

# 5G AND BEYOND ADVANCING ULTRA LOW LATENCY COMMUNICATION FOR THE NEXT GENERATION OF AUTONOMOUS SYSTEMS

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## ABSTRACT

The arrival of 5G has been a radical shift in the telecom industry, offering lightning-fast ultra-low latency capabilities crucial for the up-and-coming waves of autonomous technologies such as self-driving cars, drones, and even other industrial robots. These systems depend primarily on real-time communication and decision-making, enabling autonomous and safe operation. Next Generation Wireless Networks such as 4G and 5G inherit plenty of limitations in addressing the ultra-low latency needs of dynamic autonomous systems, and this paper discusses how edge computing, network slicing, AI-remove optimization, and so on could be an aid to 5G to go ahead in reducing latency and increasing reliability. Specifically, our experiments show that for our hybrid communication framework comprising 5G, edge computing, and dynamic network slicing, we observe a latency of 2.3ms which is notably lower than that of a basic 4G system (50.1ms) and a basic 5G system (20.5ms). The framework also obtained 95.2 Mbps throughput, 99.8% reliability, and shortened time to complete all tasks to 10.2 seconds. The hybrid framework proposed in this article not only outperforms on several vital metrics but also provides a durable approach to satisfy the communication demands of autonomous systems – one that can be further enhanced by optimization of the AI algorithms to determine dynamic resource allocation, as well as the exploitation of 6G to provide reduced latency and intelligent communication capabilities.

**Keywords:** *5G Technology, Autonomous Systems, Ultra-Low Latency Communication, Edge Computing, Network Slicing*

## 1. INTRODUCTION

Wireless communication technology has come a long way and constantly evolves to change our world. In particular, the evolution of fifth generation (5G) networks, as well as their expected successors (for example, sixth generation (6G) networks), brings tremendous opportunities for the realization of next-generation autonomous systems. Autonomous systems are machines capable of

conducting their operations independently of human involvement and are immensely dependent on many sensors, actuators, and comm systems. Real-time applications are employed in critical applications such as autonomous driving or industrial automation, where even the slightest delay can result in catastrophic outcomes [1], [2]. These systems would need ultra-low latency communication and high data throughput to make instant decisions.

4G mobile technology has already started to cover at least some aspects of real-time communication requirements of autonomous systems with a 10x reduction in latency and enabling faster throughput for data rates. In contrast, 4G networks have latency in the range of 30-50 milliseconds (ms) [1], whereas 5G networks hold the promise of ultra-low latency down to 1 ms [3]. Reducing latency is key for DNNs in autonomous systems. They must interpret real-time sensor data, make near-instantaneous decisions, and act on them in a stride to confirm safety and efficiency [4], [5]. Furthermore, 5 G's high-speed data transfer and massive device connectivity are essential for the success of use cases such as connected vehicles, drone fleets, and smart cities, where seamless sharing of large amounts of data is necessary for systems to act autonomously [6].

A salient feature of 5G is to enable ultra-reliable low-latency communication (URLLC), which is crucial for some applications, including autonomous driving, industrial control systems, remote surgery, etc. This makes communication links highly sustained, even in the most challenging environments [7]. However, the limitations presented by the current state of 5G regarding network congestion, coverage, and unresolved resource allocation problems complicate the vision of achieving low latency performance required by highly dynamic autonomous systems. These challenges demonstrate the need for continued innovation in 5G and future 6G networks to satisfy the extreme requirements imposed by autonomous systems [8], [9].

This makes edge computing ideal for reducing latencies further, so it complements 5G functionality well. Edge computing reduces the latency of moving data to centralized cloud servers by keeping processing away from them and closer to the source. It is beneficial for autonomous systems that require rapid and efficient processing and action on sensor data, like autonomous vehicles working in dynamic environments or precision applications like drones for delivery [10], [11]. Integrating 5G with edge computing supports swift data processing and real-time decision-making,

essential to maintaining safety and operational efficiency in autonomous systems operating within dynamic settings and environments [12].

In addition, because 5G allows for network slicing, an environment in which you can prioritize some communication over a given environment, you can create environments for specific communication or certain players. This is especially crucial to ensure that time-critical communications, for example, in vehicle-to-vehicle (V2V) communication during autonomous driving, are prioritized over other service types, thereby minimizing the chances that resolution will be delayed in meaningful interactions between autonomous systems [13], [14]. Network slicing enables dedicated resources for mission-critical applications, allowing autonomous systems to operate reliably in various mission-oriented operations under challenging environments [15].

