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OPEN RAN-BASED ON-DEMAND 6G AGRICULTURAL NETWORKS: ADAPTIVE EDGE INFRASTRUCTURE FOR AUTONOMOUS FARMING SYSTEMS

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Abstract:
The rapid advancement of Open Radio Access Network (Open RAN) technologies has created new opportunities for deploying flexible, scalable, and cost-effective wireless infrastructures in agricultural environments. This paper proposes an Open RAN-based on-demand 6G agricultural network that integrates Private 5G connectivity, edge computing, artificial intelligence, and emerging THz communication concepts to support autonomous farming systems. Unlike conventional agricultural communication architectures, the proposed framework dynamically allocates network resources according to field conditions, crop monitoring requirements, unmanned aerial vehicle operations, and autonomous agricultural machinery. Open RAN enables multi-vendor interoperability and programmable radio resource management, while edge computing facilitates low-latency processing of sensor data and AI inference close to the farming environment. Private 5G enhances secure and reliable communication among IoT devices, drones, robotic equipment, and cloud platforms. Future THz-enabled links further improve bandwidth availability for high-resolution imaging and large-scale environmental sensing. The proposed architecture improves network scalability, spectrum utilization, operational flexibility, and autonomous decision-making while reducing deployment costs and communication latency. Simulation-based performance evaluation demonstrates improvements in network throughput, energy efficiency, task completion latency, and resource utilization compared with conventional agricultural wireless architectures. The proposed framework provides a practical pathway toward intelligent, sustainable, and highly adaptive 6G-enabled precision agriculture ecosystems.

Keywords: Open RAN,6G Agriculture, Private 5G.Edge Computing, Autonomous Farming, Precision Agriculture, THz Communication, Smart Agriculture.

I. INTRODUCTION

Agriculture is rapidly transitioning toward intelligent and autonomous production systems supported by advanced wireless communication technologies. Modern farms increasingly rely on IoT sensors, unmanned aerial vehicles, autonomous tractors, robotic harvesters, and AI-driven analytics to improve productivity and sustainability. These applications require highly reliable, scalable, and low-latency communication infrastructures capable of supporting thousands of heterogeneous devices across large geographical areas. Traditional cellular networks often face limitations in coverage, flexibility, vendor dependency, and deployment costs, particularly in rural environments. Open Radio Access Network (Open RAN) has emerged as a transformative architecture that disaggregates hardware and software components, enabling interoperable and programmable radio access networks. Combined with Private 5G deployments, Open RAN allows agricultural enterprises to establish dedicated communication infrastructures tailored to seasonal workloads, crop monitoring activities, and autonomous farming operations. Edge computing further enhances these deployments by processing sensor data locally, minimizing communication delays and reducing dependence on centralized cloud services.

The evolution toward 6G introduces advanced communication capabilities, including AI-native networking, integrated sensing, and THz communication, enabling real-time coordination of autonomous farming equipment and high-resolution environmental monitoring. Future agricultural networks will dynamically allocate communication resources according to field conditions, weather changes, machinery movement, and crop health status.

This paper presents an Open RAN-based on-demand 6G agricultural architecture that combines Private 5G, edge intelligence, AI-based resource orchestration, and emerging THz communication technologies.

II. LITERATURE SURVEY

Recent advancements in wireless communication technologies have accelerated the adoption of intelligent agriculture through the integration of Open Radio Access Network (Open RAN), Private 5G, edge computing, artificial intelligence (AI), and emerging 6G concepts. Open RAN introduces an open and disaggregated architecture that enables interoperability among multi-vendor network components, reducing deployment costs while improving network flexibility. Researchers have demonstrated that Open RAN supports software-defined resource management and dynamic network slicing, making it suitable for scalable agricultural communication infrastructures.Private 5G networks have gained significant attention for precision agriculture due to their ability to provide secure, reliable, and low-latency connectivity for autonomous tractors, unmanned aerial vehicles (UAVs), environmental sensors, and smart irrigation systems. These dedicated networks ensure uninterrupted communication in remote farming areas while supporting mission-critical agricultural operations. However, most existing implementations rely on fixed network configurations that cannot efficiently adapt to changing seasonal workloads and varying field conditions.Edge computing has further enhanced agricultural applications by processing sensor data near the source instead of transmitting all information to centralized cloud servers. This approach minimizes latency, reduces bandwidth consumption, and enables real-time decision-making for crop health monitoring, pest detection, and autonomous machinery control. Additionally, AI-based models deployed at edge nodes improve predictive analytics, resource optimization, and automated farm management.

