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Internet of Things for Sustainable Mining

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Chapter 8
Internet of Things for Sustainable Mining

Abstract The sustainable mining Internet of Things deals with the applications of IoT technology to the coupled needs of sustainable recovery of metals and a healthy environment for a thriving planet. In this chapter, the IoT architecture and technology is presented to support development of a digital mining platform emphasizing the exploration of rock–fluid–environment interactions to develop extraction methods with maximum economic benefit, while maintaining and preserving both water quantity and quality, soil, and, ultimately, human health. New perspectives are provided for IoT applications in developing new mineral resources, improved management of tailings, monitoring and mitigating contamination from mining. Moreover, tools to assess the environmental and social impacts of mining including the demands on dwindling freshwater resources. The cutting-edge technologies that could be leveraged to develop the state-of-the-art sustainable mining IoT paradigm are also discussed.

8.1 Introduction

The mining is the process of acquiring minerals from mines. In addition to the resource development, it has many economic, social, and environmental aspects. Recently, considerable progress has been made towards attaining sustainable mining practices and improving environmental quality [10, 13, 39, 41, 48]. Moreover, significant technical developments have also improved the mining practices. However, there are substantial efforts required to make mining sustainable [2, 32, 60].

8.1.1 Sustainable Mining

Apparently, it seems that there is no compatibility between the mining operations and sustainability and both seems contradictory due to the limited nature of mining resources. Since the sustainability is related to capability of maintaining a certain level of resources for current and future needs, the sustainable development in mining is difficult to achieve if the rate of the minerals extrication process continues to increase the replenishment rate of the geological processes [59]. The advances in mining practices (e.g., sensing, monitoring, and communications technology development) are needed in the areas of explorations, mining, and metal processing to improve productivity, safety, and health [29]. In 2002, the International Council on Mining and Metals (ICMM) Council espoused the Toronto Declaration for the Global Sustainable Development Initiative (MMSD) that underscores the value of technology tools and systems for the sustainable development (SD) initiative [51]. It also highlighted the importance of the best-practices and verification protocols, best-practice protocols, and reporting for SD. The importance of the integrated mines and material management throughout the minerals value chain was also emphasized.

The mining practices conducted keeping in view the environmental and socio-economic factors and the sustainable development goals (SGDs) are considered sustainable [10]. The exploration and development of novel technologies also makes mining sustainable. The three vital factors of the sustainable mining are:

- Analysis of current and future demands in mining
- Development of integrated approaches for decision making and adoption of practices based on SGDs and community involvement
- Advancements in metal recycling and reclamation methods

8.1.2 IoT for Sustainable Mining

Mine monitoring techniques seek to establish a proper environment to avoid accidents, destruction of equipment, loss of ore reserves, and closure of the mine with greatest effectiveness. Accidents happen because of roof fall and side fall that often take toll of human lives [56]. Proper mine monitoring minimizes these loses, maximizes response to other management practices, and optimizes mining. Mining management without real-time monitoring can also significantly reduce the potential for profitability. Proper mine monitoring using IoT will help to reduce the potential for runoff, run-on, deep percolation, nitrogen and other chemical leaching to the ground and surface water resources, and reduce soil erosion and mine contaminant movement into surface and groundwater [14].

Among existing techniques, Internet of Things in Mine Monitoring (IMM) is a growing technology in mining operations [9, 11, 19, 20, 53, 57, 62]. However, there is a significant lack of data and procedure development in terms of fundamental understanding and quantification of mine minerals. Current mine sensing technologies are not best suited to provide IMM systems with almost real-time minerals data to facilitate fast decision making. Thus, accurate monitoring cannot be applied at the right place of a mine at the right time. Failure to consider the monitoring in active working face, goaf, and sealed off areas in mining decisions results in mining accidents. Accordingly, human lives are wasted and the potential for chemical leaching from the mine is increased.

Timely information of temporal and spatial mining patterns can significantly aid mining producers in better managing their mine operations to achieve higher production efficiency. Real-time knowledge of spatial contaminant distribution can also further advance our understanding of variable soil water and minerals distribution as well as mine dynamics. Accordingly, more effective IMM strategies can be developed to enhance productivity and reduce leaching. This improvement, conservatively, can result in significant dollar savings. Challenges in communication between within-field sensors and decision making systems, however, prohibit these research results to be successfully transformed into wide-spread mining practices. In general, sensors can be buried at different depths and wired to a data logger above the surface, which can be used for manual data collection or wireless data transfer. Manual data collection is labor-intensive and requires significant amount of travel time. More importantly, by the time when the data are incorporated into decision making, it is late to achieve proper mining actions. Thus, mining companies, especially those with large-scale mining operations, are looking for more effective, within-field, faster, and more robust data harvesting technologies.

On the other hand, existing wireless communication solutions are disruptive to mine operations. A tower and temporarily installed sensors need to be deployed before exploration and must be retrieved during constructions due to the interference of the sensors and towers with the mine operations, adding to the maintenance, labor, and time costs. Moreover, high costs prohibit sensors to be deployed in multiple locations in a mine. Accordingly, mine variability cannot be captured by existing techniques. As a result, the spatial and temporal variability of the field and mine conditions cannot be accounted for within mine monitoring decisions. This project will address real-time and variable information acquisition challenges to enable autonomous mine monitoring solutions guided by in situ sensor information. It enables autonomous decision making for mining operation, minimize or eliminate the human error associated such decisions, and enhance operation efficiency. The sustainable mining IoT is envisaged as to provide key infrastructure and technology advancements for the next-generation integrated mine monitoring (IMM) practices, in which mining systems are tightly coupled with proper underground mine minerals monitoring. These systems have the potential to provide significant advancements for mine monitoring in unmanaged or poorly managed systems, where mining decisions are not based on quantitative sensor indicators. To this end, novel wireless underground communication techniques in IoT can be employed.

- Real-time Mining Sensory Data: Communication challenges prohibit real-time information gathering from highly variable mines (both spatial and temporal variability) with multiple sensors. The recent wireless underground communication techniques provide tools to gather real-time mineral information. However, real-time information has not yet been collected from practical mine fields. The sustainable mining IoT can be utilized for real-time data collection.
- Autonomous Mine Monitoring: The theoretical/scientific understanding of real-time and/or autonomous mine monitoring has not been well established for mining efficiency improvement. This is partly due to lack of technological

advances that enable such data collection and autonomy on a mine scale. Even when the data collection from the mines that have spatial and temporal variability is accomplished, a scientifically- and research-based practical tool for integration of all these data and information into central location for decision making for IMM does not exist. There is need to develop such a tool to integrate real-time mine disaster monitoring and early warning system coupled with environment data to allow effective and fast decisions for proper IMM practices.

