The Anatomy of an Infrastructure for Digital Underground Mining

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Abstract: Over 41.6 billion IoT devices are expected to come online by 2025, collectively capable of generating 80 zettabytes (ZB) of data. Despite the relentless progress in adoption of smart devices occurring around all us - in our smart homes, our wearable devices, our smart cities and workplaces -, progress in the adoption of smart technology in the mining sector has languished. Yet the mining sector powers our energy systems and makes components for smart devices possible, while employing over 4.5 million people world-wide in some of the most extreme & hostile environments. This paper presents the design of a prototype industrial IoT platform for large-scale industrial automation of conventional mines.

1 INTRODUCTION

Mines in India are located in some of the country’s most remote and inhospitable areas. In these sites, poor digital connectivity leads to operational deficiencies on a wide range of issues, such as dangerous working conditions, loss and pilferage of products and low productivity. Situations like these prevail in mining operations across most low-income and developing countries in Latin America, Africa and Asia. To say that mining is a critical sector is an understatement. Large emerging countries still rely on coal mining to fulfil their energy needs - over 49.7% of India’s electricity demands come from coal. Moreover, mined materials are also needed to construct roads and buildings, build automobiles, and even make computers and satellites that power the modern economy - mining powers our modern civilization. However, mining is a dangerous business - the global mining sector collectively accounts for an estimated loss of 15,000 lives each year. More recently, several active working groups and committee set up by sovereign governments are accelerating the digitization of mines to make them more productive, sustainable and safer to operate. As a result, there is considerable pressure on the mining industry from the government in most emerging countries to accelerate the adoption of digitized mining practices. These initiatives collectively fall under the encompassing umbrella theme – advancing ‘Connected Mining’ (or Mining 4.0) adoption.

The 'Connected Mining' market is not entirely new – it is estimated to be worth USD 12.7 billion in 2022, growing annually by 13.3%. But, our current research focuses on digitizing the largely underdeveloped underground coal mine operation in emerging countries. In India, these mines number a total of 273 individual sites. Typically, a large mining company manages upwards of twenty such geographically distributed remote mining sites. A typical site may have 3-10 levels (or seams), typically covering an underground area of 1-4 sq. km. One way to conceptualize such a site is to consider that a mining facility sits atop several floors of the mining zone. Each floor is stacked one on top of the other like slices of bread, and they can cover an area as large as a small rural town.

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We aim to provide intelligent automation and connectivity to these remote underground mining sites.

2 MOTIVATION

Over 81% (2.53 million sq.km.) of India's vast mineral reserves remain untapped. Why? - Poor network connectivity in mines limits automated mining adoption in the industry. Moreover, the conventional, labour-intensive mining practice warrants that work in the sector is punishing and dangerous. It also consequently leaves vast portions of active mining sites unexplored and untapped. The main reason is that no technology existed that balanced - cost-effective deployment and adaptability to the dynamic nature of mining operations while operating through virtually impenetrable bedrock. Consequently, MineNet, a path-breaking subterranean mesh networking technology, was developed by researchers at IIT-ISM as a prerequisite connectivity fabric to enable cost-effective alternatives to connected mining solutions in the industry. The infrastructure detailed in this paper is the first generation of a comprehensive platform for autonomy in mining that emerged out of the MineNet initiative, under development at IIT-ISM.

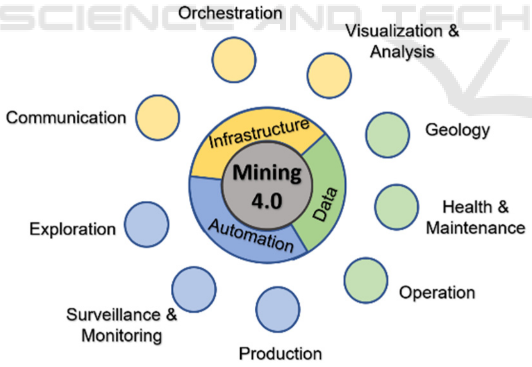


Figure 1: Capability Matrix of Mining 4.0.

