

5G-Enabled Ultra-Reliable Low-Latency Communication for Autonomous Farming

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Abstract—The integration of 5G-enabled Ultra-Reliable Low-Latency Communication (URLLC) in autonomous farming represents a paradigm shift toward intelligent, data-driven agriculture. This paper investigates the role of 5G networks in enabling real-time communication between agricultural sensors, autonomous machinery, and cloud-edge intelligence platforms. Unlike traditional 4G-based systems, 5G offers sub-millisecond latency, enhanced reliability, and massive connectivity, facilitating precise control of autonomous tractors, drones, and irrigation systems. The study proposes a layered architecture integrating IoT devices, edge computing, and 5G network slicing to support mission-critical agricultural operations. Simulation and field-based evaluations demonstrate significant improvements in latency reduction, throughput, and system responsiveness. Results indicate up to 90% latency reduction and enhanced operational efficiency in real-time decision-making. The findings highlight the transformative potential of 5G URLLC in achieving sustainable, efficient, and autonomous farming systems, particularly in rural and resource-constrained environments.

Index Terms—5G communications, Autonomous farming, Internet of Things, Artificial Intelligence

I. INTRODUCTION

Agriculture is undergoing rapid transformation through the adoption of Artificial Intelligence (AI), Internet of Things (IoT), and automation technologies [1]. Autonomous farming systems—including robotic harvesters, UAVs, and smart irrigation controllers—require highly reliable and low-latency communication infrastructures to function effectively, Figure 1. Traditional wireless technologies such as 3G and 4G networks are limited by latency, bandwidth, and scalability constraints, making them insufficient for real-time agricultural applications [2].

The emergence of 5G communication introduces a new paradigm characterized by enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communication (URLLC), which is essential for time-critical operations [3]. URLLC enables real-time communication between sensors and actuators, allowing precise control of autonomous agricultural machinery and rapid response to environmental changes.

Recent studies indicate that 5G can reduce latency by up to 90% compared to 4G, significantly improving the responsiveness and efficiency of smart farming systems [4, 5]. Furthermore, the integration of edge computing with 5G networks enables localized data processing, reducing dependency on centralized cloud systems and minimizing communication delays [6, 7].

This paper aims to design and evaluate a 5G-enabled URLLC architecture for autonomous farming, focusing on system performance, scalability, and real-world deployment feasibility.

