Safety Assurance and Rescue Communication Systems in High-Stress Environments - A Mining Case Study

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Abstract

Effective communication is critical for response and rescue operations; however, the capricious behavior of communication devices in high-stress environments is a significant obstacle to effectiveness. High-stress environments in which disaster response and recovery operations are needed include natural calamities such as earthquakes, tsunamis, hurricanes, tornadoes, fires, floods/flash floods in urban areas; salvage, search and rescue operations in underwater, urban war zones, mountainous terrain, avalanches, underground mine disasters, volcanic eruptions, plane crashes, high-rise building collapses, and nuclear facility malfunctions; and deep-space communication in outer-space exploration. We have observed a correlation between the channel characteristics that effect the performance of the communication devices across these extreme environments. The contribution of this article is three-fold. First, it generates a list of characteristics that affect communication in all high-stress environments and then evaluates it with respect to the underground mine environment. Second, it discusses current underground mine communication techniques and identifies the potential problems. Third, it explores the design of a wireless sensor network (WSN) based communication and location sensing system that could potentially meet the current challenges. Finally, we discuss some preliminary results of an empirical study of the wireless communication characteristics of off-the-shelf MicaZ wireless sensor nodes in an underground mine in Parkes, NSW, Australia.

1 Introduction

Communication devices coupled with wireless connectivity have become an integral part of our daily life. It is difficult to imagine a world without them. They have become the lynchpin and mainstay of any social interaction, cutting-edge research, successful business, and government diplomacy. But, do they really meet our expectations in terms of reliability and availability? Are they able to adapt to any extemporaneous situation? The capricious and vacillating behavior of the communication devices in high-stress environments is a ground truth that cannot be ignored. The outbreak of bush fires in Australia, hurricanes in US, underground mining accidents in China, tremors of the tsunami and earthquakes in Asia and south-east Asia are only a few of the incidents that have resulted in gigantic loss of human life. Some of these casualties could have been avoided if a robust communication infrastructure was in place.

Quantitatively defining high-stress environments is difficult, yet they can be qualitatively illustrated by numerous examples: Natural calamities such as earthquakes, tsunamis, hurricanes, tornadoes, fires, floods/flash floods in urban areas; salvage, search and rescue operations in underwater, urban war zones, mountainous terrain, avalanches, underground mine disasters, volcanic eruptions, plane crashes, high-rise building collapses, nuclear facility malfunctions; and deep space communication in outer-space exploration. We shall discuss in detail one such harsh environment - *Underground Mines*.

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. The overall mining process is highly mobile and the mining machines have to be shifted as the mining operation progresses; consequently, the communications environment continually changes. The combination of ever-changing ground conditions with dynamic mining systems generates a variable profile of risks.

Hundreds of miners die from mining accidents every year. The Beaconsfield mine collapse in Tasmania, Australia [1]; Sago coal mine disaster in West Virginia, USA [2]; Shandong coal mine flood [3], Shanxi mine blast [4], Sunjiawan mine disaster [5], Shanxi mudslide [6], Nanshan Colliery gas explosion [7] in China; Chasnala mining disaster in India are just few of the major mine catastrophes. A comprehensive list of mining accidents and disasters has been compiled in [8]. The human casualties in mine accidents are relatively higher in developing economies such as India and China because of inadequate safety measures.

Thwarting these malignant situations in an underground mine requires:

- Monitoring gas concentrations [28, 40], which mainly includes methane that can lead to mine explosions when it exceeds a threshold level.
- Monitoring underground structures [37, 33, 32], as the unstable nature of geological construction in mines makes an underground tunnel prone to structural changes.
- Determining the location of miners [27, 44] and providing a way out of the mine in case of disaster.
- Monitoring dust concentration [47] and the risk of water irruption [25].

Figure 1.1: Summary of the mining problems.

In order to enhance rescue efforts in the event of a mine accident, the availability of the following information [9] would be extremely useful:

1. The location of trapped miners, which would facilitate the rescue team to devise the most appropriate plan to reach the victims in the least possible time.
2. Two-way communication between the trapped miners and the surface control station, which would be helpful in reporting the status and health of the trapped personnel and provide conselling assistance in order to boost their morale.
3. The environmental conditions along the rescue path to the trapped miners, including temperature and concentration of methane or other undesirable gases, which would aid in determining suitable rescue equipment and improving preparedness against any unforseen situations.

Effective communication has been critical to response and rescue operations, regardless of the type of high-stress environment. Communication failures in hostile environments often occur because of physical destruction of the network infrastructure and because of network congestion. In addition, by analyzing many high-stress environments, we observed a correlation between the channel characteristics that affect the performance of the communication devices. This observation suggests that conventional communication equipment may never be sufficient in high-stress environments, and that we should identify and investigate the various characteristics that affect communication in such environments.

