Underground Mine Communication and Tracking Systems : A Survey

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Technical Report
UNSW-CSE-TR-0910
March 2009

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Abstract

This article presents a survey of the state-of-the art underground mine communication and tracking systems. Underground mines are extensive labyrinths. They employ hundreds of mining personnel working at any point of time under extreme conditions. To ensure the safety of workers and perform co-ordination of tasks, a communication and tracking system is one of the more important infrastructures that needs to be deployed and is expected to deliver satisfactory performance in terms of communicating in routine and rescue operations. To develop an engineering and scientific foundation, we need to understand the underground channel characteristics along with the challenges faced by wired and wireless communication solutions.

1 Introduction

The combination of these two words - UNDERGROUND and MINES - portray a conception of a highly challenging operating environment. As a common man, if we ask ourselves as to what are the conditions responsible for creating this notion in our mind, we would hardly be able to state any reasons. Our negligence is the result of the lack of interest in trying to know the working conditions that prevail in an underground mine. Despite all of these, we do acknowledge the fact that there is a high level of risk involved in underground mining operation as compared to any other industry. Underground mines are extensive labyrinths. The mine tunnels are long and narrow. They are usually a few kilometers in length but only a few meters in width. They employ hundreds of mining personnel working at any point of time under extreme conditions. Hence to ensure the safety of workers and perform co-ordination of tasks, a communication and tracking system is one of the more important infrastructures that needs to be deployed and is expected to deliver satisfactory performance in terms of communicating in routine and rescue operations.

The underground mining environment is remarkably different from the conditions present on the surface. Underground mines are structurally non-uniform. They contain many crosscuts, escape ways, first-aid stations and blockages. Most of the hallways have railroads on the ground. The walls are rough and the ground surface is uneven and may have small amount of accumulated water. Some parts of the wall and ceilings are strengthened with wooden grids and metal [1]. As our focus is on the communication aspect inside the mines, hence the general conditions that are noteworthy in this regard can be stated as follows:

- *Dynamic change in underground topology :* The walls of the mines may shift on a daily basis as a result of the cutting of the mineral faces.

- *Unstable nature of geological construction :* A mineral face consists of collapse and safe zones. In the safe zones, there are hydraulic supporters to avoid collapses. In collapse zones, there are no supporters and can easily collapse either when the zone becomes larger or in the event of mine quakes resulting in structural changes [2].

- *Limited Line-of-Sight (LOS):* This arises from the presence of pillars and undulations following the mineral seam. These underground structures get carved and come into existence in the due course of the mineral extraction process.

- *Low loss dielectric medium :* At certain frequencies, the mine tunnel acts a low-loss dielectric [3] resulting in the degradation of the communication system.

- *Ionized air :* The air gets ionized as a result of fires inside the mine. The self ignition of coal seams results from an exothermic reaction of coal and oxygen. If the concentration of oxygen is more than 3% then the oxidation heat is released from the coal and gives way to fires [4].

- *Humid and warm conditions :* The relative humidity is greater than 90% and the temperature is around 28 degrees [4].

- *Gaseous environment :* The main component of the gases that effuse with the extraction of coal from the coal seams is **Methane**. When the concentration of Methane exceeds a threshold value, it leads to gas blasts/coal-dust explosion [2]. Hence, there is continuous ventilation to decrease the built-up of the gas. However, in case of a disaster, the power supply to the mines is often cut down leading to the compromise of the ventilation system [5].

These natural conditions present inside the mine pose challenges to electronic communication. Besides these, every mine has its unique environment which is specific to its itself. Hence, communication solutions need to be engineered that cater to these varying conditions. The design and implementation of any communication solution needs to be carefully engineered as the slightest of issues can lead to mine accident resulting in loss of human life. As per the US government regulations for mines, electrical communication devices have to be approved by the Mine Safety and Health Administration (MSHA) as **permissible**. Permissibility can be achieved through *Explosion Proof (XP)* and *Intrinsically Safe* (IS) designs.

To develop an engineering and scientific foundation, we need to understand the underground channel characteristics along with the challenges faced by wired and wireless communication solutions. Section 2 and 3 address these requirements. Section 4 presents the existing communication systems used in mines. A comprehensive survey of the latest underground mine tracking systems has been outlined in section 5. The following section 6 concludes the article with possible research directions in this area.

2 Underground Channel Properties

The major factors that impact communication with Electromagnetic (EM) waves in the underground mines [6] can be summarized as follows:

- *Extreme path loss* : Lower frequencies experience less attenuation than higher frequencies due to material absorption. The rate of attenuation would increase with the increase in humidity as well. The path loss increases as the square of the distance travelled by the wave.

