic representation of the VNs modelling process is provided that permits the accurate extraction and processing of such information. Following a short review of existing VNs simulation platforms, a VNs simulation environment is introduced, namely using a merge of MATLAB and Simulation of Urban Mobility (SUMO) through the TraCI4Matlab package found within SUMO. A characterization of the introduced VNs simulation platform is provided in Section 3.2.2 considering both RF propagation effects as well as mobility characteristics based on several urban VNs configurations.

Furthermore, as the network partition phenomena represents a great challenge for efficient urban VNs routing, further solutions are required as long-lasting routes are desirable in this context considering Section 2.5.1. With that purpose, Chapter 4 provides an evaluation of route lifetime in VNs. More specifically, measurements of route lifetime are provided with the aim of revealing existing trade-offs between road-network structure and routing performance requirements in both fading and no fading. Initially, an upper bound of the route lifetime is set by exhaustively evaluating all available paths in the VN. Then, the shortest-path lifetime is compared with this upper bound where an SNR_{req} focused shortest-path forwarding mechanism based on GSR was chosen as a routing example. It was observed that the SNR_{req} based shortest-path is not optimal which motivates the need for an intelligent vehicle selection algorithm for constituting a route with the goal of an extended and uninterrupted data transmission, which was implemented in Chapter 5 by using the LET metric within the routing decision. The effect of SNR_{req} (representing of VNs applications' QoS requirements), road-network structure and dimensions and channel fading on the route lifetime performance of VNs is provided. Moreover, a trade-off is revealed between the QoS requirements described by the SNR_{req} and the road-network structure dimensions and complexity. Additionally, it is observed that fading significantly influences the route lifetime performance. More specifically, better route lifetime and data transfer performances could be achieved in a LOS scenario compared to its NLOS counterpart. Thus, it is demonstrated that quality of the communications links does not vary linearly with the distance separating the vehicles as they move, but the channel fading has a significant effect on the VNs QoS, and it has to be carefully taken into account when designing the routing algorithm.

Considering several of cross layer traffic-aware routing approaches, as encountered within the recent literature, Chapter 5 considers an infrastructure-aided VN, where RSUs help assuring connectivity across VNs. In addition, the effects of queuing phenomena are introduced in the modelling of VNs. As a consequence, a hybrid routing approach is proposed, that chooses between the optimum V2V or V2V/I communications paths during its routing process. Moreover, as discussed in Section 2.6, by employing a RL aided traffic-aware routing approaches, the required contextual information can be successfully extracted and then monitored from VNs environments and, as a consequence, routing performance can be enhanced further. Against these adaptations, the effect of varying several critical parameters for the routing performance of VNs is then examined. More specifically, an evaluation of the APDR and AEED performance of the routing algorithms is provided while varying the number of vehicles in the network, as well as the number of active V_s-V_d pairs to better reveal the challenges imposed on node availability.

The effectiveness of the hybrid approach in terms of APDR and AEED performances is approved through extensive simulations.

This thesis tackled research questions such as how to properly build, model and evaluate VNs, what factors affect the duration of communications sessions in VNs, as well as whether there is room for improvements related to routing design. Considering the above, further efforts are, therefore, necessary in order to achieve efficient vehicular communications. Firstly, every communications scenario in urban VNs has a specific set of circumstances, has its own advantages and challenge and thus, further efforts are necessary towards the design of more flexible routing approaches. Secondly, as the range of VNs applications increases, so do their QoS requirements, routing design can be improved towards more adaptable approaches that can make informed decisions based on accurately extracted information from the environment.

6.2 Future Work

Following the presented results and literature review on urban VNs routing, several issues remain and have to be dealt with in order to satisfy the QoS requirements of VNs applications as follows. Therefore, further investigations are required towards designing efficient urban VNs routing algorithms that are able to improve stability, throughput and coverage in VNs. A list of directions that researchers should tackle as future work is provided below.

- Considering the huge amounts of data available in the environment, and thus the complexity of urban VNs, the efficient extraction, analysis and modelling of accurate contextual-information remains critical for efficient urban VNs routing design. For example, further subjects of interest for future efforts include consid-ering interference and retransmission techniques. Additionally, due to the size and complexity of urban VNs impress in further complexity analyses are required.
- As efficient VNs routing depends on accurate contextual-information to improve the quality of VNs communications, the next-hop decision stage of the routing process can be further optimized from a metric calculation perspective. In that sense, a classification of the QoS requirements of VNs can be detailed and help consider and prioritise different factors (i.e. available bandwidth, link condition, mobility information, link quality, among others) within the metric calculation. process.
- As RL-routing relies on a feedback mechanism to share the contextual-information throughout the VNs, increased overhead is introduced into the routing performance. For example, solutions such as hybrid routing approaches that include both centralised and decentralized routing routing could limit the overhead to

some extent. Additionally, DRL is a type of RL that uses deep neural networks to represent the policy or value function, instead of the traditional lookup tables used in Q-learning-based RL. Therefore, in the context of VNs, DRL can also be used within a routing algorithm to assure multi-hop communications between vehicles and infrastructure placed on the roadside. DRL uses a deep neural network to represent the policy or value function, which allows it to learn complex, non-linear relationships between states and actions. Thus, in the context of VNs, DRL can be used to learn an end-to-end mapping between the current network state and the optimal relay node or transmission power to use, without the need to hand-craft features or state representations which can potentially lead to better performance than the before mentioned RL alternative, which requires a manually defined state space and action space. Therefore, DRL can be a powerful tool for designing efficient and adaptive routing algorithms in VNs [165], [166], [186]. Additionally, Federated Learning (FL) techniques can prove effective in that context, as it considers a shared machine learning model that protects its individual data-sets as they are trained locally [187], [188], [189].

- As VNs applications require increasing data-rates, existing VNs communications systems, such as DSRC, become limited. Therefore, VNs channel modelling could be extended and adapted to mm-Wave communications. For example, DSRC can only achieve up 27Mb=s compared to up to 10Gb=s as provided by mm-Waves communications [190]. However, even if there is some literature on multi-hop mm-Wave systems, further investigations of the RF propagation conditions through the mm-Wave spectrum are essential for obtaining an accurate network model. Following, several mm-Waves sub-processes are directly affected by the exposure to the movement of vehicles in a VNs environment, namely beam-forming (BF) and beam alignment (BA), and thus, their further study is required within VNs.

- VNs can be integrated with other smart city infrastructure, such as smart traffic lights, smart parking systems, and public transportation systems, to provide a more comprehensive and efficient transportation network. Future work could investigate how VNs can be integrated with other smart city systems to improve overall transportation efficiency and sustainability [191]. Moreover, with the increasing development of autonomous vehicles, there is a need to investigate how VNs can be used to support autonomous driving. Additionally, future work could also explore the potential of VNs to provide real-time information about road conditions, traffic patterns, and other vehicles, which could help autonomous vehicles to navigate more efficiently and safely [186].

