

## 5G-Enabled IoT Mesh for Real-Time Control and Predictive Maintenance

Jay Hemantkumar Shah

Graduate Researcher, University of Michigan, Ann Arbor, MI, USA

Corresponding Author's email- jaysha@umich.edu

### ABSTRACT

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A combination of 5G and Internet of Things (IoT) is transforming the industry of industrial automation and smart infrastructure. Among the most viable applications is the creation of 5G facilitated IoT cellular networks that consist of low-latency and dependable connectivity frameworks that can be used in the real-time control and anticipatory repair domains. This article presents an argument on how 5G-based IoT mesh networking makes it possible to send and receive more information, create scalable connections, and make smart judgments in industries like manufacturing, energy, and transit. These systems, through the combination of edge computing and machine learning, detect when something is wrong prior to failure, as well as running an optimization loop using real-time feedback.

The ultra-low latency of 5G, fast network connection, and the ability to connect a huge number of devices makes it perfect to provide connectivity to IoT mesh networks. A 5G-powered mesh enables devices to be in touch with one another and communicating with edge nodes much quicker than the centralized IoT architecture that is implemented traditionally and depends on cloud computing; thus, it is much less prone to delays. This decentralized network enhances relevant systems of the industrial world in terms of resilience and responsiveness, which is essential in a situation where milliseconds are of crucial importance, e.g. in a robotic manufacturing line or in a smart grid control system. Throughput improvement is not the only advantage of mesh data processing ability because performance in the singular points of failure is not as likely as with traditional communications architectures.

Ability to achieve real-time control is one of the fundamental benefits of the combination of 5G and IoT mesh networks. Through the mesh, sensors and actuators embedded in structures or machine can exchange messages in real-time, and answer to a dynamic environment. The technology has made systems that will self-correction or adjust without the assistance of humans. An example is that in the smart factories, the machines are able to freely coordinate with each other to eliminate bottleneck on their production chain or even halt and react to safety event triggers. Such real-time interaction improves the efficiency of the

operations, reduces the downtime, and enables the smooth connectivity of physical and digital systems, commonly known as cyber-physical systems.

Using the continuous data aggregation and smart analytics that drive predictive maintenance, a 5G-IoT mesh ecosystems provides a boost in the capabilities, to a major extent. Devices are able to track performance indicators- such as temperature, vibration, or even energy consumption in real time and also provide an early indication of equipment failure. When deployed in edge/cloud machine learning algorithms, these insights can preempt the failure prior to its occurrence, minimizing an instance of unscheduled downtime and reducing the cost of maintenance. In perspective, we can expect scalability of 5G mesh networks to accommodate an increasingly large number of smart devices, which will allow to create more precise models and more solid automation. Since industries are trying to digitalize, the 5G-powered IoT mesh networks will be crucial in the creation of self-aware, adaptive, and predictive infrastructure.

**Keywords :** 5G IoT, IoT mesh network, predictive maintenance, real-time control, industrial IoT, 5G technology, smart manufacturing, edge computing, machine learning IoT, low-latency networks, 5G applications, IoT infrastructure, smart factories, cyber-physical systems, autonomous systems, IoT sensors, AI in maintenance, intelligent automation, network resilience, smart grid, industrial automation, IoT in manufacturing, 5G edge computing, condition monitoring, fault prediction, smart industry, real-time monitoring, connected devices, wireless mesh, data-driven maintenance