The remainder of this article is outlined as follows: Section 2 conducts a general study of the channel characteristics for all high-stress environments, and then examines these characteristics in the specific case of underground mines. Section 3 explains the various communication techniques used in underground mines and provides a brief survey of the location sensing/tracking devices that are being crafted for these conditions. Wireless Sensor Networks (WSNs) have been proposed as a possible solution, so Section 4 provides a concise background and overview of existing work on WSNs and then proposes a design of a WSN-based communication system. This design is supported by an empirical study of the wireless communication characteristics of off-the-shelf MicaZ motes in an underground mine in Parkes, NSW, Australia. The final Section 5 highlights research directions in the field of underground mine communication and concludes with a summary of the important lessons we have learned during our investigations, which we believe will provide practical benefits to other engineers who are working on similar problems and projects.

2 A Study of the Communication Channel Characteristics

This section first investigates the general channel properties that are characteristic of numerous hostile environments and then investigates additional extreme channel conditions prevalent in underground mines.

2.1 High-Stress Environments

The various channel characteristics that affect communication in high-stress environments [22, 23, 42, 43, 21, 29] can be listed as follows:

- *Extreme path loss*: There are two main causes:
    - *Attenuation*: This phenomenon is the result of material absorption of the communication signals in the medium of propagation. Attenuation losses increase with the humidity of the ambient atmosphere. Loss is greater in water than in air. Loss is directly proportional to the square of the distance traveled by the wave. Loss increases with signal frequency. In the case of underwater rescue and salvage operations, acoustic wireless communications links are (much) more effective than contemporary electromagnetic(radio)/optical links, as they experience absorption rates which are approximately three (3) times lower in magnitude. Even though sea water is conductive, electromagnetic waves experience high absorption rates on the order of $45\sqrt{f}$ dB per kilometer, where f is the frequency in Hertz [43]. On the other hand, optical waves, though less vulnerable to absorption, are severely affected by attenuation caused by scattering of the signal and hence require precise pointing of narrow laser beams [22]. Acoustic signal absorption is caused by the conversion of acoustic energy into heat energy, which is absorbed by the water. Other causes of absorption and subsequent loss are reverberation, scattering, and refraction at the ocean surface. In outer space, lack of gravity and atmosphere are the prime reasons for acoustic signal attenuation.
    - *Geometric spreading*: This is the omni-directional spreading of the signal when traversing from the transmitter to the receiver; loss is dependent on the distance between them.
- *Extensive multipath propagation and fading*: This is caused by the scattering of the waves when they strike an irregular surface or when they propagate through an atmosphere with varying temperature gradients. The random addition of multiple propagational paths causes fluctuations in signal strength with position and frequency, and movement of reflectors, transmitters or receivers in time. The severity is escalated in the event of rescue operation from underneath rubble or during propagation of acoustic waves through varying water temperature at different sea heights. This may also lead to frequency-dependent fading.
- *Combinatorics of Reflection and Refraction*: Due to the extremity of the operating conditions and surrounding environment, some of the waves may

be totally reflected, partially reflected, or refracted into the communication medium. This is an adverse situation as each of these individual waveforms may add up to result in a completely new signal pattern which would be interpreted as noise at the end receiver.

- *Rapidly changing time varying channels*: Rescue/salvage operations in the event of disaster prevention or recovery may result in communication equipment being rapidly shifted from one location to another. This would result in rapidly changing time-varying channels. Underwater communication devices may encounter these conditions as a result of the movement of the ocean surface and internal waves.
- *Large propagational delay and high delay variance*: This is a prime challenge faced by communication devices and protocols used for space exploration and deep space communication as well as underwater oceanic rescue and response activities. Transmitting radio signals over long distances in space is problematic. Performance of the Transport Control Protocol(TCP) degrades because its acknowledgment-based paradigm makes round-trip-time (RTT), which may be very large in space communications, a significant factor in delay, throughput, and memory requirements. Likewise, in the case of underwater communication, the slower speed of sound in water (vs. air) results in increased propagational delay, leading to increases in system response time.
- *Random fluctuating Doppler shifts and long delay spreads*: The inconsistent motion of the transmitter/receiver as well as the multiple arrival of signals from various sources and locations are the main reasons for these characteristics, which result in high bit-error-rate (BER).
- *Temporal distortion*: This results from the multiple traversal of the signal in different propagation modes.
- *Noise*: In a disaster response and recovery situation, there can be many factors responsible for the generation of noise. It can be caused by man-made devices such as electric motors/appliances, rescue machinery and other equipment carried by first responders (fire fighters, medical teams, police, rescue personnel etc.) and/or natural/environmental phenomena such as tides, storms, rain, seismic activities, thick smoke, etc. The noise level gets severe in outer space because of cosmic rays, gamma rays emission from distant galaxies, electromagnetic radiation, solar storms, meteoroid strikes, etc. In addition, the communication devices themselves produce thermal noise (which is characteristically white).
- *Extreme Power Constraints*: Most mobile communication devices are battery-operated and require recharging on a regular basis. During and after disaster events, much of the power supply may be disrupted, rendering useless such equipment when batteries are exhausted.
- *Topological Changes*: Frequent position changes of the communication devices(nodes) render a dynamic topology. Such dynamic topology brings additional challenges for neighbour detection, routing of information, path selection, etc. In case of outer space, planetary motion, the interference of

