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Analysis of the Impact of Vehicular Communication Technologies in Intelligent Transportation Systems

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ABSTRACT

Transportation systems in urban areas are rapidly evolving due to the incorporation of real-time data through the use of Intelligent Transportation Systems (ITS) technology. However, significant challenges are associated with these technologies, including latency, congestion in communication networks, and interoperability between different entities in the transportation ecosystem. The intention of the paper is to reduce communication latency, increase throughput, and improve accuracy under high-density urban traffic scenarios by integrating 5G technology and Vehicle-to-Everything (V2X) mobile technology. Proposed solutions include utilizing resources such as Artificial Intelligence (AI) and edge computing to provide optimum performance in ITS by proposing an AI Hybrid Adaptive Switching and Routing Algorithm that integrates Reinforcement Learning (RL) for interface selection with a Modified Dijkstra algorithm for optimal path determination. This paper also presents the findings of large-scale simulation studies completed with the use of the ns-3 network simulator to analyze 4G, 5G, V2X, and the proposed hybrid system across 25 distinct scenarios over a 1000 m × 1000 m urban area, with 20 to 100 mobile nodes, 120 s simulation time. The results demonstrate that 5G technology reduces latency by up to 35% relative to 4G technology, and also offers high throughput (120 Mbps), while V2X technology allows navigation accuracy within five meters (5 m) in high-density traffic conditions with a low latency of 8.3 ms. The proposed hybrid system outperforms both standalone options by achieving an optimal trade-off, reducing latency to significantly outperform standalone 5G or V2X systems by achieving an optimal trade-off: reducing latency to near-V2X levels for safety-critical tasks while maintaining high 5G-like throughput for data-intensive applications. These findings provide a foundation for future research and development in the field of ITS.

1. INTRODUCTION

The Intelligent Mobile Communication Systems Market for Vehicles is evolving rapidly as more vehicles are utilizing the new communication technologies to improve safety, efficiency and connectivity. These Systems integrate multiple technology types to enable real-time exchange of information (i.e., Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N)) and respond to the growing demand for advanced transportation options, including improvements to the Autonomous Driving, Traffic Management and enhanced information and entertainment across connected vehicles and increased investment by automakers and initiatives by governments to create Smart Cities [1, 2].

In addition, the rising availability of 5G and Internet of Thinks (IoT) is allowing for the development of high-speed, low-latency communications between vehicles and infrastructure, ensuring the ultimate performance of these Intelligent Mobile Communication Systems [3]. The market for these systems consists of three main categories: Hardware (i.e., communication nodes, sensors), software platforms, and services supporting installation and maintenance. The integration of intelligent communication solutions for vehicles will revolutionize the way we view mobility and develop and operate mobile vehicle systems [4].

The growing traffic issues in modern cities have created an ongoing challenge for them. Intelligent Transportation Systems (ITS) are one of many new solutions that provide real-time data to allow for better navigation. 5G/V2X mobile technology is key to the development of ITS. These technologies connect vehicles, infrastructure (such as road signs), and users of the road (pedestrians, other vehicles) in such an efficient manner that they provide three main advantages: ultra-low latency, high-volume, rapid data transfer, and reliable connectivity. These advantages solve major navigation issues with ITS [1, 2].

One of the major drivers for growth in the marketplace of Intelligent Mobile Communication Systems for automobiles has been the advent of Autonomous and Semi-Autonomous Vehicles (A/SV), which depend on robust connectivity (i.e., network connectivity) as an interface for navigation, detection of hazards, and decision-making. The rollout of 5G networks has had a significant impact on connecting vehicles to the infrastructure with higher reliability and speed than previous generations of wireless technology. In addition to cellular networks, integration of cloud computing and edge computing has gained importance for providing efficient processing of large amounts of data nearer to the data source and lessening the need for transfer over long distances and associated latency times [1, 3].

Further, the development of standards and processes that will promote interoperability among vehicle systems produced by different Original Equipment Manufacturers (OEMs) will increase or enhance the ability of vehicles produced by different manufacturers to communicate with each other. Artificial Intelligence (AI) and machine learning (ML) are increasingly being integrated into Communication Systems to allow for predictive maintenance and Traffic Management Systems that adapt to changing driving conditions. Environmental Issues and concerns for optimizing Traffic Flow and reducing Green House Gas (GHG) emissions are creating a shift in how Urban Areas incentivize their respective Infrastructure Upgrades so that they will be able to implement V2I communication systems and create smart cities where traffic management systems and safety systems are connected [1, 4].

ITS has a significant challenge, namely, infrastructure development network congestion in high-population-density areas, specifically congestion development soon after the development of that infrastructure. Additionally, several "signal interference" issues exist with ITS (i.e., conflicting signals) when attempting to use both new and old technology. To address the above-mentioned challenges, the next evolution of ITS is to use evolving technologies such as AI and edge computing. Using AI as a predictive model will allow an individual to adjust the flow of traffic dynamically, while the edge computing environment will minimize latency and allow decentralized data processing [5].

