Integrating 5G into VANETs: Methodological Approaches and Performance Evaluation Through Simulation

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Abstract: The integration of 5G technology with Vehicular Ad-hoc Networks (VANETs) represents a significant advancement in the field of Intelligent Transportation Systems (ITS). This paper explores the potential of 5G to enhance real-time communication between vehicles and infrastructure, aiming to improve road safety and traffic management. Using simulation tools such as OMNeT++ and SUMO, various traffic scenarios were modeled to assess the performance of the integrated 5G-VANET system. Key performance indicators including end to end latency, packet loss, and node acceleration behaviour were evaluated. The results indicate that the integration of 5G reduces communication latency to below 10 milliseconds and achieves packet delivery rates exceeding 95% in high-density traffic situations. This study demonstrates the feasibility of 5G-enhanced VANETs, highlighting their potential to contribute to safer and smarter transportation systems.

1 INTRODUCTION

The transportation sector is undergoing a transformative shift with the integration of emerging communication technologies aimed at improving road safety, reducing traffic congestion, and supporting autonomous vehicle operations. Vehicular Ad-hoc Networks (VANETs) (Balen, 2022), a subset of Mobile Ad-hoc Networks (MANETs), play a crucial role in this transformation by enabling real-time communication between vehicles (V2V) and between vehicles and roadside infrastructure (V2I). VANETs allow for the exchange of critical information such as vehicle position, speed, and traffic conditions, which are essential for safety applications like collision avoidance, emergency vehicle routing, and traffic flow optimization. However, existing communication networks such as 4G LTE are unable to fully meet the stringent requirements of modern VANET applications, particularly in terms of latency, bandwidth, and connection density. The emergence of Fifth Generation (5G) mobile networks (Banafaa, 2024) is seen as a game-changer for vehicular communication systems. 5G networks provide ultra-reliable low-latency communication (uRLLC), enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC), all of which are critical for supporting the complex and dynamic environment of VANETs. These features enable faster data transmission, improved reliability, and the ability to connect a vast number of devices, making 5G the ideal network for supporting intelligent transportation systems (ITS).

One of the key challenges in vehicular networks is maintaining reliable and low-latency communication, especially in high-speed environments where vehicles frequently enter and leave communication ranges. 5G's low-latency features are designed to address this issue by enabling real-time communication between vehicles and infrastructure, which is vital for applications such as cooperative collision avoidance and autonomous driving. Moreover, 5G's ability to support dense networks with numerous connected devices ensures that VANETs can operate efficiently even in high-traffic areas. As the number of vehicles on the road continues to increase, the limitations of current communication technologies become more apparent. 4G LTE networks, while adequate for many applications, struggle to support the high-speed, low-latency communication required by safety-critical vehicular applications. The main challenges addressed by this project are:

- Network Scalability: In dense urban environments, the number of connected vehicles

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and devices places a heavy burden on the network, leading to congestion and packet loss. Traditional networks cannot scale effectively to meet this demand.

- Reliability: Vehicular communication must be reliable, even in challenging environments such as tunnels, urban canyons, and high-speed highways. Ensuring consistent connectivity and data transmission in these environments is critical.

The problem, therefore, lies in finding a way to enhance VANET communication by leveraging 5G's capabilities to provide faster, more reliable data exchange and ensure network performance, even in the most demanding conditions.

Various approaches to enhance communication performance and reliability in vehicular networks have been conducted. To maintain optimal traffic flow, a swarm intelligence-based method was developed to support the formation and evolution of platoons (Mushtaq, 2021). A fuzzy logic-based weighting model was introduced to prioritize vehicles in traffic (Abbasi, 2022), and a 3D road network model using digital surface models was developed to support multi-level communications (Brummer, 2019). Authors in (Irani, 2024)] present VSIM, a new simulator for MANET and ad hoc networks that balances user-friendliness, modularity, scalability, and open-source accessibility, providing accurate, reliable results validated against NS-2 and supporting a range of routing protocols, mobility models, and performance evaluation tools. Project (Taher, 2024) evaluates the use of the software-defined network (SDN) protocol with AODV and OLSR protocols in LTE-based VANETs, demonstrating that SDN enhances packet delivery ratio (PDR) and reduces delivery delay by leveraging SDN controllers for optimal routing, outperforming AODV and OLSR in varying vehicle densities and speeds. Paper (Zanotto, 2024) extends the Veins vehicular network simulator to incorporate 3D factors—such as building height, obstacles, altitude, and antenna positioning improving the accuracy of mobile network coverage assessments with only a limited increase in simulation time.