an asteroid or a spacecraft, or orbital obscuration may result in periodic link outages with the loss of line-of-sight.

- *Synchronization problems*: The erroneous synchronization of the communication equipments may lead to faulty timestamps and location estimates which may be critical in emergency situations. It may be caused by random delay in transmission, variable link speeds, intermittent connectivity, temperature variance and electromagnetic effects.
- *Lack of interoperability*: Many devices and their related designs may be proprietary or otherwise non-compliant with standards. This leads to impairment or outages as users contracted with one service provider may be unable to communicate effectively with users served by other providers.
- *Lack of fixed communication infrastructure*: Emergency situations demand *ad hoc* deployment of communications infrastructure, which may be shifted from place to place according to the demands of the moment. As a result, devices operating under the assumption of a configured topology may need to be reset and re-configured, either automatically or manually. This may lead to brownouts or outages.

As a consequence of these channel properties, communication devices may suffer from limited bandwidth, intermittent link connectivity, high link error and signal/packet loss rates, unacceptable jitter and delay (in the case of low-latency applications such as voice and video conferencing) and reduced data communication rates with an increase in intersymbol interference (ISI), resulting in high bit-error-rate (BER).

2.2 Underground Mines

The underground mining environment is significantly different from that of 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 amounts of accumulated water. Some parts of the wall and ceilings are strengthened with wooden grids and metal [49]. Environmental conditions that affect communications include:

- *The dynamic change in underground topology:* The walls of the mines may shift daily as a result of the cutting of the mineral faces.
- *The unstable nature of geological construction:* A mineral face consists of safe and collapse zones. In the safe zones, there are hydraulic supporters to avoid collapses. In collapse zones, there are no supporters and they can easily collapse either when the zone becomes larger or in the event of minequakes, resulting in structural changes [35].
- *Limited Line-of-Sight (LOS):* This arises from the presence of pillars and undulations following the mineral seam. These underground structures are created during the mineral extraction process.
- *Low loss dielectric medium:* At certain frequencies, the mine tunnel acts as low-loss dielectric [39]. Waves propagating through a dielectric medium experience a reduced propagation velocity compared to that of air.

- *Ionized air:* Air ionizes 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 oxidation heat is released from the coal and may cause fires [46].
- *Humid and warm conditions:* The relative humidity is greater than 90% and the temperature is approximately 28 degrees C [46].
- *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, gas blasts/coal-dust explosions may occur [35]. Hence, there is continual ventilation to decrease the build-up of the gas. However, in the case of a disaster, the power supply to the mines is often cut, leading to the compromise of the ventilation system and then dangerous gas concentrations [10].

Besides these natural conditions, every mine has its uniqueness. The combination of inherent characteristics and circumstances may result in significant path loss, multipath propagation and fading, reflection and refraction, and reduction in the propagation velocity of the communication signals. In addition to the above discussed channel properties in extreme environments, the other unique channel characteristics in underground mines are as follows:

- *Realistic waveguide effect*: The tunnel acts a low-loss dielectric at certain frequencies and leads to a waveguide effect. In an ideal waveguide effect, electromagnetic waves are confined and guided by the mine tunnel, but in a realistic scenario, the reflection and absorption losses along the path result in an increase in signal attenuation.
- *Noise*: Environmental noise in the form of lightning strikes under stormy conditions have an adverse effect on communication systems. This flow of current in the form of electrical charges give rise to EM waves of high intensity, which interfere with radio communications. The noise caused by electric motors, machinery, power lines and appliances are in the frequency bands in which underground communication devices operate [38].

3 Underground Mine Communication

This section describes the different communication techniques applied in underground mines and provides a crisp discussion about the latest communication/tracking devices under research, development or testing phases.

3.1 Communication Techniques

There are three communication techniques applied in mines [38]:

1. *Through-the-Wire (TTW)*
2. *Through-the-Air (TTA)*
3. *Through-the-Earth (TTE)*

These can be classified on the basis of communication types (wire-line/wireless) as shown in Fig. 3.1.