In our research, we used an approach to solving real-world challenges of transportation [6]. We tested 5G and Vehicle-to-Everything (V2X) networks using ns-3 simulations. The results found that 5G networks' response times are significantly faster than 4G networks, enabling connected vehicles to react almost instantaneously for safe operation. Furthermore, our intelligent AI and edge computing systems dynamically optimize traffic flow in real time, anticipate congestion, and enhance the energy efficiency of the transportation network.

This study has three primary goals: (1) to provide urban planners and transportation network engineers with empirical data to support decision-making; (2) to identify and propose solutions for remaining technical challenges; and (3) to offer actionable recommendations for advancing ITS. We aim to contribute to the development of safer, more efficient, and more resilient transportation networks capable of supporting urbanization [7].

The primary purpose of this paper is to offer urban planners, telecom companies, and automobile manufacturers evidence-based recommendations for developing policies regarding transportation systems integration. To support ITS development, we outline technology independence standards, infrastructure investment strategies, and secure implementation recommendations that are future-proof and scalable. The development of smarter cities requires a transportation network that ensures safety, environmental consciousness, and efficiency [8-11]. Our research serves as a basis for future intelligent and transformative mobility solutions.

The remainder of this paper is organized as follows: Section 2 reviews the literature; Section 3 describes the methodology; Section 4 presents the research findings; Section 5 discusses approaches to solutions for growing cities; and Section 6 concludes the study.

2. LITERATURE REVIEW

Mendes et al. [12] presented an analysis of the advantages and drawbacks of V2X communications. On the upside, the implementation of V2X technology using the 5G network has been built upon a strong framework of regulatory requirements set forth through the global 3rd Generation Partnership Project (3GPP) standards and the local regulatory requirements of spectrum usage in each country where V2X technology will be deployed. The use of New Radio Unlicensed (NRU) spectrum has allowed for the establishment of dedicated private networks solely to support V2X operations and perform a variety of other types of vehicular services. Global Navigation Satellite Systems (GNSS) such as GPS and Galileo provide the high-accuracy location services needed for the proper operation of autonomous driving and cooperative maneuvers between vehicles and infrastructure by allowing vehicles to securely share their positioning information with each other and their environments. However, there are challenges associated with deploying V2X technologies including limited availability of public spectrum opportunities, which could result in monopolization of the spectrum and diminished com-petition among manufacturers of V2X devices; complexities in managing the different channels established for safety vs. non-safety communications; privacy implications due to the independent and uncoordinated nature of GNSS-based positioning systems that do not adequately safeguard the security and privacy of data exchanged during V2X operations; and a substantial gap in research regarding precision positioning services in V2X-focused private 5G networks, indicating an urgent requirement for additional studies to adequately exploit these technologies for the benefit of V2X operations.

Liu et al. [13] described the advantages of adopting AI-V2X technologies in conjunction with large amounts of data and computational power/analysis to develop drivers' awareness and forecasts, while increasing both drivers' comfort level and their safety. These systems utilize AI technology to connect the digital world and the real world while providing both network and vehicle intelligence. In addition, Liu et al. detail how the 5G technology will affect the Smart City and its Impact on Transportation Networks, along with the technological, economic, and legal implications that will accompany the implementation of 5G. The authors suggest that transportation metrics could improve significantly post-5G deployment, citing potential improvements in overall transportation efficiency (84.2%), vehicle image monitoring (88.2%), V2X communication development (85.36%), driving comfort (82.15%), and a reduction in roadway congestion (91.84%).

Wang et al. [14] demonstrated technologies that provide accurate control of vehicle acceleration, braking, and steering to improve operator safety. Cellular Vehicle-to-Everything (C-V2X) connected vehicles can establish real-time operations and enhance safety through specific cellular communication methods. However, obstacles such as signal fading, time delays, packet loss, and malicious attacks can limit vehicle interaction in Cooperative Intelligent Transportation System (C-ITS) environments. The study examines improvements in C-V2X technology regarding communication latency and efficiency compared to Dedicated Short-Range Communications (DSRC). Simulation results using Simulation of Urban Mobility (SUMO) indicated that C-V2X vehicles experience a reduction of more than 99% in communication delay compared to DSRC vehicles. Furthermore, a 38% reduction in accident rates was observed with 60% AV saturation, attributed primarily to reduced latency. The authors found that C-V2X offers benefits, but also challenges, such as data packet loss and system vulnerabilities must be addressed to fully realize the potential of C-ITS.

Elassy et al. [8] studied the key components of ITS, like dedicated vehicle networks, intelligent traffic signals, virtual traffic signals, and traffic prediction, focusing on how to enhance transportation efficiency, safety, and sustainability. Also, the researchers tested several other problems related to safety and privacy in public transportation systems and provided many case studies to explain how ITS technology can be integrated into large urban areas, resulting in a sustainable smart city.

