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ADVANCEMENTS IN COMMUNICATION AND SAFETY SYSTEMS IN UNDERGROUND MINES: PRESENT STATUS AND FUTURE PROSPECTS

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ABSTRACT

Mine accidents in underground workings have motivated for better development of communication system infrastructure. Accurate knowledge of the environmental conditions gives a great ease to the rescue team at the time of emergency and this can be achieve by means of proper communication only. This paper discusses the different features which are common to coal and metal mines and may affect the performance of communication deployment in underground mines. Some recent works and future prospects are also discussed for better understanding of underground mine communication and monitoring systems.

Keywords: mine communication, underground sensors, underground tracking

1 INTRODUCTION

Continuous efforts and research in the field of communication provided us a reliable and easy to handle devices for our daily life as well for industry in a normal environment. Underground mines have very harsh environment for daily activities and operations. Mine personnel and various mining equipment are distributed all over the mine. By virtue of underground mines structure and characteristics, it is very difficult to provide reliable communication throughout the mine. The underground mining activities are highly mobile therefore communication range changes continuously. Due to this dynamic nature it creates a great challenge to maintain the communication and monitor the environment all the time. Continuous monitoring and tracking of assets inside the underground mines necessitated the requirement of robust communication systems for daily operations and to maximize the productivity [1]. Communication fails in harsh and hostile environment due to disruption in network infrastructure and damages caused after a mine accident either due to fire, explosions, roof- falls, haulage etc. Underground mining industries really need a full working proof communication system which may capable to withstand in emergency as well also full fill daily work requirements. In present scenario the developed systems are mostly based on the IEEE802.11 (WI-FI) or 802.15.4 (ZigBee) radio specification using 2.4 GHZ frequency. In the view of future applications, researchers are developing systems using Radio Frequency Systems' (RFS) Radiaplex cable which supports long distance communication as compared to yellow stranded cable widely used in leaky feeder system. It serves as a power conductor (12 volts dc) as well antenna for the developed systems [2]. Mine Safety and Health Administration (MSHA), reported in their technical report about different proposals received by the manufacturers dealing in communication systems based on the ultra-wide band (UWB) radio transmission, wireless mesh networking and very low frequency through the earth [3]. Six proposed systems were tested at Consol Energy Inc., McElroy Mine, West Virginia during March 28 to April 27, 2006. The performance details and shortcomings of the communication and tracking systems can be found in [3]. Fig. 1 depicts a typical view of underground mine tunnel. The rest of the paper is arranged as follows: The next section presents a general underground mine characteristics for communication channels. We then outline the communication techniques and communication systems used in underground mines. After that we provide a brief survey on recent existing work. The final section suggests the future prospects and research directions of communication and safety systems for underground mines.