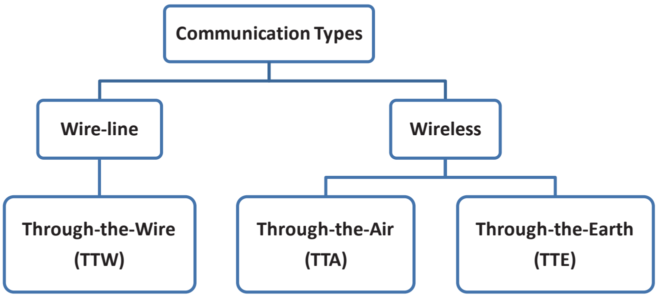


Figure 3.1: Classification of Underground Mine Communication.

Through-the-Wire (TTW)

The 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*, *fiber optic* and *leaky feeder* [11]. 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. 3.2). The increase in signal range is the result of lower attenuation in the cable as compared to the free space propagation in the mine.

Though the performance of the TTW is satisfactory for routine operations, yet it is not robust as it is subject to failure/wear and tear under the conditions of roof falls, mine fires and explosions, power failure, interference from other machinery and inadequate maintainability [11]. Additionally, leaky feeder cable systems have limited coverage in cross-cuts and hence additional splitters/cables are required to be installed.

In order to improve the reliability of the existing systems, various cable protection schemes have been applied. They include putting the cable in a

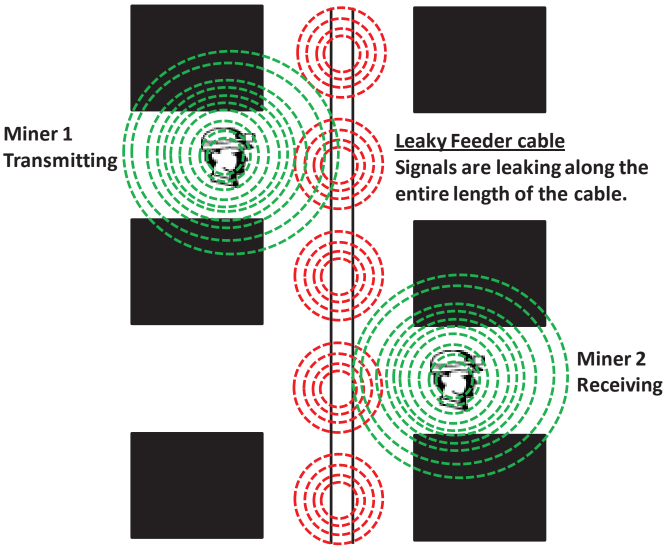


Figure 3.2: Communication achieved through Leaky Feeder cables

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 [11]. However, these methods are not only expensive but also add to the maintenance and complexity of the system. Moreover, the borehole cable protection method has its own set of problems that include impedance of the radio signal and being 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. Fiber optic cables have a profound advantage over conventional wired communication techniques as they are insusceptible to electrical interfence. The existing communication devices [39][38] that use the technique of TTW have been tabulated in Table 3.1.

Through-the-Air (TTA)

The TTA communication technique refers to radio communication used in mines. Both metalliferous and coal mines present an unique set of challenges for radio communication. The undulating structures inside the mine are unfavorable 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 [26]. Transmission takes the form of waveguide propagation in the tunnel, since the wavelengths of the UHF waves are smaller than the tunnel dimensions. An EM wave can propagate in any of the 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

Table 3.1: Communication Devices

Name	**Type**	**Advantages**	**Disadvantages**
Telephones	TTW	1.Easy operation	1.Vulnerable to damage from roof falls, mine fires and explosions
Pager Phones	TTW	1.Cheap 2.Easy operation	1.Battery operated 2.Noisy transmission
Trolley Phones	TTW	1.Fixed/Mobile 2.Provide communication to all rail haulage vehicles	1.Limited Coverage 2.Noisy transmission due to: a)constant vibration b)warm, humid and dusty conditions c)wiring of the transmission lines across various machineries
Hoist Phones	TTW	1.Easy operation	1.Limited to communication between the hoist cage (used to raise and lower conveyances within the mine shaft) and the surface/underground
Walkie Talkie	TTA	1.Wireless radio communication (half duplex only) 2.Portable 3.Bidirectional 4.Better coverage area	1.Used in conjunction with leaky feeder cables and line amplifiers for signal transmission across corners and bents

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.

