Performance Evaluation of 5G C-V2X for V2V in Semi-Enclosed Environments

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***Abstract*— The rapid advancement of 5G technology has accelerated the development of vehicular networks, where reliable Vehicle-to-Vehicle (V2V) communication is essential for intelligent transportation systems. This study evaluates the performance of Cellular Vehicle-to-Everything (C-V2X)-based V2V communication using a trace-driven simulation approach in a semi-enclosed environment. A realistic mobility model is generated using Simulation of Urban Mobility (SUMO) based on OpenStreetMap data and integrated with the WiLabV2Xsim simulator implementing the 3GPP C-V2X Mode 4 standard. The evaluation is conducted using Packet Reception Ratio (PRR), Channel Busy Ratio (CBR), and packet delay under varying vehicular densities. The results show that increasing vehicle density leads to a significant degradation in PRR while increasing CBR and delay, indicating higher channel congestion and communication interference. Increasing bandwidth improves communication reliability, whereas higher transmission power provides limited benefits in dense scenarios. These findings highlight the importance of efficient resource allocation and congestion-aware mechanisms to ensure reliable V2V communication in 5G-enabled vehicular networks. However, this study is limited to simulation-based evaluation and does not consider real-world deployment constraints. The study contributes to understanding the scalability and performance behavior of C-V2X systems in realistic vehicular environments.**

Keywords*— *5G, C-V2X, Packet Reception Ratio, Trace-Driven Simulation, V2V Communication, Vehicular Networks.

I. INTRODUCTION

The rapid advancement of fifth generation (5G) communication technology has significantly accelerated the development of Intelligent Transportation Systems (ITS). One of the key components of ITS is Vehicle-to-Everything (V2X) communication, which enables vehicles to exchange information with other vehicles (Vehicle-to-Vehicle/V2V), infrastructure (Vehicle-to-Infrastructure/V2I), and cellular networks to improve road safety, traffic efficiency, and real-time decision-making [1].

Cellular Vehicle-to-Everything (C-V2X), standardized by the 3rd Generation Partnership Project (3GPP), has emerged as a promising alternative to Dedicated Short-Range Communication (DSRC) due to its enhanced reliability, scalability, and support for high mobility scenarios [2]. C-V2X operates through two main interfaces, namely the Uu interface and the PC5 interface (sidelink), which enable direct communication between vehicles. The integration of C-V2X with 5G technology supports Ultra-Reliable Low-Latency Communication (URLLC), which is essential for safety-critical vehicular applications [3].

Fig. 1 illustrates the architecture of a C-V2X-based V2V communication system, where vehicles communicate directly through the PC5 interface while also interacting with infrastructure elements such as roadside units (RSUs) and cloud services. The vehicular cloud enables data aggregation and processing, supporting advanced applications such as traffic management and safety services. This architecture highlights the integration of direct vehicle communication and network-assisted services in modern vehicular networks.

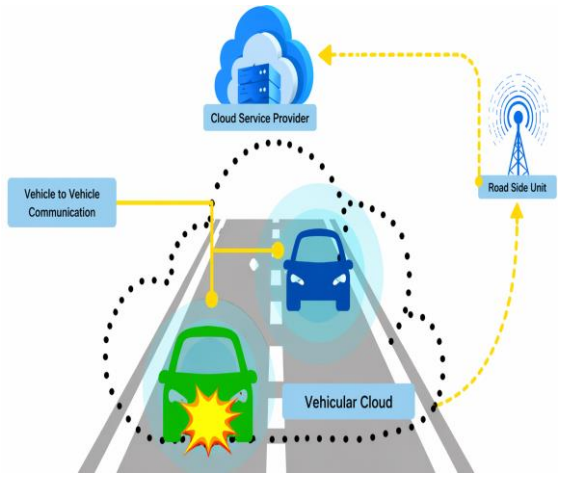


Fig. 1. Architecture of the C-V2X-based V2V communication system integrated with roadside units (RSUs) and a vehicular cloud.

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Despite these advantages, the performance of C-V2X communication is highly influenced by environmental conditions and vehicular density. Most existing studies focus on highway or open urban environments, while limited attention has been given to semi-enclosed scenarios characterized by constrained road structures and physical obstructions. These conditions introduce challenges such as multipath propagation, shadowing, and increased channel contention.

To address this gap, this study evaluates the performance of C-V2X-based V2V communication in a semi-enclosed environment using a simulation-based approach. A realistic mobility scenario is generated from OpenStreetMap data and integrated with the WiLabV2Xsim simulator. The main contributions of this study are as follows:

1. Performance evaluation of C-V2X under varying vehicular densities in a semi-enclosed environment.
2. Analysis using Packet Reception Ratio (PRR), Channel Busy Ratio (CBR), and packet delay.
3. Investigation of the impact of network density on communication reliability and channel congestion.

II. Research Methodology

A. Research Framework

This study evaluates the performance of Vehicle-to-Vehicle (V2V) communication based on Cellular Vehicle-to-Everything (C-V2X) using a simulation-based approach. The proposed framework integrates vehicular mobility modelling and communication simulation to provide a realistic evaluation environment.

