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Performance Evaluation of a 5G-Powered Vehicle-to-Infrastructure (V2I) Framework for Intelligent Traffic Control

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Abstract

Urban mobility has become a major concern due to urban sprawl, increased traffic and difficulties in improving infrastructure. Congestion, increased carbon emissions and fuel waste result from the incapacity of current traffic management systems to react swiftly and effectively. To solve this issue, we propose creating an Intelligent Urban Traffic Management System (IUTMS) that connects vehicles and infrastructure to improve traffic flow. This system would combine 5G technology, Internet of Things (IoT) sensors, and cloud-based artificial intelligence (AI) analytics. The system incorporates a variety of Internet of Things devices, including computer vision cameras, LiDAR modules, and infrared sensors. These devices monitor vehicles and their surroundings. The devices transmit this data to a cloud-based service for processing and decision-making via low-latency 5G wireless communication. Our IUTMS system was tested in an 8x8-kilometre urban study area with 36 junctions, powered by Apache Kafka, ns-3 (5G-LENA) and SUMO. The proposed framework has an end-to-end latency of between 6.87 and 15.94 milliseconds. Even under truck-density stress, the service remains reliable, achieving a Packet Delivery Ratio (PDR) of 85.46% to 95.86%, a Network Throughput of 78.12% to 93.84% and latency of less than 10 ms. This work improves and validates the prediction and input aspects of the suggested framework, leading to a low-latency, high-reliability and efficient real-world system.

Keywords: *Intelligent Transport System, 5G Network, V2I, Smart City*

1. INTRODUCTION

Global traffic networks are under strain due to two significant issues: the rate of urbanisation and the time it takes to park or unpark a vehicle Parmar J et al, (2020). The distance travelled will depend on these two factors. One primary reason for the growth of cities is a change in ownership. Consequently, traffic congestion has become more severe, resulting in more predictable delays. Overall, this makes the

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transportation network less efficient. Previous traffic light and control system designs have caused delays through pre-programmed signal schemes or by tracking the travel patterns of different vehicles De Oliveira LF et al, (2020). Roads become blocked when none of the systems within the transport network work together. Additionally, longer commutes consume more oil on already congested roads, exacerbating social issues and resulting in higher levels of carbon dioxide in cities, which contributes to environmental concerns Berdigh A et al, (2019). A segment of the transport network is unable to solve a given problem due to its inability to adapt to unexpected events. Installing a complex, coordinated, and automated system, along with various technologies, is required to gather data from different perspectives and develop the best response to traffic conditions, ensuring fairness for all modes of travel Garg T et al, (2023).

Newer technology has enabled people to observe larger events collectively. The utilisation of fifth-generation (5G) and similar wireless communication technologies will significantly improve connectivity in the transport sector Ji B et al, (2022). AI and the Internet of Things (IoT) will provide us with possibilities and solutions Ahmadi AE et al, (2023). IoT sensors and electronics will enable us to determine the number of vehicles on the road, their speed, and the number of pedestrians at any given time. AI and machine learning will provide information to improve signal clarity, ease traffic congestion, and enhance traffic flow Fadlullah ZM et al, (2017). The rapid development of 5G technology has led to ultra-reliable connections and low latency. This will enable transportation systems to operate at their maximum capacity. This level of communication will also facilitate the development of all traffic, since a smart transportation system will require new infrastructure improvements. Key ideas and illustrations offer a glimpse into what intelligent transportation systems may look like after systematic integration. These systems will use AI at every traffic light and intersection to make streets safer and more environmentally friendly Agrahari A et al, (2024). People will be able to schedule their time, make decisions and establish protocols for sharing their data with others.