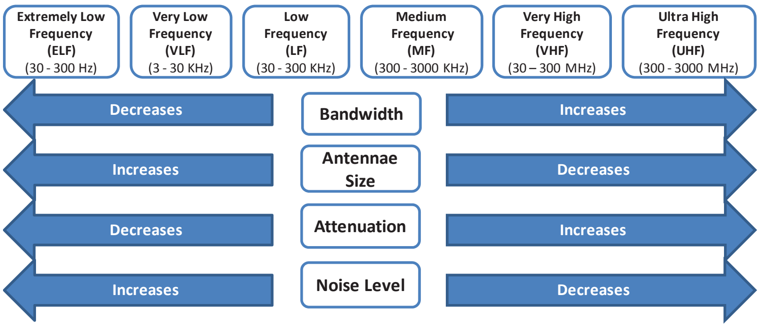


Figure 3.3: Impact of Frequency Selection

The frequency selection has a major impact on the signal propagation [10]. Fig. 3.3 explains the dependency of signal bandwidth, attenuation, antennae size and noise level on the selected frequency. Research has shown that medium frequency (MF) offer better usability in underground mine communication. *Walkie-Talkie* is a TTA communication device (Table 3.1).

Through-the-Earth (TTE)

The operating frequency that is used by the TTA systems is unable to penetrate the rock strata and becomes unoperational in the event of mine accidents. TTE communication systems prove to be superior as they do not require pre-existing cables/communication technology and use ultra low frequency signals for communication [38] thereby removing the dependency on additional network infrastructure. The antenna is located on the mine surface which provides coverage to various parts of the mine (Fig. 3.4), thus reducing the risk of damage in emergency. However, such a system is prone to various challenges [12]:

- EM waves get reflected off the surface of the earth or experience substantial attenuation and weaken as they penetrate through the underground earth surface. As a result, the waves are not able to travel more than a few feet below the surface.
- Large antennas have to be designed for receiving ultra low frequency signals.
- Low frequencies have low bandwidth and hence the TTE system would face technical limitations in sending voice data.
- Communication using TTE system would be challenged by machinery noise as most of them exist at low frequencies.

Nevertheless, research in TTE communication has shown that the use of frequencies less than 10KHz can transmit to depths of the order of thousands of feet below the surface but a thorough investigation is still required to circumvent the above mentioned limitations.

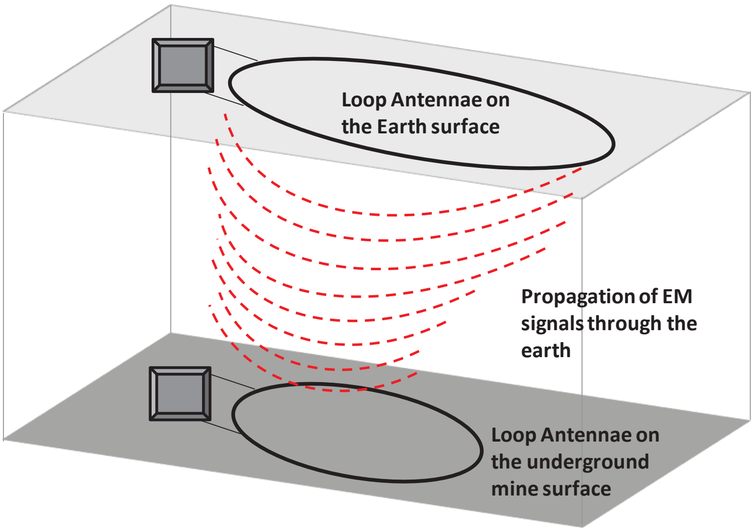


Figure 3.4: TTE Communication

3.2 Tracking Systems

The majority of tracking devices are based on *Radio Frequency Identification (RFID)* technique. It consists of 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. 3.5). However, the latest tracking systems are based on digital data networks which include *TCP/IP, Ethernet, WiFi, Wireless Mesh Networks, VoIP, Cell phone technology.*