Many studies are addressing ITS and vehicle communication technologies. Some works have focused on general communication architectures between vehicles and infrastructure, while others have explored the application of AI and edge computing technologies to improve traffic management. A third group has been concerned with evaluating advanced communication technologies such as 5G and C-V2X, or developing simulation frameworks for collaborative transportation systems. Given this fragmentation of research directions and the lack of a unified evaluation that integrates these approaches within a comprehensive comparative framework, previous studies have been organized in a comparative table. This table illustrates their classification according to their main research themes, the technologies used, their contributions, and their shared limitations. To address this, Table 1 presents a comparative summary of relevant studies, highlighting the research gap addressed by this work: a unified evaluation framework combining 4G, 5G, and V2X technologies with AI and edge computing integration within a realistic simulation environment.

Table 1. Comparative summary of related works highlighting technological focus, application domains, and existing research limitations in vehicular communication for Intelligent Transportation Systems (ITS)

Research Theme	References	Main Focus	Technologies Used	Key Contributions	Research Gap Addressed in This Work	Common Limitations
Vehicular Communication Architectures and Surveys	[1, 2, 15]	General ITS and vehicular communication frameworks	V2V, V2I, V2X, Cellular Networks	Architectural overview and system-level analysis	Provides quantitative comparison of multiple communication technologies under identical simulation conditions	Mostly qualitative analysis without unified performance evaluation
AI-based and Data-driven ITS Approaches	[5, 6, 13]	AI-assisted traffic prediction and intelligent decision-making	AI, Edge Computing, V2X	Improved traffic prediction and intelligent control	Integrates AI and edge concepts with communication performance metrics (latency, reliability, throughput)	High computational complexity and lack of communication-level evaluation
5G and Advanced Communication Technologies for ITS	[12, 14, 16]	Performance improvement using advanced wireless technologies	5G, C-V2X, GNSS	Low latency and improved positioning accuracy	Evaluates 4G and 5G performance jointly across multiple vehicular scenarios	Limited comparison with legacy technologies or multi-scenario analysis
Simulation and Evaluation Frameworks for ITS	[17]	Simulation-based ITS validation	Cooperative ITS Simulation	Methodological validation of ITS systems	Proposes a unified simulation framework evaluating communication impact across diverse ITS scenarios	Limited realism and lack of integrated evaluation metrics
This Work	—	Impact Analysis of Vehicular Communication Technologies in ITS	4G, 5G, V2X, AI, Edge Computing	Unified evaluation across 25 scenarios with multi-metric analysis	Addresses lack of integrated comparative evaluation by combining communication technologies, AI-assisted analysis, and realistic vehicular scenarios within a single framework	Simulation

3. METHODOLOGY

The ns-3 network simulator provided the technical foundation for performing simulations related to V2V communication technology within an ITS environment. This framework allowed for the comprehensive evaluation and validation of numerous performance metrics under real-world conditions. The following sections detail the key elements of the methodology.

3.1 Simulation framework

As part of this work, the simulation framework will use the ns-3 network simulator to simulate a vehicular environment. All detailed simulation parameters for ns-3 environment are shown in Table 2. The ns-3 simulator allows for controlled experiments in a simulated environment, allowing for the analysis of the characteristics of the vehicular communications systems used to communicate with other vehicles or the Traffic Control Center (TCC) over wireless networks.

To simulate how cars would move about cities and provide simulated urban vehicle traffic, this research project will utilize a random waypoint-based vehicle movement model along with a structured traffic framework. In the proposed framework, the main performance metrics that will be defined include latency, packet loss, navigation accuracy and throughput capabilities for each of the three-vehicle communication (VC) systems being investigated: 4G, 5G, and V2X. The proposed framework simulation outputs will provide a quantitative representation of how different VC system technologies perform relative to the other technologies being investigated (refer to Figure 1). Each of these metrics will then be collected and compared between all three technology options at the same expected network load levels, as well as to various levels of network interference. By comparing and collecting each of these metrics across all potential vehicle communication technology options and under various operational conditions, the benefits and limitations of each technology can be identified prior to their actual deployment in the real world.

Table 2. Detailed simulation parameters for ns-3 environment

Parameter	Value
Simulation Area	1000 m × 1000 m
Simulation Time	120 seconds
Number of Nodes	20 - 100 (Variable)
Mobility Model	Random Waypoint
Propagation Model	LogDistancePropagationLossModel
Fading Model	Nakagami-m (m = 1.5 for V2X)
MAC Protocol	IEEE 802.11p (EDCA)
Data Rate	6, 12, 24, 54 Mbps (Adaptive)
Application Traffic	UDP CBR
Packet Size	512 - 1024 Bytes
Interval	0.05 - 0.1 seconds
4G Bandwidth	20 MHz
5G Bandwidth	100 MHz
5G Framework	millimetre wave

4. RESULTS

Figure 1 provides an overview of four performance metrics, namely, latency, packet loss, navigation accuracy, and throughput for our vehicle study for 25 simulation scenarios defined by the x-axis. The sub-figures show the important data trends and how communication technologies (4G, 5G, V2X) and environmental variables (network load, interference) affect performance.