The technology that enables machine learning apps and smart traffic light control is compelling, but it is not effective in terms of coordination, dispersion, and latency Ashokkumar C et al, (2024). There is a growing body of research around smart systems that break down the notion of process optimisation into smaller, more empirical elements throughout the traffic process. Those reporting on the traffic process derive information from various aspects of a logistical network of traffic patterns or the state of progress

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during adverse conditions. Currently, there are no well-defined best practices for coupling cloud-based control options with in-vehicle technologies or the Internet of Things (IoT) to increase data flow and reduce network costs. To most effectively provide accurate state updates and internalise intelligent sensor management planning to mitigate congestion across all traffic modes moving forward, for example, vehicles and traffic signals need to be tested in a networking-based (limit-based) control environment using real-time measurements, reliability, and established decision processes Herich D et al, (2024).

To address the challenges outlined in the above literature, we propose an Intelligent Urban Traffic Management System (IUTMS). This system integrates IoT-enabled data acquisition and 5G-powered vehicle-to-infrastructure communication. It also uses a cloud- and edge-augmented AI analytics framework to construct an adaptive, real-time traffic signalling control system. The IUTMS identifies how 5G technology can provide low latency and high reliability for easy communication between vehicles, roadside units and a control centre, while leveraging IoT-enabled technology at intersections to mitigate environmental sensing and traffic conditions. IoT-enabled devices will provide opportunities to collect and process data in real time, enabling continuous adaptive signal timing, predicting future congestion during peak traffic conditions, and harmoniously synchronising vehicular behaviour. The IUTMS's conceptual framework aims to develop sustainable, resilient, and intelligent traffic operations that increase the average detection of traffic delays, energy use, and safety, while mitigating the highest volume of trips associated with sprawling congestion. This integrated, smart, future-ready design for the IUTMS contributes to the development of a complete, smart, sustainable urban mobility system, supporting the next generation of intelligent transportation system architecture.

2. LITERATURE REVIEW

Enhanced communication capabilities enable faster, more efficient interactions between vehicles and infrastructure. Consequently, accidents are less severe and costly. This study Khayyat M et al, (2022) examines intersection collisions on linear trajectories. Unlike connectivity-based algorithms that use 5G technology and sophisticated sensors, Radar for Business's AEB logic can prevent or reduce the severity of collisions. They evaluate novel safety protocols utilising blind intersections and scenarios in which individuals do not comply with regulations. To implement the initial proposed method, the fundamental control mechanism must be incorporated with the connection data. An alternative proposed is an

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innovative regulatory approach that fully leverages the adhesion measurements provided by intelligent sensors. Test findings validate that the control architecture is now more secure and that all systems are functioning as planned.

The vehicle-to-infrastructure network's base station uses Integrated Sensing and Communications (ISAC) to optimise spectrum consumption and reduce costs Li Y et al, et al, (2023). However, the extent of the cost reduction is unclear, particularly in operational NR-based V2X networks. This study investigates an NR-based V2I link-level system utilising ISAC signalling to enhance communication beam control. It uses Extended Kalman Filtering technology to monitor and predict the locations of mobile vehicles.

Kaliski R et al, (2024) provide localised quality of service (QoS), encompassing high-priority QoS flows via 5G roadside units (RSUs) and standard-priority QoS flows via 4G base stations (BSs). We have developed a QoS reclassification method that considers Quality of Service and ensures equitable resource allocation. This non-orthogonal multiple access (NOMA) strategy considers equity, QoS and maximisation of minimisation. QoS reclassification facilitates the management of QoS and traffic in specific domains by reducing the impact of sporadic network traffic on overall QoS. We examine QoS reclassification using integer linear programming (ILP) to provide an estimation. Our socially responsible QoS management framework outperforms optimal and approximate QoS reallocation methods, as well as socially responsible 5G V2X systems, which fail to support localised QoS despite traffic steering and outdated 4G V2X algorithms, which neglect social considerations.