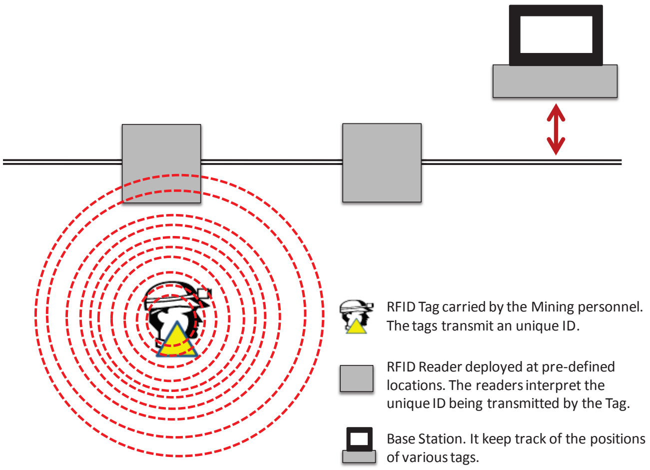
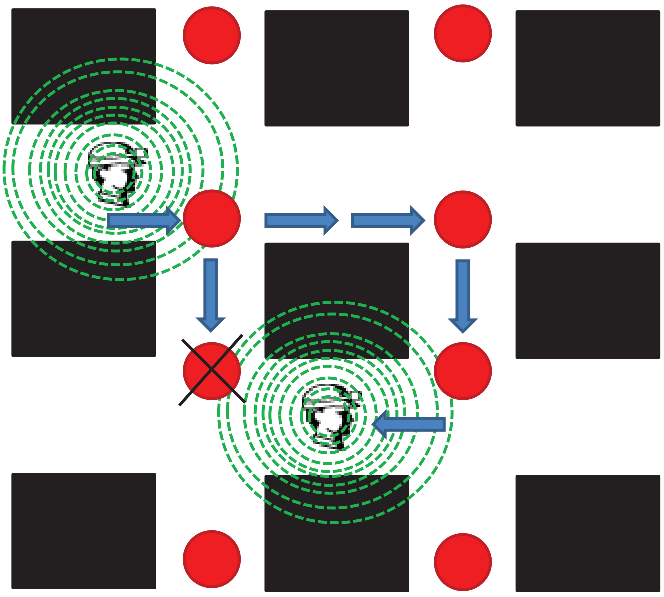


Figure 3.5: RFID Tag based communication

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 [13] [14] [15] [16] [17]. The U.S. Bureau of Mines, CSIRO (Australia), CSIR (South Africa) are some of the noteworthy organizations in this regard. 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. [18] gives a complete list of MSHA approved communication and tracking devices. Designing and developing such systems for underground mines should have certain de facto standards. [19] gives a list of the ideal requirements for confined space communication systems.

[36] provides a survey of the commercially available underground mine communication and tracking systems available with the manufacturers and vendors. However, an assessment of performance and limitations has not been described in [36] as the utilization of these products in mines is presently not known and the compiled information is from the respective company websites which feature mostly on the promised functionality. However, [20] presents a brief report on the test results for some of the communication and tracking devices mentioned in [36]. The discussed underground mine tracking systems can be classified into the following types based on the tracking type [10]:



The system reconfigures when a node in a route fails and determines a new route for communication.

Figure 3.6: Node based tracking systems : A Wireless Mesh Network

- *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 (Fig. 3.6). Resolution depends on the number of nodes and the fidelity of the signal processing technique.

4 Wireless Sensor Networks in Mines

Having discussed the various communication channel characteristics for high-stress environments in general and underground mines in particular, as well as understanding the communication techniques (TTW,TTA,TTE), it is evident that the current technologies are inadequate to address the various challenges. A majority of the existing communication devices used in mines are wire-line systems. The drawbacks of using wired systems in mines have been extensively discussed in the previous section. Additionally, there are very limited environmental monitoring capabilities in the current systems. These open issues need to be addressed in order to provide safety assurance and rescue communication capabilities to administer the hostile environment of an underground mine. This section investigates feasibility of the emerging wireless sensor networking technology for a location sensing and environmental monitoring system and discusses related work and our own experiences in the deployment of a WSN in an underground mine in Parkes, NSW, Australia.

4.1 Background

Recent developments in Wireless Sensor Networks (WSNs) provide a new option for portable wireless systems as the WSN nodes provide the means to link the physical world to the digital world in a cheap and efficient manner. Individually, these resource-constrained devices appear to be of little value. However, deploying these sensors on a large scale across an area of interest can be quite effective. Placing the sensors in hostile or inaccessible regions may allow for data collection, which was previously impossible. Hence, they offer excellent remote monitoring capabilities. Using WSNs, the moving miners and machinery can estimate their location by co-operating with nearby objects by sharing the sensor data in order to minimize the overall location error [41, 30]. With a moderate upgrade of the processor used in the traditional sensor nodes built for simple tasks such as temperature/humidity measurements, fast and efficient object tracking can be performed. In addition, these devices could have additional sensors to monitor gas and dust concentration inside the mines and the stability of underground structures.

A portable wireless system would be a better option in mines because it offers the best resistance against dynamically changing situations as they are resilient to damage from roof falls inside the mines, fires, and explosions. A compact system that can be carried by miners and does not require pre-existing infrastructure in terms of pre-installed antennas may be desirable.

4.2 Requirements for a WSN in harsh environments : Methodology

There are a number of important questions that must be considered in order to devise a WSN implementation of a location sensing and environmental monitoring system for underground mines:

- Type of sensors required for present and future integrability and enhancement.