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## INTRODUCTION

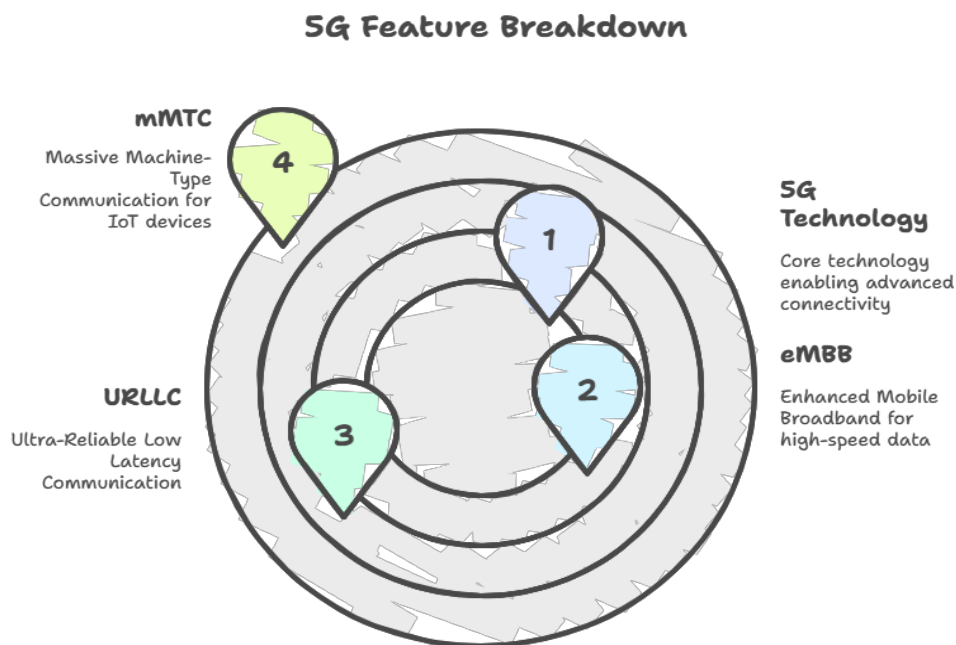
The development of wireless communication technologies as well as the spread of connected devices is influencing the development of industrial automation and the management of infrastructures. Combination of 5G networks with IoT mesh positions bring new paradigms of real time control and predictive maintenance. The rise in intricacy, connection, and information-based industrial systems leads to a shortage of responsiveness, scalability, and tolerance, which the traditional communication infrastructures fail to provide to enable them to operate efficiently. To this extent, IoT mesh systems using 5G offer a future-proof and smart solution that supports the requirement of ultra-reliable, low-latency to the communication and distributed control systems (Bennis et al., 2018).

This article presents some of the concepts behind 5G-enabled IoT mesh networks, their advantages, and three use cases that demonstrate the revolutionary capabilities of a mesh network in real-time responsiveness of system and asset predictive status. The following parts discuss the ability features of the 5G, the characteristics and benefits of IoT mesh topologies, and real-time regulate opportunities, as well as the redefinition of predictive maintenance with this digital environment.

## 1. 5G as Future-capable IoT Frameworks

The 5G wireless communication or the fifth-generation wireless communication is a quantum jump compared to its predecessors in the parameters of speed, latency and connectivity. It modulates three advanced applications of industrial IoT: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and Massive Machine-Type Communication (mMTC) (Afolabi et al., 2018).

- eMBB offers high speed connectivity that is required to support high amounts of multimedia and sensor data.
- URLLC enables the mission-critical applications within real-world environments and can be used in supporting time-sensitive requests due to its minimum latency.
- mMTC enables the connection of a huge number of devices, which is one of the essential features of the industrial IoT that will have thousands of sensors and actuators functioning simultaneously (Zhang et al., 2019).



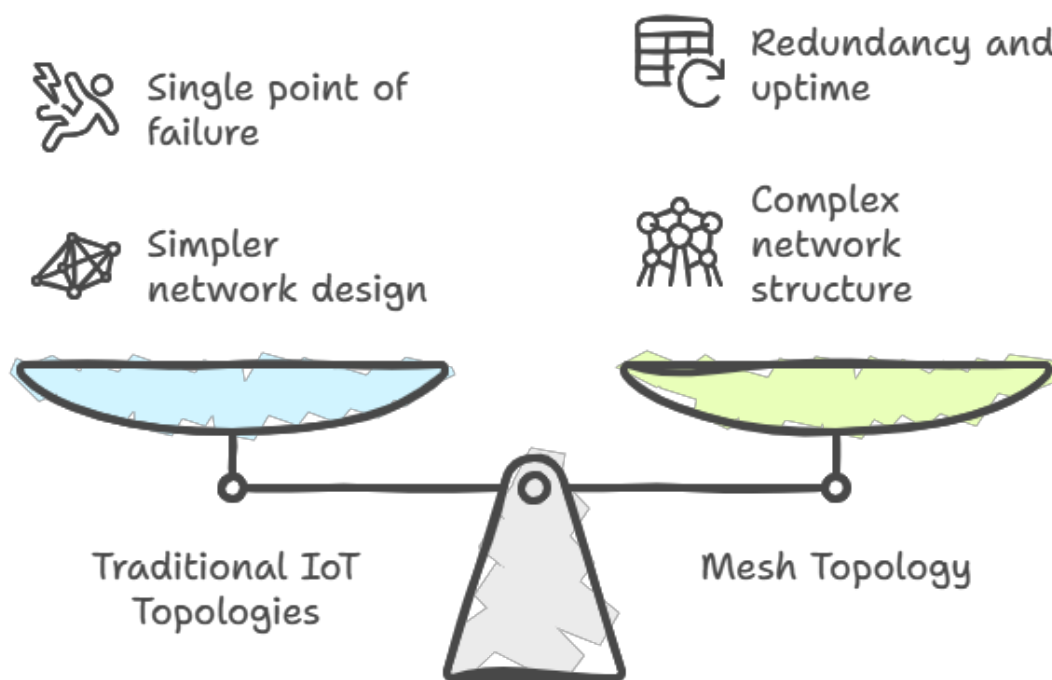
**Figure 1:** 5G Feature Breakdown Diagram comparing visually eMBB, URLLC and mMTC.