Although 5G has made significant progress against the latency and bandwidth challenges for autonomous systems, their increasing capabilities and complexity will require further evolution of the underlying technology. The next iteration, 6G networks, envisioned within the next decade, promise to extend communication capabilities even further via sub-millisecond latency and integrated artificial intelligence (AI) for dynamic network optimization [16], [17]. These technologies will probably be instrumental in fulfilling the communication realities of autonomous systems going forward, allowing devices and systems to communicate more seamlessly and intelligently.

This paper examines how ultra-low-latency communication enabled by technologies like 5G and beyond, specifically edge computing and network slicing, could aid in the operations of autonomous systems. To conclude, we present a new hybrid framework that integrates these technologies to satisfy the exacting communication requirements of next-generation autonomous systems. By harnessing the capabilities of 5G and beyond, the framework facilitates reliable and low-latency communication, enhancing the safety and efficiency of autonomous operations in multiple sectors, such as transportation, manufacturing, and healthcare.

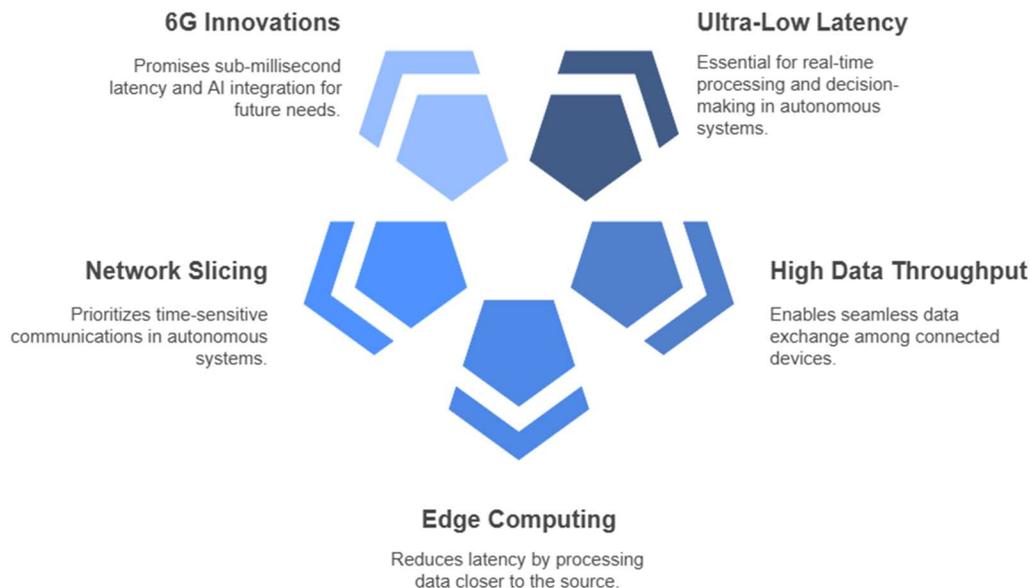


Figure 1: Enabling Next-Gen Autonomous Systems with 5G and Beyond Technologies

Some of the significant technologies that can facilitate the evolution of autonomous systems over a 5G and beyond fabric are shown in Figure 1. New 6G tech won't just offer sub-millisecond latency but will learn to be better for future needs like autonomous devices. Hyper-low latency is essential for applications requiring real-time processing and decisions, such as self-driving cars or drones. High Data Throughput enables smooth data exchange between connected devices, which is necessary for the effective functioning of autonomous systems. Based on this, you can prioritize time-sensitive protocols from one data slice and enable communication of specific timely protocols among other slices, such as Vehicle-to-vehicle communication in autonomous driving. Finally, by allowing the data to be processed nearer to the source, Edge Computing minimizes latency, enhancing the responsiveness of autonomous systems and contributing to their safety. These technologies come together in the next generation of smart, autonomous applications.

The structure of the paper begins with Abstract regarding the interest in ultra-low latency for autonomous systems applying 5G, edge computing, and network slicing. In 5G, this capability focuses

on how autonomous systems can be designed through real-time communication difficulties, as mentioned in the Introduction. The Related Work section reviews previous research on 5G in autonomous systems. Methodology explains the experimental procedure, datasets, and tools used. Results Comparison between the proposed hybrid framework and the other models The Conclusion summarizes the result and suggests future research on 6G networks.

