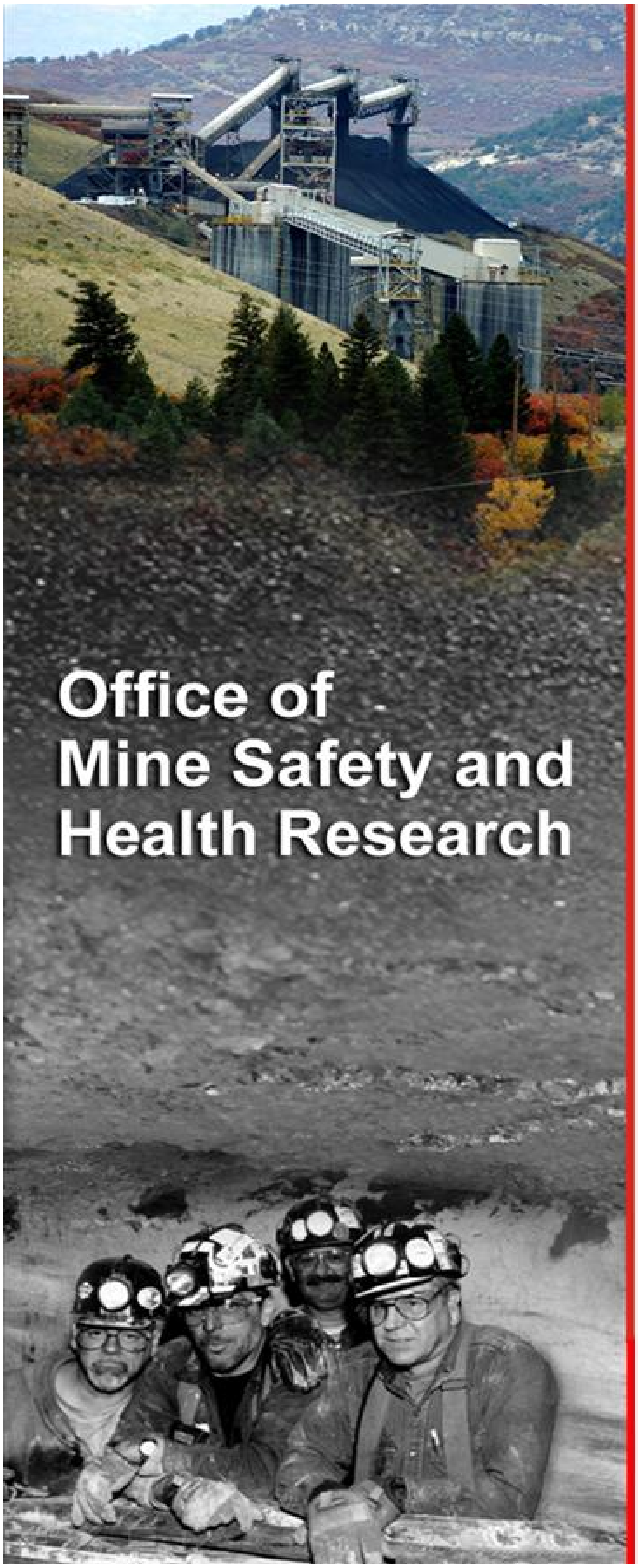

Tutorial on

Wireless Communications & Electronic Tracking

Working Draft

May 2009

CDC Workplace Safety and Health

NIOSH

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PREFACE

This document is being provided to the mining industry as a working draft. The intent is to make information available to labor, industry, regulators, and academia that is relevant to the Communications and Tracking systems that are being installed for compliance with the MINER Act.

As a working draft, the document has not yet been through the rigorous external peer review process that NIOSH publications require before being distributed as an official NIOSH document. The document has been reviewed internally; however, it was determined that NIOSH review and release process would not likely be completed for the June 15, 2009 compliance date that is required by the MINER Act. Therefore, the decision was made to distribute this document as a working draft and to follow with a final publication as quickly as possible.

We would like to acknowledge the contributions of the Defense Information Systems Agency, Joint Spectrum Center, Annapolis, MD which prepared much of the material contained in this document under an Inter-Agency Agreement (IAA) with NIOSH. We also want to acknowledge the contributions of the NIOSH research staff, whose extraordinary effort made this document possible in an exceptionally short period of time.

TABLE OF CONTENTS

1. INTRODUCTION 4

2. CT TECHNOLOGY OVERVIEW 6
2. 1 COMMUNICATIONS BASICS 6
2.1.1 Physical Communications Links 7
2.1.2 Networks 8
2.1.3 Wireless versus Wired Systems 10
2.2 COMMUNICATIONS SYSTEMS PRINCIPLES OF OPERATION 11
2.2.1 Hardwired Systems 11
2.2.2 Wireless Systems 12
2.3 TRACKING SYSTEMS PRINCIPLES OF OPERATIONS 24
2.3.1 Manual Tracking Systems 24
2.3.2 Reader-based Tracking Systems 24
2.3.3 Radio Node-Based Tracking Systems 28
2.4 NETWORK OPTIONS 29
2.5 MINE OPERATIONS CENTER 31
2.5.1 Tracking Displays 31
2.5.2 Surface Communications 32

3. COMMUNICATIONS SYSTEM PERFORMANCE 34
3.1 GENERAL PERFORMANCE CONSIDERATIONS 34
3.1.1 Physical Communications Link 34
3.1.2 Network Performance 42
3.1.3 Management of the Electromagnetic Spectrum 43
3.1.4 Modeling and Analysis 44
3.1.5 Maintenance and Testing 46
3.1.6 Performance Goals and Metrics 46
3.1.7 Wireless Systems Considerations 50
3.2 Point-to-Point Communications 51
3.3 Wired Communications 51
3.3.1 Twisted Pair 51
3.3.2 Ethernet Cable 51
3.3.3 Fiber Optic Cable 52
3.4 LEAKY FEEDER SYSTEMS 52
3.4.1 Description 52
3.4.2 Components 53
3.4.3 Transmission Media 55
3.4.4 Network Operations 57
3.4.5 System Implementation 58
3.4.6 Maintenance and Inspection 60
3.4.7 Performance & Limitations 61
3.5 MEDIUM FREQUENCY SYSTEMS 62
3.5.1 Description 62
3.5.2 Components 64

3.5.3 Transmission Media 65
3.5.4 Network Operations 66
3.5.5 System Implementation 66
3.5.6 Maintenance and Inspection 71
3.5.7 Performance & Limitations 72
3.6 NODE-BASED SYSTEMS 74
3.6.1 Description 74
3.6.2 Components 79
3.6.3 Transmission Media 80
3.6.4 Network Operations 82
3.6.5 System Implementation 84
3.6.6 Maintainability and Inspection 85
3.6.7 Performance and Limitations 86
3.7 THROUGH-THE-EARTH SYSTEMS 89
3.7.1 Description 89
3.7.2 Components 91
3.7.3 Transmission Media 91
3.7.4 Network Operations 92
3.7.5 System Implementation 92
3.7.6 Maintenance and Inspection 93
3.7.7 Performance and Limitations 94
3.8. Communications Technology Comparisons 95
3.8.1 Comparison Matrix 96

4. ELECTRONIC TRACKING SYSTEM PERFORMANCE 96
4.1 Tracking Techniques 97
4.2 Reader-Based 98
4.2.1 Zone-Based RFID 98
4.2.2 Reverse RFID 107
4.3 Node-Based Communications with Integrated Tracking 116
4.3.1 Description 116
4.3.2 Components 117
4.3.3 Transmission Media 117
4.3.4 Network Operations 117
4.3.5 System Implementation 118
4.3.6 Maintainability and Inspection 118
4.3.7 Performance and Limitations 118
4.4 Inertial Navigation 119
4.5 Tracking Technology Comparison 120
4.5.1 Comparison Matrix 121

5. CT SYSTEM SURVIVABILITY, RELIABILITY, AND AVAILABILITY 121
5.1 General Considerations 122
5.1.1 Objectives and Approaches 123
5.2 Survivability and Reliability 123
5.2.1 Techniques to Enhance Survivability and Reliability 129

5.2.2 Calculation and Modeling 138
5.3 Availability 139

6. CT SYSTEM SAFETY 141

6.1 Permissibility 141
6.1.1 Explosion-Proof Enclosures 142
6.1.2 Intrinsic Safety Certification 143
6.2 Battery Requirements 143
6.3 Hazards of Electromagnetic Radiation 144
6.3.1 Personnel 144
6.3.2 Explosive Atmosphere 145
6.3.3 Electro-Explosive Devices 145
6.4 Electromagnetic Compatibility 147
6.4.1 Electromagnetic Interference 147
6.4.2 Standards and Regulations 148
6.4.3 Design and Construction Guidelines 149

7. MINE OPERATIONS CENTER 150

7.1 Tracking Displays 150
7.2 Surface Communications 151

8. BIBLIOGRAPHY 154

8.1 References 154
8.2 Additional Resources 155
8.3 Acronyms 156
8.4 Glossary 159

A. CT SYSTEMS ENGINEERING SPECIFICATIONS A-1

B. THEORY.. B-1

1. INTRODUCTION

The MINER Act of 2006 requires mine operators to adopt underground communications and electronic tracking (CT) systems that meet specific performance goals. The Mine Improvement and New Emergency Response Act of 2006 (MINER ACT) was signed into law on June 15, 2006. It amended the Federal Mine Safety and Health Act of 1977 and was intended to improve the safety of miners. Among other things, it provides updated requirements for emergency response, incident command and control, mine rescue teams, and incident notification.

The MINER Act provides two sets of requirements for communications and tracking:

- The first set of requirements went into effect no later than 60 days after enactment of the MINER Act. It required an emergency response plan (ERP) to be submitted that provided for a redundant means of communication with the surface for persons underground, such as a secondary telephone or equivalent two-way communication. The ERP also must provide for above ground personnel to be able to determine the current, or immediately pre-accident, location of all underground personnel. Any system so utilized must be functional, reliable, and calculated to remain serviceable in a post-accident setting.
- The second set of requirements goes into effect no later than three years after enactment of the MINER Act (June 15, 2009). It requires a plan to be submitted for approval that provides for post accident communication between underground and surface personnel via a wireless two-way medium, and an electronic tracking system that permits surface personnel to determine the location of any persons trapped underground or set forth within the plan the reasons such provisions cannot be adopted. Where such plan sets forth the reasons such provisions can not be adopted, the plan must set forth the operator’s alternative means of compliance. Such alternative must approximate, as closely as possible, the degree of functional utility and safety protection provided by the wireless two-way medium and electronic tracking system.

One of the goals of the Act is to provide wireless communications and location information between underground workers and surface personnel following an underground accident. The CT technology that is available, or anticipated to be available soon, to meet these goals may be unfamiliar to the mining professionals who need to purchase or use this technology. The purpose of this tutorial is to introduce the different types of CT technologies, describe how they work, and provide guidelines or metrics that allow the reader to evaluate and compare systems.

This tutorial addresses the needs of three different types of readers:

- People who require a basic understanding of the distinguishing features and operations of different CT systems.
- People with a technical background who need more information to compare systems or whose job responsibilities require advanced knowledge.
- Communications experts who need to understand how the underground environment influences the performance of CT systems.

The audience is assumed to be associated with coal mining and therefore, familiar with coal mining operations and terminology.

Chapter 2 provides a brief overview of CT systems intended to meet the needs of the first type of reader. Chapters 3 through 7 provide more detailed description as might be required by the second type of reader. The Appendices present information intended for experts in CT technology. After reading the appropriate chapters, the reader should walk away with an adequate understanding of:

- CT technologies that are being proposed for use in underground coal mines.
- How the different CT systems work.
- Advantages and disadvantages of different CT systems.

2. CT TECHNOLOGY OVERVIEW

This chapter provides a brief overview of the technologies proposed for underground coal mine wireless communications and electronic tracking. People with CT knowledge or those desiring a more complete explanation may wish to skip to Chapter 3.

The term *system* describes a collection of components that must be connected or operated together to make a working arrangement — in this case a communications system or a tracking system. A mine may have a communications system that is completely separate from the tracking system. An *integrated system* is a single system that provides both communications and tracking. Communications systems and electronic tracking systems have similar principles of operation, but because they address different needs, they are best understood if discussed separately. Therefore, this chapter breaks CT systems into five parts: Communications Basics, Communications Systems Principles of Operations, Tracking Systems Principles of Operations, Network Options, and the Mine Operations Center.

2.1 COMMUNICATIONS BASICS

All modern communications and electronic tracking (CT) systems depend on the transmission and reception of energy. *Electromagnetic energy* is energy associated with CT systems for nearly all modern systems, and for all of the systems discussed in this tutorial. Electromagnetic energy is everywhere in the environment and examples include radio waves, visible light, and x-rays. Many common devices depend upon sending or receiving electromagnetic energy for their operation. Some examples are televisions and radios, cell phones, automatic garage door openers, and remote keyless entry fobs for cars. Electromagnetic energy can be visualized as a traveling wave of electric and magnetic energy. All waves are characterized by their *wavelength* and *amplitude*.

The *wavelength* is the distance between adjacent peaks of a wave. Notice that the wavelength of the blue wave in Figure 2-1 is longer than that of the pink wave. The unit of measure for wavelength is meters or feet. The *amplitude* is a measure of how tall the wave is. The blue wave in Figure 2-1 has greater amplitude than the pink wave.

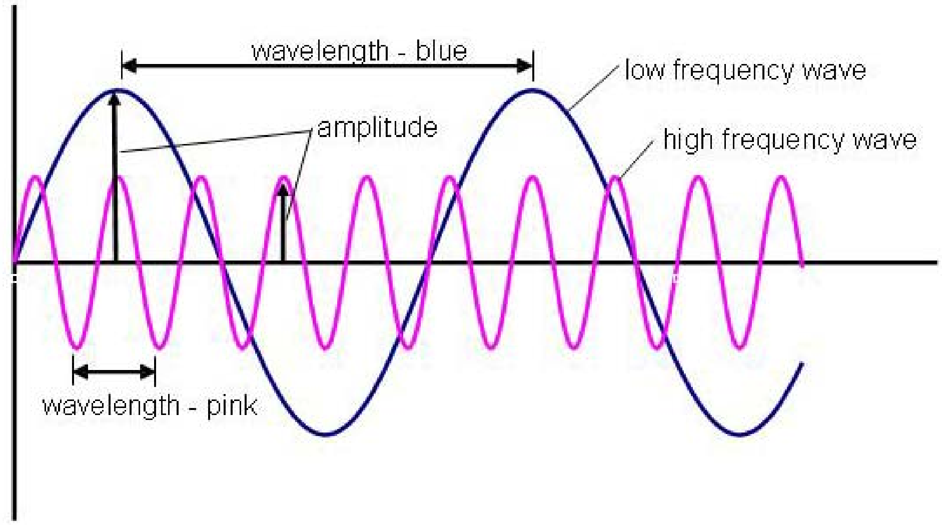

Figure 2-1. The Main Characteristics of Waves

In discussing their CT systems, manufacturers will typically mention the frequency at which the systems operate. The frequency relates directly to the wavelength. *Frequency* is a measure of the number of up and down oscillations or repetitions of the wave over a fixed length of time. The fewer oscillations that a wave has within a fixed period, the lower the resulting frequency will be (and the longer the wavelength). The blue wave in Figure 2-1 has fewer oscillations than the pink wave, so it has a lower frequency. Cycles per second, or Hertz (Hz), is the measure of frequency. Low frequency waves have longer wavelengths while high frequency waves have shorter wavelengths.

The frequency (or wavelength) of a particular CT system is a very important factor in its design and operation because certain wavelengths lend themselves well to traveling through a given transmission media. For instance, very long wavelengths can travel a significant distance through the earth. Radio communications use short wavelengths, which travel well through the air or down tunnels, while extremely short wavelengths are required to travel within fiber optic cables. For a more detailed discussion of frequency, please see Appendix B.

This fundamental background in electromagnetic energy leads us to the principles of operation behind communications systems.

2.1.1 Physical Communications Links

Communications technology involves electronic devices that allow people to talk or send information to each other. In its most elementary form, a communications system is made up of a transmitter, transmission medium, and a receiver. Figure 2-2 shows these basic components. The transmitter is the device that sends out the signal, and the signal contains the information in the form of an electromagnetic wave. The information could be part of a conversation or a text message. The signal travels through or along a transmission medium such as air, wires, metallic pipes, fiber optic cable, or even the ground. A receiver then picks up the signal and a physical communication link is accomplished.