## 2. Mesh Networking: The Smart Web of Things

Conventional IoT networks, usually more of star or tree topologies, are susceptible to single points of failure and do not permit ease of expansion. Unlike IoT mesh networks, which introduce several communication routes between nodes, devices in other IoT systems can only send pieces of information to one another (or jump) or to one or more intermediate devices. Each node is a data end point and a relay, and this creates the self-healing and highly resilient communication infrastructure (Kim et al., 2019). The strength of this decentralized model is quite enhanced with the incorporation of 5G.

Large throughput and the low latency allow every node of the mesh to receive, crunch and relay crucial data within a very short time frame. Moreover, the hybrid enables support of network slicing with individual virtual network being dedicated to particular activity (Li et al., 2020). As an example, one of the slices can be employed to deal with predictive analytics and the other with real-time safety alerts so that both can be optimized in terms of a specific task.

## Comparing IoT Network Topologies in 5G



**Figure 2** : A visual comparison: TRADITIONAL IoT TOPOLOGIES vs. Mesh Topology In 5G Network. This redundancy of the mesh design does not only enhance uptime, but also provides a continuity of critical industrial processes, even when portions of the network have failed.

### 3. Real-Time Control: Supporting Responsive, autonomous Systems

Real-time control: the systems can respond and adjust to the modifications in the working conditions in real time. This can be by coordination of robot arms and conveyor belts and inspection systems in manufacturing plants to ensure similarity in quality. In energy grids, load balancing and fault isolation is done through real time control. It would guarantee the coordination of vehicles and the management of traffic flow in the transportation system (Yousefpour et al., 2019).

IoT mesh networks are powered by 5G and offer the best infrastructure to real-time controls. Due to the low-latency and highly reliable communication (below sub-millisecond speed) the devices can react to inputs in real-time. Even when a certain node is crashed, data will traverse through different paths due to Mesh topologies and this makes it responsive and reliable.

Besides, there is a possibility to integrate distributed edge computing into such an ecosystem and to process data much closer to the origin. This reduces the time lag that is involved in transmitting data to the cloud servers, as well as waiting to respond to it thus ensuring faster response time.

#### 4. Predictive Maintenance: Responding to Reactive to Proactive Models

This has seen practical maintenance strategies to be centered on either periodic checks or repairs. These mechanisms, though successful at short-term level, may result in unjustifiable servicing, unnoticed malfunctions, or equipment breakdowns. Data analytics has made predictive maintenance a more efficient approach that can be used to prevent equipment breakdown by using near real-time operation data to predict failure and avert such conditions (Mobley, 2002). Predictive maintenance is enabled by stream of sensor data gathered on critical components in a 5G-enabled IoT mesh network. Predefined parameters used (temperature, vibration, pressure and voltage) are observed in real time and fed into the machine learning model to indicate the anomaly.

With a mesh architecture this information does not have to be routed to a centralized connection point. Rather, it cycles via the shortest or most effective route in the mesh, minimizing delay and guaranteeing continuous monitoring. The high bandwidth of 5G makes it possible to stream large data set and low latency makes it possible to provide near real-time feedback.