Our research focuses on the integration of 5G with VANET technologies, aiming to enhance vehicular communication systems by leveraging the advanced capabilities of 5G networks. The study adopts the V-model for the development and validation of the integrated system, ensuring a structured approach that includes rigorous testing at each phase of the project. Through extensive simulations, this research evaluates key performance indicators (KPIs) such as end to end latency, packet loss, and node acceleration behaviour, providing insights into the benefits of 5G-enhanced VANET systems under various traffic scenarios. To address these challenges, the project proposes the integration of 5G networks into VANET systems, focusing on improving the reliability and speed of vehicular communication. The proposed solution includes the following components:

- On-Board Units (OBUs) and Roadside Units (RSUs): Vehicles equipped with OBUs will communicate with RSUs using 5G-enabled protocols, ensuring that data can be exchanged quickly and reliably, even in high-speed environments. These units will handle critical data such as vehicle speed, position, and trajectory to enable safety applications.
- uRLLC: 5G's uRLLC feature will be employed to minimize latency, ensuring that vehicles can share real-time data, such as accident warnings or traffic updates, almost instantaneously. This is essential for applications such as cooperative adaptive cruise control (CACC), where vehicles must react to changes in road conditions or traffic behaviour in real time.
- Scenario Testing and Evaluation: The system will be tested in simulated environments to evaluate how it performs in different scenarios. For example, high-density urban traffic, freeway driving, and emergency vehicle routing will be simulated to assess the system's ability to maintain low latency and high throughput under various conditions.

The rest of this paper is organized as follows: Section 2 presents the methodological approach used in this study, detailing the V-model and justifying its selection over other methodologies such as Scrum. Section 3 describes the simulation setup, tools and presents the results of the simulations, analyzing the performance of the 5G-VANET system under different conditions. Finally, Section 4 concludes the paper with a summary of the findings and suggestions for future research directions.

2 METHODOLOGY

2.1 Methodological Approach

For this project, two software development methodologies were considered: The V-model and Scrum. The V-model, also known as the Verification and Validation model, is a highly structured approach that requires sequential development. Each phase of development has a corresponding testing phase, ensuring that any issues are identified and resolved before moving to the next stage. This approach is particularly well-suited for projects with stable requirements and where quality and accuracy are paramount. In contrast, Scrum is an Agile methodology that focuses on iterative development, promoting flexibility and collaboration among team members. Scrum is better suited for projects with evolving requirements, allowing for rapid adjustments and continuous delivery of working software. Given the stable and well-defined requirements of the VANET and 5G integration, the V-model's sequential approach offers better accuracy and ensures high-quality deliverables. Although Scrum is widely used in modern software development, its flexibility is not required for this project, and the additional overhead of iterative cycles would not provide significant benefits. Therefore, the V-model was deemed more suitable for ensuring that all critical phases were carefully tested and validated before moving to the next.

2.2 VANET Implementation

Implementing VANETs with 5G technology comes with its own set of challenges, scenarios, routing protocols, and security concerns.

2.2.1 Challenges

While the integration of 5G into VANETs offers numerous benefits, several challenges must be addressed:

- **Network Stability:** Maintaining stable connections in high-speed and rapidly changing environments is difficult due to vehicles moving in and out of communication range frequently.
- **Data Privacy and Security:** Ensuring secure communication between vehicles and infrastructure is crucial, as malicious attacks could compromise safety. Security measures must be robust enough to protect against data breaches and unauthorized access.
- **Interoperability:** As different manufacturers develop their own communication standards, achieving interoperability between various systems is essential for seamless integration.