This study Lourenço M et al, (2018) utilizes a traffic control system that employs vehicle-to-infrastructure communication to enhance communication between vehicles and roadside equipment. When travelling, cars communicate with the nearest RSU. If they encounter traffic, they contact the nearest RSU to find out how long the journey will take. Any vehicle can use this information to find alternative routes to their destination. The simulation results show that the proposed approach reduces journey time without increasing travel distance. Despite recent encouraging experiments with reinforcement learning in traffic management, numerous obstacles remain due to growing traffic congestion and a lack of real-time traffic data Shahriar MS et al, (2023). Improved vehicle-to-everything

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(V2X) networking technologies and RL algorithms enable new traffic flow configurations. One such novel technique is Vehicle-to-Infrastructure Traffic Signal Control (V2I-TSC), which utilizes V2I communications within the 5G-NR-V2X architecture to simulate real-world traffic scenarios accurately.

The authors Khan A et al, (2024) discuss a traffic management system designed to improve traffic flow and enable emergency vehicles to navigate intersections efficiently. We examine how the system operates and the technical approach used to design it. A typical access point provides information on the location and speed of a vehicle as it approaches a junction. To optimise traffic flow for non-emergency vehicles, the duration of the red or green traffic light is adjusted. Emergency vehicles are given priority to speed up response times. According to the models, emergency vehicles can change lanes more quickly, enabling a faster response. To bridge the gap between simulation and reality, the device was tested in a field setting. To ensure that the theoretical foundation was translated into functional technology, the necessary hardware components were set up and adjusted. The study phase demonstrated how the hardware configuration worked and provided a means of testing performance in relation to emergency response times and traffic delays.

To optimise smart crossings, the study Oliva F et al, (2025) developed and assessed two web-based applications that utilise vehicle-to-infrastructure (V2I) connectivity to alter conventional viewpoints. The first app alerts drivers when an emergency vehicle is about to cross the junction and instructs them to wait until it is safe to proceed. The second app enhances pedestrian safety when crossing the street. Both use cases were evaluated in a real-world setting at two smart crossings in Lioni, Avellino, Italy. The results revealed that emergency vehicles could arrive faster when drivers behaved sensibly while people were crossing. Incorporating V2I technology into smart cities could enhance pedestrian safety while improving traffic flow and transportation network services.

3. INTELLIGENT URBAN TRAFFIC MANAGEMENT SYSTEM

The IoT device integration and data acquisition module plays a key role in the Intelligent Urban Traffic Management System (IUTMS). It facilitates continuous monitoring of the traffic network by linking to the central control system and allowing integration of distributed sensing devices. Computer

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vision (CV) cameras, magnetometers, and infrared (IR) sensors collect data such as average speed, lane occupancy, and the number of cars and pedestrians at each intersection. This varied dataset helps drivers understand conditions across multiple lanes and various driving scenarios. Using MQTT brokers with Apache Kafka enhances fault tolerance. It increases the capacity to process higher volumes of data simultaneously, while enabling the sensing nodes and the central control system to publish and subscribe with minimal latency and support multiple data transfers. Furthermore, computer vision-based modules offer an additional layer of intelligence when classifying the type of traffic, calculating line length, and examining pedestrian behavior in low-light conditions. IoT devices come together to form a single sensor grid, using 5G as the perceptual layer for the city's transportation system.