- *Reflection/refraction* : As mentioned earlier, the tunnel acts a low-loss dielectric at certain frequencies and leads to a waveguide effect. Waves that impinges on a wall of the tunnel are partially refracted into the surrounding dielectric and partially reflected back into the waveguide resulting in signal losses. The reflected waves may result in a completely new pattern that may not be recognized as information by the receiver but as noise.

- *Multi-path fading* : The random addition of multiple propagation paths causes fluctuations in signal strength with position and frequency, and, if reflectors, transmitters or receivers are moving, also in time.

- *Reduced propagation velocity* : Waves propagating through a dielectric medium would experience a reduced propagation velocity compared to that of air. With the change in underground temperature, the dielectric property of the medium will change. Hence, an increase in undermine temperature would alter the dielectric properties and lead to increase in signal attenuation.

- *Noise* : The performance of the communication system is highly dependent on the EM noise in the environment. Clouds contain electrical charges that are evidenced as lightning stokes under stormy conditions. This flow of current gives rise to EM radio waves with sufficient intensity to interfere with radio communications. A good amount of noise ends up in the extremely low frequencies (ELF), voice frequencies (VF) and very low frequencies (VLF) frequency band, which have a negative impact on the receivers. The noise caused by electric motors, power lines, appliances etc. is in the frequency bands which are most suitable for underground communications [7].

- *Realistic waveguide effect* : In an ideal waveguide effect, the electromagnetic waves are confined and guided by the mine tunnel but in a realistic scenario, the reflective and absorption losses along the path result in the increase in signal attenuation.

3 Underground Communication Techniques

There are 3 ways of communication inside mines [7]:

- *Through-the-Wire (TTW)*
- *Through-the-Air (TTA)*
- *Through-the-Earth (TTE)*

3.1 Through-the-Wire (TTW)

TTW communication technique utilizes the wired communication infrastructure present in the mine where the equipment that is carried by the mining personnel has to be tethered to a cable. The type of cables used are *twisted pair*, *coax*, *CAT5 (specially constructed twisted pair)*, *trolley cable*, *leaky feeder* and *fiber optic* [8]. The most popular cable among these is the Leaky Feeder. It is designed to radiate over the entire length and hence derives the name **Leaky** for this characteristic (Fig. 3.1). The increase in signal range is the result of lesser attenuation rate by the cable compared to the free space propagation in the mine.

Though the performance of the TTW is moderately satisfactory for routine operations, it is subject to failure and wear and tear under the conditions of *roof falls*, *mine fires and explosions*, *power failure*, *interference from other machinery* and *inadequate maintainability.* In order to improve the reliability of the existing systems, various cable protection schemes have been applied. They include putting the cable in a *conduit(armor cable)*, *burying the cable*, *feeding cables through borehole connection to main lines*, *loop-around* and *redundant cabling* where multiple cables feed the same portion of the system. However, these methods are not only expensive but also add to the maintainability and complexity of the system. Moreover, the borehole cable protection method has

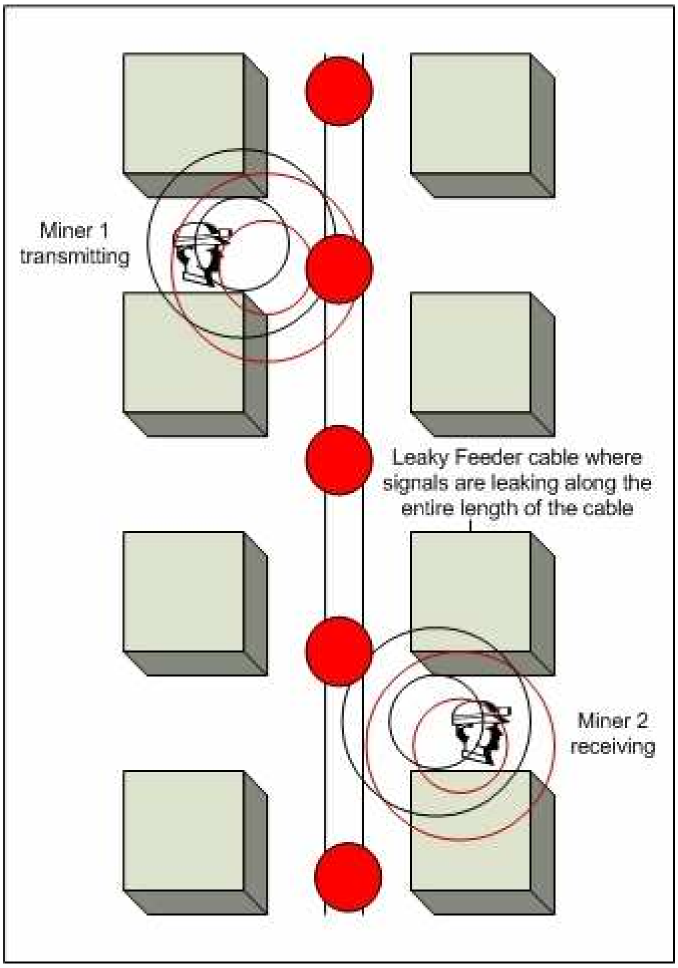

Figure 3.1: Communication achieved through Leaky Feeder cables

its own set of problems that include impedence of the radio signal and are highly vulnerable towards water getting into the cables. The material absorption, material scattering, splice and bending losses result in attenuation of the signals in the wired medium.