In the example shown in Figure 2-2, there is only one transmitter and receiver pair involved in the communications path, or one physical communication link. Obviously, for two people to talk

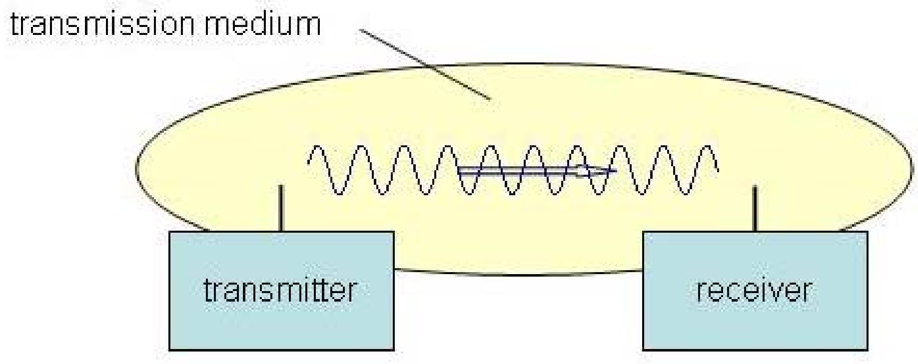

Figure 2-2. The Basic Components of a Physical Communications Link

back and forth a transmitter and receiver are required on both ends of the communication. A *transceiver* is a device that combines the transmitter and receiver into one unit; a walkie-talkie is a good of example of such a device.

In most communications systems, the needs are more complex than that depicted in the diagram because multiple physical communication links may be involved in establishing the connection between the sender and receiver. For example, a cell phone may transmit over the air to a cell tower, which transfers the signal to a telephone line, and then to a different cell tower, and finally over the air to another cell phone. The connection between the sender and the receiver involves multiple physical communication links from the user's phone, to the cell tower, to the phone line, through the telephone system, back to another cell tower, and finally to the receiver's phone. These multiple link systems are called *networks*.

2.1.2 Networks

Two people using walkie-talkies to communicate will find that as they increase their separation distance, eventually the distance becomes large enough that they can no longer communicate. This limitation established by the separation distance, or *range*, comes about due to energy being lost within the transmission media. The transmission media dissipate energy until the energy is so low that the receiver can no longer "hear" the transmitter.

Another factor limiting the range between two transceivers is *noise*. Noise is unwanted electromagnetic energy that makes it difficult for the receiver to "hear" the transmitter. A parallel can be drawn to trying to communicate with someone across a crowded, noisy auditorium. To be heard a person may have to shout (increase power) or get the audience to be quiet (lower the noise level).

Whether the cause is dissipation of energy in the transmission media, noise, or a combination of both, eventually the range of a single physical communication link becomes limited. Adding a *node* between the transceivers can increase the allowable distance between them. Among other functions, the node acts as a *repeater*, which relays the message from one transceiver to the next (in either direction) by automatically retransmitting the signals it receives. This retransmission may also involve converting the transmission frequency so that it can transmit across a different transmission medium, such as a wire. The retransmission may also involve sending the signal to multiple destinations or amplifying the signal. With the additional device of a node in the communications link, the result is a simple communications network. A communications network is a system of interconnected pieces of communications equipment used to transmit or receive information.

In the network in Figure 2-3, there are two physical communication links: one from the radio to the node (repeater) on the left and one from the repeater to the radio on the right. Generally, the same antenna on the node receives and re-transmits the message, but there may be separate antennas dedicated to each function. In the figure, the node receives the RF signal from the radio on the left. The signal travels into the node where internal electronics process the signal, amplify it, and then retransmit it. The radio on the right then receives the signal. In this case, the situation is more complicated than simply connecting two radios by an air medium.

It is easy to imagine extending the range of the communications shown in Figure 2-3 even further by adding an additional repeater between the two radios. Figure 2-4 shows two nodes, each with a defined communications range. The pink dotted line shows the range of the pink node and the blue dotted line shows the range of the blue node. The antennas of the nodes are within the range of each other, because the pink node’s antenna is within the blue oval and the blue node’s antenna is within the pink oval. Because the nodes are within each other’s range, they can pass communications in either direction between the two nodes. With this network, two radios within range of either node will be able to communicate with each other.

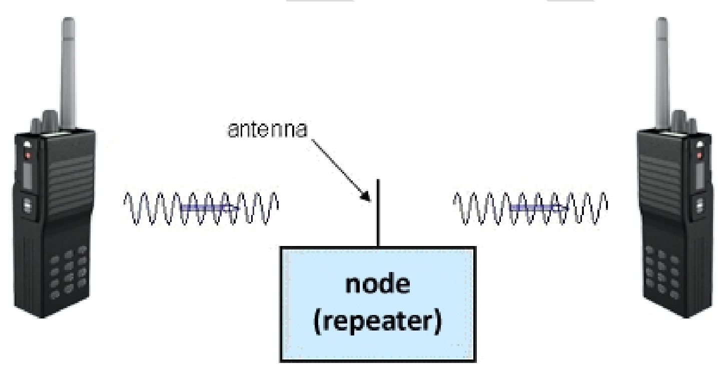

Figure 2-3. Example of a Very Simple Network

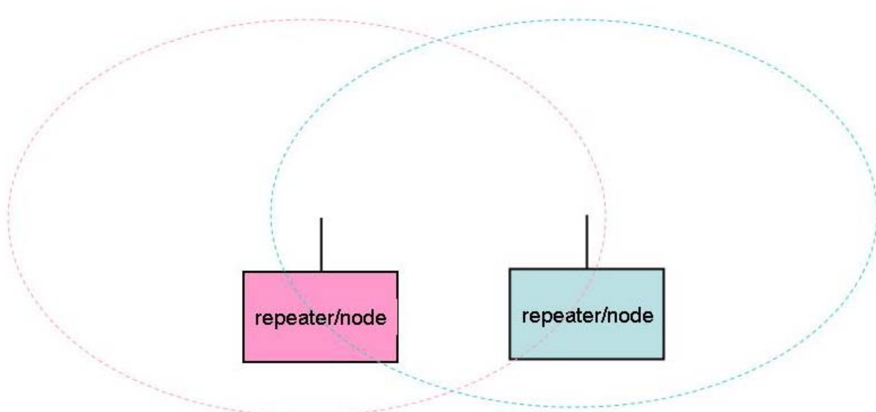

Figure 2-4. The Communications Range of Two Nodes

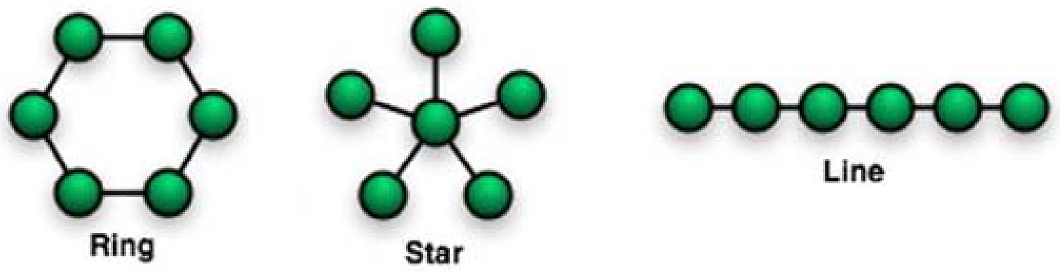

Figure 2-5. Examples of Network Configurations

The communications path between two radios can be referred to as direct point-to-point (involving only one physical communication link), or it can be achieved through a complex network that connects the source and destination (involving multiple physical communication links). The interconnection between the nodes in the network can be wireless or wired. Fiber optic cable or other means can also be used to connect the nodes. Figure 2-5 shows three examples of network configurations for interconnected nodes.

The solid lines in the above diagrams (Figure 2-5) represent physical communication links between the nodes. A well-designed network configuration increases the *survivability* of communications (the potential for the system to continue operating after an accident) should one or more of the nodes fail. For example, if one of the nodes in the ring configuration fails, the remaining communications can survive by reversing the direction of traffic in the region of the failed node. In the star configuration, the failure of an outlying node does not disrupt the rest of the network, but the failure of the center node will shut down the entire network.

2.1.3 Wireless versus Wired Systems

The definition of the term wireless as used in this document, and as it relates to underground mines, bears some discussion here. Most people consider a cell phone to be a *wireless* device, but many cell phone calls actually travel over conventional telephone lines before reaching the receiving party's cell phone. Neither person recognizes the use of conventional telephone lines during the communication. The main convenience for the user is that there are no wires or cables connected to the handheld device, even though they are integrally involved in the signal transmission. This example of "wireless" communications is consistent with the definition adopted for this tutorial: "a system that operates locally without wires" (see the Glossary for more details).

Two people using walkie-talkies that can communicate over significant distances exemplify another possible definition of wireless. In this case, there is only one type of physical communication link. It is common to call such communication devices *radios*, and the communication between these radios is *wireless.* For simplicity in relation to mining applications, some suggest that the definition of wireless should be restricted to this concept of "one physical link" (no intervening cables, nodes, or devices of any kind). Another definition of wireless that has been suggested is that the system can contain multiple physical communication links but that each link has to be wireless.

There has been considerable debate over exactly what Congress intended in the MINER Act by requiring “wireless” communications via “a wireless two-way medium.” To address this issue within the context of this tutorial, two assumptions were made: First, for practical purposes, the communications system miners use must be an *un-tethered* device, i.e. one without connecting wires or cables. This un-tethered device, such as a small radio, can be worn or carried by the miner. Second, the principal intent is to ensure a survivable connection between the miner and the surface throughout the area where the miner may need to work or travel. Within this tutorial, a wireless communications system is defined as one that does not require a physical connection to the miner’s handheld radio. Therefore, in this context, wireless refers to any system in which the miner uses an un-tethered device for communications. Readers should review the latest guidance from the Mine Safety & Health Administration, and state regulatory agencies, for their definition of wireless and detailed requirements for compliance with the MINER Act.

2.2 COMMUNICATIONS SYSTEMS PRINCIPLES OF OPERATION

2.2.1 Hardwired Systems

Many underground coal mines use some form of telephone as the primary means for communications between the surface and the underground miners. It is easy to imagine two phones (or transceivers, as introduced in Section 2.1.1) directly connected by wires to form the physical communication link. Referring to the previous discussion of Figure 2-2, the energy from the transmitter directly couples into the transmission media, which in this case is a wire or cable. For mine pager phones, which are the most common form of communications in underground mines, two wires are typically used. Connecting additional phones into the same wires forms a network of phones. With this network configuration, the phones operate in a page mode in which all the telephones broadcast simultaneously when a button is pressed on the transmitting pager phone. The system works well in the case of an emergency when all miners must be notified. However, there is no capability for private or simultaneous conversations.

Some mines use a dial telephone system similar to a commercial phone system, but the mine phones are completely separate from, and cannot communicate with, the commercial phone system. Private conversations are possible. Key personnel are assigned ring codes to indicate when the phone is for them. Personnel must also remember the phone numbers of other people to whom they wish to talk.

Another type of hardwired communications system is the trolley wire or carrier phone. Mines with extensive rail haulage use trolley phones. The electromagnetic (EM) signal couples to the trolley power line. The physical link is similar to the telephone described above, except the wire is the trolley power line. Phone locations include the trolley powered vehicles and key stationary points. Communication to cages and elevators in vertical and slope shafts use the same system.

Despite their capabilities, hardwired communications systems are generally not robust. The typical network configuration for a hardwired phone system is the bus structure shown in Figure 2-6. The connecting wires are easily broken or shorted by rock falls. Once a line is shorted, the communications may be severely affected or cease altogether. These systems lack *redundancy*, which is the ability of the network to maintain communications with the surface with the disruption of a single pathway. In an underground coal mine the network configurations available are highly limited. The long, linear tunnels and the limited access pathways to the surface restrict the design choices.

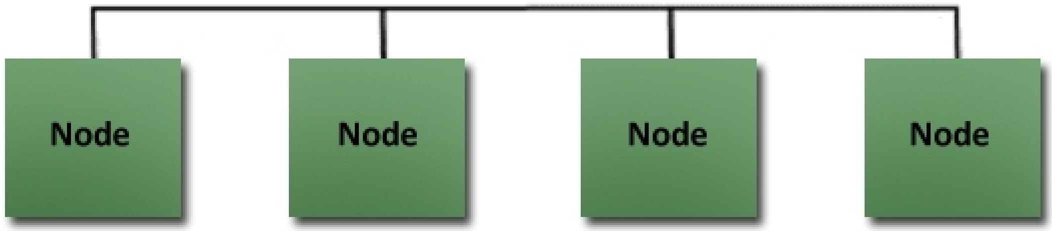

Figure 2-6. A Bus Network

2.2.2 Wireless Systems

The following sections present four different wireless communications technologies. The primary difference between them is their frequency bands of operation. Each of the frequency bands uses a different mechanism for the propagation of the EM waves. Each of these systems has the advantage of permitting the miner's radio to be un-tethered, as discussed in Section 2.1.3.

As shown in Figure 2-7, in a wireless communications link the antennas couple the EM energy from the transmitter to the transmission medium and capture the energy at the receiver location from the medium. The *coverage range* is the maximum distance between the transmitter and receiver while still maintaining good quality communications. The *coverage area* is the area within which radio communication is possible.

There are two broad categories of antenna systems — *discrete* (single-point) *antenna* and *distributed antenna* (multi-point) systems. Most people are familiar with discrete antenna systems, which are often made of simple pieces of wire. Examples of discrete antennas are TV antennas on a house or the radio antenna on a car. Sometimes the wire is contained in some sort of enclosure for protection, such as the rubber or plastic antenna protectors found on portable radios and cell phones.

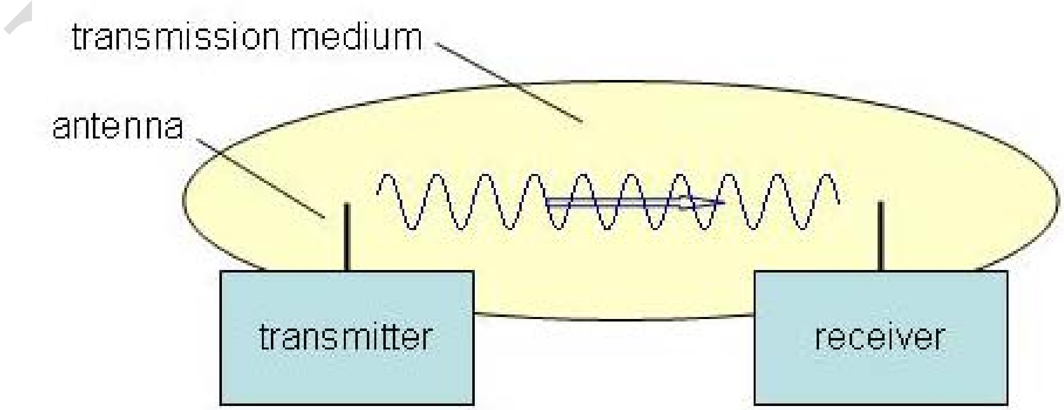

Figure 2-7. Basic Components of Wireless Communications Link

There are two types of discrete antennas — *directional* and *non-directional*. A non-directional antenna (sometimes called an omni or omni-directional antenna) radiates energy more or less uniformly in all directions. This is analogous to how a lighted match or a light bulb radiates light in all directions. On the other hand, a directional antenna focuses the energy in one direction. Using the light analogy, a directional antenna is similar to a flashlight. A flashlight points most of the light energy in one direction. A flashlight uses a reflector behind the bulb shaped to focus the energy in the desired direction. Similarly, reflectors behind an EM energy source create highly directional antennas, such as in a satellite dish.

In most discrete antenna systems, one antenna both transmits and receives from the transceiver. However, some systems use separate antennas for the transmit and receive functions. A discrete antenna has a rather limited and localized physical size, and the dimensions of the antenna are much smaller than the coverage area or range.

The other broad category of antenna systems is the distributed antenna system (DAS). Unlike a discrete antenna system, where the energy transmits and receives at one location, a DAS distributes the energy over a broad area and the antenna system can be quite large. The use of DAS has been popular for years for providing radio coverage in confined spaces such as tunnels. More recently, DAS systems have been used to provide cellular radio coverage inside large buildings and other hard to reach areas, such as parking garages and casinos. Given this heritage, DAS systems are good candidates for applications in underground mining.

Most DAS applications create a continuous coverage area by having many overlapping radiation points or continuous radiation along the length of the system. The leaky feeder system discussed in the next section is an example of a DAS that has continuous radiation along the length of the system.

An important limitation of the DAS is that parts of the system require power to boost or amplify the signal. As the signal travels along the length of the DAS, energy is lost due to the energy radiated along the length. To offset this loss, electrical power is required for the amplifiers within the DAS to boost the signal. The availability of power and the safe handling of this power is an important limiting factor in using a DAS in an underground coal mine.

Another limitation to the DAS system is that it receives the signal along its entire length; therefore, it is also receiving noise over its entire length. As discussed earlier, in Section 2.1.2, noise can reduce the coverage range of a system; therefore, the cumulative noise can limit the size of a DAS.

2.2.2.1 Leaky Feeder Systems

The leaky feeder system as used in an underground coal mine typically involves a single large transceiver on the surface that can communicate with any miner radios along the length of the system. The transceiver on the surface, called a base station, connects to a distributed antenna system (DAS). These systems operate at a frequency that two-way voice radio communications conventionally use, with the electromagnetic energy transmitted and received through RF (Radio Frequencies). Figure 2-8 shows the main components of a leaky feeder communications system.

