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Review

Advancements in Mine Communication Systems: The Efficacy and Applications of 5G and LoRa Technologies in Modern Mining Operations

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Abstract

In the transition towards digitalization and automation of mining processes, high volumes of data are generated, including data from distributed sensor and actuator networks, voice communications, videos and vehicle telemetry data. This generated data is preprocessed on-site and subsequently transferred not only to headquarters for detailed analysis but also between mining machines and vehicles in case of automation or autonomous mining. Stable and efficient communication in the mining industry and particularly in underground environments is essential for increasing safety and productivity, support fast and secure transportation and facilitate logistical processes, ensuring continuous and smooth operations. Several different communication technologies and protocols exist related to the mining field, each with its unique characteristics, advantages, or limitations. This article focuses on two essential technologies that, despite their shared goal of enhancing communication networks, exhibit notable contrasts in some of their characteristics: Long Range (LoRa) as an existing technology in the industry since years and the technology of the fifth generation (5G) of cellular network will be presented and discussed in this article, highlighting the significant differences in their properties and applications. This provides an important basis for understanding the limits and possible trade-offs of the wireless communication technologies required in the mining industry for large scale sensor networks.

Keywords: communication; mining industry; 5G; LoRa; digitalization; automation; data transfer

1. Introduction

Digitalization and automation in mining are accelerating the deployment of sensing, analytics and control across extraction, haulage, ventilation, and safety. These functions depend on resilient communication networks that operate under harsh and dynamic underground conditions. This paper examines the suitability of 5G and LoRa as complementary wireless technologies for modern mining operations that addresses heterogeneous requirements in data rate, latency, range and also energy consumption. This positions 5G and LoRa technologies against wired and alternative wireless options.

1.1. Motivation and Operational Necessity of Communication in Mining

The mining industry as important part of the primary sector is equipped with a wide range of machinery and systems. The number of implemented technologies and systems in this field are continuously increasing to enhance the efficiency and safety of processes from extraction to transportation, storage and logistics. The need for continuous real-time monitoring of various parameters such as gas concentration, equipment status, and environmental conditions in mines underscore the importance of reliable and efficient communication systems. Therefore, a significant amount of data must be generated to fulfill the requirements. The generated data is used not only by the machines on site, but also it needs to be transferred to other machines or systems for further processing and analysis. Data transfer can be executed from a few centimeters to several meters or even kilometers through cables or wirelessly. Reliable and scalable communication system is a prerequisite for increasing safety and productivity in modern mines. Without this, real-time monitoring, automation, and decision support are all infeasible.

Communication techniques in mines are typically classified into Through the Earth (TTE), Through the Wire (TTW) and Through the Air (TTA) communications. Additionally, a combination of them forms a fourth category of Hybrid System (refer to the Table 1) *[1]*.

Table 1. Classification of typical communication technologies in mines *[1]*.

Categories	Technologies
Through the Earth (TTE)	PED device, TeleMag, Tram guard miner track, Subterranean wireless communication system, etc.
Through the Wire (TTW)	Magneto type, Sound powered, Bell signaling, Paging phones, Dial and page, Carrier current systems (Hoist rope phones, Trolly current phones), Ethernet, etc.
Through the Air (TTA)	Wireless networks, Wi-Fi, Walkie-Talkie, UWB communication, etc.
Hybrid System	RFID, Leaky feeder, Lamp system, etc.

1.2. Aim and Research Questions

This paper is a technical review and synthesis, which evaluates 5G and LoRa for mining communications by bringing together operational needs and performance aspects. It addresses three main questions: What operational requirements in mining (e.g. latency, reliability, coverage) relate to 5G and to LoRa? How do 5G and LoRa perform relative to wired and some other wireless options in typical mining use cases? When and how should mines deploy either technology or a hybrid architecture to meet safety, productivity, and cost targets? Together, these questions define the scope used in the comparative assessment that follows.

1.3. Structure of the Paper

The first section introduces the topic and aim of the research. It follows with a survey on wired and wireless communication technologies relevant to the field of mining. It first outlines wired technology and then reviews the wireless ones: Wi-Fi, Bluetooth, Through-The-Earth (TTE) communication, Ultra-Wideband (UWB) and ZigBee, emphasizing their physical constraints, deployment patterns and typical use cases.

Section 3 focuses on 5G technology, standards and regulatory frameworks, representative applications in mining, and its limitations in mine operations.

The fourth section examines LoRa technology, standards and regulatory context, applications in mining, and limitations of LoRa.

Section 5 provides the discussion, synthesizing requirements, comparing 5G and LoRa against the other technologies and outlining integration patterns (including when hybrid deployments are beneficial).

The last part presents the conclusions, highlighting practical guidance and the outlook for future work.

2. Wired and Wireless Communication Options in Mining

2.1. Wired Technology

Historical technologies in mines had been based mostly on wired networks which were reliable and stable. The current wired data transmission offers more improvements and advantages in comparison with the traditional methods. This type of communication can be facilitated through Local Area Network (LAN) cables, fiber optics, coaxial cables, and other technologies, each with its improved properties such as bandwidth, stability and speed. To transfer large volumes of data up to 100 Gbps, the utilization of optical fiber communication infrastructure is necessary. In comparison, Wi-Fi 6 and 5G providing up to 10 Gbps [2] and 20 Gbps (downlink speed) [3], respectively, optical fibers have no competitor in terms of speed and bandwidth [4]. When comparing the reliability of transferring data, comparing wireless communication such as Bluetooth or Wi-Fi and wired technologies like shielded LAN cables in mining environments, shielded cables can clearly offer a more stable connection in most cases. The presence of heavy machinery and other sources of electromagnetic interference in mines can significantly disrupt wireless signals. In contrast, wired technologies are more immune against such electromagnetic interferences, ensuring a consistent and secure data transmission path crucial for mine operations [5].