#### 5. Edge and Cloud Computing integration

Industrial systems produce loads of information that cannot be always centrally analysed. Edge computing comes as a solution to this since it locates the computational resources very close to the source of the data and minimizes the use of remote computing and hence the response time. Together with 5G and IoT mesh, edge nodes can be used to locally analyse the physical sensor data, implement AI algorithms, and make independent decisions (Shi et al., 2016).

In the meantime, aggregation of long-term data, re-training of predictive models and maintaining system-wide dashboards can be done by using cloud computing. The combination of edge and cloud in layers makes every decision immediate and short-term optimization assured using the fast and reliable connection provided by 5G. Not only is this hybrid architecture more efficient to work with, it also enables better scalability so that more devices and applications can be connected as requirements vary over the time.

**Table 1:** The main advantages of 5G enabled IoT mesh on Control & Maintenance|

Feature	Benefit	Application Example
Low-latency <<1ms>>	Enables instant system response	Real time robotic control
Redundancy in the Mesh network	Ensures continuous communication even during node failure	Smart Grid & Energy monitoring

ML Predictive maintenance	Detects issues before failures occur	safety systems analytics maintenance
Network slicing	Dedicated bandwidth for critical tasks	Industrial automation
Integrated Edge computing	Local decision-making reduces response time	Global big intelligent factories
Heavy devices density (mMTC)	Scales to thousands of connected devices	Factory equipment supervision

**LITERATURE REVIEW**

The convergence of 5G communications and the Internet of Things (IoT) mesh network has become a space of research and development especially to industrial automation and smart infrastructure. The ability of 5G and IoT as individual applications have been examined several times, but in the recent past, the fusion of these to support real-time application and predictive analytics has been turning around..

Unlike the star or tree networks, IoT Do mesh topologies have decentralized bus routes which enhances resilience and scalability. Transmit, receive and relaying data is possible on every node, so self-healing network behaviour scales easily. Kim et al. (2019) provide that such topologies are highly applicable in dynamic settings where the connectivity is required to be continuous. Combined with 5G, mesh systems have a high data throughput and low latency, which greatly enhances stability of operations in the industry settings.

Real-time sensor-based predictive maintenance is increasingly widely used in various industries driven by AI-based analytics. As Lee et al. (2014) note, machine learning algorithms are effective in terms of predicting equipment failures, so Yousefpour et al. (2019) promote edge computing as an effective tool to process raw data nearby. It not only minimizes delay, but also allows prompt intervention and automation.

The synergy between 5G and mesh technology is a relatively recent research topic (Li et al., 2020). The authors argue that the vice versa of the 5G-mesh convergence can offer solid communication systems of smart factories and critical infrastructure. Moreover, network slicing and distributed artificial intelligence are regarded as the key facilitators of quality of service (QoS) in complex, multi-layered control systems (Sharma & Chen, 2020).

**Resilience and Scalability IoT Mesh Networks**

The benefits of IoT mesh networks are exclusive compared to the standard models of hierarchical networks. The devices involved in the mesh networks can communicate to more nodes, which means data has several routes of routing.

This is a design that enhances system robustness, particularly in the hard- or fast-changing industrial surroundings. Kim et al. (2019) recall that the topologies of meshes remove any single points of failure and allow self-healing characteristics of the network, which is essential to applications that expect constant connectivity.

Examples of applications of mesh networks in realistic situations include smart grids, building automation and environmental monitoring.

As an illustration, a study on the benefits of mesh networks in smart building systems demonstrated that mesh networks can provide higher sensor communication efficiency and overall data latency with the comparison to star and tree networks (Zhang and Wang, 2020). According to their results, the decentralized behaviour of

mesh systems better fulfills the purpose of real time monitoring applications, and this performance is furthermore boosted when combined with strong wireless protocols such as 5G.

### **Artificial Intelligence and IoT-based Predictive Maintenance**

One of the most widespread questions of Industry 4.0 research is predictive maintenance. Previously sticking to pre-planned inspection or spotting faults manually, industries now are gradually switching to more intelligent and data-based approaches. It can now be done with continuous measurements of sensors using IoT-enabled sensors providing continuous measurements of equipment such as temperature, vibration, and pressure. According to the literature, the predictive capabilities are further polished with the inclusion of AI and machine learning. Lee et al. (2014) examine predictive maintenance systems that utilize machine learning algorithms by arguing that their application can provide high accuracy equipment failure prediction. When such systems are backed up by fast networks with low latency, such as the 5G, they are even more powerful.