The initial goal of this project is to improve mine safety and sustainability in remote Indian mines using recent advances in industrial automation and communication technology. Longer-term, we intend to leverage the inherent capabilities of emerging technologies like private 5G networks, AI/ML & robotics to advance mining practices, thus ushering in a new phase of accelerated adoption of digital technologies to augment the conventional approaches. The concept diagram in Figure 1 landscapes the capabilities the platform is eventually expected to support. The current release focuses on integrating advanced industrial IoT – Mining 4.0 – to enable real-time surveillance and tracking systems of equipment and personnel operating on a remote mining facility. While doing so, we assume we are also laying a foundation for open innovation on unexplored areas for advancement in autonomous mining - including visualization, robotic & drone-assisted systems in the future.

2.1 Concept Description

The presented system consists of two functional parts: an automation platform for large-scale deployment of autonomous systems and a wearable application platform to provide miners with real-time information about their environment. The project's initial focus is to address immediate challenges in mining safety and operational efficiency. Future platform generations are expected to evolve around learning models around accrued operational data and sensor telemetry, thus opening as yet unexplored avenues into AI-assisted use cases.

2.1.1 Distributed Automation

The system's core is a centralized orchestration platform that serves as the network operations nerve center for the entire site. Complementing the core system is a rapidly deployable off-grid mesh communications infrastructure designed to enable, among other things - collaborative mapping, texting, and emergency beaconing. The infrastructure is expected to permeate every nook and corner of the mine, providing ubiquitous connectivity for all miners. A family of field apparatuses complements the infrastructure to facilitate telemonitoring and teleoperation.

2.1.2 Wearable Computing

Central to this infrastructure is a wearable router to be carried by the field staff, which creates a mobile 'wireless bubble' hotspot around each individual. These bubbles are interconnected through a network of router devices forming a highly-resilient, robust, wireless spinal cord that spans the entire area of off-grid workspace. The infrastructure is a built around a novel long-range, low-SWaP (size, weight & power) short-burst wireless radio technology designed to network large off-grid areas (such as a UG coal mine), that are usually inaccessible through conventional telecommunication technology.

Beyond its original conception for interpersonal communication, the proposed mesh serves both people and smart devices (sensors & controllers) for applications including: location tracking, telemetry acquisition, search & rescue, surveillance & patrol planning and alerts.

2.1.3 Thing Computing

The aforementioned use cases are only a few exemplars conceived by our research team. By opening up the platform by delivering software development kits & hardware toolkits to the broader research academic community we are also concurrently developing several useful applications of digital mining that harness sensor networks, robotics, drones & predictive modelling to augment conventional practices in existing mining sites.

3 RELATED WORK

The adoption of contemporary industrial automation technology has reached an inflection point wherein, driven by the accelerated adoption and promise of AI/ML; the industry is transitioning to emergent models for large-scale automation. As such, although a large corpus of academic literature exists on industrial automation platforms, only a few address the challenges of large-scale distributed automation from a general-purpose, full-stack platform perspective (Chehida, 2022). Such generalization unintentionally ignores the practical element of usability in edge case conditions - like mine safety. Others explore theoretical paradigms - Ramachandran (2021) has proposed a software engineering framework for IoT and CPS, which can also be adapted for industrial IoT (IIoT) and Wireless Sensor Networks (WSN).

3.1 Automation Platforms

Recognizing that as industrial IoT has matured, more recent approaches to the problem take a domain-centric approach at its core leading to highly specialized solutions in healthcare (Said, 2021), smart cities (Meiling, 2018) and farming (Fruhner, 2019). Consequently, our design takes a human-centric approach to mining applications - putting the miner at the heart of the problem to explore novel ways to ensure his safety and alleviate the drudgery of his occupation while he operates in extraordinarily hostile and inhospitable environments. In doing so, we have designed a full-stack, turnkey platform purpose-built for the mining sector.