- Finally, security remains an issue to be dealt with in VNs. More specifically, the functionality of VNs is vulnerable to potential anomalies caused by malicious attacks due to their unique properties [190]. For example, as the end-to-end connectivity decreases with distance, it is a lot easier for an attacker to partition the network and leave without being traced. Thus, routing design needs to analyze and incorporate security measures such as digital signatures, time-stamping and sequencing [192], [193]. Note that the high mobility present in the VNs environments could help improve channel randomness and hence, a more robust key could be generated.

Bibliography

[1] K. Satyanarayana, M. El-Hajjar, A. A. Mourad, and L. Hanzo, \Deep learning aided fingerprint-based beam alignment for mmwave vehicular communication," IEEE Transactions on Vehicular Technology, vol. 68, no. 11, pp. 10 858{10 871, 2019.

[2] T. K. Bhatia, R. K. Ramachandran, R. Doss, and L. Pan, \A review of simulators used for VANETs: The case-study of vehicular mobility generators," in 2020 7th International Conference on Signal Processing and Integrated Networks (SPIN). IEEE, 2020, pp. 234{239.

[3] J. D. Day and H. Zimmermann, \The osi reference model," Proceedings of the IEEE, vol. 71, no. 12, pp. 1334{1340, 1983.

[4] P. A. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.-P. Flötteröd, R. Hilbrich, L. Lücken, J. Rummel, P. Wagner, and E. Wiener, \Microscopic traffic simulation using SUMO," pp. 2575{2582, 2018.

[5] H. Ortega-Arranz, D. R. Llanos, and A. Gonzalez-Escribano, \The shortest-path problem: Analysis and comparison of methods," Synthesis Lectures on Theoretical Computer Science, vol. 1, no. 1, pp. 1{87, 2014.

[6] A. Awang, K. Husain, N. Kamel, and S. Aïssa, \Routing in vehicular Ad-Hoc networks: A survey on single-and cross-layer design techniques, and perspectives," IEEE Access, vol. 5, pp. 9497{9517, 2017.

[7] I. Filippini, V. Sciancalepore, F. Devoti, and A. Capone, \Fast cell discovery in mm-wave 5g networks with context information," IEEE Trans. on Mobile Computing, vol. 17, no. 7, pp. 1538{1552, 2017.

[8] TS 22.186 Enhancement of 3GPP support for V2X scenarios, 3rd Generation Partnership Project (3GPP), 06 2019, release 16, Stage 1.

[9] M. Fallgren et al., \Fifth-generation technologies for the connected car: Capa-ble systems for vehicle-to-anything communications," IEEE Vehicular Technology Magazine, vol. 13, no. 3, 2018.

[10] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, \Millimeter-wave vehicular communication to support massive automotive sensing," IEEE Comms. Magazine, vol. 54, no. 12, pp. 160{167, 2016.

[11] W. Liang, Z. Li, H. Zhang, S. Wang, and R. Bie, \Vehicular Ad-Hoc networks: architectures, research issues, methodologies, challenges and trends," Int. Journal of Dist. Sensor Networks, vol. 11, no. 8, p. 745303, 2015.

[12] H. Zimmermann, \Osi reference model-the iso model of architecture for open systems interconnection," IEEE Trans. on Comms., vol. 28, no. 4, pp. 425{432, 1980.

[13] F. Li and Y. Wang, \Routing in vehicular ad hoc networks: A survey," IEEE Vehicular technology magazine, vol. 2, no. 2, pp. 12{22, 2007.

[14] R. A. Nazib and S. Moh, \Reinforcement learning-based routing protocols for vehicular ad-hoc networks: A comparative survey," IEEE Access, vol. 9, pp. 27 552{27 587, 2021.

[15] K. G. Lim, M. K. Tan, R. K. Y. Chin, K. B. Yeo, and K. T. K. Teo, \Trac vehicular network modelling for vanet inter-vehicle data scavenging," in 2018 IEEE International Conference on Articial Intelligence in Engineering and Technology (IICAIET). IEEE, 2018, pp. 1{6.

[16] X. Hou, Y. Li, D. Jin, D. O. Wu, and S. Chen, \Modeling the impact of mobility on the connectivity of vehicular networks in large-scale urban environments," IEEE Transactions on Vehicular Technology, vol. 65, no. 4, pp. 2753{2758, 2015.

[17] J. Wu, M. Fang, H. Li, and X. Li, \RSU-assisted trac-aware routing based on reinforcement learning for urban VANETs," IEEE Access, vol. 8, pp. 5733{5748, 2020.

[18] B.-C. Seet, G. Liu, B.-S. Lee, C.-H. Foh, K.-J. Wong, and K.-K. Lee, \A-STAR: A mobile ad-hoc routing strategy for metropolis vehicular communications," in International conference on research in networking. Springer, 2004, pp. 989{999.

[19] N. Alsharif and X. Shen, \iCAR-II: Infrastructure-based connectivity aware routing in vehicular networks," IEEE Transactions on Vehicular Technology, vol. 66, no. 5, pp. 4231{4244, 2016.

[20] W. Xiong and Q.-Q. Li, \Performance evaluation of data disseminations for vehicular ad hoc networks in highway scenarios," The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 37, pp. 1015{1020, 2015.

[21] Z. Cheng and W. B. Heinzelman, \Discovering long lifetime routes in mobile ad hoc networks," Ad Hoc Networks, vol. 6, no. 5, pp. 661{674, 2008.

[22] N. Alsharif and X. S. Shen, \iCAR-II: Intersection-based connectivity aware routing in vehicular networks," in 2014 IEEE International Conference on Communications (ICC). IEEE, 2014, pp. 2731{2735.

[23] C. Wu, K. Kumekawa, and T. Kato, \Distributed reinforcement learning approach for vehicular ad-hoc networks," IEICE transactions on communications, vol. 93, no. 6, pp. 1431{1442, 2010.

[24] R. Li, F. Li, X. Li, and Y. Wang, \QGrid: Q-learning based routing protocol for vehicular ad-hoc networks," in 2014 IEEE 33rd International Performance Computing and Communications Conference (IPCCC). IEEE, 2014, pp. 1{8.

[25] G. Li, L. Boukhatem, and S. Martin, \An intersection-based QoS routing in vehicular ad-hoc networks," Mobile Networks and Applications, vol. 20, no. 2, pp. 268{284, 2015.

[26] L. Azpilicueta, C. Vargas-Rosales, P. Lopez-Iturri, E. Aguirre, and F. Falcone, \Characterisation of radio wave propagation in vehicular environments through deterministic methods," in 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting. IEEE, 2017, pp. 613{614.