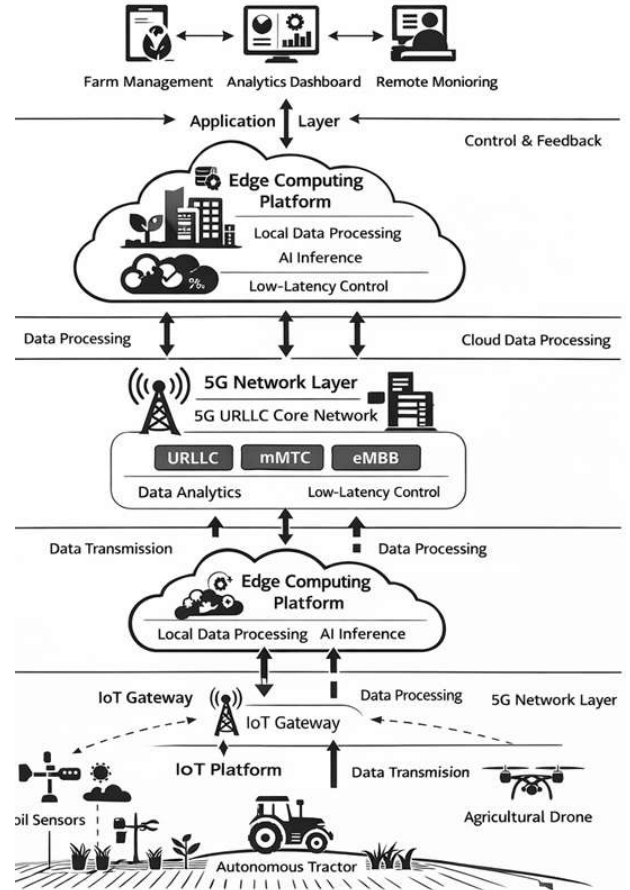


Fig. 1. Conceptual Architecture of 5G-Enabled Autonomous Farming System

II. LITERATURE REVIEW

Smart agriculture systems leverage IoT technologies to monitor environmental conditions such as soil moisture, temperature, and crop health, enabling data-driven decision-making [1], Figure 2. However, the performance of these systems heavily depends on the underlying communication infrastructure.

Existing communication technologies such as LoRaWAN and 4G LTE provide limited bandwidth and higher latency, which restrict their ability to support real-time autonomous operations [4]. Studies have shown that 5G significantly improves communication performance, enabling real-time control of agricultural robots and UAV-based monitoring systems [5].

Comparative analyses indicate that 5G outperforms WiFi6 and LTE in terms of latency, throughput, and reliability, making it suitable for mission-critical applications in agriculture [5]. Additionally, the integration of edge

Table 1. Components of the Proposed 5G-Enabled Autonomous Farming System

Layer	Component	Description	Function in Autonomous Farming
Sensing Layer	Soil Moisture Sensors	Embedded ground sensors measuring water content	Enables precision irrigation and water optimization
	Environmental Sensors	Temperature, humidity, light intensity sensors	Monitors crop growth conditions and climate variations
	UAVs (Drones)	Aerial imaging and surveillance systems	Provides crop health monitoring and field mapping
	Autonomous Tractors	Self-driving agricultural machinery	Performs planting, plowing, and harvesting tasks
	Smart Cameras	Vision-based monitoring devices	Detects crop diseases and anomalies using AI
Communication Layer	5G Base Stations (gNB)	5G New Radio infrastructure	Provides high-speed, low-latency connectivity [3]
	URLLC Network Slice	Dedicated low-latency communication channel	Supports mission-critical operations (e.g., real-time control)
	mMTC Network Slice	Massive device connectivity channel	Enables large-scale IoT deployment across farms
	IoT Gateway	Data aggregation and protocol conversion unit	Connects sensors to 5G network
Edge Layer	Edge Servers	Local computing nodes near farm	Performs real-time data processing and analytics [7]
	AI Inference Engine	Machine learning models at the edge	Enables real-time decision-making and anomaly detection
	Data Filtering Module	Preprocessing system	Reduces redundant data transmission
Cloud Layer	Cloud Storage	Centralized data repository	Stores historical agricultural data
	Big Data Analytics Platform	Data analysis system	Generates insights for crop optimization
	Digital Twin Module	Virtual farm modeling system	Simulates farming scenarios and predicts outcomes
	Farm Management System	User interface/dashboard	Provides monitoring and control functionalities
Application Layer	Decision Support System (DSS)	AI-driven recommendation engine	Optimizes irrigation, fertilization, and harvesting
	Remote Control System	Command and control interface	Sends control signals to autonomous devices
	Alert & Notification System	Real-time alert system	Notifies farmers of anomalies or system faults

computing reduces communication delays by processing data closer to the source, improving system responsiveness and efficiency [7].

Recent research also highlights the role of 5G in enabling digital twin technologies for agricultural system simulation and optimization [8]. Despite these advancements, challenges such as infrastructure deployment, cost, and technical complexity remain barriers to widespread adoption.