- Modifications required on the sensor mote to be directly usable in the mining environment. As the system would be operated in a highly noisy environment, a good signal reconstruction is one of the prime requirements that would reduce the chances of false positive for identification purpose. The sensor mote should have high resolution signal sampling processor to address this requirement.
- Sensor life-span: Scope for increase in longetivity without replacement. This can be achieved through long lasting batteries that do not require replacement before a substantially long time frame and should not be a fire/explosion/electrical hazard.
- Sensor protection: Need for effective shielding to prevent permanent damage or faulty operations in normal/mine accident circumstances. The protective casing shield should be fire- and dust-resistant. Additionally, dessicants (silica gel) can be applied inside the protective casing to prevent the sensor node from succumbing to the high humidity inside the mines.
- How, in what form, when and where should the information be retrieved and stored/exchanged in order to ensure reliability under harsh operating conditions. The system should be delay-tolerant to compensate for failed nodes or slow communication among nodes, which may be achieved through local buffering and data redundancy techniques.
- System health information: Need for monitoring the functional status during normal conditions as well as after the occurrence of a mine accident.
- How can the system be repaired for erroneous behavior? Is human intervention required or can it be done efficiently from a remote control station?
- How should the distributed-sensors data received from the system be converted into meaningful information for best possible decisions under a given circumstance?

The amalgamation of associated design principles would facilitate in devising an improved system.

4.3 Empirical Study in an Underground Mine

In order to understand the limitations faced by the currently available state-of-the-art sensor motes, we conducted a set of empirical experiments using off-the-shelf wireless sensor nodes in underground gold and copper mines in Parkes, NSW, Australia. Off-the-shelf MicaZ motes were used in the deployment and testing phase. The objective of these experiments were to investigate the fidelity of wireless communication using sensor motes and to learn about deployment challenges in harsh environments such as underground mines.

Deployment

Getting access to a mine is a methodical process wherein the entrants had to undertake a safety induction program prior to entering the mine. All equipments that were being carried into the mine had to be tested and cleared of potential mine accident threats. All the motes were programmed before entering the mine. The MicaZ motes were placed in plastic boxes to act as a protective casing. A hole was drilled in the boxes to get the antennae of the sensor motes out of the casing.

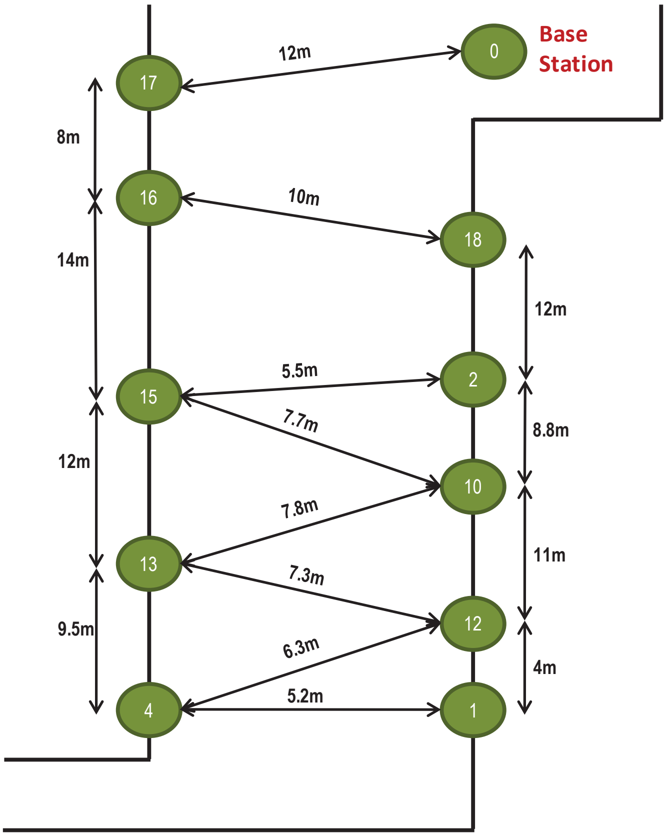


Figure 4.1: Experimental setup inside the mine.

The mine tunnel that was accessible for experimentation was approximately 5 meters in width and 10 meters in height. The walls of the mine had bolts sticking out approximately 2 meters from the base tunnel surface. The plastic boxes (concealing the MicaZ motes) were hung up on these bolts using a zip tie. Mote 0 was configured as the base station while all the other motes (1-18) were placed along both walls of the tunnel as depicted in Fig. 4.1. An experiment was conducted to test whether the motes (1-18) are able to successfully send packets to the base station(Mote 0).

Discussion

Setting up the experiment proved to be more difficult than expected. The humid and dusty environment inside the mine proved to be a great hindrance. When the motes were placed at a distance of 15 meters from each other, no packets were received by the base station from majority of the motes. Hence, in the second setup, the motes were placed much closer to each other as depicted in Fig. 4.1.