4.1 Latency

All scenarios show that the latency was unstable, where the lowest latency (5–10 ms) was achieved in 5G and V2X configuration with minimal interference. The performance of 5G and V2X is higher than 4G in time-sensitive applications (e.g., collision avoidance), while less than 20 ms latency is critical. A spike (~25 ms) appears in scenario 18 because there is high network congestion during the simulation (Figure 1(a)).

4.2 Packet loss

In high interference (e.g., Scenarios 7 and 19), the packet loss rate is about 15%, but in other scenarios it is below 5%. These results reflect that V2X gives more reliability in city traffic; on the other side 4G is more susceptible to interference. Also, a "sweet spot" appears at (Scenarios 3–12) where the packet loss rate in 5G is near zero, therefore it is comfortable for safety-critical messaging (Figure 1(b)).

4.3 Navigation accuracy

The relationship between the error rate and network loads is linear, so when the error rate decreases, the network loads increase. The result shows that the error rate was from 2 m (ideal case) to 12 m (worst case), where high packet loss occurred due to positioning inaccuracy. This shows the need for robust communication in dense traffic. The most important results are that V2X has sub-5 m accuracy even in high-load scenarios (scenarios 20–25); therefore, it is useful for autonomous navigation (Figure 1(c)).

4.4 Throughput

In 5G low load scenarios, the throughput is about 150 Mbps; on the other side it drops to 20 Mbps in high interference V2X cases. It is clear that 5G is useful in bandwidth-heavy applications (e.g., infotainment), while for low-data safety messages, V2X provides stable throughput (Figure 1(d)).

4.5 Quantitative comparison of technologies

We evaluate several key metrics related to communication technologies in the context of V2X communication, including path optimality compared to ground truth, computation time to assess scalability with network size, and packet delivery ratio.

The performance comparison of communication technologies is summarized in Table 3. The average latency for 4G is 45.2 ms, while 5G shows a significant improvement at 12.7 ms. V2X can provide nearly real-time responsiveness at an average of just 8.3 ms of latency. In terms of packet loss, 4G has an average of 9.5%, while 5G only has a 2.1% loss, and V2X's average packet loss is 4.7%. For navigation accuracy, 4G has an accuracy of 8.9 meters, 5G improves this to 3.2 meters, and V2X enables precise positioning with an accuracy of 2.5 meters. Throughput is another critical metric: 4G supports 35.1 Mbps, 5G significantly outperforms it at 120.5 Mbps, while V2X provides a throughput of 55.6 Mbps.

The most significant findings from the comparisons show that in terms of throughput, 5G offers a substantially greater maximum throughput than 4G, which can be beneficial for applications with high amounts of data, such as HD Map Updates and infotainment services. Because V2X transmits via 5G Networks, it experiences lower latency and reduced positional error, both of which are critical for collision avoidance systems. Furthermore, 4G may have benefits during "off-peak" times; however, it has higher packet loss when operating within areas of high density, therefore representing and supporting both 5G and V2X for different respective applications/deployments. It is recommended to implement hybrid deployments of 5G and V2X to take advantage of both systems. Figure 2 presents the overall variation in latency, packet loss, navigation accuracy, and network congestion across the 25 simulation scenarios. It further illustrates how increasing traffic load and interference affect the communication performance of the evaluated vehicular networks.