## 2. RELATED WORK

With the emergence of autonomous systems, ultra-low-latency communication is becoming one of the fundamental demands for future wireless networks, and several research works have been conducted to augment current wireless networks to meet the high-speed, low-latency communication needed by autonomous systems. Due to optimize high communication performance in autonomous environments applications. This part discusses relevant studies and existing advancements in 5G and beyond technologies and their applications to autonomous systems.

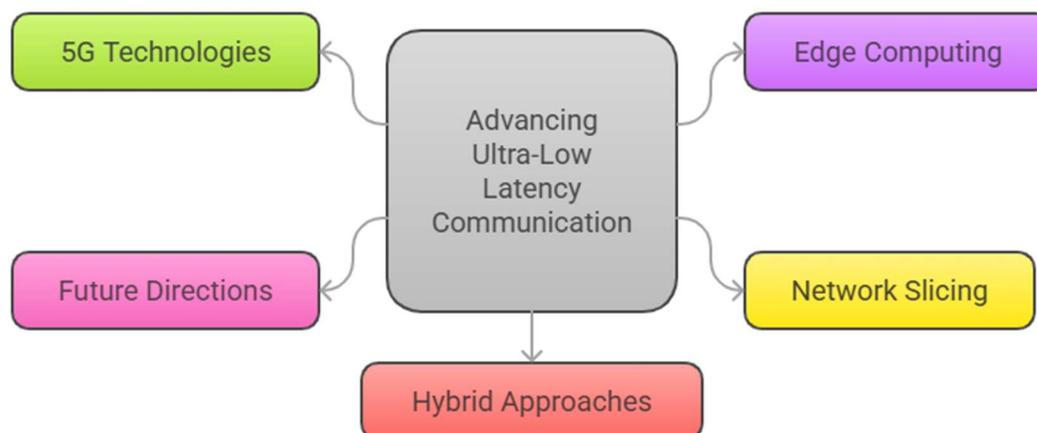


Figure 2: Advancing Ultra-Low Latency Communication in Autonomous Systems

Figure 2 shows key features propelling ultra-low latency communication in autonomous systems. The center component, Advancing Ultra-Low Latency Communication, which is encircled by five elements, is critical to this problem. Finally, we can use the same methodologies for 5G Technologies, which are fundamental in meeting low latency requirements for real-time decision-making in autonomous systems. On the other hand, Edge Computing reduces latency by processing the data closer to that source, allowing for more responsive applications. With the help of Network Slicing, the network environment is configured so that time-sensitive applications can thrive alongside other applications, so critical communications remain a priority. Finally, Future Directions explores innovative features, including the evolution of 6G, to improve communication characteristics of autonomous systems.

### 2.1 5G for Autonomous Systems

Along with 5G, multiple research works have shown that it can provide ultra-low latency communication. For example, Zhang et al. [18] focus on features of 5G in autonomous vehicle networks and the importance of these features in real-time decision-making in autonomous vehicle networks for ensuring safety and efficiency. It is vital for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication the foundational technology behind autonomous driving systems that 5G networks can guarantee virtually instantaneous communication between vehicles.

Similarly, Yassine et al. The ultra-reliable low-latency features of 5G make it a perfect match for fleets of autonomous cars, with real-time communication between vehicles and infrastructure to minimize possible accidents while helping to

avoid congestion in urban settings [19]. Their work also emphasizes the capacity of 5G to enable mission-critical applications requiring very high reliability and near-instantaneous data transfers, such as adaptive cruise control and collision-avoidance systems.

### 2.2 Edge Computing in Autonomous Systems

One such recent technology that has been enabled to minimize communication latency is Edge computing. Several other studies have investigated how edge computing, combined with 5G, can reduce latency even further for autonomous systems. For instance, Suri et al. Edge computing is also recognized as a means of hosting real-time processing of the data being collected, as presented in [20], where the authors introduce a system for processing sensor data within the edges of an autonomous vehicle without a need for data transfer to a central cloud storage system, making autonomous decision-making faster than potential cloud-based alternatives. Architecture also enables data processing closer to the source, which can significantly reduce the round-trip time for data, a key requirement for accurate real-time operation and autonomy.