Each technology has its unique advantages and limitations. In comparison with wireless communication, according to physical connections between the systems and nodes in the wired communication, they are limited in physical flexibility, as any changes in network topology, equipment relocation, or tunnel extension require physical re-wiring and modification of the mine infrastructure. These systems can be expensive in terms of installation and maintenance. In contrast, wireless technologies overcome these weak points and address these limitations by providing greater flexibility and potentially lower costs, leading to their increasing adoption in the mines. The attempts to utilize wireless communication in mines originated in the early 1920s. These were primarily driven to establish a communication with miners during disasters in coal mines [6,7].

In this paper, the focus is on wireless technologies especially LoRa and 5G within the mining industry due to their ability to surmount the limitations inherent to wired communication systems. LoRa and 5G were selected because they represent two complementary extremes of wireless communication technologies suitable for mining applications. LoRa offers long-range, low-power transmission ideal for large-scale monitoring while 5G enables high-speed, low-latency data exchange for automation and safety-critical operations. Compared to other technologies like Wi-Fi or ZigBee, these two can provide the best balance between coverage, reliability and performance in harsh mining environments. Despite the high reliability and security that wired connections offer, their rigid infrastructure, limited range, and the high costs associated with installation and maintenance render them less adaptable to the dynamic and expansive nature of mining operations. Wireless technologies, by contrast, offer enhanced flexibility and scalability, potentially reducing operational costs and accommodating the complex topologies of mines more effectively.

2.2. Wireless Technology

Given that this research focuses on 5G and LoRa, it is essential to review other wireless communication technologies firstly, which are relevant to mining. This provides a clearer understanding of their characteristics and limitations, allowing 5G and LoRa to be distinguished more precisely in terms of their technical advantages and suitability for mining applications. Overall, this section aims to establish a comparative framework that highlights why 5G and LoRa serve as the central focus of this study. Wi-Fi

2.2.1. Wi-Fi

The IEEE 802.11 standard, which was introduced in 1997 became the first widely adopted WLAN standard. Wi-Fi, particularly the latest Wi-Fi 6 standard, offers substantial bandwidth (up to 9.6 Gbit/s) and is commonly used in mines communication infrastructure for data transfer, communication, and supporting operations like remote control of machinery. [8] Wi-Fi predominantly operates within the frequency bands of 2.4 GHz and 5 GHz. Recent advancements have led to the adoption of the 6 GHz frequency band, offering enhanced bandwidth and reduced interference compared to the traditional 2.4 GHz and 5 GHz bands [9]. Although Wi-Fi offers high bandwidth and is a low-cost device, several limitations constrain its use in mining. Performance degrades with non-line-of-sight tunnel geometry due to severe path loss and multipath effect, that leads to unstable communication and variable latency. Coverage cells are small, so frequent

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handovers for mobile equipment can cause packet loss, and dense deployments increase interference, especially at 5 and 6 GHz. [9–11].

2.2.2. Bluetooth

Bluetooth is primarily used for short-range communication and tracking within mines, which was developed by Ericsson, functions within the 2.4 GHz frequency band [9]. This technology is aimed to facilitate the transmission of information, including data and voice communications by segmenting these transmissions into smaller packets [12]. Bluetooth technology transmits data packets across 79 designated channels, each spaced by 1 MHz, setting the bandwidth for Bluetooth Classic [13]. Bluetooth Low Energy (BLE) is also engineered to optimize power consumption, significantly enhancing device battery longevity [14]. BLE doubles this bandwidth, utilizing 40 channels with a 2 MHz bandwidth each [15]. Despite these, Bluetooth generally provides low bandwidth communication. This optimization is achieved through the strategic use of subrated connections, which enable the establishment of persistent, low-duty-cycle connections that necessitate minimal energy usage. These connections maintain the capability to seamlessly transition to a high-duty-cycle, high-bandwidth mode without introducing a perceivable delay for the user. This dual operational mode underscores the flexibility and efficiency of BLE technology in managing power consumption while accommodating varying data transmission requirements [15]. This can be particularly suitable for wearable devices for miners with its low energy consumption.

2.2.3. Through-The-Earth (TTE) Communications

This communication technology is particularly related to underground mining environments. The transmission mechanism typically employs magnetic induction which operates at frequencies below 30 kHz. This enables the signal to penetrate through materials in the mine that block higher frequency bands. It can carry simple, reliable messages, evacuation calls, chamber check-ins, SOS from trapped miners, and a backup alarm channel when normal radios do not work. This methodology, however, is constrained by several limitations, including a narrow bandwidth and significant propagation losses. Furthermore, TTE systems are notably affected by external interference factors. Atmospheric noise and alternating current harmonics, originating from nearby transmission lines and various types of electrical equipment, pose substantial challenges. Such constraints underscore the need for advanced mitigation techniques and system designs to enhance the reliability and performance of TTE communication systems in underground settings. This technology is adequate for both communications inside the mine and from underground to surface communications. [16]

2.2.4. Ultra-Wideband (UWB)

UWB technology is known for its high precision in location tracking, which is used for accurate indoor positioning and collision avoidance systems [17]. In addition to localization, UWB also supports short-range and high reliability wireless communication [18]. One of the capabilities of this technology is accurately locating equipment and personnel within mines, which is critical for safety and logistical planning. UWB's advantage is in line-of-sight conditions, achieving precise results with minimal multipath propagation interference navigating the complex and hazardous environments of underground mines, demonstrating UWB's promise in improving mining safety and efficiency [19].