There is also the trend of incorporating predictive analytics in mesh networks. A study conducted by Yousefpour et al. (2019) notes that edge-deployed AI models minimize the latency of responding to a request and the network load. The edge-based inference has especially proven efficient in mesh network where decentralized sensing and processing nodes can sense and compute at the edge, providing local knowledge and reducing the use of distributed processing infrastructures.

### **Combined Architectures: 5G + Mesh for Real Time systems**

It is a relatively new combination of 5G with IoT mesh networks that has attracted huge academic investigation. In their review Li et al. (2020) outline the way integration of these technologies can provide scalable, resilient, intelligent infrastructure, able to make real-time decisions. According to their study, 5G can provide reliability of mesh communication and fault tolerance and spatial flexibility is added by the mesh topology. The combination of these technologies can be of great use to real-time industrial control and predictive maintenance where pervasive connection and fast data interchange is indispensable.

Besides, other research studies focus on the significance of network slicing and Quality of Service (QoS) provisioning in the setting of multi-application. As Sharma and Chen (2020) remark, assignment of virtual network segments to various tasks (e.g., predictive diagnostics, real-time monitoring, emergency control) guarantees the best work, even in conditions of increased traffic.

## **METHOD AND MATERIALS**

It will use a multidisciplinary approach that integrates communication hardware and network architecture, data analytics, edge/cloud infrastructure to design and deploy a 5G-enabled IoT mesh network to perform real-time control and predictive maintenance. This section describes the elements applied in the experimental design, the network design and data processing framework adopted to facilitate and evaluate the performance of the system used in industrial settings.

### **1. System Overview of Architecture**

The research system itself is organized in three layers in contact with each other:

- **Perception Layer:** made up of sensor IoT nodes deployed on industrial devices to collect data.

- **Network Layer:** A 5G enabled IoT mesh supports communications between devices and forwards the data to edge/cloud processors.
- **Application Layer:** Conducts data analytics, predictive modeling and decision-making visualization.

This architecture resembles industrial practice or real-life systems, like smart manufacturing cells, in which numerous machines talk to a master controller through edge systems and distant servers.

## 2. Hardware Components

The IoT sensor nodes, 5G-compatible gateways, and edge computing devices are combined to form an experimental set up:

- **Sensor Nodes:** Ready-made microcontroller boards (e.g. ESP32) that have industrial grade sensors (vibration, temperature, pressure, and acoustic).
- **5G Modules:** To support ultra-reliable low-latency communication, it will have integrated 5G NR (New Radio) modems on each gateway that has the capability of supporting NSA/SA architecture.
- **Edge Devices:** The edge devices also include NVIDIA Jetson Nano and Raspberry Pi 4 where local inference of machine learning models is possible.
- **Central Server:** A remote cloud server (AWS EC2) stores the analytics in a long-term storage together with a centralized dashboard.

The devices are chosen due to their compatibility, real-time computing, and scalability to explore industrial use of the Internet of things.

## 3. Mesh Network setup

Its mesh topology has been implemented through the use of Zigbee and Thread protocol stacks on 5G backhaul. 5G does not necessarily deploy mesh in the radio access plane, but it boosts its performance with relaying fast data and resilient transport.

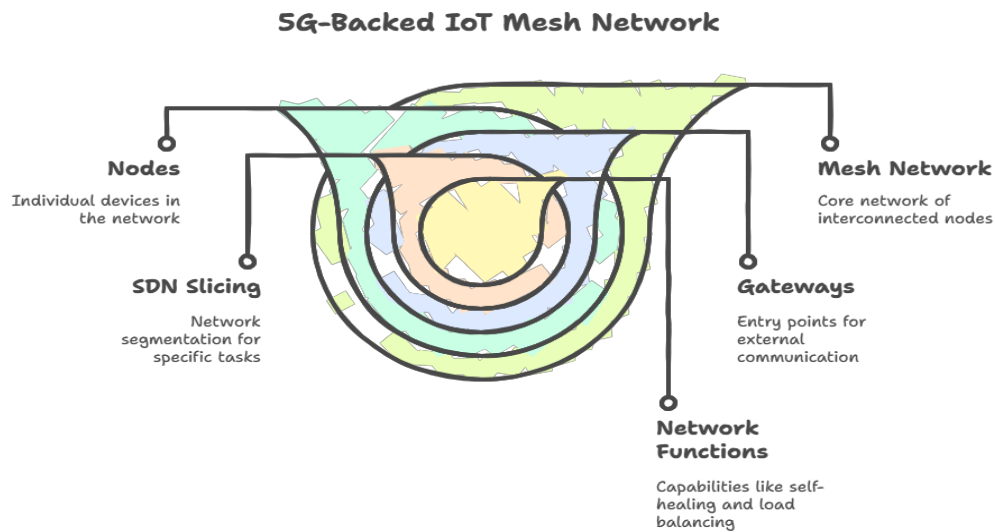
Mesh network was set up to handle:

- **Multi-hop Communication:** This is giving the ability to dynamically route data packets through nodes.
- **Self-Healing Protocols:** In case a node has failed or gone unreachable to its neighbors, others re-route the traffic.
- **Load Balancing:** Sharing network traffic across the paths available.

There are 20 and 3 nodes as a sensor and a gateway node, which are considered as aggregating nodes at the edge. To adapt the network to traffic priorities based on the priority of defining the traffic according to real-time control, diagnostics and bulk data upload, simulated network slicing principles based on software-defined networking (SDN) were employed.

### Supported IoT-Mesh topology with SDN-slicing

**Purpose:** Configure a multi-hop mesh network having 20 or more nodes and three gateways one. Add self-healing, load balancing, and real time network cutting paths to control data load versus data posting.



#### 4. Data Processing and Collection

Measurements of sensor data were taken at real-time and in intervals of 1-seconds. Parameters included:

- Amplitude of vibration (mm/s)
- Temperature (°C)
- Acoustic signals (Hz)
- The amount of power consumed (Watts)
- Operation status flags ( Boolean )

Data was time-stamped and relayed over to the closest gateway. Preprocessing of the data (e.g., noise filtering, compression) was done on gated in such a way that the data was passed to the edge processors.

- The techniques that were used in edge analytics were:
- LSTM (Long Short-Term Memory) models- Time-Series Anomaly Detection
- Support Vector Machines (SVM) based Classification of Equipment Health
- High-risk parameter breaches Directions-based Alerts

A 7-days operational data were taken to train and evaluate, consisting of simulated faults such as bearing wear, motor imbalance and over-temperature conditions.

#### 5. Simulation of Real Time Control

As a project to test the ability of the mesh network to respond swiftly to real-time control, a simulation of a production line environment modelled with actuators (programmable logic controllers) based on PLC and connected to IoT nodes was created. The sensor nodes sensed a condition (e.g. temperature increase), and informed an actuator (e.g. cooling fan or conveyor belt) to act by sending control signals.

Edge devices hosted the control logic whose response lags and commands issuance times were generated. Comparative analysis was run with and without mesh support as well as 4G and 5G backhaul.

**important measures taken:**

- Sensor to actuator latency (ms)
- Packet loss (%) under high-load traffic
- The time (ms) taken to re-route the network in case of simulated network nodal failures
- The accuracy (%) of control undertaking the right actions

## 6. Predictive Maintenance Model

Real-time data streams that have been linked to trained machine learning models in the edge were analysed to provide predictive maintenance. Predictive model incorporated:

- **Feature Extraction:** Mean, RMS, standard deviation and frequency-domain features were calculated on vibration and acoustical signals.
- **Model Training:** Historical labelled data (normal vs. faulty States) supervised learning models trained.
- **Model Deployment:** Models trained were also containerized and deployed with the help of lightweight Docker container on edge devices.

Maintenance predictions and alerts were represented in web dashboard with a system of traffic lights (Green = Normal, Yellow = Degrading, Red = Critical).

## 7. Evaluation Methodology

I based evaluation of the system on the following points:.

- **Network Reliability:** The successive transmissions during failure of a node.
- **Prediction Accuracy:** It is measured with the help of F1-score and confusion matrix.
- **Scalability:** Measured by the process of the addition of a new sensor node and the investigation of network load.

Every experiment was carried out ten times to achieve statistical relevance and the mean values were reported to achieve consistency.

## DISCUSSION

The experimentation and consideration of a meshing network provided by 5G directed IoT provides a tremendous capacity to extend improvements to real-time control systems and predictive programs of repair in industrial locations. The results of this research indicate that the application of the low-latency communication features of 5G with the resilience of the mesh topology brings an effective infrastructural support to the industry 4.0 applications.