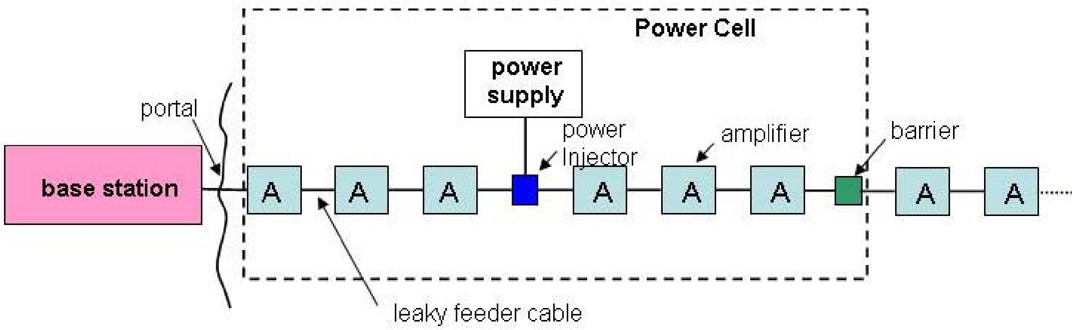

Figure 2-8. A Leaky Feeder Communications System

The DAS consists of a specially designed coaxial cable (commonly called leaky feeder cable) and amplifiers. This leaky feeder cable "leaks" the radio signal in or out along its length, thus creating a continuous coverage area along the tunnels in which the cable is strung. The coaxial cable has regular openings in the outer shield, as shown in Figure 2-9, which permit RF energy to enter or leave the cable. It can receive and transmit signals down its entire length. Wherever a mine desires communications, it installs leaky feeder cable down the entries. In addition to transporting the RF signal, the center conductor of the cable also carries the DC power (typically 12 volts) for the amplifiers.

Leaky feeder systems for coal mines are commonly marketed as VHF (Very High Frequency), operating around 150 MHz (Megahertz, or one million cycles per second), or UHF (Ultra High Frequency), operating around 450 MHz. At these operating frequencies, the handheld radios can establish a physical communication link through air, but the range is very limited underground. The leaky feeder system overcomes this range limitation by extending the receiver antenna (the leaky feeder cable) to the general area of the handheld radio, which greatly extends the range and permits surface personnel to talk with distant underground miners. The radio transmits the RF signal, which the leaky feeder cable receives if the radio is within range. The signal travels down

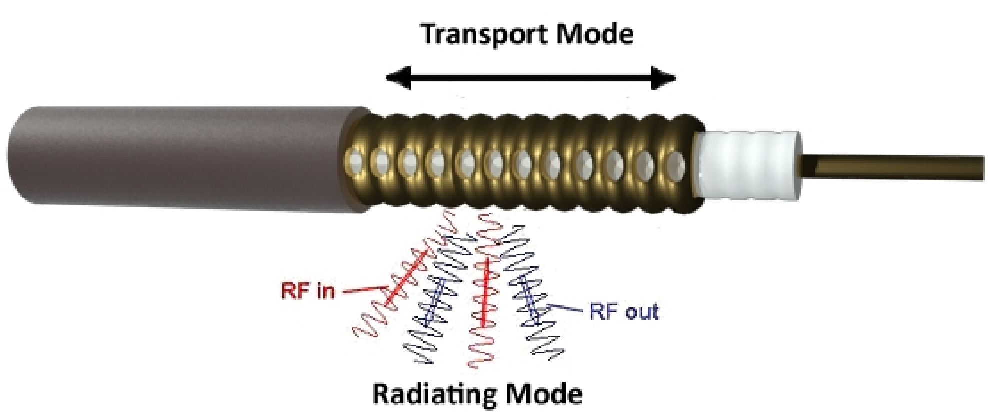

Figure 2-9. Example of a Leaky Feeder Coaxial Cable

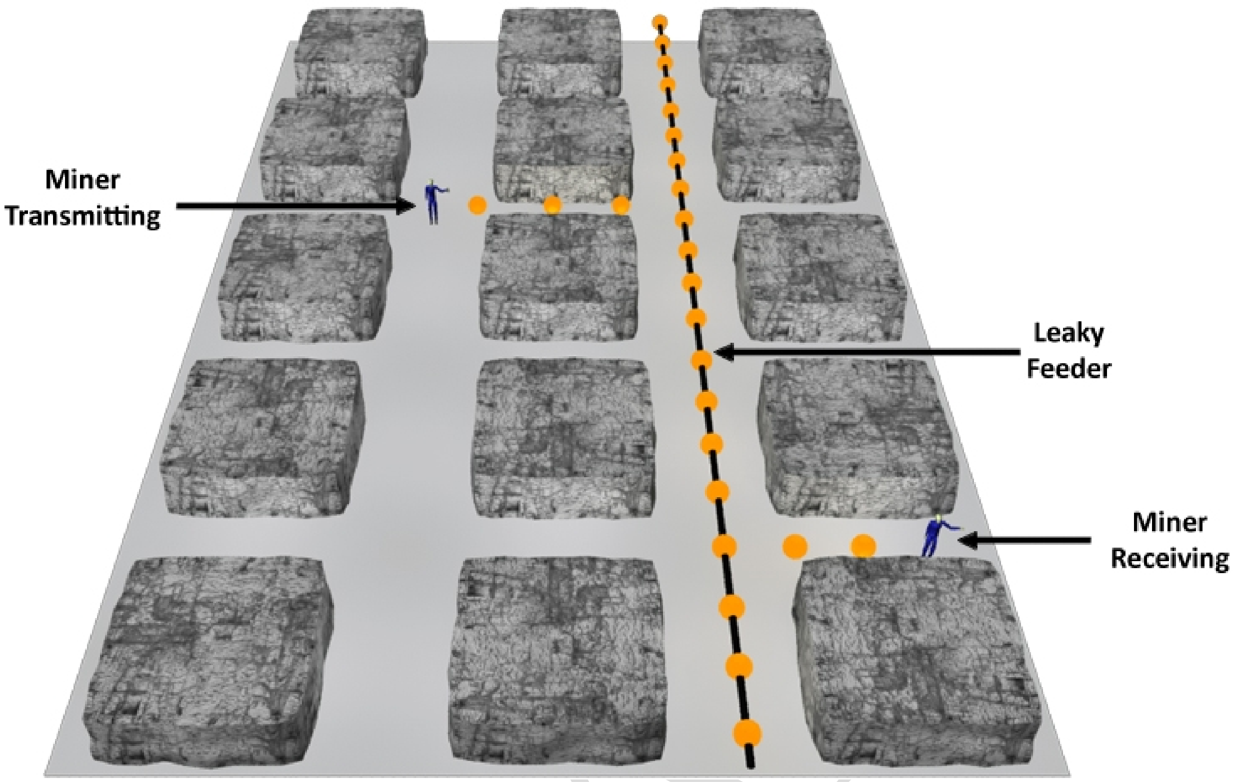

Figure 2-10. Example of a Leaky Feeder Communications System

the cable, radiating as it travels. If the receiving radio is within RF range of the cable, it receives the signal and makes the connection. Figure 2-10 shows a cut-away view of an underground room-and-pillar coal mine with a leaky feeder cable installed down one entry. The orange dots represent the path of the RF signal.

Leaky feeder cables cannot transport radio signals for indefinite distances. There is *attenuation* (signal power loss) in the cable itself and there is the continual radiation of RF energy through the openings in the outer shield. Therefore, a mechanism that periodically boosts the strength of the RF signal is required. Amplifiers are electronic components periodically inserted in the cable to boost the signal by increasing its amplitude. The amplifiers receive their power from a power supply through the center conductor of the cable. For underground coal mine applications, one power supply can generally support six amplifiers. The power supply, amplifiers, and sections of leaky feeder cable form a building block for the leaky feeder system — called a *power cell*. Figure 2-11 shows the power cell components of a leaky feeder system. In an underground coal mine, a typical power cell might be 8,700 feet in length.

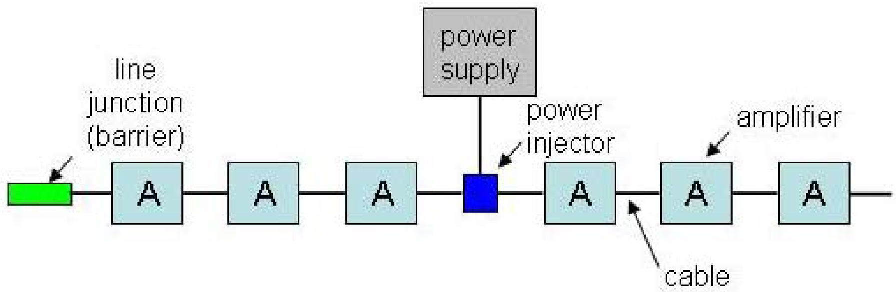

Figure 2-11. Leaky Feeder Power Cell Structure

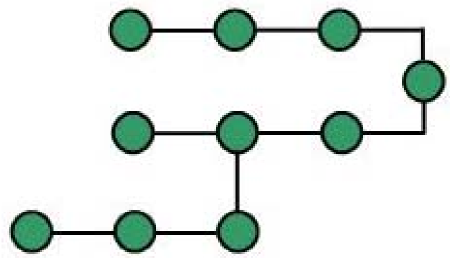

Figure 2-12. A Tree Configuration of Power Cells

In a long entry, multiple cells are used to provide radio communications coverage everywhere along the entry. To establish interconnections between power cells, leaky feeder networks typically use a tree configuration as shown in Figure 2-12. The circles are the power cells of the leaky feeder system. The cell furthest to the right is either on the surface or just inside the portal and provides the communications connection to the mine operations center. Should something happen to that power cell, communications with the surface are lost. Therefore, to increase the network's survivability, some leaky feeders use an *alternate communications path* to the surface, perhaps through another portal or a borehole to the surface. For the communications link at the surface, ordinary conductors, fiber optic cable, or through-the-air transmission can be used to complete the connection to the mine operations center.

2.2.2.2 Node-Based System

Node-based systems refer to systems that use discrete antennas connected to small transceivers called "nodes." The nodes also contain small computers (microprocessors) that perform a variety of functions. In all node-based systems, the node can detect when a miner's radio is in range and provide an automatic connection to the network. Beyond that basic function, the capabilities of nodes vary greatly depending on the manufacturer and choice of technology.

In node-based systems, the access link is the first link, which is through the air from the miner's handheld radio to a node. The *access node* is the node providing the service to the miner. The *backhaul* is the communications path from the access node to the surface. The backhaul links are the connections between nodes — through wires, the air, or both. Thus, node-based systems come in many forms.

Node-based communications systems for coal mines can be assembled from a number of different technologies. Wi-Fi or Wireless Fidelity, which is another name for Wireless Local Area Networks (WLAN) is the foundation of one node-based system used for underground coal mines. Common uses for Wi-Fi systems are in the home, the local coffee shop, and airports to provide wireless access for a computer to the internet or any device or network that uses standards-based Internet Protocol (IP). The advantage of these systems is that many devices and networks support IP, offering a variety of potential applications such as video monitoring or remote control via the internet. In these systems, the access nodes need to communicate with a gateway node located at the mine operation center, which provides the communications link to the surface facilities and supplies addressing information and other control information to the access node. The backhaul link is from the access node to the gateway node through wires, fiber, or other radio links. Some proprietary variations of Wi-Fi systems use the wireless link between nodes as alternate backhaul links.

Using UHF radios is another approach to node-based communication. In the underground coal mine environment, UHF radios can communicate directly with each other over significant distances, perhaps 1,000 feet. To extend the communications range, it is necessary to use repeaters (also called nodes) as intermediate components in their communications route. Section 2.1.2 introduced the concept of a node as a device that relays an RF message from one device to the next by automatically retransmitting the signals it receives. Figure 2-13 shows a wireless link between two radios that involves two nodes to complete the connection.

The communications connection between the sender and the receiver is generally from the transmitter to the air, air to node, node to node to node, and finally, node to air to receiver. Note that the node-to-node link is also through the air. The manner in which a UHF radio wave travels through the air in the coal mine is different from on the surface. In an underground mine, the tunnel opening guides the UHF waves, which bounce off the walls, floor, and roof. The tunnel acts as a guide, or pipe, for transporting the radio waves. This guiding effect is important because it contributes to a loss of signal power in the RF link through the air, which determines the effective range of the communications link.

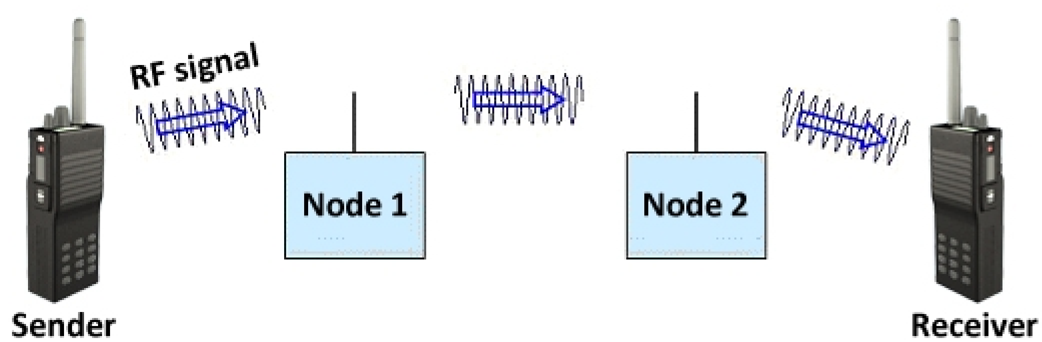

Figure 2-13. A Wireless Route Using Two Intermediate Nodes

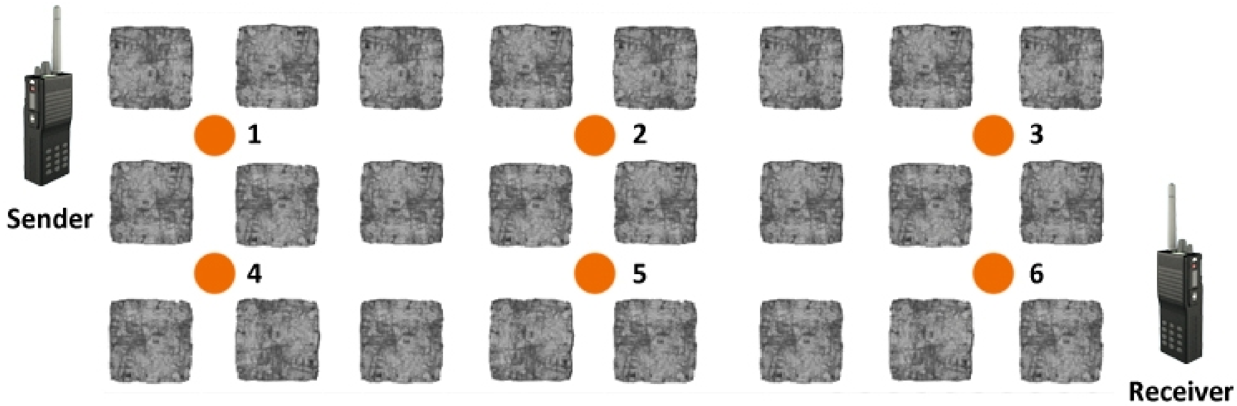

Figure 2-14. Node (Orange Dots) Based Communications System

The number of nodes participating in the connection between the sender and receiver will depend on the locations of the radios and the nodes, and the path or route taken through the nodes to link the radios. Figure 2-14 shows six nodes (numbered orange dots) in a portion of a mine. The route from the sender to the receiver could be through nodes 1-2-3-6, or 1-4-5-6, or one of several other possible combinations of nodes.

For a UHF network, fiber optic cables or metallic conductors can connect the nodes in the entries. However, because the UHF nodes both receive and transmit UHF signals, a wireless connection is possible, with no cabling needed.

In addition, each node can contain a small computer programmed to detect when another node is within RF range and that node's identity. The computer can automatically establish a wireless connection between the nodes. When a sender and receiver wish to link, the computers work in concert to determine the optimum route between the participating nodes.

Figure 2-15 shows a cut-away view of a mine with a UHF node-based communications system. Orange dots indicate the RF signal route between miners 1 and 2. Should an incident occur that disables one of the nodes, it is possible for the node computers to recognize the loss and to determine a new route to re-establish the communications link, as shown in Figure 2-16.