3.2 Through-the-Air (TTA)

TTA communication technique refers to the radio communication used in mines. Both metalliferous and coal mines present an unique set of challenges towards radio communication.

The undulating structures inside the mine are unfavourable for TTA communication as it requires a clear line-of-sight for propagation. At frequencies in the range of 200-400 MHz, the rock and the coal bounding in the coal mine acts as relatively low-loss dielectrics with dielectric constants in the range of 5-10 [9]. Transmission takes the form of waveguide propagation in tunnel, since the wavelengths of the UHF waves are smaller than the tunnel dimensions. An

EM wave can propagate in any one of a number of allowed waveguide modes. All of these are lossy modes as any part of the wave that impinges on a wall of the tunnel is partially refracted into the surrounding dielectric and partially reflected back into the waveguide. The refracted part propagates away from the waveguide and represents a power loss. However, the propagation of some frequencies is enhanced by a waveguide effect due to the sandwiching of radio signals between layers of varying electrical properties. Wall roughness and uneven tunnel cross section leads to an increase of the longitudinal attenuation. With respect to coal mines, the electrical properties of coal attenuate certain frequencies more than others and hence a small fraction of the radio signals are able to propagate down the coal mine. Heavy mining machineries, trolleys, high voltage power cables operating inside the mines lead to signal interference and thus affect the propagational behavior of the signals. Other challenges include ionized air, adverse environment and mine dynamics.

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The frequency selection has a major impact on the signal propagation [5].

- The mine acts as a waveguide to propagate signals at Very High Frequency (VHF) and Ultra High Frequency (UHF). They have high bandwidth and the devices using them would require small antennae. However, they suffer from attenuation, corner losses and require a clear line of sight for propagation.

- Extremely Low Frequency (ELF), Very Low Frequency (VLF) and Low Frequency (LF) suffer less attenuation but can experience electrical interference from motors and other machinery. These systems have limited bandwidth, have significant distance limitations and require large antennas for operation.

- Medium Frequency (MF) have less attenuation characteristics than VHF and UHF signals. It does not experience the high noise levels of lower

Table 3.1: Frequency Band Range

Abbreviation	Name	Frequency Band
ELF	Extremely Low Frequency	30 - 300 Hz
VLF	Very Low Frequency	3 - 30 Hz
LF	Low Frequency	30 - 300 KHz
MF	Medium Frequency	300 - 3000 KHz
VHF	Very High Frequency	30 - 300 MHz
UHF	Ultra High Frequency	300 - 3000 Hz

frequencies. These systems have limited bandwidth and require larger antennas than VHF/UHF systems.

Research has shown that MF offer better usability in underground mine communication. Table 3.1 gives the frequency band for each frequency.

3.3 Through-the-Earth (TTE)

The operating frequency used by the conventional systems are unable to penetrate the rock strata and become unoperational in the event of mine accidents. TTE communication systems prove to be better as they do not require preexisting cables/open-air communication technology and use ultra low frequency signals for communication [7]. The antenna is located on the mine surface which provides coverage to various parts of the mine, thus reducing the risk of damage in emergency. Some of the TTE communication systems researched by the US Bureau of Mines are as follows and can be useful in certain critical situations.

- *Ground conduction*: It consists of transmitting and receiving signals through the ground medium through ground stake connections.

- *Seismic* : The entire setup of the seismic communication system is carried on a truck and there is no requirement of any accessories to be carried by the miners for location detection. Trapped miners generate a seismic signal by pounding on the mine surface such as roof, floor and ribs. Geophone sensors, installed on the surface or underground, detect these signals.

4 Existing Underground Communication System

The existing underground communication systems [3][7] can be broadly classified as *general communication* and *tracking systems*. The general communication systems include the following:

- *Telephones :* The basic operationality of the underground mine phones is similar to that of the surface-type phones. The Private Branch Exchange (PBX) inside the mine is responsible for the make/break of the call and these telephones are interconnected by multiple pair cables. Circuit breakers and lightning arrestors are responsible for protecting the system from sudden energy surges by limiting the electrical energy to safe levels. These telephone systems are easy to use but are vulnerable to damage from roof falls, mine fires and explosions.