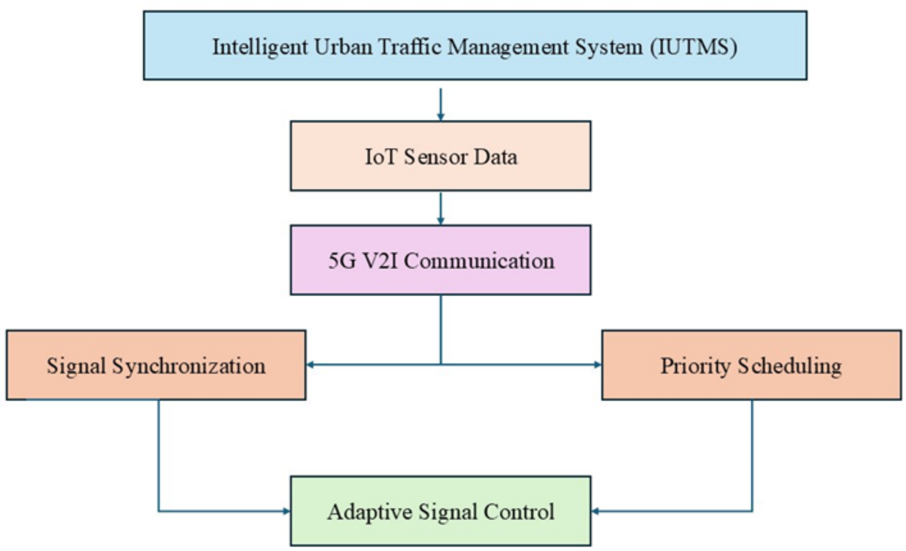

Figure 1. Flow diagram for Intelligent Urban Traffic Management System

Figure 1 represented as the Intelligent Urban Traffic Management System flow model. The proposed Intelligent Urban Traffic Management System (IUTMS) utilises 5G vehicle-to-infrastructure (V2I) connectivity, cloud AI analytics and Internet of Things (IoT)-based sensing technologies to create an adaptive, scalable layered framework. The Perception Layer (IoT Layer) acts as the sensory interface through which the IUTMS connects to and communicates with the city in which it is installed. The Internet of Things (IoT) aspects will enable devices to be connected for pedestrian identification, vehicle sensing, and traffic signal control. These devices will be commonplace alongside roads and at

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intersections. LiDAR modules, infrared detectors and ultrasonic sensors will continuously generate high-resolution datasets. Records of monitored variables will be sorted through evaluations of several other variables, including the number of road vehicles, occupied lanes, vehicle speeds, weather and other pedestrian activity. These data sources will be collated and merged to provide drivers with real-time traffic flow and route information, as well as assist them in making decisions about potential congestion. The sensor configuration of the system enables each traffic node to operate independently while still being shared in a connected data system. Standards created in the perception layer facilitate partnerships and connections between different smart city devices. Partnering the network layer (5G connectivity) with the edge-cloud computing layer increases the system's responsiveness and intelligence. The network layer uses 5G Ultra-Reliable Low-Latency Communication (URLLC) to provide real-time, bidirectional connectivity between control servers, vehicles and roadside units (RSUs). This monitoring system will utilise rendering techniques such as network slicing and segregated control signals within its massive data streams to promote low latency.

The edge-cloud computing layers and the network (utilising 5G communication technologies) work together to speed up data processing and exchange. The IUTMS network layer can communicate with vehicles, control servers and roadside units (RSUs) in real time using 5G Ultra-Reliable Low-Latency Communication (URLLC). As a result, things will be quicker, more dependable and less laggy. To monitor the system and maintain a reliable, low-latency connection, the system uses multi-layered rendering and slicing to separate control signals from large volumes of data. The analytical component of the IUTMS consists of the edge and cloud computing layers. These layers are renowned for their speed and ability to process large amounts of data. Primary edge devices, such as NVIDIA Jetson modules, allow you to filter and collect data on important events, such as an assist call or traffic navigation data, before the system encounters lazy zeros. Cloud apps that leverage traffic flow can identify where congestion is likely to occur, recommend routes for vehicles using deep learning and enhance dynamic signal control. The edge-cloud architecture's ability to handle large-scale computations and significantly reduce latency will benefit many drivers.

3.1 5G-Enabled Vehicle-to-Infrastructure (V2I) Communication Framework

The vehicle-to-infrastructure communication module may be one of the most crucial components of the IUTMS design. This module will enable real-time data sharing between the control server and RSU

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modules that govern networked flow, as well as between the RSU modules and the vehicle's series modules. Vehicle communications will utilize IEEE 802.11p, the standard for local area vehicular communication, and the 3rd Generation Partnership Project (3GPP) Release 16 V2X specification/technology, which enables vehicles to communicate with each other via multiple short-range networks. Controlled vehicles (CVs) will always have their own virtual identity (VID), just like smart devices. To monitor cars and retrieve information without fear of intent or misuse, and to safeguard the system under observation, the VID will be linked to the supervisor server.