3.2 Communication Technologies

Underground coal mining operations fall under one of 4 categories: room-and-pillar, longwall, short-wall, and thick-seam. They differ in operational characteristics, but in all cases, personnel and machinery operate in tight and constrained compartments deep under layers of bedrock accessed through portals: drifts, slopes and shafts. Typically, vertical shafts may interconnect compartments with specific functional roles.

The proposed communication system that would operate in this environment would be a wireless, ad-hoc network for both interpersonal communication & telemetry in the future (eg: ground control, ventilation, haulage, drainage, power supply, lighting, and communication. These goals can only be achieved by using devices that are lightweight, durable, long-lasting and inexpensive. Moreover, the network must be decentralized for resilience and easy deployment and to support the mobility of mining personnel. Lastly, the network needs to cover as large an area of the underground mining network as well. Ramanathan (2005) explores the challenges of implementing such a network.

The ideal technology for these requirements is a radio device with a long range and the ability to multi-hop or mesh a network of such devices into a single self-organizing ad-hoc network. It must also be lightweight enough to be wearable. Existting solutions built around off-the-shelf technology (Wi-Fi, LTE, 5G, ZigBee, Bluetooth, LoRaWAN) fall short on one or more the following requirement criteria: low cost, decentralized, wearable, long-range, mesh network, low-cost, light-weight and requiring no public commercial infrastructure.

Our wireless router technology utilizes a proprietary WIFI-over-radio (WFoR), multi-hop, mesh-networking technology built over long-range radio (1-4 km), making it possible for anyone to create a reliable, off-grid, peer-to-peer, ad-hoc, communication network at will (Ramanathan, 2018). This proprietary radio technology makes it suitable for short burst radio communication for inter-personal texting, emergency beacons and transfer of critical data.

4 SYSTEM ARCHITECTURE

4.1 Design Principles

Industrial IoT has entered its next phase – large-scale industrial automation. Over 7 million micro-devices are projected to come online by 2030 in the coal sector in India alone as the mining sector begins to digitize proactively. This transformational number is only the tip of the iceberg when it includes other mining sectors (mineral mines or open cast mines) and the prospect of global sectoral transformations across Latin America, Africa or other Asian countries. Moreover, such micro-devices for industrial applications will include the entire gamut of emerging IoT applications today: networking equipment (like routers and hubs), sensors, smart controllers and wearable devices, and as such, the ideal solution for the industry must also foment solution convergence, and therefore it must have the following characteristics:

- Modelled for adoption of turnkey industrial automation technology that can be deployed in stages to enable effective cost control on capital investment.
- Solutions that augment and co-exist with existing operational and regulatory practices, to minimize transformational downtime.
- Reliable and fault-tolerant systems that are resilient to failures that occur often in such dangerous environment.
- Turnkey platforms that operate entirely off-grid while still adopting the advantages of conventional technology paradigms in cloud computing.
- Open platforms with established industry standards that can evolve and co-opt, over time thus allowing easy integration through multi-vendor solution offerings.
- Human-centric solutions that factor in safety and ease of adoption at the heart of its design so as to accelerate the adoption of technologies substantially.

In order to deliver a scalable solution that addresses all of the aforementioned constraints, we have adopted the following requirements and