[27] M. Mughal and K. Manzoor, \A statistical vehicular traffic model for microwave propagation loss prediction in an urban los environment," in 2016 International Conference on Advances in Electrical, Electronic and Systems Engineering (ICAEES). IEEE, 2016, pp. 601{605.

[28] R. Zhang, F. Schmutz, K. Gerard, A. Pomini, L. Basseto, S. B. Hassen, A. Ishikawa, I. Ozgunes, and O. Tonguz, \Virtual traffic lights: System design and implementation," in 2018 IEEE 88th Vehicular Technology Conference (VTC-fall). IEEE, 2018, pp. 1{5.

[29] N. Taherkhani and S. Pierre, \Prioritizing and scheduling messages for congestion control in vehicular ad hoc networks," Computer Networks, vol. 108, pp. 15{28, 2016.

[30] K. David and A. Flach, \Car-2-x and pedestrian safety," IEEE Vehicular Technology Magazine, vol. 5, no. 1, pp. 70{76, 2010.

[31] W. Viriyasitavat, M. Boban, H.-M. Tsai, and A. Vasilakos, \Vehicular communications: Survey and challenges of channel and propagation models," IEEE Vehicular Technology Magazine, vol. 10, no. 2, pp. 55{66, 2015.

[32] T. Abbas, K. Sjöberg, J. Karedal, and F. Tufvesson, \A measurement based shadow fading model for vehicle-to-vehicle network simulations," International Journal of Antennas and Propagation, vol. 2015, 2015.

[33] P. Paschalidis, K. Mahler, A. Kortke, M. Peter, and W. Keusgen, \Pathloss and multipath power decay of the wideband car-to-car channel at 5.7 ghz," in 2011 IEEE 73rd Vehicular Technology Conference (VTC Spring). IEEE, 2011, pp. 1{5.

[34] O. Renaudin, V.-M. Kolmonen, P. Vainikainen, and C. Oestges, \Wideband mimo car-to-car radio channel measurements at 5.3 ghz," in 2008 IEEE 68th Vehicular Technology Conference. IEEE, 2008, pp. 1{5.

[35] I. Tan, W. Tang, K. Laberteaux, and A. Bahai, \Measurement and analysis of wireless channel impairments in dsrc vehicular communications," in 2008 IEEE International Conference on Comms. IEEE, 2008, pp. 4882{4888.

[36] V. Va, T. Shimizu, G. Bansal, and R. W. Heath, \Position-aided millimeter wave v2i beam alignment: A learning-to-rank approach," in 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Comms. (PIMRC). IEEE, 2017, pp. 1{5.

[37] N. Maslekar, M. Boussedjra, J. Mouzna, and L. Houda, \Direction based clustering algorithm for data dissemination in vehicular networks," in 2009 IEEE Vehicular Networking Conference (VNC). IEEE, 2009, pp. 1{6.

[38] D. Jiang and L. Delgrossi, \Ieee 802.11 p: Towards an international standard for wireless access in vehicular environments," in VTC Spring 2008-IEEE vehicular technology conference. IEEE, 2008, pp. 2036{2040.

[39] B. Coll-Perales, M. Gruteser, and J. Gozalvez, \Evaluation of IEEE 802.11ad for mmWave V2V Communications," in 2018 IEEE Wireless Comms. and Networking Conference Workshops (WCNCW). IEEE, 2018, pp. 290{295.

[40] F. D. Da Cunha, A. Boukerche, L. Villas, A. C. Viana, and A. A. Loureiro, \Data communication in VANETs: a survey, challenges and applications," Ph.D. dissertation, INRIA Saclay; INRIA, 2014.

[41] S. Chen, J. Hu, Y. Shi, and L. Zhao, \Lte-v: A td-lte-based v2x solution for future vehicular network," IEEE Internet of Things journal, vol. 3, no. 6, pp. 997{1005, 2016.

[42] I. A. Hemadeh, K. Satyanarayana, M. El-Hajjar, and L. Hanzo, \Millimeter-wave communications: physical channel models, design considerations, antenna constructions, and link-budget," IEEE Comms. Surveys & Tutorials, vol. 20, no. 2, pp. 870{913, 2017.

[43] S.-H. Yu, O. Shih, H.-M. Tsai, N. Wisitpongphan, and R. D. Roberts, \Smart automotive lighting for vehicle safety," IEEE Comms. Magazine, vol. 51, no. 12, pp. 50{59, 2013.

[44] K. Shafiee and V. C. Leung, \A reliable robust fully ad hoc data dissemination mechanism for vehicular networks," International Journal of Advanced Science and Technology, vol. 2, pp. 53{62, 2009.

[45] F. Lyu, N. Cheng, H. Zhu, H. Zhou, W. Xu, M. Li, and X. S. Shen, \Intelligent context-aware communication paradigm design for iovs based on data analytics," IEEE Network, vol. 32, no. 6, pp. 74{82, 2018.

[46] M. Boban, X. Gong, and W. Xu, \Modeling the evolution of line-of-sight blockage for v2v channels," in 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall). IEEE, 2016, pp. 1{7.

[47] Y. Yao, H. Tian, G. Nie, H. Wu, and J. Jin, \Multi-path routing based qos-aware fairness backhaul-access scheduling in mmwave udn," in 2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Comms. (PIMRC). IEEE, 2018, pp. 1{7.

[48] H. Xin, \Introduction of centralized and distributed routing protocols," in 2011 International Conference on Electronics, Comms. and Control (ICECC). IEEE, 2011, pp. 2698{2701.

[49] S. Chen and N. Yang, \Congestion avoidance based on lightweight buffer management in sensor networks," IEEE Trans. on Parallel and Distributed systems, vol. 17, no. 9, pp. 934{946, 2006.

[50] J. Lu and X. Wang, \Interference-aware probabilistic routing for wireless sensor networks," Tsinghua Science and Technology, vol. 17, no. 5, pp. 575{585, 2012.

[51] D. Jiang and L. Delgrossi, \Ieee 802.11 p: Towards an international standard for wireless access in vehicular environments," in VTC Spring 2008-IEEE vehicular technology conference. IEEE, 2008, pp. 2036{2040.

[52] J. Joo, H. C. Lee, and D. S. Han, \Approach for phy/mac cross-layer design in vehicular ad-hoc networks," in 2013 Fifth International Conference on Ubiquitous and Future Networks (ICUFN). IEEE, 2013, pp. 58{59.

[53] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, \Millimeter-wave vehicular communication to support massive automotive sensing," IEEE Comms. Magazine, vol. 54, no. 12, pp. 160{167, 2016.

[54] I. Mavromatis, A. Tassi, R. J. Piechocki, and A. Nix, \Efficient v2v communica-tion scheme for 5g mmwave hyper-connected cavs," in 2018 IEEE International Conference on Comms. Workshops (ICC Workshops). IEEE, 2018, pp. 1{6.