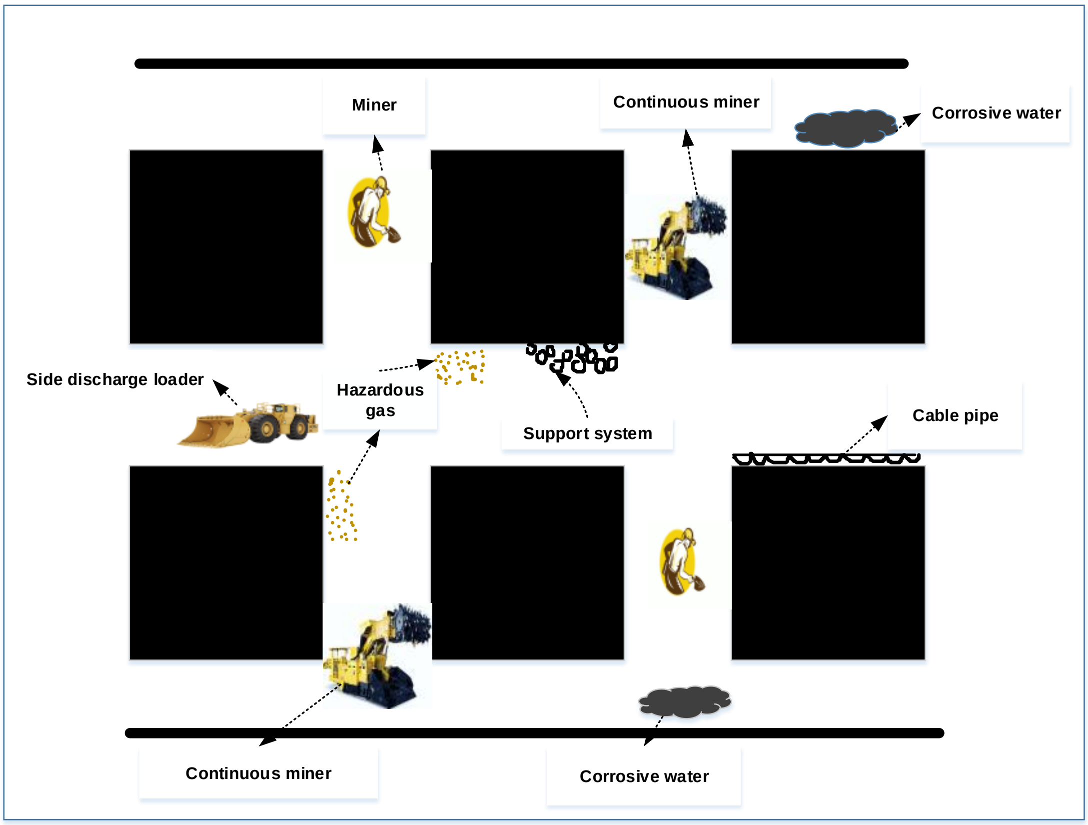

Figure1: Simplified layout of underground mine tunnel

2 UNDERGROUND MINE CHARACTERISTICS FOR COMMUNICATION CHANNEL

Underground mines are interconnected network of cross cuts, uneven structures, tunnels, sub-stations, shafts, escape routes and rail tracks [1]. Different types of support systems are present either in the form of wood, metal, hydraulic props and bolted reinforcement [4]. Following are some major characteristics of underground mines that may affect the performance of communication systems:

2.1 Uneven Structure

The underground mines do not have smooth surface throughout the mine. The hang wall & footwall walls from mine to mine have discontinuity in the thickness. This leads to the poor signal strength at the receiver end because of scattering and reflection phenomena inside underground mines.

2.2 Poor Line of Sight

A direct LOS provides an efficient communication process because the transmitter can direct sends signal to the receiver which results in enhanced signal strength at the receiver. Attenuation and propagation delay affects the overall communication where there is no line of sight path between the transmitter and receiver. Moving vehicles, equipment, mine personnel, blockages are also some times causes of no direct line of sight for transmission.

2.3 Noise

Noise due to the operation of mining equipment inside the underground mine degrades the signal quality; transmitted by a transmitter. This may affect the performance of a communication system seriously. Noise in the signal added either externally or internally reduces the coverage range of the communication system [1]. Although in case of rescue operation this is somewhat reduced due to power failures but electronic devices and other mechanical rescue equipment carried by the rescue team may add noise to the transmitted signal [1].

2.4 Tunnel as a Waveguide

It has been observed that an underground mine tunnel behaves as waveguide at certain frequencies thus the transmitted signal has enhanced coverage range [5]. High coverage range for communication can achieve due to waveguide effect inside the mine tunnel. This causes less propagation effect for a communication system operating on these frequencies [1].

2.5 Gaseous Environment

Different gases are present inside the mine tunnels. The main concerns in underground mines are methane which is highly flammable. Other toxic gases are also there which may also cause degradation of signal quality [1].

2.6 Warm Conditions and Humidity

A mining environment also has relative humidity up to 90% [1]. Usually as we go deeper the temperature rises. This high humidity can affect the signal propagation for communication between the transmitter and receiver. The communication devices should be intrinsically safe for normal operations and activities as per the mining regulations [1].