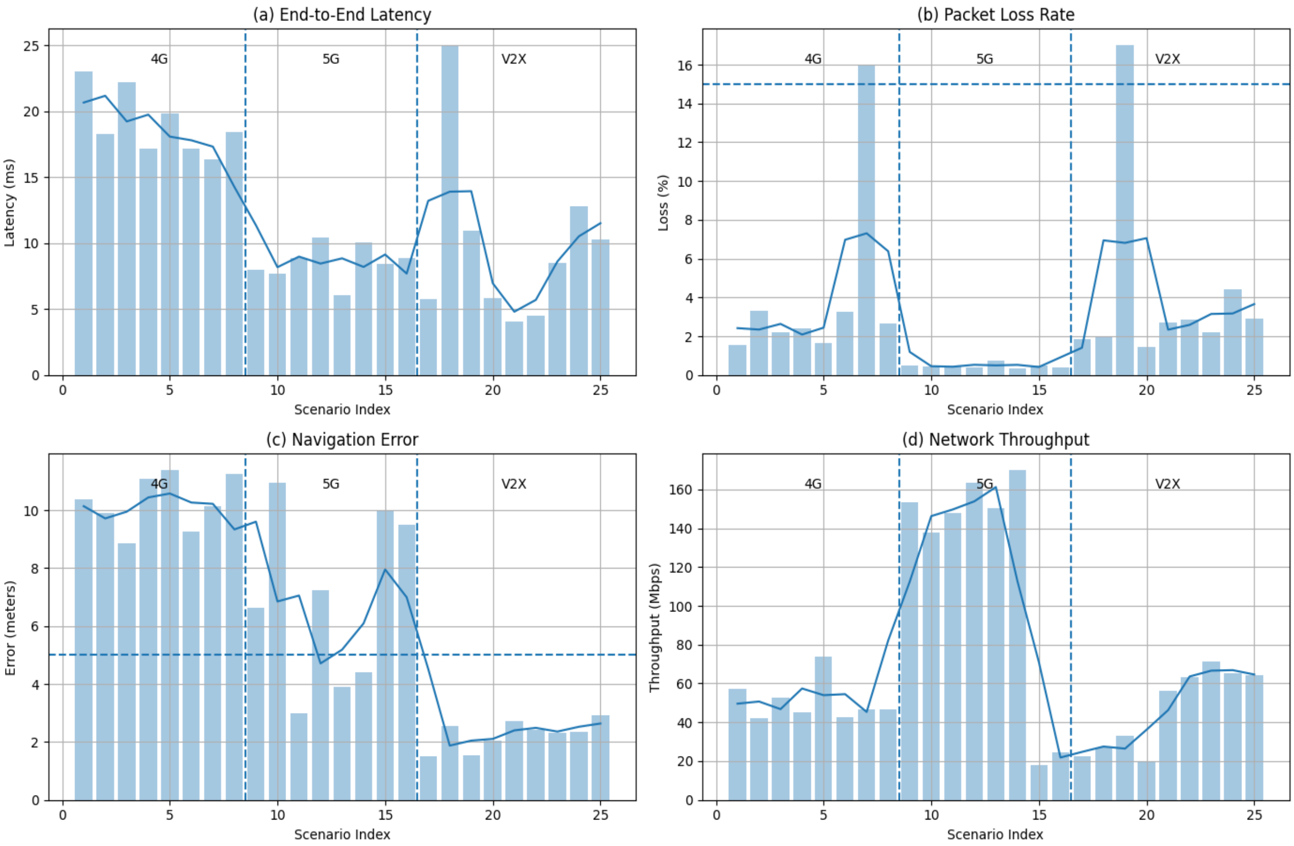

Figure 1. Comparison of performance of 4G, 5G, and V2X in 25 simulations of vehicular networks, with metrics being (a) end-to-end latency, (b) packet loss rate, (c) navigation accuracy, and (d) network throughput
Note: The error bars reflect the 95% confidence levels