- Field-based Mining Prescription: Mine monitoring practices heavily rely on the field properties, mineral type, mine type, climate, and more importantly, their interactions. Consequently, it is not possible to develop one-size-fits-all solutions. Instead, deep understanding of advanced mine monitoring tools for different fields is required so that mine monitoring prescriptions tailored to these properties can be developed and applied in various field conditions. These insights necessitate the development of a proof-of-concept sustainable mining IoT architecture for autonomous mine monitoring that enables extensive experimentation of next-generation mine monitoring practices in different types of fields.
- Sustainable Mine System Operation: The real-time mine disaster monitoring and early warning systems have the potential to transform mining practices to help realize more efficient and sustainable mining solutions. Within this broader context, it is also important to devise sustainable system solutions for underground sensing systems. To this end, it is desirable to improve system efficiency in terms of communication reliability and energy consumption. With the long-term vision towards developing fully automated mine monitoring solutions, the mining IoT paradigm supports development of autonomous system that enables autonomy in mine monitoring with a capability to evaluate technology in practical conditions to devise autonomous mine monitoring solutions that advance mining practices. The sustainable mining IoT can be realized through advanced sensing, communication solutions, and information systems. An overview of sustainability mining IoT components is presented in Fig. 8.1.

8.2 Sustainable Mining Things

The mining methods are classified into four types depending on the type of the ore deposits(depth and inclination), depth, strength, and thickness of the rocks, roof/floor type. These are shown below:

- Surface mining for shallow deposits
- Underground mining to access deeper deposits
- In situ mining and augering to dissolve minerals in place
- Placer mining for shifting and placement of mineral

Fig. 8.1 Overview of sustainability mining IoT

The sustainable mining IoT things are presented in the following:

- Metals, mineral deposits, ores, rocks
- Mining-influenced groundwater and surface water
- Mineland, subsidence, land use, and reclamation
- Tailings, acid rock drainage
- Solid wastes, effluents, waste rock, and soil
- Hazardous materials

8.3 Research Challenges in Sustainable Mining IoT

In this section, various research challenges to enable technological drivers in sustainable mining IoT are discussed.

The development of novel sensors and sensing techniques is vital for sustainable mining IoT [24]. This includes analytical sensors to detect chemical and mineralogical properties of ores and rocks with portable, mobile, fixed static settings [8, 21, 23]. For geophysical sensing, the aircraft and drones technology holds promise for seismic sensing [52] of surface features at shallow depths and hyperspectral sensing for detailed 3D analysis and to produce the geo-hydrological, chemical, and environmental models needed for ore deposits [18, 34]. The alternatives to seismic sensing are electromagnetic (EM) sensing and ground penetrating radar (GPR) [1, 12, 16, 58]. The ore-grade analyzing systems can be utilized for mineral quality and quantity assessment in both surface and down-hole configurations [49]. The sustainable mining IoT has the potential to integrate different type of sensors such as location sensors, gas, obstacle-detection, and water quality sensors. Models and simulations are also needed for to get better insights into mineralogy, geological and hydrological processes in mines, and rock and soil properties [26, 31]. Moreover, the sensing data integrated would be beneficial for sustainable mining IoT decision support systems. These innovations in sustainable mining IoT will lead to reduction in lead times and improve the efficiency of recovery process.

The availability of variety of sensing and detection method is useful to get better perspective and resolution in different applications of sustainable mining IoT [24]. Real-time data processing and visualization techniques can be used to display the mine data for different type of mining applications. Moreover, channel models are needed for the mine based communicationschannels for in-mine and mine to surface communications [38, 45]. Robotics can be utilized to automate mining operations such as nonexplosive rock fragmentation, drilling, transport, and mapping. The need of the total resource recover in mines without impacting the environment cannot be overemphasized [43, 46, 65]. The advancements are needed in fine and ultra-fine minerals and particles recovery such as techniques to separates solids and liquids [54]. In this regard, developments of novel in situ methods to access deposits where ore permeability is low including casing, fracturing, rubblization techniques for in situ leaching and boreholes mining, and drilling [27]. The reduced cost of biomining approach where bio-agents are used to extract mineral will reduce waste and environmental impacts. In this regard, integration of innovations in biomedical, chemical, and physical sciences integration with mining practices will aid to attain sustainable development goals. The fracture process in mining consists of blasting, rock fracturing, drilling, excavation, comminution. Currently, hydraulic fracture process is applied to petroleum and geothermal mining. It has many negative effects on air and water pollution. It has higher probability of oil spills with harmful impact on vegetation and soil. The sustainable mining IoT is envisioned to bring technology in cutting and fragmentation, where computer-aided cutting and blasting can inform the optimal fragment size with accurate procession. It can also reduce the dust by reducing the processing time and thrust and improved timing and tailoring of explosives. Moreover, for sustainable mining, the development of efficient water treatment is necessary for mining-influenced water (MIW) [50]. The mining process will benefit from developments in dewatering [33], dissolution of minerals [40], flotation [64], grinding and classification and other developments in chemical reagents [47], electrochemistry [61], thermodynamic and kinetic data [28], and microbiological agents [55].

The proper monitoring of mining pollutants is important to ensure that nearby water bodies are not impacted from it [63]. For environmental monitoring applications, sondes are used to sense conductivity, TDS, pH, salinity, and other parameters [3]. The development of strata control procedures is important for effective slope monitoring where excavation and rock properties (rock mass and intactness) is observed for stability and safety [22]. The improvements in technology for difficult-to-mine deposits (e.g., thin coal seams) in longwall and continuous coal mining approaches are needed [15]. The existing directional drilling technology of petroleum and geothermal drilling can be applied. Moreover, in geochemical and geophysical exploration systems, there is need for portable and down-hole analytical equipment to characterize cross bore hole and to get improved insights into soil particles mobility. Use of drones in aerial geophysics will improve shallow seismic methods and better representation of hyperspectral data [35, 42].

For mining operations, the industry can benefit from research in advanced imaging methods with capability to propagate through surface vegetation and cover. The increased resolution and coverage is needed for magnetic, radiometric, gravitational, and spectral methods. For mineral processing, potential research avenues are to make advances in flotation systems, blasting alongside crushing, finding alternatives to electromechanical energy and phosphogypsum production, and modeling, and autonomous control. Similarly, innovations in hydro-metallurgical and bio-technological techniques will advance metal extraction.