3 UNDERGROUND MINE COMMUNICATION

This section describes major communication techniques adopted in underground mines and discusses merits and demerits of different communication systems. Underground mine communication techniques can be broadly classified into mainly three categories [4]: Through the Earth (TTE), through the Wire (TTW) and through the Air (TTA) apart from these, other techniques are also used for communication and safety purposes which include Carrier current systems and Hybrid systems[4]. Fig 2 depicts the classification of different mine communication techniques and communication systems based upon the techniques.

3.1 Through the Earth (TTE)

Through the earth communication techniques has been widely researched for communication purpose as well for rescue operation in emergency. Very low frequencies are used to increase the range because the attenuation in Electromagnetic signals decreases with the frequency [4]. It involves very large transmitting loop antenna managed on the surface of mine. Through the earth communication techniques are used by following communication systems: Personal Emergency Device (PED), TeleMAg, Tram Guard Miner Track and Subterranean wireless electrical communication system Communication is limited to text messages because the data rate is very poor operating on these low frequencies [4].

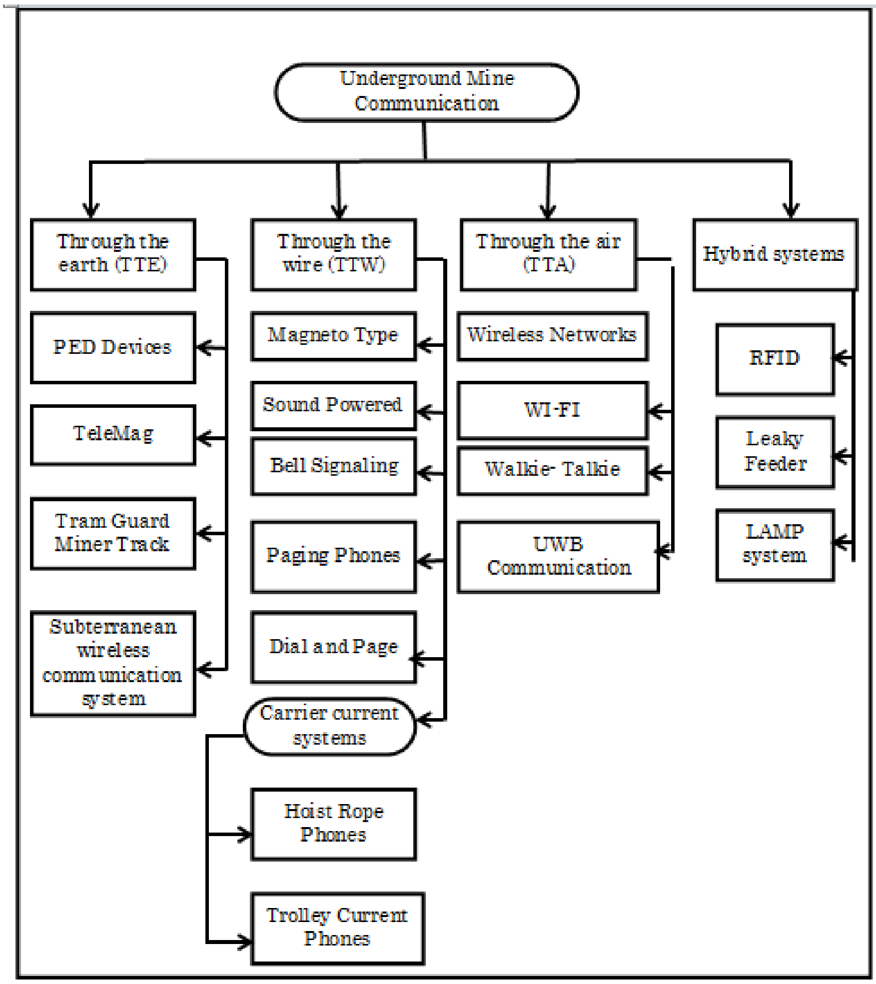

Figure 2: classifications of communication systems

3.2 Through the Wire (TTW)

Through the wire communication technique provides long distance communication in a routine operation of the mine due to fixed infrastructure [5]. Table1. Gives brief highlights of these communication systems used in underground mines. It works well in normal mining operation but is highly vulnerable to damage and may lead to entire system breakdown in accidents involving roof falls, fire, and mine collapse and so on. Different kind of electrical conductors are used for signal transmission (for e.g. twisted pair, co-axial cable, and optical fiber). Some of communication devices used in mines are: sound powered phones, Magneto type phone, Bell signaling, Paging phones, Dial and page phones, trolley carrier phone and hoist rope phone. Various cable protection schemes have been implemented to support reliable communication of TTW communication systems involving deployment through borehole connections to main lines, burying the cable and conduit [1].