Specifically, vehicular mobility is generated using Simulation of Urban Mobility (SUMO), while the communication process is simulated using MATLAB-based WiLabV2Xsim, which implements the 3GPP C-V2X Mode 4 standard [4]. This integration enables the analysis of communication performance under realistic traffic conditions.

A trace-driven approach is adopted, where mobility traces generated from SUMO simulations are used as input for the communication simulation. This approach is considered more realistic than purely analytical models, as it preserves the dynamic behavior of vehicles within a vehicular communication ecosystem. Furthermore, trace-based mobility allows a more accurate evaluation of V2V communication performance under varying network densities and diverse wireless channel conditions [5].

To ensure a systematic evaluation, the study is conducted through several sequential stages, including map modelling, vehicle mobility generation, data preprocessing, configuration of the C-V2X communication simulation, and network performance analysis. These stages follow a standard V2X performance evaluation framework that integrates realistic mobility modelling with scalable simulation environments, along with the configuration of communication parameters and the assessment of key performance metrics such as communication reliability and channel utilization [6].

Fig. 2 illustrates the overall research workflow of the proposed simulation framework. The process begins with map acquisition from OpenStreetMap, followed by network modelling and vehicle mobility generation using SUMO. The generated mobility traces are then pre-processed and integrated into the WiLabV2Xsim environment for C-V2X communication simulation. Finally, performance evaluation is conducted using key metrics such as Packet Reception Ratio (PRR), Channel Busy Ratio (CBR), and packet delay.

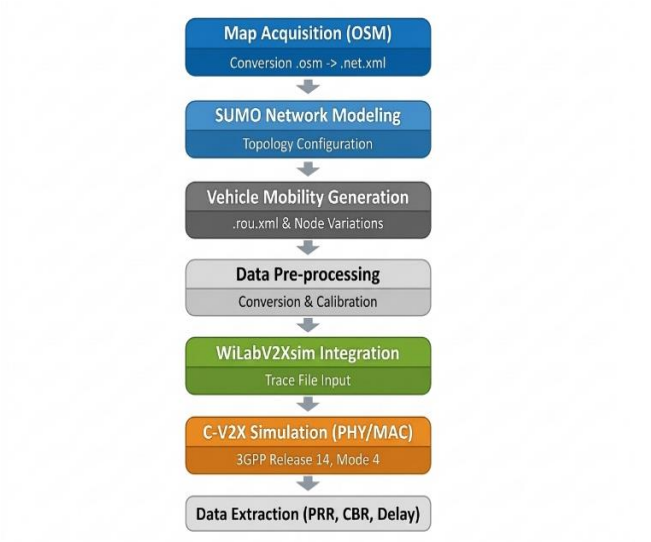


Fig. 2. Research workflow of the proposed C-V2X simulation framework

B. Simulation Environment and Vehicle Mobility Modeling

The simulation environment represents a semi-enclosed urban scenario derived from a university campus area in Bandung, Indonesia. The environment is characterized by moderate traffic density, intersections, and constrained road segments, making it suitable for evaluating V2V communication under realistic conditions.

Geographic data were obtained from OpenStreetMap (OSM) and converted into a SUMO network format (.net.xml) using the netconvert tool. Fig. 3 shows the simulation area, which serves as the basis for generating realistic vehicular mobility scenarios.

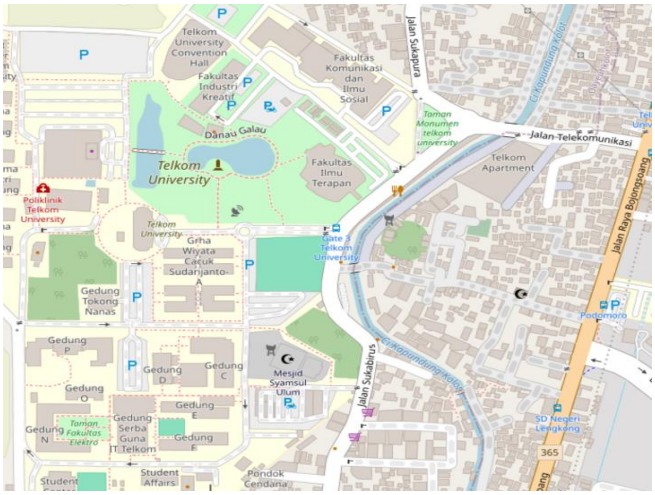


Fig. 3. Simulation area derived from OpenStreetMap represents a semi-enclosed environment.

Vehicle mobility is simulated using a microscopic traffic modeling approach, where each vehicle (node) operates independently in terms of speed and routing behavior. This approach enables realistic modeling of traffic dynamics and interactions among vehicles within the V2X communication environment [7].

The mobility scenario is defined using a route configuration file (.rou.xml), which includes vehicle routes, node density, average vehicle speed, and simulation duration. The main configuration file (sumo.cfg) is used to load both the network and route files during the simulation process. The SUMO simulation generates an output file (.xml) containing time-dependent vehicle position data, which is later used as

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mobility trace input for the communication simulation. Table I summarizes the mobility configuration parameters used to generate realistic vehicular traffic conditions.

