FUTURE X FOR INDUSTRIES:CONNECTIVITY SOLUTIONS FOR DIGITAL MINING*

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Abstract

We are at the beginning of an era of profound transformation and human progress — a new industrial revolution. This “Automation of Everything” era will be brought about by digital interfaces, data analysis and control of the physical world through networks employing the Nokia Bell Labs Future X1 architecture — networks to support the digitization and connection of everything and everyone with the goal of automating much of life. The interconnection of robots, machines, drones, sensors, processing platforms and people through Future X networks will provide transformative tools for the automation and optimization of factories and warehouses, ports, electric grids, transportation networks, food, healthcare, construction, logistics and supply chain, emergency response, mining, and other physical industries. To date, the level of automation has been modest at best. Automating these physical industries — industries that account for 70 percent of the US Gross Domestic Product, for example — has the potential to drive significant increases in the world’s economic productivity.2 Realizing the potential of this next industrial revolution will require billions of wirelessly connected endpoints for high fidelity physical-to-digital conversion, millisecond response times to tightly control and coordinate machines and robots, and intelligent analysis to optimize real-time decisions — tasks beyond the reach of current networks. Increased levels of automation are already being achieved through the use of 4G advanced wireless access technologies. The untethering of sensors and actuators in industrial environments through the low-latency, high-bandwidth, high-reliability, and massive scale provided by 5G wireless access will complete this evolution, providing an unprecedented ability to digitize, analyze, comprehend and manipulate the physical world at a scale never previously thought possible. These new capabilities will enable us to create digital models of the physical world with ever higher levels of fidelity, further enhancing our ability to improve operational efficiencies and increase productivity and worker safety. Doing this will require a dramatic evolution in network architecture toward massively distributed cloud control and baseband capacity to achieve the required ultra-low latency and ultra-high bandwidth for industrial and infrastructure automation services — the Future X architecture. In early 2019, Nokia Bell Labs will publish a sequel to “The Future X Network: A Bell Labs Perspective”. “Future X for Industries: A Nokia Bell Labs Perspective” will explore how the Future X architecture will automate many of the world’s physical industries, including chapters devoted to electric power, cities, rail, mining, public safety, manufacturing, ports, logistics and supply chain, and an overarching chapter devoted to securing this highly automated world. To give you a small taste of the feast that’s to come, we’re sharing with you an initial installment — “Future X for Industries: Mining” — the Nokia Bell Labs view of how mining will be transformed through a Future X architecture..

Keywords: Technology (;)Connectivity (;)Industries4.0 (;)Critical-Mission.

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1 INTRODUCTION

The very existence and lifestyle of humans in today's world is made possible by minerals. We rely on minerals to satisfy our most basic human needs including shelter, clothing, food, transportation, energy, communications and health. For instance, an average car consists of more than 1,000 kg of steel, 25 kg of copper, and 140 kg of aluminum, and there are well over a billion cars running on roads worldwide. Over the past two decades, continuous advances in automation have more than doubled production at mines to meet the huge market demand for minerals such as iron ore. The amount of crude iron ore and coal extracted worldwide today exceeds 3 billion and 6 billion metric tons per annum, respectively, and mining generates more than $500 billion in revenue for the top 40 companies in the industry.

In a strong economy, the mining industry benefits from an insatiable demand for minerals. When economic conditions are favorable, mining productivity is primarily limited by bottlenecks in mineral production or in the supply chain. Despite high demand, however, the industry is subject to volatile fluctuations in commodity prices due to temporal uncertainty in demand for individual minerals (or metals). The industry is also plagued by excessive operational costs and capital expenses (e.g., as high as $1m per worker, $6m per haulage truck). These factors encourage the mining industry to look for much higher efficiencies. In addition, the hazardous nature of mining environments, which are characterized by dust, the use of high explosives, extremely high temperatures and moving heavy equipment, encourages greater emphasis on worker safety.

The need for continuous improvement of safety, productivity and efficiency has created an unprecedented demand for digitizing, automating and optimizing all aspects of mining operations from pit-to-port, placing the mining industry at the cutting edge of industrial automation in the 21st century.

In the future, we envision mining operations that are free from injuries or fatalities, employ just-in-time productivity to deliver tonnage on demand and provide 100x improved efficiency (cost incurred per ton) relative to current operations. Four essential elements are required to realize this vision:

1. **Extreme autonomy:** Achieving the desired goals of safety, productivity and efficiency in mining will require replacing all manual mining operations — exploration, drilling and blasting, digging, loading, hauling, crushing and transportation — with fully autonomous systems. This transformation will enable an extreme degree of autonomy in mining operations. Autonomous equipment and systems can function 24/7 in a predictable manner, ensuring safety to human workers or machines and maximizing equipment lifetime. Higher levels of autonomy have the additional benefit of reducing expenses associated with ventilation and other processes needed to support human workers operating in hazardous mining environments.

2. **Mission-critical network:** As mining operations evolve to incorporate hyper-scale sensing and extreme autonomy, a mission-critical network that provides at least five 9s (99.999 percent) availability will become the essential anchor that provides rich connectivity among sensors, machines and humans. This ultra-reliable network needs to provide connectivity for massive numbers of fixed and mobile sensors, precision localization and tracking of humans and machines, seemingly infinite capacity for near-real-time backhauling of data and low-latency remote control of equipment. The network needs to be rapidly reconfigurable to adapt to changes in mine operations. Self-organizing capabilities will be needed to ensure the network adapts to changes in the terrain caused by blasting while also healing itself from any failures of equipment.