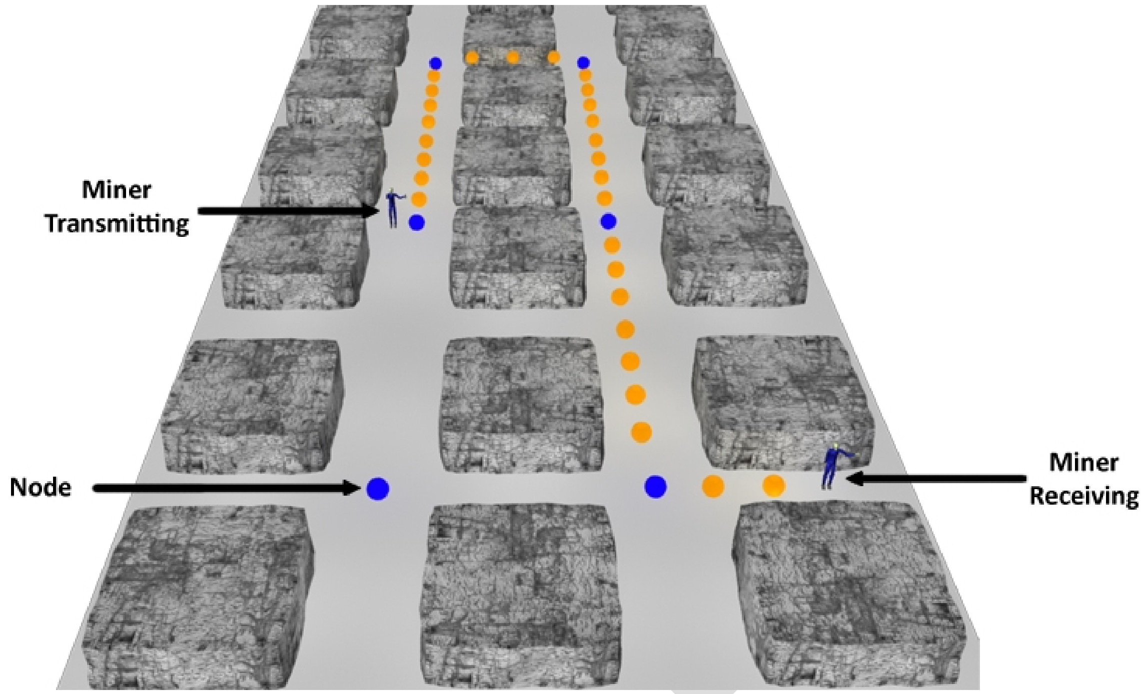

Figure 2-15. UHF Node-Based Communications System

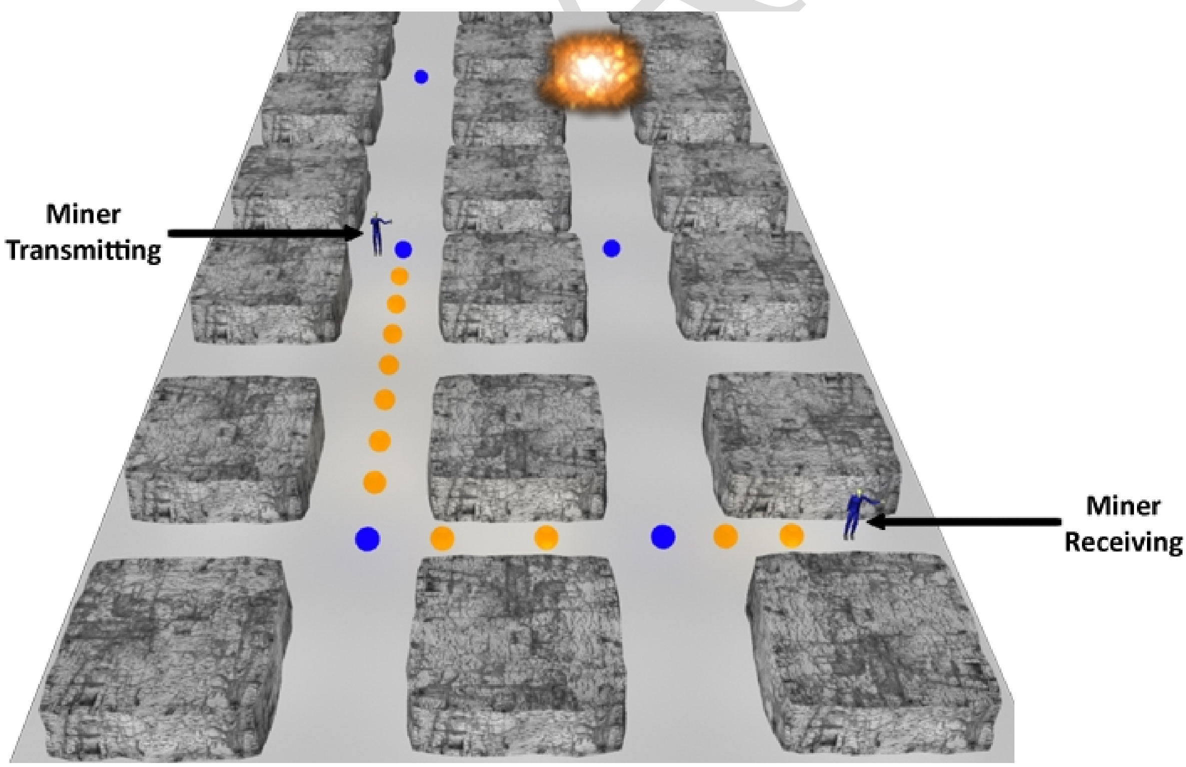

Figure 2-16. Node-Based Network Establishes Alternate Communications Path

As demonstrated, a UHF node-based communications system can be made to be quite robust, i.e., able to re-establish or reconfigure itself following an accident. To provide an alternate communications path following an accident, two things are required. First, there must be enough nodes within RF range of each other to establish alternate routes when required. This requirement is partly a cost issue; additional nodes cost additional money. Second, the nodes must be capable of automatically reconfiguring the network. This means that the manufacturer must install the computer chips and appropriate programming into the nodes.

The type of node-based network described above, using UHF radios as an example, is a *mesh* network. Mesh networks come in a variety of types. A mesh network where all the nodes, including the miner's radio, can relay the network traffic and automatically reconfigure the network over any arbitrary route in real time is an *ad-hoc mesh* network. A mesh network that can only reconfigure periodically, one with the re-configuration dependent on pre-defined alternate routes, or one in which the miner device cannot relay traffic is a *constrained mesh*. A *full mesh* is a network in which each node connects to every other node by a direct physical communication link. A *partial mesh* is a network where each node connects to several other nodes, but not to all nodes. Because room and pillar mines can extend for miles, a full mesh may be impossible. The nodes in Figures 2-15 and 2-16 are able to communicate with the adjacent outby and inby nodes, as well as the adjacent node in the crosscut. These nodes are forming a partial mesh network.

2.2.2.3 Medium Frequency System

Medium Frequency (MF) communications systems typically operate at around 500 kHz (Kilohertz, or one thousand cycles per second). In addition to their operating frequency, what distinguishes them from other communications systems is the way the RF signals travel in the mine. At these frequencies, the radio signals couple onto metallic conductors such as power lines, phone lines, wire lifelines, other electrical wiring, and metal pipes. The conductors play the same role as the coaxial cable does in the leaky feeder systems, as conduits for the radio signal. MF radio signals travel along the conductor. In addition, the conductor acts as a distributed antenna, able to transmit and receive signals continuously along its length, just like the leaky feeder cable.

Direct MF radio to MF radio communication distance is very limited unless metal conductors are present along the communications path. Since many mine entries already have conductors and because installing simple conductors is inexpensive, the MF communication distance easily extends to miles without the need for a repeater or amplifier. Figure 2-17 shows a typical connection between two MF radios.

MF radios and antennas are considerably heavier and larger than UHF or VHF handheld radios. Therefore, it is not likely that the miner would continuously carry these devices while performing daily work. The MF radio might be used as a redundant communications system or a system used mainly for emergencies.

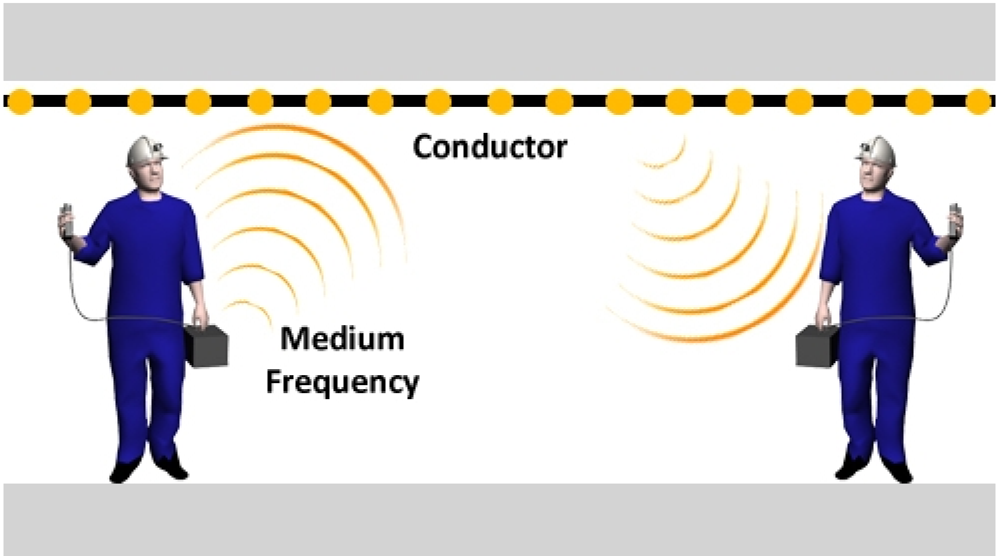

Figure 2-17. Typical Connection between Two MF Radios

An up/down frequency converter is able to interconnect MF and higher frequency systems like UHF or VHF. The device changes RF signals received in one frequency band to RF signals transmitted in a higher or lower frequency band. For example, the converter can down-convert signals received in UHF to signals transmitted at MF, or conversely, receive MF and transmit UHF. Thus, the converter is somewhat like a repeater, except that it re-transmits the signal it receives at a different frequency. These up/down frequency converters are referred to as *bridge repeaters* or *bridge nodes*.

The bridge repeaters provide flexibility in networking by permitting hybrid systems — systems that combine multiple technologies. Figure 2-18 shows a sample hybrid configuration. A miner, using a UHF handheld radio, can transmit to a bridge repeater that receives the UHF and re-transmits MF, which, in turn, couples to a conductor. The conductor transmits and receives MF as the signal travels along. At some point, another bridge repeater picks up the MF signal, which then transmits the message in UHF. Another miner with a UHF handheld radio can receive the message. The receiving miner can send a reply, which will be transmitted through the reverse of the above process.

An extension of the hybrid system in Figure 2-18 is one in which one of the miners is replaced by a nearby UHF leaky feeder cable, which acts as an extended antenna, able to receive or transmit RF signals. The leaky feeder system would likely be the main communications system in the mine. The MF portion acts as an extension of the UHF leaky feeder and the bridge repeater provides the conversion between the UHF leaky feeder and the MF system. Such a combination is one way to extend communications to the working face of the mine without having to extend the leaky feeder cable as the face advances.

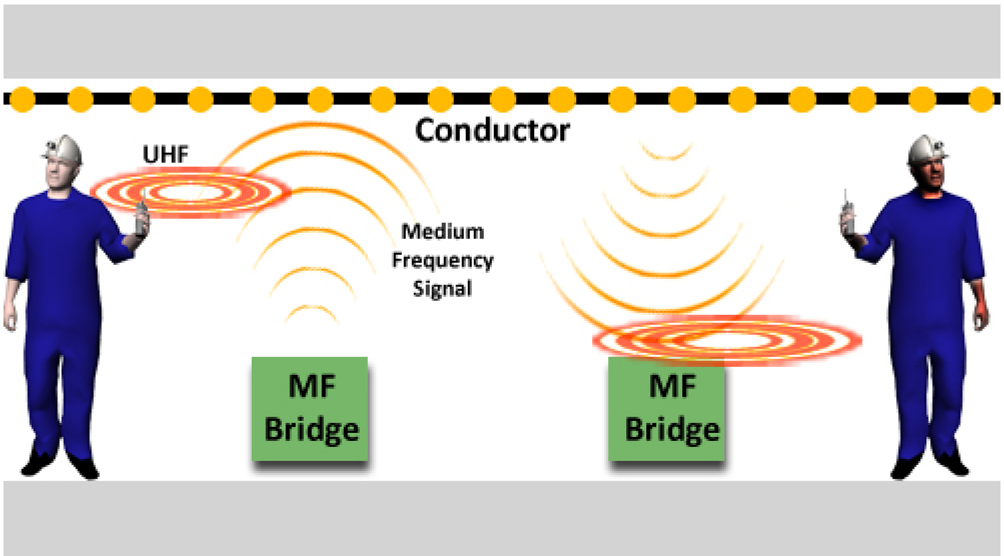

Figure 2-18. A Hybrid or Combination of MF/UHF Communications Systems

2.2.2.4 Through-the-Earth Systems

Through-the-Earth (TTE) communications technology is the only technology that can transmit an electromagnetic signal between a sender and receiver with one underground and the other on the surface without relying on a network or other additional *infrastructure*. Most electromagnetic waves normally reflect off the earth, or rapidly weaken as they pass into the earth, such that they penetrate only a few feet below the surface. However, at frequencies less than about 10 kHz, it is possible for the waves to propagate more than a thousand feet through the earth. There are several factors that limit the potential applications for TTE in underground coal mines: antenna design, the low frequencies necessary to transmit the signal, and other noise sources.

Antenna design has a large impact on TTE systems. An *antenna* is a metallic device for transmitting and receiving electromagnetic waves. Antennas provide the mechanism to convert between electromagnetic waves traveling in air, for example, and radio signals on wires in circuits. The radio signals on the wires are electrical currents that carry the signal information. When those currents flow on the antenna, they generate an electromagnetic wave. Similarly, if an electromagnetic wave impinges on an antenna, it generates currents on the antenna.

Antennas are most effective at transmitting and receiving RF wavelengths that are comparable to the largest dimensions of the antenna. This can be a problem for the very low frequency TTE waves. A 10 kHz electromagnetic wave has a wavelength in air of about 19 miles, which is not a practical size for an antenna. Thus, all practical TTE antennas are much smaller than a wavelength. The resulting inefficiency in the antenna means that only a very small fraction of the electromagnetic energy applied to the antenna radiates. Similarly, on reception, only a small portion of the electromagnetic energy contacting the antenna converts to an electrical signal on the wires connected to the antenna.

Loops or coils of wire are effective antennas for generating TTE electromagnetic waves because they increase the surface area available for contact with the electromagnetic waves without increasing the overall footprint, and it is relatively easy to lay out a loop in a room and pillar mine. For example, wrapping wires around a coal pillar creates a loop antenna. Figure 2-19 shows a representative TTE configuration — a loop on the surface transmitting a signal to a loop underground. To obtain a strong enough radio signal between the two loops, their coverage areas must partially overlap.

The low frequencies needed for TTE communications also limit the amount of information transmitted in the message and may delay the receipt of the message by several minutes. This limited information flow makes it very difficult to use TTE for voice communications, and difficult to include TTE communications links in a network.

Another limiting factor in the use of TTE communications is the variety of natural and a man-made noise sources existing at these low frequencies, including electromagnetic energy from power lines and electromagnetic noise naturally occurring in the atmosphere. These noise sources further limit the range and information flow of a TTE communications link.

Given the constraints on antenna size, signal power, message size and delivery delay, TTE systems are most likely to be used only in emergencies. An advantage of a TTE communications link is that it is highly survivable. As such, a TTE system could play a significant role as an emergency *alternate communications path.* Section 2.4 discusses alternate communications paths further.

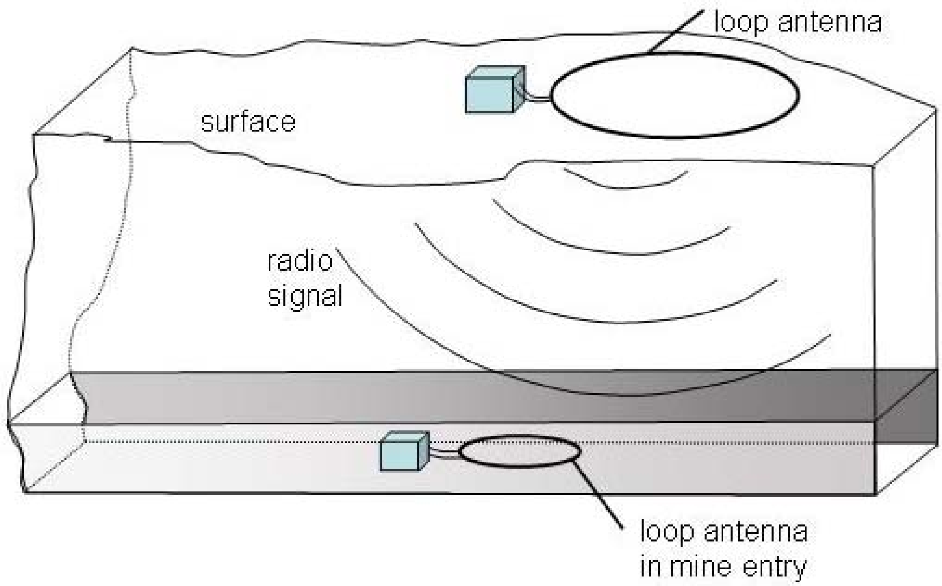

Figure 2-19. Example of a TTE Communications System

2.3 TRACKING SYSTEMS PRINCIPLES OF OPERATIONS

2.3.1 Manual Tracking Systems

The intent of a tracking system is to record who is underground and where they are located. The mine operations center displays this information on the surface, so that in case of an underground emergency, rescue workers can effectively plan their operations.