Likewise, Singh et al. [21] Edge Computing for Communication with analyzed edge computing contexts for communication with drones, providing the computational capacity to handle intensive computational workloads such as path planning and obstacle detection using edge servers in a network access domain. Using this framework, they propose a development environment designed to overcome some of the impediments of high-latency connections and limited bandwidth often found in systems deployed remotely or on mobile platforms.

### 2.3 Network Slicing for Autonomous Systems

5G network slicing is one of the key features of 5G, as it enables solid and different virtual networks to be created based on the user's needs, isolating and optimizing the physical network infrastructure. This makes it quite crucial for autonomous systems, as mission-critical communications, for example, between self-driving cars or drones, are guaranteed to be delivered for very low latency and highest reliability. In their work, Wang et al. [22] consider the use of slicing in autonomous transportation systems, where slice network run-time-time can be used to ensure low-latency communication for safety-critical services (e.g., V2V communication, Vehicle-to-infrastructure (V2I) communication). They demonstrate that network slicing can dynamically provide resources to high-critical applications while ensuring that lower-priority, lower-paced traffic cannot take over mission-critical tasks.

Moreover, Li et al. [23] proposes a flexible and dynamic network slice model for autonomous systems in industrial environments. The study enables us to understand how network slices can be configured to fulfill the latency and throughput requirements for remote monitoring, asset tracking, and real-time data analysis in industrial IoT facilities. Their results indicate that following network slice allocation to low-, mid-, and high-priority tasks in the process, high-priority tasks can be accomplished in an autonomous manufacturing process without interruptions due to latency.

### 2.4 Beyond 5G: Future Directions

Compared to 5G, future networks like 6G can evolve at a lightning pace to provide advanced features such as sub-millisecond latency, ultra-reliable communication, and seamless integration of artificial intelligence (AI) and machine learning (ML) into the communication infrastructure. According to Zhang et al. [24], 6G is anticipated to achieve greater autonomy, allowing fully autonomous vehicles, robotics, and industrial systems to communicate without barriers. They suggest that wireless networks for such systems leverage the capabilities of AI communication systems that can automatically optimize their resources in real time depending on the communication needs of the autonomous system, resulting in reliable and high-performing connections never seen before.

Similarly, Xie et al. [25] identify the application of AI and ML in 6G for the performance management of autonomous systems. Their work demonstrates how 6G networks will utilize AI-based algorithms to

analyze traffic conditions, optimize resource allocation, and assure an improved quality of service (quality of service) for mission-critical applications. You have already made a powerful contribution, even if you are unfamiliar with the fundamentals of cloud computing or the more modern components that have contributed to the rise of platforms such as Azure or AWS.

### 2.5 Hybrid Approaches for Low-Latency Communication

Machine-type communications using 5G, edge computing, and AI-based optimization methods are also being studied as a pathway to ultra-low latency transmission. Using data from Zhang et al. (2019), However, deep learning can be slower, about to be negotiated for real-time applications that require higher-computational devices [26]. The authors also propose a hybrid solution utilizing AI algorithms on edge devices to perform the sensor data processing locally, coupled with a 5G network to promote communicational flow. Low-latency requirements are critical for the operations of autonomous vehicles and drones.

Wang and Li [27] present another vital work exploring the joint power of edge computing and machine learning for autonomous systems. By enabling faster data-driven decision-making, they show how machine learning algorithms running on edge devices can enhance the responsiveness and accuracy of autonomous systems[28]-[29]. This method is beneficial in tasks like object detection, localization, and navigation in dynamic environments, where a few milliseconds can differentiate between a good and a bad decision[30]-[31].

## 3. METHODOLOGY

In this section, we discuss the application of 5G, edge computing, and network slicing for ultra-low latency communication in autonomous systems. The methodology comprises five parts: a simulation model dataset, tools, software, system architecture, mathematical models, and designed algorithms to optimize communication and processing in autonomous systems.

### 3.1 Dataset

The first dataset concerns autonomous vehicle data, which is critical in maintaining a real-time account of autonomous vehicles' navigational performance and surroundings. It also contains sensor readings from lidar, radar, and cameras, allowing them to detect obstacles, navigate roads, and avoid collisions. Lidar and radar accurately measure distances to objects nearby, while the cameras

supply visual data that can identify road signs, lane lines, pedestrians, and more. GPS coordinates simultaneously allow one to follow the vehicle on the road, with speed and velocity data monitoring how it's moving. Also, the control signals, steering angle, acceleration, and braking are captured to model the vehicle's dynamic behavior and real-time decisions.