The UWB technology has been allocated in the unlicensed spectrum ranging from 3.1 GHz to 10.6 GHz for its deployment. The Federal Communications Commission (FCC) has limited transmission power of UWB to -41.3 dBm/MHz to prevent interference with other radio technologies [17,20]. This power limitation ensures that UWB can coexist with existing wireless services without causing disruptive interference. According to FCC the UWB signal is one with a bandwidth exceeding 500 MHz or a fractional bandwidth greater than one-quarter of its center frequency. The expansive bandwidth of UWB signals directly enhances channel capacity, given the direct proportionality between channel capacity and bandwidth [20]. These environments, characterized by narrow routes and reflective surfaces, cause significant challenges to conventional wireless communication technologies. UWB's inherent capability to resist multipath interference due to its narrow band in time domain enables more reliable and accurate positioning within such complex terrains [17,21].

2.2.5. ZigBee

ZigBeeis a low-power, cost-effective solution designed for applications in fields of automation, sensor networks, smart energy, and health care monitoring. It features devices that can operate for years on small batteries, with some achieving up to years of battery life [22]. The technology supports 20 to 250 kbps data-rate within the frequency bands of 68 MHz in Europe, 915 MHz in the USA and Australia, and 2.4 GHz in most countries worldwide [23], which is suitable for monitoring of a sensor platform and control tasks. Its scalability accommodates networks ranging from a few to thousands of devices [22]. ZigBeeis often employed in sensor networks for monitoring environmental conditions such as measuring gas concentration, temperature, and humidity. This technology is also used to monitor equipment status in mines and is used for proximity localization and worker tracking. It enables wireless data transmission between underground sensors, robots, or UAVs and surface control systems to enhance safety management. [24]

In the following sections, additional radio communication technologies, 5G and LoRa are presented in detail. These technologies will be thoroughly examined, highlighting their unique characteristics, applications, and the technical advancements they bring to the field of wireless communication in the mines.

3. 5G Technology

The introduction of the Fifth Generation Mobile Network Technology (5G technology) in mines has increasingly revolutionized data communication, offering high-speed connectivity. Recognized globally for its strategic importance, 5G technology is often integrated into national infrastructure plans due to its transformative potential. It represents an important shift in technologies, characterized by several key features such as its high bandwidth, low latency and large capacity to transfer data. It enhances the ability to transmit a large volume of data faster than the previous technologies with its potential for uplink speed up to 10 Gbps [2]. This enables large data transfer, real-time monitoring, and supports the integration of IoT devices for smart mining operations. According to Federal Communications Commission (FCC), 5G technology can be classified into low-band (under 1 GHz), mid-band (between 1-6 GHz) and high-band (over 6 GHz) [25]. The higher frequency bands can offer more network capacity and increased data-rate, which can also lead to a higher propagation loss and subsequently limited coverage range [26]. In the European countries, the allocation of 5G spectrum has been predominantly within the mid-band range, which is mostly centered around 3.7 GHz, with substantial allocations also made in the low-band spectrum around 700 MHz. Lower bands offer more extensive coverage and better penetration in the materials. Higher bands provide very large bandwidths for multi-Gb/s links. Therefore, the low-band spectrum is particularly esteemed in industrial applications due to its extensive coverage and enhanced capacity, thus is particularly well-suited for mining operations, where it can utilize these attributes to facilitate transferring larger data volume over extended distances [25].

From physical layer perspectives, 5G New Radio (NR) manipulates the amplitude, phase and also frequency of carrier waves through advanced modulation formats to encode large volumes of data efficiently. Like LTE and Wi-Fi, 5G employs Orthogonal Frequency Division Multiplexing (OFDM) but introduces scalable subcarrier spacing from 15kHz up to 960 kHz and flexible slot durations [27]. This allows ultra-low latency and efficient use of spectrum. For example, rather than transmitting 100 Mbps on a single wide carrier that would be highly vulnerable to fading and distortion, OFDM distributes the same data across many narrow subcarriers. In this case, around 1000 subcarriers and each carry 100 kbps. If some of these subcarriers are disturbed by noise or interference, error correction coding and frequency diversity allow the receiver to recover the information which ensures robust overall transmission.

5G NR provides up to 100 MHz per carrier in low-band and 400 MHz in high-band with carrier aggregation reaching up to 800 MHz. Therefore, 5G can deliver peak data-rates above 10 Gbps in enhanced mobile broadband scenarios [28]. By contrast, Wi-Fi 6 (IEEE 802.11ax) supports from 20 MHz to 160 MHz channels (including 80+80 MHz configurations) with multi gigabit throughput [29]. Bluetooth 5.0 is limited to 2 MHz channels and around 2 Mbps [30] and ZigBee (IEEE 802.15.4) provides around 250 kbps in 2 MHz channels at 2.4 GHz frequency, which are optimized for low power sensor networks [31].

The 5G technology as a network infrastructure to support Ultra-Reliable Low-Latency Communication (URLLC) achieves a maximum transmission delay of 1 ms under high network reliability in specific scenarios for URLLC applications [32]. The 5G New Radio standard, specifically 3GPP Release-15, emphasizes Enhanced Mobile Broadband (eMBB) and URLLC services, targeting 99.999% reliability with millisecond latency. This is achieved through a flexible physical layer and a scalable radio architecture. [33] This so-called five nines reliability corresponds to an annual downtime of only around five minutes. Sustaining very high reliability while maintaining high spectral efficiency is critical for safety relevant and capacity-intensive applications in mining. This is achieved by a combination of advanced channel coding via Low-Density Parity-Check (LDPC) for user data and polar codes for control channels, together with Hybrid Automatic Repeat Request (HARQ) and adaptive modulation. In addition, massive Multiple Input, Multiple Output (MIMO) and beamforming improve link robustness and spectral reuse in dense or obstructed underground environments, where multipath fading and interference are so common [28]. In traditional single antenna systems, signals often suffer from multipath fading. Massive MIMO addresses this problem by employing many antennas at the base station. Each antenna captures a slightly different version of the transmitted signal, and advanced signal processing then combines these paths in a way that strengthens the desired transmission while suppressing noise and interference [28].

