Evaluating V2X Communications in the CARLA Simulator for a Collaborative Planning Use Case

Daniel Villalobos*, Santiago Montiel-Marín*, Rodrigo Gutiérrez-Moreno*,
Navil Abdeselam*, Antonio Moratilla†, Luis M. Bergasa*

***Abstract*—Vehicle-to-Everything (V2X) communication is pivotal for enhancing the safety and efficiency of autonomous driving. The CARs Learning to Act (CARLA)simulation platform is a key tool for evaluating these technologies. This research implements a Robotic Operating System (ROS) module and an infrastructure server in CARLA to study V2X communication using Message Queuing Telemetry Transport (MQTT) protocol for a collaborative planning use case. An infrastructure module manages communication among the different agents of a traffic scene and a reactive route calculation system allows real-time route recalculation for each vehicle based on alerts received from the infrastructure and other vehicles. Evaluations of A* and Dijkstra planning algorithms reveal that A* is more efficient on small maps, while Dijkstra excels on larger maps. Our results validate the system's effectiveness, offering a foundation for future research in autonomous vehicles and traffic management.**

***Index Terms*—V2X communication. CARLA Simulator. MQTT. Route planification. ROS. A-Star. Dijkstra**

I. Introduction

Vehicle-to-Everything (V2X) communication is key to improving traffic safety and efficiency by enabling real-time information exchange between vehicles and infrastructure [1], [2], [3], [4], [5], [6]. Advances in technologies like 5G and cloud computing have further accelerated V2X adoption, allowing for fast and reliable data transfer [7], [8], [9], [10]. V2X enhances road safety through early collision warnings and improves traffic flow by enabling smart infrastructure, such as adaptive traffic lights.

For autonomous vehicles, V2X plays a crucial role by expanding their perception capabilities beyond onboard sensors, facilitating better decision-making in complex scenarios. However, challenges such as communication latency and data synchronization issues can impact its effectiveness [11], [12], [13], [14].

This study uses the CARLA simulation platform [23] to evaluate V2X communication with the MQTT protocol, focusing on real-time vehicle route recalculations. By comparing A* and Dijkstra algorithms, the research aims to identify the most efficient route-planning method in various scenarios, contributing to the advancement of autonomous vehicle systems [15].

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* Affiliated with Departamento de Electrónica, Universidad de Alcalá (UAH), Alcalá de Henares (Madrid), Spain. {santiago.montiel,rodrigo.gutierrez,navil.abdeselam,luism.bergasa}@uah.es

† Affiliated with Departamento de Ciencias de la Computación, Universidad de Alcalá (UAH), Alcalá de Henares (Madrid), Spain. antonio.moratilla@uah.es

II. State of the Art

Various protocols, including CoAP, AMQP, DDS, and MQTT, have been investigated for V2X communication, with MQTT being a preferred option due to its lightweight architecture, efficient management of persistent connections, and robustness in high-latency networks [16], [17], [18], [19], [20]. Standardized V2X messages by ETSI, such as Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM), play a vital role in ensuring interoperability between vehicles and infrastructure. CAMs periodically broadcast vehicle data like position and speed to maintain situational awareness, while DENMs communicate specific events like accidents or road hazards [21], [22], [23], [24].

Key issues in V2X communication include latency, which is the delay in data transmission, and challenges like packet loss, interference, and network congestion, all of which affect the performance of vehicular applications [25], [26]. Addressing these problems is critical for the reliability and safety of V2X systems.

Simulation platforms are essential for testing V2X communication. SUMO, VEINS, and CARLA are widely used for simulating traffic and vehicle interactions in controlled environments. CARLA is particularly suited for this work due to its hyper-realistic scenarios and open-source nature, bridging the gap between simulations and real-world V2X implementation [27], [30], [31]. CARLA allows the testing of V2X systems in varied conditions, helping to mitigate real-world challenges such as sensor imperfections and adverse weather [32], [33], [34], [35], [36], [37].

ROS (Robot Operating System) is commonly used in CARLA simulations to coordinate autonomous vehicle components. Integrating ROS modules with MQTT within the CARLA environment creates a robust setup for testing V2X communications and collaborative planning [38], [39], [40], [42]. Collaborative perception in V2X allows vehicles to share sensor information, which enhances situational awareness and supports safer decision-making, particularly in challenging conditions [11].