8.4 Sustainable Mining IoT Technologies and Monitoring Systems

The exploration (mineral identification), drilling, comminution (breaking to separate ore and waste), resource gathering, production, processing (crushing and grinding), closure, and land reclamation are important steps in the life cycle of the mine [17, 25, 36]. Therefore, the development of new technologies in these areas to reduce the environmental impact and waste will be beneficial for sustainable development. Due to hazardous and complicated conditions of mines, continuous monitoring of mines and early warning systems is vital to ensure safety, to avoid health-related issues in miners. These disastrous events in mines include fire, explosion, water surge, and roof fall [4]. An architecture of sustainable mining IoT is shown in Fig. 8.2.

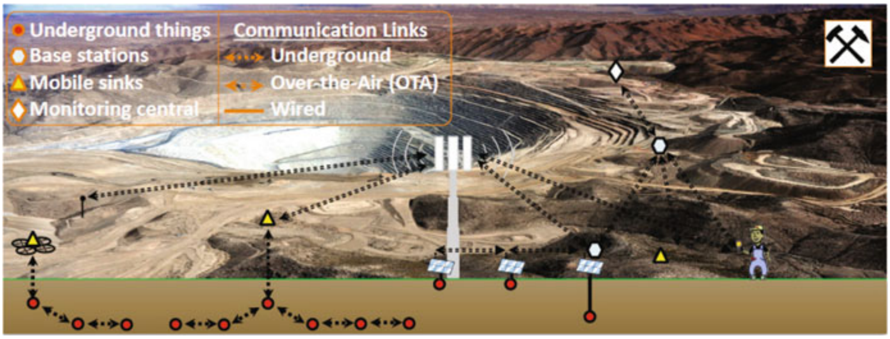


Fig. 8.2 The architecture of sustainable mining IoT

The sustainable mining IoT technologies and monitoring system collect data using different types of sensors and transmit this information to the database and cloud by using wireless communications. In this section, the technologies and monitoring systems for sustainable mining IoT are discussed.

8.4.1 Mine Monitoring for Health and Safety

The sustainable mining IoT is useful to monitor the safety conditions in mines, where technology is used to detect obstacles and obstructions to avoid hazards such as fall, berm, and equipment. The robust and reliable technology can also be used to assess health conditions in mining atmosphere to sense and identify the miners mix-mode exposure to the oxidation, dust, diesels, and cutting pollutants. By using wireless communications, this information is then used for real-time alert system. Moreover, the lack of proper mine ventilation is another important health concern in mines. The presence of sufficient amount of oxygen is necessary to support breathing. Sustainability IoT based mine ventilation systems are used to monitor air quality, cooling and control the air movement through direction and blocking.

8.4.2 Environmental Monitoring

The environmental monitoring in sustainable mining IoT is vital to protect the environment. For acid rock drainage, the acid-generating materials are identified to lessen and remove accumulation in pit floors and walls and to prevent encapsulation of wastes and passivation. Accordingly, the acidic wastewater and pit water can be treated by removal of metals and nitrate and novel techniques of dewatering and consolidating slimes can be developed. Through sensing and improved predictive modeling the cyanide can be destroyed in situ. The new technology is needed to aid evapotranspiration, impede infiltration, and fine particle emission.

8.4.3 Earth Crust Monitoring

The integrated mine monitoring system can be used to monitor the Earth's crust, where different type of subsurface sensors are used detect seismic activity and other underground conditions. The ground motion, displacement, and other disturbances can also be measured. The seismometers and vibration sensors are examples of some of the sensors used in earth crust monitoring. Because of the mining stress and deformations, the equilibrium of mine strata is disturbed. It depends on the mining technique used, rock mass and other proprieties, and depth of the strata. Accordingly, it results in falling rocks in mines. Therefore, the sustainable mining IoT can be used to ass stains, load, stress, and deformation by using extensometers, electromagnetic and mechanical methods including linear variable differential transformer (LVDT), strain sensors, micro-electro-mechanical systems (MEMS), resistance sensors, stress sensors, and vibration sensors.

In the opencast mining, a large amount of overburden is removed. With continuous accumulation of waste, the dump level can increase and becomes susceptible to failure. Similarly, in open-pit mines, the sheer slants can fail and cause damage to mine equipment and machinery. Therefore, a slant strength monitoring system in sustainable IoT can be used to monitor the firmness of the dam and sheer slants using geo-sensors which can monitor different parameters (e.g., roof load and convergence, pillar pressure and seismic activity resulting from blasting and fracturing).

8.4.4 Transportation Management

The sustainable monitoring system can be used to monitor the different aspects of the transportation in the mining such as mineral measurements and vehicle loading, route management, and illegal vehicle activity to detect unauthorized access. This information can be viewed in real-time using wireless communications. The examples of sensors used in these systems are inductive loop, IR, and ultrasonic sensors, and acoustic arrays.

Moreover, mining machinery is often used under high load conditions. The machinery monitoring in mines is done using the sensors installed on the machinery for the purpose of health, load, location, and fuel assessment. The sustainable mining IoT enables prediction and early warnings of machinery faults using sensors such as thermocouples, accelerometers, acoustic sensors, and tachometers The sustainable mining IoT has the great potential to benefit in real-time decision making, production management, and projections on resources. Through this paradigm the mining machinery (e.g., dumpers and shovels) can be minimized which leads to profit maximization.

8.4.5 Gas Detection

The gas emissions in mines are caused by either burning or from the crust of the earth due to seismic event, displacement, and rock fracturing. Miners come into contact with these various types of inflammable and toxic gases in mines such as nitrogen, carbon monoxide, sulfur dioxide, methane, carbon dioxide, and hydrogen sulfide. The sustainable IoT gas monitoring systems are used to mitigate and monitor gases using different types of sensors and chromatograph. Accordingly, real-time warning and alarm systems are developed. To monitor methane, the catalytic ball sensors are used to accurately sense different levels of methane. However, the different factors such as exposure to high concentration of gases, silicones, and hydrogen sulfide negatively affects the performance of the sensor. The local methane detector (LMD) works operates by using IR sensing. Accordingly, improved techniques for collection of methane drainage and dilution.

A summary of site monitoring and characterization techniques for gas is given below:

- Biosensors
- Colorimetric test kits
- Detector tubes
- Fiber optic chemical sensors (FOCS)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Gas Chromatography (GC)
- Gas Chromatography/Mass Spectrometry (GC/MS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Immunoassay test kits. Three categories of field analytical methods use biological systems to measure target analytes: Immunoassays, immunosensors, and enzyme-based assays that do not require the binding of an antibody to a target analyte as antigen
- Inductively Coupled Plasma Spectrophotometry (ICP)
- Liquid Chromatography (LC)
- Membrane Interface Probes
- Mercury vapor analyzers
- Surface Acoustic Wave Sensors (SAWS)

8.4.6 Goaf Fill Monitoring

The goaf is cave formed due to mineral extraction in the underground mines such as in coal and classified into working (active) and sealed (closed). The subsidence is caused by the goaf formations. Therefore, the stowing is used to pack the different material (soil, sand, and rocks) in order to fill goaf. The monitoring of the strata in goaf is important to assess the stability and strength of the structure and to reduce subsidence. The gas accumulation in goaf carries the risk of explosion. Therefore, goafs are also monitored using gas sensors.