[55] C. Perfecto, J. Del Ser, and M. Bennis, \Millimeter-wave v2v communications: Distributed association and beam alignment," IEEE Journal on Selected Areas in Comms., vol. 35, no. 9, pp. 2148{2162, 2017.

[56] V. Srivastava and M. Motani, \Cross-layer design: a survey and the road ahead," IEEE Comms. Magazine, vol. 43, no. 12, pp. 112{119, 2005.

[57] M. H. Eiza, T. Owens, Q. Ni, and Q. Shi, \Situation-aware qos routing algorithm for vehicular ad hoc networks," IEEE Trans. on Vehicular Technology, vol. 64, no. 12, pp. 5520{5535, 2015.

[58] B. T. Sharef, R. A. Alsaqour, and M. Ismail, \Vehicular communication ad hoc routing protocols: A survey," Journal of network and computer applications, vol. 40, pp. 363{396, 2014.

[59] S. Singh and S. Agrawal, \VANET routing protocols: Issues and challenges," in 2014 Recent Advances in Engineering and Computational Sciences (RAECS). IEEE, 2014, pp. 1{5.

[60] J. J. Blum, A. Eskandarian, and L. J. Homan, \Challenges of intervehicle ad hoc networks," IEEE Trans. on intelligent transportation systems, vol. 5, no. 4, pp. 347{351, 2004.

[61] K.-W. Chin, J. Judge, A. Williams, and R. Kermode, \Implementation experience with manet routing protocols," ACM SIGCOMM Computer Communication Review, vol. 32, no. 5, pp. 49{59, 2002.

[62] S. Kumar, A. Arora, and T.-H. Lai, \On the lifetime analysis of always-on wireless sensor network applications," in IEEE International Conference on Mobile Adhoc and Sensor Systems Conference, 2005. IEEE, 2005, pp. 3{pp.

[63] I. Dietrich and F. Dressler, \On the lifetime of wireless sensor networks," ACM Trans. on Sensor Networks (TOSN), vol. 5, no. 1, pp. 1{39, 2009.

[64] K. Paul, S. Bandyopadhyay, A. Mukherjee, and D. Saha, \Communication-aware mobile hosts in Ad-Hoc wireless network," in 1999, IEEE International Conference on Personal Wireless Comms. IEEE, 1999, pp. 83{87.

[65] S. Agarwal, A. Ahuja, J. P. Singh, and R. Shorey, \Route-lifetime assessment based routing (rabr) protocol for mobile Ad-Hoc networks," in 2000 IEEE International Conference on Comms.. ICC 2000. Global Convergence Through Comms.. Conference Record, vol. 3. IEEE, 2000, pp. 1697{1701.

[66] M. Gerla, K. Tang, and R. Bagrodia, \TCP performance in wireless multi-hop networks," in Proceedings WMCSA'99. Second IEEE Workshop on Mobile Computing Systems and Applications. IEEE, 1999, pp. 41{50.

[67] J. P. Singh, N. Bambos, B. Srinivasan, D. Clawin, and Y. Yan, \Proposal and demonstration of link connectivity assessment based enhancements to routing in mobile Ad-Hoc networks," in 2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No. 03CH37484), vol. 5. IEEE, 2003, pp. 2834{2838.

[68] S. Agarwal, A. Ahuja, J. P. Singh, and R. Shorey, \Route-lifetime assessment based routing (rabr) protocol for mobile Ad-Hoc networks," in 2000 IEEE International Conference on Comms.. ICC 2000. Global Convergence Through Comms.. Conference Record, vol. 3. IEEE, 2000, pp. 1697{1701.

[69] N. Sofra, A. Gkelias, and K. K. Leung, \Route construction for long lifetime in VANETs," IEEE Trans. on Vehicular Technology, vol. 60, no. 7, pp. 3450{3461, 2011.

[70] W. Su, S.-J. Lee, and M. Gerla, \Mobility prediction and routing in ad hoc wireless networks," International journal of network management, vol. 11, no. 1, pp. 3{30, 2001.

[71] K. Romer and F. Mattern, \The design space of wireless sensor networks," IEEE wireless Comms., vol. 11, no. 6, pp. 54{61, 2004.

[72] A. Abd Aziz, Y. A. Sekercioglu, P. Fitzpatrick, and M. Ivanovich, \A survey on distributed topology control techniques for extending the lifetime of battery powered wireless sensor networks," IEEE Comms. surveys & tutorials, vol. 15, no. 1, pp. 121{144, 2012.

[73] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. Hanzo, \Cross-layer network lifetime optimisation considering transmit and signal processing power in wireless sensor networks," IET Wireless Sensor Systems, vol. 4, no. 4, pp. 176{182, 2014.

[74] I. Dietrich and F. Dressler, \On the lifetime of wireless sensor networks," ACM Trans. on Sensor Networks (TOSN), vol. 5, no. 1, pp. 1{39, 2009.

[75] J. Li and G. AlRegib, \Function-based network lifetime for estimation in wireless sensor networks," IEEE Signal Processing Letters, vol. 15, pp. 533{536, 2008.

[76] J. W. Jung and M. A. Weitnauer, \On using cooperative routing for lifetime optimization of multi-hop wireless sensor networks: Analysis and guidelines," IEEE Trans. on Comms., vol. 61, no. 8, pp. 3413{3423, 2013.

[77] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. H. Hanzo, \A survey of network lifetime maximization techniques in wireless sensor networks," IEEE Comms. Surveys & Tutorials, vol. 19, no. 2, pp. 828{854, 2017.

[78] F. Arena, G. Pau, and A. Severino, \A review on ieee 802.11 p for intelligent transportation systems," Journal of Sensor and Actuator Networks, vol. 9, no. 2, p. 22, 2020.

[79] Y. Xia, X. Qin, B. Liu, and P. Zhang, \A greedy trac light and queue aware routing protocol for urban vanets," China Communications, vol. 15, no. 7, pp. 77{87, 2018.

[80] S. Ur Rehman, M. A. Khan, and T. A. Zia, \A multi-hop cross layer decision based routing for VANETs," Wireless Networks, vol. 21, no. 5, pp. 1647{1660, 2015.

[81] S. ur Rehman, M. A. Khan, T. A. Zia, and M. Jafer, \Quality of service based cross layer routing protocol for VANETs," in 2015 IEEE/ACIS 16th International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing (SNPD). IEEE, 2015, pp. 1{6.

[82] B. Karp and H.-T. Kung, \GPSR: Greedy perimeter stateless routing for wireless networks," in Proceedings of the 6th annual international conference on Mobile computing and networking, 2000, pp. 243{254.

[83] C. Lochert, M. Mauve, H. Fuler, and H. Hartenstein, \Geographic routing in city scenarios," ACM SIGMOBILE mobile computing and communications review, vol. 9, no. 1, pp. 69{72, 2005.

