WHITE PAPER

Smart Mining with Private 5G Technology: Revolutionizing Industry

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Abstract

Private 5G technology has the potential to revolutionize the mining industry. Over time, private 5G technology is expected to increase mining operations' sustainability, safety, and efficiency, which will enhance the operator's return on investment. Real-time communication and remote monitoring will be possible thanks to private 5G technology, which will also improve the automation, measurement, and overall productivity of mining operations. In this white paper the authors address how mining can be modernized by adopting private 5G technology which can resolve current challenges, streamline processes, and open up new growth opportunities.

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Introduction

In India, there has been a significant focus on the need for adoption of new technology for the mining industry for key operations like drilling, blasting, excavation, and ore transportation. In this transition, organizational and environmental factors also need to be taken into account. Using outdated technologies decreases efficiency and makes ecological protection more challenging. Furthermore, India's social and cultural dynamics can complicate the introduction of automation and modern technologies.

Overcoming these obstacles requires cooperation among mining companies, service providers, research institutions, and educational bodies. A detailed strategy is necessary, focusing on developing new technologies, enhancing tools and data analysis, revising educational programs, and creating government programs and initiatives to modernize India's mining sector.

Historically, the mining industry has been struggling with sustainability, safety, and efficiency. The sector must adopt new technology as the demand for minerals is rapidly increasing on a global scale. The private 5G network is a revolutionary solution that offers lightning-fast, reliable connections, robust security, and the capacity to link thousands of Industrial IoT devices. It facilitates so-called "smart mining" by enabling artificial intelligence (AI) and machine learning (ML) to enhance data transmission rates, facilitate real-time data processing and activate remote-control and monitoring capabilities, resulting in real-time insights and flexibility in digital supply chains and operations. Private 5G is a crucial technology driving the industry's shift to digital transformation.

This white paper proposes a framework for implementing a private 5G network to address challenges in the mining sector by providing high-speed, low-latency connectivity, and will demonstrate how private 5G technology is expected to revolutionize the mining industry. Private 5G enables quality of service (QoS) for seamless communication between surface and underground operations, facilitating unmanned mining and improving safety. Its high data rates, low latency, and advanced Radio Access Network (RAN) make it suitable for a variety of mining applications, including block cave mining.

Figure 1: Underground Mine and Surface Mine

Current Status of the Mining Industry

The mining sector has long faced several obstacles that impede their growth and operational efficiency:

Safety Concerns

The mining industry is one of the sectors where workers are most likely to encounter a hazardous work environment. Potential threats include cave-ins, explosions, toxic air, and equipment accidents, leading to serious injuries and fatalities, as well as long-term health issues from dust and chemical exposure. Mining companies are constantly seeking ways to improve safety conditions.

Operational Efficiency

The traditional mining methods frequently lack efficiency because of old networks which depend on antiquated technologies and the corresponding equipment that hinder productivity as well as hinder real-time decision-making. Much of the networking equipment in use is based on turn of the century 2.5G and 3G technology, making it difficult to monitor performance and promptly address problems.

Environmental impact: The effects on the environment of mining are substantial, often leading to increased carbon emissions, habitat destruction, and water contamination.

Data management: Data management is a complex task that requires intelligent solutions for real-time information analysis and action, especially considering the vast volumes of data generated by modern mining operations.

These challenges can be seen in Odisha. While it contributes approximately 6% to Odisha's GDP, the economic advantages of mining are not as significant as those provided by the manufacturing sector. To address these issues and promote responsible mining practices, it is essential to enforce regulations rigorously and conduct regular geospatial monitoring.

Figure 2: Existing i3MMS Technology in Odisha Mining

In resource-rich Odisha, the government has implemented an Integrated Intelligent Mineral Management System (i3MMS) to improve the management and security of mining operations. Satellites, drones, GPS, and RFID are being integrated into i3MMS for monitoring and tracking minerals, which improves safety, productivity, and environmental management. Satellite monitoring can be used to detect illegal mining. Drone images provide detailed data to enable land-use studies and environmental impact assessments. GPS tracking is used to prevent illegal transportation of material and streamline mineral income administration. IoT sensors are being deployed to enhance safety. Automated weigh bridges ensure regulatory compliance. Relying on legacy 2.5G/3G technology for connectivity may hinder the ability to achieve the desired results from these modern methods.

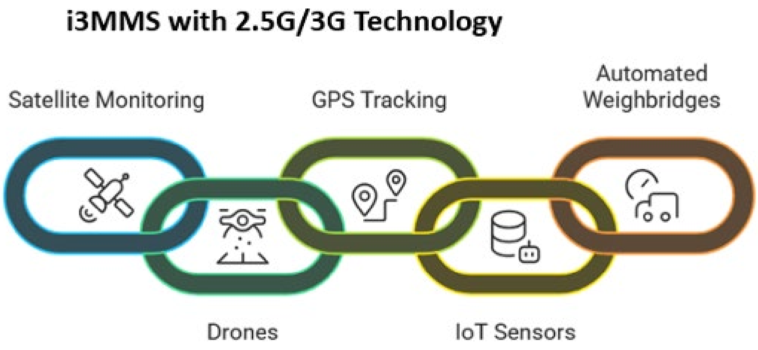


Figure 3: Odisha i3MMS based on 2.5G and 3G technology

The dangerous and inaccessible nature of underground mines necessitates a move to private 5G technology for improved safety and operational efficiency. An important 5G feature is ultra-reliable low latency (URLLC) connectivity, which is essential for real-time automation like machine-to-IoT sensor (machine-to-machine or M2M) applications. URLLC ensures that M2M connections used for operating, monitoring and managing equipment can handle the high data rates demanded by automated machinery like Autonomous Haulage Systems (AHS). AHSs are autonomous trucks used in mining and are vulnerable to cyber-attacks, underscoring the critical importance of secure connectivity in these environments. The extreme underground circumstances can make wireless technology implementation challenging. The goal of this white paper is to present the proof-of-concept technologies that are best suited to specialized jobs in this environment, including automation, tracking, and long-range monitoring.