8.4.7 Mine Fire Monitoring

One major concern in mines is fire hazard. The mine fire causality is attributed to friction, explosions, and combustion. The coal mines are more prone to mine fires as compared to the mineral mines because of being innate oxidized. In coal mines, fire proliferation process is very rapid. Therefore, accurate and robust fire warning systems are needed. The sustainability mining IoT enables fire detection, control and warning systems through sensing of temperature, and gas. The IR sensors are used for the purpose of temperature at various locations in the mines. The ratios of concentration of oxygen and carbon monoxide at various places in mine needs continuous sensing. Accordingly, alarm is generated based on the threshold values. The 3D temperature maps are also helpful in mine monitoring.

8.4.8 Conveyor Belt Monitoring

A conveyor belt is used in many mines for long haul mineral and coal transport. The conveyor belt monitoring includes broken ball and idle bearings, broken cage, and failure detection on the belt. A fiber optic cable alongside the belt which detects these failures by using pulse transmission and Rayleigh back-scatter. Accordingly, the sustainable mining IoT enables smart conveyor belt control, sensing, and communications systems.

8.4.9 Water Monitoring

The groundwater is significantly impacted by the mining activities. The groundwater incursions happens because of the cracks and geological faults in structures and high water pressure and the temperature. The water properties monitoring is important due to many factors to prevent the water related hazards and to prevent deterioration of water quality. The groundwater has high resistivity (reciprocal of conductivity). Hence, resistivity based geophysical sensing methods are employed to water sensing in sustainable mining IoT.

8.4.10 Miners Tracking

By using miner tracking, the fall hazards can be detected and trapped miners can also be located in case of accidents. The localization methods are used to locate miners in mines. The wireless and wires localization approaches are utilized by using general communication equipment such as routers. Accordingly, the 3D maps can be produced showing mine workers location.

8.5 Paradigm-Shift Technologies for Sustainable Mining IoT

Many novel paradigm-shift technologies are emerging in mining.

- Autonomous mining. In this fully robotic based mining process, the robotics systems are used for underground mining. In fully automated and manless mines, the robots can operate drills in mines (remote connected drilling) and ore carriers (self-driving ore trucks). The autonomous mining systems can be used in harsh, remote, and inaccessible areas (e.g., space and sea floor). Moreover, the robots can work alongside humans as assistants and carry out the mine monitoring and producing mine images.
- Waste utilization. It includes use of mine waste in construction industry and building material (such as tiles, bricks, cement, and pozzolana).
- Biomining. In biomining, the biological agents (e.g., bacteria, virus, and other microbes) are employed in the metals, minerals, and coal extraction process from the ores and rocks. This has become possible because of the recent advancements in the genetic manipulations of microorganisms. These techniques are more energy efficient and produce less pollution.
- Advanced rock fragmentation analyses. Development of new methods to find distribution of fragment size and uniformity index.
- Soil reclamation. It includes rapid development of different types of soils in mine wastes through different methods including vegetation.

8.6 3D Underground Mine Modeling

The underground mine safety threat include falling rocks, suffocation, and explosions. The 3D underground mine models help to improve the safety of miners and provide easy navigation. These are also utilized to characterize and assess resources, in geochemical mine engineering, groundwater modeling, and geothermal resources, stochastic coupled dynamical systems, and reservoirs. The reliable 3D scans and models can be produced by using different methods such as by using photogrammetry solutions and laser scanner. Modeling and visualization approaches also use virtual reality for training, and in design of engineering systems, and to model fluid flow.

- Photogrammetry systems use high resolution photographs of the mine sites to generate 3D models by using advanced commercial cameras.
- Laser scanners use time of travel of the laser waves (IR pulses) to produce high quality images by using point cloud model at different position and orientation. Laser scanners produce accurate maps and are capable of operating at long-range distances.

8.7 Use of Time-Domain Reflectometry in Mining

The time-domain refractometer is an emerging technology to ascertain ground movements in surface mines, tailings, and underground mines related subsidence. It is also used for subsidence and slant monitoring. It operates by sending EM pulses in transmission line (coaxial cables) and then detecting the reflections resulting from faults. The time of travel of the pulses is used to calculate distance based on the speed of the wave propagation. By using the TDR approach, ground movements can be detected through magnitude and rate of able deformation.

A time-domain reflectometry system with transmission cable is shown in Fig. 8.3. It consists of a pulse generator, oscilloscope, and a sampler. The reflected wave (also shown in Fig. 8.3) is used to determine the properties of the understudy material.

8.7.1 Treatment Technologies for Mining-Influenced Water

The mining-influenced water (MIW) is defined as any water whose chemical composition has been affected by mining or mineral processing and includes acid rock drainage (ARD), neutral and alkaline waters, mineral processing waters, and residual waters. MIW can contain metals, metalloids, and other constituents in concentrations above regulatory standards. The steps involved in mine water treatment process are shown in Fig. 8.4. Some major MIW treatment technologies are shown in Table 8.1.

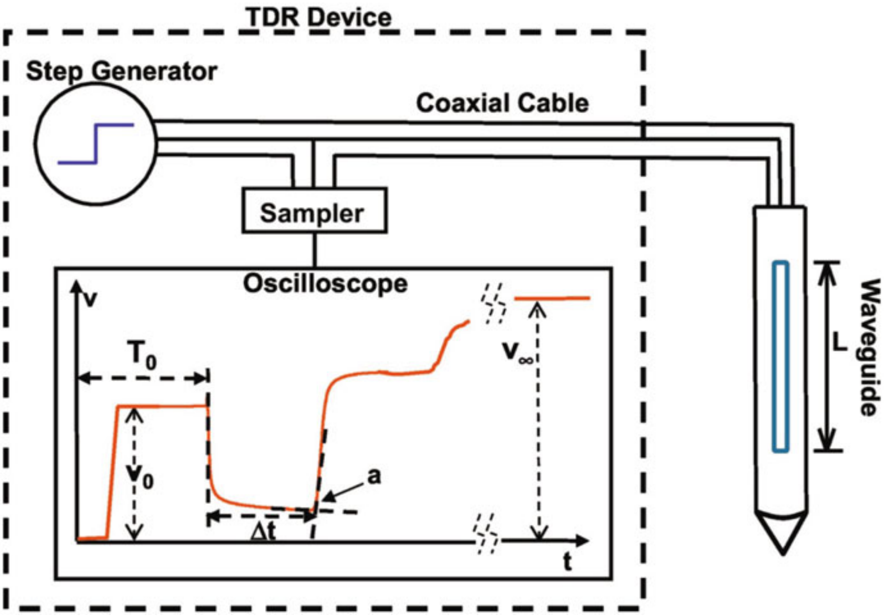


Fig. 8.3 Typical TDR system and waveform of a TDR penetrometer showing travel time determined using the dual-tangent-line method and a constant time offset [7]

