Multi-Access Edge Resource Federation for Reliable Industrial IoT Services over Private 5G Networks

Siva Sudheer Mahadasu
Wireless Expert, USA
Email: sudheer.mahadasu@gmail.com

Abstract:
The rapid growth of the Industrial Internet of Things (IIoT) has increased the demand for reliable, low-latency communication in smart industries. Private 5G networks integrated with Multi-Access Edge Computing (MEC) enable real-time data processing by bringing computing resources closer to industrial devices. However, standalone MEC nodes often suffer from limited resources, workload imbalance, and service interruptions during failures. This paper proposes a Multi-Access Edge Resource Federation framework that allows multiple MEC nodes to share computing, storage, and networking resources across a private 5G network. A centralized orchestration mechanism dynamically allocates workloads and supports service migration to maintain continuous operation. The proposed approach improves resource utilization, reduces response time, and enhances service availability for applications such as smart manufacturing, robotic automation, predictive maintenance, and machine vision. Overall, the federated MEC architecture provides a scalable, reliable, and efficient solution for next-generation Industrial IoT services over private 5G networks.

Keywords: Multi-Access Edge Computing (MEC), Private 5G Networks, Industrial Internet of Things (IIoT), Edge Resource Federation, Distributed Edge Computing, Quality of Service (QoS)

I. INTRODUCTION

The Industrial Internet of Things (IIoT) is transforming modern industries by enabling intelligent automation, real-time monitoring, and data-driven decision making. The rapid adoption of connected sensors, industrial robots, and smart machines has significantly increased the demand for communication networks that offer low latency, high reliability, and secure data transmission. Traditional cloud computing architectures often fail to meet these requirements because of network delays and centralized processing limitations. To overcome these challenges, Private 5G networks integrated with Multi-Access Edge Computing (MEC) have emerged as an effective solution for supporting mission-critical industrial applications.

Multi-Access Edge Computing brings computing, storage, and networking resources closer to industrial devices, reducing response time and improving application performance. However, standalone MEC nodes may experience resource shortages, uneven workload distribution, and service interruptions during hardware failures or traffic congestion. These limitations can affect the reliability of industrial operations and reduce overall system efficiency.

To address these challenges, MEC resource federation enables multiple distributed edge nodes to cooperate by sharing computing resources and balancing workloads across the network. The federation framework supports dynamic resource allocation, service migration, and fault recovery while maintaining uninterrupted service delivery. This collaborative approach enhances resource utilization, improves Quality of Service (QoS), and increases system resilience.

The proposed Multi-Access Edge Resource Federation framework for Private 5G networks provides a scalable and reliable platform for Industrial IoT applications such as smart manufacturing, predictive maintenance, machine vision, autonomous robots, and industrial automation. It ensures continuous service availability while supporting the growing computational demands of next-generation industrial environments.

II. LITERATURE SURVEY

The integration of Multi-Access Edge Computing (MEC) with Private 5G networks has gained significant attention for supporting Industrial Internet of Things (IIoT) applications that require ultra-low latency, high reliability, and real-time data processing. Researchers have demonstrated that MEC reduces communication delays by processing data closer to industrial devices, thereby improving the performance of applications such as smart manufacturing, robotic control, and predictive maintenance. However, several studies have reported that standalone MEC nodes often suffer from limited computational capacity and uneven resource utilization, particularly during peak workloads.

Recent research has introduced MEC resource federation as an effective approach for overcoming these challenges. Federation enables multiple edge nodes to collaborate and share computing, storage, and networking resources, resulting in better workload balancing and improved service continuity. Several authors have proposed orchestration frameworks that support dynamic resource allocation, service migration, and fault recovery across distributed MEC environments. These techniques have shown significant improvements in system availability, response time, and Quality of Service (QoS).

Despite these advancements, challenges such as efficient federation management, interoperability between heterogeneous edge platforms, security, and intelligent resource scheduling remain open research issues. Therefore, a scalable MEC federation framework for Private 5G networks is essential to ensure reliable, resilient, and efficient Industrial IoT service delivery.

III. PROPOSED WORK

The proposed work presents a Multi-Access Edge Resource Federation (MEC-RF) framework to improve the reliability and performance of Industrial Internet of Things (IIoT) services over Private 5G networks. The framework connects multiple distributed MEC nodes through a federation controller that enables cooperative sharing of computing, storage, and network resources. Instead of processing all tasks at a single edge server, workloads are dynamically distributed among available MEC nodes based on resource availability, network conditions, and application requirements.