Figure 4: Autonomous Haulage Systems (AHS)

Another advantage of 5G technology over earlier network generations is its ability to support the increasing quantity of data generated by automation. 5G produces packets transmitted in the user and control plane over the air interface with remarkable efficiency. The system utilizes flexible numerology (μ=0,1,2,3,4), which allows for varying subcarrier spacings tailored to different use cases, thereby optimizing both capacity and latency. Furthermore, implementing adaptive networks supporting up to 256-QAM (Quadrature Amplitude Modulation) as needed will achieve higher data rates, enhancing spectral efficiency by encoding more bits per symbol and improving overall network performance.

Odisha Addresses 5 Key Challenges to Enhance Mining Operations

Odisha has implemented a comprehensive suite of technology-driven solutions to modernize its mining sector, improve transparency, ensure regulatory compliance, and promote sustainable practices. These systems cover the entire mining lifecycle, from exploration and extraction to transportation and environmental monitoring. Here's a breakdown of the key technologies in use:

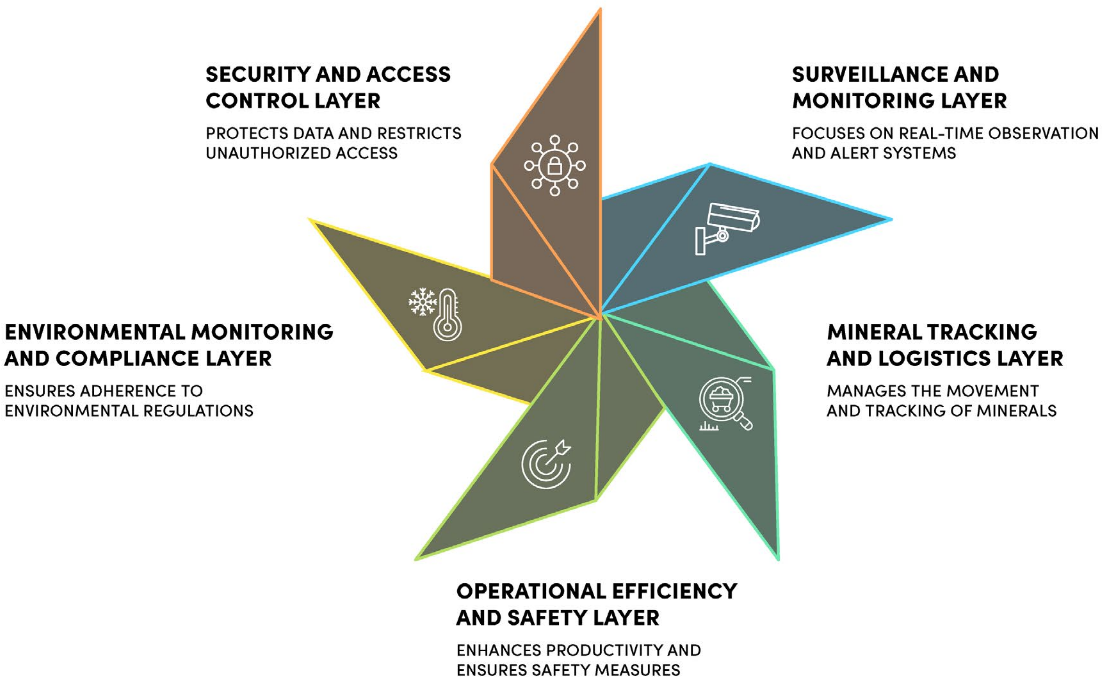


Figure 5: Transformative Impact of Private 5G on Smart Mining and Logistic

Surveillance and Monitoring

Satellite-Based Monitoring and Surveillance System (SATMMS): This system developed by ORSAC uses satellite images to monitor production boundaries, detect illegal activities, and change the level of land use including forest cutting.

Settings through GPS: GPS is installed on mining vehicles and monitoring equipment to prevent unauthorized production and illegal transportation and of minerals.

Observation through drones: Drones provide air images and videos in hard-to-reach areas in real time to provide economically effective solutions for land research and to ensure compliance with terrain monitoring, environmental impact assessments, extraction limits and operational progress.

Mineral Tracking and Logistics

Radio-Frequency Identification (RFID): RFID technology is deployed in mining vehicles and mineral containers to enable real-time tracking of mineral movements. This promotes logistical transparency and halts illegal activities by ensuring that minerals are transmitted via approved routes. This technology helps to fight illegal mining by increasing transparency and ensuring accountability throughout the process. RFID not only helps prevent overloading, but also reduces the possibility of fraudulent activity, ensuring that the extracted and shipped datasets match perfectly. It also optimizes track routes in real time to ensure production targets are reached efficiently and on time.

i3MMS Online mineral transport and shipping management system: This all-in-one online platform follows every stage of mineral production in real-time. The moment minerals are extracted from the pit they are tracked on their journey to storage and shipment. The system is designed to improve transparency and ensure accountability throughout the entire process.

Automated weighbridges: These automated weight measurement systems for trucks, which are outfitted with integrated cameras and sensors, significantly address challenges associated with fraudulent practices like overloading and enhance the reliability of the datasets related to extraction and dispatch operations.

Fleet management and dispatch system: This system autonomously schedules mining equipment in accordance with production demands and allocates tasks to mining machinery, thereby optimizing the utilization of mining devices in real-time.

Operational Efficiency and Safety

Mine Management Systems (MMS): Centralized MMSs digitally monitor and control mining operations – from ore extraction to transportation – enabling real-time data integration, resource tracking, enhanced efficiency, reduced human intervention, and improved compliance.