When using manual tracking, at the beginning of each shift, the mine foreman provides the dispatcher with a list of names of people and where they are going in the mine. Once underground, if a miner needs to go to a different area to work, the miner notifies the dispatcher using the underground dial phone. The dispatcher then updates the list.

Manual tracking has a number of limitations. A miner may report a location as being within a working section, but that can be quite a large area, perhaps covering two square miles. Occasionally a miner will forget to notify the dispatcher when changing work locations. Also, the dispatcher has many duties and may not be available when a miner calls to notify the surface of a change in location. In an emergency, the phone system may not be operational.

Electronic tracking systems can address most, if not all, of these limitations. The following sections discuss several types of electronic systems.

2.3.2 Reader-based Tracking Systems

2.3.2.1 Radio Frequency Identification (Zone-Based)

Nearly all department stores have vertical sensor plates near their doors that shoppers have to pass through on their way out of the store. If a customer has not paid for the merchandise an alarm sounds. Radio Frequency Identification (*RFID*) is the basis for security systems such as this. Within the item being purchased is a small *tag*, typically about the size of a postage stamp, containing an electronic circuit. The vertical sensor plates at the exits are continuously emitting an RF signal. The sensor plates are RFID *readers*. If the reader signal reaches a tag (*interrogates* it), the tag sends back a response that is detected and read by the sensor plate and the alarm is sounded. On checkout, the tag is de-activated when the purchased item is rubbed on a particular region of the counter, producing a magnetic field that interacts with the circuit of the tag, making it inoperable.

The tags used in the department stores are *passive* tags, because the tag has no internal power source. Thus, the tag is passive and does not emit any RF energy until interrogated by the reader. Once interrogated, the tag absorbs a small amount of the RF energy from the interrogating signal and uses it to send a reply. Passive tags are very inexpensive because they are simple and have no internal battery. However, the range of the reader and tag system is quite short, typically a few feet; that is why the vertical readers at the store's exit are so close together.

A more advanced level of RFID tracking can be used to track the locations of underground miners. To extend the tag-to-reader range, an *active* tag is used. Active tags have an internal battery to power the signal transmission. The tag is a very small radio, able to transmit and receive messages. Each miner wears a tag that transmits a unique identifier. Whenever the miner passes within the RF range of a reader, it interrogates the tag. The reader relays the detection information to a central location, usually the mine operations center, over wires, through fiber optic cable, or even wirelessly. Each RFID reader has its own identification and a location associated with that identification. When a given reader interrogates a tag, then forwards the information to the operations center, personnel at the center know that the miner is within a certain distance of that reader's location.

Figure 2-20 shows an example of RFID readers (blue circles) installed in a mine. Each reader has a location associated with a survey marker (black circles, each with a unique number). The blue ovals illustrate the RF range of each reader. The red ovals show the RF range of the miner's tags. Miner A is within the RF range of the reader at survey marker 58301. Miner B is not within range of any reader, but if he had recently left the reader at marker 58289, his location would be his last recorded position. This is *zone-based RFID* because each reader only detects tags within its RF range or zone.

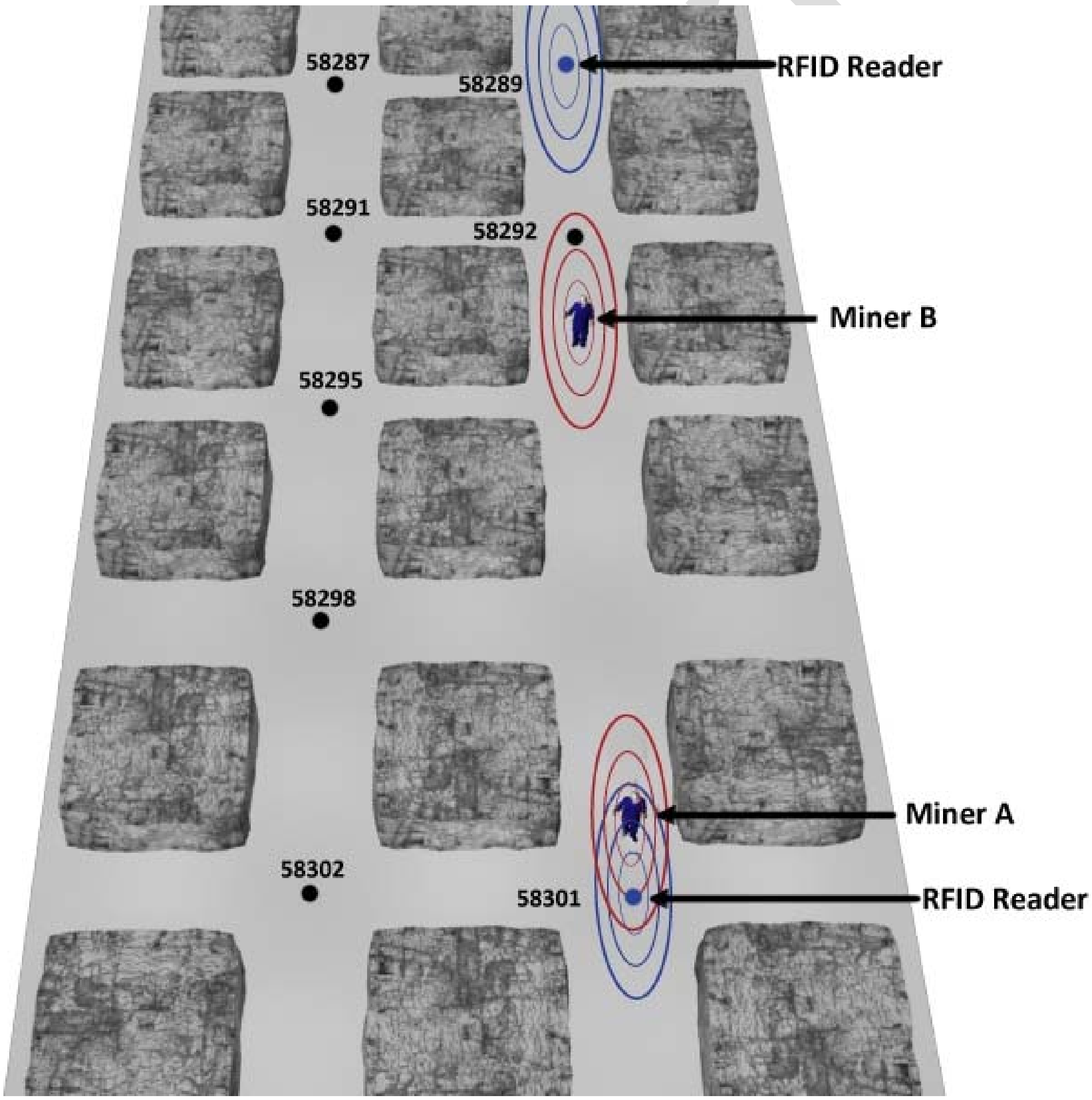

Figure 2-20. Zone-based RFID Tracking

The tracking system as presented in Figure 2-20 is independent of the communications system. Both the tracking and communications systems need to provide a link to the surface; therefore, it may make sense to integrate the two systems. For example, the RFID readers could transmit their location information to a leaky feeder cable, which would then transfer the information to the operations center.

Not all RFID zone-based systems operate in the same way or use the same frequencies. Each manufacturer will develop features unique to their product. Given that flexibility, a representative RFID reader range is about 300 feet. In this case, the identified miner is within a circle with a radius of 300 feet (100 meters), centered at the RFID reader, as shown in Figure 2-21. Interpreting this figure allows us to determine possible locations for the miner. Clearly, the miner is not located within the coal; he is either in the entry with the reader or in one of the crosscuts. It is unlikely he is in a parallel entry (even though the 300-foot circle would permit it), because the RFID reader requires a *line-of-sight* with the tag, i.e., an unobstructed straight-line path between the tag and reader. Therefore, the miner must be within the red shaded zone shown in Figure 2-21.

The *resolution* of a tracking system is a measure of the smallest detectable change in position or location of the miner. For RFID reader-based systems, a miner's position is associated with a particular reader's location and the resolution is the reader spacing. Therefore, if a higher or better resolution required, more readers required, thus increasing the cost of the system.

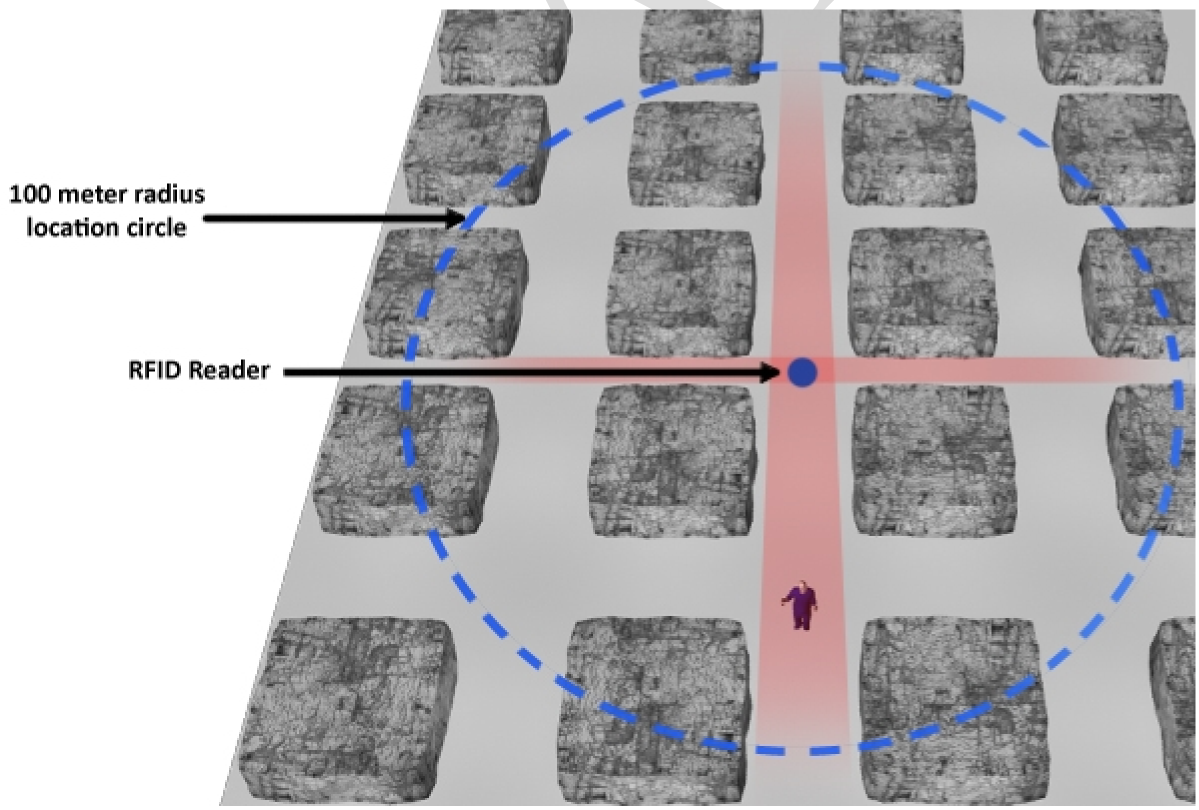

Figure 2-21. Miner Location with RFID Reader

2.3.2.2 Reverse RFID

Zone-based RFID systems are well-established and are being used increasingly for industrial applications. However, for high-resolution applications over large areas these systems require a large number of readers, which in turn increases the cost and complexity. This section will discuss a relatively new approach that some manufacturers are considering, which is referred to as *Reverse RFID*.

In the zone-based RFID system, each miner wears an RFID tag and the readers are in fixed, known locations. The location information obtained by the RFID reader must still reach the mine operations center. To accomplish this, the reader has a radio transmitter that periodically transmits the miner's location data to the mine's *backhaul* (the network's backbone or the main route to the operations center) communications system. Figure 2-22 illustrates a Reverse RFID system in which the backhaul is a UHF leaky feeder system.

The RFID tag periodically emits its identification information, shown in red in Figure 2-22. A separate antenna, possibly mounted on the miner's cap, receives the RFID tag signal. The RFID information transfers to the transmitter on the miner's belt, relays to the leaky feeder cable, and ultimately to the mine operations center. A UHF transmitter mounted on the miner's belt transmits the location information to the leaky feeder cable.

RFID tags are relatively inexpensive, especially compared to the RFID reader. Tags can be located close together so that the miner's location can be determined accurately. Each tag contains a battery, which makes maintenance a concern, but the batteries can last 10 years.

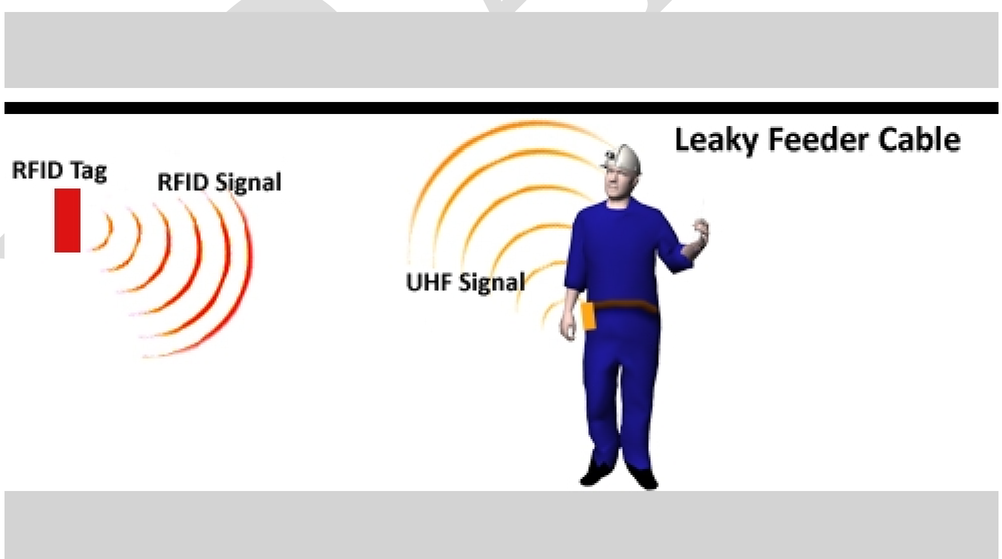

Figure 2-22. Example of Reverse RFID System with UHF Leaky Feeder Backhaul

Using a more sophisticated approach than just recognizing when a miner is in a certain zone can further enhance the location accuracy. If a miner is within RF range of two RFID tags at the same time, comparing the received signal strengths from the two tags can determine the miner's location within 50 feet. As the miner approaches one tag, the strength of the signal from that tag increases. On the other hand, as the miner walks away from the other tag, the strength of the signal from that tag decreases. A comparison of the rates of change of signal strengths pinpoints the miner's location. Analysis of this comparison also determines the miner's speed and direction of travel. The formal name of the technique is *Received Signal Strength Indicator* (*RSSI*).

2.3.3 Radio Node-Based Tracking Systems

Radio node-based tracking systems use the same physical components as the node based communications systems. Radio node-based tracking uses the known locations of the fixed position nodes as reference points. Each handheld radio has a unique identifier assigned to it shared by a specific miner. Thus, node-based communications systems often have all the necessary components for electronic tracking, at least to the resolution of the node range (i.e., the maximum radio range over which an access node maintains communication over a physical communication link).

Applying the same concept of comparing radio signal strengths (RSSI), which was introduced in the Reverse RFID as a technique for determining location, increases the resolution of a radio node-based tracking system. In a Reverse RFID system that is utilizing RSSI, the tags are in fixed, known locations and the miner wears a receiver that detects and measures the signals radiated by the tags. Since a node-based UHF communications system has all the necessary components to implement the RSSI technique, it needs no RFID tags. In a node-based system, the access node and/or the miner's radio make the signal strength measurements.

Positioning the nodes close enough so that there is continuous communications coverage allows the handheld radio to receive signals from multiple nodes and to determine the signal strengths. Each signal also contains information identifying from which node it came. In some systems, the information accumulates in the miner's radio, and then transmits back to the mine operations center for analysis. Other systems compare the signal strength received from two or more nodes at the miner's radio. The location is resolved using RSSI, which determines the distance of the miner from each of the nodes within the miner's RF range.

Figure 2-23 illustrates the main features of a radio node-based tracking system. The red arcs represent the RF signals transmitted from the nodes. The picture looks almost identical to the depiction of node-based communications, which is why electronic tracking is easy to implement in a node-based communications system.

