

Deploying Private 5G Networks in Remote and Hazardous Mining Environments: A Comprehensive Analysis

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Abstract— The mining industry is currently experiencing a paradigm shift toward "Mining 4.0," driven by the integration of automation, the Internet of Things (IoT), and real-time data analytics. This transformation requires a communication infrastructure capable of providing ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC) in underground and remote locations. This research paper examines the deployment of Private 5G (P5G) Standalone (SA) networks as the core connectivity layer for modern mining. It compares the architectural benefits of 5G SA versus traditional Wi-Fi and LTE systems, focusing on network slicing and Mobile Edge Computing (MEC). The paper explores the physics of radio signal propagation in tunnel environments, referencing recent 2025 studies on multipath fading and waveguide effects. It also discusses the engineering standards required for hazardous explosive atmospheres (ATEX/IECEx) and assesses operational impacts through case studies of Rio Tinto, Boliden, and China Mobile. The results suggest that P5G deployments can increase equipment utilization by over 15% and greatly enhance safety by removing personnel from dangerous zones.

Keywords: Private 5G, Underground Mining, Industrial IoT, Signal Propagation, ATEX, IECEx, Autonomous Haulage Systems, Mobile Edge Computing, Tele-operation.

I. INTRODUCTION

The extraction of mineral resources is increasingly occurring in deeper, more remote, and geologically complex environments. As the industry faces the "trilemma" of declining ore grades, volatile commodity prices, and strict safety regulations, operators are turning

to digitalization to maintain profitability and safety [1] [2]. The concept of the "Connected Mine" depends heavily on wireless teleoperation and autonomous systems, which require a level of network determinism that legacy technologies struggle to deliver.

Historically, mines have relied on proprietary radio systems for voice communication and Wi-Fi (IEEE 802.11) for data transfer. However, Wi-Fi's contention-based access mechanism and limited mobility support lead to unacceptable latency spikes and connection drops in mission-critical applications such as remotely controlling heavy machinery [1].

This paper argues that Private 5G Standalone (SA) networks provide the necessary technical features, such as licensed spectrum, deterministic scheduling, and seamless handover, to support the next wave of mining applications. We analyze the system architecture, radio propagation challenges in tunnels, compliance with hazardous area standards, and the economic impacts of this technological shift.

II. STRATEGIC IMPERATIVES: 5G VS. LEGACY CONNECTIVITY

The decision to migrate to Private 5G is driven by particular technical limitations of Wi-Fi 6 and 4G LTE in industrial settings.

A. The Limitations of Wi-Fi in Mining

While Wi-Fi 6 (802.11ax) provides high theoretical throughput, it operates on unlicensed spectrum, making it vulnerable to interference. In a mining environment, this interference causes variable latency (jitter). For Autonomous Haulage Systems (AHS), consistent latency is more important than peak speed. If a vehicle control packet is delayed beyond a safety threshold (usually 100ms), the vehicle's safety system will initiate an emergency stop, halting production [1]. Additionally, Wi-

Fi depends on client-controlled handovers, often resulting in "sticky client" issues where moving vehicles stick to weak signals, leading to packet loss [1].

B. The 5G Standalone Advantage

Private 5G SA addresses these issues by managing handovers through the network and utilizing licensed spectrum.

- **Deterministic Latency:** 5G enables reserving resources for specific data flows, ensuring latency targets [3].
- **Coverage:** A single 5G macro cell provides extensive wide-area coverage that significantly exceeds that of Wi-Fi, enabling mines to replace dense access point networks with fewer tower sites and considerably reducing the maintenance needs of roadside infrastructure [4].
- **Mobility:** 5G supports handovers at speeds up to 500 km/h, far exceeding the requirements of mining trucks [5].