TABLE I. VEHICLE MOBILITY SIMULATION CONFIGURATION IN SUMO

Parameter	Value	Description
Number of Nodes	100, 200, 300, 400, 500	Variation of vehicle density
Simulation Duration	300 s	Total simulation time
Average Speed	10 – 30 km/h	Campus Traffic Conditions
Departure Interval	1-3 s	Variation in vehicle generation
Output	Output.xml	Vehicle position over time

Based on Table I, the number of nodes varies from 100 to 500 vehicles to evaluate the impact of different vehicle density levels on communication performance. A simulation duration of 300 s is selected to ensure sufficient observation time for evaluating network behaviour.

Furthermore, the average vehicle speed ranges from 10 to 30 km/h, reflecting typical campus traffic conditions where vehicle movement is relatively slow due to intersections and pedestrian activity. The departure interval of 1–3 s is applied to introduce variability in vehicle generation, thereby preventing simultaneous vehicle entry and creating a more realistic traffic flow.

Fig. 4 shows that vehicles move along predefined routes derived from the OpenStreetMap-based road network, including intersections and roundabout structures. The distribution of vehicles across multiple road segments reflects dynamic traffic flow and realistic vehicular interactions under varying node densities.

This visualization is important to validate that the generated mobility traces accurately represent real-world traffic behaviour before being integrated into the communication simulator for evaluating V2V performance. This mobility modelling approach ensures that the communication performance evaluation is conducted under realistic and dynamic traffic conditions.

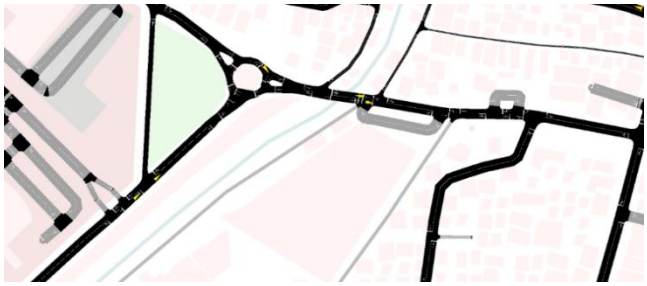


Fig. 4. The illustration of the visualization of vehicle mobility generated by the SUMO simulation.

C. Mobility Trace Preprocessing and Integration

The preprocessing stage is performed to ensure the compatibility of mobility data with the WiLabV2Xsim simulation environment. This stage transforms raw mobility traces generated from SUMO into a structured format suitable for communication simulation.

The preprocessing process consists of several steps, including conversion of mobility data from .xml to .csv format, removal of incomplete or anomalous entries, alignment of simulation time steps, and coordinate calibration within the MATLAB environment. The processed data are then converted into a formatted .txt file, which is used as input for the communication simulation.

The resulting trace file contains time-indexed information, including simulation time, vehicle ID, position coordinates (x, y), and vehicle speed. This ensures that the mobility behaviour is accurately represented during the communication simulation process.

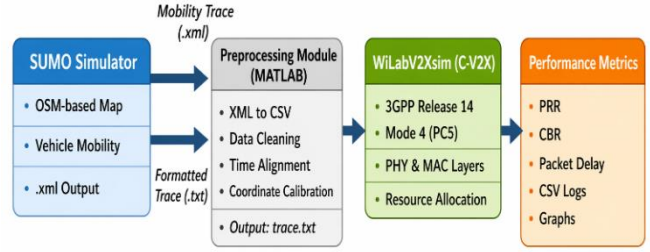


Fig. 5. Integrated system architecture of the proposed C-V2X simulation framework.

As shown in Fig. 5, the overall process begins with mobility data generation using SUMO, followed by preprocessing in MATLAB, and integration into the WiLabV2Xsim environment for C-V2X communication simulation. Finally, performance evaluation is conducted using metrics such as Packet Reception Ratio (PRR), Channel Busy Ratio (CBR), and packet delay.

To provide a structured representation of the simulation workflow, the overall process is summarized in Algorithm 1 (Algorithm 1. Integrated Mobility and Communication Simulation Workflow)

Input : OpenStreetMap-based road network
Output : PRR, CBR, packet delay

// Mobility Generation
1: Generate vehicular mobility using SUMO
2: Export mobility trace in XML format

// Preprocessing
3: Convert XML data into CSV format
4: Remove incomplete and anomalous entries
5: Align simulation time steps
6: Perform coordinate calibration

// Communication Simulation
7: Convert processed data into formatted trace (.txt)
8: Load mobility trace into WiLabV2Xsim
9: Configure C-V2X Mode 4 parameters
10: Execute V2V communication simulation and record communication logs

// Performance Evaluation
11: Compute Packet Reception Ratio (PRR)
12: Compute Channel Busy Ratio (CBR)
13: Compute packet delay
14: Generate performance evaluation results

D. C-V2X Communication Simulation Configuration

The communication simulation is conducted using WiLabV2Xsim, which implements the 3GPP C-V2X Mode 4 sidelink communication standard aligned with 5G-enabled vehicular communication. The configured parameters include the physical layer (PHY), medium access control (MAC) layer, traffic model, and resource allocation mechanism.