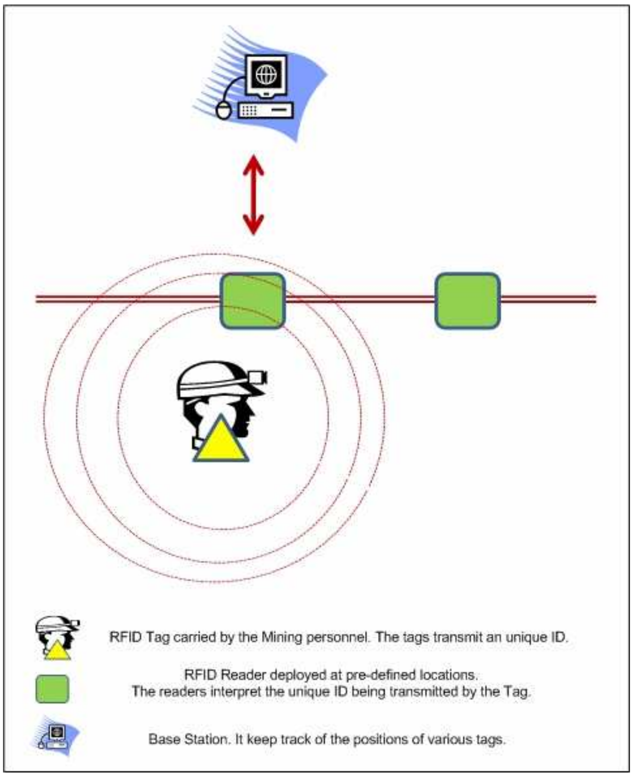

Figure 4.1: RFID Tag based communication

- *Pager Phones :* The pager phones are battery operated, party line telephones with provision for loudspeaker paging. It is cheap and simple but is noisy even in the usual transmission mode.

- *Trolley Phones :* Trolley phones can be fixed or mobile (carried on locomotives). The mobile units are subjected to constant vibration and suffer the temperature extremity along with humid and dusty conditions. The transmission lines pass across various mining machineries which result in degradation of the communication quality. The main advantage is that they provide communication to all the rail haulage vehicles using trolley cables but are limited in coverage.

- *Hoist Phones :* It is a communication facility between the persons in the hoist cage (used to raise and lower conveyances within the mine shaft) and the surface/underground wherein a phone line directly connects the cage to the mine communication system.

- *Walkie Talkie :* It is a portable, bi-directional radio transceiver which has the appearance of telephone handset with an antennae. It is basically a half duplex communication system wherein only one person can talk at a time. They provide a wireless communication system with an better coverage area but have to be used in conjunction with leaky feeder cables and line amplifiers for signal transmission across corners and bents.

The tracking systems include the following:

- *RFID Tag based communication :* It consists of Radio Frequency Identification (RFID) tags that is carried by the workers/machinery. As it passes the tag readers pre-positioned at fixed locations throughout the mine, they are able to recognize the object by the coded RF signal emitted. This information is sent to a central location for monitoring (Fig. 4.1).

5 A Survey of Underground Mine Tracking Systems

The underground mine tracking systems can be classified into the following types based on the tracking type [5].

- *Zone/Proximity based systems :* They are able to detect the presence of the object in a particular region. The RFID based systems belong to this category. Resolution depends on number of readers installed in a surveillance area.

- *Node based systems :* A radio device capable of communicating with other nodes is carried by the miner. The location is determined by identifying the node with which the miner was able to communicate. Resolution depends on the number of nodes and the fidelity of the signal processing technique (Fig. 5.1).

- *Autonomous systems :* They determine the location independent of any deployed mine infrastructure.

The latest tracking systems are based on digital data networks which include *TCP/IP, Ethernet, WiFi, Wireless Mesh Networks, VoIP, Cell phone technology.*

There are many research agencies and manufacturers that have conducted extensive research on developing effective tracking systems for underground mines. A detailed list is available at [10] [11] [12] [13] [14]. The U.S. Bureau of Mines, CSIRO (Australia), CSIR (South Africa) are some of the noteworthy names in this regard. The U.S. Bureau of Mines had extensively focused its research on operational and post-disaster communication systems during the period from 70s to 80s [15]. This lead to development of numerous mining communication products that include selectable pager phones, visual paging, multiplexed communication system, UHF extended system, EM deep mine transmitter, adaptive transmitter systems, TTE voice communication and many more. [16] gives a complete list of MSHA approved communication and tracking technologies. Designing and developing such systems for underground mines should have certain de facto standards. [17] gives a list of the ideal requirements for confined space communication systems.