Table 1: Technical Comparison of Connectivity Standards for Mining [1] [5] [6] [7]

Feature	Wi-Fi (802.11ax)	4G LTE Private	5G Standalone (SA)
Spectrum	Unlicensed (2.4/5/6 GHz)	Licensed / Shared	Licensed / Shared
Handover	Client-Controlled (High Latency)	Network-Controlled	Network-Controlled (~0ms interruption target)
Latency	10–50ms (Variable)	20–30ms	1–10ms (Deterministic)
Connection Density	Low	~100,000 / km ²	~1,000,000 / km ²
Uplink Capacity	Moderate	Limited	High (Configurable TDD patterns)
Security	WPA3	SIM-based	SIM + IMSI Encryption

III. SYSTEM ARCHITECTURE: DESIGNING FOR THE EDGE

To ensure safety-critical applications, the network must be designed for autonomy and survivability.

A. Standalone (SA) Architecture

5G Standalone (SA) architecture is essential for mining because it separates the 5G Radio Access Network (RAN) from the 4G Core. This allows the use of the cloud-native 5G Core (5GC), which supports Network Slicing [8]. Slicing enables a mine to operate multiple virtual networks on a single physical infrastructure [3] [8]:

1. **URLLC Slice:** Reserved for autonomous truck control and emergency stops [3] [8].
2. **eMBB Slice:** Used for high-definition video streaming from remote cameras [3] [8].
3. **mMTC Slice:** Used for thousands of battery-powered environmental sensors [3] [8].

B. Mobile Edge Computing (MEC)

Because most mines are in remote locations, backhaul to the internet (via satellite or microwave) is often high-latency and unreliable. Mobile Edge Computing (MEC) places data processing resources on-site [9]. Traffic from mining equipment is routed directly to the local MEC server (Local Breakout) without leaving the mine. This ensures that even if the satellite link to corporate headquarters fails, the autonomous trucks continue to operate in "island mode," processing video data and control commands locally [10].

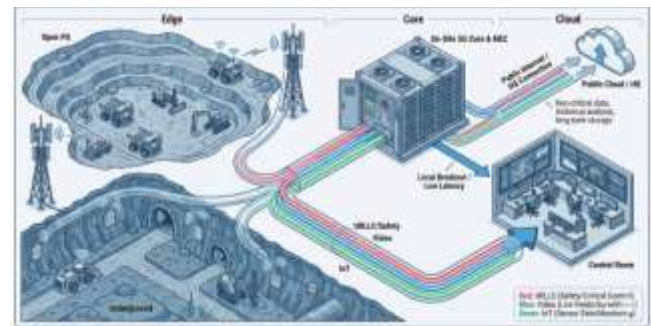


Figure 1: Private 5G Standalone Network Architecture for a Mining Site, depicting Local Breakout & Network Slicing for Safety and Low Latency

IV. SIGNAL PROPAGATION IN SUBTERRANEAN ENVIRONMENTS

Underground mines encounter unique Radio Frequency (RF) challenges, including rough surfaces, confined spaces, and complex topologies like tunnels, drifts, and stopes.

A. Tunnel Waveguide and Polarization

Tunnels function as large waveguides. Research shows that the tunnel's shape significantly affects signal loss. In rectangular tunnels, horizontal polarization often results in less attenuation than vertical polarization because the horizontal dimension (drift width) is typically larger than the vertical one, reducing the interaction with the side walls [11].

B. Multipath and Delay Spread

The roughness of tunnel walls causes multipath scattering. Measurements at 3.5 GHz in underground mines show that RMS delay spreads usually range from 20 to 100 ns [12]. While these values are higher than in open air, they are still within the standard Cyclic Prefix of 5G, ensuring reliable performance without special tuning, unlike legacy Wi-Fi, which often had difficulty with such multipath [12].

- **Corner Effects:** A 90-degree corner in a tunnel can lead to a signal attenuation of 10–15 dB/m immediately after the turn [12].
- **Modeling:** Advanced Close-In (CI) path loss models are used to predict coverage, expressed as:

$$PL_{CI}(f, d) = FSPL(f, 1m) + 10n \log_{10}(d) + X_{\sigma}$$

Where n is the path loss exponent, which can drop below 2 (free space) in straight tunnels due to the waveguide effect but rises sharply in non-line-of-sight (NLOS) zones [13].