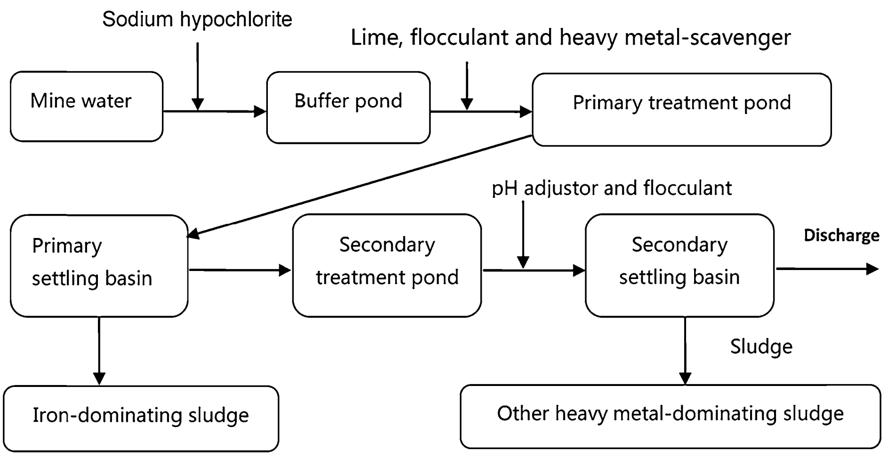


Fig. 8.4 The mine water treatment process. [44]

Table 8.1 The MIW treatment technologies

Technology	Description	Elements treated	Limitations
Electrocoa-gulation	The electrolysis MIW with cathodes and anodes	Arsenic, copper, lead, zinc, total suspended solids, heavy metals, phosphates	High energy consumption
Bioreactors	The contaminants transformation using microorganisms	Selenium, cadmium, copper, nickel, lead, zinc, arsenic, chromium	Large footprint
Aquafix	pH levels raise	Aluminum, copper, iron, manganese, zinc	Iron hydroxides clogging and granular lime accumulation
Nanofiltration membrane technology	Semi-permeable membrane based filtration	Metals, sulfate	Low tolerance levels of membrane
Photoreduction	Ultraviolet light the electron-hole pair generation using ultraviolet light (wavelength of 380 nanometers)	Selenium	Sophisticated equipment
Successi ve alkalinity producing system	The combined organic substrate and ALD system	Acidity, aluminum, copper, iron, manganese, zinc	Complicated design
Reverse osmosis	Pressure driven separation	Metals, sulfate	Requirements of high operating pressure
Permeable reactive barriers	In situ permeable treatment zone	Trace metals, including: chromium, nickel, lead, uranium, technetium, iron, manganese, selenium, copper, cobalt, cadmium, zinc radionuclides, anion contaminants, including: sulfate, nitrate, phosphate, arsenic various methanes, ethanes, ethenes, propanes, and aromatics	Long treatment periods
Ion exchange	The exchange of contaminantions with good ions	Metals, hardness	Pre-filtration needed
Fluidized bed reactor (FBR)	The contaminated water is passed through a granular solid media at high enough velocities to suspend or fluidize the media	Selenium, perchlorate, nitrate	High energy requirements
Iron Co-precipitation	A two-step physical adsorption	Selenium, arsenic	High costs
Electrodialysis reversal (EDR)	Electrochemical separation process in which ions are transferred through ion exchange membranes	Arsenic, radium, nitrate, dissolved solids	Sophisticated operation

8.8 Applications of Nanotechnology in Mining

Nanotechnology is a developing field through which unique systems, devices, and materials are created in dimensions of nanometers (1–100 nm). Recently many advancements have been made in the field of biotechnology in mining. Novel nanoscale materials (e.g., dendrimers, nano-tubes, ferritin, metalloporphyrinogens, and silica) are being developed for contaminant adsorption and destruction contaminants through in situ or ex-situ techniques in groundwater remediation. The nano-materials are classified into three different types: (1) nano zero-valent iron (nZVI), (2) bi-metallic nanoscale particles (BNP), and (3) emulsified zero-valent iron (EZVI). There is need to improve the performance and efficiency of these nanoscale materials. The activated carbon (AC) is also being used for in situ remediation of soil and groundwater by using emplacement of AC-based amendments. Moreover, various types of sensors are also being developed using this technology. Furthermore, researchers are working to get insights into the fate and transport of various nanoscale materials in environment, to assess their persistence and toxic impact on different biological systems.

8.9 Mining Site Uncluttering and Restoration

The sustainability mining IoT has a great potential in cleanup and restoration of mining sites by providing characterization tools for this purpose. The characterization of physical and chemical properties of the mine wastes is a complex process. However, by using sensing tools for contamination sensing, the health and environmental impact can mitigated along with selection of proper techniques for restoration and prospective future use of forsaken mine lands.

The mines which are located close to the water sources can release main pollutant of surface water also called abandoned mine drainage (AMD) to lower mines under treatment, hence, causing recontamination, wastage of efforts and resources, restoration delay. Therefore, the proper selection of mine treatment approach is important. The sustainability IoT can benefit from this process of mine cleanup and restoration through its connected, decision support based holistic approach. Accordingly, the watershed contamination caused by these deserted mine lands can be avoided by proper cleanup.

The approaches for mine cleanup and restoration are discussed in the following section. The important mining waste treatment technologies are also discussed.

- Electrokinetics—The electrokinetic remediation (ER) is operated by desorption and elimination of polar organics and metals by applying electrical current electrodes in ground. It is an in situ remediation technology that works in soils, marine dredging, sludge, and mud having low value of permeability. It can treat a wide range of concentrations from few ppm to high ppm. The applications of the electrokinetic method of remediation are shown in Fig. 8.5.