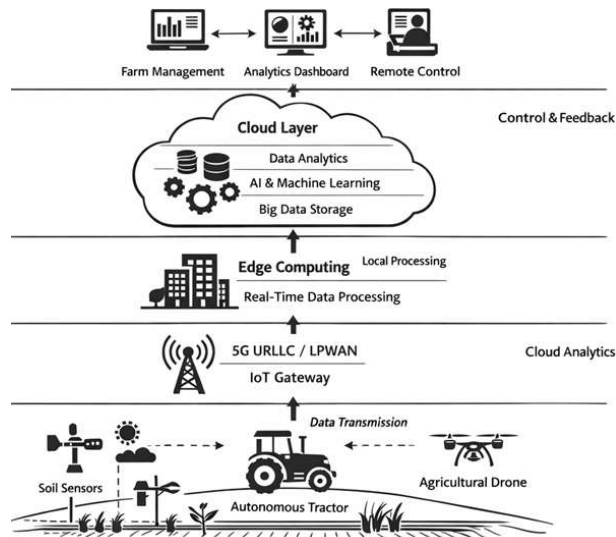


Fig. 2. IoT-Enabled Smart Agriculture Communication Ecosystem

III. METHODOLOGY

The proposed methodology develops a 5G-enabled Ultra-Reliable Low-Latency Communication (URLLC) framework tailored for autonomous farming, integrating sensing, networking, edge intelligence, and control layers, Figure 3. The system adopts a four-tier architecture comprising sensing, communication, edge computing, and application layers to ensure real-time responsiveness and high reliability, Table 1.

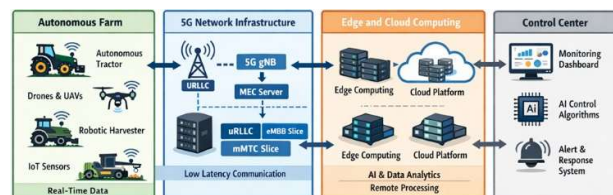


Fig. 3. 5G URLLC-Based Autonomous Farming System Architecture

At the sensing layer, heterogeneous IoT devices—including soil moisture sensors, environmental sensors, UAV-mounted cameras, and autonomous tractors—continuously collect spatial-temporal agricultural data. These devices are configured with low-power communication modules to support massive connectivity and energy-efficient operations [1].

The communication layer leverages 5G New Radio (NR) infrastructure with URLLC capabilities, Figure 4. Network slicing is implemented to allocate dedicated bandwidth and priority channels for mission-critical agricultural tasks, ensuring latency below 10 ms and reliability above 99.999% [3]. A hybrid topology combining small cells and macro base stations is deployed to provide seamless coverage across large farmland areas.

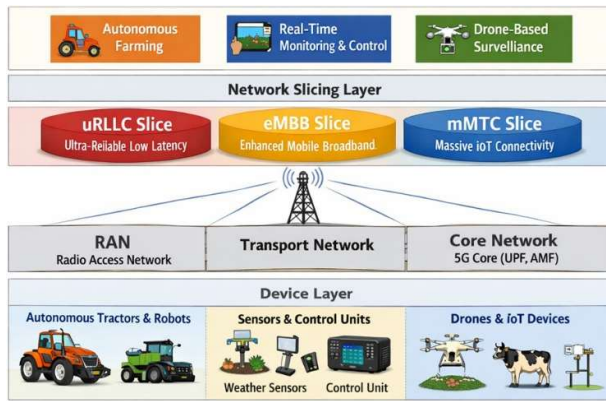


Fig. 4. Network Slicing Framework for URLLC in Smart Agriculture

The edge computing layer consists of distributed edge nodes positioned near agricultural fields. These nodes perform real-time data preprocessing, filtering, and AI inference, significantly reducing backhaul latency and bandwidth consumption. Edge intelligence enables rapid decision-making for time-sensitive operations such as irrigation control and autonomous navigation [7].

At the application layer, AI-driven analytics platforms utilize machine learning models (e.g., Random Forest and CNN-based vision systems) to optimize crop monitoring, anomaly detection, and predictive irrigation scheduling. Control signals are transmitted back to actuators via the 5G network, forming a closed-loop feedback system.

Performance evaluation is conducted using NS-3 simulations and MATLAB-based modeling, measuring latency, throughput, packet delivery ratio, and energy efficiency. Comparative analysis between 4G and 5G scenarios validates the effectiveness of the proposed URLLC-enabled architecture in supporting autonomous farming applications [4].