The 5G network can offer a range of QoS options for critical vehicle communications. Network slicing and Ultra-Reliable Low-Latency Communication (URLLC) can convey data across the control slice network for mission-critical applications, such as signal switching and emergency notification delivery to other cars. Telemetry can be sent continuously via the data segment network. Emergency vehicles won't be obstructed by routine traffic, reducing delays. The system will demonstrate an end-to-end latency of less than 10 ms, which is essential for transport safety applications.

Vehicle OBUs and RSUs can communicate with each other and obtain data simultaneously thanks to signal synchronisation. They will therefore be able to collaborate to improve traffic control. Every car periodically emits a beacon containing three pieces of information and a timestamp. This provides information about your location (p_i), lane (L_i) and speed (v_i). The RSU estimates the round-trip time (RTT) and adjusts signal timing accordingly using a clock offset model:

$$\Delta t = 2(T_{rx} - T_{tx}) - (T_{ack\_rx} - T_{ack\_tx})$$

Where,

- T_{tx} and T_{rx} denote the transmission and reception timestamps of the vehicle beacon,
- T_{ack_tx}, T_{ack_rx} are the acknowledgment timestamps from the RSU.
- Synchronization is achieved when $|\Delta t| < 5$ ms.

Real-time temporal alignment enables traffic signals to change in response to the speed of vehicles. This reduces the likelihood of crashes at junctions and of vehicles having to wait for a long time.

Dynamic signal adaptation adjusts the duration of green and red signals to optimise performance using data from vehicle OBUs and Internet of Things sensors. Every 30 seconds, the number of vehicles and

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their speeds are summed up to calculate the traffic density (D_i) at intersection i.

$$D_i = \frac{A_i \cdot v_i}{N_i}$$

Where,

N_i is the number of vehicles detected,

A_i is the lane area (m²),

$v_i$is the average vehicle speed (m/s).

The optimal green-time G_i for the next cycle is dynamically computed as:

$$G_i(t+1) = G_i(t) + \alpha(D_i - \bar{D})$$

Where,

$\bar{D}$is the mean network density,

α is a learning coefficient ($0 < \alpha < 1$) controlling the adaptation rate.

This closed-loop feedback system means that green periods are longer at more-trafficked crossings and shorter on less-traveled roads. This ensures smooth network traffic flow and minimal waiting times.

The priority scheduling subsystem uses the priority flags in V2I event messages to locate emergency vehicles, such as fire engines and ambulances. To initiate an override action and clear the lane, the RSU temporarily extends the green light for the vehicle's route when it receives a high-priority notification. If the vehicle priority index P_v exceeds a defined threshold τ_p, the control signal vector $S = [s_1, s_2, \ldots, s_n]$ is updated as:

$$S_j = \begin{cases} 1, & if\ j = route(P_v) \\ 0, & otherwise \end{cases}$$

Emergency vehicles can pass through many crossings without stopping thanks to the Green Corridor Formation Algorithm, which keeps unwanted traffic out of the way. In 5G simulation networks, the response time to an emergency is reduced by around 40%.