The following subsections present a concise overview of the commercially available tracking products available with the manufacturers and vendors. An assessment of performance and limitations has not been described as the utilization of these products in mines is presently not known and the compiled

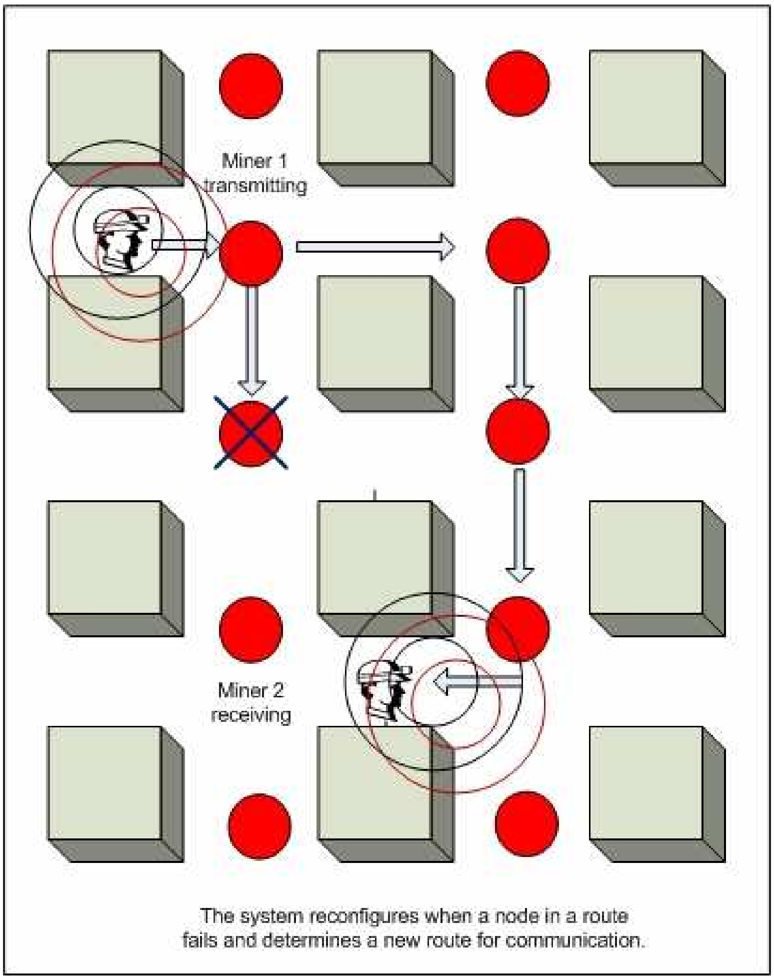

Figure 5.1: Node based tracking systems : A Wireless Mesh Network

information is from the respective company websites which feature mostly on the promised functionality. Nevertheless, it can serve as a good starting point for research in this area. Table 5.1 categorizes the tracking systems discussed in the following subsections based on the type of tracking.

5.1 Location and Monitoring System for Personal Safety (LAMPS)

It was proposed by CSIRO, Australia. The key idea of this system is to distribute the traffic along a key number of redundant paths [18]. Hence, with the disruption of a path, the communication would still be possible through other paths. It requires a network of wireless beacons distributed throughout the mine. The system consists of equipping miners cap-lamp with a transponder that transmits the miners ID, his location and vital health signs to the wireless beacon. A control and monitoring system on the surface gathers the communication traffic from different paths and displays the location information. In case of emergency, it serves to communicate escape route information for indication by the individual beacons. The personal transponders have a receiver. In case, the personal transponders fail to maintain communication with the network, two alarm conditions can be flagged. The underground staff can be alerted when they are beyond the network coverage as well as when the surface control station loses communication contact with the underground staff.

5.2 Nexsys Real-time risk management system for underground mines

CSIRO Australia, in collaboration with the Japan Coal Energy Centre (JCOAL), has developed the Nexsys Real-time Risk Management System for underground mines [19]. The system is comprised of:

- The Nexsys software package
- Electronic report-capturing system
- Suite of Ethernet-based, fiber optic and communications devices.

Nexsys can gather information directly from existing proprietary systems. It then integrates and interprets the data in accordance with a pre-determined set of rules and can autonomously initiates a response to breeches of these rules. Information and real-time risk profiles are continuously displayed on handheld wireless units such as pocket PDAs.

5.3 Emergency two-way communications for underground miners

CSIRO Australia with the support from the Australian Coal Association Research Program has developed a two-way TTE communication [20] system. Using this technology, miners will be able to ask for information, report their conditions and location and guide rescuers in emergencies. Even though, it has been designed for general communication purposes, it can serve the purpose of tracking.

5.4 Wireless location technologies for tracking and data collection

It has been developed by CSIRO Australia. Though this technology is not specifically targeted for mining environments, using radio frequency tracking, it is suitable for locating objects in challenging radio environments such as mines [21].