3.3 Through the Air (TTA)

TTA communication technology has drawn a significant attention of researchers and different manufacturers across the globe due to the need of infrastructure less communication systems and reliability in emergency scenarios. These techniques use a wireless link for signal transmission. Underground mine environment either in coal mines or metal mines creates a very big challenge for wireless communication. As an underground mine has different characteristics for signal propagation discussed in the above section affect the performance of communication systems. Wireless networks, WI-FI, Walkie-Talkie, UWB communications are classified into through the air categories [4]. TTW communication systems have certain limitations, hence it forced the mining industry to have options for TTA communication technology which is more reliable, easy to maintain and economic in comparison to TTW communication systems.

3.4 Hybrid Systems

This communication system avails the advantages of both through the wire (TTW) and through the air (TTA) communication techniques. This leads to the better coverage range communication systems for underground mines. Hybrid system approach can further extend to forward and receive signals to a node using wireless mesh network upon short wireless link. Leaky feeder system and RFID based systems are widely used in mines now a day to achieve two way communications. This kind of deployment of hybrid system has the option of multipath for transmitting and receiving which are in the coverage range to each other [1]. Hybrid systems support both voice and video communication in underground mines with high data rates [1]. Table 1 gives the short details on communication devices presently used in underground mines for communication and monitoring purposes.

4 RECENT DEVELOPMENTS

This section briefly discusses the new work carried and emerging solution in the direction of communication and safety systems deployment in underground mines. Misra et al. [1] experimented for assessment of commercially available wireless sensor nodes for wireless communication in underground mines. The tests have been carried out in gold and copper mine located near Parkes, New South Wales, Australia having width of 5 meter and height 10 meter with projecting bolts 2 meter above the tunnel floor. The sensor deployment scenario is displayed in figure 3. MicaZ sensor nodes have been used for study, all the nodes were programmed using tiny OS and nes C. Results suggested that the success rate is high of those nodes which had clear line of sight (LOS) and placed near to the base station. They have reported that dynamic behaviour of channel due to moving objects during tests, misalignment of antennas and reflection phenomena from mine walls resulted in low data rate. The success rate obtained during studies is represented in figure 4.

Table 1: Summary of communication devices used in underground mines

Communication System	Description	Merits	Demerits	Communication Technique Used
Magneto Phones	Generates a current that is strong enough to make bells of other phones ring in a private line manner	-Simplicity -easy to use	−Battery power requirement −Modification requirement with mine expansion −Specific coding requirement to page a person −signal strength is poor	TTW
Sound-Powered Phones	Uses the voice of the speakers and converting them into electrical signals by electro-mechanical transducers	- No external energy source required -Suitability for rescue missions -small in size	−short range -works as independent intercom system	TTW
Paging Phones	Based on party line fashion. Each individual device has its own battery to feed audio amplifiers which strengthen the audio signals	-Reliable, - easy to install -maintenance simple	−No simultaneous communication −Internal battery required	TTW
Dial-and-Page Phones	Combines the features of sound powered and paging systems	-Multiple functionality (dial and page) in a single system	−installation is complex	TTW
Trolley Carrier Phone	Based on the connection between the receiver and transmitter through the trolley wire and a coupler capacitor and operates at 60- 140 KHZ	-Improved range -A better insulation compared to the telephone systems - Easy to maintain -signal with good clarity	−dependent on the carrier frequency -Limited coverage -constant vibration -quickly warm	Carrier current system
Personal emergency device(PED)	Based on ultra-low-frequency (ULF) transmission that propagates through rock strata,	- Reliable -no dependency on cables/wires	-one way -underground to surface communication is not possible	TTE
Ultra–Wide Band Systems	Based on narrow pulses and requires very low energy	-High data rate with low power -Very high accuracy in location tracking applications	−Short range due to low power	TTA
Walkie -Talkie	Wireless communication; uses ultra-high frequency (UHF)with an antenna at the top of the system	- handheld -portable with two way communication	Generally poor range but may have good LOS performance	TTA
WI-FI	It uses radio frequency to transmit data through air and based on IEEE802.11 standards.	-two way communication -supports voice and data communication	-limited coverage -poor traffic management -power consumption is high	TTA
Leaky feeder system	Signals leak over the entire length hence, prevents from external signal interference	-mobile communication -reliable -two way voice and data communication -capable for video communication	-limited range -weak performance where NLOS	Hybrid system