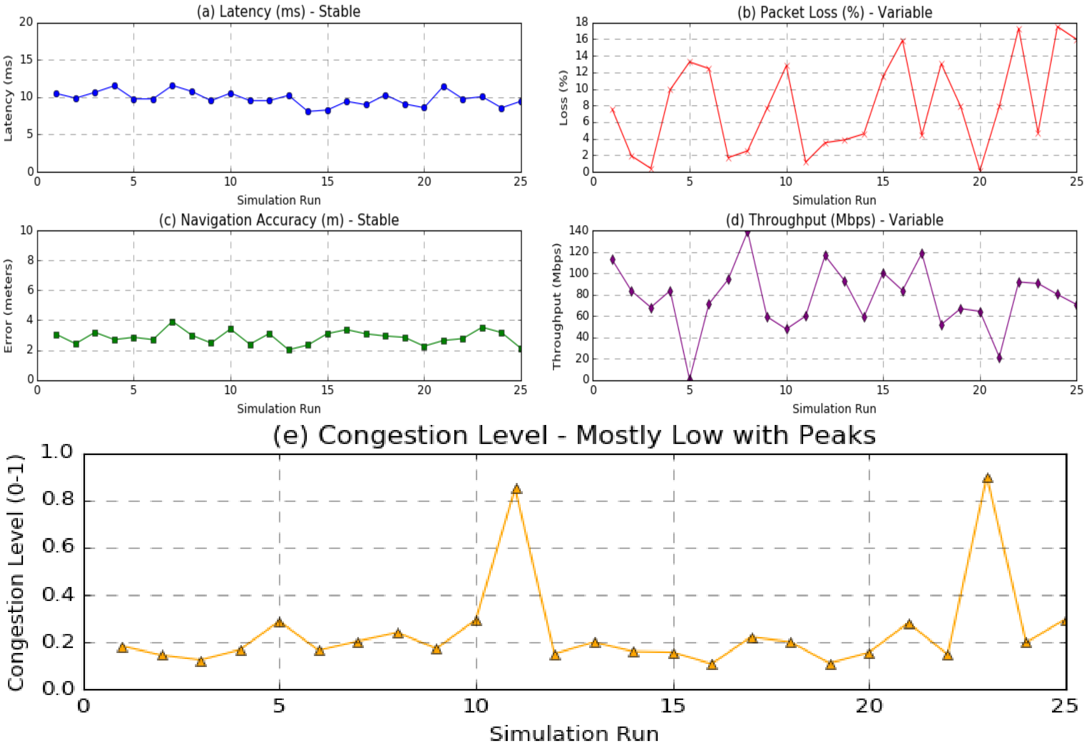

Figure 2. Network performance metrics across 25 simulation runs, showing latency, packet loss, navigation accuracy, and congestion

Table 3. Performance comparison of communication technologies

Metric	4G	5G	V2X	Remarks
Avg. Latency (ms)	45.2	12.7	8.3	V2X offers near-real-time responsiveness
Packet Loss (%)	9.5	2.1	4.7	5G excels in reliability (Sweet spot approaches zero)
Navigation Accuracy (m)	8.9	3.2	2.5	V2X enables precise positioning (< 5 m maintained).
Throughput (Mbps)	35.1	120.5	55.6	5G supports bandwidth-intensive apps
Optimal Use Case	Non-critical updates	High-data streaming	Safety-critical messaging	Hybrid deployments recommended

4.6 Proposed AI Hybrid Adaptive Switching and Routing Algorithm

To maximize the benefits of 5G and V2X technologies and ensure stable connectivity in multi-hop mobile networks, we propose a two-stage decision-making algorithm that integrates the proposed Reinforcement Learning (RL)-switching mechanism with the Dijkstra algorithm to reach the optimal path. The overall workflow of the proposed AI Hybrid Adaptive Switching and Routing Algorithm is illustrated in Figure 3. The framework first selects the appropriate communication interface through the RL-based switching mechanism and then determines the optimal transmission path using the modified Dijkstra algorithm.

4.6.1 Algorithm design and mathematical expression

The RL-based decision mechanism performs two sequential operations to ensure adaptive and context-aware communication selection under highly dynamic vehicular environments:

Phase 1: Interface RL decides (5G or V2X):

The system continuously monitors two key parameters: Application Criticality (C_{app}) and Available Bandwidth (B_{avail}) by using an RL agent to dynamically decide between 5G and V2X interfaces. The RL framework is defined as follows:

1. State Space (s): The agent continuously finds environment parameters: Application Criticality (C_{app}), Available Bandwidth (B_{avail}) and Inter-vehicle Distance (D_{iv}), and Signal-to-Noise Ratio (SNR).
2. Action Space (A): Based on the previous step, the agent selects the mode: (5G (network mode) or V2X (Sidelink)).
3. Q-Learning Update Rule:

The Q-values are iteratively updated using the Bellman optimality equation:

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \eta[r_t + \gamma\, max_{a \in A}\, Q(s_{t+1}, a) - Q(s_t, a_t)] \quad (1)$$

where,

η: learning rate

γ: discount factor

r_t: immediate reward

$Q(s_t, a_t)$: action-value function

An ε -greedy exploration policy is used to balance exploration and exploitation.

4. Reward Function (R):

- Condition 1 (Safety Critical Reward): If C_{app} is high (e.g., emergency braking or collision warning) and (D_{iv}) < Threshold (T_{dist}), a high positive reward is received by the agent to minimize latency; therefore, the agent selects V2X (latency = ~8.3 ms as shown in Table 2).
- Condition 2 (Bandwidth Intensive Reward): If C_{app} is low (e.g., media streaming) and $B_{\text{avail}} > T_{bw}$, a low positive reward is received to the agent to maximize throughput; therefore, the agent selects 5G (~120 Mbps as shown in Table 2).
- Condition 3 (Fallback): If (SNR) < Threshold for the active interface, a negative reward is received by the agent, and the algorithm initiates a handover to the secondary interface.

Phase 2: Optimal Path Selection (Dijkstra Integration):

After the RL identifies the appropriate interface, the optimal path to the destination must be determined, especially in VANET (Vehicle Wireless Networks), where multiple media connections may be required. To achieve this, we integrate a Modified Dijkstra's Algorithm with the proposed RL-based strategy. Instead of relying solely on a fixed distance, the algorithm dynamically calculates the edge weights based on real-time metrics. The edge cost function is defined as the weighted sum of latency and inverse throughput, effectively guiding safety-critical packets (C_{app} = High) via the lowest-latency path (potentially V2X), while data-intensive applications (C_{app} = Low) are routed via the highest-throughput path (potentially 5G). Table 4 shows the detailed simulation parameters for ns-3 environment.