3. **Augmented intelligence and cognitive operations:** In the future, mining will not only leverage the mechanical advantage of automated equipment but will also gain a cognitive advantage in all stages of operations including exploration, production and transportation. In each of these stages, massive amounts of data are collected and analyzed. Hyper-scale sensing allows the physical world of mining to be virtually represented using its digital twin, or

replica in the digital world, allowing problems or anomalies in operations to be proactively detected and the impact of remedial actions to be instantaneously validated prior to implementation.

Data collected from a vast multitude of sensors below and above ground, with the help of a mission-critical network, allows miners to improve safety and optimize operations across pit, rail, and port by gaining near-real-time visibility and identifying potential bottlenecks at every step of the process. Leveraging advances in augmented human and machine intelligence, miners can dynamically track assets and deploy them on demand, perform predictive maintenance on equipment, ensure the health and safety of personnel, and deliver just-in-time productivity (i.e., tonnage on demand) with extraordinarily high efficiency.

4. **Virtual telepresence and action at a distance:** In a mining environment, equipment stoppages may occur for safety reasons or due to failure of equipment. In such scenarios, it becomes essential to enable a human operator to take control of equipment remotely and command it to perform certain actions (action at a distance). In the future, as the mission-critical network evolves to support virtual or augmented reality (VR/AR) and low-latency control, it will be possible for a human operator to gain 360° situational awareness and remotely operate machinery from the safe confines of a command center across the globe.

A major digital disruption in mining is about to take hold where augmented human and machine intelligence drive higher order automation to create economic value. With these essential elements in place, the mine of today will be digitally transformed to a fully integrated and highly automated mining paradigm where augmented cognition delivers continuous improvements in safety, productivity and efficiency.

2 The past and the present

Mining has been practiced since the dawn of early civilization when metals or minerals such as flint were extracted to make tools. Over time, the quest for automation began as people searched for more efficient methods of large-scale mining. The ancient Romans developed hydraulic mining techniques using aqueducts to deliver water to wash away the rock and soil, or overburden, covering a body of ore. Open-pit mining later gained popularity in medieval Europe due to the growing demand for iron, copper and precious metals such as gold or silver. The American and Australian gold rushes during the 19th and 20th centuries stimulated mining for coal and other base metals such as copper, lead and iron creating a burgeoning mining industry on those continents.

Open-pit mining is typical in areas where minerals are found close to the earth’s surface. In this form of mining, commonly practiced in remote areas, the ground is blasted to create a large crater or pit from which ore is extracted. With years of blasting and digging, open-pit mines can grow to be several hundred meters deep and several kilometers across. In areas where ore veins run much deeper, underground mines are prevalent. Underground mining involves the construction of a network of underground tunnels that provide access to ore veins from the surface. Underground mines can be much deeper than open-pit mines and can have several thousand kilometers of underground tunnels with road or rail access.

Throughout history, miners have looked to improve safety and gain a mechanical advantage through automation. Early tools were replaced by heavy machinery that performed tasks such as drilling, digging, loading, hauling and crushing. While most of these machines are manually operated today, some mining companies have begun taking steps to incorporate semi-autonomous or autonomous drills and haulage via autonomous trucks and trains, to gain further benefits in safety, productivity and efficiency. A recent example of such automation is in the open-pit iron ore mines of the Pilbara in Western Australia, where autonomous trucks are used to ensure 24/7 safe operations and have provided upwards of 15 percent gain in productivity and efficiency with autonomous haulage in place for just 20 percent of the operations. [4][5]

The challenges of safely and efficiently extracting large amounts of ore from the ground apply quite broadly to both open-pit and underground mines. However, underground mines pose some additional challenges, including precision geolocation of equipment and personnel, navigation through tight spaces and the need to closely monitor structural integrity, water, gas and radiation levels. While the following discussion is mainly described in the context of open-pit mining, much of it applies broadly to underground mining as well.

3 Current mining operations

The search for a new mine site always begins with exploration for ore deposits. The exploration process is extremely time consuming and involves analyzing massive amounts of data to build a business case for a mine site that is expected to be in operation for a few decades. Once exploration is complete and an open-pit mine site is created by drilling and blasting, production processes commence to extract ore from the ground. The supply chain for open-pit mining spans the pit and its associated industrial plant, rail for transporting ore to the port and the port itself where ore is loaded into ships bound for their destination. Processes at the pit include digging the ground to extract ore-laden dirt, loading it onto trucks, hauling it to crushers where ore is separated from waste, stockpiling processed ore at the mine site and loading ore onto freight trains running between the mine site and the port. There are many sources of bottlenecks in this pit-to-port supply chain resulting in loss of productivity and efficiency.

The scheduling of all production processes and autonomous trucks is carried out from a remote operations monitoring and command center provisioned with high-bandwidth fiber connectivity across long distances to remote mine sites. The advantage of locating a remote operations center in a major city is the ability to gain visibility and manage operations across multiple mine sites with easy access to skilled expertise when problems need to be addressed.

Most of the operations today are manual requiring miners to function in hazardous environments where they are exposed to huge amounts of dust, extreme temperatures and moving heavy machinery. Furthermore, the costs of manual operations are high. To reduce these expenses, some mining companies have introduced semi-autonomous or teleoperated drills. Human operators of this equipment rely on multiple video camera feeds to guide them. In addition, autonomous trucks have recently been introduced for haulage at mine sites, and autonomous trains have also been introduced to ferry ore between the mine sites and the port. Autonomous trucks can make repetitive runs continuously during day and night, thus there is no need to subject drivers to long hours of repetitive driving where they could get easily fatigued or exposed to large amounts of dust.