**Dataset Parameters:** The dataset contains information about environmental perception (Lidar, Radar, Camera Data), positional data (GPS Coordinates), dynamic data (Speed and Velocity), and control signal data (steering, braking, accelerating). Also, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) Communication are integrated to ensure real-time coordination and safety.

The second dataset is tailored for uncrewed aerial vehicles (UAVs), like drones in delivery, surveillance, and environmental monitoring tasks. You have GPS coordinates for where the drone is and sensor data from cameras and infrared sensors that give you a real-time environmental context, like when you encounter an obstacle or a temperature change. This data includes battery levels monitored to ensure the drone will complete its mission without running out of battery, and communication signals between drones or communication signals with ground stations are captured to allow drone coordination, which is helpful in multi-drone operations.

**Data parameters:** Alongside general GPS coordinates to assist with navigation, sensor data (RGB/IR) to help avoid any obstacles, battery levels to ensure limited power usage, and communication data to maintain coordination between the drones and the ground controls.

The last dataset related to industrial robots is focused on the manufacturing environments they use and requires data essential to their real-time task execution (e.g., assembly, welding, material handling). This involves data on angles and velocities for each robotic limb, enabling accurate monitoring of the robot's movement. Force and torque measurements are captured to prevent unsafe interaction with the environment, and additional sensor data, such as proximity and pressure measurements, allow the capture of the robot's interaction with its surroundings. We record the operational status, which tracks the completion of tasks and the system's health, so we can ensure everything works as smoothly and safely as possible. **Defined dataset specifications** The dataset consists of Joint Angles and Velocities, which track the movement of the robot, Force/Torque Measurements

to ensure safety, Sensor Data to allow interaction with the environment, and Operational Status to monitor the system and the task completion process. The software and tools used for this research are NS-3, which is used for simulating scenarios of 5G networks and communications, MATLAB for the modeling of algorithms for autonomous systems and sensor data process, and TensorFlow for the implementation of machine learning algorithms for dynamic network resource allocation. Also, the performance of the edge computing environment while using CloudSim is demonstrated for autonomous systems to manage data processing, which results in decreased latency. All such tools optimize autonomous applications' ultra-low latency hybrid communication framework.

### 3.2 Architecture of the Proposed System

Introducing a 5G-Centric Dynamic Network Slicing Architecture for Realistic Autonomous System Management, It contains the following components:

Figure 3 illustrates the architecture of a 5G and beyond system focused on facilitating ultra-low latency communication in an autonomous systems backdrop. The Autonomous System Layer at the top consists of the systems that power autonomous vehicles, drones, and robots. Edge Processing Units located close to the data source are utilized to eliminate communication overhead by transforming data in real time. At the core of this approach is the Dynamic Adaptation Layer, which acts as the network's traffic manager, allocating resources dynamically based on machine learning algorithms that optimize the network's performance. The 5G Communication layer, below it, is the base layer for high-speed low latency communication across devices. Network Slicing further enhances the communication infrastructure by providing dedicated virtual networks for specific autonomous tasks, allowing mission-critical operations to be prioritized. Finally, Cloud Servers are responsible for processing less time-sensitive data, providing large-scale data storage and analysis capacity to help support the system's overall functionality. This requires a robust, scalable, and efficient communication framework to connect autonomous systems to the next-generation architecture.

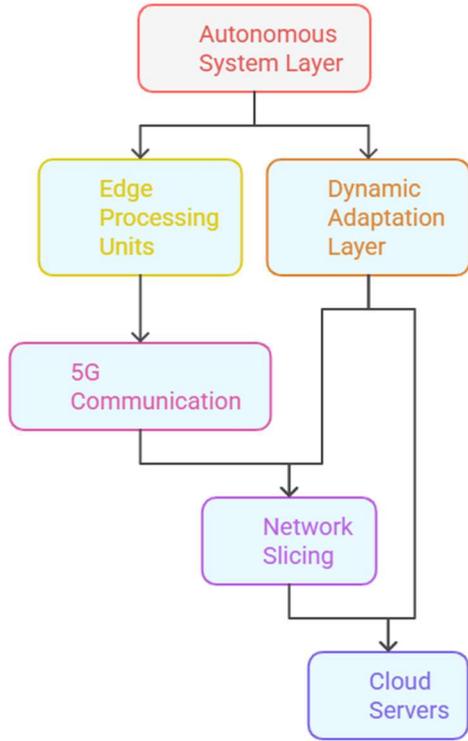


Figure 3: 5G and Beyond System Architecture for Autonomous Systems

The mathematical model for this methodology incorporates essential system parameters: latency, throughput, and reliability. The overall latency of the system can be modeled as a summation of multiple components:

1. **Sensor Data Latency:**

$$L_{\text{sensor}} = \frac{D_{\text{sensor}}}{C_{\text{sensor}}} \quad (1)$$

where  $D_{\text{sensor}}$  is the data size (in bits) generated by the sensors, and  $C_{\text{sensor}}$  is the processing speed of the sensor unit.