2.2.2 Scenarios

Various scenarios can be simulated to evaluate the effectiveness of VANETs in real-world conditions:

- Urban Traffic Management: Scenarios involving dense urban environments where vehicles must navigate through heavy traffic and communicate with traffic signals to optimize flow.
- Emergency Response: Simulations of emergency vehicles utilizing V2V and V2I communication to navigate through traffic quickly, reducing response times in critical situations.
- Highway Driving: Evaluating the performance of vehicles in high-speed environments to ensure that communication remains stable and reliable during rapid vehicle movement.

3 IMPLEMENTATION AND RESULTS

This section covers the tools, environment setup, and results from the simulation of vehicular networks using 5G technology. The simulation was implemented with SUMO (SUMO, 2024) for traffic simulation, OMNeT++ (OMNeT, 2024) for network simulation, and Veins (VEINS, 2024) for VANET simulation, deployed on the Cloud.

3.1 Environment Setup and Tools

The simulation environment was built using a combination of hardware and software tools. Hardware included an Intel Core i5 processor with 16GB RAM. Key software components used:

- **OMNeT++**: A modular C++ simulation library for building network simulators, used for handling discrete event simulations.
- **Veins**: A framework for simulating VANETs, integrated with OMNeT++ and SUMO.
- **INET Framework**: Used for simulating communication networks, protocols, and applications.
- **SUMO**: A traffic simulation package that provides accurate road traffic models.
- **JOSM**: An application for editing and extracting maps for use with SUMO to generate realistic traffic models (JOSM, 2024).

3.2 Work Environment Configuration

The simulation environment required the installation and configuration of OMNeT++ and the Veins/INET framework. Steps involved extracting files, importing projects into OMNeT++, and configuring various project references. Veins and INET were crucial for simulating vehicular communication with 5G capabilities. Veins was used to simulate vehicle communication protocols (V2X), focusing on ultra-reliable low-latency communication (uRLLC). INET provided a broader range of protocols and performance evaluation tools for testing the throughput, latency, and packet loss in 5G networks.

3.3 AODV Integration with Veins

The simulation incorporated the AODV routing protocol to manage vehicle-to-vehicle communication. This required configuration of INET and Veins to enable seamless operation in the OMNeT++ environment. The protocol was configured in the omnetpp.ini file, and its behaviour was tested under various traffic and accident scenarios. The following points show the cade enabling the integration of AODV in routing for nodes with :

*node[*].ipv4.configurator.typename = "HostAutoConfigurator": Specifies that IPv4 addresses will be automatically configured for each node.

*.node[*].ipv4.configurator.interfaces = "wlan0": Specifies the interface to be used for IPv4 configuration.

*.node[*].ipv4.configurator.mcastGroups = "224.0.0.1": Configures multicast groups for IPv4. Mobility:

*.node[*].mobility.typename = "VeinsInetMobility": Configures mobility using the Veins framework with INET mobility support.

*.manager.updateInterval = 0.1s: Sets the update interval for the VeinsInetManager.

*.manager.host = "localhost": Specifies the host for the manager.

*.manager.port = 9999: Specifies the port for communication.

*.manager.autoShutdown = true: Enables automatic shutdown of the manager.

*.manager.launchConfig = xmldoc("square.launchd.xml"): Specifies the launch configuration file for the manager.

*.manager.moduleType = "vanettutorials.veins_inet.VeinsInetRoutingCar": Specifies the module type for the manager. Vector Recording:

**.vector-recording = true: Enables vector recording for the simulation. Routing:

**.router = "Aodv": Specifies the routing protocol to be used. Here, it's set to AODV

3.4 Collision Avoidance Simulation

An accident scenario was introduced in the simulation, focusing on the behaviour of nodes (vehicles) during an accident. Node 5 was set to simulate an accident, affecting its communication and network performance. The impact of this accident was analyzed, particularly in terms of packet loss and deceleration behaviour. In the accident scenario involving Node 5, communication delays led to the late transmission of emergency braking messages to nearby vehicles. This delay caused increased reaction times, resulting in near-collision events for vehicles within a 50-meter radius. After integrating the AODV protocol now we are looking for nodes behaviour when an accident occurs:

Node 5 experiences an accident which impacts the network performance and traffic flow. This scenario is critical for evaluating the robustness and reliability of the vehicular network under emergency conditions.