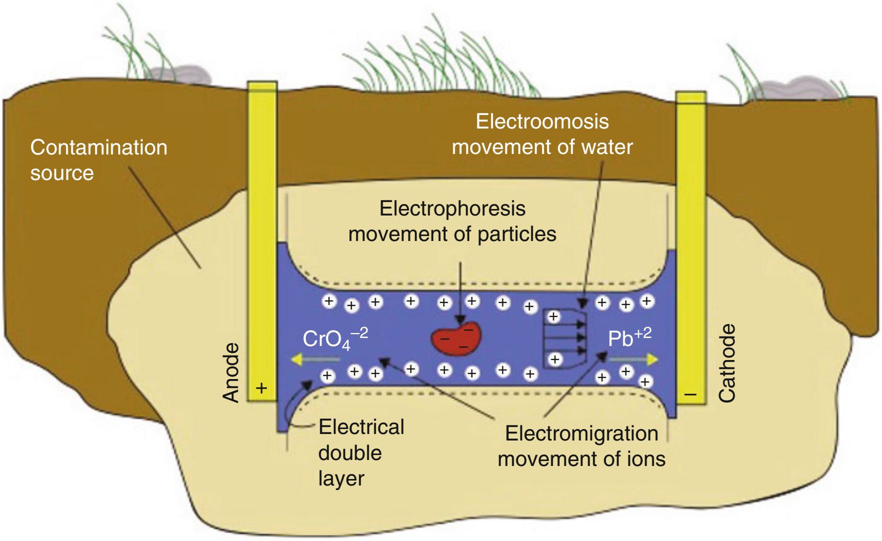


Fig. 8.5 Application of the electrokinetic method of remediation [5]

- Excavation and Disposal. The excavation and disposal process involves removing contaminations by using heavy machinery in tailings, soil, and sediment. This process is generally tailored to the specific site based in the site condition. After the excavation, the targeted treatment techniques are applied to the remaining material. The excavated material is either buried on site in a suitable depository or it is transported off-site for reuse in recycling.
- The process of re-vegetation involves the re-planting and reclaiming the soil of the mines in cleanup and restoration process.
- Soil Amendments. This process involves making amendment to soil by adding nutrients to support re-planting. It revitalizes and enables sustainable plant life development. Different factors are considered such as impact on subsurface, likelihood of leaching to surface waters, and the potential impact on animal and plant life.
- Covering. In covering approach the solid mining wastes are covered to reduce environmental impacts of the waste. It also prevents erosion, harmful dust emissions to the environment, and water contaminant leaking to the surface water.
- Subaqueous Disposal. In this process the contaminated material is removed from the surface and placed in subsurface environment to prevent exposure. It also reduces waste oxidation, acid generation, and release of metals.
- Biosolids. In this approach the nutrient rich biosolids and other organic matter materials are utilized for stabilization, reclamation, and re-vegetation of mine wastes.

- Chemical Stabilization. This ex-situ and in situ treatment approach uses phosphate (phosphoric acid) to reduce the transport of heavy metals. It is considered as the permanent fix to the mine waste.
- Biological Treatment. The biological treatment uses a biological layer to filter metals from the mining-influenced water (MIW).
- Passivation Technologies. In this process the acid-generating materials are passivated by removing contact of sulfide with water and oxygen. This can be achieved by eliminating one of the water, sulfide minerals oxygen, and bacteria.
- It uses plants restoration in tailings, mining solid wastes (MSW), and mining-impacted waters (MIW) and acts as a hydraulic control for drainage.
- Reuse and Reprocessing. After the application of the treatment technologies, the contaminants are removed. Afterwards, the reuse and reprocessing technologies turn the leftover mine waste into environment safe useful products.

8.10 Sensing in Sustainable Mining IoT

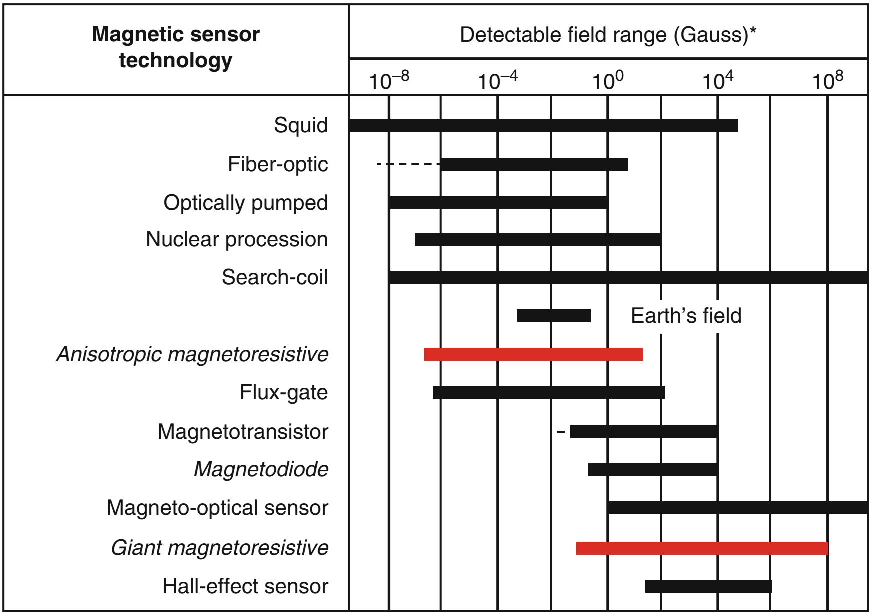
The sustainable mining IoT can be used to sense surface and groundwater in mines and geo-technical behavior of tailings as they transition from mineral slurries to soils. Remote sensing including unmanned aerial systems (UAS) and satellite imagery can be used to analyze, assess, monitor, and identify mining activities, water properties, soil contamination, and active geological faults. The sensing technologies for sustainable mining IoT are discussed in this section.

8.10.1 Ore Bodies Sensing

In this section, different approaches for ore bodies sensing are discussed.

8.10.1.1 Underground Gravity Sensing and Rock Mapping

Gravity measurements is a process to locate locating deposits of ore bodies and dense metallic minerals in Earth's crust. Accordingly, the mapping of different ore bodies, types of rocks, and their geological structures is carried out. It can be used to produce density layers at different depths. The gravity and density distribution is impacted by changes in rock strain and stress, relocation due to slides, and water infiltration. A special instrument called the gravimeter is used for gravity sensing. There are two types of the gravity meters: (1) absolute, and (2) relative gravity meter.



*Note: 1 Gauss (Gs) – 10^{-4} Tesla (T) – 10^{5} Gamma (*Y*)

Fig. 8.6 The sensitivity range of various types of magnetometers. [6]

8.10.1.2 Magnetic Sensing

The steel materials, mineral ore deposits, and sedimentary rocks impact the magnetic field of the earth. A magnetic sensing is done to sense and map these changes in the magnetic field of the earth. Many different features of the ores can be mapped (e.g., location, size, and shape). Magnetometers, a very high precision instrument, are used to conduct the magnetic sensing by measuring the magnetic field. The magnetometers use an electric coil as antenna by employing proton rich fluids. When the current is applied, it generates a magnetic field, which causes the polarization of protons. Accordingly, the magnetic flux density is measured. There are two types of magnetometers used for sensing: (1) vector magnetometers, and (2) scalar magnetometers (quantum magnetometers). Magnetic sensing can be done using magnetometers mounted on aircraft. However, the aerial magnetic sensing is challenging due to the height and terrain issues. To overcome this challenge, the backpack mounted Overhauser quantum gradiometer can be used. The sensitivity range of various types of magnetometers is shown in Fig. 8.6.