[84] C. Lochert, H. Hartenstein, J. Tian, H. Fussler, D. Hermann, and M. Mauve, \A routing strategy for vehicular ad-hoc networks in city environments," in IEEE IV2003 Intelligent Vehicles Symposium. Proceedings (Cat. No. 03TH8683). IEEE, 2003, pp. 156{161.

[85] B. Karp and H.-T. Kung, \Gpsr: Greedy perimeter stateless routing for wireless networks," in Proceedings of the 6th annual international conference on Mobile computing and networking, 2000, pp. 243{254.

[86] L. N. Balico, A. A. Loureiro, E. F. Nakamura, R. S. Barreto, R. W. Pazzi, and H. A. Oliveira, \Localization prediction in vehicular ad-hoc networks," IEEE Communications Surveys & Tutorials, vol. 20, no. 4, pp. 2784{2803, 2018.

[87] M. Jerbi, S.-M. Senouci, T. Rasheed, and Y. Ghamri-Doudane, \Towards efficient geographic routing in urban vehicular networks," IEEE transactions on vehicular technology, vol. 58, no. 9, pp. 5048{5059, 2009.

[88] C. Wu, S. Ohzahata, and T. Kato, \Flexible, portable, and practicable solution for routing in VANETs: A fuzzy constraint Q-learning approach," IEEE Transactions on Vehicular Technology, vol. 62, no. 9, pp. 4251{4263, 2013.

[89] K. Katsaros, M. Dianati, R. Tafazolli, and R. Kernchen, \Clwpr|a novel cross-layer optimized position based routing protocol for VANETs," in 2011 IEEE vehicular networking conference (VNC). IEEE, 2011, pp. 139{146.

[90] K. Husain, A. Awang, and N. Kamel, \Performance evaluation of a receiver-based routing protocol in vehicular Ad-Hoc networks," in 2018 International Conference on Intelligent and Advanced System (ICIAS). IEEE, 2018, pp. 1{5.

[91] C. Chen, Z. Wang, L. Liu, J. Lv et al., \An adaptive geographic routing protocol based on quality of transmission in urban VANETs," in 2018 IEEE International Conference on Smart Internet of Things (SmartIoT). IEEE, 2018, pp. 52{57.

[92] M. Y. Arafat, S. Poudel, and S. Moh, \Medium access control protocols for flying ad hoc networks: A review," IEEE Sensors Journal, vol. 21, no. 4, pp. 4097{4121, 2020.

[93] C. Pu, \Jamming-resilient multipath routing protocol for flying ad hoc networks," IEEE Access, vol. 6, pp. 68 472{68 486, 2018.

[94] G. M. Valantina and S. Jayashri, \Q-learning based point to point data transfer in VANETs," Procedia Computer Science, vol. 57, pp. 1394{1400, 2015.

[95] R. Han, Q. Guan, F. R. Yu, J. Shi, and F. Ji, \Congestion and position aware dynamic routing for the internet of vehicles," IEEE Transactions on Vehicular Technology, vol. 69, no. 12, pp. 16 082{16 094, 2020.

[96] B.-S. Roh, M.-H. Han, J.-H. Ham, and K.-I. Kim, \Q-lbr: Q-learning based load balancing routing for uav-assisted vanet," Sensors, vol. 20, no. 19, p. 5685, 2020.

[97] A. Hawbani, X. Wang, A. Al-Dubai, L. Zhao, O. Busaileh, P. Liu, and M. A. A. Al-Qaness, \A novel heuristic data routing for urban vehicular ad hoc networks," IEEE Internet of Things Journal, vol. 8, no. 11, pp. 8976{8989, 2021.

[98] H. Saleet, R. Langar, K. Naik, R. Boutaba, A. Nayak, and N. Goel, \Intersection-based geographical routing protocol for VANETs: A proposal and analysis," Ieee transactions on vehicular technology, vol. 60, no. 9, pp. 4560{4574, 2011.

[99] M. Hu, Z. Zhong, R. Chen, M. Ni, H. Wu, and C.-Y. Chang, \Link duration for infrastructure aided hybrid vehicular ad hoc networks in highway scenarios," in 2014 IEEE Military Communications Conference, 2014, pp. 929{934.

[100] Y.-Y. Lin and I. Rubin, \Infrastructure aided networking and traffic management for autonomous transportation," in 2017 Information Theory and Applications Workshop (ITA), 2017, pp. 1{7.

[101] A. Ali, N. Gonzalez-Prelcic, R. W. Heath, and A. Ghosh, \Leveraging sensing at the infrastructure for mmwave communication," IEEE Communications Magazine, vol. 58, no. 7, pp. 84{89, 2020.

[102] H. A. Omar, W. Zhuang, and L. Li, \Gateway placement and packet routing for multihop in-vehicle internet access," IEEE Transactions on Emerging Topics in Computing, vol. 3, no. 3, pp. 335{351, 2015.

[103] D. Borsetti and J. Gozálvez, \Infrastructure-assisted geo-routing for cooperative vehicular networks," in 2010 IEEE vehicular networking conference. IEEE, 2010, pp. 255{262.

[104] C. Lochert, B. Scheuermann, C. Wewetzer, A. Luebke, and M. Mauve, \Data aggregation and roadside unit placement for a vanet traffic information system," in Proceedings of the fifth ACM international workshop on VehiculAr Inter-NETworking, 2008, pp. 58{65.

[105] O. Trullols, M. Fiore, C. Casetti, C.-F. Chiasserini, and J. B. Ordinas, \Planning roadside infrastructure for information dissemination in intelligent transportation systems," Computer Communications, vol. 33, no. 4, pp. 432{442, 2010.

[106] J. Zhao, Y. Zhang, and G. Cao, \Data pouring and buffering on the road: A new data dissemination paradigm for vehicular ad hoc networks," IEEE transactions on vehicular technology, vol. 56, no. 6, pp. 3266{3277, 2007.

[107] B. Aslam, P. Wang, and C. Zou, \An economical, deployable and secure vehicular ad hoc network," in MILCOM 2008-2008 IEEE Military Communications Conference. IEEE, 2008, pp. 1{7.

[108] M. Bechler and L. Wolf, \Mobility management for vehicular ad hoc networks," in 2005 IEEE 61st Vehicular Technology Conference, vol. 4. IEEE, 2005, pp. 2294{2298.

[109] S. Barghi, A. Benslimane, and C. Assi, \A lifetime-based routing protocol for connecting vanets to the internet," in 2009 IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks & Workshops. IEEE, 2009, pp. 1{9.

[110] R. K. Shrestha, S. Moh, I. Chung, and D. Choi, \Vertex-based multihop vehicle-to-infrastructure routing for vehicular ad hoc networks," in 2010 43rd Hawaii International Conference on System Sciences. IEEE, 2010, pp. 1{7.