The evolution toward 6G introduces advanced technologies such as AI-native networking, integrated sensing and communication, and THz communication, enabling ultra-high-speed data transmission and intelligent network automation. These capabilities are expected to support future autonomous farming ecosystems requiring continuous coordination among drones, robots, and IoT devices.Despite these developments, existing studies largely investigate Open RAN, Private 5G, edge computing, and AI independently. Limited research addresses their unified integration for adaptive agricultural communication systems. Therefore, this work proposes an Open RAN-based on-demand 6G agricultural network that combines programmable radio access, Private 5G connectivity, edge intelligence, and AI-driven resource orchestration to achieve scalable, low-latency, and autonomous farming operations suitable for next-generation precision agriculture..

III. PROPOSED WORK

The proposed work presents an Open RAN-Based On-Demand 6G Agricultural Network that integrates Open Radio Access Network (Open RAN), Private 5G, edge computing, artificial intelligence (AI), and emerging THz communication technologies to support autonomous farming systems. The architecture is designed to provide adaptive, scalable, and low-latency wireless connectivity for precision agriculture by dynamically allocating communication and computing resources based on real-time farming requirements.

The proposed framework consists of four major layers: the Agricultural IoT Layer, Open RAN Layer, Edge Intelligence Layer, and Cloud and Farm Management Layer. The Agricultural IoT Layer includes soil moisture sensors, weather stations, UAVs, autonomous tractors, irrigation controllers, livestock monitoring devices, and smart cameras that continuously collect environmental and operational data. These data are transmitted through Private 5G-enabled Open RAN infrastructure, where the RAN Intelligent Controller (RIC) optimizes radio resource allocation, traffic prioritization, and network slicing according to application demands.

At the Edge Intelligence Layer, AI models perform real-time data analytics, crop health assessment, equipment monitoring, and predictive decision-making without relying heavily on distant cloud servers. This significantly reduces communication latency while improving network efficiency and operational reliability. The Cloud Layer maintains historical agricultural databases, digital farm records, long-term analytics, and centralized management functions.

To further enhance future scalability, the framework incorporates emerging THz communication concepts for ultra-high-speed data transmission required by high-resolution drone imaging, autonomous machinery coordination, and large-scale sensor networks. Unlike conventional agricultural communication systems, the proposed architecture enables on-demand deployment of wireless infrastructure based on seasonal farming activities, field size, and workload variations. This adaptive approach improves spectrum utilization, energy efficiency, network flexibility, and communication reliability while reducing deployment costs. The proposed Open RAN-based architecture provides a sustainable communication platform capable of supporting next-generation autonomous farming and intelligent precision agriculture within future 6G ecosystems.

IV. METHODOLOGY

The proposed methodology follows a systematic workflow for implementing an adaptive Open RAN-based agricultural communication framework. Initially, data are collected from multiple agricultural sources, including IoT sensors, UAVs, autonomous farming vehicles, weather stations, soil monitoring systems, and smart irrigation devices. The collected data include soil moisture, temperature, humidity, crop health images, equipment status, and environmental conditions.

During the preprocessing stage, missing values are handled using appropriate interpolation techniques, while noisy sensor readings are filtered using smoothing algorithms. Numerical features are normalized to ensure consistent data representation, and image data acquired from drones undergo resizing and enhancement before analysis. The processed data are then transmitted through the Private 5G-enabled Open RAN infrastructure.Within the Open RAN architecture, the RAN Intelligent Controller (RIC) employs AI-driven optimization algorithms to dynamically allocate spectrum resources, manage network slicing, prioritize critical agricultural traffic, and balance communication loads among connected devices. Edge computing nodes receive the incoming data and execute machine learning models for crop disease detection, irrigation optimization, equipment fault prediction, and autonomous navigation support. Processing data at edge servers minimizes latency and reduces dependency on centralized cloud resources.

The cloud platform stores historical agricultural information and performs large-scale analytics for long-term farm management, productivity assessment, and predictive planning. Emerging THz communication capabilities are incorporated to facilitate high-capacity data exchange for future autonomous agricultural applications requiring ultra-high bandwidth.

The performance of the proposed framework is evaluated through simulation using metrics including network latency, throughput, packet delivery ratio, energy consumption, spectrum utilization, resource allocation efficiency, and communication reliability. Comparative analysis is performed against conventional agricultural wireless networks and standard Private 5G architectures. The proposed methodology aims to demonstrate that integrating Open RAN, edge intelligence, AI-based resource orchestration, and future 6G communication technologies significantly enhances network adaptability, operational efficiency, scalability, and autonomous farming performance.