Open-pit mine sites, such as those employed for iron ore and copper, are huge sprawling areas with mission-critical communications requirements for both personnel and machines for improving safety, productivity and efficiency. There are requirements for extensive monitoring in mine pits, on rail and in ports for safety reasons, as well as to optimize use of equipment. Reliable wireless coverage is required for the safe operation of autonomous and manually operated equipment such as diggers, haulers and drills throughout mine sites. Multiple disparate networks are currently used to provide wireless services at mine sites:

- Land Mobile Radio (LMR) technologies based on TErrestrial Trunked Radio (TETRA) and Project 25 (P25) for Push-to-Talk (PTT)
- Wi-Fi for local enterprise connectivity and for the support of mission-critical operational technology
- Commercial service from wireless operators for handheld devices such as smartphones and tablets.

In addition, some mining companies are deploying private networks based on 3GPP LTE standards to support their operations and are also considering the use of low-power wide area network technologies for sensor connectivity.

4 The case for LTE in mining

Currently, Wi-Fi technology is often employed to support the automation needs within mines, primarily due to its ability to operate in unlicensed spectrum. This approach, however, often encounters several problems that degrade the productivity and efficiency of operations:

1. **Reduced downtime and personnel expenses**: Due to the range limitations of Wi-Fi, a rather large number of trailer-mounted access points (in the range of 100–200 for a typical mine site) is needed; whereas the same area could be covered by fewer than 10 LTE macro cells. Since solar panels are typically used to power cells or access points in open-pit mines, higher solar panel maintenance costs are incurred for Wi-Fi since solar panels need to be cleaned often (to improve photovoltaic efficiency) at a much larger number of site locations. Also, Wi-Fi access points cannot be deployed inside blast zones and must be relocated whenever blasting needs to occur. Wi-Fi access points may be moved around as often as up to five times a week, and new site planning is required each time to ensure coverage for mission-critical operations. The movement of trailers results in downtime for mine operations and requires more personnel, which incurs costs and exposes additional personnel to safety hazards. In contrast, LTE does not incur similar overhead in downtime or cost since macro cells may be deployed in fixed locations around blast zones while still providing coverage inside blast zones.

2. **Reliable operation with mobility:** Handoffs with LTE are much more reliable since the system is designed to handle mobility. If any loss of connectivity occurs (as is often the case with Wi-Fi), autonomous vehicles stop to ensure safety. This gradually snowballs into mine-wide stoppages of vehicles and production, requiring manual intervention before operations can be restarted. With LTE, such stoppages are avoided, leading to increased productivity.

3. **Narrowband internet of things (NB-IoT):** In addition to connectivity for vehicles, there is a need to wirelessly report data from a huge number of sensors deployed on vehicles, in machinery, and in fixed locations throughout the mines. LTE supports NB-IoT, which is specifically designed to support short packet access, long battery life (up to 10 years) and extended coverage with these sensors.

4. **Mission-critical PTT:** Currently, workers at mine sites rely on LMR technologies such as TETRA or P25 to fulfil their mission-critical PTT needs. However, LTE already supports mission-critical features such as PTT, broadcast and pre-emption. Quality of service (QoS) support allows all these services to be carried over a common network. In addition to mission-critical voice, LTE can also provide site-wide connectivity for workflow automation (e.g., remote access to instruction manuals for equipment diagnostics or repair).

5. **Video on demand:** In the future, there is a need for high throughput to support on-demand uplink and downlink video (e.g., for drills, drone inspections and teleoperated vehicles), and it is impractical to deploy Wi-Fi access points at every location where monitoring may be required. The evolution path from LTE to 5G cellular provides built-in capabilities, such as multi-antenna support, carrier aggregation and multi-connectivity, that allow a plethora of network resources (including Wi-Fi) to be leveraged in meeting the capacity needs for video.

In addition to operations in unlicensed spectrum, mining companies either own licensed spectrum or can lease spectrum from operators in remote regions where they operate. Furthermore, these remote regions are also not typically areas where there is a lot of wireless network infrastructure to serve broadband connectivity needs. These conditions make it particularly well suited for private network deployments.

Private LTE (with an evolution path to 5G) is an attractive option for the type of mission-critical network access needed within mines. It requires a much smaller number of sites (20x fewer sites) and 4x less personnel to move/maintain sites than Wi-Fi. In addition, private LTE provides ultra-reliable coverage with seamless mobility/handover, built-in support for a wide range of services, including PTT and IoT, and network slicing to dynamically handle different application demands. A simple analysis shows that reduced downtime with private LTE can yield savings in operational expenses of approximately €70m per mine site per year compared with Wi-Fi. It should come as no surprise then that private LTE is already being deployed in the mines in Western Australia, replacing current Wi-Fi deployments.

5 The mine of the future

The mine of the future needs to ensure safe operation for humans and machines, eliminating all injuries or fatalities and accidents involving machines. In a world where certain minerals cannot be extracted quickly enough, while the demand for others wane, the mine of the future should be designed for just-in-time productivity, delivering tonnage on demand with 100x greater efficiency than current operations. An improvement of this scale can only be delivered through massive functional automation with extreme autonomy and cognitive operations characterized by connected workers, remote operations, integrated platforms and ecosystems, and augmented human/machine intelligence derived from sensing, analytics and decision support. A recent study by the World Economic Forum estimates that the economic value created through such a transformation for the industry, customers and society can exceed $400bn. [6]

6 Extreme autonomy

Mine sites exist in the most remote reaches of the planet where it is extremely difficult and expensive to maintain a large workforce for manual operations. Conditions at mine sites are extremely hazardous with significant potential for injuries and fatalities. Excessive dust can lead to poor driver visibility or respiratory distress while extreme temperatures lead to the risk of dehydration. In addition, any failure to follow burdensome safety protocols can result in serious accidents.

Due to these factors, mining companies need to pursue a strategy of extreme autonomy, i.e., where all manually operated equipment including diggers, haulage trucks, crushers and trains are replaced with their autonomous counterparts. Taking advantage of mission-critical network connectivity, such as precision localization technologies (using global satellites and real-time kinematics), local sensing (cameras, radar, LIDAR), and software-definable operation,
autonomous equipment can safely and predictably run 24 hours a day, 7 days a week. This not only reduces the need for physical presence of human operators at mine sites but also maximizes equipment lifetime.