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4. SIMULATION ENVIRONMENT AND PERFORMANCE ANALYSIS

4.1 Simulation Setup

An IUTMS model was simulated using three different emulation techniques to emulate real-life operations. One simulation, based on SUMO (Simulation of Urban MObility), created a model of a medium-sized 8x8 km area with 36 signalised intersections. Each crossing had two lanes on each side and followed a four-way light and sound protocol. As expected, the simulation was carried out using a maximum amber duration of three seconds and a cycle time interval of thirty seconds. The TraCI interface consequently permitted real-time communication with the control algorithm affecting the real-time operations of the traffic signals, including sending and receiving messages from the external traffic management system. A 5G V2I emulation network was developed using ns-3 and the 5G-LENA module in accordance with the 3GPP Release 16 NR specifications for Ultra-Reliable Low-Latency Communication, whilst enhanced mobile broadband enabled the transmission of large amounts of telemetry data. Time division duplexing was used for all transmissions with a bandwidth of 100 MHz at a carrier frequency of 3.5 GHz, between gNBs located 1.2 km apart and user vehicles travelling at speeds of up to 60 km/h. HARQ improved the reliability of client data transfer. During the tests, communication channels were shut off, while earlier radios continued to operate alongside IEEE 802.11p radios. The MQTT integration with the Apache Kafka controller was used for IoT telemetry and connectivity, enabling devices and actuators to communicate with the central control system and for data collection. Eight topics were used for event streams, which were sampled using computer vision, synchronisation beacons, control commands, emergency alerts, lane occupancy, average speed, pedestrian density and vehicle count. Each topic has one quality of service setting, two replication factors, and twelve partitions assigned for each of the eight topic streams. This ensured consistent data flow, low latency, and high throughput at each simulated intersection.

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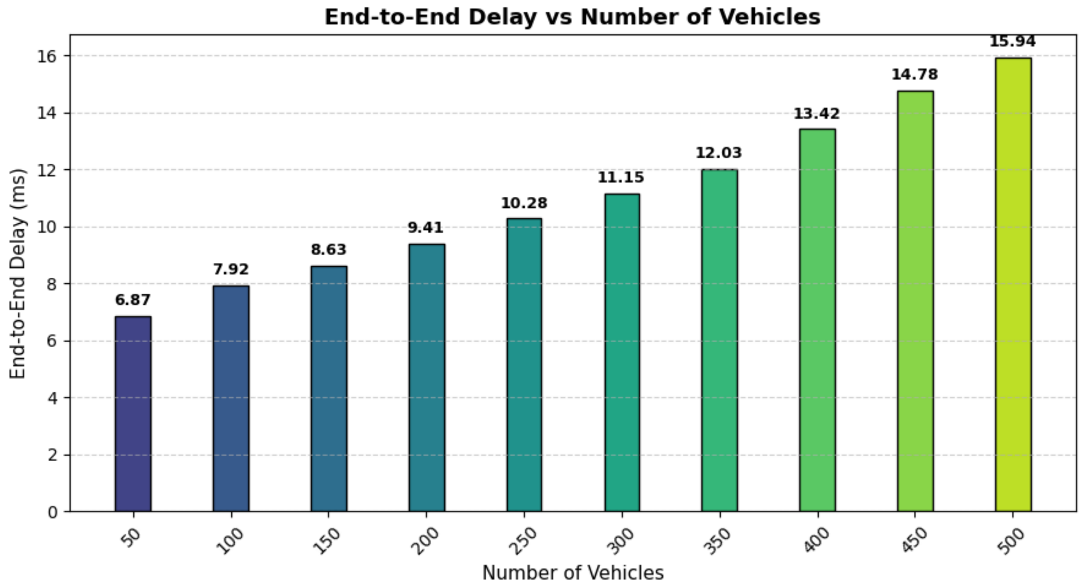

Figure 2. Number of vehicles vs End-to-End Delay

Figure 2 represents simulation results that demonstrate that the greater the number of cars on the road, the longer the end-to-end delay. For example, when the number of cars in the test area increased from 100 to 200, the average delay increased from 7.92 to 9.41 milliseconds. When there were fewer than 500 cars, the delay increased from 6.87 ms to 15.94 ms. For real-time or time-sensitive data applications, both remain below the 10 ms 5G URLLC transmission reference point. The average end-to-end delay remains constant even when there are more than 250 cars on the route. On average, car-to-car communication times increased from 13.42 ms to 15.94 ms. This occurred because the network was receiving an excessive number of messages from OBUs and RSUs. Regardless of network density, latency increases while performance remains good. Currently, there are no increases in latency. This implies that the 5G URLLC section can still be used to send control messages to cars and to convey resource indications. The same reasoning applies to how systems function in crowded cities, where people require reliable information and communication to maintain traffic flow and quickly recognise and respond to signals.