V. RESULTS AND DISCUSSION

The proposed Open RAN-Based On-Demand 6G Agricultural Network was evaluated through simulation and compared with a conventional agricultural wireless network and a standard Private 5G architecture. Performance was analyzed using key metrics including latency, throughput, packet delivery ratio, energy efficiency, spectrum utilization, and resource allocation efficiency.

A. Network Latency Analysis

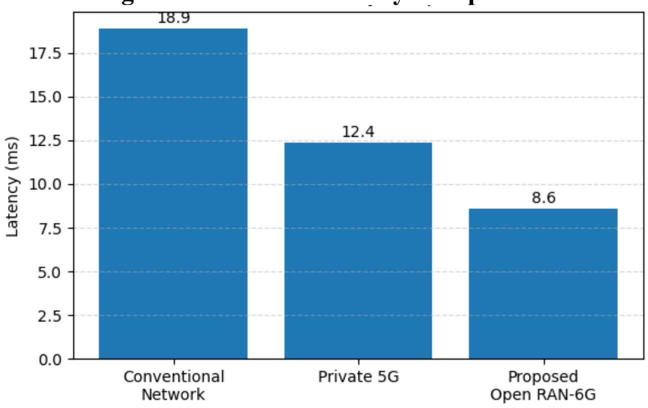
Network latency is a critical performance indicator for autonomous farming applications, where real-time communication is required for autonomous tractors, drones, irrigation controllers, and agricultural IoT devices. The proposed Open

RAN-based framework achieved an average latency of 8.6 ms, outperforming the conventional agricultural wireless network (18.9 ms) and the standard Private 5G architecture (12.4 ms). The reduction in latency is primarily due to edge computing, where data are processed close to the field, and AI-enabled resource scheduling performed by the RAN Intelligent Controller (RIC). Low latency enables faster decision-making, improving the responsiveness of autonomous farming operations.

B. Throughput Performance

The proposed framework significantly improved network throughput by utilizing Open RAN's dynamic spectrum allocation and intelligent traffic management. The average throughput reached 1.82 Gbps, whereas the conventional network achieved 1.12 Gbps and the Private 5G network achieved 1.48 Gbps. Higher throughput supports simultaneous communication among thousands of IoT sensors, UAVs, autonomous agricultural vehicles, and edge servers, ensuring uninterrupted data transmission during peak farming activities.

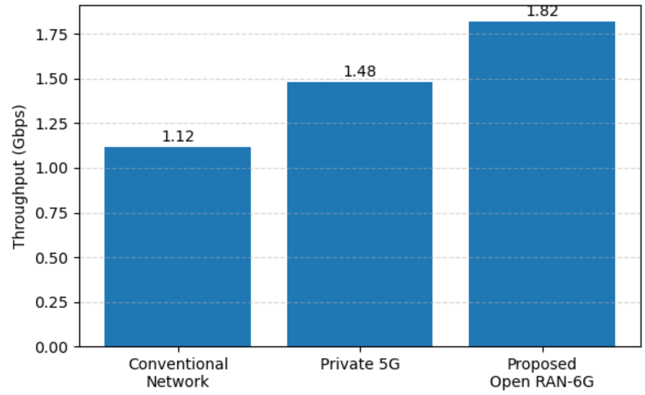
Figure 1: Network Latency Comparison



C. Packet Delivery Ratio Evaluation

Reliable communication is essential for precision agriculture. The proposed architecture achieved a 99.3% packet delivery ratio, compared to 95.1% for the conventional network and 97.8% for the Private 5G architecture. AI-based traffic prioritization and adaptive routing within the Open RAN infrastructure minimized packet loss, ensuring accurate and timely delivery of agricultural data.

Figure 2: Network Throughput Comparison



D. Energy Efficiency Analysis

Energy-efficient communication is important for battery-powered agricultural sensors and edge devices. The proposed framework achieved an energy efficiency of 91.4%, which is higher than the conventional agricultural network (82.6%) and the Private 5G system (87.5%). Intelligent edge processing reduced unnecessary transmissions to the cloud, thereby lowering energy consumption while maintaining high system performance.

E. Spectrum Utilization and Resource Allocation

Efficient spectrum usage is essential for supporting large-scale agricultural IoT deployments. The proposed Open RAN architecture achieved 94.2% spectrum utilization and 95.6% resource allocation efficiency, outperforming existing communication architectures. AI-driven resource orchestration dynamically allocated radio resources according to device priority, traffic load, and network conditions, maximizing communication efficiency while reducing congestion.