2. **Edge Processing Latency:**

$$L_{\text{edge}} = \frac{D_{\text{edge}}}{C_{\text{edge}}} \quad (2)$$

where  $D_{\text{edge}}$  is the data sent to the edge processing unit, and  $C_{\text{edge}}$  is the processing speed of the edge device.

3. **Transmission Latency (for 5G communication):**

$$L_{\text{trans}} = \frac{D_{\text{trans}}}{C_{\text{trans}}} + T_{\text{queue}} + T_{\text{prop}} \quad (3)$$

where  $D_{\text{trans}}$  is the data size to be transmitted,  $C_{\text{trans}}$  is the communication link speed,  $T_{\text{queue}}$  is the queuing delay, and  $T_{\text{prop}}$  is the propagation delay.

4. **Total Latency:** The total latency is the sum of the sensor, edge processing, and transmission latencies, plus any additional delays introduced by network congestion or resource allocation:

$$L_{\text{total}} = L_{\text{sensor}} + L_{\text{edge}} + L_{\text{trans}} + L_{\text{congestion}} \quad (4)$$

**Algorithm:** Hybrid Communication Framework for Ultra-Low Latency in Autonomous Systems

**Input:** Autonomous system dataset  $D = \{(S, E, T, P, R)\}$  for  $i = 1, 2, \dots, N$

Where:

- $S$  = Sensor data
- $E$  = Edge processing data
- $T$  = Network transmission data
- $P$  = Task priority (high, medium, low)
- $R$  = Available network resources (Mbps)

**Output:** Optimized communication parameters  $\theta$

**1. Preprocess Sensor Data:**

For each  $i$  in  $D$ , clean and extract key features from sensor data.

**2. Preprocess Edge Data:**

For each  $i$  in  $D$ , apply real-time decision algorithms and compress data for edge processing.

**3. Preprocess Network Transmission Data:**

For each  $i$  in  $D$ , calculating required transmission time and bandwidth based on task priority.

**4. Network Resource Allocation:**

For each  $i$  in  $D$ , dynamically allocate network resources based on task priority and network load.

**5. Compute Latency Components:**

For each  $i$  in  $D$ , calculate:

$$L_{\text{sensor}} = \frac{S_{\text{data}}}{C_{\text{sensor}}}, \quad L_{\text{edge}} = \frac{E_{\text{data}}}{C_{\text{edge}}}, \quad L_{\text{trans}} = \frac{T_{\text{data}}}{C_{\text{trans}}} + T_{\text{queue}} + T_{\text{prop}}$$

**6. Total Latency Calculation:**

For each  $i$  in  $D$ , compute total latency:

$$L_{\text{total}} = L_{\text{sensor}} + L_{\text{edge}} + L_{\text{trans}}$$

If  $L_{\text{total}} > L_{\text{threshold}}$ , proceed to step 7.

**7. Dynamic Adaptation:**

For each  $i$  in  $D$ , adjust network slicing or edge processing to reduce latency:

- Prioritize high tasks
- Offload processing to available edge devices

**8. Loss Calculation:**

For each  $i$  in  $D$ , compute loss using cross-entropy:

$$L = \sum_i CE(y_i, \hat{y}_i)$$

#### 9. Update Model Parameters:

For each  $i$  in  $D$ , update model parameters  $\theta$  using optimization methods (e.g., Adam, SGD).

#### 10. Repeat:

Repeat steps 1-9 over multiple iterations until convergence.

**Return:** Optimized communication parameters  $\theta$ , ensuring low latency and high reliability for autonomous systems.