At the physical layer, the system operates at a carrier frequency of 5.9 GHz, with configurable bandwidth, transmit power, propagation model, and shadowing parameters. At the MAC layer, C-V2X Mode 4 is employed using a sensing-

based semi-persistent scheduling mechanism for distributed resource allocation among vehicles.

The traffic model adopts periodic packet transmission in the form of Cooperative Awareness Messages (CAM), which are transmitted at predefined intervals to emulate V2V communication scenarios.

Table II summarizes the configuration of the physical layer and communication access parameters used in the C-V2X simulation.

TABLE II. CONFIGURATION OF PHYSICAL LAYER AND COMMUNICATION PARAMETERS IN THE C-V2X SIMULATION.

Parameter	Value	Description
Seed	10	Seed for the random number generator
Technology	5G-V2X	Communication Technology
Type Of Scenario	Traces	Trace-driven mobility scenario
Nblocks	1	Number of roadblocks
Nlanesblockh	1	Number of horizontal lanes (1+1 configuration)
Nlanesblockv	1	Number of vertical lanes
Road Width	3.5 m	Lane width
vStDev	0.0	Vehicle speed standard deviation (stable condition)
Noise Figure (F)	9 dB	Receiver noise figure
Tx Antenna Gain (Gt)	3 dB	Transmitter antenna gain
Rx Antenna Gain (Gr)	3 dB	Receiver antenna gain
Transmit Power (Pt)	26 dBm	Total transmission power
Bandwidth	10 MHz	System bandwidth
Carrier Frequency	5.9 GHz	Intelligent Transportation Systems (ITS) band
Shadowing Variance	3 dB	Shadowing variance
Decorrelation Distance	25 m	Shadowing decorrelation distance
Propagation Model	WINNER+ B1	Urban propagation model
Packet Interval	100 ms	Packet transmission interval
Packet Size	350 byte	Data packet size
MCS NR	4	QPSK modulation with a coding rate of 0.3
SINR Threshold	Auto	Automatic SINR threshold
Subchannel Size	10 PRB	Subchannel size
Number of Subchannels	5	Total number of available subchannels
Max Replicas	1	Retransmission disabled
Resource Keep Probability	0.4	Resource retention probability
RSRP Threshold	−126 dBm	Sensing threshold
T1	1 ms	Minimum time allocation
T2	1 ms	Maximum time allocation
Trace File Path	Input/tripinfo*.txt	Mobility trace file
Trace Format	time nodeID x y speed	Trace data format
Packet Reception Ratio	True	PRR output logging
Channel Busy Ratio	True	CBR output logging
Packet Delay	True	Shadowing decorrelation distance

Based on Table II, the simulation is configured using a trace-driven scenario with predefined mobility input, ensuring realistic vehicular movement patterns. The system bandwidth is set to 10 MHz, operating in the 5.9 GHz ITS band, which is commonly used for vehicular communication.

The propagation environment is modelled using the WINNER+ B1 model, which represents urban microcell conditions with moderate shadowing effects. The receiver noise figure is set to 9 dB, while both transmitter and receiver antenna gains are configured at 3 dB.

In terms of communication settings, the packet size is set to 350 bytes, and the transmission follows periodic intervals to simulate Cooperative Awareness Messages. The number of available subchannels is configured to five, allowing resource allocation among vehicles in the network.

Furthermore, the resource keep probability is set to 0.4, which controls the persistence of resource allocation in the semi-persistent scheduling mechanism. The SINR threshold is configured automatically, enabling adaptive reception performance under varying channel conditions.

Overall, these parameter configurations enable the evaluation of V2V communication performance under realistic channel conditions and varying network densities.

E. Simulation Execution and Performance Evaluation

The simulation is executed using the main script *WiLabV2Xsim.m*, which reads the predefined simulation configuration file (.cfg) along with the mobility trace input. The simulation results are exported in .csv format and subsequently processed for graphical visualization and performance analysis.

The system performance is evaluated using the following metrics:

1. Packet Reception Ratio (PRR)
2. Channel Busy Ratio (CBR)
3. Packet delay

The Packet Reception Ratio (PRR), as defined in (1), measures the reliability of communication between vehicles. Meanwhile, the Channel Busy Ratio (CBR), as defined in Bazzi et al. [2], is used to assess channel utilization under varying network densities [8].

In addition, packet delay is used to measure the time required for a packet to be successfully delivered from the transmitting node to the receiving node, reflecting the latency performance of the V2V communication system.

III. SCENARIO DESCRIPTION AND PERFORMANCE EVALUATION

A. Simulation Scenario Description

This study evaluates C-V2X-based Vehicle-to-Vehicle (V2V) communication in a semi-enclosed environment within a 5G-enabled vehicular network context. The simulation is conducted using two main platforms: SUMO for realistic vehicular mobility modeling and WiLabV2Xsim for communication performance evaluation.

The simulation area is generated using OpenStreetMap (OSM) data, which are processed in SUMO to create the network file (.net.xml) and vehicle route file (.rou.xml). The use of real-map data has been shown to improve the accuracy of road network representation and vehicular mobility patterns compared to synthetic models [9].