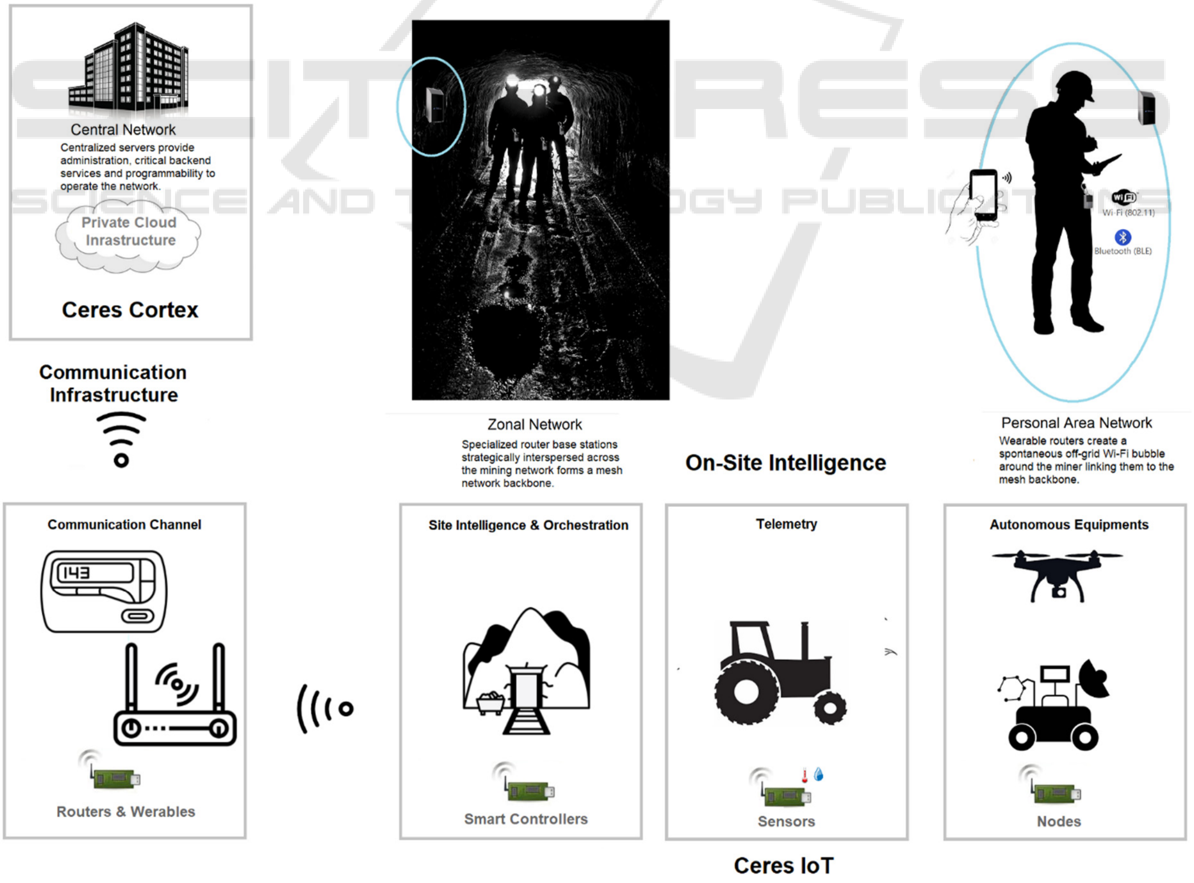


Figure 2: Conceptual Design of Platform.

principles as design guidelines.

- A simple wearable device work by each miner and serves as the functional user interface for the miner regardless of where he is. The device must have a built-in application platform that allows its capabilities to be extended boundlessly and a deployment platform to provision and administer it from a central location.
- An on-premises, private-cloud platform that provides all the conventional services that we assume standard on mainstream cloud platforms, including: storage services, compute services, databases and messaging systems.
- A low-cost, unified, hybrid (wired+wireless) internetworking fabric providing ubiquitous connectivity over the entire mining area. It is both resilient to failures (e.g., outages, accidents, calamities) while also able to deliver a range of service capabilities to support: large data transfers for sensor telemetry, real-time messaging for interpersonal communication and system-wide machine-to-machine control messaging.
- A low-code IoT platform that operates on commercial off-the-shelf (COTS) hardware to accelerate the prototyping and development of data acquisition (sensors) & teleoperation (controllers) solutions.
- A plug-n-play network architecture based on REST-based web services, wherein open-source and third-party vendor solutions can be integrated quickly.