As shown in Figure 1, node 5 is depicted in red to indicate that an accident has occurred at this location. The red color is used to highlight the status of Node 5, making it immediately recognizable as a critical event in the simulation. This visual representation helps in quickly identifying nodes that are involved in

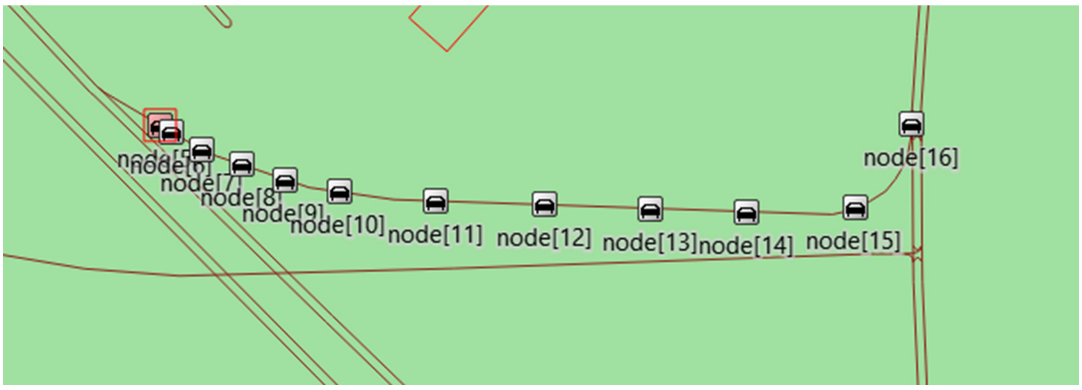

Figure 1: Node 5 has experienced an accident.

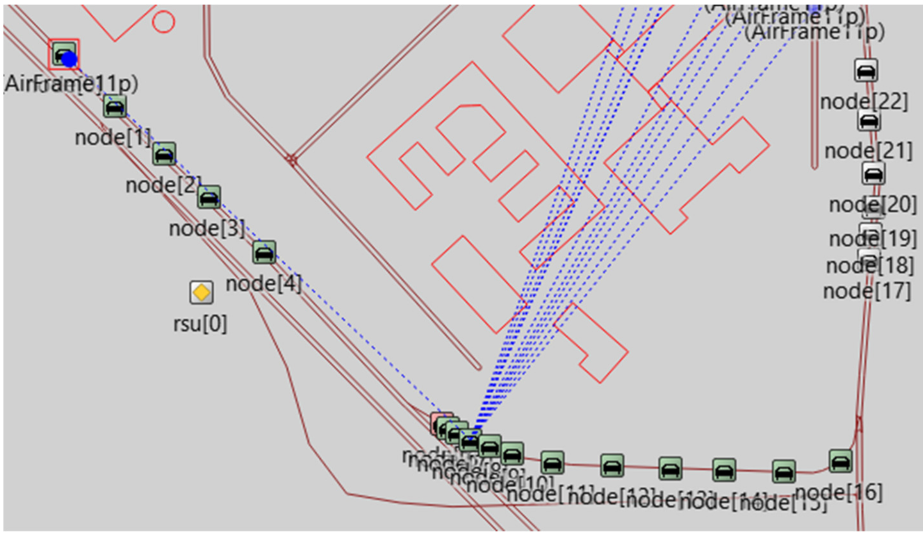

Figure 2: RSU Communicating with nodes.

accidents, allowing for a more efficient analysis of how such incidents impact network performance and traffic flow.

After running the simulation, the nodes turn green due to successful communication with the RSU. The green color indicates that the nodes are receiving signals and exchanging data with the RSU, confirming active participation in the vehicular network as depicted in figure 2.

3.5 Simulation Parameters

Key simulation parameters included the playground size, node behaviour during accidents, transmission power, and noise floor. Table 1 outlines the key parameters used in the simulation. The playground size is set to 2500 meters in both the X and Y directions and 50 meters in the Z direction. Node [5] is configured to experience an accident starting at 73 seconds into the simulation and lasting for 50 seconds. The network configuration does not use the service channel, and the nodes transmit with a power of 20 milliwatts at a bit rate of 6 Mbps. The minimum power level for the physical layer is set to -110 dBm, and noise floor usage is enabled with a value of -98 dBm. The decider and analogue models are specified through XML configurations.