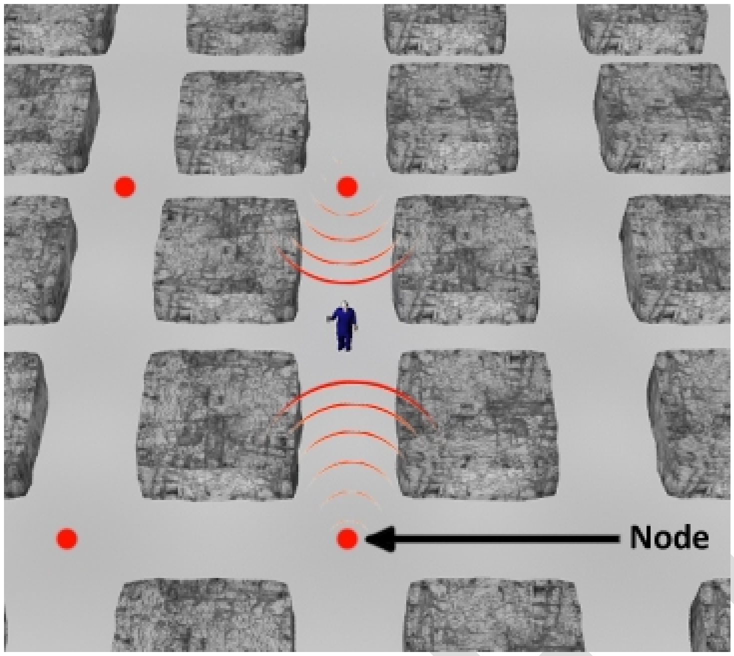

Figure 2-23. Radio Node-Based Tracking

Unfortunately, there are many factors in the underground mine environment that introduce uncertainties into the RSSI determination of location. These factors include any blockage that reduces or eliminates line-of-sight between the access node and the miner, including stoppings, equipment in the entries, turns in the entries, undulation in the coal seam, etc. With these uncertainties, the miner's location may not be resolved to better than about half the spacing of the distance between the nodes.

2.4 NETWORK OPTIONS

Section 2.1.2 introduced the concept of networks. A communications network is an interconnection of communications components that allow a user to send a message to a specified destination. The network receives, interprets, transports, and delivers the message to the destination. For simplicity, this discussion focuses on communications networks, but it applies equally well to electronic tracking networks.

Figure 2-24 illustrates the main responsibilities of a network — *access* and *transport*. The concepts of access and transport are analogous to a city bus network. The buses travel predefined routes and pick up riders at specified locations, but to achieve transport, a rider must access the system (go to a bus stop). Similarly, in a communications or tracking network, the interconnected nodes provide the message transport, but the user must access the network in order to send the message.

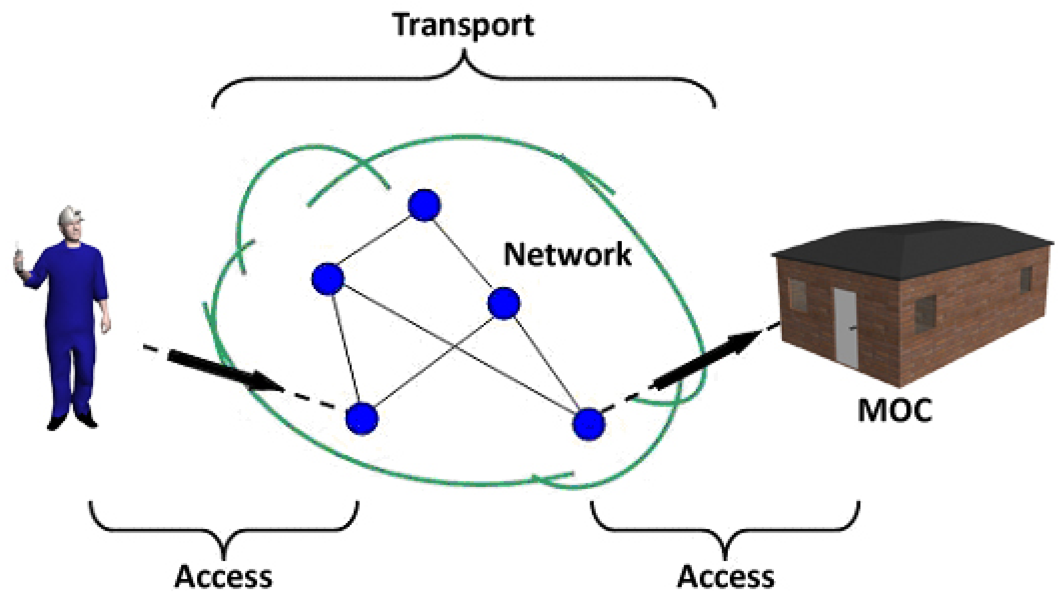

Figure 2-24. Main Responsibilities of a Network: Access and Transport

Section 2.2.2.1 on leaky feeders introduced the idea of an *alternate communications path*. Alternate communications paths provide the key to ensuring the survivability of systems in a coal mine, and the support of these alternate communications paths is a critical consideration in evaluating a mine operator's network option.

Figure 2-25 shows a leaky feeder system, which establishes redundancy by providing an alternate communications path by means of an overland, fiber-optic link between the airshaft and the primary base station at the elevator shaft. The surface link maintains the communications even if there is damage to the underground connection between the two shafts. Figure 2-25 introduces the issue that an alternate communications path typically emerges at some point on the surface separated, possibly by miles, from the primary path exit point. In this example, the primary base station would generally be located at the Mine Operation Center (MOC) and a mechanism is required to connect the secondary base station back to the MOC. As shown in Figure 2-25, the overland connection could be fiber optic cable. Other options include hard wiring through leased lines from the telephone company, or a wireless link.

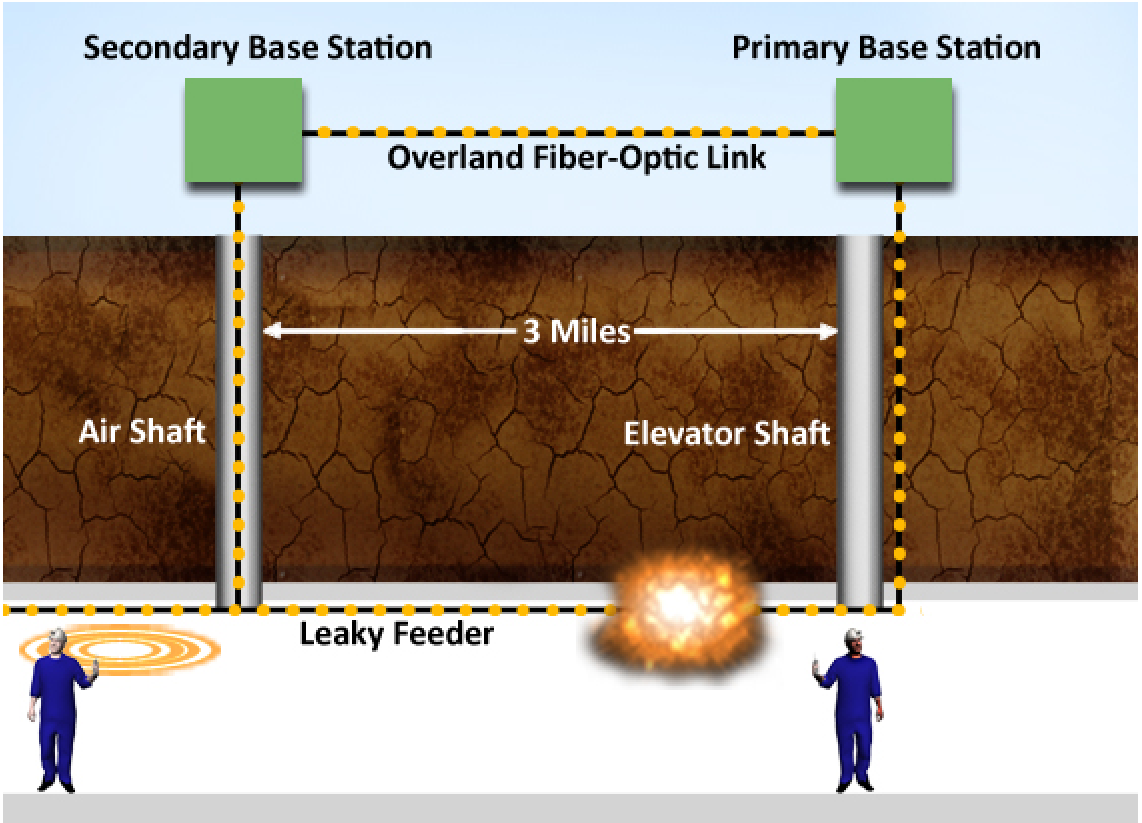

Figure 2-25. Example of an Alternate Communications Path

2.5 MINE OPERATIONS CENTER

The MINER Act requires wireless communications between underground miners and surface personnel. Meanwhile, using electronic tracking systems, information on the location of people underground must also be available at the surface. A natural, central location on the surface to meet both these requirements is the MOC.

2.5.1 Tracking Displays

The MINER Act specifies that surface personnel must have the current or immediately pre-accident location of all underground miners. There are a number of ways to display miner locations. One would be a simple listing of the names or identifying employee numbers of all miners underground along with the nearest survey spad station. However, a display that is easier to interpret would present the mine map with the names of the personnel working underground. Zoom and pan features would make it possible to view the entire underground mine, including the current location of all personnel. Figure 2-26 shows a sample display.

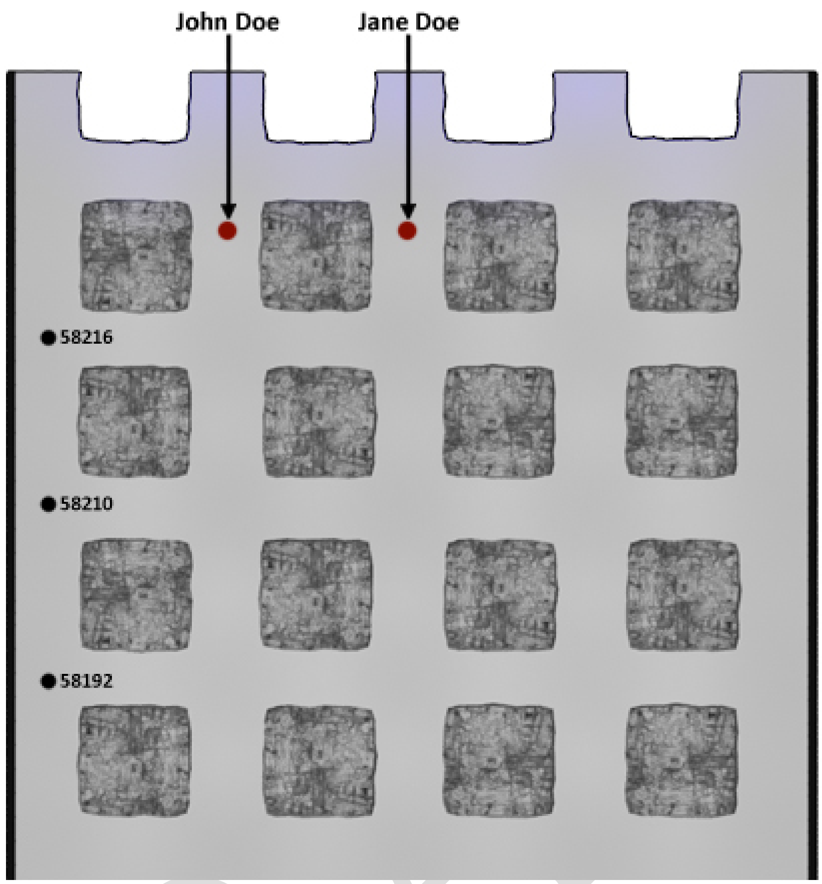

Figure 2-26. Sample Display of Miner Locations

2.5.2 Surface Communications

The communications network established underground must provide access to surface personnel. As discussed in Section 2.4, there may be multiple points where the alternate communications paths exit the mine to the surface. These locations are referred to as surface Points of Presence (POPs). Each of these surface POPs should be linked, or be able to be linked in the case of an emergency, to the mine operations center.

There are a variety of options available for linking these secondary points back to the operations center. Where the mine operator has access to the required real estate and surface rights, the operator could install fiber cable, wires, or a wireless link directly back to the mine operations center. Another option is to lease copper lines from the telephone company. These lines appear to the mine operator as a directly wired line to the secondary point and the operator can connect his communications directly to the lines.

A third option, with widespread availability due to the proliferation of Internet Protocol (IP) capable devices and "broadband" networks, is to lease a connection that relies on the Internet. Such options include DSL modems through the telephone companies, cable modems through cable television companies, and satellite modems through satellite service providers. While not all mine communications natively support IP protocols, the equipment vendors will begin to offer such an option and there are converters available that will allow mine communications through the Internet.

An advantage of using the Internet-based approach is that mines can remotely monitor their communications links and other systems. Some equipment vendors and third party providers already offer services to monitor the systems, thus eliminating the burden of the local mine operations personnel of monitoring and troubleshooting the networks.

Because many of the communications systems are for day-to-day routine use as well as emergencies, when an emergency occurs there needs to be a way to ensure that the dispatcher immediately recognizes the emergency communications. This generally will include audio alarms for voice communications systems or visual alarms that display on the screen for text systems.

3. COMMUNICATIONS SYSTEM PERFORMANCE

Chapter 2 presented a brief overview of Communications and Tracking (CT) systems. Beginning with Chapter 3, the remaining portion of the tutorial is a stand alone presentation, with more technical detail, on CT systems appropriate for the underground (UG) coal mining environment. The reader is assumed to be familiar with coal mine operations and to have a technical background.

3.1 GENERAL PERFORMANCE CONSIDERATIONS

The discussion of communications systems begins by considering the general characteristics of the systems, addressing the following questions:

- What is necessary to establish communications between two radios?
- How are communications components interconnected to form a network?
- Why is a network necessary?
- How does a network configuration or topology affect the ability of the network to survive an accident?
- On what basis are different systems or technologies compared?
- What are the appropriate metrics for measuring performance?

3.1.1 Physical Communication Link

The essence of communications between two radios is the establishment of a physical communication link between the devices. Figure 3-1 shows the factors that contribute to the simplest communications link between a transmitter (Tx) and receiver (Rx). The RF power flows from the sender to the receiver along this link. For example, the power applied to the Tx antenna travels down the cable connecting the transmitter to the Tx antenna, then to the Tx antenna, through the medium in which the electromagnetic (EM) signal travels, through the Rx antenna, and through any cable that might be used to connect the Rx antenna to the receiver. At this point in the communications link, the power is referred to as the receiver power.

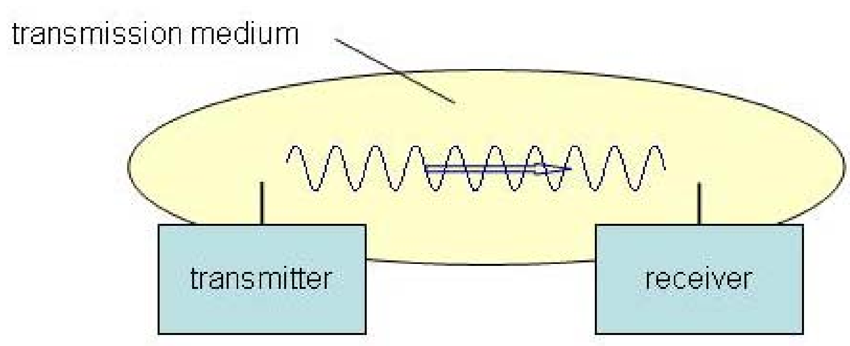

Figure 3-1. Components of a Simple Communications Link

A *link budget* analysis is the quantitative evaluation of the factors that contribute to RF power gain or loss in establishing a communications link between a transmitter and receiver. The purpose of a link budget analysis is to calculate the allowable path loss (Lp). The allowable path loss is the maximum energy that can be dissipated in the transmission medium before the communications link is no longer possible. Since the path loss increases with the distance, the maximum path allowable path loss can be used to estimate the maximum distance possible between the transmitter and receiver, which is referred to as the transmission or coverage range. The link budget analysis can also be used to compare the performance of different systems and system configurations. The maximum path loss is calculated as follows:

$$L_p(dB) = P_t - P_{mr} + G_t + G_r - L_{misc} \qquad (1)$$

Equation (1) shows that the allowable path loss L_p, is dependent on the Tx power P_t, Rx signal level threshold or minimum received power P_{mr} (which accounts for noise), Tx antenna gain G_t, and the Rx antenna gain G_r. Any additional losses, such as cable losses, are categorized as a miscellaneous term, L_{misc}. All terms are in dB units; the antenna gains are in dBi; and Tx and Rx powers are in dBm or dBW (see Appendix B.1.1.). To establish the communications link, the received power has to be above the receiver signal level threshold; otherwise, the signal may be too weak, meaning the receiver cannot process the signal and the link cannot be created.

Most of the terms in equation (1) that contribute to establishing and maintaining the communications link are fixed by the equipment being used. The values of those terms can be obtained from the manufacturers, except for the P_{mr} term which includes natural and manmade noise and is a site-specific consideration. The equation yields the *path loss* or *propagation loss*, L_p. *Propagation* is the common term used for describing electromagnetic waves (or energy) traveling through a medium. The propagation loss is largely a function of the transmission medium characteristics and the wavelength of the electromagnetic energy as will be discussed in Section 3.1.4.

At very low frequencies, EM waves can propagate directly through the earth. At somewhat higher frequencies, EM waves couple to, and are transported by, metallic conductors. At higher frequencies yet, the waves may propagate significant distances entirely through the air. For each of these media and frequency ranges, the attenuation due to propagation loss is quite different. In addition, as the frequency changes, the performance and size of the antennas change dramatically. The link budget analysis is used to account for these changes.