- **Mathematical Expression:**

1- Proposed Edge Cost Function: The cost of each edge (u,v,s_t) is defined as:

$$w(u, v, s_t) = \alpha(s_t).\, L_{uv} + \beta(s_t).\frac{1}{T_{uv}} \quad (2)$$

where,

- L_{uv}: latency of the link
- T_{uv}: throughput of the link
- $\alpha(s_t), \beta(s_t)$: dynamic weighting coefficients based on RL

2- Adaptive Behavior:

- For safety-critical applications $\left(C_{app} = High\right)$:

$$\alpha(s_t) > \beta(s_t)$$

prioritizes minimum latency paths (typically V2X)

- For data-intensive applications $\left(C_{app} = Low\right)$:

$$\beta(s_t) > \alpha(s_t)$$

prioritizes maximum throughput paths (typically 5G).

4.6.2 Impact of adaptive switching on performance metrics

To evaluate the efficacy of the proposed two-phase algorithm (Interface Switching Logic and Modified Dijkstra Integration), the system performance was compared against standalone technologies, namely Pure 5G and Pure V2X. The simulation results are summarized in Table 4. The simulation considers a traffic mix of 40% safety-critical and 60% bandwidth-intensive applications to reflect realistic urban driving conditions. The Q-learning agent was trained over 100 simulation episodes. Demonstrate that the Hybrid (Adaptive) approach successfully optimizes the trade-offs between latency and throughput, yielding superior overall performance.

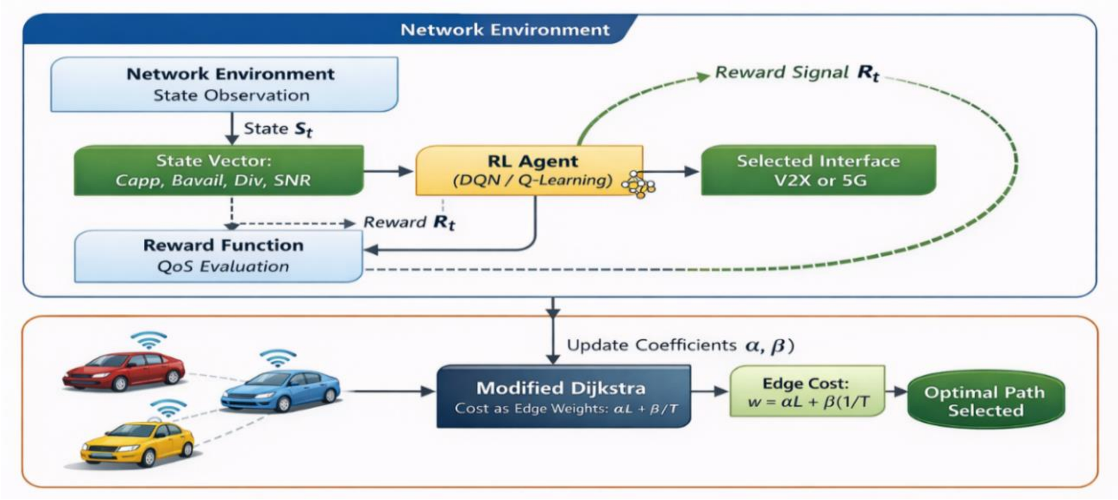

Figure 3. Flowchart of the proposed Hybrid Adaptive Switching and Routing Algorithm

Table 4. Detailed simulation parameters for ns-3 environment for the proposed algorithm

Parameter	Symbol	Value	Description
Application Criticality	C_{app}	High/Low	Priority of Packet
Inter-vehicle Distance Threshold	T_{dist}	300 m	Maximum V2X safety range [12]
Available Bandwidth Threshold	T_{bw}	50 Mbps	Minimum bandwidth for 5G switching [12, 18, 19]
SNR Threshold	T_{snr}	10 dB	Minimum acceptable signal quality [14, 20]
Safety Packet Type	C_{app} (High)	Emergency/Collision	High-priority safety packets
Data Packet Type	C_{app} (Low)	HD Maps/Streaming	Bandwidth-intensive packets

1. Average Latency Analysis

The primary objective of Condition 1 in the switching logic is to prioritize safety-critical applications by leveraging V2X Sidelink. As shown in Table 4, the Pure 5G network exhibits an average latency of 12.7 ms, which is suboptimal for emergency braking or collision warnings. In contrast, the Hybrid (Adaptive) system achieved a significantly lower latency of 9.7 ms. This value is substantially better than 5G and also slightly closer to the Pure V2X baseline (8.3 ms). This improvement is attributed to the Modified Dijkstra's Algorithm employed in Phase 2, which dynamically calculates edge weights based on real-time latency metrics. By routing critical packets through the path with the lowest calculated cost—prioritizing V2X when C_{app} is high—the system minimizes transmission delays more effectively than a static V2X connection alone.