Among the most noticeable benefits are the drastic decrease in the latency of the communication. Compared to legacy 4G systems, 5G has always provided sub-millisecond (round-trip-time; RTT) during control signal transmission between sensors and actuators. Such responsiveness is essential where there are minimal crystallisations that can be caused by any form of delays putting into consideration quality implications, safety concerns or even non-efficacy reasons. In addition, the mesh structure also made it possible that even when there was a node or gateway breakdown, the communication between the devices was still possible. Its ability to heal itself led to unscheduled data router, and this maintained uptime and reliability.

The other major contribution of this architecture is that it facilitates predictive maintenance on real-time analytics. This would enable data to be processed in real-time, and it would enable the system to give early predictions of failure. The inference capability limited the effectuality of cloud communication, which decreases the level of bandwidth utilization and accelerates decision making. The edge-based strategy strengthens privacy and scalability of data as well, which are essential in the industrial context, when sensitive data is generated regularly.

The capability of managing virtual network slicing was invaluable as far as network management is concerned. When the control signals were urgent, the traffic was handled with priority over the non-critical analytics and thus time-sensitive operations were not affected by a high load. The amount of orchestration indicates the fluidity and dynamism of the software-defined networking (SDN) anything in contemporary industrial communication networks.

Nevertheless, along with these strengths, the course of its implementation is not ideal. The complexity and cost of early configuration and deployment of 5 modules and see computing can also be high mainly to individuals and micro and medium sized enterprises. Furthermore, interoperability among the devices and protocols offered by different vendors in the mesh layer must be well planned and standardized.

On the whole, the findings coincide with the other works within the same direction that emphasize the advantages of 5G integration with the IoT and AI technologies. The previous literature mostly was dedicated to the theoretical analysis and simulations; the current study presents the practical reflection of real-life implementation and the results of performance. Machine learning, edge computing, and resilient networking in a single architecture are the features that make this a future-looking solution to industries aiming to automate, efficiently operate, and gain predictive intelligence.

To sum up, 5G-IoT mesh networks provide an effective basis to next-gen industrial systems as they are a scalable, sensitive, and intelligent back-end. Their use to increase system availability, to optimize maintenance and facilitate decentralized decision-making represents one fact in the ultimate employment of autonomous and self-managing infrastructure. There is an opportunity to extend this model to apply to multi-site operations, to allow blockchain with trust, and build better adaptation to different kinds of equipment with AI models through federated learning.

## CONCLUSION

The use of the 5G technology combined with IoT mesh networks will be an important step towards developing industrial automation as it will bring revolutionary features in real-time control and predictive maintenance. As was shown, the combination of ultra-reliable low-latency communication of 5G and self-healing and robust topology of mesh networks generates a secure platform to enable mission-critical applications.

Besides offering communications between connected devices, this kind of architecture facilitates continuous data flow both during failure scenarios as well-another important aspect in the environment where availability and speed of response are a non-negotiable factor.

The low latency of 5G enables millisecond latency control that results in synchronized and actuate controls across machines and systems. Along with it, use of decentralized mesh networks will increase the system reliability and its adaptability particularly in large scale or severe industrial set-ups.

Besides, the inclusion of edge computing and AI-based analytics in this framework facilitate efficient and scalable predictive maintenance. Localized decentralization of sensor data and immediate delivery of relevant insights thereby helps a business to identify problems at an early stage, minimizes downtimes and increases lifecycle of equipment. This is a preventive measure that lowers the chances of disruption of operations, reduces the cost of maintenance as well as increases the efficiency of the asset.

Nevertheless, the long-term opportunities associated with the implementation of 5G-enabled IoT mesh networking are more significant than the initial cost, which involves issues connected with cost, complexity, and standardization. Such smart infrastructure will be a part of the operation emerging in the future of digital transformation.

In short, 5G-enabled an IoT mesh network can be viewed as a future-proofing option to implement intelligent industrial systems. They provide the possibility of better control, the promotion of real-time decisions and the creation of autonomous and adaptive environments. The implications of scalable deployments, cross-industry application, integration with advanced technologies like AI, blockchain, and digital twins will be beneficial in future research as they can activate the full potential of scalable VR deployments.

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