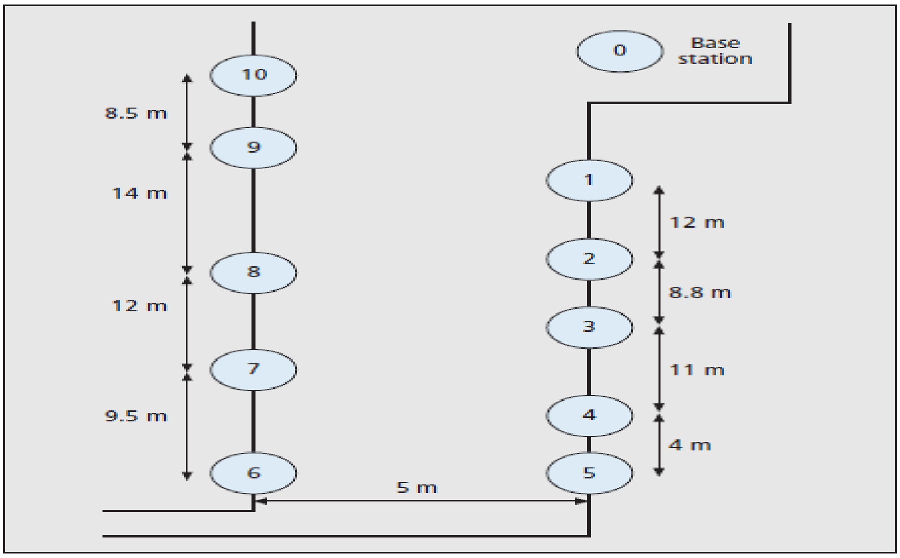

Figure 3: sensor deployment inside mine [1].

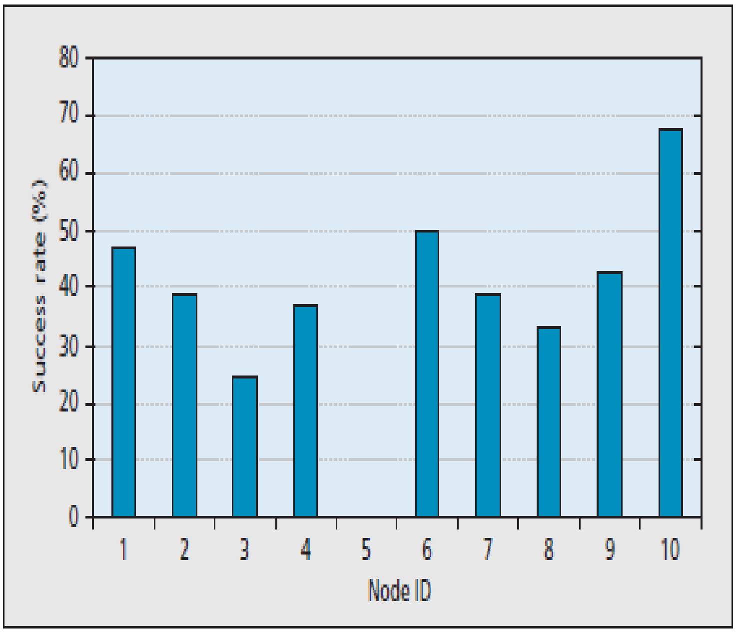

Figure 4: Success rate vs node id obtained in experimental studies in [1].