3.6 Simulation Results

In this section, we conduct a detailed analysis of the packet behaviour during accidents. The data reveals that accidents significantly impact packet transmission, resulting in increased packet loss and fluctuations in packets sent. This analysis is crucial for understanding and improving the robustness of VANET systems in real-world scenarios.

3.6.1 Total Distance

The bar plot of the Figure 3 depicts the total distance for each module. Key insights include:

Table 1: Simulation Parameters.

Parameter	Value
Playground Size (X)	2500m
Playground Size (Y)	2500m
Playground Size (Z)	50m
Node[5] Accident Count	1
Node[5] Accident Start	73s
Node[5] Accident Duration	50s
Use Service Channel	false
Transmission Power	20mW
Bitrate	6Mbps
Minimum Power Level	-110dBm
Use Noise Floor	true
Noise Floor	-98dBm
Use Propagation Delay	true

- There is a noticeable variation in the total distance covered by different nodes.
- Some nodes cover significantly higher distances, which could indicate specific roles or activities within the experiment that require more extensive movement.
- nodes with lower distances might be involved in more static or localized tasks.
- The plot allows for easy comparison across nodes, highlighting which nodes are outliers in terms of distance covered.

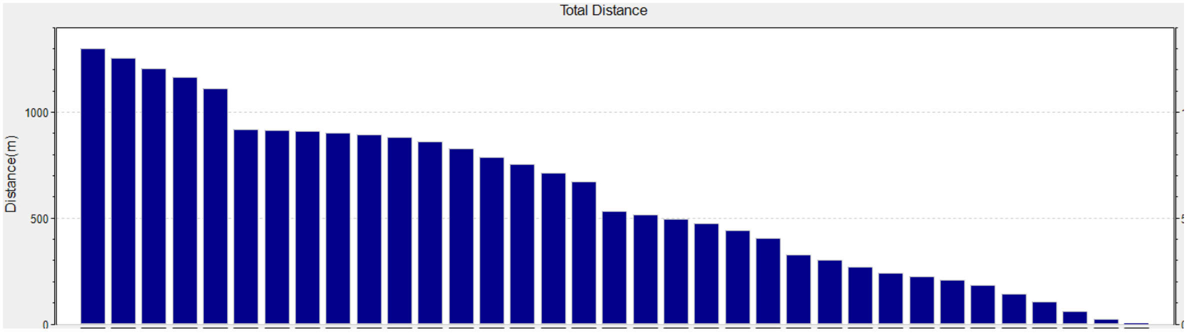

Figure 3: Total distance for each module.

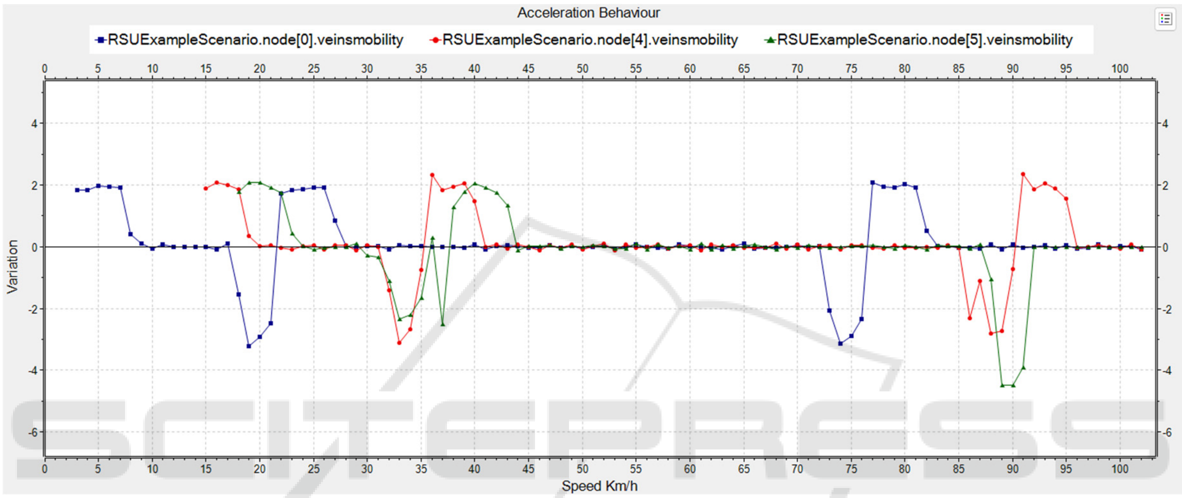

Figure 4: Acceleration Behaviour for nodes when the accident happens.