A variety of factors determine the effective receiver sensitivity P_{mr} and the effective transmit power P_t. Essentially, P_{mr} is the ability of the receiver to “hear” the signal and P_t is how “loud” the signal is when sent out from the transmitter antenna.

For a physical communication link, the RF information is transferred in the form of a voice or text message, or in the case of a sensor, a data message. Text messages can be entered into a computer-like device to generate an electrical version of the message (the data are already in an electrical format), while spoken communications are sound waves (pressure waves in air) that must be converted to an electrical format through the use of a microphone. A microphone has a speaker in it, and oscillations of the speaker diaphragm convert the pressure waves into electrical signals.

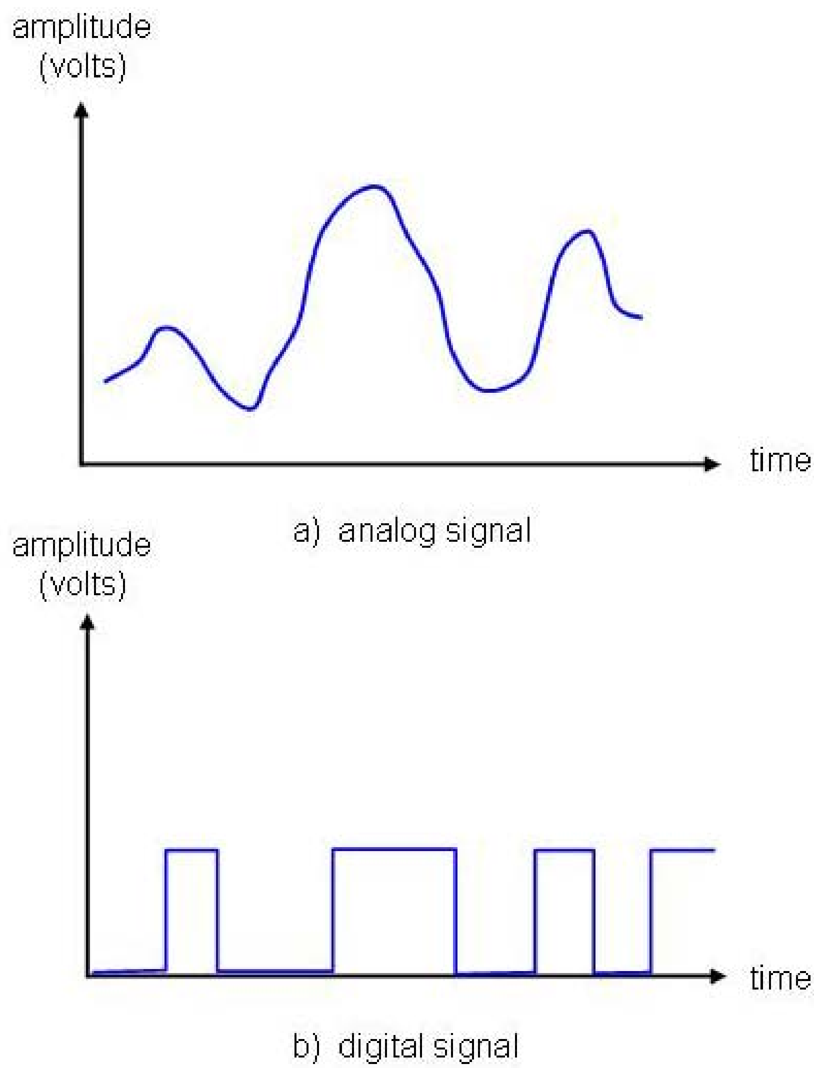

Figure 3-2. Analog and Digital Signals

The electrical version of the voice signals from a microphone are analog signals; they are continuous current or voltage signals that vary smoothly with time, as shown in Figure 3-2a. In contrast, a text or data message is likely to be a digital signal. A digital signal is one in which the signal intensity maintains a constant amplitude for some period of time and then abruptly changes to another constant level, as shown in Figure 3-2b.

CT systems are available that operate using either analog or digital format. Analog systems generally have fewer components and are less expensive than digital systems, but digital signals have the advantage that computers can read, store, and manipulate them. Digital signals can also be copied an unlimited number of times and transmitted long distances without the pattern changing or degrading as long as the digital information is not lost or corrupted.

Just as a message can be in digital (text message) or analog (voice) format, the transmission of the message can be in either digital or analog format. Figure 3-3a shows a simplified analog transmission model (the message transmits as an analog signal). The source message, which might be voice or data, can be in analog or digital format. The *modulator* combines the analog or digital signal with the *carrier frequency* (the assigned or advertised frequency of operation); i.e. the modulator modulates the carrier frequency along with the analog or digital signal. The modulated signal travels to the transmitter, where the analog message transmits. When an analog signal arrives, the process repeats in reverse order to recover the analog message.

Figure 3-3b shows a digital transmission system. The encoder/decoder, also called a codec when applied to analog signals, digitizes the analog signal by sampling it at certain time intervals as shown in Figure 3-4. There are several methods of digitizing analog signals; one is discussed briefly here.

Figure 3-4a illustrates the digitization of an analog signal. Figure 3-4b illustrates the sampling of the voltage amplitude of the signal at discrete time intervals represented by the regularly spaced vertical dashed lines. A discrete value is chosen from the closest to one of 2^n allowable values, where n is the number of *bits* represented in the voltage amplitude at each time interval. As an example, if the voltage amplitude is confined to the interval of -1 to +1 volts and an 8-bit digitizer (n = 8) is chosen, the number of voltage levels is $2^8 = 256$; the voltage resolution is the voltage interval divided by the number of levels, (1-(-1))/256 ~ 7.8 millivolts. Each voltage level would be represented by an 8-bit number containing only 0s and 1s, such as 01101001. A sequence of binary values now represents the analog signal. Using this example, Figure 3-4c shows what a reconstructed signal might look like.

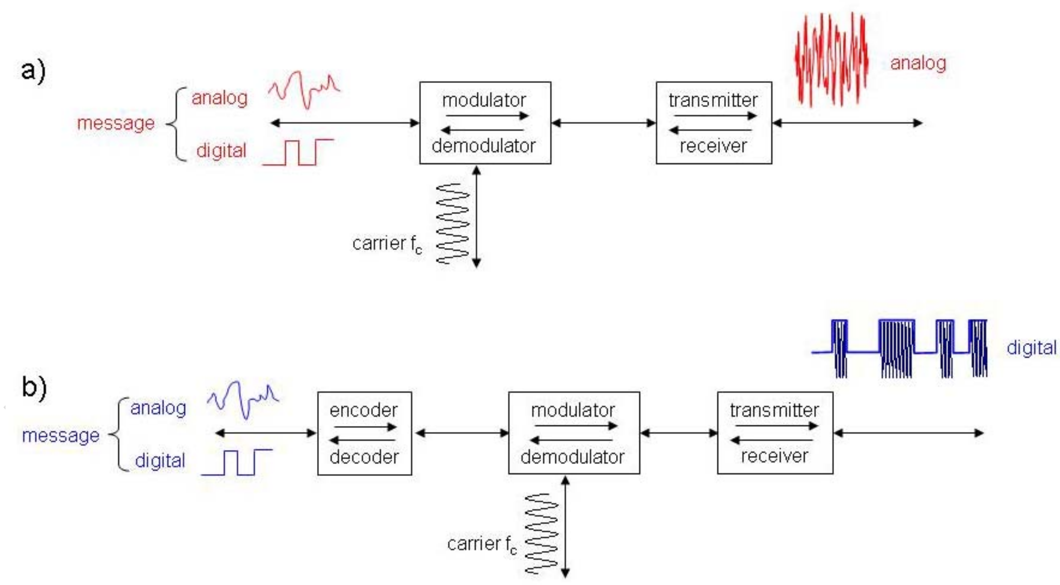

Figure 3-3. Simplified Communications Model

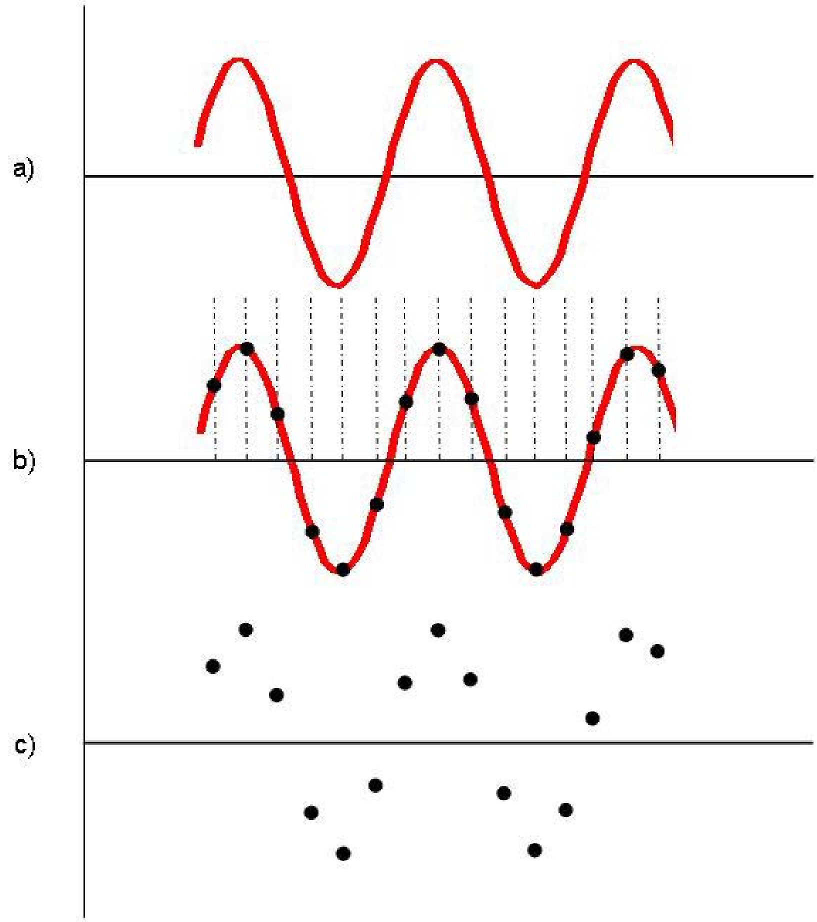

Figure 3-4. Digitization of an Analog Signal

The data rate or number of bits per second (bits/s) that a channel can transmit defines the *channel capacity*. There is an upper limit to the data rate, given by Shannon's Channel Capacity Theorem [Stallings 2007]:

$$C = B\log_2\left(1+\frac{S}{N}\right) \tag{2}$$

Where:
C = channel capacity (bits/s)
B = channel bandwidth (Hz)
S = signal strength (watts)
N = noise power (watts).

Equation (2) indicates that if the signal-to-noise ratio (S/N) increases, the channel capacity C also increases. If the noise power N increases while the signal level remains fixed, S/N decreases as does the channel capacity. A larger channel bandwidth, B, will accommodate a higher data rate, C, if the other terms in the equation are unchanged.

For all communications systems, the received signal is a combination of the transmitted signal, various distortions imposed by the transmission system, and unwanted signals inserted somewhere between the transmission and reception process. The later, undesired signals are noise.

One category of noise is thermal noise. *Thermal noise* is due to thermal agitation of electrons and is present in all electronic devices. Thermal noise is uniformly distributed across the channel bandwidth and is calculated from the formula:

$$N = k_B T B \tag{3}$$

Where:
N = noise power (watts)
k_B = Boltzman's constant (1.38 X 10^{-23} J/K)
T = system temperature, usually assumed to be 290 K
B = channel bandwidth (Hz).

Consider the thermal noise as the theoretical noise floor for an ideal receiver. A real receiver noise floor will always be higher due to additional noise sources within the device. The *noise figure* (NF) is a measure of the amount of noise added by the receiver itself. A typical receiver might have a NF ~ 7 to 15 dB.

As an example, a receiver might have a bandwidth B = 80 kHz for a voice channel. Assuming the device has a NF = 7 dB, the receiver noise floor is

$$\begin{aligned} N &= (1.38 \cdot 10^{-23} J/K)(290 K)(80{,}000 Hz) \\ N &= 3.2 \cdot 10^{-13} mW \\ N &= -125 dBm \\ \text{Receiver noise floor} &= -125 + 7 = -118 dBm \end{aligned} \tag{4}$$

The receiver signal-level threshold, P_r, is a number usually supplied by the manufacturer, but it may be estimated if the modulation technique and allowable error rates are known. As mentioned earlier, modulation is the method of converting analog or digital information to signals at the desired RF transmission frequency. A number of modulation techniques are available and the method selected impacts the system bandwidth, power efficiency, sensitivity, and complexity.

Amplitude modulation (AM) and frequency modulation (FM) are common examples of modulation methods used in commercial radio. Other examples of modulation techniques [Stallings 2007] are frequency shift keying (FSK), phase shift keying (PSK), and orthogonal frequency shift keying (OFSK). For the purposes of this tutorial and link budget analysis, it is necessary to understand that the modulation technique determines the signal level above the noise or the *signal-to-noise ratio* (*S/N* or *SNR*) necessary for a receiver to achieve a specified level of reliability in reading bits. The bit-error-rate (BER) is the probability of incorrectly reading a bit. In binary digital communications systems, an information sequence consisting of binary digits (bits) can represent the data. Each bit has one of two possible values (0 or 1) and is associated with a distinct waveform. Consequently, bits have several properties that derive from their waveform representation:

- The bit duration T_b (bit duration, s) is the duration of the waveform associated with each bit.
- The bit rate (or data rate) R (bits/s or Hz) is the number of bits transmitted per second.
- The bit energy E_b (energy required per bit of information, Joule) is the energy contained in the bit waveform.

The bit rate relates to the bit duration by:

$$R = \frac{1}{T_b} \tag{5}$$

The bit energy relates to the signal power S (watts) by:

$$E_b = ST_b \tag{6}$$

Assume that the thermal noise power is uniform over the bandwidth, then

$$N = N_o B \tag{7}$$

Where:

N and B were previously defined and
N_o = thermal noise in 1 Hz of bandwidth.

The SNR is

$$SNR = \left(\frac{E_b}{N_o}\right)\left(\frac{R}{B}\right) \tag{8}$$

if the value of E_b/N_o is known. Equation 8 suggests that if the data rate increases, the SNR must also increase. If a larger bandwidth signal is used, the required SNR decreases.

Figure 3-5 shows BER plots for PSK and OFSK modulation schemes. Acceptable BER values typically range from 10^{-3} to 10^{-6}. As an example in applying the equations above, suppose the acceptable BER is given as 10^{-6}. Assume that the required data rate R = 40 kilobits per second (kbps) for a digital voice channel communications. If the modulation technique is PSK, then Figure 3-5 gives the corresponding E_b/N_o value of about 10.4 dB = 11, and from equation (8)

$$SNR = 11 \cdot (40\,kbps / 80\,kHz) = 5.5 = 7.4\,dB \tag{9}$$

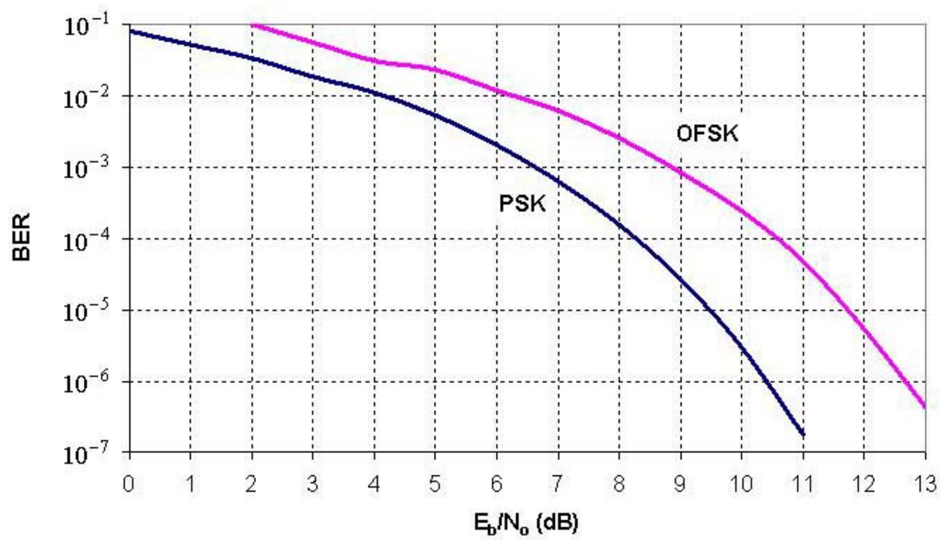

Figure 3-5. Probability of Bit Error (BER) for Two Modulation Methods

For this example, the receiver signal must be 7.4 dB above the receiver noise floor to achieve the desired BER or

P_r = receiver signal level threshold = -118 dBm + 7.4 dB = -110.6 dBm

In interpreting this example, notice that the receiver signal power started at a level limited by thermal noise, -125 dBm. The receiver components raised the noise floor 7 dB to -118 dBm. The signal had to be greater than the noise level by 7.4 dB to achieve the required BER, raising the required receiver threshold level to -110.6 dBm. The receiver power is a large negative number because the receiver is very sensitive; -110.6 dBm is equivalent to 8.7×10^{-15} mW, but the terms that make the receiver level a less negative number (in dBm) mean that the required power is increasing. This increasing receiver power affects the path loss of equation (1). The maximum path loss depends on the magnitude of Pr; as the magnitude decreases, the maximum path loss decreases, as does the allowable separation distance between the Tx and Rx. Hence, an increased noise level, or a larger required SNR, will decrease the maximum separation distance between a Tx and Rx.