V2X communication also enables dynamic route management, where real-time information can optimize vehicle routing in response to changing conditions [45]. Two widely used algorithms in path planning are Dijkstra's algorithm and A*. Dijkstra's algorithm calculates the shortest path by exploring all possible routes from a source to destination [46], while A* improves efficiency by guiding the search towards the most promising routes, reducing computation time [47].

In this work, we aim to implement a ROS module and a bidirectional infrastructure server in CARLA to simulate and analyze V2X systems, particularly focusing on collaborative route planning. We will compare the performance of Dijkstra and A* algorithms for recalculating routes in response to infrastructure messages, studying how network conditions such as latency and saturation impact system performance. Additionally, the effects of shadow zones in communication will be explored. This research aims to advance the understanding of vehicular communications and their role in autonomous driving.

III. Our Proposal

This research was conducted using the CARLA simulation platform. To interact with CARLA's vehicles and actors, a ROS module was developed, connecting with CARLA's Python API. V2X communication was implemented using the MQTT protocol, with Eclipse Mosquitto software, known for its efficiency in high-latency environments [48], [49], [50], [51].

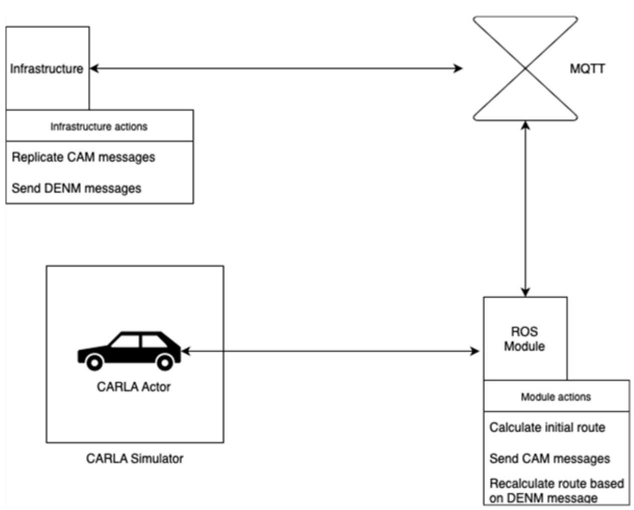

Fig. 1: System Architecture

A Python infrastructure module was designed to manage communication between actors in the simulated environment, replicating and forwarding messages according to ETSI standards. This module ensures interoperability between vehicles and the infrastructure while efficiently handling message traffic.

The proposed architecture, shown in Figure 1, illustrates the interaction flow. A ROS module interfaces with CARLA vehicles, calculating initial routes and generating CAM messages to inform other network participants about the vehicle's state.

The ROS module connects to an MQTT broker, allowing bidirectional communication with the infrastructure. Through MQTT, it sends and receives CAM messages from other vehicles, ensuring real-time updates. Additionally, it can receive DENM messages, alerting vehicles to incidents and prompting route recalculations.

The infrastructure receives CAM messages from vehicles, replicating and forwarding them via the MQTT broker. This redundancy ensures that messages are not lost due to connectivity issues. Furthermore, the infrastructure sends DENM messages to warn vehicles of hazards, facilitating dynamic adaptation and improving safety.