3.6.2 Acceleration Behaviour

Figure 4 delineates the graphical representation when the nodes had and accident and their behaviour before and after the accident. The behaviour of each node can be understood through their acceleration profiles. Nodes with high deceleration and variability, such as Node 5, are likely facing significant obstacles or events that force them to slow down frequently, potentially leading to packet loss due to unstable connectivity. In contrast, nodes with positive or stable mean acceleration and lower variability maintain more consistent speeds, resulting in better network performance and fewer packet loss incidents.

3.6.3 Insights

- Node 0 has the highest average acceleration and also exhibits the highest maximum acceleration value, indicating more significant speed changes compared to the other nodes.
- Node 5 and Node 6 have similar mean accelerations, which are slightly negative, suggesting that on average, these nodes might be decelerating slightly more often than accelerating.
- The standard deviations indicate that the accelerations of all nodes fluctuate significantly, with Node 5 showing the highest variability.
- The minimum acceleration values for all nodes are quite similar, with Node 5 showing the lowest minimum value, which indicates a significant deceleration event.

These statistics and the visual representation provide insights into the behaviour of the nodes during the simulation, particularly in response to events such as accidents. This analysis can help understand how nodes react and adapt their speed, which is critical for evaluating the performance and safety of the vehicular network.

3.6.4 Overall Packet Loss

The total number of lost packets across all nodes 19. These plots help identify specific nodes that might be experiencing higher-than-expected packet loss,

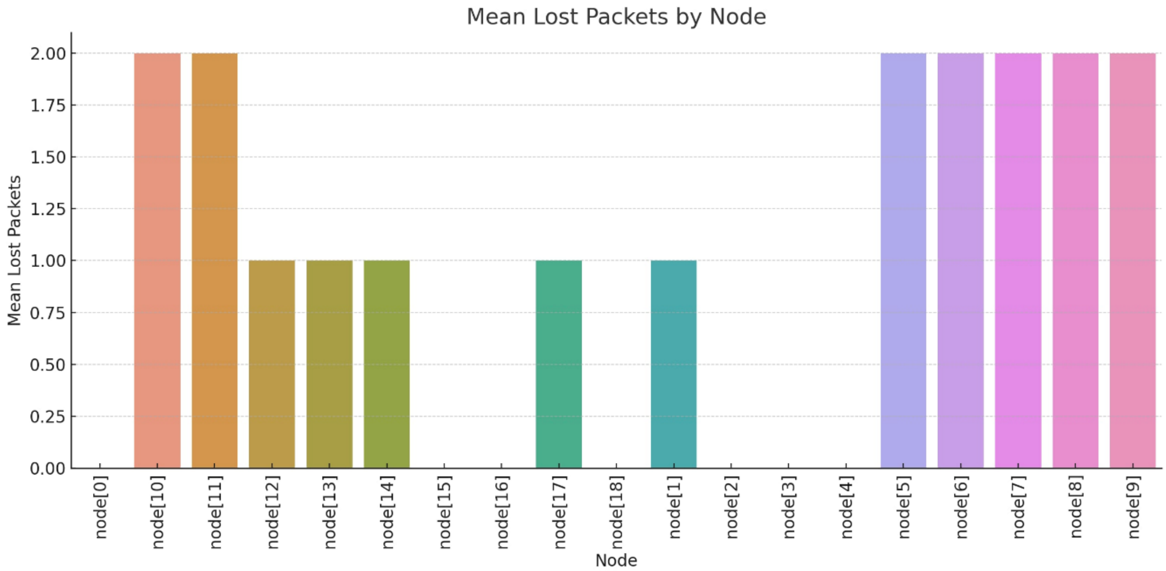

Figure 5: Tatal number of lost packets.