7 Augmented intelligence and cognitive operations

Sensing at massive scale allows the physical world of mining to be translated with high fidelity
into the digital domain where it can be analyzed, controlled and optimized to achieve the desired goals of safety, productivity and efficiency. This digital twin concept has been applied successfully in other industrial domains to prevent problems from occurring, reduce downtime
and plan enhancements. An analogous digital-twin approach in mining can be applied to proactively detect and solve problems in current operations while also aiding in planning enhancements for the mine of the future.

8 Hyper-scale untethered sensing

The entire mining supply chain, spanning the pit, rail and port, is akin to a large industrial plant. Numerous sensors are installed for dust and temperature monitoring, stockpile tracking, ore grade and provenance tracking, machine health monitoring, monitoring of rail (i.e., tracks, locomotives and ore cars), slope radar to track the movement and integrity of slopes, dewatering telemetry, status of ship loading at ports, driver fatigue monitoring, position reporting, and production process monitoring and control. While connectivity for many of these sensors has typically been provided using wired networks or Wi-Fi in the past, future operations must support 1,000x more sensors that are untethered, deployed over a wide area and, possibly, mobile.

9 Digital personal protective equipment

At mine sites, workers are typically required to wear personal protective equipment (PPE) to protect them from falling objects, chemicals and dust. The mine of the future will support digital PPE, which allows tracking the location of personnel and health monitoring, while accounting for any privacy concerns that may arise. Digital PPE may also be used in a geofencing application to regulate unauthorized access to hazardous areas where there is a danger of falling objects, heavy moving machinery, chemical spills or fallen electrical cables.

10 Optimized pit-to-port operations

Current mining actions tend to be reactive, the focus being on extensive data collection followed by manual intervention when problems are detected. In the mine of the future, the focus will be on proactive digital value creation through hyper-scale sensing, data analytics, augmented cognition and self-healing via autonomous control. By gaining near-real-time visibility into every step of the supply chain, miners can identify bottlenecks or under-utilized resources and re-deploy equipment at much faster timescales than previously thought possible. Operations can be optimized across all mining stages including exploration, production operations in the pit, rail transportation and port operations to ensure that inefficiency in one segment does not lead to the build-up of stockpiles somewhere else. Dynamic tracking of machine health and diagnostics allows predictive maintenance to be performed on equipment so that the lifetime and utilization of capital-intensive equipment can be maximized.

The mine of the future needs to be part of a connected ecosystem where data exchange with suppliers, partners and customers ensures that problems extending into other domains are suitably addressed and any impact to mining operations is minimized. Taking advantage of advances in augmented human and machine intelligence, and the availability of an ultra-reliable mission-critical network, the mine of the future can evolve to a model where any corrective actions may be taken autonomously, i.e., without manual intervention. This ensures that mining operations can be made self-healing. For example, the stoppage of an autonomous truck can trigger an automatic drone inspection, and operations may be automatically restarted once the root cause of the problem is identified and addressed. Another example of self-healing operation is when large rocks in the ore get stuck in a crusher, leading to its stoppage. In this case, upon detecting and diagnosing the problem from sensor data, a robotic hammer may be automatically deployed to break the rock into smaller fragments, and the crusher may then be automatically restarted without requiring any manual intervention by mine workers.

11 Virtual telepresence and action at a distance

In the mine of the future, there are several scenarios that can benefit from virtual telepresence at mine sites. One important use case is teleoperation where human operators remotely control machinery such as drills, diggers or trucks from a “virtual cockpit” located at a command center. Teleoperation may be further enhanced through use of haptic feedback, allowing human operators to use their sense of touch to perform precision operations. In such cases, the operator controls the vehicle by responding to visual feedback with commands, which requires very low latency from the mission-critical network.

In another use case, moving machinery or vehicles may cease to operate due to safety reasons or failure of equipment. These stoppages often cascade through the mine site, causing widespread bottlenecks that may result in complete shutdown. Current procedures require the dispatch of personnel to perform safety inspections before operations can be restarted; this is a slow process that can lead to several hours of downtime in operations. In such cases, it becomes essential to enable the 360° situational awareness that is necessary for action at a distance, i.e., where a human operator can remotely perform safety inspections, take control of equipment and command it to perform certain actions.

12 360° situational awareness

Certain equipment, such as teleoperated drills, is already equipped with multiple video cameras (typically four to six) to allow precision drilling. It is also important to equip vehicles, such as autonomous or teleoperated haulage trucks, with high-resolution video cameras that provide visual images of the drive route on demand. Cameras may be equipped for 360° visibility at any point on the horizontal or vertical azimuth. When equipment or vehicles stop, a drone may be dispatched to perform a reconnaissance flyover. It can provide high-resolution video for safety inspections and repair at the mine sites, on the rail lines or at the port. The use of VR/AR will not only enrich the experience for a human operator in a virtual cockpit, it will also greatly enhance safety and precision. For example, augmented reality may be employed to overlay obstacle detection on topographical maps. The ability to gain 360° situational awareness on demand ensures continuity of operations and resilience in the event of any disruption.