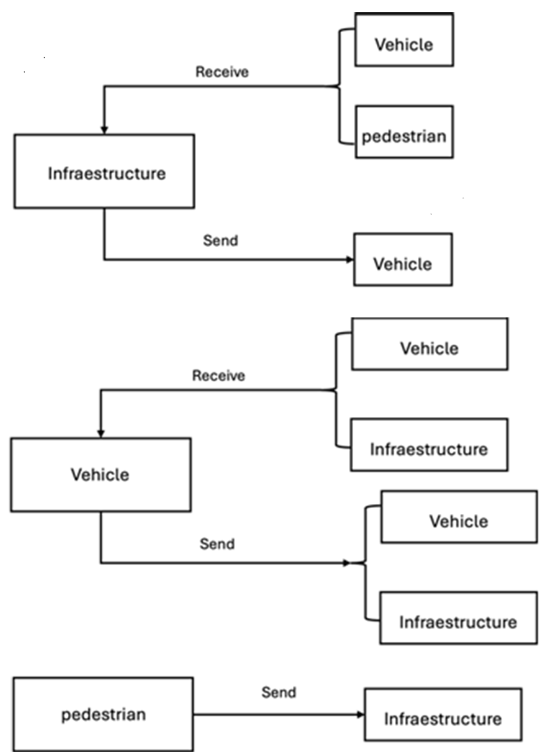

Fig. 2: Message Flow

As shown in Figure 2, the infrastructure can receive messages from vehicles, forward them, and detect pedestrians via city systems. Vehicles can also communicate directly with each other. Pedestrians, however, remain passive actors and do not receive messages.

These communications use the MQTT protocol, with infrastructure and vehicles publishing to different topics. This topic-based system allows vehicles to subscribe and efficiently aggregate the information, simplifying the categorization of data origins.

For route calculation, A* and Dijkstra algorithms were compared using CARLA's map topology. This topology, compliant with the OpenDRIVE standard [52], [53], is represented as a graph, with nodes as waypoints and edges as road segments.

The CARLA API enabled the export of this topology and the generation of the graph.

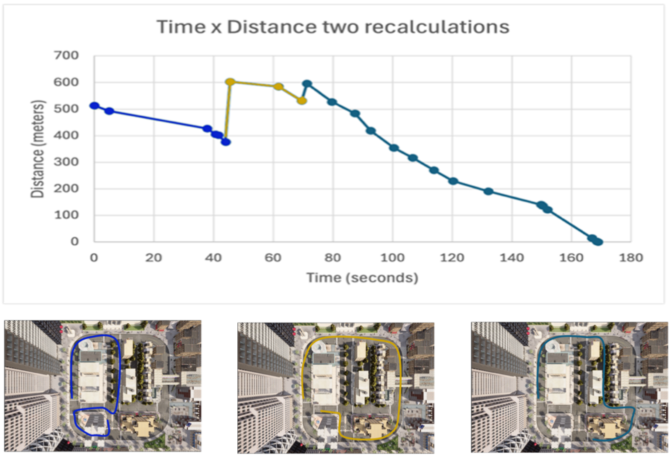

Fig. 3: Distance graph during route recalculations

When a vehicle enters the simulation, it calculates the optimal route to its destination. Upon receiving a DENM from the infrastructure alerting about a road incident, the vehicle recalculates the route.

Figure 3 shows the relationship between the vehicle's distance to its destination over time. Normally, this distance decreases, but when a route recalculation occurs, the distance briefly increases, as seen in the graph's peaks.

IV. Results and Discussion

This study used the CARLA simulator to evaluate vehicular communication and routing algorithms through three main experiments:

1) **Latency:** We measured the time taken for message processing as the number of vehicles increased.
2) **Communication failures:** The impact of shadow zones on message delivery success rates was analyzed.
3) **Collaborative re-planning:** We compared the performance of A* and Dijkstra algorithms across multiple re-planning scenarios.

The simulations were conducted on a computer system with the following specifications:

- **Processor:** Intel Core i5-12400F .
- **RAM:** 32 GB DDR4 at 3200 MHz.
- **Graphics Card:** NVIDIA GeForce RTX 3060 with 12 GB VRAM.
- **Storage:** Crucial P5 Plus 1 TB M.2 NVMe SSD

To assess system performance, we ran several benchmarks:

CPU:

- *Geekbench 6*: Multi-core score of 9,999 pts, single-core score of 2,834 pts.
- *CrystalDiskMark*: Multi-core score of 88,696 pts, single-core score of 11,073 pts.

GPU:

- *Cinebench*: Score of 8,499 pts.
- *Unigine2 Superposition (1080p High)*: Score of 15,257 pts.

A. Latency

A test to check the system's latency was carried out on the Town10 of CARLA. The number of vehicles within the CARLA simulation was gradually increased to check the time taken for the CAM message creation process, its sending, reception by the infrastructure, and its decoding. This test was divided into 7 parts, with each part progressively increasing the number of vehicles in the scenario (1, 10, 25, 50, 100, 150, and 200 vehicles). In each phase, 12,000 messages were sent, and the average times for CAM message creation, sending, reception by the infrastructure, and decoding were extracted.