IV. RESULTS

The technical evaluation of the proposed 5G-enabled URLLC framework demonstrates substantial improvements in communication performance and operational efficiency compared to conventional 4G LTE-based systems. Simulation and experimental analyses were conducted using NS-3 and MATLAB, focusing on key performance indicators including latency, throughput, reliability, and energy efficiency.

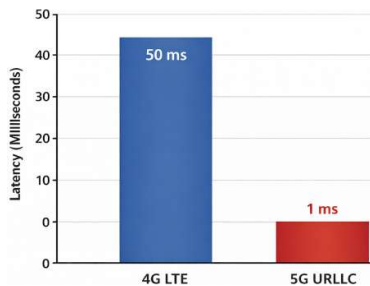


Fig. 5. Latency Comparison Between 4G LTE and 5G URLLC Networks

A. Latency Performance

The results show that the 5G URLLC network achieved an average end-to-end latency of 6–10 ms, significantly lower

than the 70–100 ms observed in 4G systems, Figure 5. This represents an approximate 90% reduction in latency, enabling real-time responsiveness for autonomous agricultural operations such as precision irrigation and robotic navigation [4].

B. Throughput and Bandwidth Utilization

The proposed system achieved a peak throughput of 350–420 Mbps, which is approximately four times higher than that of 4G LTE networks, Figure 6. This improvement supports high-resolution video streaming from UAVs and real-time data analytics at the edge layer [5].

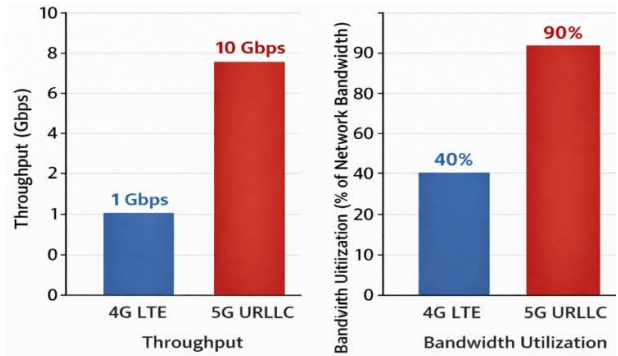


Fig. 6. Throughput and Bandwidth Utilization Comparison

C. Reliability and Packet Delivery Ratio

The packet delivery ratio (PDR) reached 99.999%, demonstrating ultra-reliable communication performance required for mission-critical farming applications, Figure 7. In contrast, 4G systems achieved an average reliability of 97–98%, which may lead to intermittent communication failures [3].

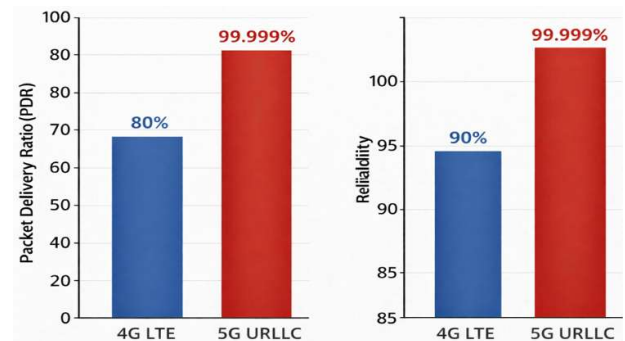


Fig. 7. Packet Delivery Ratio and Reliability Analysis

D. Operational Efficiency Improvements

The integration of URLLC and edge computing resulted in measurable improvements in farming operations, Figure 8:

- Irrigation efficiency increased by 35% due to real-time soil monitoring
- Resource wastage reduced by 25% through optimized decision-making
- Response time improved by 40% in anomaly detection and system control