The selected environment represents a university campus area in Bandung, Indonesia, characterized by semi-enclosed conditions due to the presence of buildings, vegetation, and constrained road segments. These environmental factors may introduce propagation challenges such as multipath fading and signal shadowing [10].

The simulation is conducted under varying network configurations to evaluate the impact of system parameters on communication performance. Specifically, three levels of vehicle density (100, 300, and 500 nodes) are considered. In addition, two bandwidth configurations (10 MHz and 20

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MHz) and two transmission power levels (23 dBm and 26 dBm) are applied to analyze their effects on Packet Reception Ratio (PRR) and Channel Busy Ratio (CBR). Fig. 6 shows the simulation area derived from OpenStreetMap and converted into a SUMO network model.



Fig. 6. Simulation area derived from OpenStreetMap and converted into a SUMO network model.

Table III summarizes the main simulation parameters and scenario configurations used in this study.

TABLE III. SUMMARY OF SIMULATION PARAMETERS AND SCENARIO CONFIGURATIONS.

Parameter	Value	Description
Operating Frequency	5.9 Ghz	Band C-V2X (ITS)
Bandwidth	10 MHz	Communication Channel
Transmit Power	26 dBm	Transmit Power
Propagation model	WINNER + B1 Urban Micro	Urban Propagation Model
Simulation time	300s	Simulation Duration
Mobility Model	Trace-Driven SUMO	Realistic Vehicle Mobility
Environment	Semi-Enclosed (Urban)	Telkom University Bandung campus area
PHY/MAC Layer	5G-V2X Mode 4	Communication V2V
Output Metrics	PRR, CBR, Delay	Network Performance Indicator

Based on Table III, the system operates at a carrier frequency of 5.9 GHz within the Intelligent Transportation Systems (ITS) band. The propagation environment is modelled using the WINNER+ B1 Urban Micro model to represent semi-enclosed urban conditions.

The mobility model is based on a trace-driven approach using SUMO-generated vehicle movement, ensuring realistic traffic behaviour. The simulation duration is set to 300 s to capture sufficient network dynamics, while performance is evaluated using key metrics, including PRR, CBR, and packet delay.

B. Channel Model and Communication Configuration

The propagation model adopted in this study is the WINNER+ B1 Urban Micro model, which represents semi-enclosed urban environments by considering the effects of multipath propagation and small-scale fading. This model is suitable for capturing realistic signal behaviour in environments with physical obstructions such as buildings and vegetation.

Each node is configured to periodically transmit Cooperative Awareness Messages (CAMs) at an interval of 100 ms, in accordance with the specifications defined in 3GPP TS 36.885. Periodic CAM transmission plays a crucial role in supporting vehicular safety applications by enabling continuous exchange of vehicle status and positional information among neighbouring vehicles [11].

The communication configuration employs C-V2X Mode 4, which utilizes a distributed resource allocation mechanism based on sensing-based semi-persistent scheduling. The main communication parameters include an operating frequency of 5.9 GHz, bandwidth configurations of 10 MHz and 20 MHz, and transmission power levels of 23 dBm and 26 dBm.

C. Units

Packet Reception Ratio (PRR) is employed as a key performance metric to evaluate the reliability of packet reception between vehicles. It is defined as:

$$\text{PRR} = \frac{Nreceived}{Nsent} \quad (1)$$

where $N_{received}$ represents the number of packets successfully received by the receiver, while N_{sent} denotes the total number of packets transmitted by the sender.

A high PRR value indicates a reliable vehicular communication link, whereas a low PRR reflects increased interference, propagation loss, or channel congestion. Fig. 7 shows the PRR as a function of inter-vehicle communication distance under different node density scenarios.

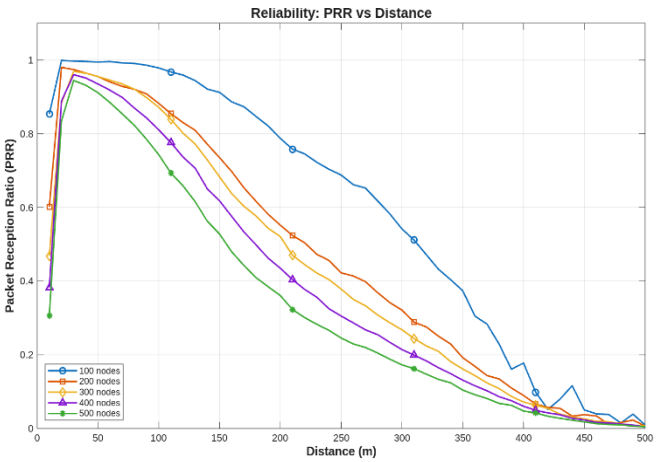


Fig. 7. Packet Reception Ratio as a function of communication distance under varying node densities.

As shown in Fig. 7, PRR decreases as both communication distance and node density increase across all evaluated scenarios. This behavior indicates that communication reliability degrades in dense vehicular environments due to increased packet collisions and channel contention.