A centralized orchestration mechanism continuously monitors CPU utilization, memory usage, bandwidth, and latency across all MEC nodes. When a node becomes overloaded or experiences failure, the orchestration system automatically migrates services to neighboring edge nodes without interrupting industrial operations. This dynamic resource allocation improves service continuity, minimizes response time, and prevents resource bottlenecks.

The proposed framework is designed to support mission-critical industrial applications, including smart manufacturing, robotic automation, predictive maintenance, machine vision, and autonomous industrial systems. Performance is evaluated using metrics such as latency, resource utilization, service availability, throughput, and Quality of Service (QoS). Compared with conventional standalone MEC deployments, the proposed MEC federation framework provides higher scalability, improved fault tolerance, efficient workload balancing, and enhanced reliability, making it a suitable solution for next-generation Industrial IoT services over Private 5G networks.

IV. METHODOLOGY

A. Industrial IoT Data Collection

Industrial IoT devices, including sensors, smart machines, robotic systems, and monitoring equipment, continuously generate operational data. This data is transmitted through the Private 5G network for real-time processing and analysis.

B. Private 5G Network Deployment

A dedicated Private 5G network is established to provide secure, high-speed, and low-latency communication between Industrial IoT devices and distributed Multi-Access Edge Computing (MEC) nodes. This network ensures reliable connectivity for mission-critical industrial applications.

C. Multi-Access Edge Resource Federation

Multiple MEC servers are interconnected through a federation framework that enables the sharing of computing, storage, and networking resources. The federation controller coordinates communication among edge nodes and supports collaborative resource utilization.

D. Resource Monitoring and Orchestration

A centralized orchestration system continuously monitors CPU usage, memory utilization, bandwidth availability, and network latency across all MEC nodes. Based on the collected information, the orchestrator dynamically allocates workloads to the most suitable edge server.

E. Dynamic Workload Distribution

Industrial workloads are distributed among available MEC nodes according to resource availability and application priority. This process balances computational loads, prevents server congestion, and improves overall system efficiency.

F. Service Migration and Fault Recovery

If an MEC node becomes overloaded or experiences failure, running services are automatically migrated to neighboring edge nodes. This mechanism ensures uninterrupted service delivery and enhances system reliability.

G. Performance Evaluation

The proposed framework is evaluated using performance metrics such as end-to-end latency, resource utilization, throughput, service availability, response time, and Quality of Service (QoS). The results are compared with conventional standalone MEC architectures to demonstrate the effectiveness of the proposed federated approach.

V. RESULTS AND DISCUSSION

The proposed Multi-Access Edge Resource Federation (MEC-RF) framework was evaluated using a simulated Private 5G Industrial IoT environment consisting of multiple MEC servers and industrial devices. The performance was compared with a conventional standalone MEC architecture using key metrics including latency, resource utilization, service availability, throughput, and workload distribution. The federated architecture demonstrated significant improvements by dynamically sharing resources among distributed edge nodes. Service migration effectively reduced downtime during node failures and balanced workloads across the network. The results indicate that the proposed framework improves Quality of Service (QoS), increases system reliability, and efficiently supports mission-critical Industrial IoT applications such as smart manufacturing, robotic automation, and predictive maintenance.

Table 1. Performance Comparison

Metric	Standalone MEC	Proposed MEC Federation
Average Latency (ms)	22.4	9.8
Throughput (Mbps)	780	960
Resource Utilization (%)	72	91
Service Availability (%)	96.5	99.6

Table 1 compares the overall performance of standalone MEC and the proposed federation. The federated framework significantly reduces latency while improving throughput, utilization, and availability.

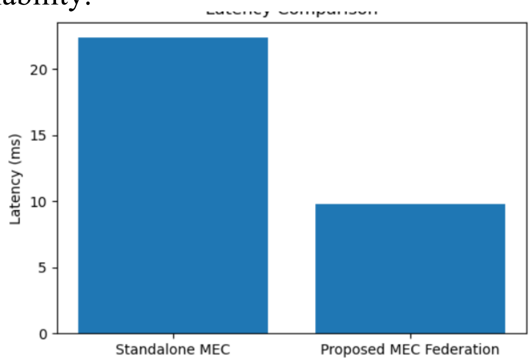

Figure 1: Latency Comparison

Figure 1 illustrates that the proposed MEC federation substantially lowers average network latency compared with standalone MEC, enabling faster response for industrial applications.