By comparing, Wi-Fi 6 also employs LDPC coding but relies on contention-based channel access (devices take turns after detecting a free channel), which makes latency and reliability hard to predict in highly loaded networks. Low power standards such as ZigBee and Bluetooth 5.0 use simpler modulation and coding. For example ZigBee and Bluetooth are also combined with retransmission mechanisms (sending the same packet again if no acknowledgment is received or an error is detected, to improve the chance it gets through) to ensure basic robustness at low energy cost [30,33]. While these approaches are sufficient for non-critical sensing and short-range communication, they cannot guarantee the stringent reliability levels (e.g. availability of ≥99.999% or latency of ≤10 ms, which are mentioned in the next sections) needed for mission-critical control or autonomous machinery in mining.

3.1. 5G Standards and Regulatory Frameworks

The 5G technology standards are governed by the 3rd Generation Partnership Project (3GPP) which is a collaboration between groups of telecommunications standard associations. Some key aspects of its document 38.913 include the new radio specifications, antenna configuration and spectrum utilization of 5G technology [34]. For a comprehensive and compliant 5G implementation, 3GPP standards are the primary technical guidelines, which should be followed. It is also necessary to consider the regulations of International Telecommunication Union (ITU) for global harmonization and spectrum management and the standards of the Institute of Electrical and Electronics Engineers (IEEE) for integrating complementary technologies. The documentation 38.913 from 3GPP outlines different scenarios and requirements to ensure that 5G networks meet high performance, reliability, and efficiency standards. This addresses various implementations, consisting indoor hotspots, dense urban environments, and other areas considering peak data-rate, spectral efficiency, latency, etc. Additionally, it addresses the interoperability with existing networks, the advanced antenna systems, and robust security and privacy.

For example, for outdoor areas the rural deployment scenario is more relevant according to its large, continuous coverage, which employs carrier frequencies around 700 MHz or 4 GHz for extensive coverage and supporting high-speed movements. The indoor hotspot scenario, using frequencies around 30 GHz or 4 GHz, is ideal for high-capacity networks in indoor places. This ensures reliable connectivity in such areas. This considers high reliability, low latency, and flexible spectrum use to balance coverage and capacity which also makes it possible to achieve robust connectivity for critical applications like remote control, safety systems, and IoT networks in challenging industrial indoor environments. [34]

3.2. Potential Applications of 5G in Mining

There are now many companies who are delivering the industrial Internet of Things (IIoT) and are planning the integration of the 5G networks in mines. The integration of IIoT devices in mining, leveraging 5G for reliable, fast, and secure connectivity, essential for efficient operation and monitoring. For example, to the integration of communication solutions with Nokia's private 4.9G/LTE technology, Sandvik commenced the implementation of a Nokia 5G standalone private network within its experimental mining facility located in Tampere, Finland. [35] Due to its low latency, employing 5G for the autonomous operation of mining equipment, including vehicles, enabling more efficient and safer mining processes. By reducing the time lag in command execution, crucial for safety and efficiency in dynamic mining environments, autonomous operations can be executed. However, the potential of 5G depends strongly on real deployment conditions underground, where signal attenuation, reflections, dust, and complex tunnel geometry create highly variable environments.

Beyond its capabilities, the important question is how 5G behaves in real mines. The following section provides concrete details and contrasts 5G with other wireless technologies. These use-cases set closer look at deployment realities. To enhance the clarity and relevance of this section, it is essential to examine specific mining applications and to notice why 5G is technically suited for them.

Video Transfer: By the applications requiring the transfer of high-definition video content, such as remotely operating machinery and safety monitoring over 4K videos, the utilization of 5G technology is essential. High-definition video streaming allows operators located outside hazardous areas to control e.g. drilling, haul trucks, and loaders without direct exposure to dust, gas, vibrations or any other risks. This significantly increases worker safety and contributes to more efficient resource utilization. A single 4K video stream or high quality picture transfer typically require up to 30 Mbps depending on compression algorithms such as H.265/HEVC while multiple simultaneous camera streaming can easily exceed 100 Mbps in bandwidth [36,37]. Such applications also require low latency and minimal jitter to ensure reliable command execution and real-time operator feedback. These kind of applications also demand the transmission of substantial data volumes coupled with minimal latency. If the latency exceeds for example over 100 ms, operators experience noticeable delays in control feedback, which can compromise precision and safety during the operations. 5G networks, in contrast to other network technologies, possess the requisite bandwidth capacity and reduced latency characteristics essential for these high-demand applications, making them uniquely suited for tasks where both high data throughput and low time delays are crucial. In contrast, legacy technologies such as LTE or Wi-Fi 6 may provide adequate throughput, but they cannot consistently guarantee ultra-low latency in such underground settings, limiting their effectiveness for critical video-based control. While 5G clearly improves latency, some camera monitoring tasks like periodic belt conveyor inspections do not require 5G and can operate efficiently over Wi-Fi. Therefore, 5G is justified only when real-time control or multi-stream high-resolution video is required.