The presented platform has evolved through several iterations of the design. Consequently, our current approach to achieving the previously mentioned design goals has culminated in developing a distributed automation solution that integrates field apparatus, devices, communications and software applications. The system is also designed to support the orchestration of all autonomous mining activities from a centralized network operations center.

4.2 System Overview

Delivering on the requirements above resulted in the development of two disparate yet complementary, interoperating platforms:

- **Ceres Cortex Cloud Platform:** A private-cloud infrastructure that serves as the central orchestration & administration platform for all system services and IoT devices. It includes cloud platform services, web applications serving the console, grid-wide centralized messaging and storage and database services.
- **Ceres IoT Platform:** An open-source operating system for automating large-scale, distributed, mesh-based IIoT infrastructure. Running on any conventional embedded platform as a host operating system, it provides a low-code, managed environment for rapid edge device development. It also serves as a unified interface into a seamless distributed internetworking fabric to allow distributed automation & edge computation capabilities.

Conceptually, the system operates as the brain integrated with appendages through a distributed nervous system as detailed in Figure 2.

4.2.1 Cloud Platform

Cortex is a complete, on-premise, private IoT Cloud infrastructure that allows you to customize and deploy our entire suite of solutions on a secure, private network, fully uncoupled from the Internet.

Cortex is a turnkey solution providing industrial orchestration capabilities for a disconnected remote industrial site located in places with unreliable or no internet connectivity. It can also be deployed in locations where cloud connectivity is impossible or undesirable (e.g., for security reasons). In either of these environments, Cortex ensures that all equipment deployed within an industrial site inter-operate seamlessly without needing a public cloud infrastructure (like AWS, Azure, or GCP) or a local area network (LAN). Cortex achieves this by cooperating with the suite of networking solutions that create a secure, wireless radio perimeter around the site for all Ceres-compatible devices. The capabilities of Cortex allow it to:

- Provide an off-grid cloud infrastructure for remote and offline sites, where computational tasks and data needs to be located on-premise either for security or performance reasons.
- Provide advanced reporting and control capabilities of all autonomous operations running on field apparatus across the entire site.
- Act as a fault tolerant, centralized exchange for all inter-process communication occurring between devices deployed at disparate zones in the subterranean mine working areas.
- Serve as a central repository and administrative console for device profiles that define the behaviour of individual IoT devices deployed at the site.

- Provide API services through REST-based programming interfaces for integration with third-party software and tools.

(Sreedharan, 2019)

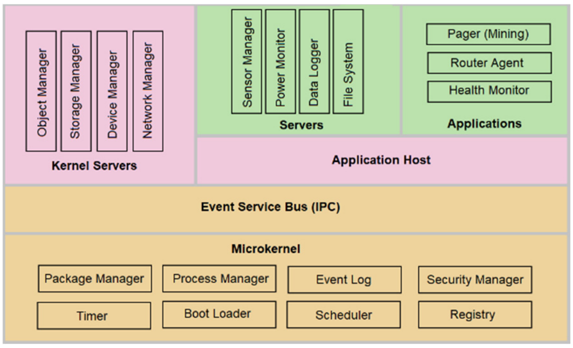


Figure 3: Ceres IoT Architecture.

4.2.2 IoT Platform

Ceres IoT is an operating system for off-grid & occasionally-connected industrial equipment. Ceres is purpose-built to address the delivery of AI-enabled industrial automation at a massive scale. It allows the central administration, provisioning & analysis of equipment in mines. At scale, equipment powered by Ceres can be connected over a geographically distributed network using wired, wireless or mobile networks.