IoT-based sensors: Sensors on mining equipment are used to monitor temperature, gas emissions, vibrations, and equipment health, enhancing safety (e.g., gas leak detection) and enabling preventive maintenance to avoid equipment failure.

Automated drilling and blasting control: This technology improves the precision and safety of drilling and blasting operations, enhancing efficiency and reducing risks.

Excavator and payload monitoring: AI-powered systems monitor excavator tooth condition and assess shovel loads, reducing downtime and optimizing equipment utilization.

Real-time analytics: Integrated data platforms collect and analyze performance data, enabling predictive maintenance and minimizing unexpected equipment failures.

Remote access and control: These systems allow remote oversight of mining operations from anywhere, with vernacular language support for improved accessibility across diverse teams.

Environmental Monitoring and Compliance

The Odisha State Pollution Control Board (OSPCB) is a leader in environmental stewardship, utilizing state-of-the-art automated stations to monitor critical environmental factors in real-time. This includes monitoring the integrity of both air and water, as well as noise pollution and dust levels. The OSPCB department utilizes IoT components to monitor air and water quality, detect hazardous gases, and locate industrial emissions in order to ensure ecological equilibrium and adherence to environmental regulations.

Security and Access Control

Smart helmets and biometrics are deployed to ensure that only authorized personnel enter restricted areas. The integrated biometric dataset keeps a record of face, fingerprint, and iris scanning of employees and the smart helmet keeps track of location. A centralized orchestrator is used to manage and act on the data. This enhances operational security and worker safety.

Odisha's goal is to establish a mining sector that is more sustainable, efficient, and transparent, while also minimizing environmental impact and optimizing resource utilization through the integration of these advanced technologies. In this white paper, the authors propose a whole network architecture and logistics management to support this smart mining goal to boost efficiency, productivity, strategic operations, and advanced logistic management.

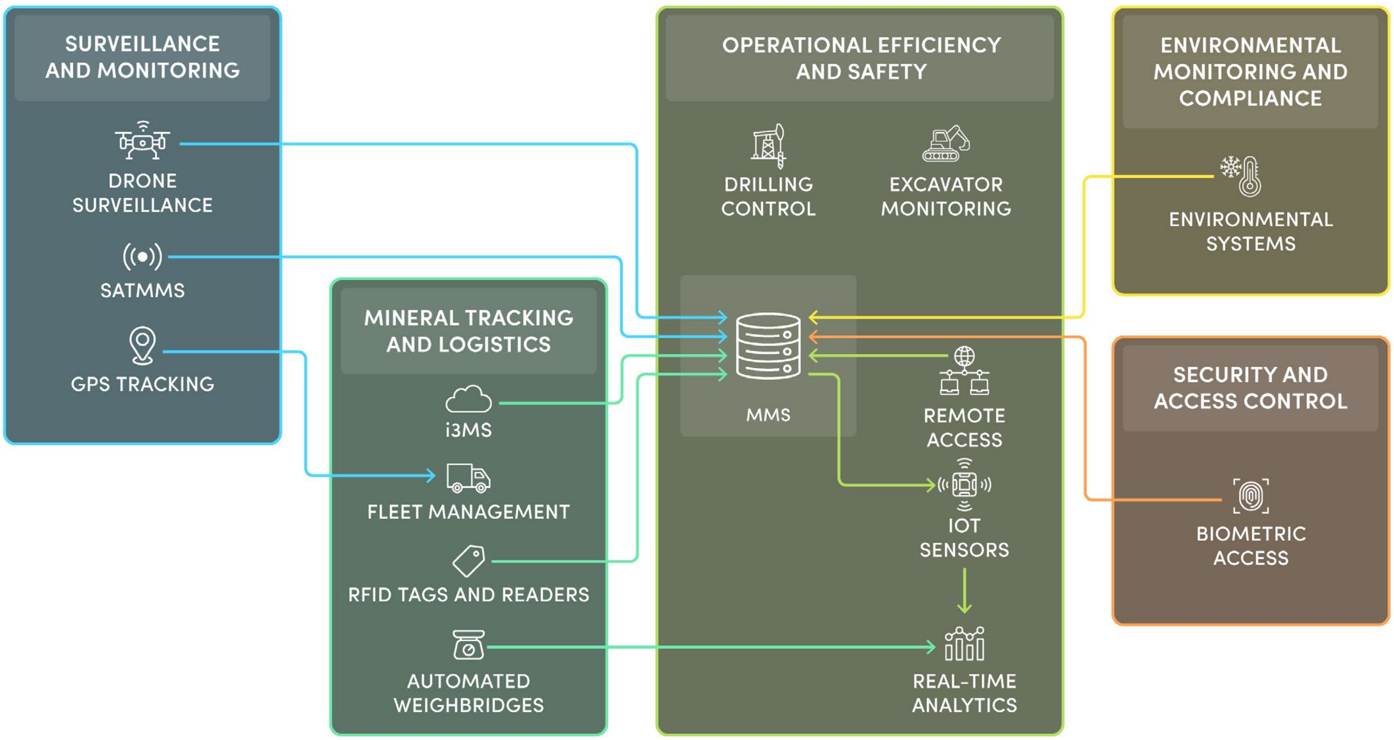


Figure 6: Transformative Architecture of Private 5G Smart Mining and Logistics

As seen in Figure 6, private 5G provides a whole network architecture to support smart mining and logistics with modern wireless connectivity. Private 5G technology delivers advanced protocols like URLLC, Software-defined networking (SDN), network slicing, and enforcement of network within the network to securely meet key performance requirements. Each layer will contain their specific roles and policies, using smart logic to integrate work and data flows within a centralized system. The arrows in Figure 6 show data flows and interactions between each node and towards the centralized 5G Multimedia Messaging Service (MMS). This approach leverages the security, speed and low-latency of 5G to drive modern automation applications that will provide visibility, enhance mining productivity, and support sustainability.