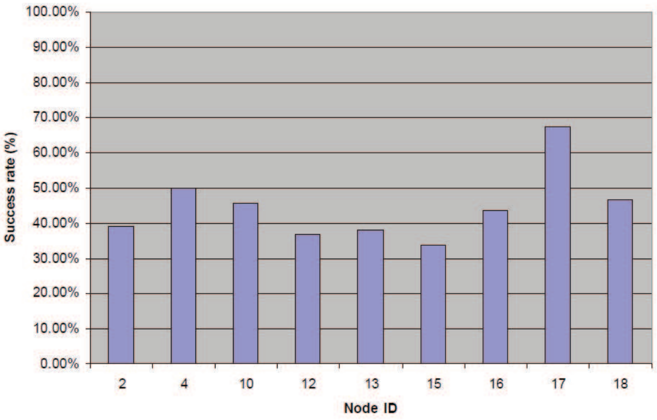


Figure 4.2: Success Rate Vs Node ID

Deployment of sensor motes inside a dark underground mine tunnel is a non-trivial task as the acoustics properties do not permit people to communicate with each other if they are more than 50 meters apart. Fig. 4.2 shows the percentage of successfully received packets at the base station (mote 0) for each of the individual motes. The success rate of packets received is less than 50% for most of the motes.

Sensor motes hung up on the bolts on the mine walls, attained their stable position in a skewed angle. There were various objects attached to the mine wall and people were walking up and down the tunnel. All of these factors resulted in severe signal attenuation. There was a difference in the quality of the motes as some motes achieved good signal strength in the communication while others failed to communicate at the same distance in a severe situation. Besides these, there were anomalies in antenna capabilities and battery functioning. All of these experiences suggest that the currently available sensor nodes are not suitable for underground mine communication.

4.4 Existing Work

We provide a brief survey focusing only on the systems design and deployment effort of WSNs in underground mines.
Li et al. [33] presents sensor network deployment and collaborative communication strategy to detect the structural changes in the event of underground mine collapses. Field studies were conducted through the deployment of a prototype system consisting of 27 Crossbow Mica2 motes in the D.L coal mine in China. The prospects of using ultra-wide-band (UWB) signals in conjunction with WSNs for localization in underground mines has been studied in Chehri et al. [24]. Measurement data for simulation were collected from the CANMET experimental mine in Canada. Xuhui et al. [48] describes the implementation of a methane gas sensor and proposes an automatic calibration technique with the help of network connectivity. FireFly, a new sensor hardware platform based on cross-layer solution for tracking and voice communication in harsh environments, was introduced in Mangharam et al. [34]. The experimental results were

collected in a NIOSH experimental coal mine. Xiaodong et al. [44] describes the experiences in monitoring the coal mine conditions through a wireless network consisting of Crossbow MicaZ sensor nodes equipped with custom developed multi-functional sensor boards. Xiaoguang et al. [45] describes a distributed heterogeneous hierarchical mine safety monitoring prototype system based on WSNs capable of monitoring gas concentration and locating the position of miners The performance of this scheme was evaluated in Dayan Coal Mine, inner Mongolia province. Lanzisera et al. [31] has presented measurement results and ranging accuracy for RF time-of-flight(TOF) between two Mica sensor motes in an non-functional coal and silica mine.

5 Research Direction and Conclusion

Performance of communication and tracking systems in underground mines is an area that has not been actively researched as extensively as contemporary surface-based systems. There are few existing systems and there is limited information regarding the actual implementation in mines. Ensuring safety of the mining personnel is one of the dominant issues. However, the texture and attributes of mines, and the paucity of practical solutions has curtailed the genesis of a robust safety system. In lieu of the experiences learned from mining accidents, there is a need to research the applicability of new technologies in mine environments. The current systems lack proactiveness in predicting the possible occurrence of an accident. There is a need for engineering early warning systems to bridge this gap because there is very limited capability to control the intensity and impact of a disaster when it strikes.

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. 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 outlines various types of high-stress environments and generalizes the characteristics that affect communication under such deployments. It presents an insight into the working environmental conditions present inside the mine which elucidate the fact that it possesses various challenges to communication. The design and implementation of a communication solution, underground channel properties and various communication techniques have been discussed. The article then provides a description of the state-of-the-art communication and tracking systems currently available. We have also discussed the emerging WSN technology and its feasibility in high stress environment such as underground mines. In the final part of the paper, our preliminary attempt of deploying and testing the working of a general purpose WSN node (MicaZ) has been described.

We anticipate that this paper will serve as as building block for researchers interested in developing communication and location sensing systems for high-stress environments.

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