For the 10 MHz bandwidth configuration, PRR decreases significantly as the number of nodes increases, with a noticeable drop from approximately 0.59 for 100 nodes to around 0.34 under higher-density conditions. A similar trend is observed for the 20 MHz configuration, where PRR declines from approximately 0.54 to 0.35 as node density increases.

This degradation trend is consistent with previous studies, which show that increasing node density raises the probability of packet collisions and inter-vehicle interference [12].

Furthermore, increasing the bandwidth to 20 MHz results in an average PRR improvement of approximately 8–12% compared to the 10 MHz configuration. This improvement is attributed to increased channel capacity, which reduces congestion and enables more efficient resource allocation.

In contrast, increasing transmission power from 23 dBm to 26 dBm improves PRR under low-density scenarios due to enhanced signal strength and extended communication range. However, under high-density conditions, the improvement becomes marginal. This is primarily caused by increased interference among neighboring nodes, which offsets the benefits of higher transmission power, as also reported in Khan et al. [11].

D. Channel Busy Ratio (CBR) Analysis

Channel Busy Ratio (CBR) is employed to quantify the level of channel occupancy at the physical layer and is defined as:

$$\text{CBR} = \frac{Tbusy}{Ttotal} \quad (2)$$

where T_{busy} denotes the duration during which the communication channel is sensed as occupied, and T_{total} represents the total observation time. CBR is widely used as an indicator of channel utilization and network congestion in vehicular communication systems [13]-[15].

Fig. 8 presents the cumulative distribution function (CDF) of the Channel Busy Ratio under varying node densities.

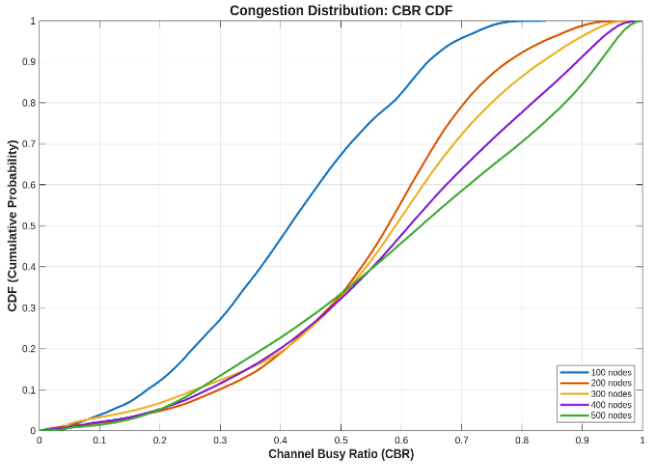


Fig. 8. Cumulative distribution function of Channel Busy Ratio under varying node densities.

As shown in Fig. 8, the distribution of CBR shifts toward higher values as the number of nodes increases. This trend indicates a consistent increase in channel utilization across different vehicular densities. In low-density scenarios, most CBR values remain within a narrow range, reflecting limited packet transmissions and longer idle periods of the communication channel.

In contrast, high-density scenarios significantly increase channel occupancy due to more frequent packet transmissions, which leads to higher contention and inter-node interference [16]. Similar observations have been reported in recent studies on C-V2X and NR-V2X systems, where increasing vehicle density results in more frequent channel access due to periodic safety message exchanges [17].

Fig. 9 shows the average Channel Busy Ratio as a function of vehicle density. The results in Fig. 9 indicate a near-linear increase in CBR with respect to the number of nodes. For the 10 MHz bandwidth configuration, the CBR reaches approximately 0.63 at 500 nodes, indicating that the channel approaches saturation. In contrast, the 20 MHz configuration results in a lower maximum CBR of approximately 0.57, reflecting improved channel stability due to higher bandwidth availability.

Furthermore, increasing the transmission power expands the interference range, which contributes to higher CBR values, particularly under dense network conditions. This behavior is consistent with findings in Arockiasamy and Vinel [18], where higher transmission power increases channel interference in vehicular networks.

When analyzed together with the PRR results, an inverse relationship between CBR and PRR can be observed. As node density increases, higher channel occupancy leads to increased packet collisions and interference, resulting in a degradation of PRR.

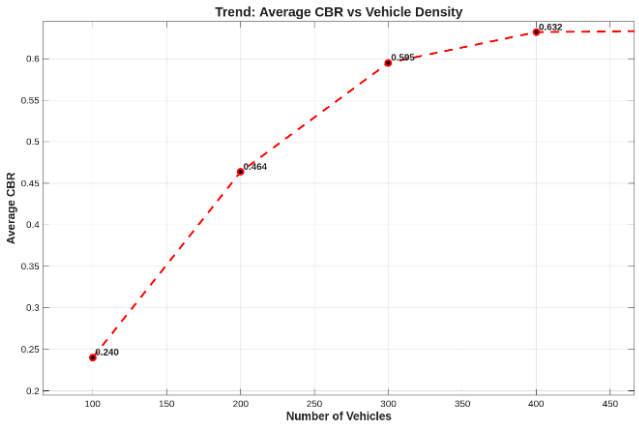


Fig. 9. Average Channel Busy Ratio as a function of vehicle density.

This trade-off highlights the importance of balancing channel utilization and communication reliability in C-V2X systems.