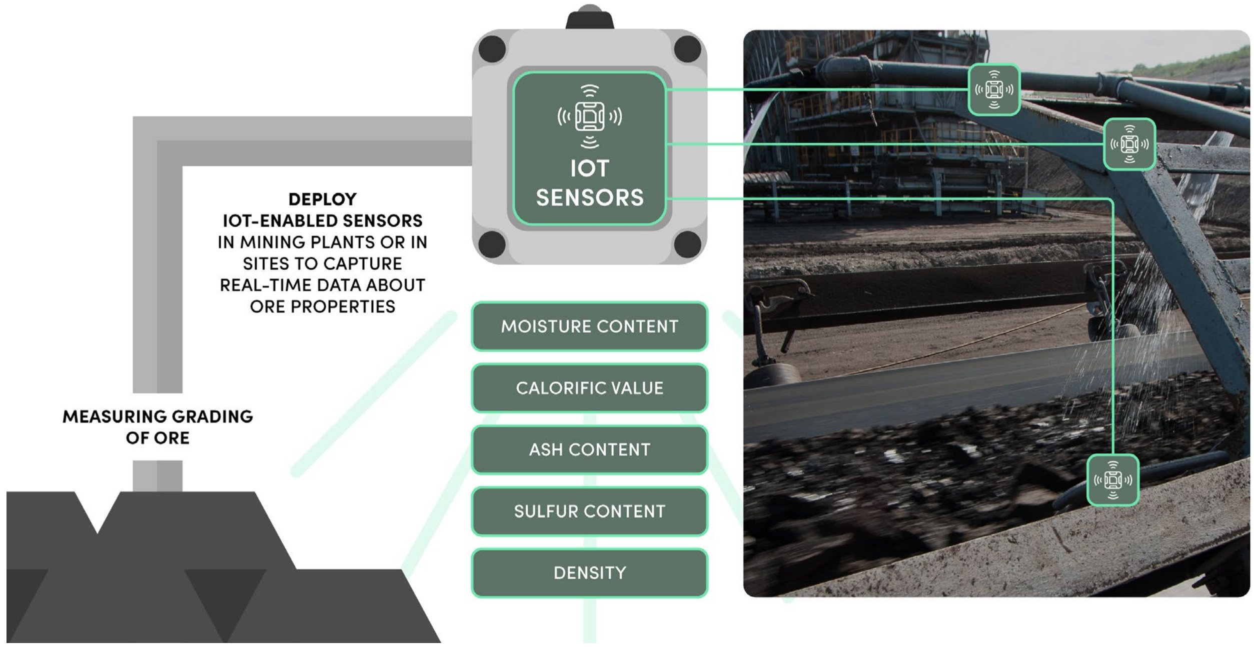


Figure 7: Grading Coal with IoT Sensors

Figure 7 shows a concrete example of how this all comes together in a specific application – using IoT sensors for grading coal. IoT sensors can be deployed at the mining site or in the plant to capture real-time data about coal properties, such as moisture content, calorific value, ash content, sulphur content, and density, greatly reducing processing time. Determining the grade of coal using IoT sensors running on private 5G can take advantage of several advanced technologies enabled by the high speed, low latency, and massive connectivity of 5G.

New Possibilities with Private 5G

Figure 8: Transformative Impact of 5G on Smart Mining and Logistic Industry

Private 5G technology will open new possibilities for the mining industry, including:

Autonomous Mining Operations

Driverless trucks, drones, and robots will be able to work in hazardous conditions without the need for human intervention, improving safety and efficiency.

Environmental Monitoring

AI models can be applied to real-time environmental data for rapid response to improve ecological protection.

Logistics and Supply Chain

RFID and ruggedized scanners can be deployed for real-time tracking that feeds data into smart inventory management systems, increasing operational efficiency and reducing loss.

Real-time Data Analytics

IoT sensors for applications such as coal grading will generate real-time data, which can be analyzed instantly using AI models to optimize production, improve resource allocation, and reduce environmental impacts.

Enhanced Safety

With 5G's low-latency capabilities, sensors can be deployed to detect and respond to gas leaks and other hazards, and self-driving vehicles and mining operations can be remotely monitored and controlled from anywhere in the world, enabling quicker responses to issues and reducing the need for on-site personnel in hazardous environments.

Methodology

Figure 9 represents the basic smart mining network architecture built on the Celona 5G LAN:

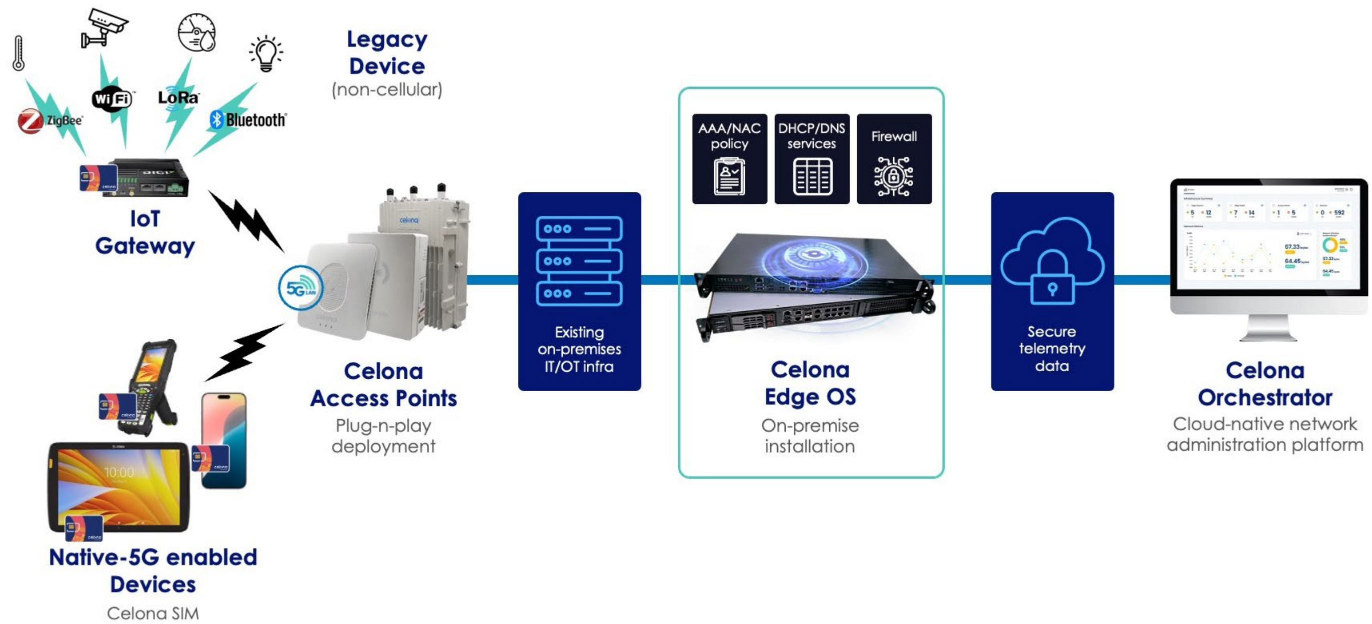


Figure 9: Basic Private 5G Network Architecture for Smart Mining

The successful implementation of private 5G networks in smart mining requires a well-structured deployment framework that ensures seamless connectivity, minimal latency, and efficient data processing. Deployment follows a simple yet structured methodology:

1. **Assessment and planning:** Assess the current mining infrastructure and identify areas where private 5G can provide the most benefit. Plan for the installation of private 5G equipment, including 5G access points and IoT devices.

2. **Pilot testing:** Conduct pilot tests in select areas of the mining operation to validate the technology's effectiveness and refine systems based on lessons learned.

3. **Integration with existing systems:** Integrate the private 5G network with existing automation and data analytics systems to ensure seamless operation.

4. **Deployment and scaling:** Gradually scale up private 5G deployment across the entire operation, ensuring that all systems are fully integrated and optimized.

5. **Continuous monitoring and improvement:** Continuously monitor system performance and make adjustments based on real-time data to optimize mining operations.

Figure 10 represents some of the most common use cases and IoT devices deployed on the Celona 5G LAN for smart mining today.

Figure 10: End-to-end Solution for Smart Mining

The vast amounts of data generated by these IoT sensors can be transmitted to the cloud or can be kept on on-site for processing. Private 5G's ultra-low latency and high-bandwidth connectivity ensures seamless data transmission, even in areas with high sensor density. Large volumes of data can be processed and analyzed in real time, enabling immediate insights and decision-making, especially when AI/ML models are applied. Private 5G also enables edge computing, where data processing occurs at the edge of the network, further reducing latency and improving overall system efficiency.

AI & ML: Shaping the Future of Autonomous Mobility and 6G Connectivity

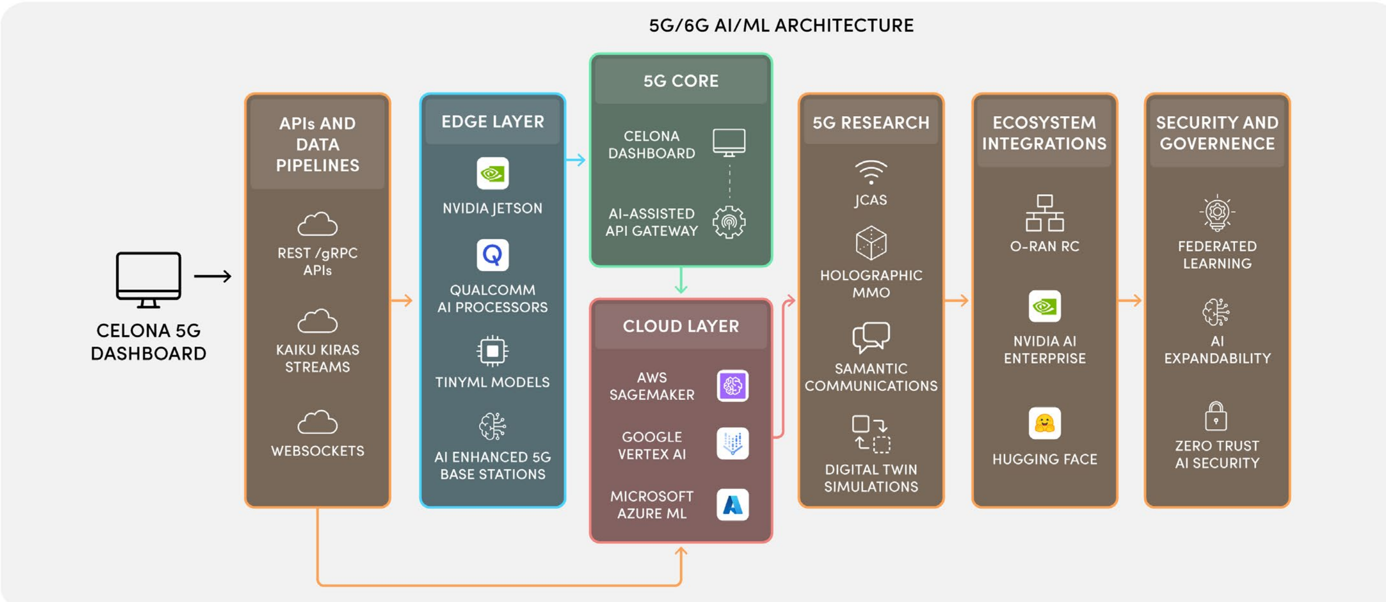


Figure 11: Architecture of Central Hub Integrating Edge/Cloud AI and Third-party APIs for Autonomous Network Orchestration

Celona 5G LAN integrates AI/ML capabilities directly into its network orchestration dashboard, enabling advanced automation and real-time analytics. As the industry progresses toward 6G, Celona's architecture is uniquely positioned to support next-generation AI/ML model integration. The platform's open APIs and edge-native design allow seamless interfacing with optimized AI/ML frameworks, accelerating data processing, reducing latency, and enabling deep learning applications at scale.