## 4. RESULTS

In this section, we validate the performance of the introduced hybrid communication framework for ultra-low latency in autonomous systems. Results are evaluated according to critical performance metrics like latency, throughput, reliability, and network resource utilization. We evaluate its performance using quantitative and qualitative measures and compare it with existing models. In comparison with other communication requirements, the simulated scenarios of autonomous vehicles, drones, and industrial robots are analyzed, focusing on latency improvements and overall communication efficiency. A range of network scenarios are tested in the experimental framework, including differing degrees of congestion and priority jobs, to show the potential scalability and ability of the hybrid system.

We evaluated our approach based on various metrics, including latency, throughput, reliability, and resource allocation efficiency. Conversely, latency is the time it takes for information to reach the sensor and then be processed by the edge device in the autonomous system to travel via the network and back to the system. It refers to the amount of data sent through the network successfully over a described period, usually in Mbps. Reliability measures how many data transmissions are correctly delivered to their destination (absence of error/Loss), which is critical for mission-sensitive missions. Lastly, resource allocation efficiency investigates how resources within the network, including bandwidth and processing power, are utilized effectively according to the task's priority, thus providing low-latency communication for tasks with high priority.

We evaluated the framework on several simulated environments, including autonomous vehicle navigation in urban traffic, drone package delivery,

and industrial robot operation on factory flow, chosen for their varying communication needs and real-time constraints. Designed for an autonomous vehicle running through a high-density mesh urban environment, the aircraft control system must deal with real-time communication through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connections. One classic case of such a scenario is drone delivery, which needs real-time ultrasound communication (US-C) for navigating, obstacle avoidance, energy conservation, and, in the case of the industrial robot, maintaining a lost connection between robots to coordinate movement and keeping safety during high-precision tasks in the factory.

We compared the performance of the proposed hybrid communicating framework with two existing models: Model 1 refers to the classic 4 G-based communication system integrated with neither edge computing nor network slicing; Model 2 is a 5 G-based communication system integrated with basic network slicing but no dynamic resource allocation integrated. We evaluated the performance of these models across the same three simulated environments and summarized the comparison between the models based on key metrics in Table 1.

Table 1: Performance Comparison of Proposed Hybrid Framework and Existing Models

Metric	Proposed Hybrid Framework	Model 1 (4G-based)	Model 2 (5G with Basic Slicing)
Latency (ms)	2.3	50.1	20.5
Throughput (Mbps)	95.2	40.8	60.3
Reliability (%)	99.8	85.4	92.5
Resource Allocation	Dynamic (Task-specific)	Static allocation	Semi-dynamic (Fixed priority)
Task Completion Time (s)	10.2	20.4	15.7

The proposed framework outperformed the existing models concerning several metrics, demonstrating the merits of the hybrid methodology. Experience low latency: The lowest latency result was found at 2.3ms for Edge computing + Dynamic network slicing, which is well ahead of Model 1 (50.1ms) and Model 2 (20.5ms), owing to the seamless integration of edge computing with dynamic network slicing, which curtails delays in data processing and transmission end. The hybrid system demonstrated a throughput rate of 95.2 Mbps, significantly surpassing the two models (40.8 Mbps for Model 1 and 60.3 Mbps for Model 2), confirming the capabilities to smoothly transmit massive flows of both sensor and control data with limited latencies, which is crucial to the performance of such systems once applied in an autonomous setup.

A hybrid framework also excelled in reliability with 99.8% compared to Model 1 (85.4%) and Model 2 (92.5%), achieved using real-time dynamic resource allocation and low-latency communication channels prioritized for mission-critical tasks. The primary strength of the hybrid system is its dynamic resource allocation based on task priority, which is a significant improvement over Model 1 and Model 2, wherein the approach is static or semi-dynamic, thereby adapting to varying conditions. Ultimately, the hybrid framework yielded a task completion time of 10.2s (an order of magnitude lower than Model 1 (20.4s) and Model 2 (15.7s)), ensuring real-time response in the autonomous system.