Kennedy et al. [5] developed a “Zonal Location Tracking “system for tracking mine personnel, vehicles and plant in underground mines. They used ZIgBee Pro Mesh wireless networking standard based system comprises of ZigBee router (ZR) devices installed at known locations. The system had 40 mobile nodes to support a large enough network. Results had shown that to capture the all mobile devices, polling interval should be ten seconds or less for a nominal distance of 50m. They have reported in their work that if the polling interval is decreasing then the success rate is very high but limited to 15 nodes only. Furthermore, they have compared their results with worst case parameters which are: Large volume at low speed, Moderate volume at high speed, large volume at high speed. Results observed were satisfactory for first two parameters. Also, they concluded that there is a very distinct relationship between the polling interval and number of devices. Bandyopadhyay et al. [6] have developed a wireless safety system for underground mines. The system had ZigBee complaint active Radio Frequency Identification (RFID) devices as a core component which was based on wireless mesh network infrastructure. The system was tested and is certified in the view of intrinsically safe and radiation proof use inside underground mine by the competent authorities Electronics Regional Testing Laboratory (East) Kolkata and Society of Applied Microwave Electronics Engineering & Research, Kolkata in India. They followed three different modes for experiment process which are: 1) maximum operating distance between the coordinator and end device in line of sight (LOS) communication, 2) remote coordinator to end device using multi hop routing and 3) remote coordinator to end device in no line of sight (NLOS) using multi hop. It has been reported that packet delivery ratio is inversely proportional to the distance between end nodes to coordinator. Furthermore they have also concluded that number of hops also affected the packet delivery ratio. Monitoring system has been developed by Kumar et al. using wireless sensor node (WSN) for underground mines [7]. The system was developed using MSP430 microcontroller and nRF24L01 radio transceiver operating on 2.4 GHZ license free band and consumed very low power. Although authors initially reported good results in lab but real time implementation yet to be perform. Zhu et.al [8], designed and analysed the system performance of the developed system considering various communication parameters and safe operation requirements. The network consisted of one mobile node, several fixed nodes and a sink node. To ensure intrinsic safety Varistor and RC circuits were used in the reset circuit of a sensor node for minimizing discharge energy risks. The designed system followed ZigBee protocol standards for communications. In this proposed design the authors only assumed the reliability of the performance in terms of packet loss and delay profiles and neglected other physical parameters of the underground mines like multipath effects, reflection and communication modes. They tested their system in simulation environment assuming a mine tunnel of length 700 meters and width 5 meters. The nodes which are taken as fixed nodes were placed on the sides of the tunnel at the interval of 90 meters. Results obtained in virtual mine environment revealed that the maximum communication delay of the network is about 0.11 seconds and the maximum packet loss rate is about 0.13. These results assured that the reliability of the system. However, neglecting other critical characteristics of the underground wireless channel is still an issue to consider for performance evaluation of the proposed system. Chehri et.al [9] carried an experiment at MMSL-CANMET laboratory mine in Canada. They used IEEE802.15.4 ZigBee based platform for real time implementations. They tested there developed kit in both cases line of sight and no line of sight. Results obtained revealed that the received signal strength is good in the case of LOS and significantly less in NLOS. They concluded their work stating that behaviour of radio transmission in underground mine tunnel is far away from an ideal normal environment for wireless communication. And also the geological structures of mine galleries acted as scatters which caused for fading in signal strength at receiver. Table 2 lists the communication systems and tracking devices approved by MSHA since 2011 up to 06/17/2013.

5 FUTURE PROSPECTS

Ensuring safety and support for maximization of productivity are promising issues which have to be addressed with the means of reliable communication. Harsh environment of the underground mines created havoc for miners and mining industries as well. Research efforts should continue with the view of open architecture and compatibility with future products. Hazardous environment of underground mines restricts the practical approaches and practices to the development of reliable and robust systems. Communication and tracking systems available are mostly based on zone based.