Following are the key components represented in the Figure 11 architecture diagram:

APIs & Data Pipelines

- Flow: 5G telemetry → Kafka/Kinesis → AI models (anomaly detection, QoS) → Optimized outputs
- Enhancements: NLP-driven network analysis, dynamic API prioritization

Edge-to-Cloud AI

- Edge: TinyML on Jetson/Qualcomm for congestion detection
- Cloud: SageMaker/Vertex AI for traffic prediction
- Enhancements: GNNs for traffic analysis, and edge data deduplication

Network Slicing & Digital Twins

- AI Slicing: Reinforcement learning for autonomous vehicles/AR/VR
- Digital Twin: Simulates 6G (terahertz, URLLC, mMTC, eMBB) via NetSim/MATLAB/Ansys

Ecosystem

- SA RAN: AI-driven RAN optimization
- AI Marketplaces: Certified OEM vendors successfully interface for model deployment

Security

- Federated Learning: Privacy-preserving AI for healthcare/IIoT
- Explainability: SHAP/LIME for transparent decisions

6G Research

- JCAS (AI for sensing/communications), Holographic MIMO, Semantic AI

Several advanced technologies contribute to the success of smart mining by enabling real-time monitoring, automated decision-making, and efficient smart mining management. These key technologies include:

Internet of Things (IoT)

A network of smart sensors and drones continuously collect real-time environmental data, including soil moisture, temperature, and humidity. These data points provide a granular understanding of field conditions, allowing staff to make informed decisions about the current situation of the site.

Artificial Intelligence (AI)

AI-powered models analyze incoming sensor data and generate predictive insights to optimize operations. By identifying such things as patterns, textures, acidification, and weather, AI helps anticipate and measure the grade of the ore and implement data-driven interventions for transparency and accountability.

Big Data Analytics

The ability to process and interpret large volumes of mineral data enables mine operators to optimize resource allocation, apply effective rotation, and yield predictions. Machine learning techniques extract valuable insights from historical and real-time datasets, improving mining efficiency and sustainability.

Drones and Robotics

Autonomous drones monitor mining conditions by capturing high-resolution aerial imagery and sensor data. Meanwhile, robotic mining equipment automates labour-intensive processes, improving operational efficiency and reducing human risk and workload.

Edge Computing and Private 5G

Instead of relying on cloud-based processing, edge computing allows data to be processed locally, reducing latency and enabling instant AI-driven decision-making. Private 5G networks provide the high-speed, low-latency communication infrastructure necessary for real-time smart mining automation.

Machine Learning Model Selection

According to the desired throughput results, one can select the models that balance inference speed and computational efficiency in constrained network environments. The following models were chosen based on their ability to operate effectively within the private 5G architecture:

Random Forest Classifier: An ensemble learning model that reduces overfitting and improves decision-making through multiple decision trees.

Logistic Regression: A simple yet effective statistical model for binary classification, requiring minimal computational resources.

Decision Tree Classifier: A model that makes hierarchical decisions based on feature thresholds, enabling fast inference.

Neural Network (MLP Classifier): A deep learning-based model with hidden layers to capture complex relationships while maintaining reasonable throughput performance.

XGBoost Classifier: A gradient-boosting algorithm optimized for speed and accuracy, making it well-suited for edge computing applications.

The following architecture will process machine learning data within a private network, as represented in Figures 12a and 12b.