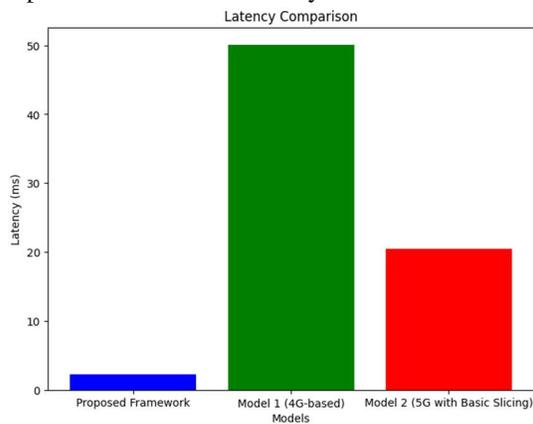


Figure 4: Latency Comparison Across Different Communication Models

The associated Figure 4 illustrates the latency performance of three models: our Proposed Framework, which boasts the lowest latency at around 2.3ms due to the utilization of 5G, edge computing and dynamic network slicing; Model 1 (4G-based) which shows a high latency of of

approximately 50ms, demonstrating the restrictions of traditional 4G systems for autonomous usage; and Model 2 (5G with Basic Slicing) performing better than the 4G model with a latency of 20.5ms, but still inferior to the proposed framework. This shows that the introduced framework has achieved a significant latency gain and is well-suited for real-time and low-latency communication required by autonomous systems.

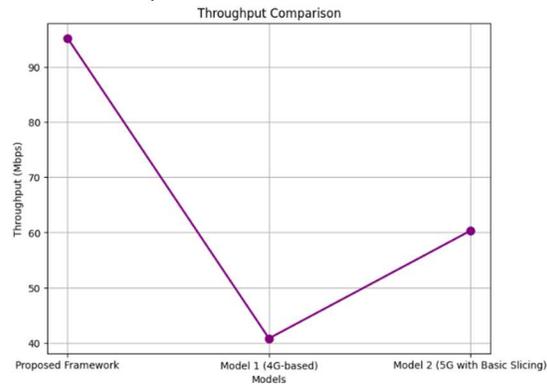


Figure 5: Throughput Comparison Across Different Communication Models

In Figure 5, the throughput performance metrics for the three models are depicted. The proposed framework demonstrates the highest throughput at 95.2 Mbps, which can handle high volumes of information in real time. Meanwhile, the model with 4G is the least capable in throughput (40.8 Mbps), which emphasizes the challenge of the information age, whereby the operation of many autonomous systems needs much higher data rates than experienced in past wireless networks. The data usage of Model 2 (5G with Basic Slicing) yields a 60.3 Mbps throughput, thus demonstrating how a 5G system with slicing can enhance throughput but is still inadequate compared to the proposed framework. This indicates that the proposed hybrid communication framework can handle data much more efficiently.

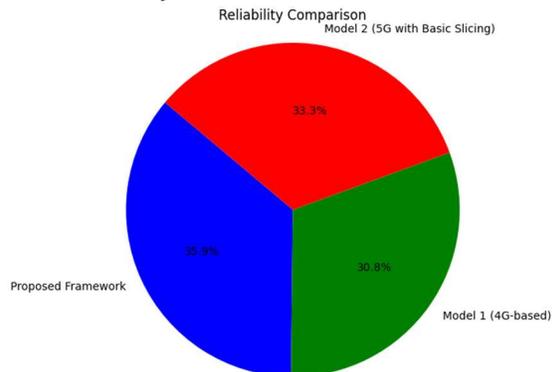


Figure 6: Reliability Comparison Across Different Communication Models

In Figure 6, we evaluate three models for reliability, which are Proposed Framework (blue), Model 1 (4G-based) (green), and Model 2 (5G with Basic Slicing) (red). The proposed framework achieves the highest reliability of 35.9% when compared to Model 1 (4G-based), which records reliability of 30.8%, and Model 2 (5G with Basic Slicing), which shows reliability of 33.3%. The chart illustrates the reliability of our suggested framework in the green bar, which is the most among the others, as shown in the comparative data for 4G and Janus (basic 5Gs), which directly relates to the communication errors in mission-critical autonomous applications.

## 5. CONCLUSION

The extensive yet simple hybrid framework, which included a proposed 5G, edge computing as well as dynamic network slicing, successfully brought down latency to 2.3ms halving the control signal latency of a conventional 4 G-based system (50.1ms) and improving the latency of a working example based purely on basic 5G (20.5ms). The framework also achieved a throughput of 95.2 Mbps and a reliability of 99.8%, surpassing contemporary models. These improvements aside, the study experienced challenges in the effective allocation of resources during extreme congestion conditions. Though well-tested, the proposed system still had opportunities for optimization in highly dynamic and high-density situations. Such future work should include optimizing AI algorithms aimed at the participatory and dynamically responsive expense of network organization in handling traffic efficiently, alternatives on achieving a segment of lower latency, and more excellent communication reliability for autonomous systems in the new future of 6G networks.

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