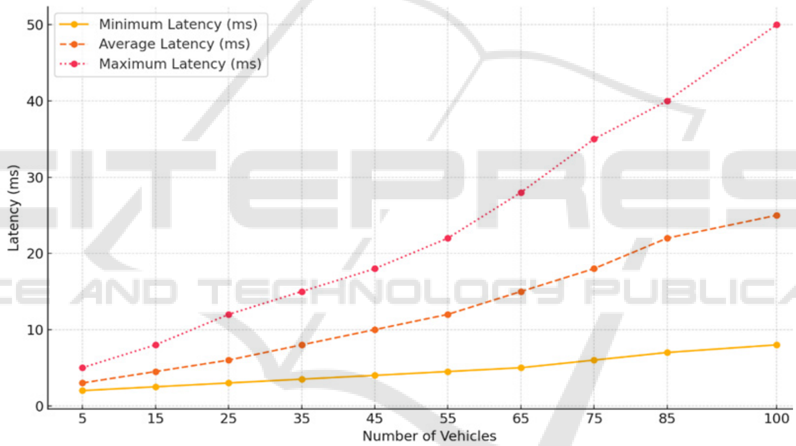

Figure 6: End to end latency variation.

making it easier to pinpoint potential issues for further investigation or optimization. Total Lost Packets by Node: This bar plot shows the sum of all lost packets for each node, providing an overview of which nodes experienced the highest and lowest total packet loss as shown in the Figure 5.

3.6.5 Acceleration Insights

• Node 0:

– Highest average acceleration and maximum acceleration.

– More significant speed changes compared to other nodes.

• Nodes 5 and 6:

– Similar mean accelerations, slightly negative (indicating slight deceleration on average).

– Node 5 has the highest variability in acceleration.

– Node 5 also has the lowest minimum acceleration value (significant deceleration event).

3.6.6 End-to-End Latency

In the context of this simulation scenario, we meticulously assessed the end-to-end latency within a 5G-VANET framework where the vehicular count fluctuated between 5 and 100 within a spatial extent of 2500 m x 2500 m, facilitated by a single base station (gNodeB). Each vehicle is programmed to transmit periodic messages (CAM) comprising 1,500 bytes at a transmission rate of 6 Mbps, occurring at an interval of 100 ms. The empirical findings elucidate that the minimum latency consistently remains low (<8 ms) even in the presence of 100 vehicles; however, both the average and maximum latency exhibit a considerable escalation in correlation with an increase in vehicular density, ultimately reaching 25 ms and 50 ms for 100 vehicles, respectively. This phenomenon can be attributed to network congestion and the augmented message processing demands placed on the gNodeB. Figure 6 depicts the evolution of end to end latency depending on the number of nodes.

3.7 Discussion

The simulation results indicate that integrating 5G technology into VANETs offers substantial improvements in communication performance, which can lead to enhanced road safety and more efficient traffic management. The reduced latency and high packet delivery rates highlight the potential of 5G to support real-time applications, allowing vehicles to communicate critical information such as sudden braking or hazardous road conditions without delay. However, the results also suggest that there are areas for further optimization. For instance, while the performance metrics were strong, the system's performance in extreme scenarios—such as during severe weather conditions or in high-density emergency situations—could be further investigated to ensure robustness. The findings underline the importance of selecting appropriate routing protocols, such as AODV, which were shown to effectively manage communication in dynamic environments. Additionally, addressing security concerns is vital for ensuring the integrity of communications, particularly given the potential risks associated with malicious attacks on vehicular networks. Overall, the simulation results demonstrate the feasibility of 5G-enhanced VANETs and their significant potential for contributing to the development of safer and smarter transportation systems.

4 CONCLUSION

This study has illustrated the substantial advantages of amalgamating 5G technology with VANETs to improve the efficacy of vehicular communication systems. The results of the simulation studies highlight improvements in key performance metrics such as reduced latency, increased packet delivery rates, which are essential for the development of advanced safety applications. The 5G-enabled VANET system proves capable of supporting real-time applications crucial for collision avoidance and traffic management, thereby contributing to enhanced road safety. However, challenges remain, particularly in maintaining network stability in dynamic and high-density environments, as well as ensuring robust security against potential threats. Future work should focus on addressing these issues through optimized routing protocols and enhanced security frameworks.

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