5.5 Trapped Miner Locating System

CSIR, South Africa has developed this application. It consists of a uniquely coded miners tag that can be worn with the belt and a portable search unit [22]. Inbuilt LEDs and a buzzer inform that a miner has been detected by the searching unit. The push button on the belt enables the miner to communicate with the searching team. The testing prototype was able to detect and locate trapped miners at the distance of 30m through solid and fragmented rocks.

5.6 Electromagnetic Location System for Trapped miners

The Institute for Advanced Physics, University of Innsbruck , Austria has developed an tracking application for trapped miners [23]. It consisted of a transmitter (beacon) contained in the miners cap lamp and a hand-held location receiver that could search for the trapped miners location by tracking the transmitter. The transmitter emits an ELF field of which amplitude and direction is measured in at least 3 points with a receiver. It is able to measure amplitude and direction of the magnetic field with three orthogonal receiving antennas. The research showed that the location of a trapped miner is possible with magnetic signals in the VLF-ELF region. The theoretical basis and limits for the parameter frequency and distance depending on the medium parameters have been proposed in [23]. Field tests at the Schewaz/Tirol mine demonstrated a detection accuracy of 50 cm.

5.7 Personal Emergency Device (PED)

PED has been developed by Mine Site Technologies, Australia. It is an ultra low frequency TTE communication system used for paging, control, centralized blast initiation as well provide service in case of emergency [24]. The system has the ability to send text messages to warn or inform specific situations. It uses either a surface or underground antennae loop which radiates a radio frequency signal enabling one way communication to the miners. It can track the people/machinery with the help of tags worn by miners or attached to moving machinery.

5.8 TRACKER Tagging

Mine Site Technologies, Australia has developed this product. It is an underground tracking system that tracks active Tags. These tags are carried by the personnel or attached to the moving vehicles and other equipments [24]. The system consists of 3 main components:

- RFID tags : Transmit unique ID.
- The Readers/Beacons : Wireless access points that receive the Tag IDs transmitted by the Wi-Fi signal and then transmit this data to the monitoring systems through the mine Ethernet or other type of digital network.
- The TRACKER software : Records all the Tag logins and known locations in real time.

5.9 TeleMag

It has been developed by Transtek, USA. It is a TTE, real time, two-way voice communication between the surface and underground [25]. It employs a single sideband modulated carrier technique and a digital signal processor based tracking comb filter for attenuating harmonic-induced noise, which improves the signal-to-noise ratio thus improving the range of the system. It is not portable. ComCell and ResQCom are two other system designed to complement the functionality of TeleMag. ResQCom is a portable system designed for mine rescue and other emergency situations.

5.10 Delta Electromagnetic (DeltaEM) Gradiometer Beacon Tracking System

It has been developed by Stolar, USA. It is a system consisting of beacon transmitter and a wave gradiometer (receiver) [26]. The receiver is portable and is used on the surface of the mine to locate the beacon transmitter. A global positioning system (GPS) receiver and a radio frequency (RF) modem are integrated into the gradiometer. The gradiometer sensor data are time and position stamped with information from the GPS. The RF modem allows wireless communication with the gradiometer receiver.

5.11 RadCAT

It has been developed by Stolar, USA. The system provides a two-way voice and text messaging communication among moving miners, mine rescue team and between the surface monitoring center and underground personnel [26]. It also provides tracking capabilities for moving, trapped and barricaded miners. The system consists of:

- Tracking beacon.
- Multi mode cap lamp transceiver for voice and text messaging.
- Delta Tracker for locating trapped miners from the surface.
- Directional fox hunter antenna.
- F1/F1 repeater network
- Surface network computer..
- Personal data assistant.

5.12 Subterranean Wireless Communication System (SWECS)

SWECS is being developed for the US Army Communications and Electronics Research, Development and Engineering Center (CERDEC)[27]. The portable system consists of:

- Digital Radio
- PDA type of display
- Small and portable antenna

It can provide two-way voice, text and image transfer through a stationary multi-node network as well as TTE. The nodes will establish an ad-hoc mesh network and the portable units can communicate with these stationary nodes as well as between peer and peer. It uses Software Defined Radio. The system can also be configured such that in an emergency such as a roof fall where multiple nodes fail, the node to node communication can be via a lower earth penetrating frequency that can hop over disabled nodes to establish the link connectivity.

5.13 Digital Radio for Underground Miners (DRUM)

The system is under funding from the National Institute for Occupational Safety and Health (NIOSH) and has been developed by Kutta Consulting, USA. The system is an emergency backup communication system in large mines and primary communication system in medium and small mines [27]. The system uses the existing metallic mine infrastructure to propagate the radio signals. It consists of a collection of portable radios and fixed repeaters that collaborate to transmit, receive and forward digital data using medium frequency wireless antennae.