Ceres IoT is designed to operate in highly constrained and hostile physical environments. It is, therefore, ideally suited for deployment in a farm where computers are expected to work with minimal power, often on batteries, and are exposed to harsh environmental conditions like dust, rain and heat. The capabilities of Ceres allow it to:

- Augment existing industrial infrastructure with intelligence deployed either on the cloud or on-site
- Facilitate rapid reconfiguration and upgrade of autonomous equipment on a large scale using existing mobile or wireless networks.
- Dramatically reduce the cost of industrial automation deployment & maintenance by leveraging wireless interconnects, 5G networks & enhanced capabilities of modern low-cost embedded devices
- Allow a heterogeneous set of sensors & switches from disparate vendors to interoperate over a shared network
- Facilitate the acquisition of large amounts of real-time sensor measurements for further analysis and monitoring.
- Allow big data, machine learning, and AI to power the industrial transformation of mining using data sciences.
- Synchronize execution of distributed tasks based on a universal clock, scheduled by a fleet of connected devices, thus enabling large-scale orchestration.

(Sreedharan, 2022)

An important lesson is that standardizing the entire network architecture around a common portable, managed operating-system environment allows us to simultaneously simplify the deployment use cases and accelerate solution development of field apparatus (like sensors and controllers). It also enables a versatile communication fabric that spans the entire industrial site, with assured interoperability across devices. This design approach allowed us to offload a substantial amount of the computing capability to the edge, reducing the throughput demands on the network while also making the platforms highly resilient to zonal outages and accidents. Figure 4 outlines the Ceres architecture.

Although not a comprehensive list of current solutions – and it will undoubtedly continue to evolve, the following classes of devices are implemented entirely using Ceres IoT in the current generation of the platform.

- **Wireless Sensor Networks:** A growing family of sensor devices is either delivered or under development on-premises. The sensors include air quality & toxic gas sensors, micro-seismometers, environmental sensors, activity monitors and incendiary sensors.
- **Networking Components:** A family of low-cost, industrial-grade gateways & hubs provide the main communication backbone that integrates a wide range of technologies like smart switches or environmental sensors using WIFI-over-radio, over long distances. The current generation of solution includes a suite of routers built using LoRa-based, wireless LPWAN (low-power, wide-area network) technologies. These routers make deploying and integrating Wi-Fi-capable Ceres-compatible devices easier over long distances.
- **Wearable Pagers:** A smart wearable, called ‘pagers’, operating on a personal area network (PAN) that interfaces with an indigenously developed LPWAN-based wireless mesh networking technology that bridges over a wide range of conventional backbone network (5G, SPE or RS485) to provide ubiquitous tracking and communication capability for miners.

4.3 Communication

Implementing wireless technology in underground mines is challenge (Ranjan, 2013). The fundamental limitation is that the transmissibility of radio is limited in any form or rock. The amount of energy powering the transceiver. To circumvent these limitations, we developed a novel variation of a mobile ad-hoc network (MANET) (Ramanathan, 2019) that mimics the behavior of swarm insects in colonies – in particular, ant colonies

The internetworking platform is built atop MineNet, a path-breaking mesh networking for ubiquitous underground mine connectivity. The networking technology behind MineNet functions by segregating the entire network into three logical subnets. A Layer-2, LPWAN radio & serial transport ensure interoperability across the subnets. Traffic is moderated using a variation of the OSPF routing protocol (Baccelli, 2010), with proprietary extensions optimized for scalable, decentralized, short-burst communications over long-range radio possible.

- **Central Network:** Located on the surface, usually within an office environment, it serves as the brain of the network. Components of the entire mesh are provisioned & administered through applications running on a central server setup with a Private IIoT Cloud Infrastructure software. One or more Gateways provide a Layer-2 (MAC) abstraction whereby every single device on the network may be addressed and accessed over LPWAN radio and Modbus. The gateways expose those devices over HTTP/REST services via Wi-Fi, thus providing a universal interface to program the radio mesh network over LAN.
- **Zonal Network:** A fleet of fixed and portable routers strategically placed within range proximity are interspersed across the entire underground mine environment to cover shafts, compartments and other areas of activity. Collectively these zonal routers form the spinal cord of the network. They function as moderators for inter-zonal traffic while also brokering administrative & control signals from the central network to devices connected to the mesh.
- **Personal Area Network:** A wearable router, usually attached to a belt buckle, creates a 'wireless bubble' hotspot around the miner. This device is paired with a Wi-Fi or BLE-compatible hand-held device (iPhone/Android phone or, optionally, a custom-built touch screen computer) or sensor. It provides Layer-3 protocol abstractions for a wide range of applications (e.g.: communication, telemetry, emergency beaconing), on the hand-held device.