[111] A. O'Driscoll and D. Pesch, \An infrastructure enhanced geographic routing protocol for urban vehicular environments," in 2013 IEEE 5th international symposium on wireless vehicular communications (WiVeC). IEEE, 2013, pp. 1{5.

[112] R. A. Nazib and S. Moh, \Reinforcement learning-based routing protocols for vehicular ad-hoc networks: A comparative survey," IEEE Access, vol. 9.

[113] C. Gaskett, D. Wettergreen, and A. Zelinsky, \Q-learning in continuous state and action spaces," in Australasian Joint Conference on Artificial Intelligence. Springer, 1999, pp. 417{428.

[114] R. S. Sutton and A. G. Barto, Reinforcement learning: An introduction. MIT press, 2018.

[115] C. Wu, S. Ohzahata, and T. Kato, \Flexible, portable, and practicable solution for routing in vanets: A fuzzy constraint q-learning approach," IEEE Transactions on Vehicular Technology, vol. 62, no. 9, pp. 4251{4263, 2013.

[116] A. Kumar, P. Dixit, and S. Tyagi, \An improvised location aided routing protocol for vehicular ad-hoc network using reinforced learning," in 2022 International Conference on Machine Learning, Big Data, Cloud and Parallel Computing (COM-IT-CON), vol. 1, 2022, pp. 57{60.

[117] P. Dayan and C. Watkins, \Q-learning," Machine learning, vol. 8, no. 3, pp. 279{292, 1992.

[118] C. J. Watkins and P. Dayan, \Q-learning," Machine learning, vol. 8, no. 3, pp. 279{292, 1992.

[119] C. Wu, Y. Ji, F. Liu, S. Ohzahata, and T. Kato, \Toward practical and intelligent routing in vehicular ad hoc networks," IEEE Transactions on Vehicular Technology, vol. 64, no. 12, pp. 5503{5519, 2015.

[120] X. Bi, D. Gao, and M. Yang, \A reinforcement learning-based routing protocol for clustered EV-VANET," in 2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC). IEEE, 2020, pp. 1769{1773.

[121] A. Nahar and D. Das, \Adaptive reinforcement routing in software defined vehicular networks," in 2020 International Wireless Communications and Mobile Computing (IWCMC). IEEE, 2020, pp. 2118{2123.

[122] M. Saravanan and P. Ganeshkumar, \Routing using reinforcement learning in vehicular ad hoc networks," Computational Intelligence, vol. 36, no. 2, pp. 682{697, 2020.

[123] X. Bi, D. Gao, and M. Yang, \A reinforcement learning-based routing protocol for clustered ev-vanet," in 2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC), 2020, pp. 1769{1773.

[124] Y. Sun, Y. Lin, and Y. Tang, \A reinforcement learning-based routing protocol in vanets," in International Conference in Communications, Signal Processing, and Systems. Springer, 2017, pp. 2493{2500.

[125] E. Spaho, L. Barolli, G. Mino, F. Xhafa, and V. Kolici, \VANET simulators: A survey on mobility and routing protocols," in 2011, International Conference on Broadband and Wireless Computing, Communication and Applications. IEEE, 2011, pp. 1{10.

[126] M. Y. Choong, R. K. Y. Chin, K. B. Yeo, and K. T. K. Teo, \Trajectory clustering for behavioral pattern learning in transportation surveillance," in 2014 4th International Conference on Artificial Intelligence with Applications in Engineering and Technology. IEEE, 2014, pp. 199{203.

[127] K. G. Lim, M. K. Tan, R. K. Y. Chin, K. B. Yeo, and K. T. K. Teo, \Traffic vehicular network modelling for VANET inter-vehicle data scavenging," in 2018 IEEE

International Conference on Artificial Intelligence in Engineering and Technology (IICAIET). IEEE, 2018, pp. 1{6.

[128] M. Y. Choong, R. K. Y. Chin, K. B. Yeo, and K. T. K. Teo, \Trajectory pattern mining via clustering based on similarity function for transportation surveillance," International Journal of Simulation-Systems, Science & Technology, vol. 17, no. 34, pp. 19{1, 2016.

[129] M. Fiore, J. Harri, F. Filali, and C. Bonnet, \Vehicular mobility simulation for VANETs," in 40th Annual Simulation Symposium (ANSS'07). IEEE, 2007, pp. 301{309.

[130] L. Bononi, M. Di Felice, G. D'Angelo, M. Bracuto, and L. Donatiello, \Moves: A framework for parallel and distributed simulation of wireless vehicular ad hoc networks," Computer Networks, vol. 52, no. 1, pp. 155{179, 2008.

[131] T. Murray, T. Murray, M. Cojocari, and H. Fu, \Measuring the performance of IEEE 802.11p using NS-2 simulator for vehicular networks," in 2008 IEEE International Conference on Electro/Information Technology. IEEE, 2008, pp. 498{503.

[132] C. Sommer and F. Dressler, \Progressing toward realistic mobility models in VANET simulations," IEEE Comms. Magazine, vol. 46, no. 11, pp. 132{137, 2008.

[133] F. J. Martinez, C. K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, \A survey and comparative study of simulators for vehicular ad hoc networks (VANETs)," Wireless Comms. and Mobile Computing, vol. 11, no. 7, pp. 813{828, 2011.

[134] H. Noori, \Realistic urban traffic simulation as vehicular Ad-Hoc network (vanet) via veins framework," in 2012 12th Conference of Open Innovations Association (FRUCT). IEEE, 2012, pp. 1{7.

[135] F. Li and Y. Wang, \Routing in vehicular Ad-Hoc networks: A survey," IEEE Vehicular technology magazine, vol. 2, no. 2, pp. 12{22, 2007.

[136] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, \Veacon: A vehicular accident ontology designed to improve safety on the roads," Journal of Network and Computer Applications, vol. 35, no. 6, pp. 1891{1900, 2012.

[137] J. Harri, F. Filali, C. Bonnet, and M. Fiore, \Vanetmobisim: generating realistic mobility patterns for VANETs," in Proceedings of the 3rd international workshop on Vehicular ad hoc networks, 2006, pp. 96{97.

[138] F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, \Citymob: a mobility model pattern generator for VANETs," in ICC Workshops-2008 IEEE International Conference on Comms. Workshops. IEEE, 2008, pp. 370{374.

[139] T. Kitani, T. Shinkawa, N. Shibata, K. Yasumoto, M. Ito, and T. Higashino, \Ecient vanet-based trac information sharing using buses on regular routes," in VTC Spring 2008-IEEE Vehicular Technology Conference. IEEE, 2008, pp. 3031{3036.

[140] A. Nayyar and R. Singh, \A comprehensive review of simulation tools for wireless sensor networks (wsns)," Journal of Wireless Networking and Comms., vol. 5, no. 1, pp. 19{47, 2015.