Unlike previous studies that primarily focus on highway or urban scenarios with synthetic mobility models [18], [19]; this study adopts a real-map-based mobility scenario in a semi-enclosed campus environment. This approach provides a more representative evaluation of communication performance under complex propagation conditions, including multipath effects and dynamic node density variations.

Overall, the results demonstrate that channel congestion is a key limiting factor in dense vehicular networks, emphasizing the need for adaptive resource management mechanisms to maintain reliable V2V communication.

E. End-to-End Packet Delay Analysis

End-to-end delay is a critical metric in evaluating V2V communication performance, as it represents the total time required for a packet to be transmitted from the sender to the receiver. This metric directly reflects the latency performance of the communication system and significantly impacts the reliability of time-sensitive vehicular applications.

Previous studies [8], [20]-[23] have shown that increasing vehicle density and channel load leads to higher latency due to increased channel contention, interference, and packet collisions. Fig. 10 shows the end-to-end packet delay as a function of communication distance under different node density scenarios.

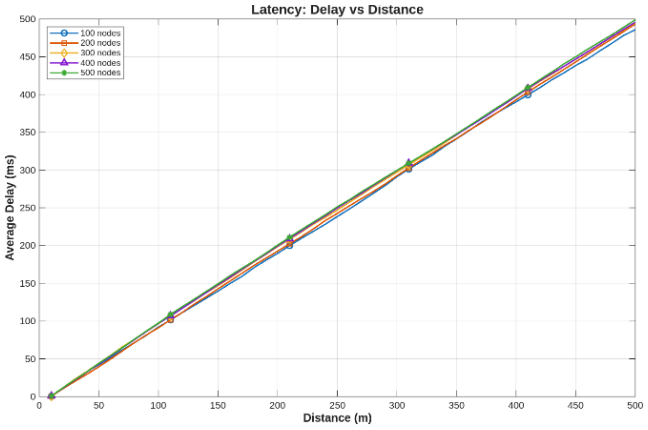


Fig. 10. End-to-end packet delay as a function of communication distance under varying node densities.

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As shown in Fig. 10, the packet delay increases almost linearly with communication distance across all evaluated scenarios. This behaviour is primarily caused by propagation delay and increased transmission time as the communication range expands.

In addition to distance, vehicle density also contributes to increased delay. In high-density scenarios (400–500 nodes), the delay curves slightly exceed those of lower-density scenarios, indicating the compounded impact of network load and channel contention.

Furthermore, higher Channel Busy Ratio (CBR) values under dense network conditions result in more frequent channel occupation. This forces each node to wait longer for available radio resources, thereby increasing transmission latency. This observation is consistent with the previously identified inverse relationship between PRR and CBR.

These results indicate that delay performance in C-V2X systems is influenced by both propagation characteristics and network load. As vehicle density increases, the combined effects of interference, contention, and channel congestion lead to higher latency.

The findings are consistent with prior studies [24]-[29], which demonstrate that increased vehicle density in C-V2X and NR-V2X networks significantly degrades latency performance, particularly in scenarios involving periodic safety message transmission.

F. Relationship Between PRR and CBR

The analysis reveals an inverse relationship between the Packet Reception Ratio (PRR) and the Channel Busy Ratio (CBR). As node density increases, CBR rises due to intensified spectrum access contention, which subsequently leads to a decline in PRR as a result of increased packet collisions and channel interference.

This relationship highlights the fundamental trade-off between channel utilization and communication reliability in C-V2X sidelink communication. Higher channel occupancy, as indicated by elevated CBR values, reduces the probability of successful packet reception, thereby degrading PRR performance.

These findings are consistent with previous studies, which demonstrate that increasing transmission power in dense vehicular networks does not necessarily improve PRR. Instead, it may exacerbate interference and reduce the Signal-to-Interference-plus-Noise Ratio (SINR), ultimately degrading communication reliability [8], [11], [20].

Furthermore, the combined observations from PRR, CBR, and delay analyses indicate that network performance in dense vehicular environments is predominantly interference-limited rather than power-limited. This implies that simply increasing transmission power is insufficient to improve communication performance under high node density conditions.

Collectively, these results emphasize the importance of adaptive resource management strategies, including power control, dynamic resource allocation, and congestion control mechanisms, to maintain reliable V2V communication in dense C-V2X networks.

G. Comparison with Recent Studies

To further substantiate the contribution of the proposed framework, Table IV provides a comprehensive quantitative comparison with representative C-V2X and NR-V2X studies published between 2022 and 2025. The comparison encompasses the simulation environment, mobility modeling strategy, communication technology, performance evaluation metrics, and key findings to position the proposed work within the current state of the art. In contrast to existing studies, which predominantly consider highway or generic urban scenarios, the proposed framework employs a trace-driven mobility model derived from the actual road topology of Telkom University Bandung. This realistic mobility representation enables a more faithful characterization of V2V communication performance under the complex propagation conditions of a semi-enclosed campus environment, thereby enhancing the practical relevance and applicability of the simulation outcomes.