13 The mission-critical Nokia Bell Labs Future X architecture for mining

The mine of the future will require mission-critical reliability, bandwidth, low-latency and high-fidelity representations of physical mine assets in the digital domain. It will need to support a wide range of capabilities as summarized below:

1. Ultra-reliable operation with extreme autonomy across the entire supply chain, i.e., at mine sites, on rail and at ports
2. Communications from massive numbers of sensors on the ground, machines, vehicles and personnel
3. 360° situational awareness where bandwidth for video, virtual or augmented reality capabilities can be invoked on demand from ground, vehicle or drone-mounted cameras to enable teleoperation from long distances, remote safety inspections or root cause analyses.
4. Digital PPE allowing personnel health and safety monitoring including geofencing of unauthorized or unsafe areas
5. Near-real-time equipment, ore and personnel localization and tracking from remote locations for improved safety, productivity and efficiency
6. Field force automation with PTT capability and remote access to instructions for equipment diagnostics and repair
7. Pit-to-port optimization of mining operations and self-healing capability through augmented cognition based on data analytics and machine learning.

All of this can only be enabled with a mission-critical network and platforms that create digital value, driving best-in-class results in safety, productivity and efficiency. The future mission-critical network of the mine must support massive-scale access for sensors, machines and humans, a multi-access edge cloud for low-latency control and operational resiliency, and converged cloud-hosting network and service automation engines, augmented cognition systems and integrated remote operations management platforms.

The future mission-critical mining network must support converged wireless and wireline access with high-bandwidth fiber connectivity within and between mine sites and remote command centers that may be located thousands of miles away. Since many of the future mining connectivity needs are distributed over a wide area and require mobility, wireless networks based on the cellular technology evolution path from 4G to 5G are well positioned to handle the access requirements. Specifically, these technologies are designed to operate using licensed or unlicensed spectrum, already support the service requirements for voice, sensor data and video, and are now evolving to meet future bandwidth and latency requirements for VR/AR and real-time motion control.

The rapid turnaround required by future low-latency applications, such as real-time motion control or virtual reality, will be supported through a multi-access edge cloud platform (some teleoperations, particularly those that require visual or haptic feedback, require network latencies of 5 ms or less [7]). The edge cloud can also provide the local data storage and processing needed for a mine site to function by itself in the event of any loss of connectivity to a command center. Achieving “seemingly infinite capacity” for the mine of the future will require a smart tunable network fabric that integrates many of the modular virtualized access and core network functions needed to interconnect mine sites with each other and with remote command centers. This network fabric can be controlled using a programmable network operating system that is context-aware and adaptive, and leverages software-defined networking (SDN) in conjunction with network functions virtualization (NFV) to address the dynamically changing end-to-end needs of mining services.

The recently introduced concept of network slicing is especially important in the context of the mine of the future. Instead of overlaying disparate dedicated networks for PTT, enterprise connectivity and mission-critical operational technology, slicing allows the networking, storage and computational needs for all these services to be dynamically managed with a single mission-critical network.

The wealth of data acquired at different timescales from mine sites, rail and ports may be used in augmented cognition systems employing a wide range of machine learning and predictive analytics techniques to assess, control and optimize operations. The digital value created by these insights may then be reflected in actions taken by mining resource management platforms or exchanged within connected ecosystems through data brokering arrangements to create additional value.

14 Achieving 360° pit-to-port situational awareness

Achieving 360° situational awareness is critically important in the mine of the future since it enables on-demand telepresence to minimize supply chain disruption. The mission-critical network must rise to the challenge of meeting the excessive bandwidth (and latency in certain cases) demanded by video and VR/AR across the entire coverage area spanning mine sites, rail and ports. For example, a single teleoperated drill may require three or more full-resolution video feeds during operations (requiring data rates of up to 18 Mb/s or more); these requirements are only expected to grow as video resolution increases. Wireless capacity can be increased by adding more cells, more spectrum or more antennas (at each cell and potentially also jointly processed across cells). Densification with more trailer-mounted small cells is not preferred at mine sites since these trailers will need to be moved often as discussed earlier. More spectrum (licensed and unlicensed) and more antennas are better alternatives than densification in these locales. Adaptive bit rate (ABR) video coding can also be employed to adjust video resolution based on available bandwidth.

15 The future begins now

While the vision outlined here may seem somewhat futuristic, it should be noted that there are several access technologies already available or being developed in the 3GPP-based 4G to 5G cellular evolution path, such as PTT, NB-IoT, multi-antenna processing, carrier aggregation, multi-connectivity (allowing integrated operation with Wi-Fi), and unlicensed LTE (MuLTEfire), that can be leveraged in conjunction with new edge/core cloud and analytics capabilities in this transformation to the mine of the future. Connectivity for autonomous equipment (e.g., haulage trucks and drills), field force automation, sensors, digital PPE and connected and autonomous trains is already possible with 4G networks. For mining companies that already own spectrum licenses or operate in remote areas where interference in unlicensed spectrum is not a significant problem, private networks based on LTE are already possible, and in fact, are currently being deployed.

In the future, when site-wide 360° situational awareness needs to be enabled for personnel, vehicles and drones, additional spectrum is needed. In the US, there is an option to acquire additional spectrum in the 3.5 GHz band earmarked for Citizens Broadband Radio Service. Other high band options such as cm/mmWave spectrum (39 GHz/60 GHz) are also possibilities, especially since a strong line-of-sight signal component is available in many of the mining scenarios.

The stringent capacity and latency requirements posed by 360° situational awareness and real-time motion control also mark the beginning of the transition to 5G technology, which is currently under standardization and development. With the advent of 5G, the mining industry will suddenly be able to richly visualize and control their operations at a timescale never previously thought possible. 5G will enable new low-latency safety applications, augmented and virtual reality, precision robotics and control of cooperative drones, robots and machines. Procedures for automated network slicing will ensure that different applications can dynamically share network resources without ever being starved of capacity.

As the transformation to the mine of the future takes place, operations from pit-to-port will harness continuous improvements in safety, productivity and efficiency through enhanced mission-critical connectivity, control and augmented intelligence. When this future vision is realized, operations will be fully integrated and automated, leveraging the digital disruption enabled by the mission-critical Nokia Bell Labs Future X architecture for mining.