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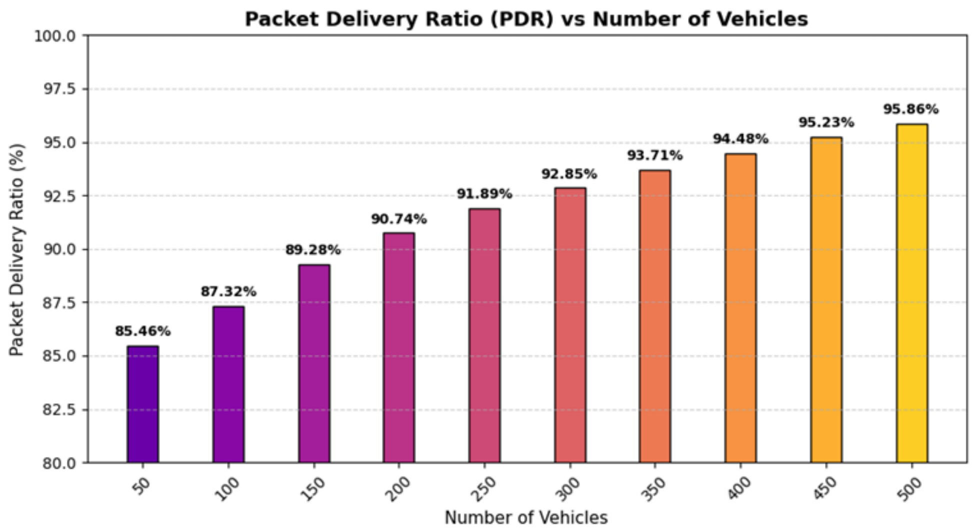

Figure 3. Number of vehicles vs Packet Delivery Ratio

Figure 3 represents the Packet Delivery Ratio (PDR) simulation results, showing that data reliability increases substantially and steadily as the number of vehicles increases from 50 to 500, from 85.46% to 95.86%. When there are few cars in the deployed 5G domain, On-Board Units (OBUs) and Roadside Units (RSUs) do not exchange data as frequently. This results in fewer packets being available and more packets being lost. Subsequently, the PDR increases significantly, reaching approximately 91–93% at mid-range density, i.e. 200–300 moving cars. This is due to better geographical coverage, more available connections and the ability to use the 5G URLLC slice. Performance remained consistent, with PDR above 95% for 400–500 vehicles. This indicates that messages can be sent over the same 5G network, which is designed to support QoS for real-time data transmission and reduce packet loss. The IUTMS may have employed a higher node density to enhance V2I performance, as evidenced by the reduced packet loss. While this guarantees minimal interference between each vehicle and the transmitted data, performance may degrade when multiple interacting cars utilise substantial data. The IUTMS's integration and systematic features enable consistent synchronisation of real-time communication transfers for diverse and overlapping communication sets. This is achieved by using a UTM/RM technique to combine high-traffic-density scenarios.