Remote Monitoring and Control: 5G networks can facilitate real-time monitoring and control of mining processes and equipment. In mining operations, 5G enables remote monitoring of equipment's health, environmental conditions and safety of the workers, allowing timely interventions to prevent accidents or equipment failures [38]. 5G becomes more relevant when thousands of sensors have to transmit data simultaneously with low latency and also high reliability (something that ZigBee or Wi-Fi cannot guarantee) in dense underground networks. This advantage makes remote monitoring of the systems more effective, since both massive sensor data and critical control commands can be transmitted with minimal delay. This leads to better remote diagnostics and predictive maintenance, leading to efficient asset management and reduced downtime of machinery and processes. This fact enables operators to control machinery and processes remotely with near real-time feedback, minimizing potential delays in decision-making and action. In Shanxi, China, the Yanjiahe Coal Mine, managed by Shanxi Xiangning Coke Coal Group and supported by China Unicom and Huawei, has significantly improved its operations using a 5G private network. This advanced network system enhances safety and boosts efficiency by enabling real-time monitoring of the mine’s environment and equipment. It supports a comprehensive underground monitoring setup and transfers high-quality video footage for safety checks. Additionally, the 5G network connects over 10,000 sensors and allows for remote operation of mining machinery, leading to increased productivity. [39] This is essential for integrating thousands of sensors in mines e.g. for vibration, gas, temperature and geotechnical monitoring. Combined with its ultra-reliable low latency feature for mission-critical tasks such as remote drilling and haul truck control, 5G technology provides a high capability that none of the previous wireless technologies offered. In an underground drift, 5G was tested during live 3D LiDAR point-cloud streaming from a mobile robot. The roundtrip was 10 ms on an idle network and, consistent with the 5–10 ms URLLC targets in Table 2, which is required for such applications. This value rose to 104 ms near saturation, exceeding URLLC bounds and highlighting the need for load management, reliability tactics or prioritizing controls [40].

Table 2. URLLC Industrial Applications: Latency and Reliability Requirements.

Use Case	End-to-End Latency $^{1}_{50}\downarrow$	Reliability
Discrete automation, motion control	1 ms	99,9999%
Electricity distribution, high voltage	5 ms	99,9999%
Remote control	5 ms	99,999%
Discrete automation	10 ms	99,99%
Intelligent transport systems, infrastructure backhaul	10 ms	99,9999%
Electricity distribution, medium voltage	25 ms	99,9%
Process automation, remote control	50 ms	99,9999%
Process automation, monitoring	50 ms	99,9%

Augmented Reality (AR) and Virtual Reality (VR): 5G can also enable the use of AR and VR technologies for training, maintenance and remote assistance in industrial settings like mining operations. For example, the miners can use AR glasses equipped with 5G to access real-time data, visualize equipment status, and receive step-by-step instructions for complex tasks. To utilize AR and VR technologies, which require generally ultra-low latency of below 40 ms and high bandwidth over 400 Mbps in advanced or extreme resolutions [41], a sophisticated network architecture is required. The integration of mobile edge computing and network function virtualization is crucial for tailoring network responsiveness and flexibility because sending raw video streams to distant data centers would create unacceptable delays in some cases. The proposition of the field of view rendering solution, aimed at optimizing video streaming by edge processing, emerges as a promising method to mitigate bandwidth and latency challenges. The advent of 5G technology, with its inherent capabilities for high data-rate and low latency, appears to be an important factor in fulfilling these requirements. AR/VR is a field where 5G is required. Traditional Wi-Fi networks often struggle with stable low-latency mobility in networks. Because this technology can manage and schedule data transmission in a more controlled and predictable way in situations where machines or people are constantly moving [42].

Table 2 illustrates URLLC use cases and requirements for specific industrial applications, highlighting the critical role of URLLC network infrastructure. It notes that the time it takes for data to travel from the source to the destination ranges between 1 ms to 50 ms and emphasizes the high reliability rates essential for these applications which is the probability that data transmission will be successful without errors, while also considering the impact on network design and overall system performance.

For Tele-remote loading or drilling underground, the networks must deliver around 10 Mbps for each machine for video and telemetry with a round-trip latency of < 40 ms (with seamless coverage) to keep the operator in the control loop [43]. Higher automation levels soften these bounds. This can relate to the above Table mentioning up to 10 ms for discrete automation and targets and the 5 ms for remote control. 5G (rather than Wi-Fi) is identified as the feasible URLLC candidate in GHz bands given these constraints.

Autonomous Process: Another critical application is underground autonomous haulage, where motion-control latency requirements directly influence braking behavior and the stability of teleoperation. Tele-remote drilling similarly depends on URLLC performance to preserve operator awareness of the situation. Hence, autonomous haulage systems in underground mines require ultra-reliable, low-latency communication to enable safe and continuous connectivity and real-time operational feedback. [44] Wi-Fi 6 may theoretically reach the required throughput, but its latency becomes unstable when multiple users share the same access point or when the tags move between access points [45].

3.3. Limitations of 5G in Mine Operations

Despite of the use cases and the advantages of employing 5G in the mine operations, there are several challenges to implement complete wireless coverage in coal mines using 5G communication technology. Firstly, the base station integrated from multiple advanced technologies leads to significant power demands, with the components like the Active Antenna Unit (AAU) containing the Remote Radio Unit (RRU) and the antenna, consume much power even in the kilowatt range [2,46]. The increasing complexity of the architecture of base station, particularly the AAUs has intensified concerns regarding the power efficiency and sustainability of 5G systems [47]. Although several approaches have been proposed to save energy and reduce the power consumption, there is still insufficient understanding of the power consumption behavior of advanced base stations and the influence of varying parameters of the network. Therefore, it cannot be used in some areas and under special conditions of power consumption.

Although 5G offers significantly higher energy efficiency in terms of data transmitted per joule compared to 4G, the absolute power demand of 5G base stations in multi-carrier and multi-antenna configurations is substantially higher. Studies indicate that the power consumption of such 5G sites can be two to four times greater than that of 4G systems. For example, network sites, which are operating with more than five frequency bands may consume more than 10 kW while large installations with ten or more bands can exceed 20 kW. These high energy requirements not only increase operational costs but also show challenges for deployment in remote or underground areas, such as mines, where power availability and heat management are already limited. Consequently, improving energy efficiency and power management is essential for the sustainable integration of 5G technology in industrial and mining applications. [48]

Secondly, the coverage range of 5G base stations is relatively limited depending on the frequency bands it is functioning with, which hinders the ability to establish a comprehensive network across the mine roadways with limited transceivers. In higher frequency bands the cell coverage can reach up to 100 m, which will be increased in lower frequency bands [26]. In mining environments, direct data transfer from 5G devices to the base station or headquarters over some hundred meters is often limited due to obstacles. To overcome these challenges especially in the private 5G networks, a mesh network architecture with multiple relay nodes and gates can be implemented, where each node extends the coverage of the previous one [49]. However, such multi-hop configurations increase the complexity of the whole system and also require good synchronization and latency management. Alternatively, the data collected from 5G antennas can be transmitted to the base station via high-speed ethernet cables or optical fibers. These wired connections ensure reliable and low-latency communication in combination with 5G technology but cause significant installation costs and maintenance efforts especially in dynamic or expanding mining operations.