8.10.1.3 Ground Penetrating Radar Subsurface Sensing

In mining operations the ground penetrating radar (GPR) is widely used sensing/imaging method used to identify underground objects and structures (fractures, joints, and faults) by using radar pulses. GPR operates by transmitting the EM waves to the earth by using one antenna as transmitter and other antenna as a receiver to receive the reflected signal. The bedrock depth in the subsurface environment is obtained using GPR which is then subsequently used for analysis purpose (e.g., planning, texture, and density estimation). Other applications include explorations of minerals, mass stability, grading of deposits, and marking of ore zones.

- Tunneling and Underground Mines. The GPR provide solutions to many of the geological issues (rock mass stability examination, exploitation of mineralogy zones for potash and salt) by providing deep insights into the subsurface environment.
- Placer and Mineral Exploration. The GPS is commonly used in exploration of the iron-rich minerals, diamond and gold fluvial deposits (gold and diamonds) and beach deposits (e.g., titanium) and iron-rich heavy minerals. It is also used to detect and track fault zones, mineral veins, and in nickel exploration.
- Structural Integrity Sensing. The GPR can sense the integrity of the structures to detect cracks and other issues for development and planning purpose.

8.10.1.4 Seismic Sensing

In seismic sensing approach, the shock waves are transmitted through the Earth. The propagation speed of these waves is impacted by the density and other properties of the rocks. These variations in the speed of the wave are used to identify different underground materials. Generally, the transverse, exchange, and longitudinal waves are employed. Different seismic sensing approaches include side-scan sonar, wireless, flip-flop source, and slip sweep.

8.10.1.5 Tomographic Sensing

The tomography is used to measure and visualize the three-dimensional (3D) Earth's reflectivity and velocity distribution, by using multiple transmitters and receivers. Different types of the tomographic sensing are discussed below:

- In transmission tomography, the propagation measurements are done in different type of wireless channels (e.g., surface to borehole, surface to surface, and borehole to borehole). The borehole tomography is used for exploration and identification of underground geological structures and soil profile. A setup for the field experiment is shown in the Fig. 8.7.

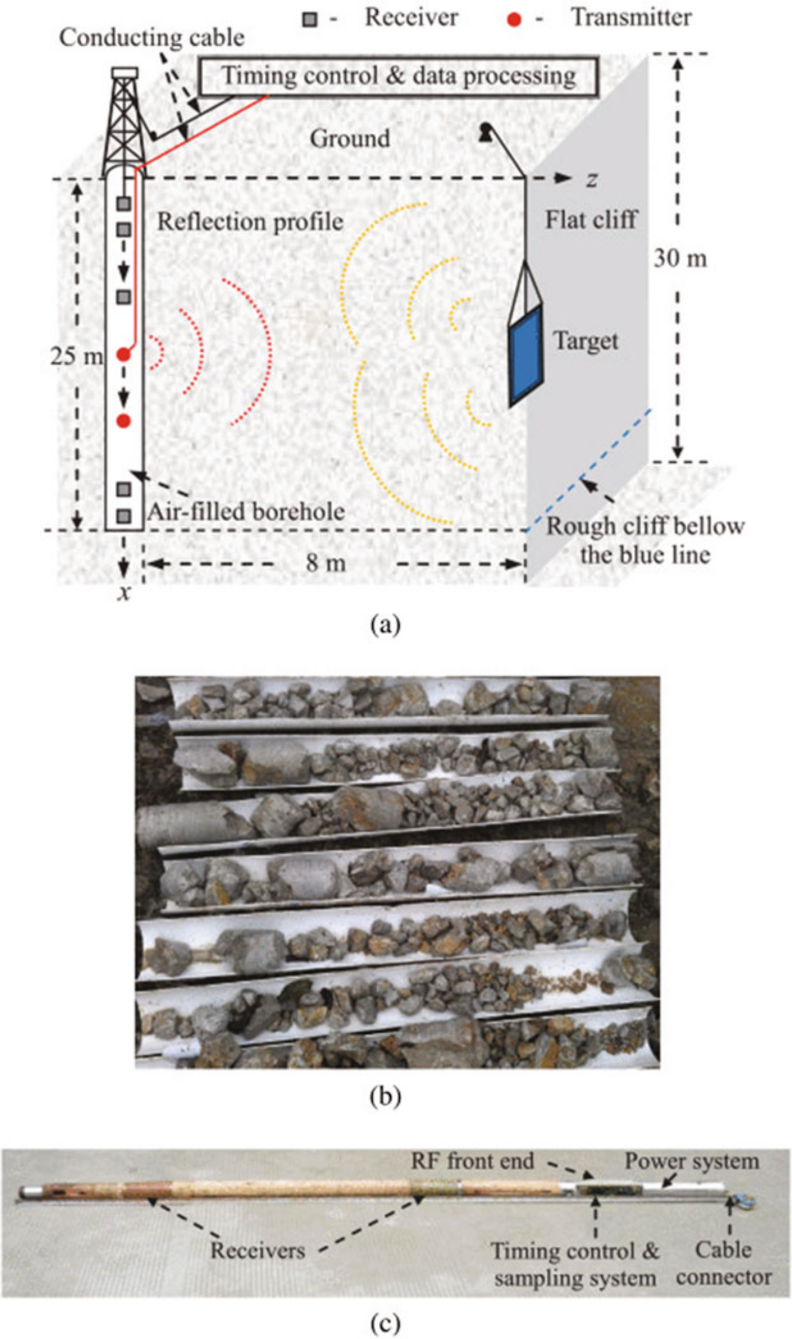


Fig. 8.7 Setup of the field experiment. (**a**) Schematic of the experimental field setup. (**b**) Sample of the surroundingmedia. (**c**) Subsurface system of the borehole radar [30]

- The reflection tomography is based on the reflection seismology.
- In diffraction tomography, the Fermat's principle is used for analysis instead of Snell's law.

8.10.2 Mine Water Sensing

The groundwater sensing in mining operations is vital to assess the quality and to detect variations in chemical properties of the water both in underground and at point of emission. It is required to ensure compliance with regulatory standards. The water mine sensing can also be used to control the flow and emissions of mine-influenced water (MIW) in and around mining sites.