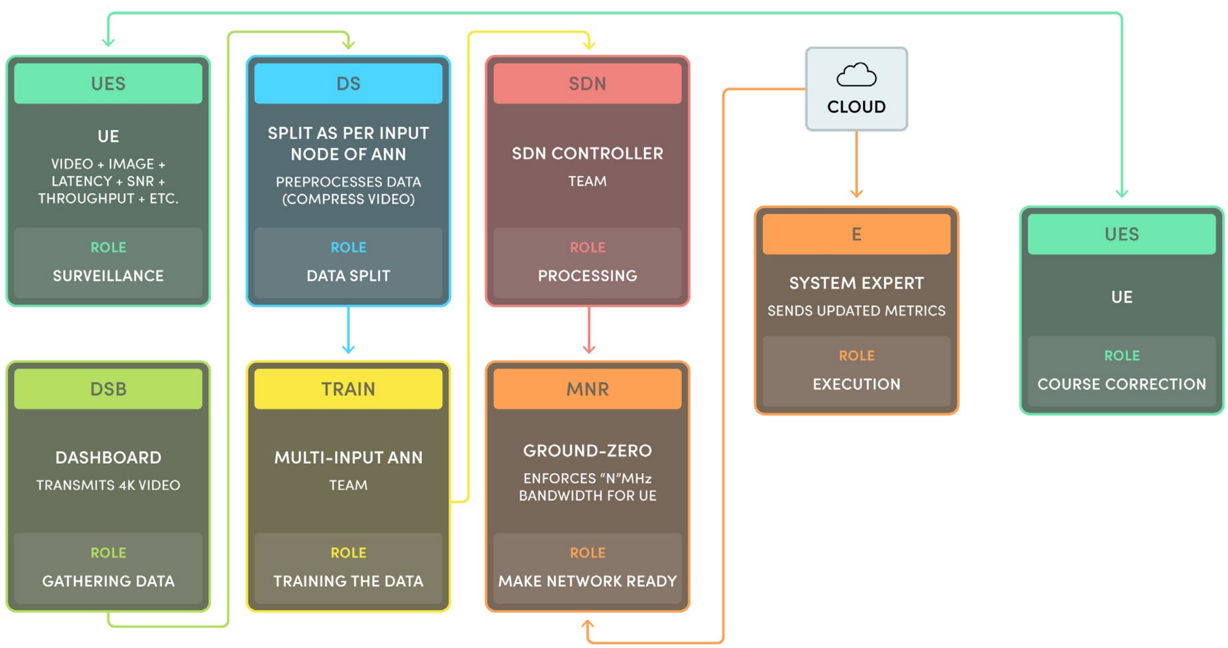


Figure 12a: Working Principle of ANN/ML Model within Private 5G

Figure 12a represents the working principle of the ML/ANN model within private 5G in smart mining. Each model is trained and tested by using some sample of data split to ensure generalization and prevent overfitting to achieve the desired throughput.

Cloud-based processing involves an inherent delay due to data transmission. We can calculate network delays by considering some ***n***-MB data packet size per EU data transmission. The transmission delay can be computed as: ***Latency = Data Size (MB)/Bandwidth (Mbps)***

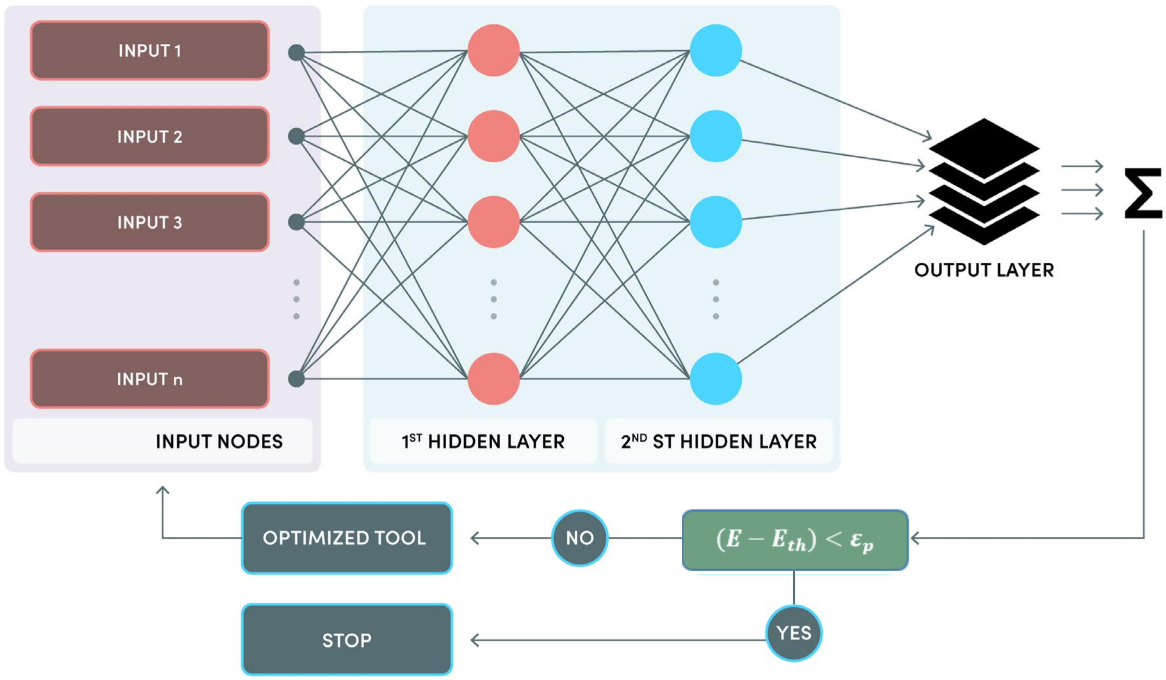


Figure 12b: AI-Based Feedback Control System for Edge Processing

The efficiency of data-driven smart mining is directly linked to how quickly and effectively sensor data is analyzed and acted upon. Private 5G networks enable continuous, high-speed data transmission, which is crucial for real-time AI-based decision-making rather than sending data to a centralized cloud server. The edge computing infrastructure processes information locally, drastically reducing latency and network congestion.

Limitations of Traditional Connectivity Solutions:

Public 4G/5G Networks

While urban areas benefit from dense network coverage, rural regions often experience weak signal reception, network congestion, and slow data transmission speeds. Additionally, public networks are optimized for consumer use, making them unsuitable for large-scale, industrial IoT applications like the precision grading of coal.

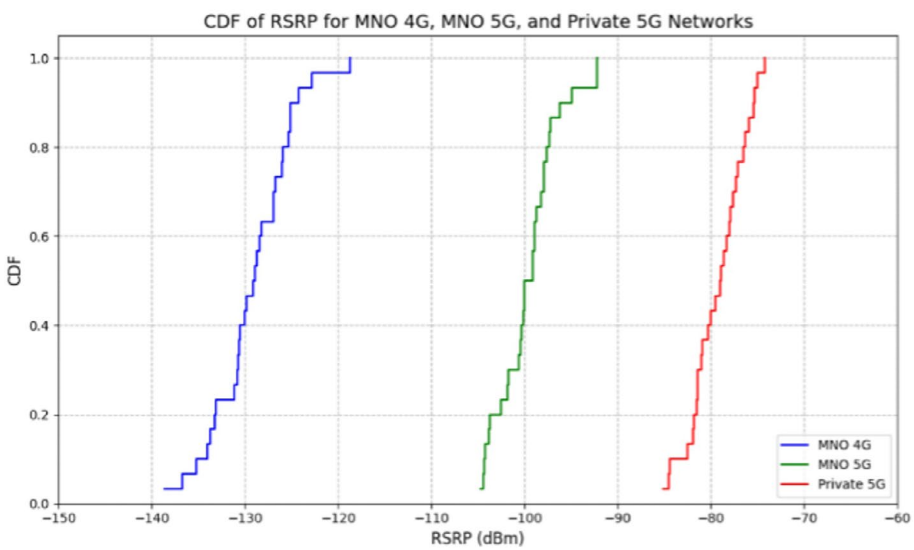
Satellite-Based Internet (Starlink, VSAT)

While satellite internet provides connectivity in remote locations, high latency, limited bandwidth, and costly deployment make it impractical for real-time IoT applications requiring instantaneous AI-based decision-making.