Finally, the transmission of 5G signals at high frequencies results in significant diffraction losses, thus failing to maintain consistent communication. To avoid this, the operator must function in low frequencies [2]. At such high frequencies, the wavelength is very short and obstacles can act as strong blockages rather than scatterers, which reduces the effectiveness of diffraction strongly [50]. Therefore, when a 5G antenna transmits in a mining environment with rock walls, shafts, vehicles or other structures, maintaining consistent connectivity to a base station becomes more challenging. To overcome this problem, operators have to either use lower frequency bands (where diffraction and penetration losses are weaker) or implement mesh network architectures that cascade through multiple nodes until the signals reach the base station. Alternatively, the output of the 5G antenna may need to be transported via high-speed ethernet or optical fiber, which ensures better connectivity but leads to higher infrastructure costs and operational complexity [50]. Each of these alternatives demands increased resources, power, and careful planning factors that must be weighed when designing a 5G system for harsh mining environments.

4. Long Range (LoRa) Technology

LoRa stands out for its long-range communication capabilities, often reaching up to 5 km in dense areas and 16 km in areas free of obstacles and in open environments [51]. In mines, it facilitates low-power, wide-area network (LPWAN) communication, ideal for monitoring and tracking applications where high-speed data transmission is not critical.

The choice of technology depends on some factors like range, bandwidth requirements, power consumption and the specific operational environment of the mines. LoRa utilizes Chirp Spread Spectrum (CSS) modulation, which is a method originally developed to achieve reliable and long-range wireless communication at very low power consumption. In CSS, the frequency of the signal changes gradually over the time and it is increased (up chirp) or decreased (down chirp), which allows the signal to remain detectable even under high levels of noise and interference [52]. This approach enables LoRa to maintain high sensitivity and stable connectivity over kilometers, making it particularly suitable for challenging environments such as underground mining or dense open pit mines. However, this comes at the cost of lower data-rate, which is acceptable for most IoT and sensor-based applications, in which small amounts of data are transmitted.

In EU, LoRaWAN operates with the 863-870 MHz ISM frequency band, which is often referred to simply as the 868 MHz band for convenience, representing the central frequency around which LoRa channels are defined [53]. According to the LoRaWAN Regional Parameters v1.0.3rA document, this range is divided into several uplink and downlink channels (e.g. 868.1 MHz, 868.3 MHz, and 868.5 MHz) that together form a frequency window which is regulated by ETSI EN300.220. Within this frequency window, LoRaWAN supports data-rates from DR0 (SF12/125 kHz, around 250 bps) up to DR7 (FSK, 50 kbps), depending on the spreading factor and bandwidth. The maximum transmit power is usually +16 dBm and transmissions are subject to a 1% duty-cycle limit to comply with European spectrum regulations. In contrast, in the United States, LoRaWAN operates in the 902–928 MHz ISM band under FCC rules. Here, 64 channels with 125 kHz bandwidth and 8 channels with 500 kHz bandwidth are defined for data uplink, and 8 downlink channels (500 kHz) are used. Data-rates range from 125 kHz (around 980 bps) up to 500 kHz (around 21.9 kbps) with transmission powers up to +30 dBm. [53] This information highlights the trade-off between range and throughput so that the sub-GHz bands provide longer communication distances, while the 2.4 GHz band offers higher data-rate and efficiency under dense network conditions.

4.1. Standards and Regulatory Frameworks of LoRa

LoRa operates within the Low-Power Wide-Area Network system and is standardized under the LoRaWAN protocol, which defines the network communication layers above the physical modulation layer. The LoRa Alliance, a global non-profit organization founded in 2015, which maintains and develops the LoRaWAN specifications to ensure interoperability and consistency between devices, gateways and network servers [51]. From a regulatory perspective, LoRa operates in unlicensed industrial, scientific, and medical radio bands. The specific frequencies vary by region according to local telecommunications authorities. This is typically 868 MHz in Europe, 915 MHz in North America and 433 MHz in some parts of Asia [53]. These frequency allocations follow regional regulatory frameworks defined by organizations such as ETSI (European Telecommunications Standards Institute) in Europe, the FCC (Federal Communications Commission) in the United States and the ARIB (Association of Radio Industries and Businesses) in Japan. Each region also enforces power output limits and duty-cycle restrictions to prevent interference with other radio systems.

In addition to spectrum management, compliance with LoRaWAN certification programs which are continuously updated for security reasons and better performance [51], ensures that devices meet technical performance and security standards. These frameworks enable the global interoperability of LoRa networks and support their deployment in diverse applications including smart cities, agriculture, and industrial monitoring, in which low power, long range, and cost-efficient communication is essential.

4.2. Potential Applications of LoRa in Mining

In case of monitoring for long-term trends, for equipment or structures that have a long lifespan and are not subject to rapid wear or failure, periodic monitoring can be adequate. Therefore, there is no requirement to transfer significant amounts of data. This might include structural health monitoring of mine infrastructure such as buildings, tunnels, and large machinery. In such cases, sensors might only need to send data at regular intervals (daily, weekly, or even monthly), reducing the volume of data transmitted.