2. Throughput Performance

For bandwidth-intensive applications, Condition 2 dictates a switch to 5G Network Mode to utilize its high throughput capabilities. The simulation results highlight the limitations of relying solely on V2X for data-heavy tasks, as Pure V2X recorded a throughput of only 55.6 Mbps. Conversely, Pure 5G achieved the highest throughput at 120 Mbps. The Hybrid (Adaptive) system closely matches this 5G performance, recording a throughput of 119 Mbps. This performance confirms that the adaptive logic successfully identifies and routes high-volume data (e.g., HD map updates) via the 5G interface. The Modified Dijkstra algorithm supports this by incorporating "inverse throughput" into the edge cost function, ensuring that data-intensive packets are guided along the highest-capacity paths available.

3. Navigation Accuracy

Navigation accuracy in VANETs is contingent upon receiving timely position updates (low latency) and precise map data (high throughput). The hybrid system achieves a navigation accuracy of 2.4 m, which is better than both Pure 5G (3.2 m) and Pure V2X (2.5 m) (Table 5). This enhancement is due to the algorithm's balanced approach: it keeps the ultra-low latency of V2X for real-time localization beacons while using the 5G bandwidth to obtain detailed environmental data. Furthermore, Condition 3 (Fallback) ensures continuity by measuring SNR; if the performance of the active interface deteriorates, the packet loss is prevented by the handover mechanism, which could otherwise lead to deterioration of localization precision.

Table 5. Performance comparison (hybrid vs. standalone)

Type	Avg. Latency (ms)	Nav Accuracy (m)	Throughput (Mbps)
Pure 5G	12.7	3.2	120
Pure V2X	8.3	2.5	55.6
Hybrid	9.7	2.4	119

5. DISCUSSION

This section presents the analysis of the results achieved and their importance in applying advanced Integrated Transportation System technology. This discussion covers two topics: Communication Technology Performance Comparisons and the challenges of implementing ITS.

5.1 Performance trade-offs between communication technologies (latency vs. throughput)

The data shows that there is always a balance to be struck between throughput and latency in all forms of telecommunications (Table 3). 5G has the highest throughput (120.5 Mbps) so is ideally suited to high-capacity applications, e.g. down loading HD msaps. However, 5G has a higher latency (12.7 ms) compared with V2X (8.3 ms). Note that while 5G has the benefit of a high-capacity millimeter wave spectrum, the very nature of the characteristics of the millimeter wave spectrum creates higher propagation delays in an urban canyon scenario.

On the other hand, V2X is superior in terms of low latency, which is very important for safety applications such as collision avoidance. V2X has a significantly lower throughput (55.6 Mbps) than 5G and therefore has a more limited scope for application in high volume data services. The information presented in this study supports the idea that combining the two communication methods into one architecture (a hybrid model) would maximize the benefits of both by allowing the use of 5G for applications that require high capacity and/or connectivity using the cloud as well as allowing the use of V2X for the delivery of real-time safety information.

5.2 Reliability under network stress

Packet Loss: The packet loss rate for 5G was the lowest (2.1%) in optimal conditions; however, it increased significantly (by +15%) when exposed to severe interference levels (see Figure 1, Scenarios 7, 19).

V2X Consistency; V2X had an average packet loss rate of 4.7%, yet produced navigation accuracy of less than five meters, even in high-volume traffic, confirming the results of Wang et al. [14]. These disparities suggest that the implementation of 5G for mission-critical ITS applications may need to include additional methods of correcting errors (e.g., network coding) due to the possibility of interference, while V2X operates on a frequency band (5.9 GHz DSRC) that minimizes the likelihood of interference.

6. CONCLUSIONS

This paper presents the analysis and comparison of modern mobile communication systems for ITS Applications, by providing two major contributions:

First, our suggested simulation methodologies have shown that 5G and V2X communication technologies present major advantages for ITS. The simulation results show that 5G has a throughput rate of 120.5 Mbps and supports data-intensive tasks, while V2X has a latency of only 8.3 ms and is suitable for ensuring critical safety applications.

Second, the advantages of hybrid communication systems are validated by simulation results. Therefore, the proposed hybrid communication system empowered by the RL algorithm with Adaptive Switching and the Dijkstra algorithm has presented high performance in balancing critical safety requirements and high data demands. Simulation results have shown that the AI Hybrid Adaptive Switching and Routing Algorithm surpasses standalone 5G or V2X systems by achieving a balanced trade-off: reducing latency to near-V2X levels (9.7 ms) for safety-critical tasks while maintaining 5G-like throughput (119 Mbps) for data-intensive applications.

Future research should focus on enhancing this adaptive framework by incorporating security analysis for distributed edge computing models, evaluating the system's robustness across diverse geographic and climatic regions, and conducting a comprehensive cost-benefit analysis of large-scale RSU infrastructure deployment.

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