Wi-Fi and Mesh Networks

Traditional Wi-Fi based mining area networks require extensive infrastructure deployment, repeater installations, and constant maintenance, making it difficult to scale across large mining lands, mountainous terrains, or dense vegetation areas.

To demonstrate the practical implications of these restrictions, we examined three real-world connectivity scenarios depicted in Figure 13 within the campus of NIST University showing the Reference Signal Received Power (RSRP) ratio of public 4G (blue) public 5G (green) and private 5G (red). Private 5G shows huge improvements with signal power in the -80dBm range at the same location as compared to other two.



RSRP
Measures the power of the signal received from the public cell tower of mobile network operator (MNO)

Optimal Range:

- **Excellent:** ≥ −89 dBm
- **Good:** −90 to −104 dBm
- **Fair:** −105 to −114 dBm
- **Poor:** −115 to −124 dB
- **Very Poor:** ≤ −125 dBm

Figure 13: CDF of RSRP for Public 4G, Public 5G, and Private 5G Networks

Benefits/Expected Outcome

There are several important advantages delivered by private 5G technology in mining operations.

Safety Improvement

Autonomous vehicles and remote monitoring systems that operate in private 5G can reduce the likelihood of people being exposed to dangerous situations. The safety of employees will increase significantly by potentially reducing the impact of hazardous environments.

Increased Operating Efficiency

Mining companies can use automation and real-time data analysis to increase productivity, reduce costs, and maximize resources. With high-speed data transfer and applied AI models, mining operations experience improved monitoring, real-time decision-making, and predictive maintenance capabilities.

Environmental Sustainability

Improved resource management, reduced waste and more efficient energy use reduces the environmental impact of mineral extraction.

Cost Reduction

Predictive maintenance reduces the downtime of equipment and maintenance costs, while automation and remote operation reduce the need for human labour under dangerous conditions. In just the one example provided, IoT sensors can be used to streamline coal grading for significant cost reduction through process improvement.

Improvement of Efficiency

Solutions based on data simplify the task, reduce waste, and increase overall efficiency. The return on investment (ROI) is seen in the form of reduced operating costs and downtime. With the application of ML/AI models, efficiency and performance continue to increase, having a real impact on the mining industry over time.

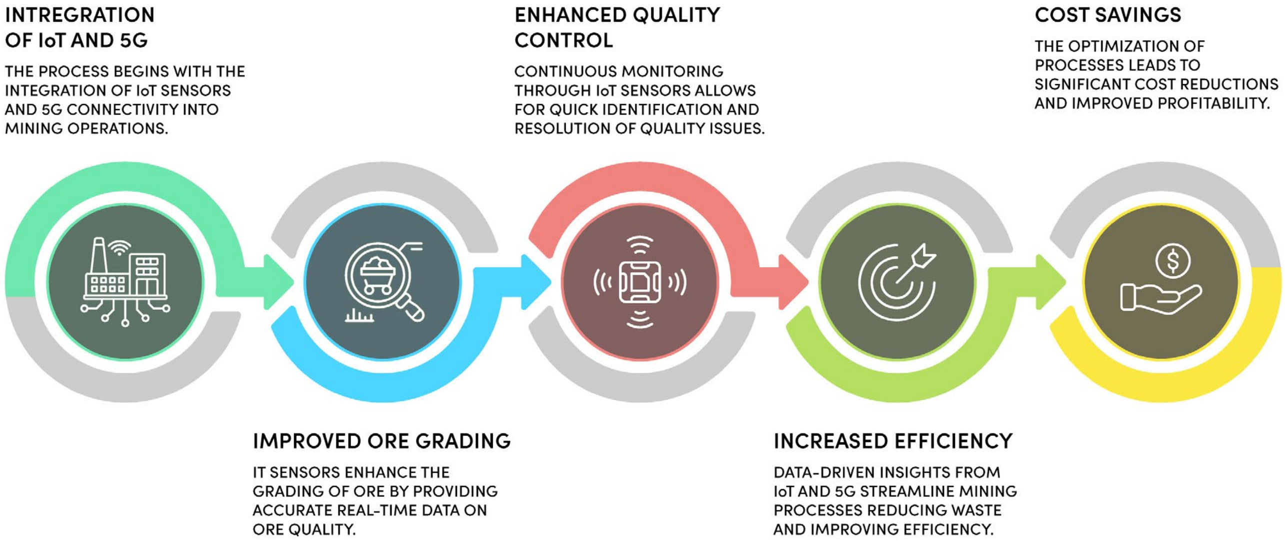


Figure 14: Operational Transformation with Private 5G

Conclusion

The advent of private 5G in mining is not merely an upgrade—it is a revolution. By unlocking unprecedented operational efficiency, enabling real-time decision-making through IoT and AI, and fostering safer, zero-harm workplaces, private 5G positions the industry at the forefront of the Fourth Industrial Revolution. As global demand for sustainable resource extraction intensifies, embracing this technology moves from a strategic advantage to existential imperative. The mines of tomorrow will thrive not by the depth of their reserves alone, but by their ability to harness private 5G's transformative power—bridging productivity, planetary stewardship, and human progress.

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