Figure 2: Radio Frequency Signal Propagation in Underground Tunnels

V. HAZARDOUS ENVIRONMENT ENGINEERING (ATEX/IECEX)

Mines, especially coal mines, are considered hazardous environments because of methane and coal dust. Equipment must be intrinsically safe to prevent ignition.

A. Certification Standards

Equipment installed in these areas must comply with ATEX (Europe) or IECEx (International) standards.

- **Zone 1:** An area where an explosive atmosphere is likely to occur during regular operation [14].
- **Zone 2:** An area where an explosive atmosphere is unlikely to occur, and if it does, only for a brief period [14].

B. INTRINSICALLY SAFE 5G ECOSYSTEM

The lack of certified user equipment (UE) was once a barrier, but the ecosystem has now matured.

1. **Isafe MOBILE IS540.1:** The world's first 5G smartphone with ATEX Zone 1/21 certification. It uses the Qualcomm QCM6490 chipset and supports standard industrial 5G bands (n77, n78). It allows workers to stream video inspections directly from the coal face [15].
2. **Ecom Smart-Ex 03:** Another Zone 1/21 certified device supporting 5G and Wi-Fi 6E, designed for digital worker applications such as augmented reality (AR) maintenance guides [16].

VI. OPERATIONAL USE CASES AND VALIDATED OUTCOMES

Deployments by major mining operators have progressed from proof of concept to full production, demonstrating clear ROI.

A. Rio Tinto: Autonomous Haulage

Rio Tinto operates one of the largest autonomous fleets in the world in the Pilbara, Western Australia. The shift to robust private cellular networks has enabled their Autonomous Haulage System (AHS) to operate trucks an average of 700 hours more per year than traditional trucks. This is achieved by removing shift changes, breaks, and operator fatigue management. The system has also led to a 15% decrease in load and haul costs [17].

B. Boliden: Tele-Remote Drilling

At the Aitik open-pit mine in Sweden, Boliden implemented a 4G/5G network to automate Pit Viper drill rigs [18] [19].

- **Utilization:** The automation enabled drills to operate during shift changes and blasting evacuations (which require humans to vacate the pit), increasing the total from approximately 5,000

manual hours to around 7,000 automated hours annually [18] [19].

- **Safety:** Operators remotely control the Epiroc Pit Viper rigs from a control room (Remote Operating Center), helping to avoid exposure to dust, noise, and vibration [18] [19].

C. China Mobile & Yangquan Coal: Deep Underground

At the Yangquan Coal Mine in Shanxi, China Mobile set up a 5G network at a depth of 534 meters. The network provides a specially optimized uplink of over 1000 Mbps to support multiple 4K video streams from the coal cutter. This low-latency connection (<20ms) enables surface operators to control the shearer in real-time, significantly reducing the number of workers needed underground [20].

VII. ECONOMIC ANALYSIS

The economic justification for Private 5G in mining is strong, motivated by productivity and safety.

- **Market Growth:** The smart mining market is expected to hit around USD 28.65 billion by 2030, with a growth rate of over 11% [21].
- **GDP Impact:** Analysis indicates that 5G applications in industrial sectors, including smart utilities and manufacturing (which share traits with mining), could add over USD 1.3 trillion to global GDP by 2030 [22].
- **Cost Savings:** Beyond AHS, predictive maintenance enabled by real-time sensor backhaul can reduce maintenance costs by 10–40% and cut unplanned outages by up to 50% [23].

VIII. CONCLUSION

Private 5G networks represent a crucial upgrade for the mining industry, surpassing Wi-Fi and LTE to deliver deterministic, highly reliable connectivity. Although challenges like underground signal propagation and hazardous-area certification remain, recent advances in channel modeling and the development of intrinsically safe 5G devices have largely mitigated these issues. Early adopters such as Rio Tinto and Boliden have demonstrated that this technology significantly enhances asset utilization and safety while lowering operational costs. As the industry advances toward the fully autonomous "Mine of the Future," Private 5G will

function as the vital nervous system connecting every sensor, machine, and worker.

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