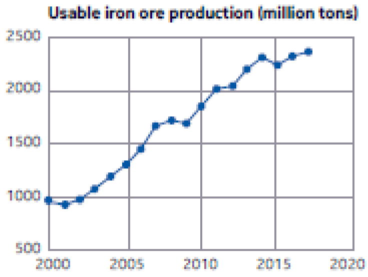
Figure 1. The importance of mining (Source: ILO [1], USGS [2][3])

>3 million
workers

~500 billion
revenue for top 40
mining companies

>6 billion
metric tons
of coal p.a.

>3 billion
metric tons of
crude iron ore p.a.



Lifetime mineral consumption of average newborn (kg)	
Lead	363
Zinc	340
Copper	680
Aluminum	1,630
Iron	14,832
Clays	12,043
Salt	12,797
Stone, sand, gravel and cement	561,593

Figure 2. The future of mining

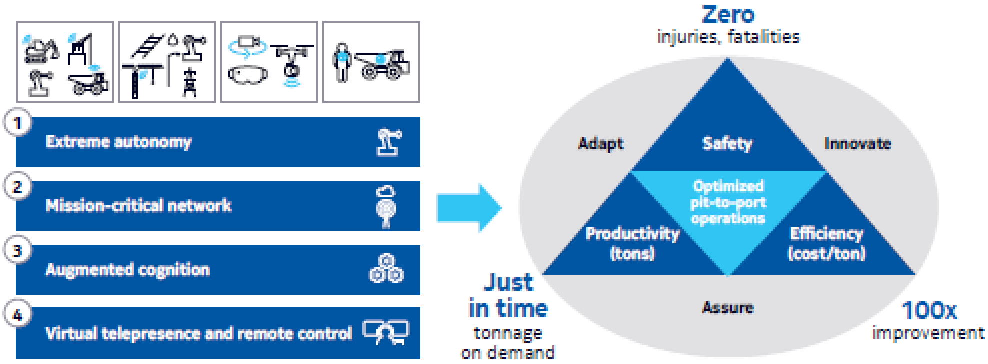


Figure 3. Current mining operations are distributed across the mine sites, rail and port, and they rely heavily on a mission-critical communications network

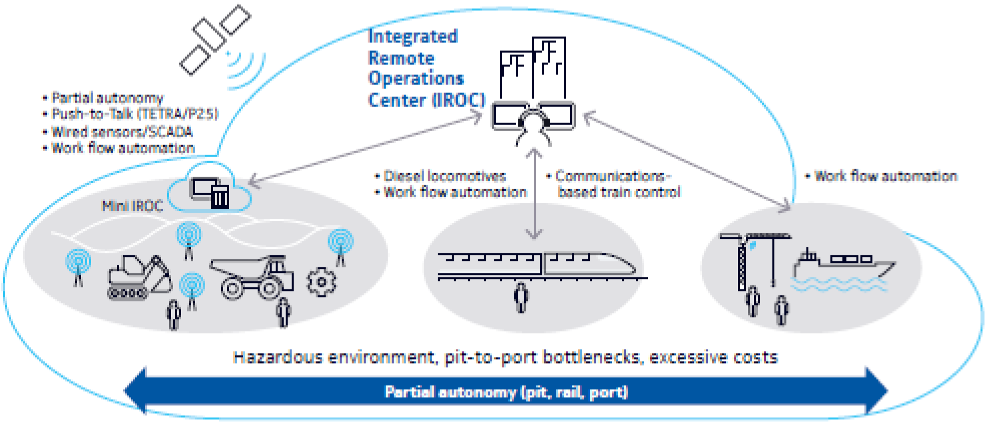


Figure 4. The case for private LTE in mining

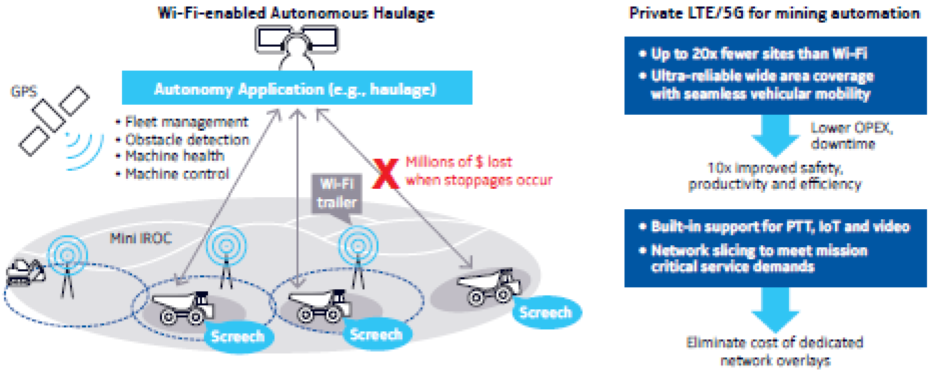


Figure 5. Economic value creation (2025 est.) by transformation to the mine of the future