5.14 Canary 2

The product was developed out of the Los Alamos National laboratory and licensed to Vital Alert, Canada. It is a two-way, real-time prototype communication system that uses very low frequency. It has designed a new underground radio that overcomes the barrier of RF signal penetration through thick surfaces [28].

5.15 TramGuard Proximity Warning System

It has been developed by GeoSteering, USA. It is a proximity-based tracking system [29]. It functions by establishing a magnetic marker field around continuous mining machines which are detected by personal alarm devices (PAD) worn by mining personnel. The PAD system warns with an audible sound. A display mounted on the continuous mining machine visually warns the miners to keep them outside the turning radius.

5.16 TramGuard Miner Track System

It has been developed by GeoSteering, USA. It is a tracking system that uses the existing field generators and personal alarm devices (PAD) that were developed for use with Geosteerings TramGuard proximity system [29]. Each miners PAD communicates via UHF to field generators located at various points around the mine which then transmit the unique ID numbers of each PAD that the system is in contact using VLF signals to surface mounted receivers. By knowing the field generator that the PAD is in contact with, the location of the PAD can be determined.

5.17 BreadCrumb

The system is currently used by the military, police, SWAT fire fighters and other first responder agencies in USA and has been developed by Rajant. It has been used to establish communication in areas that have experienced natural disasters. The system consists of portable nodes that use the 802.1b Wi-Fi networking standard at 2.4GHz [30]. The nodes can be deployed as a standalone network inside the mine or can be connected to other networks on the surface with communication links outside the mine such as satellite modem, DSL, cable modem etc. The basic unit is the SE model that provides two radios and an Ethernet port. The XL is a long range model cable of 11 MBps communication at 6 miles LOS and even greater distances at lower-speed of communication.

The XLE includes an MPEG video encoder which can be used to provide a video stream to the network. WE and ME are two smaller units that provide at least one radio and an Ethernet port. WE is portable.

5.18 AXON Transceivers

Innovative Wireless Technologies, USA has developed this product. It is a transceiver module designed to work with the IEEE 802.15.4 specifications [31]. It is deployed as an ad-hoc mesh network. The infrastructure consists of a set of fixed nodes that will be stationary throughout the mine. The mining personnel carry hand-held units to facilitate the tracking process.

5.19 Mine Net Tracking System

It has been developed by AMR, USA. The system is composed of readers with three antennas that are placed throughout the mine to define zones and sub zones [32]. The miners wear a tag that is read by the reader. The tag has a button that is used to send coded messages in emergency situations.

5.20 BeckerTag

It has been developed by Becker Mining Systems, Germany. The system consists of Active Tags that transmit their unique identification codes every second [33]. Locally connected Tag Readers via a RS485 bus interpret the code and update a centralized database over Fiber Optic, RF transmissions or WiFi. The system can distinguish between various Tags such as vehicles, personnel, assets or control tags.

5.21 RFID: Multi-read Radio Frequency Identification and Tracking

It has been developed by Davis Derby, UK. The system consists of RFID readers and antennae are strategically installed throughout the mine [34]. Each person entering the mine is equipped with tags configured with a unique ID number. The readers then automatically identify the object and pass the information to the surface control centre via the telemetry link. In the event on an accident, an alarm can be activated in the respective danger zone and the directional signals can be illuminated.

5.22 Wi-Fi based Real-time Tracking

It has been developed by Ekahau, USA. It is a real-time automated system that continually monitors the location of assets or personnel on a campus area and informs the authorized users via the corporate network [35]. It consists of tags, reference devices, data network, server software and end-user application software. It uses Wi-Fi (802.11a/b/g/n) standard access points as the reference devices for tag location and as the data network.