TABLE IV. THE PERFORMANCE METRICS

Reference	Scenario	Mobility	Technology	Metrics	Main Findings	PRR	CBR
[30]	Urban	SUMO	5G V2X	PRR, Delay	Evaluation platform	0.87	-
[31]	Urban	Generic	NR-V2X	PRR	Numerology evaluation	0.82	-
[32]	Urban	SUMO	C-V2X	PRR, CBR	Resource Allocation	0.79	0.51
[33]	Highway	Real Traffic	C-V2X	PRR	Large-scale traffic	-	-
This Work	Semi–enclosed Campus	Real OSM + SUMO	5G C-V2X	PRR, CBR, Delay	Realistic campus evaluation	0.59-0.34	0.21-0.63

As presented in Table IV, the performance metrics reported in this study should not be interpreted as a direct numerical comparison with those of previous works. Variations in mobility scenarios, propagation environments, communication configurations, traffic generation models, and network densities inevitably lead to different communication characteristics and performance outcomes. Consequently, metrics such as Packet Reception Ratio (PRR), Channel Busy Ratio (CBR), and end-to-end delay are highly scenario-dependent and must be interpreted within the context of the underlying simulation assumptions rather than as absolute performance indicators.

Nevertheless, the comparison provides a meaningful benchmark for positioning the proposed framework within the current body of C-V2X research. Most existing studies published between 2022 and 2025 primarily evaluate vehicular communications under highway or generic urban environments using synthetic mobility models and simplified propagation assumptions. In contrast, the proposed framework integrates a trace-driven mobility model generated from the actual road topology of Telkom University Bandung with WiLabV2Xsim, thereby enabling a more realistic representation of vehicular mobility and wireless propagation in a semi-enclosed campus environment. Such an environment inherently exhibits more complex radio propagation characteristics, including signal blockage, shadowing, and multipath fading caused by surrounding buildings, vegetation, and constrained road corridors.

Furthermore, unlike previous studies that predominantly investigate a single communication parameter, the proposed framework simultaneously examines the combined effects of node density, channel bandwidth, and transmission power on communication reliability, channel utilization, and packet latency. This comprehensive evaluation provides a more

holistic understanding of C-V2X network scalability under realistic vehicular traffic conditions and offers valuable insights for the deployment of intelligent transportation systems in campus-scale and other semi-enclosed environments. Therefore, the primary contribution of this work lies not in achieving superior numerical performance, but in providing a more representative, scalable, and practically relevant evaluation framework for next-generation vehicular communication systems.

IV. CONCLUSION

A. Conclusion

This study presented the implementation and performance evaluation of C-V2X-based Vehicle-to-Vehicle (V2V) communication using a simulation framework integrating SUMO and WiLabV2Xsim in a semi-enclosed environment. The trace-driven approach based on real-map data successfully captured realistic vehicular mobility and communication conditions, enabling a representative evaluation of V2V performance under varying network densities.

The results demonstrate that increasing vehicle density significantly degrades communication performance. This is reflected by the decline in Packet Reception Ratio (PRR) and the increase in Channel Busy Ratio (CBR), indicating higher channel contention, interference, and network congestion. Furthermore, the analysis reveals that system performance in dense vehicular scenarios is predominantly interference-limited, where increasing transmission power does not necessarily improve reliability due to intensified interference effects.

Based on these findings, adaptive resource management strategies, including dynamic power control, efficient channel allocation, and congestion-aware mechanisms, are essential to maintain reliable V2V communication in 5G-based C-V2X systems. For future work, the integration of intelligent optimization approaches, such as machine learning-based resource management and adaptive scheduling, is recommended to further enhance system performance under dynamic network conditions.

B. Limitation and Future Work

Despite the promising findings demonstrated by the proposed simulation framework, several limitations should be acknowledged to ensure a balanced interpretation of the results. First, the present study relies exclusively on a simulation-based evaluation by integrating SUMO and WiLabV2Xsim, without validation through real-world experiments using commercial C-V2X hardware or field measurements. Consequently, practical implementation factors including hardware non-idealities, clock synchronization inaccuracies, radio frequency impairments, and dynamic interference originating from heterogeneous wireless systems are not fully captured.

Second, the evaluation is confined to a single semi-enclosed campus environment represented by the road topology of Telkom University Bandung. Although this scenario provides a realistic representation of campus-scale vehicular communications, the resulting performance characteristics cannot be directly generalized to other deployment scenarios, such as highways, suburban areas, or highly congested metropolitan environments, each of which exhibits distinct mobility patterns and wireless propagation characteristics.

Finally, the communication framework is based on the 3GPP Release 14 C-V2X Mode 4 sidelink configuration and therefore does not exploit the enhanced capabilities introduced by subsequent NR-V2X specifications, including advanced resource allocation mechanisms, distributed congestion control, cooperative perception, and artificial intelligence-assisted radio resource management, these emerging technologies have recently been recognized as key enablers for improving communication reliability, scalability, and spectral efficiency in next-generation vehicular networks [34]-[36].

Future research will therefore focus on validating the proposed framework through real-world experimental campaigns, extending the evaluation to diverse vehicular environments, and incorporating advanced NR – V2X Release 16/17 functionalities to further improve communication robustness and network scalability under dense vehicular traffic conditions.

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