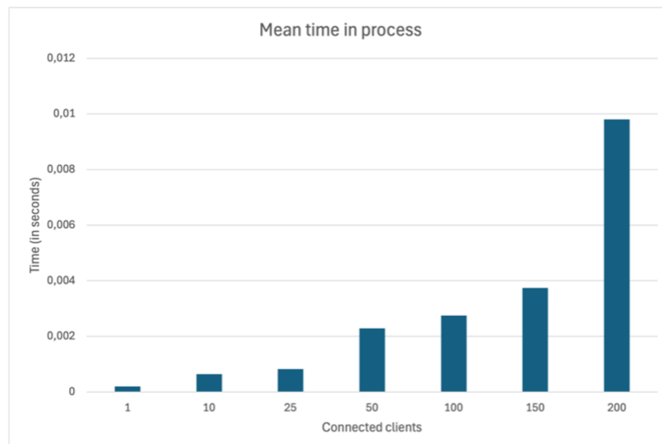

Fig. 4: Processing mean time

The results in Figure 4 show that the time required for the task increases exponentially with the number of actors, indicating that during periods of high system saturation, the infrastructure has more messages to manage, significantly increasing the processing times for each actor's transmissions. However, the absolute time for the task remains relatively small, being under 10 ms for 200 actors.

B. Communication failures

In this second scenario, some shadow zones were defined on the Town10 where communications had a probability of failing both when being sent and received, thus simulating a real scenario where there could be interference and other communication problems. The shadow zones were defined around areas with buildings and a large number of trees.

Fig. 5: Shadow zones in CARLA's map TOWN10

Figure 5 shows these zones, where the yellow zone (left) has a 20% chance of failure and the orange zone (right) has a 40% chance of failure.

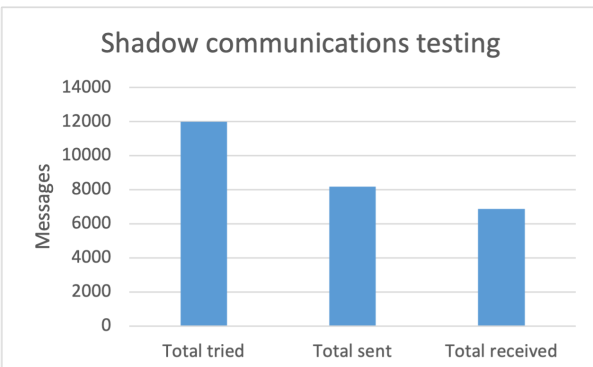

Fig. 6: Shadow test results

In the test, 12,000 messages were sent between 25 actors, and it was checked if at least one actor received the message sent by another, without it being necessary for all actors to receive it. The results show that approximately 68.11% of the messages (8,174) were sent correctly, of which 84.08% (6,873) were received correctly. Comparing the received messages with the total messages sent, it can be seen that only 57.28% of the total messages were received at least once. Although the percentage of shadow zones in a real environment can vary greatly due to various external factors such as surfaces, trees, vehicles, pedestrians, and any other physical medium, this approximation demonstrates the importance of creating resilient systems prepared for issues like interference [54], [55].

C. Collaborative re-planning

A third scenario was designed on the Town10 map of CARLA to compare the performance of the A* and Dijkstra planning algorithms for 250 vehicles in environments with multiple re-plannings. For this, the system allows the infrastructure to send DENM messages to which the vehicles could react to recalculate the route they were following. The vehicles were individually tested and grouped by the number of recalculations they had to perform: 50 vehicles would perform one recalculation, 50 two, 50 three, 50 four, and other 50 five recalculations.