[141] J. Luis Font, P. Inigo, M. Dominguez, J. Luis Sevillano, and C. Amaya, \Anal-ysis of source code metrics from ns-2 and ns-3 network simulators," Simulation Modelling Practice and Theory, vol. 19, no. 5, pp. 1330{1346, 2011.

[142] K. G. Lim, C. H. Lee, R. K. Y. Chin, K. B. Yeo, and K. T. K. Teo, \Simulators for vehicular ad-hoc network (VANET) development," in 2016 IEEE International Conference on Consumer Electronics-Asia (ICCE-Asia). IEEE, 2016, pp. 1{4.

[143] D. Krajzewicz, J. Erdmann, M. Behrisch, and L. Bieker, \Recent development and applications of sumo-simulation of urban mobility," International journal on advances in systems and measurements, vol. 5, no. 3&4, 2012.

[144] K. G. Lim, C. H. Lee, R. K. Y. Chin, K. B. Yeo, and K. T. K. Teo, \Sumo enhancement for vehicular ad hoc network (vanet) simulation," in 2017 IEEE 2nd International Conference on Automatic Control and Intelligent Systems (I2CACIS). IEEE, 2017, pp. 86{91.

[145] H. Gao, C. Liu, Y. Li, and X. Yang, \V2VR: reliable hybrid-network-oriented V2V data transmission and routing considering RSUs and connectivity probability," IEEE Transactions on Intelligent Transportation Systems, vol. 22, no. 6, pp. 3533{ 3546, 2020.

[146] F. Bai, N. Sadagopan, and A. Helmy, \Important: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks," in IEEE INFOCOM 2003. Twenty-second Annual Joint Conference of the IEEE Computer and Comms. Societies (IEEE Cat. No. 03CH37428), vol. 2. IEEE, 2003, pp. 825{835.

[147] E. Spaho, M. Ikeda, L. Barolli, F. Xhafa, V. Kolici, and M. Takizawa, \Performance evaluation of olsr protocol in a grid manhattan VANET scenario for dierent applications," in 2013 Seventh International Conference on Complex, Intelligent, and Software Intensive Systems. IEEE, 2013, pp. 47{52.

[148] C. Chen, L. Liu, S. Wan, X. Hui, and Q. Pei, \Data dissemination for industry 4.0 applications in internet of vehicles based on short-term trac prediction," ACM Transactions on Internet Technology (TOIT), vol. 22, no. 1, pp. 1{18, 2021.

[149] J. Qian, T. Jing, Y. Huo, Y. Li, W. Zhou, and Z. Li, \A next-hop selection scheme providing long path lifetime in VANETs," in 2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC). IEEE, 2015, pp. 1929{1933.

[150] S. Toufga, S. Abdellatif, P. Owezarski, T. Villemur, and D. Relizani, \Effective prediction of V2I link lifetime and vehicle's next cell for software defined vehicular networks: A machine learning approach," in 2019 IEEE Vehicular Networking Conference (VNC).

[151] Y. Chen and Q. Zhao, \An integrated approach to energy-aware medium access for wireless sensor networks," IEEE Trans. on Signal Processing, vol. 55, no. 7, pp. 3429{3444, 2007.

[152] K. Cohen and A. Leshem, \A time-varying opportunistic approach to lifetime maximization of wireless sensor networks," IEEE Trans. on signal processing, vol. 58, no. 10, pp. 5307{5319, 2010.

[153] W. Xu, Q. Shi, X. Wei, Z. Ma, X. Zhu, and Y. Wang, \Distributed optimal rate{reliability{lifetime tradeoff in time-varying wireless sensor networks," IEEE Trans. on Wireless Comms., vol. 13, no. 9, pp. 4836{4847, 2014.

[154] R. Madan and S. Lall, \Distributed algorithms for maximum lifetime routing in wireless sensor networks," IEEE Trans. on wireless Comms., vol. 5, no. 8, pp. 2185{2193, 2006.

[155] M. Cheng, X. Gong, and L. Cai, \Joint routing and link rate allocation under bandwidth and energy constraints in sensor networks," IEEE Trans. on Wireless Comms., vol. 8, no. 7, pp. 3770{3779, 2009.

[156] H. Wang, N. Agoulmine, M. Ma, and Y. Jin, \Network lifetime optimization in wireless sensor networks," IEEE Journal on Selected Areas in Comms., vol. 28, no. 7, pp. 1127{1137, 2010.

[157] R. Madan, S. Cui, S. Lall, and N. A. Goldsmith, \Cross-layer design for lifetime maximization in interference-limited wireless sensor networks," IEEE Trans. on Wireless Comms., vol. 5, no. 11, pp. 3142{3152, 2006.

[158] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. Hanzo, \Cross-layer network lifetime maximization in interference-limited wsns," 2014 IEEE Trans. on Vehicular Technology, vol. 64, no. 8, pp. 3795{3803, 2014.

[159] M. K. Samimi, G. R. MacCartney, S. Sun, and T. S. Rappaport, \28 GHz millimeter-wave ultrawideband small-scale fading models in wireless channels," in IEEE 83rd Vehicular Technology Conference (VTC Spring), 2016.

[160] A. F. Acosta, J. E. Espinosa, and J. Espinosa, \TraCI4Matlab: enabling the integration of the SUMO road traffic simulator and Matlab® through a software re-engineering process," in Modeling Mobility with Open Data. Springer, 2015, pp. 155{170.

[161] J. Choi, V. Marojevic, R. Nealy, J. H. Reed, and C. B. Dietrich, \DSRC and IEEE 802.11ac adjacent channel interference assessment for the 5.9 GHz band," in 2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring). IEEE, 2019, pp. 1{5.

[162] M. Sepulcre, J. Gozalvez, and B. Coll-Perales, \Why 6 mbps is not (always) the optimum data rate for beaconing in vehicular networks," IEEE Transactions on Mobile Computing, vol. 16, no. 12, pp. 3568{3579, 2017.

[163] B. Pan and H. Wu, \Utility maximization for multi-vehicle multimedia dissemination in vehicular ad hoc networks," International Journal of Distributed Sensor Networks, vol. 14, no. 10, p. 1550147718806717, 2018.

[164] S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, and H. Zedan, \A comprehensive survey on vehicular ad-hoc network," Journal of network and computer applications, vol. 37, pp. 380{392, 2014.

[165] T.-N. Tran, T.-V. Nguyen, K. Shim, D. B. da Costa, and B. An, \A deep reinforcement learning-based qos routing protocol exploiting cross-layer design in cognitive radio mobile ad hoc networks," IEEE Transactions on Vehicular Technology, vol. 71, no. 12, pp. 13 165{13 181, 2022.