In the mining industry, the implementation of digital monitoring and communication systems must be reliable, long-range to transfer data with the constraints of underground environments, energy efficiency, and cost. LoRa technology, which is characterized by low power consumption, extended transmission range, and robustness against interference offers an ideal solution for many applications that do not require high data throughput but demand reliable, continuous, and energy-efficient connectivity.

Geotechnical health monitoring: This is one of the primary fields of applications. Mines contain extensive infrastructures such as tunnels, shafts, slopes, and storage caverns, whose structural stability must be ensured throughout long operational time. LoRa based wireless sensor networks can monitor parameters like rock displacement, ground pressure, or vibrations. Since structural deformation evolves slowly, sensors can transmit data intermittently (e.g., every few hours or once a day) [54]. This can be executed as a multi-year monitoring with battery-powered devices and sensors. This approach provides valuable analysis for early detection of instability while minimizing data volume and power requirements. LoRa's low data-rate is well suited to geotechnical and environmental monitoring applications as the systems transmit infrequent, low-volume measurements. Low frequency bands provide better penetration through rock and obstacles compared to higher frequencies, making them optimal for underground use-cases [54]. This implementation plays an important role in preventing geotechnical failures by detecting early signs of deformation or instability in rock masses and support systems. In the context of LoRaWAN based IIoT systems, structural monitoring enables long range, low-power, real-time monitoring of structural parameters for predictive maintenance and enhancing safety, efficiency and sustainability of mining infrastructures.

Environmental and safety monitoring: LoRa networks can also support distributed sensors that measure the environmental parameters such as gas concentrations (e.g., methane, CO, CO_2, H_2S), temperature, humidity, etc. in underground and surface operations. Given that LoRa signals can propagate through the rock structures and around obstacles, the technology ensures coverage even in deep or spatially complex areas. The sensor used in this field typically transmits small data packets of tens of bytes per message in the intervals ranging from minutes to several hours, depending on the criticality of the parameter being monitored. This corresponds to effective data-rates of approximately 0.3 kbps and 50 kbps, consistent with LoRa's typical bandwidths of 125 kHz to 500 kHz [53]. Periodic transmission of environmental data allows continuous compliance with safety regulations and supports early hazard detection without the need for high-bandwidth communication infrastructure. Hydrological and tailing monitoring represents a critical use-case in modern sustainable mining. LoRa-enabled sensors can measure groundwater levels, chemical parameters in tailings dams or drainage systems. Given the slow changes of such processes, periodic data collection is sufficient while ensuring continuous surveillance and compliance with environmental regulations.

Equipment and asset monitoring: Condition monitoring of the mining equipment and assets can also benefit from LoRa. In non-critical situations and systems such as ventilation fans, pumps, conveyors, hydraulic systems, etc. low-frequency monitoring of operational parameters (e.g., vibration, pressure, or motor current) can help detect early signs of wear and optimize maintenance intervals. LoRa's low energy consumption allows sensors to be deployed in remote or inaccessible areas, enabling predictive maintenance strategies with minimal operational disruption. Due to the low energy consumption of LoRa end devices, typically 10–50 mA in transmission mode and below 10 µA in sleep mode battery-powered sensor nodes can operate for several years (often up to 10 years) [54] without maintenance, even in harsh underground environments. This enables predictive maintenance strategies that minimize downtime and improve equipment reliability while reducing operational costs. With its data-rate ranging from about 0.3 kbps to 50 kbps [53] and transmission ranges exceeding 1000 m underground [55], sensors can effectively detect early signs of mechanical wear or malfunction. By using LoRaWAN, it is not necessary to install many relay nodes every 10 to 50 meters, as required in short-range communication systems like Wi-Fi mesh networks. LoRa signals are capable of traveling over hundreds of meters up to several kilometers and they can even propagate through rocks, making the technology suitable for condition monitoring of equipment and infrastructure in mining environments.

Inventory and personnel tracking: Using LoRa-based systems to track the personnel or inventory offers a cost-efficient and energy-saving option, especially where centimeter-level localization is not required. In contrast to 5G or Wi-Fi, which provide high data-rate but demand dense infrastructure and higher power consumption, LoRaWAN enables long-range tracking (typically over 2 km underground and up to 15 km on the surface) with minimal bandwidth usage, which is often transmitting a few bytes of data every few minutes or hours. Each LoRa tag or node can operate on a battery for several years, depending on transmission frequency and signal strength, making it suitable for monitoring tools, vehicles, and workers in large-scale mining environments where maintenance access is limited. Data packets typically contain only device ID, timestamp, and signal strength (RSSI) information, requiring less than 50 bytes per message, which fits well within LoRa's maximum capacity [54,56].

4.3. Limitations of LoRa in Mine Operations

While LoRa offers the mentioned benefits for mining environments, its application in complex mine operations is constrained by several technical and environmental limitations. One of the primary challenges is the network reliability and signal propagation in deep underground or heavily reinforced mining structures. The mining environment presents many obstacles such as rocks, tunnels, machinery and even water which create significant reflections, shadowing and multi-path effect [24]. The reliability of LoRaWAN communication in underground mines is not studied well in detail yet and the LoRa connection can also fail during emergencies or when there are long delays in data transmission. Data-rate limitations cause another critical restriction. LoRa's physical layer supports the data-rates typically up to around 50 kbps in ideal conditions (and much lower under high spreading factors, although this increases the signal's robustness and range) [57]. LoRaWAN's low data-rate and uplink capacity are inadequate for use-cases that require real-time monitoring and telemetry. The reason is that it cannot deliver data with the low latency and consistent timing (bounded jitter) required by such applications. Even for a very small packet (e.g. 10 bytes) and the fastest spreading factor, the transmission time is around 40 ms [57]. Real-time industrial control systems need response times of 1-100 ms [57], so LoRaWAN is too slow even under ideal conditions. Therefore, in real-time device monitoring or in emergency cases, LoRa's low bandwidth becomes a bottleneck.