Table 5.1: Underground Mine Tracking Systems

Tracking System	Concerned Authority	Tracking Category
Location and Monitoring System for Personal Safety (LAMPS)	CSIRO, Australia	Zone/Proximity based
Nexsys Real-time risk management system	CSIRO, Australia	Zone/Proximity based
Emergency two-way communications	CSIRO, Australia	-
Wireless location technologies for tracking and data collection	CSIRO, Australia	-
Trapped Miner Locating System	CSIR, South Africa	Zone/Proximity based
Electromagnetic Location System for Trapped miners	Institute for Advanced Physics, University of Innsbruck , Austria	Zone/Proximity based
Personal Emergency Device (PED)	Mine Site Technologies, Australia	Zone/Proximity based
TRACKER Tagging	Mine Site Technologies, Australia	Zone/Proximity based
TeleMag	Transtek, USA	
Delta Electromagnetic (DeltaEM) Gradiometer Beacon Tracking System	Stolar, USA	Zone/Proximity based
RadCAT	Stolar, USA	Zone/Proximity based
Subterranean Wireless Communication System (SWECS)	Kutta Consulting, USA	Zone/Proximity based
Digital Radio for Underground Miners (DRUM)	Kutta Consulting, USA	Zone/Proximity based
Canary 2	Los Alamos National laboratory, licensed to Vital Alert, Canada	Zone/Proximity based
TramGuard Proximity Warning System	GeoSteering, USA	Zone/Proximity based
TramGuard Miner Track System	GeoSteering, USA	Zone/Proximity based
BreadCrumb	Rajant, USA	Node based
AXON Transceivers	Innovative Wireless Technologies, USA	Node based
Mine Net Tracking System	AMR, USA	Zone/Proximity based
BeckerTag	Becker Mining Systems, Germany	Zone/Proximity based
RFID: Multi-read Radio Frequency Identification and Tracking	Davis Derby, UK	Zone/Proximity based
Wi-Fi based Real-time Tracking	Ekahau, USA	Node based
Mine-NET	Embigence, Germany	Zone/Proximity based
Mine Rescue System	Falcon, USA	-
IPMine	IPackets, Canada	Zone/Proximity based
MineAX Tracking and Tagging	Tunnel Radio, USA	Zone/Proximity based
Smart Tag Resource Tracking System	Varis, Canada	Zone/Proximity based

5.23 Mine-NET

It is based on the RFID tag technology [36]. It consists of a system integrated with the underground WLAN network infrastructure where an RFID reader is integrated into a WLAN access point location. It has been developed by Embigence, Germany.

5.24 Mine Rescue System

The product has been developed by Falcon, USA. The system is packaged in a lightweight battery powered backpack that can be initiated by underground personnel in less than a minute [37]. It then broadcasts a signal that can be identified by surface sensory units. It can be used either for vertical rescue (Surface to Mine Rescue) or horizontal rescue (Mine to Mine Rescue). Both field transportable and permanent installations of the system can be implemented.

Permanent sensor installations can monitor 7x24 underground mine beacons for immediate response and rescue.

5.25 IPMine

It has been developed by IPackets, Canada. It is a a real-time, 2-way wireless communications and tracking solution that uses 802.11 interface between wireless clients and base stations [38]. When miners enter a new zone, the information from their mobile device is intercepted by Zone Access Points (ZAPs) and relayed back to the control centre. The flashing of a miners headlamp or LEDs on the device is controlled and set at different speeds to indicate normal, priority, or emergency messages.

5.26 MineAX Tracking and Tagging

It supports multiple modes of data transport including wireless readers via leaky feeder, Ethernet and hardwire [39]. In wireless mode, the tag readers can be located anywhere within the leaky feeder radio system coverage area thus providing customized coverage for each unique installation. It has been developed by Tunnel Radio, USA.

5.27 Smart Tag Resource Tracking System

It consists of active RFID tags, networked RFID readers and a PC/Server running Smart Tag software [40]. The readers connect to an Ethernet network using twisted-pair, fiber optics or Leaky Feeder. It has been developed by Varis, Canada.

6 Research Direction and Conclusion

Communication and tracking systems in underground mines is an area that has not been actively researched as contemporary surface communication and tracking systems. There are few existing system and there is limited information regarding the actual implementation of the tracking systems presented in the previous section. This implies that location sensing is an unsolved problem in mines and there is a need for technological improvement in order to cater to the challenging underground mining conditions. Currently available tracking systems only register when the person passes a certain location. Designing and developing autonomous tracking system (e.g. MEMS based Inertial navigation systems) that are capable of real time continuous tracking need to be researched.

A portable wireless system would be the best option in mines because they offer the best resistance to damage from roofs falls, fires and explosions. Besides that, the system can be carried by miners and they do not require pre-existing infrastructure in terms of pre-installed antennas. Wireless sensor networks (WSN) can be a plausible solution. Using WSNs, the objects can estimate their location by co-operating with nearby objects by sharing the sensor data in order to minimize the overall location error. With a moderate upgradation of the processor used in the sensor nodes, fast and efficient object tracking can be performed. In addition, it can be enhanced to monitor gas and dust concentration inside the mines and stability of underground structures with the addition of a few extra sensors. Hence the topic of sensor fusion can also be researched in order to derive a one-fit solution for mines. Seamless integration of the wireless solutions with the existing wired systems present in the mines and efficient sensor deployment schemes in a short period of time in order to respond to emergency situation are possible research directions. Wireless underground location systems using UltraWide Band (UWB) and Software Defined Radios (SDR) are other promising research topic in order to counter the challenges posed by radio propagation in mines.

This article presents a survey of the state-of-the art underground mine communication and tracking systems. The main objective of the article is to present its readers with a comprehensive understanding of the communication challenges with regard to underground mines in order to trigger research in this area.

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