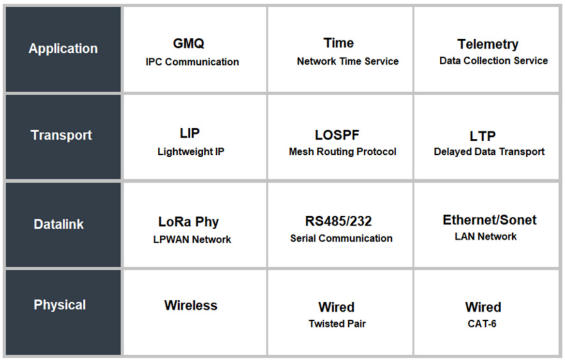
4.3.1 Network Topology

The physical network architecture closely shadows the logical network design detailed above. As such, the physical network is also broken down into three separate interoperating zones. The transport layer of the networking stack ensures that packets generated in one zone are efficiently routed to appropriate destinations. The following summary outlines the operating characteristics of each site.

- **Spinal Network:** Computing devices in the Central Network are connected to routers in the Zonal Network through several standard wired protocols. The solution deploys either an ethernet network or serial communication cables to allow reliable connectivity from the surface entrance to the active areas of the mines. The network winds through the mining tunnels to locations within meters of any mining activity. This wired network forms a spine that can extend up to 1.5 km from the entrance to areas deep in the seam.
- **Regional Network:** Mobile wireless routers called extenders are placed at strategic locations to extend the spinal network's reach by up to 200 meters at each hop from the spinal periphery. The wireless network allows mining activity to evolve organically into new working areas.
- **Team Network:** Wearable routers interact with extenders wirelessly to enable short-spurt communication to the surface. These pagers interoperate (peer-to-peer), forming a swarm cloud of networking devices that ensures reliable communication with the regional network.

4.3.2 Network Stack

The networking stack follows a layered approach drawing inspiration from the implementation of TCP/IP protocol suite and SLIP. In Figure 5, we detail the layers of the networking stack. Layering ensures that the network can provide a wide range of services including time synchronization, remote procedure calls, file transfer and data acquisition. Considering the dynamic nature of the mining operations and supporting unforeseen use cases in the future, the network is designed to be programmable through an API drawing on key design principles of a software defined network (SDN).



Application	GMQ IPC Communication	Time Network Time Service	Telemetry Data Collection Service
Transport	LIP Lightweight IP	LOSPF Mesh Routing Protocol	LTP Delayed Data Transport
Datalink	LoRa Phy LPWAN Network	RS485/232 Serial Communication	Ethernet/Sonet LAN Network
Physical	Wireless	Wired Twisted Pair	Wired CAT-6

Figure 4: Layers of the Networking Stack.

4.4 Applications

Although the platform continues to evolve and expand, the current suite of solutions includes the following components:

- **Network Operation Centre:** A centralized web application nerve centre of the operation.
- **Safety & Surveillance:** Wearable solution to track miner location and movement.
- **Teleoperation:** A family of smart controllers to schedule and control electrical equipment and flow valves.
- **Telemonitoring:** A family of sensors tracking environmental and equipment parameters.

5 CONCLUSION

Adoption of advanced industrial IoT in mining has lagged in emerging countries due to lack of practical solution alternatives. In this paper, we demonstrate how an integrated platform approach to large-scale automation, purpose-built for the mining sector, can accelerate technology adoption. More specifically, in the mining industry it promises to augment the conventional capabilities of tracking, surveillance and activity monitoring to augment them with emerging capabilities in smart wearables, industrial automation, drones & robotics, as a new era of autonomy in industries driven by artificial intelligence emerges in the horizon.

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