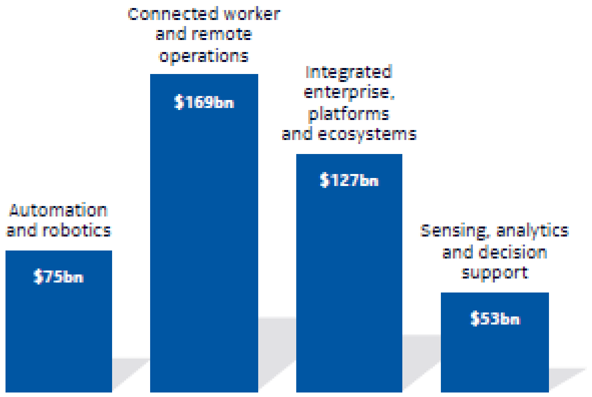
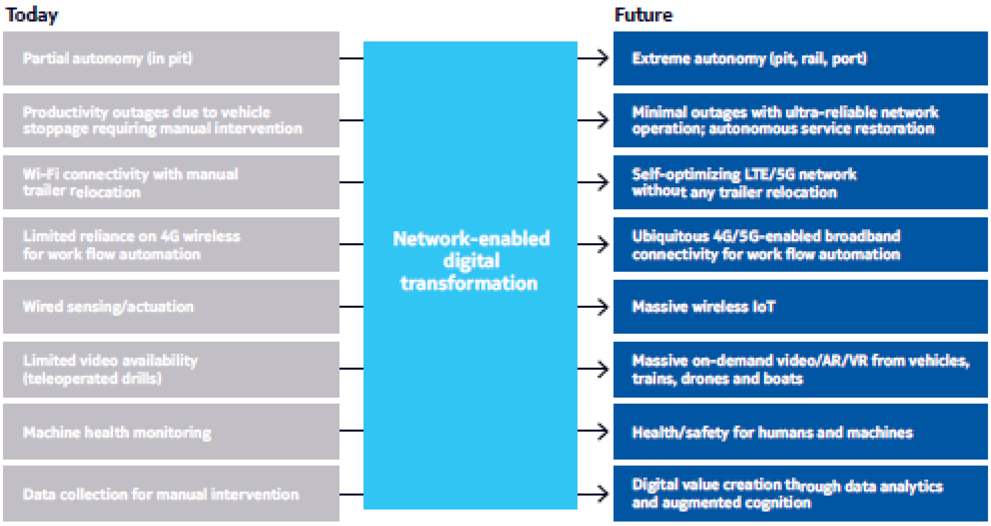
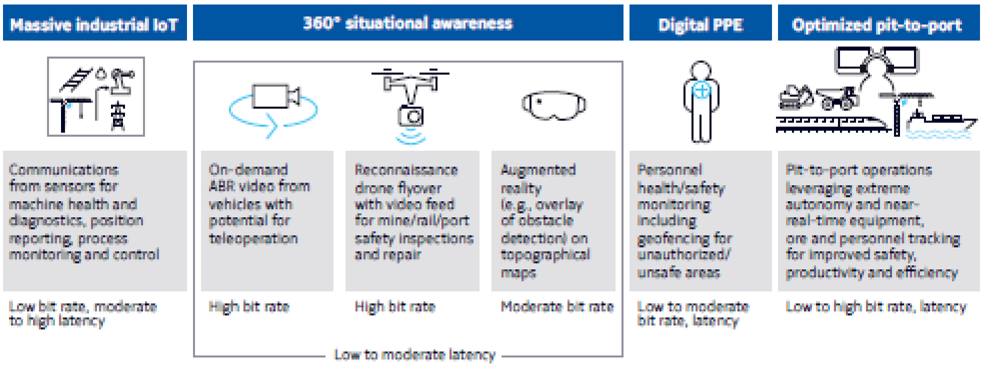


Figure 6. Applying network-enabled digital transformation to the mine of the future



Today	Future
Partial autonomy (in pit)	Extreme autonomy (pit, rail, port)
Productivity outages due to vehicle stoppage requiring manual intervention	Minimal outages with ultra-reliable network operation; autonomous service restoration
Wi-Fi connectivity with manual trailer relocation	Self-optimizing LTE/5G network without any trailer relocation
Limited reliance on 4G wireless for work flow automation	Ubiquitous 4G/5G-enabled broadband connectivity for work flow automation
Wired sensing/actuation	Massive wireless IoT
Limited video availability (teleoperated drills)	Massive on-demand video/AR/VR from vehicles, trains, drones and boats
Machine health monitoring	Health/safety for humans and machines
Data collection for manual intervention	Digital value creation through data analytics and augmented cognition

Figure 7. Services requiring mission-critical reliability, bandwidth, latency and digital-analog fidelity in the mine of the future



Massive industrial IoT	360° situational awareness			Digital PPE	Optimized pit-to-port
Communications from sensors for machine health and diagnostics, position reporting, process monitoring and control	On-demand ABR video from vehicles with potential for teleoperation	Reconnaissance drone flyover with video feed for mine/rail/port safety inspections and repair	Augmented reality (e.g., overlay of obstacle detection) on topographical maps	Personnel health/safety monitoring including geofencing for unauthorized/ unsafe areas	Pit-to-port operations leveraging extreme autonomy and near-real-time equipment, ore and personnel tracking for improved safety, productivity and efficiency
Low bit rate, moderate to high latency	High bit rate	High bit rate	Moderate bit rate	Low to moderate bit rate, latency	Low to high bit rate, latency
	Low to moderate latency				

Figure 8. Nokia Bell Labs Future X mission-critical network for mining

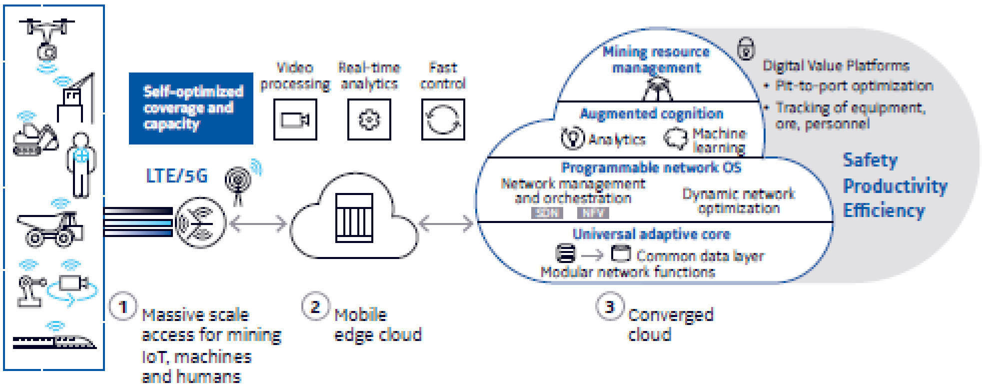


Figure 9. Achieving 360° pit-to-port situational awareness by meeting capacity needs of video on-demand, augmented or virtual reality