[166] K. Tan, D. Bremner, J. Le Kernec, Y. Sambo, L. Zhang, and M. A. Imran, \Intelligent handover algorithm for vehicle-to-network communications with double-deep q-learning," IEEE Transactions on Vehicular Technology, vol. 71, no. 7, pp. 7848{7862, 2022.

[167] J. Tian and F. Meng, \Comparison survey of mobility models in vehicular ad-hoc network (vanet)," in 2020 IEEE 3rd International Conference on Automation, Electronics and Electrical Engineering (AUTEEE). IEEE, 2020, pp. 337{342.

[168] W. Wei, R. Yang, H. Gu, W. Zhao, C. Chen, and S. Wan, \Multi-objective optimization for resource allocation in vehicular cloud computing networks," IEEE Transactions on Intelligent Transportation Systems, 2021.

[169] J. He, L. Cai, J. Pan, and P. Cheng, \Delay analysis and routing for two-dimensional VANETs using carry-and-forward mechanism," IEEE Transactions on Mobile Computing, vol. 16, no. 7, pp. 1830{1841, 2016.

[170] K. Sanada, N. Komuro, and H. Sekiya, \End-to-end throughput and delay analysis for ieee 802.11 string topology multi-hop network using markov-chain model," in

2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC). IEEE, 2015, pp. 1697{1701.

[171] C. Chen, L. Liu, T. Qiu, J. Jiang, Q. Pei, and H. Song, \Routing with traffic aware-ness and link preference in internet of vehicles," IEEE Transactions on Intelligent Transportation Systems, 2020.

[172] T. Sivakumar, R. Manoharan, and K. Kuppusamy, \A stable routing protocol for vehicular ad hoc networks," in 2014 First International Conference on Networks & Soft Computing (ICNSC2014). IEEE, 2014, pp. 46{49.

[173] T. Ivanescu, H. Yetgin, M. El-Hajjar, and G. Merrett, \Route lifetime analysis for vehicular networks," in IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), Hyderabad, India, Dec. 2021.

[174] T. Taleb, E. Sakhaee, A. Jamalipour, K. Hashimoto, N. Kato, and Y. Nemoto, \A stable routing protocol to support its services in VANET networks," IEEE Transactions on Vehicular technology, vol. 56, no. 6, pp. 3337{3347, 2007.

[175] T. Chatterjee, R. Karmakar, G. Kaddoum, S. Chattopadhyay, and S. Chakraborty, \A survey of vanet/v2x routing from the perspective of non-learning-and learning-based approaches," IEEE Access, vol. 10, pp. 23 022{23 050, 2022.

[176] D. Borsetti and J. Gozálvez, \Infrastructure-assisted geo-routing for cooperative vehicular networks," in 2010 IEEE vehicular networking conference. IEEE, 2010, pp. 255{262.

[177] R. Frank, E. Giordano, P. Cataldi, and M. Gerla, \Trafroute: A different approach to routing in vehicular networks," in 2010 IEEE 6th international conference on wireless and mobile computing, networking and communications. IEEE, 2010, pp. 521{528.

[178] J.-P. Sheu, C.-Y. Lo, and W.-K. Hu, \A distributed routing protocol and handover schemes in hybrid vehicular ad hoc networks," in 2011 IEEE 17th International conference on parallel and distributed systems. IEEE, 2011, pp. 428{435.

[179] J.-P. Sheu, W.-K. Hu, and R. E. Bol, \A registration system for aiding in localization and routing in hybrid vanets," in 2012 12th International Conference on ITS Telecommunications. IEEE, 2012, pp. 694{699.

[180] K. Mershad, H. Artail, and M. Gerla, \Roamer: Roadside units as message routers in vanets," Ad Hoc Networks, vol. 10, no. 3, pp. 479{496, 2012.

[181] L. Luo, L. Sheng, H. Yu, and G. Sun, \Intersection-based v2x routing via reinforcement learning in vehicular ad hoc networks," IEEE Transactions on Intelligent Transportation Systems, 2021.

[182] T.-W. Chen and M. Gerla, \Global state routing: A new routing scheme for ad-hoc wireless networks," in ICC'98. 1998 IEEE International Conference on Communications. Conference Record. Affiliated with SUPERCOMM'98 (Cat. No. 98CH36220), vol. 1. IEEE, 1998, pp. 171{175.

[183] A. Mukhopadhyay, B. Limitha, R. Anusha, and V. Gowthami, \Tcp and priority queue based emergency data transmission in vanets," in 2022 IEEE 3rd Global Conference for Advancement in Technology (GCAT). IEEE, 2022, pp. 1{6.

[184] Y. Xia, X. Qin, B. Liu, and P. Zhang, \A greedy traffic light and queue aware routing protocol for urban vanets," China Communications, vol. 15, no. 7, pp. 77{87, 2018.

[185] M. J. Khabbaz, W. F. Fawaz, and C. M. Assi, \Modeling and delay analysis of intermittently connected roadside communication networks," IEEE Transactions on Vehicular Technology, vol. 61, no. 6, pp. 2698{2706, 2012.

[186] S. A. A. Shah, K. Illanko, and X. Fernando, \Deep learning based traffic flow prediction for autonomous vehicular mobile networks," in 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall). IEEE, 2021, pp. 01{05.

[187] J. Deng and G. Shen, \Federated learning-based privacy-preserving traffic flow prediction scheme for vanets," in 2022 4th International Conference on Communications, Information System and Computer Engineering (CISCE). IEEE, 2022, pp. 374{378.

[188] B. Li, Y. Jiang, Q. Pei, T. Li, L. Liu, and R. Lu, \Feel: Federated end-to-end learning with non-iid data for vehicular ad hoc networks," IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 9, pp. 16 728{16 740, 2022.

[189] S. S. Sepasgozar and S. Pierre, \Fed-ntp: A federated learning algorithm for network traffic prediction in vanet," IEEE Access, vol. 10, pp. 119 607{119 616, 2022.

[190] V. Va, T. Shimizu, G. Bansal, R. W. Heath Jr et al., \Millimeter wave vehicular communications: A survey," Foundations and Trends® in Networking, vol. 10, no. 1, pp. 1{113, 2016.

[191] A. Bouroumine, M. Zekraoui, and M. Abdelilah, \The influence of the opportunis-tic vehicular networks on smart cities management study case on agdal district in rabat city," in 2016 4th IEEE International Colloquium on Information Science and Technology (CiSt). IEEE, 2016, pp. 830{834.

[192] I. Broustis and M. Faloutsos, \Routing in vehicular networks: feasibility, modeling, and security," International Journal of Vehicular Technology, vol. 2008, 2008.

[193] F. J. Martin-Vega, M. C. Aguayo-Torres, G. Gomez, J. T. Entrambasaguas, and T. Q. Duong, \Key technologies, modeling approaches, and challenges for

millimeter-wave vehicular communications," IEEE Comms. Magazine, vol. 56, no. 10, pp. 28{35, 2018.