Another factor that affects LoRaWAN performance is the scalability and collision risk in dense sensor deployments challenging mining applications. The packet delivery ratio decreases significantly when many end-devices transmit in the same frequency channel or at similar spreading factors [58]. In an underground mine where many sensors may operate, the risk of channel collisions and gateway overload increases. In a performed simulation of 6000 nodes over a 10 km radius, clustering nodes were required to achieve a packet delivery ratio over 90% [58]. Duty-cycle and regulatory constraints further limit performance. In the European ISM band, for example, devices often must adhere to duty-cycle limits (e.g., 1% maximum transmit time) [57]. Such a restriction limits how frequently sensors can transmit, delaying time-critical data and reducing responsiveness for hazard situations.

As mentioned above, latency of data transfer is an additional issue. Mining safety systems often require guaranteed communication within time bounds (e.g., for real-time ventilation control, personnel evacuation, autonomous machinery coordination, etc.). LoRaWAN uses an asynchronous ALOHA-based access protocol (in which each device or node just transmits its message whenever it has data to send without checking if the channel is free or busy), which can cause unpredictable delays and lacking real-time frameworks and even data loss [24]. As a result, LoRa may not be suitable for time-critical safety operations without supplementary network architecture.

Installation and coverage of the signals underground also affect LoRa effectiveness. Although sub-GHz bands provide better penetration in rocks than higher frequencies, the profile of mine still presents extremely challenging environments due to signal attenuation.

5. Discussion

The digitalisation of mines requires communication technologies and systems that can deliver data reliably and expand its scalability and offers energy efficiency under harsh environmental conditions. Both LoRa and 5G technologies offer complementary advantages in this case, each presenting critical limitations that influence their applicability in different mining operations. Low-power wide-area capabilities of LoRa make it suitable for those applications, which require long term monitoring with small data exchange, such as structural health, geotechnical issues and environmental monitoring. Its ability to penetrate rock structures and maintain communication across extended distances provides advanced benefits not only for open pit mines but also for underground applications. However, its limited bandwidth (ranging from 0.3 to 50 kbps [53]) and duty cycle restrictions (1% [57]) under EU regulations avoids real-time data transmission or high-throughput tasks such as video streaming or autonomous vehicle coordination.

In contrast, 5G networks provide ultra-reliable low-latency communication and enhanced mobile broadband, which are essential for real-time control, collision avoidance, and remote operation of heavy machinery. Nevertheless, its high frequency transmission leads to severe diffraction and attenuation losses, making underground operation challenging without costly infrastructure such as repeaters, optical fiber infrastructures or mesh relay networks. Furthermore, 5G base stations and active antenna units consume significant power, posing energy efficiency and thermal management concerns in enclosed mine spaces.

Hybrid Communication: Despite mentioned advantages of each technology, neither technology alone can satisfy the full range of communication requirements present in complex mining environments. A promising direction is the hybrid communication architectures that combine LoRa and 5G to take advantage of their strengths. In such systems, LoRa can manage low-frequency, low-data-rate sensing tasks (e.g., environmental or equipment condition monitoring), while 5G handles time-critical and data intensive operations such as high resolution video transmission and predictive maintenance analytics. A hybrid approach improves not only network resilience but also can reduce energy consumption by delegating tasks according to data rate and latency demands.

A hybrid multi-sensor platform is developed and tested in Aachen, Germany. The combination of 5G and LoRa communications demonstrated for an intelligent task allocation between two layers to optimize overall network performance was validated successfully [59]. Low frequency or non-critical data were transmitted via LoRa, while time-sensitive or high-volume information, such as ventilation dynamics, emergency signals or was routed through 5G. It is also explicitly mentioned that the proposed hybrid 5G-LoRa multi-sensor platform supports secure over-the-air software update, which is primarily done via 5G connection [59]. This selective data routing reduces transmission overhead, minimizes energy use, and maintains the responsiveness needed for safety-critical operations in complex environments such as mines.

In practical mining deployments such hybrid solutions enable a clear separation of data traffic, where LoRa supports battery life, distributed sensor nodes, while 5G serves mobile machinery, real-time control and safety critical actuation.

While significant progress has been achieved, several technical and operational challenges remain. The integration of different wireless systems still suffers from the absence of harmonized interoperability, inconsistent quality of service and cybersecurity risks. Moreover, efficient utilization of communication technologies and long-term reliability under harsh mining conditions remain as limitations for large-scale implementation. Further progress will require developing energy-efficient communication protocols that can be automatically adjusted to changing network structures and interference conditions. Emerging technologies such as edge intelligence, self optimizing networks, and digital twin monitoring could play a crucial role in addressing these limitations. Finally, the realization of resilient, adaptive, and intelligent communication infrastructures will be necessary to enable the vision of sustainable and human-centered mining within the framework of Industry 5.0.

6. Conclusions and Outlook

In conclusion, mining operations require resilient, energy-efficient and appropriate communication systems for diverse use-cases. While 5G and LoRa each have their strengths and weaknesses, their combination offers a robust pathway toward a fully digitalized mining environment. LoRa's long-range, low-power profile makes it ideal for monitoring applications where high throughput is not required. Meanwhile, 5G with its low latency and high data-rate is appropriate for autonomous machinery, video streaming (even with high-definition) and critical communication. Utilizing each technology to its best-fit use-case allows mining operations to optimize the cost, reliability and performance. Overall, a hybrid approach using LoRa for widespread sensor coverage and 5G for concentrated high-data channels provides a scalable energy efficient and resilient communications for the mines of the future.

Future work can reference detailed architecture for hybrid 5G-LoRa systems, including functional blocks (edge analytics, data governance, security, etc.), interface standards (MQTT/OPC UA) and processes such as configuration, monitoring and updates. Comparative methods are also needed common simulation scenarios, channel and traffic models to enable reproducible evaluation across studies.

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