Table 2: List of MSHA approved Communication and Tracking Systems since 2011up to 06/17/13

Manufacturer	Description	Approval	Approval Date
Lockheed Martin	MagneLink Magnetic Communication System (MCS) Model No.03538-MCS-UP-001	23-A110002	07/19/11
Kutta Technologies (Transferred to Receiver Kutta Radios, Inc.)	DRUM TTR-100 Tracking Tag	23-A110003	06/24/11
Kutta Technologies (Transferred to Communication System Kutta Radios, Inc.)	Model 100S UHF/VHF Communication	23-A110004	06/24/11
Newtrax Technologies Inc.	Model Network Infrastructure Device	23-A110005	11/16/11
Innovative Wire Technologies	Model SENTINEL Beacon	23-A120001	02/16/12
NL Tech.	Model Ranger Phone	23-A120002	03/15/12
L3 Communications(Transferred to Innovative Wireless Technologies,Inc.)	ACCOLADE Miner Mesh Locator(MML)	23-A120003	04/18/12
Mine Radio Systems (Transferred to PBE Netherlands Communication System B.V. (Pyott-Boone)	Model Multi COM Leaky-Feeder Communication System	23-A120004	05/30/12
Innovative Wireless Tech	Model Sentinel Mesh Handset Two-Way Radio	23-A120005	06/20/12
Immersive Technologies	Model WFP0200830 ZAP Wireless Zone Access Point	23-A120006	12/21/12
Pyott-Boone Elec.	Model 911 Emergency communication	23-A120007	10/19/12
Innovative Wireless Technologies Inc.	Permissible Portable Mesh Node System	23-A120008	11/07/12

Efforts are needed to solve the autonomous and emergency proof robust system which is capable to track and communicate over spatial distance in real time environment. Wireless sensor network is rising as an emerging solution for mining industries. It offers several advantages over traditional networks such as large coverage area, suitability to work in dynamic topology changing environments and reduced cost. Recent developments on wireless sensor networks and wireless communication technologies benefited the automation applications in underground mining tunnels. Not only for communication and tracking but also useful for enhancing productivity. In contrast with wired network systems in underground mines, wireless sensor networks have wide range of application and give the advantages in size, cost, ease of operation, simplicity and distributed computing [9]. Using a sensor network in underground mine tunnel the production can be optimize to maximum and it also helps miners to work and understanding the production activities. There are different manufacturers which are dealing with communication systems for underground mines. Devices and their designs are different and follow different standards. With the view of working conditions, this causes to outages of a communication system as a user is forced to use one proprietary which is unable to communicate with other user which has other service provider. One should keep in mind that the developed system not only use as the communication purposes but also support maximum productivity for mining industries. It is worth mentioning here, the budget is always an issue for mining industries because the mining industries hesitate to invest in new emerging solutions. So the developed system should be economic. With the wireless communication application in mines, the cost of installation can be reduced up to 20 to 80%; as it has been estimated already that the total cost of wiring installation of industries is US $130-650 per meter [5]. Therefore, economically featured systems will have a great demand in future. UWB communication system is promising and accurate communication and positioning device widely used in multipath environment of mine. Software defined radio (SDR) is another emerging research area which is able to adopt dynamic propagation criteria addressed by signal transmission limitations in underground mines.

6 CONCLUSIONS

In comparison to surface based communication systems; underground mine communication systems have not been actively researched. Current communication scenario implies that there is huge demand to strengthen the research in the field of reliable communication system which can support voice, text and video services. Through the existing wired systems for communications in underground mine is satisfactory, but in case of any accident particularly fire and explosion, inundation, roof fall etc., the communications system fails on many occasions. As a consequence, timely rescue and recovery operation is delayed causing the loss of valuable lives and properties. It is big challenge to establish a wireless communication and to detect the trapped miners' position which will greatly support the rescue operations and improve mine safety significantly. Earlier some protocols have been implemented, but they have their limitations and not reliable from the safety point of view. Design and implementation of wireless network system with the desired output will go a long way in improving the safety in underground mines. This paper outlines the current communication systems and recent developments for underground mines. Properties of underground mines and different techniques for communication deployment are also discussed. Finally this paper gives the brief idea about the new communication systems approved by MSHA and applicability of existing technologies in underground mines.

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