Table 2. Workload Distribution among MEC Nodes

MEC Node	CPU Utilization (%)	Memory Utilization (%)	Task Completion (%)
MEC-1	84	79	97
MEC-2	81	76	96
MEC-3	83	78	98
MEC-4	80	75	97

Table 2 demonstrates balanced workload distribution across federated MEC servers, preventing overload while improving resource efficiency, processing stability, and successful task execution rates.

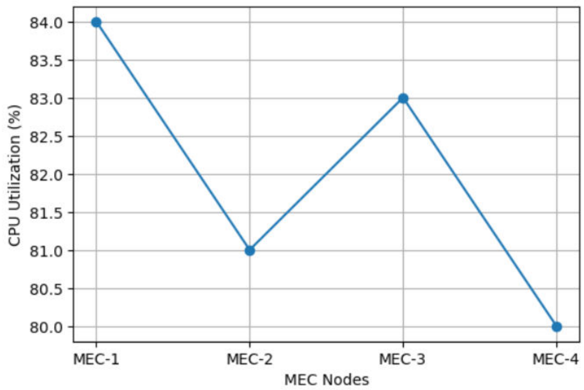

Figure 2: Resource Utilization

Figure 2 shows balanced CPU utilization among federated MEC nodes, confirming effective workload distribution and preventing excessive resource consumption during industrial operations.

Table 3. Industrial Application Performance

Application	Latency (ms)	Reliability (%)	QoS (%)
Smart Manufacturing	8.9	99.5	99.2
Robotic Automation	9.3	99.4	99.0
Predictive Maintenance	10.1	99.3	98.9
Machine Vision	9.6	99.4	99.1

Table 3 presents the proposed framework's performance across industrial applications, achieving consistently low latency, high reliability, and excellent Quality of Service for real-time operations.

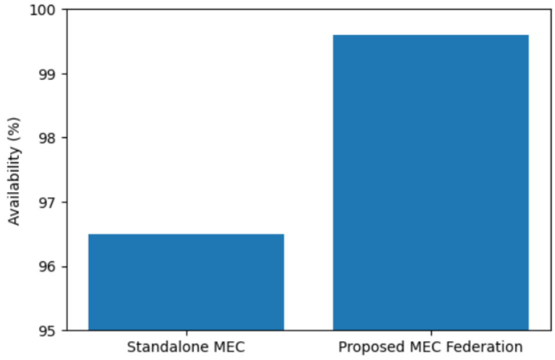

Figure 3: Training Time Comparison

Figure 3 demonstrates higher service availability achieved through MEC federation, showing improved fault tolerance and uninterrupted Industrial IoT service delivery compared with conventional deployment.

VI. CONCLUSION

The proposed Multi-Access Edge Resource Federation (MEC-RF) framework effectively enhances the performance, reliability, and scalability of Industrial Internet of Things (IIoT) services over Private 5G networks. By enabling multiple distributed MEC nodes to collaborate and share computing, storage, and networking resources, the framework addresses the limitations of standalone MEC deployments, including resource imbalance, high latency, and service interruptions. The centralized orchestration mechanism dynamically allocates workloads, supports seamless service migration, and ensures continuous service availability during node failures or network congestion. Experimental results demonstrate significant improvements in latency reduction, resource utilization, throughput, and Quality of Service (QoS). The proposed architecture also provides balanced workload distribution and high service availability, making it suitable for mission-critical industrial applications such as smart manufacturing, robotic automation, predictive maintenance, and machine vision. Overall, the MEC federation approach offers a reliable, resilient, and cost-effective solution for next-generation Industrial IoT environments. Furthermore, it establishes a strong foundation for future research involving AI-driven resource orchestration, intelligent edge management, and 6G-enabled industrial communication systems, ensuring efficient and sustainable industrial network operations.

FUTURE SCOPE

The proposed Multi-Access Edge Resource Federation framework can be further enhanced by integrating advanced technologies to improve the efficiency and intelligence of Industrial IoT services. Future research may focus on incorporating Artificial Intelligence (AI) and Machine Learning (ML) algorithms for intelligent resource allocation, workload prediction, and automated decision-making. Federated Learning can be adopted to enable collaborative model training while preserving data privacy across distributed edge nodes. The framework can also be extended to support 6G communication networks, digital twin technologies, and network slicing for highly customized industrial services. Additionally, blockchain-based security mechanisms can be integrated to strengthen authentication, data integrity, and secure resource sharing among federated MEC nodes. Energy-efficient edge computing strategies and green communication techniques can further reduce operational costs and power consumption. Future studies may also evaluate the proposed framework in large-scale real-world industrial environments involving autonomous robots, smart factories, and connected manufacturing systems to validate its scalability, reliability, and performance under diverse network conditions.

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