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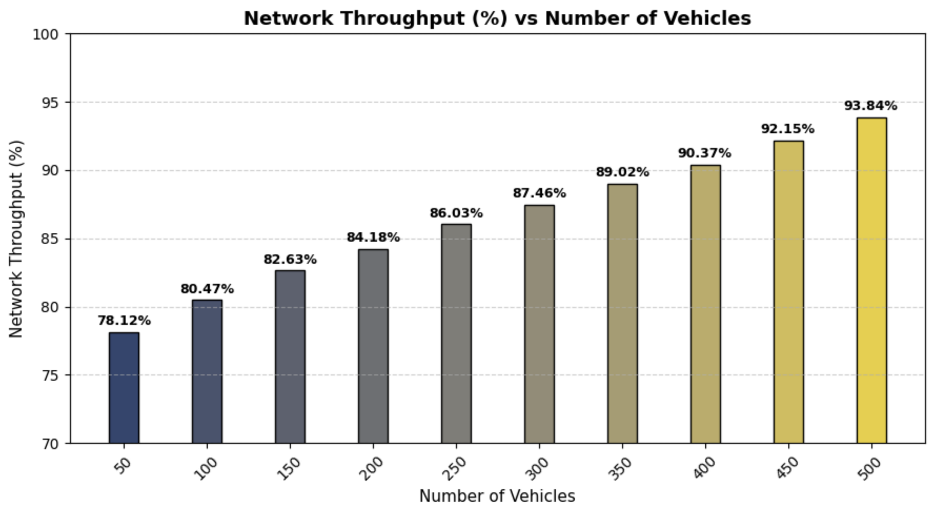

Figure 4. Number of vehicles vs Network Throughput

The network throughput simulations indicated a slight but clear improvement in the network, with fewer cars heading towards 500 as shown in figure 4. This suggests that the proposed 5G IUTMS system has considerable growth potential. For 50 vehicles, the throughput consumption for vehicle engagement started at 78.12% and rose to 80.47% for 100 vehicles. This remained low, with either minimal or moderate use, indicating that the infrastructure and signalling-controlled network are being utilized. The constant rise in throughput indicates that traffic volume can increase even when there are fewer cars, and that vehicle usage and interactions with infrastructure can still be effectively managed. During the first and second density cycles of V2I and RSUs, a large number of vehicles were involved, causing the remaining straight lines of equilibrium to shift. For 200 vehicles at a density of 150, the throughput was 82.63%. This indicates a higher likelihood of reliable data exchange and a lower possibility of data loss in that situation. IUTMS technology sends messages about real-time traffic jam analytics while keeping lanes safe and productive for generating heavier engineered-to-node capacity. Mid-program control demonstrated significant injection throughput potential, increasing rapidly from 86.03% to 89.02%. Due to density- and position-based traffic congestion signalling control, the densest traffic volumes (400–500) achieved the best throughput, with 90.37–93.84% reported. This demonstrates that more data is being reported at denser levels, speeds and manoeuvres with IUTMS fluctuations. The consistent increase in

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throughput densities suggests that having more cars in a congested 5G-V2I-IUTMS traffic control system would facilitate easier route switching and reduce idle time. This would lead to greater lane utilisation and improved reliability, flexibility and punctuality in cities with heavy traffic.

5. CONCLUSION

The Intelligent Urban Traffic Management System (IUTMS) is a game-changer for urban transportation, leveraging cloud-edge intelligence, 5G connectivity and IoT-based sensors to disrupt the status quo. By predicting congestion, modifying signal limitations and gathering real-time data, the system identifies urban mobility issues that traditional traffic management is unable to address. According to simulations, the system achieved higher throughput per density, demonstrated consistent packet delivery, and maintained latencies of less than 10 ms. Overall, the results confirm that the system is efficient and reliable, and capable of handling heavy traffic and providing prompt connections. By reducing traffic and travel time through planning, and by guaranteeing the availability of emergency responder vehicles, the IUTMS will improve travel safety. Distributed AI will leverage the ultra-reliable, low-latency communication capabilities of 5G. To make people more alert and attentive, this work proposes using artificial intelligence to create a smart mobility ecosystem that incorporates autonomous delivery technology and surrounds people with holograms. The prospect of next-generation 6G capability renders this feasible. The standard foundation of an IUTMS produces dependable, long-lasting and efficient infrastructure. The infrastructure will develop future intelligent traffic management frameworks for metropolitan areas.

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