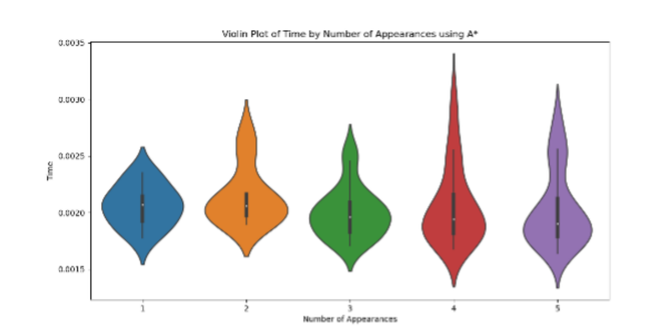

Fig. 7: Graph time for A-start algorithm grouped by number of recalculations

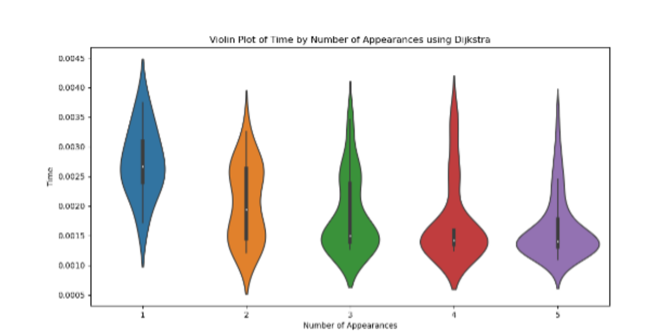

Fig. 8: Graph time for Dijkstra algorithm grouped by number of recalculations

To conduct this analysis, the average recalculation time for all recalculations performed by each vehicle was recorded. Fig. 7 presents both the distribution of these values and their variances based on the recalculations performed for the A* algorithm and Fig. 8 shows the same but for the Dijkstra algorithm. From these graphs, it can be deduced that the values for the different re-plannings are uniformly and consistently distributed for the two algorithms, with very controlled outliers.

Same conclusions can be obtained from the results of the ANOVA calculation shown in Table I, where the p-value does not show significance. Likewise, although the values are similar, A* shows slightly more uniformity and slightly lower values.

In Fig.3, an example of the temporal evolution of the distance-to-destination graph is shown for the A* algorithm, with two recalculations at seconds 43 and 70. It can be observed that the distance increases after each re-planning. Additionally, the three routes that the vehicle would have taken based on the necessary recalculations are also displayed.

These routes begin from the point where the V2X message is received, triggering the route recalculation.

After this test on the Town10 map, the same test was conducted on the Town05 map of CARLA, which has much larger dimensions, to verify if the hypotheses were independent of the maps used.

The obtained data, shown in the Table II, show that the map has a significant impact on the results, considerably increasing the times and values obtained. Additionally, it is interesting to observe that, with larger graphs, the Dijkstra algorithm shows more consistent and faster results than the A* algorithm.

CONCLUSIONS

This project presents the incorporation of a V2X communication system in CARLA, which enhances the perception of various actors about their environment, enriching simulations and minimizing the reality gap. The study highlights MQTT as a suitable system for V2X communications due to its lightweight nature and resilience, as well as architectural features like the use of TCP/IP, making it an ideal solution. The inclusion of an infrastructure module in CARLA's V2X communication system facilitates interaction capabilities with the simulated environment. This advancement allows the creation of anomalous or extreme scenarios (accidents, road closures, traffic jams, adverse weather conditions) easily through message sending and reaction. Additionally, the A* and Dijkstra algorithms were evaluated for optimal route calculation in the CARLA simulation environment. It is concluded that, due to heuristic estimation, the A* algorithm is more suitable for small maps, while Dijkstra is better suited for large simulation environments. Finally, it is observed that repeated recalculations do not significantly affect the time required to perform them, allowing simulation actors to adapt effectively to highly dynamic environments. As a result of this work, future research lines are identified in the domain of V2X communications and simulation in CARLA, focusing on optimizing interaction and perception capabilities in simulated environments. This can serve as a basis for studies aimed at improving city traffic management systems.

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Algorithm	Mean	Median	Std dev	Variance	F stat	p-value
A-star	0.002196	0.002155	0.0003407	1.1608e-07	17.4129	2.5145e-16
Dijkstra	0.002251	0.002207	0.0007045	4.9635e-07	20.3823	4.2519e-19

TABLE I: Performance comparison of A-star and Dijkstra algorithms in Town10

Algorithm	Mean	Median	Std dev	Variance	F stat	p-value
A-star	0.004787	0.004584	0.0007396	5.4707e-07	0.7211	0.8972
Dijkstra	0.003563	0.003444	0.0004821	2.3245e-07	1.0803	0.36662

TABLE II: Performance comparison of A-star and Dijkstra algorithms in Town05

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