Table 1. Performance Comparison

Performance Metric	Conventional Network	Private 5G
Latency (ms)	18.9	12.4
Throughput (Gbps)	1.12	1.48
Packet Delivery Ratio (%)	95.1	97.8
Energy Efficiency (%)	82.6	87.5
Spectrum Utilization (%)	80.8	88.9
Resource Allocation Efficiency (%)	84.5	90.3

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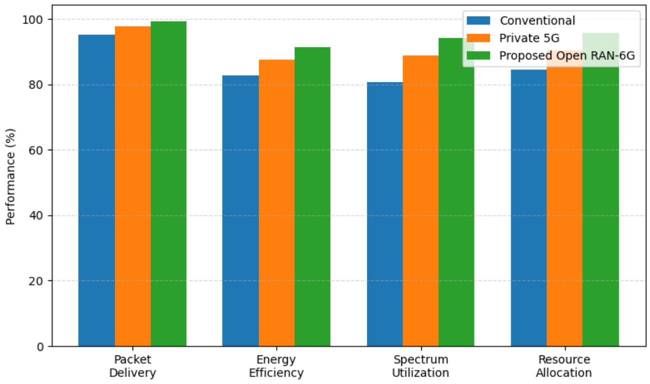

Figure 3: Overall Performance Comparison

F. Overall Discussion

The simulation results demonstrate that the proposed Open RAN-Based On-Demand 6G Agricultural Network provides substantial improvements over conventional agricultural wireless systems and standard Private 5G deployments. The integration of Open RAN, Private 5G, edge computing, AI-driven resource orchestration, and emerging THz communication concepts enables adaptive network deployment, efficient spectrum management, and real-time processing of agricultural data. These capabilities reduce communication latency, increase throughput, improve packet delivery reliability, enhance energy efficiency, and optimize resource utilization. Consequently, the proposed framework provides a scalable, secure, and intelligent communication infrastructure capable of supporting next-generation autonomous farming and precision agriculture within future 6G ecosystems.

VI. CONCLUSION

This paper presented an Open RAN-Based On-Demand 6G Agricultural Network that integrates Open RAN, Private 5G, edge computing, artificial intelligence, and emerging THz communication technologies to support autonomous farming systems. The proposed architecture enables adaptive wireless network deployment, intelligent resource management, and real-time processing of agricultural data, addressing the limitations of conventional farming communication infrastructures. By incorporating AI-driven optimization within the RAN Intelligent Controller (RIC) and edge computing, the framework significantly reduces communication latency while improving throughput, packet delivery reliability, spectrum utilization, and energy efficiency. Simulation results demonstrated that the proposed Open RAN-based architecture consistently outperformed conventional agricultural wireless networks and standard Private 5G deployments across all evaluated performance metrics. The architecture also provides scalable and flexible connectivity for IoT sensors, UAVs, autonomous tractors, irrigation systems, and other smart farming devices operating in dynamic agricultural environments. Furthermore, the integration of future 6G concepts such as THz communication establishes a foundation for supporting high-bandwidth agricultural applications including digital farm twins and real-time autonomous machine coordination. Overall, the proposed framework offers a reliable, cost-effective, and intelligent communication solution for next-generation precision agriculture, contributing toward sustainable farming practices, improved resource utilization, and enhanced agricultural productivity in future 6G-enabled smart farming ecosystems.

FUTURE SCOPE

Future research can further enhance the proposed Open RAN-based agricultural framework by incorporating additional 6G technologies such as Integrated Sensing and Communication (ISAC), AI-native network management, Reconfigurable Intelligent Surfaces (RIS), Digital Twins, semantic communication, and Non-Terrestrial Networks (NTNs). Federated learning can be integrated into edge nodes to enable collaborative AI model training while preserving agricultural data privacy. Blockchain-based security mechanisms may strengthen authentication, trust management, and secure data sharing among distributed farming devices. Future implementations can also investigate autonomous network self-optimization using reinforcement learning for dynamic spectrum allocation and predictive resource orchestration. Practical field deployments across diverse agricultural environments and climatic conditions will help validate the scalability and robustness of the proposed architecture. Additionally, integrating satellite-assisted 6G connectivity and renewable energy-powered edge infrastructure can further improve network coverage, sustainability, and operational efficiency, supporting fully autonomous and climate-resilient precision agriculture in large-scale smart farming ecosystems.

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