8.10.3 Remote Sensing

8.10.3.1 Hyperspectral Sensing

Hyperspectral sensing is a remote sensing approach, also known as imaging spectroscopy, and is used to detect and identify minerals. It operates by sensing absorption characteristics which are affected by presence of chemical bonds in a gas, solid, and liquid. A spectrometer is used to distinguish and measure different spectral components. Accordingly, a map or cube representation of the ground surface mineralogy is developed. The accurate hyperspectral sensing depends on the type, resolution, quality, signal-to-noise ratio (SNR) and its wavelength of spectrometer, and the absorption properties of the minerals understudy.

8.10.3.2 Thematic Sensing and Mapping

The Landsat Thematic Mapper is a high resolution multi-spectral mineral scanner with support for spectrum separation. With an opto-mechanical sensor, it provides 30 m resolution with capability to operate in 7 different bands.

8.10.4 Multi-Spectral Scanner

The multi-spectral scanner (MSS) transmits the S-band radio frequency spectrum used for control of the satellite, and so is not affected by the Thematic Mapper's communication difficulties.

8.10.5 Mine Water Contamination Sensors

The pathogens that are found in mine-influenced water and toxic substances present a major sustainability challenge. The detection of these disease-causing substances can be done using chemical and biological sensors. These sensors can be deployed in underwater and underground environments. These sensors operate by using organic transistors and fictionalized gate electrode, where molecularly imprinted polymer (MIP) enables detection of bio-chemical compounds. It can be integrated with sustainability IoT paradigm using wireless communications.

8.10.6 Sensor Technologies for Gas Leaks in Mines

Gas sensors are used to sense gas pressure in mines and play a major role to detect gas leaks in mines. These sensors are characterized based on different parameters which are explained in the following:

- Dynamic Range. Quantity range from low to high concentrations
- Sensitivity. A measure to detect small variations
- Limit of Detection (LOD). Sensing ability to detect lowest quantity (concentration)
- Resolution. A measure to detect smallest variation
- Selectivity. Capacity to different gases
- Response time. Time required from absent to particular quantity
- Linearity. Graphical representation in calibrated values in straight line
- Stability. Time duration to operate for longer time periods

In sustainable mining IoT, gas sensors enable real-time actuation in mines. Many types of sensor technologies for gas leak sensing are discussed in the following.

8.10.6.1 Pellistor Sensor

The combustible gases need a certain temperature for ignition but in catalytic combustion due to certain chemicals the combustion can happen well below the certain temperature. A pellistor is sensor used to sense combustible gases. It has two types: catalytic and thermal conductivity (TC).

- The catalytic sensor is based on glass-covered wire coil catalyst coated wire. When the coil is heated its temperature increases with heat generated from gas burning. Accordingly, the variation in resistance is measured.
- Thermal conductivity sensors are used for sensing based on the thermal conductivity variations of various gases in mines such as hydrogen, helium, and methane, 0%–100% volume.

8.10.6.2 Infrared Gas Sensor

The infrared gas sensing method uses infrared light for combustible hydrocarbon gas. The component of the sensor includes optical IR transmitter, receiver, and a wave length filter. The molecules absorb and emit energy IR waves depending on their properties. The absorbing molecules vibrate more as compared to reflected molecules.

8.10.6.3 Electrochemical Sensors

The electrochemical sensors consist of fuel cells and contain a cathode, an anode, and electrolyte. These are used to detect toxic gases and oxygen. A current is generated due to chemical reaction when the target gas is detected in fuel cell. The produced current represents the volume of the gas and is used for sensing.

8.10.6.4 Semiconductor Sensor

These semiconductor sensors are used for sensing of combustible hydrocarbon gas (CHC) gases. These are manufactured using silicon substrate. The gas being sensed leads to variations in conductivity of the substrate when heated. These sensors have low current leakage and capacitance.

8.10.6.5 Laser Sensor

Different types of the laser sensors are explained in the following:

- Tunable Diode Laser Absorption Spectroscopy. It has two components, (1) tunable diode lasers and (2) laser absorption spectrometer. TDLAS is used to measure gas concentration in methane and water vapor. These receivers sense the wavelength unabsorbed by concentration.
- Differential Sensor (LiDAR). It is based on backscattering wave strength from the concentration and operates in IR, UV, visible wavelengths.

8.10.6.6 Other Gas Sensors

- Fiber Optic Gas Sensor. The fiber optics sensors work on the principle of measuring the wavelength by the absorption of the target analyte.
- Mass Sensor. The Flame Ionization Detector (FID) is used to sense hydrocarbon gas concentration and operates on mass sensing instead of concentration sensing.
- Photoionization Detector. It works by sensing the organic volatile components in UV spectrum by using mobile ion spectrometer technique.

- An array of micro-electro-mechanical sensors (MEMS) on silicon substrate is used to sense different gases.
- Hydrogen Sensor. This works by detection of the resonant frequency due to molecular adsorption.

8.10.7 Autonomous Sensing of Groundwater Quality in Mines

A mining site contains multitude wells which requires the autonomous sensing systems. Therefore, sensing of the quality of the groundwater is of critical importance during mining operations. These sensors system in sustainable mining IoT improves the efficiency of mining operations by data collection and real-time decision making systems. The cloud technology is also useful in mine sensing and automation. Overall, the sustainability mining IoT has the strong potential for beneficial improvements in all areas of mining including machinery monitoring, mine sensing, exploration and mining technology advancement, environmental monitoring, and cleanup and restoration.

8.11 Global Sustainability Efforts

The following organizations are supporting the sustainable mining efforts [37]:

- The American Society of Mining and Reclamation
- The Australasian Institute of Mining and Metallurgy
- The Canadian Institute of Mining, Metallurgy and Petroleum
- The European Federation of Geologists
- The Iberoamerican Association of Mining Education
- The Institute of Geologists of Ireland
- The Peruvian Institute of Mining Engineers
- The Society for Mining, Metallurgy, Resource and Environmental Technology
- The Society of Mining Professors
- The South African Institute of Mining and Metallurgy
- The Spanish Association of Mining Engineers

8.12 Wireless Communications in Sustainable Mining IoT

The importance of the wireless communications in sustainable mining IoT cannot be overemphasized. It provides connectivity among different sensing and monitoring components of the IoT paradigm and enables real-time decision making by integration of different components of the system. The over-the-air (OTA) wireless communications discussed in Chap. 1 have limited application in some type of mining activities such as underground due to the higher path loss of radio wave propagation in wireless underground communication channel. The higher attenuation as compared to OTA is caused by the complex permittivity of the geological strata, and other multi path components forming from the uneven structure of the mines which block the line of sight (LoS) path. Therefore, empirical channel modeling and impulse response analysis are needed for detailed insights into the physics of radio wave propagation in mines.

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