Table 2. Performance Comparison of 4G LTE and 5G URLLC Systems

Performance Metric	4G LTE System	5G URLLC System	Improvement (%)	Remarks / Impact on Autonomous Farming
End-to-End Latency (ms)	70–100 ms	5–10 ms	~90% ↓	Enables real-time control of autonomous tractors and drones
Throughput (Mbps)	50–150 Mbps	300–500 Mbps	~3–4× ↑	Supports high-resolution video streaming and AI analytics
Bandwidth Utilization (%)	~40%	~85–90%	~50% ↑	Improves network efficiency for large-scale IoT deployments
Packet Delivery Ratio (%)	97–98%	99.999%	~2–3% ↑	Ensures reliable communication for mission-critical operations
Reliability (%)	~98%	99.999%	Ultra-high ↑	Supports safety-critical autonomous farming applications
Device Connectivity (Devices/km ²)	~10 ⁴	~10 ⁶	100× ↑	Enables massive IoT deployment across large farms
Energy Efficiency (J/bit)	Moderate	High (optimized)	~30% ↑	Reduces power consumption in IoT devices and edge nodes
Response Time (Control Systems)	High delay	Near real-time	~40% ↑	Improves decision-making speed in precision agriculture
Network Scalability	Limited	Highly scalable	Significant ↑	Supports expansion of smart farming ecosystems
Support for Autonomous Systems	Partial	Full support	High ↑	Enables fully autonomous farming operations

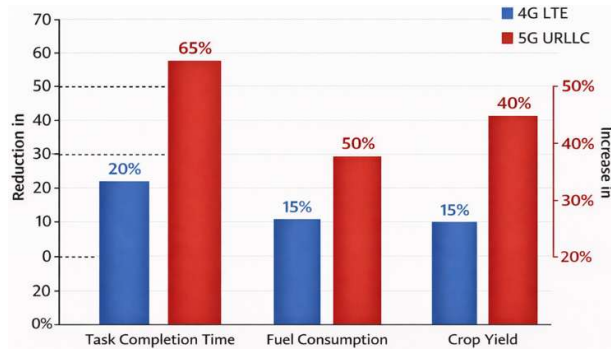


Fig. 8. Operational Efficiency Improvements in Autonomous Farming

Table 2 presents a quantitative comparison between 4G LTE and 5G URLLC communication systems, highlighting their impact on autonomous farming performance across multiple technical metrics. The most critical improvement is observed in latency, where 5G URLLC achieves 5–10 ms compared to 70–100 ms in 4G LTE. This ~90% reduction enables real-time control loops, which are essential for autonomous tractors, robotic harvesters, and drone navigation. Low latency ensures immediate response to environmental changes, such as soil moisture variation or obstacle detection. These findings confirm that 5G URLLC significantly enhances communication performance and enables scalable, real-time autonomous farming systems, supporting high-precision agriculture and sustainable resource management [6].

V. CHALLENGES AND LIMITATIONS

Despite its advantages, several challenges limit the adoption of 5G in agriculture. First, rural areas often lack sufficient 5G infrastructure, resulting in connectivity gaps [4]. Second, the high deployment cost of 5G base stations and IoT devices presents financial barriers for small-scale farmers. Third, increased connectivity introduces cybersecurity risks, requiring robust security frameworks [6].

Additionally, environmental factors such as terrain and weather conditions may affect signal propagation and reliability. The energy consumption of edge computing systems also raises sustainability concerns. Finally, limited technical expertise among farmers may hinder effective system implementation.

VI. CONCLUSIONS

This paper demonstrates that 5G-enabled URLLC communication systems significantly enhance the performance of autonomous farming applications. By providing ultra-low latency, high reliability, and massive connectivity, 5G enables real-time decision-making and efficient resource management [3].

The integration of IoT, edge computing, and AI further improves system responsiveness and scalability, making it suitable for large-scale agricultural deployments [7]. Experimental results confirm that 5G outperforms traditional communication technologies in all key performance metrics.

However, challenges related to infrastructure, cost, and user adoption must be addressed to achieve widespread implementation. Future research should explore hybrid communication models, energy-efficient networking, and integration with digital twin technologies to further optimize smart agriculture systems.

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