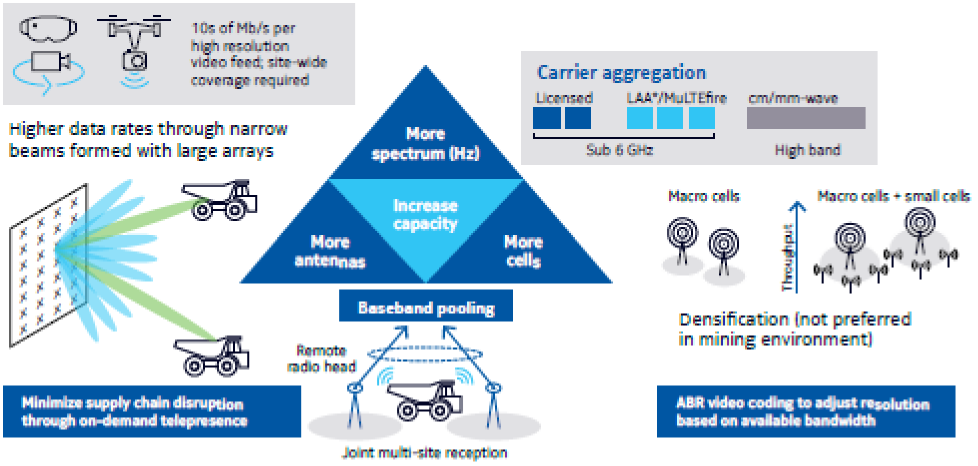


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Figure 10. Roadmap of 4G and 5G enabled applications for the mine of the future

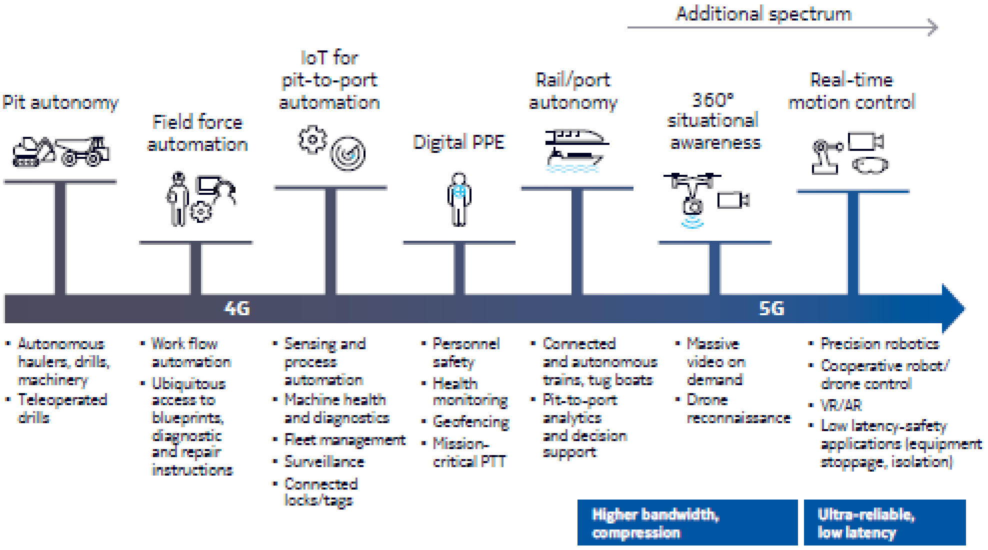
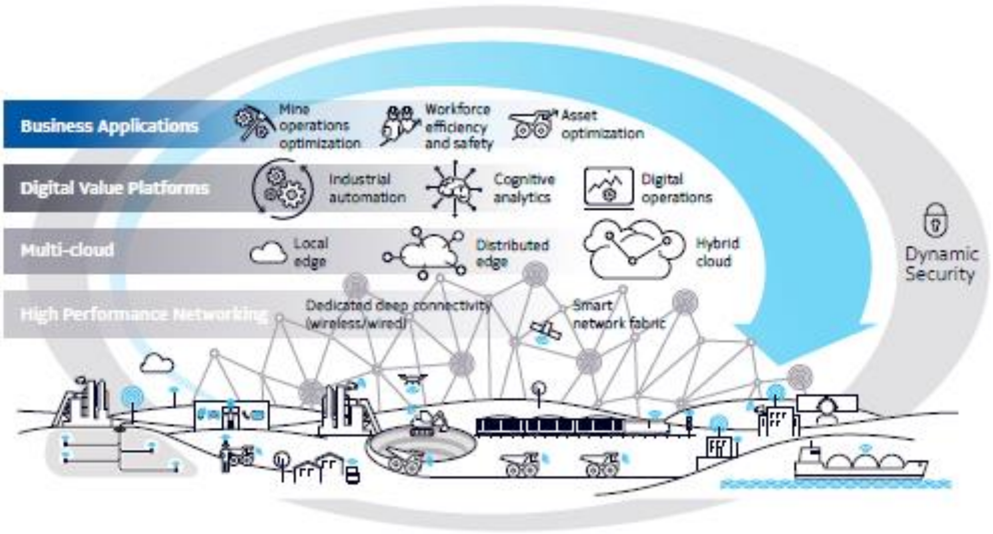


Figure 11. The Future X for industries mining architecture



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