Although the discussion in this section has focused on the factors that control a physical link between two communicating devices, in general, there are multiple links used to connect a source and destination. Figure 3-6 illustrates a more complicated communications path between the sender and receiver, but one that is also more common. The Tx and Rx access a network (inside the dashed line) to establish communications. The message relays between sequential communications components (nodes) before reaching the receiver. This leads to the discussion of networks in the next section.

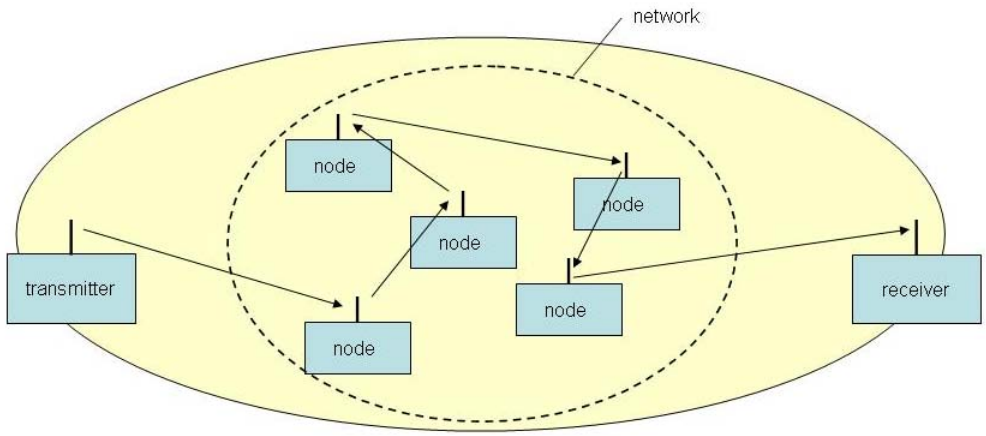

Figure 3-6. Communications via a Network

3.1.2 Network Performance

A network is the interconnection of multiple communications components designed to extend the area of coverage and the number of users able to access the services provided. Due to the limited range of a single wireless communications link and the large geographical extent of modern underground coal mines, any of the wireless communications or electronic tracking systems installed in a mine will require a network of some sort, except possibly in a very small mine (with entries less than a couple thousand feet in length). *Topology* is the configuration of the network components. The choice of topology plays a major role in the performance of the network and its likelihood to survive accidents, i.e. its survivability. Figure 3-7 shows several standard network topologies. The green circles represent nodes and the lines represent connections between the nodes. The connections may be hard-wired metallic conductors, fiber optic cables, or wireless.

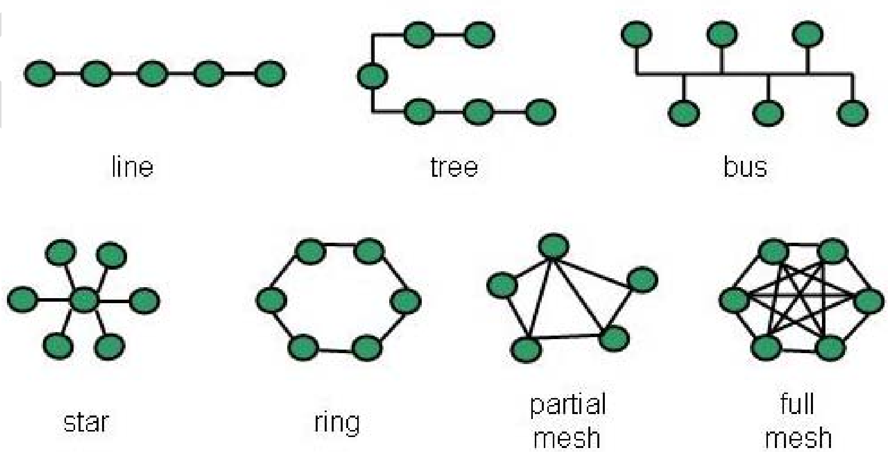

Figure 3-7. Some Standard Network Topologies

There are advantages and disadvantages to each topology pictured. The line topology is simple and failures are easy to isolate. However, if the leftmost node is on the surface and there is a failure at one of the connections or other nodes, the nodes to the right (inby) the failure have their communications cut off. Thus, the network is vulnerable to a single-point failure.

The tree topology is an improvement over the line topology simply because a failure on one of the branches does not affect the other branches, but each branch has the same single-point failure-mode potential as the linear structure. In the full-mesh topology, each node connects to every other node. Thus, a miner accessing one of the nodes with his radio link will have a choice of multiple paths to reach the intended receiver. In addition, if one node fails, there are multiple paths around the failed node. It is unlikely that the full-mesh topology would ever be implemented in a room and pillar coal mine. With the many thousands of feet of mine entries to cover, it would be impractical or impossible to interconnect each node to every other node. A partial mesh offers many of the advantages of the full mesh and is much more practical in the mine environment.

3.1.3 Management of the Electromagnetic Spectrum

The MINER Act compels mine operators to install wireless communications and tracking systems into a mine environment that previously has had a very limited number of intentional RF emitters. There is the potential for Electromagnetic Interference (EMI). EMI occurs in a system when undesired EM energy from another RF system interferes with the reception or processing of a desired signal. In contrast, Electromagnetic Compatibility (EMC) is a desirable condition in which electronic systems are performing their desired functions without causing unacceptable performance degradation to other systems. EMC is established when any potential EMI between systems has been eliminated or reduced to an acceptable level. EMC has two aspects: a system should not generate EM disturbances that cause a malfunction in another system (usually referred to as the *emission* aspect); and a system should be able to operate in its EM environment without risk of malfunction (usually referred to as the *immunity* or *susceptibility* aspect).

In trying to reduce EMI, it is essential to identify the devices emitting RF energy and to determine at what frequencies these devices are working. *Spectrum management* is the term for managing the use of radio frequencies. Table 3-1 lists possible radio frequency emitters in a coal mine.

Table 3-1. Potential RF Emitters in a Coal Mine

Frequency	Application	Comments
300 – 10,000 Hz	Personal emergency device	Through-the-Earth communications
300 – 800 kHz	Medium frequency radios	Voice or text
150 – 175 MHz	VHF leaky feeder	Voice and low bandwidth data
400 – 410 MHz	Miner or asset tracking	
450 – 470 MHz	UHF leaky feeder	Voice and low bandwidth data
490 MHz	Remote operated miner	Remote control of continuous miner
900 MHz	Active Radio Frequency Identification (RFID) tags	Miner location
900 MHz	Line-of-sight radio	
900 MHz	Rescue robots	Robot control
2.4 GHz	Rescue robots	Video
2.4 GHz	Line-of-sight radio	

Another source of interference is noise, which consists of random electrical voltages. EM noise can originate within a radio receiver, or it can be external in origin. In a receiver, EM noise is always present in the electrical circuitry. Thermal noise is internally generated noise, and is a factor in determining the sensitivity of the receiver. A signal must be at a higher level than the EM noise for it to be detected, and a receiver threshold SNR is often quoted as a measure of how much higher a signal has to be compared to the noise level.

In most environments, external noise is also present. The external noise can be classified as either as man-made noise or as natural noise. In a coal mine, man-made EM noise could be generated by electrical equipment (e.g., motors), electronic equipment (remote-control devices), transformers, power lines, and electrical/mechanical switching devices. Electrically powered machinery used in mining also produces strong, low-frequency noise when starting up or when the power demand switches from high to low (or vice versa).

Lightning is one source of naturally occurring noise. This EM noise is low frequency, and the propagation loss is so low that its possible noise contributions could come from anywhere in the entire world. Wires that run into the mine can carry lightning and other EM noise generated from outside.

3.1.4 Modeling and Analysis

The link budget, introduced earlier, is a powerful tool for estimating the maximum coverage area for a CT system. It can also help determine the spacing between any pair of antennas to ensure reliable and high quality communications.

Above ground, handheld radios can permit communications between users separated by several miles. However, those same radios may only reach a few hundred feet in an underground mine. This dramatic change in performance is due to the impact of the mine environment on the propagation of EM waves.

The EM wave radiated by the Tx antenna travels through the surrounding medium, losing energy as it travels. This process is called EM wave propagation, and results in a propagation loss or path loss. As an example, consider the EM propagation of UHF waves in a mine entry. It is possible to describe the path loss by modeling the tunnel as a wave-guide [Emslie et al. 1975]. EM waves can propagate only if the wavelength is less the twice the tunnel dimensions, and then only certain prescribed modes of propagation are allowed. The modes dictate allowable angles of reflection of the wave as it propagates down the tunnel. The fundamental or lowest order mode appears to adequately describe the path loss some distance (typically a few hundred feet) from the transmitter after including an insertion loss ($L_{insertion}$) to account for the poor coupling of the Tx and Rx antennas to the fundamental waveguide mode. The RF fundamental-mode signal attenuation (C_{mode}) after the first few hundred feet from the Tx antenna, varies linearly with the distance z down the entry. Hence, as the distance from the transmitter increases, the path loss increases.

The model [Emslie et al. 1975] also includes several other effects that impact the path loss. One effect is due to the wall roughness, which permits some of the RF energy to be diffusely scattered by the interaction of the EM wave with the walls. Because the wall scattering (C_{wall}) is assumed to occur continuously as the EM wave propagates down the tunnel, it also varies linearly with z. Another effect is due to the possibility of the wall spacing (or floor and ceiling spacing) becoming gradually smaller or larger as measured by an angle θ called the tilt angle. The attenuation due to tilt (C_{tilt}) is also a linear function of z. Additional losses can be modeled for UHF signals propagating down a turn, such as a cross cut, but these losses will not be discussed further here. Equation (10) gives the line-of-sight path loss for UHF propagation down an entry for the effects discussed. Each of the constants C may depend on the wavelength of the UHF wave, the entry height and width, and the electrical properties (relative dielectric constants) of the walls, floor, and roof.

$$L_p(dB) = 2L_{insertion} + \left(C_{\mathrm{mod}\,e} + C_{wall} + C_{tilt}\right)\left(\frac{z}{100}\right) \qquad (10)$$

Representative values of the terms on the right hand side of the equation are (assuming a 14 ft wide by 7 ft high entry, frequency of 900 MHz, wall roughness of 4 inches, and tilt angle of 1 degree): $L_{insertion}$ = 22 dB; C_{mode} = 1.4 dB/100 ft; C_{wall} = 0.2 dB/100 ft; C_{tilt} = 1.2 dB/100 ft. Hence, the path loss at 1000 ft is 72 dB. Equation (10) indicates that as the distance z increases, the path loss increases as expected. There is further discussion of the UHF wave guide modeling in Section 3.6.7. The dependence of L_p on mine-specific features illuminates the difficulty in applying generic CT performance statements to a specific mine.

As seen above, the propagation loss may depend on the surrounding medium, any blockages along the path, frequency of the propagating wave, and dimensions of the mine entry. Determining the path loss may require the development of a model of the behavior that would include a detailed computer analysis. The more likely scenario is the development of “rules of thumb” for performance in a particular mine based on device testing in different parts of the mine. These “rules of thumb” would then become the basis for designing the CT system and expansion planning, followed by system testing after installation.

In addition to link budget analysis, an EMI analysis may be used to determine the level of undesired power received by a receiving system (a possible “victim” of EMI) due to radiation from a transmitting system (a possible “source” of EMI). In order to avoid interference, an EMI analysis also may be necessary to determine the required spacing in either the distance between antennas or the frequency between the source and victim.

3.1.5 Maintenance and Testing

Coal mine communications and tracking systems will require maintenance. Although these are rugged systems, the mine environment is very harsh. The RF system manufacturers should specify periodic maintenance checks. For example, when the power shuts down during emergencies, most systems will have battery back-ups. These batteries need to be checked periodically to ensure they are operational. Even rechargeable batteries in handheld devices will have a terminable lifetime associated with them, requiring periodic replacement.

To verify that the coverage is as expected, periodic testing is necessary of communications and tracking systems. Testing can be quantitative or qualitative. Quantitative testing requires specialized equipment to measure radio signal strength as a function of location throughout an area. Qualitative testing involves spot checks of communications links using a series of "Can you hear me now?" interchanges.

3.1.6 Performance Goals and Metrics

Performance goals and metrics for CT systems in underground coal mines is a controversial topic. When it comes to specific metrics, there are diverse opinions as to what those metrics should be as well as achievable performance goals. This section reviews the diversity of opinions and the difficulties in establishing these metrics and goals. This background will be followed by a discussion of sample metrics for underground coal mines.

For the purpose of this tutorial, *performance metrics* are measures of performance based on system behavior over a given period. These measures can be either qualitative or quantitative. Qualitative measures require some level of human judgment, e.g. ease of installation and difficulty of troubleshooting. Quantitative metrics are those measured directly or involving numbers that can be explicitly assigned — for instance bit error rates, radio signal strength, and system update intervals.

A *performance goal* as used here is the minimum or maximum value achievable for a given performance metric. Generally, it is relatively easy to obtain agreement on *qualitative* performance goals. Most people would agree that CT systems should be:

- Survivable
- Reliable
- Easy to use
- Easy to install and maintain
- Able to determine a miner's location
- Able to provide two-way communications
- Able to remain operational post-accident
- Safely operable both pre- and post-accident

Quantitative performance metrics and goals, however, cause opinions to rapidly diverge. For example, for a CT system, the following questions arise:

- What forces and extent of damage must the system survive?
- How long does a system have to remain operational post-accident?

- What percentage reliability does a system need to have?
- What is the maximum time that should be acceptable for repairs?
- What is the maximum acceptable delay for a miner's message to reach the surface?
- What constitutes sufficiently safe operation of battery-powered devices in a potentially explosive environment?
- How accurately does a miner's location need to be determined?
- How is a system tested once survivability goals are established?

There are several reasons why it is very difficult to answer these questions and to establish quantitative performance metrics that will have consensus agreement. These reasons include:

1) **CT systems operate differently underground.** The propagation characteristics of electromagnetic energy are different underground as compared with "free space" or aboveground environments. Therefore, the common methods used for validating these metrics do not apply. For example,

    a. Underground coverage is a lineal parameter measured in feet or miles. Above ground, it is an area measured in square miles or square feet.
    b. Working places are constantly advancing and retreating in underground coal mines, whereas aboveground metrics are largely based on fixed infrastructure. Consequently, aboveground methods for calculating reliability and survivability are not well suited to underground applications.

2) **The underlying system drivers are different.** The primary purpose for installing CT systems in underground coal mines is to provide post-accident communications that comply with the MINER Act. Above ground, most systems exist for productivity enhancements and automation; therefore survivability and reliability are generally secondary rather than primary performance metrics.

3) **Survivability and Reliability risks and options require installation-specific considerations**. A traditional one-size-fits-all solution is not applicable in underground mines. For CT systems, survivability has as much to do with the system layout and installation as it does with the technology selection. Thus, uniformly accepted performance metrics are difficult to achieve within the mining community.

4) **There are numerous trade-offs in establishing performance goals**. In the design of CT systems, there are instances where methods to achieve one performance goal make it more difficult to achieve another. As an example, steps taken to make a system user-friendly, such as automating certain functions, could lead to a more complex design, increased cost, and perhaps reduced reliability. As another example, extending the time that a system remains operational in an emergency could lead to larger and/or additional backup power-supply locations, thus creating more potential safety problems associated with the batteries. As a third example, coverage goals could drive requirements to install active components in return airways, thus creating safety concerns.

5) **CT Systems represent a new technology area for underground mines**.
Telecommunications companies that are responsible for the reliable operations of these systems operate most communications systems above ground. In addition, aboveground companies have ready access to services companies that can design and implement systems in those cases where companies elect to have their own infrastructure. This is not the case for the CT systems proposed for use underground. As a result, three issues arise:

   a. Tools to measure and predict performance in an underground environment are limited.
   b. Expertise, experience, and data to formulate performance metrics are limited.
   c. There is very little historical information relevant to CT systems in post-disaster scenarios usable for system requirements.

In response to the above issues, new metrics and methods, and possibly even new terminology, will evolve as mine operators and regulators gain experience with these systems. Nonetheless, the industry should strive to keep these performance metrics and terminology consistent with other industries to the extent possible.

NIOSH has a variety of efforts underway that will help formulate a basis for deciding what system metrics and goals are appropriate for the underground environment. An internal working group has proposed performance metrics that fall into four broad categories:

- Functionality – system requirements from the perspective of the miner and other end users.
- Installation and maintainability – metrics associated with the installation, maintenance, troubleshooting, and expansion of the CT system.
- Coverage and range – metrics that describe the service area of the CT system.
- Survivability and post-accident safety – metrics that describe the ability of a system to continue to safely operate post-accident.

Other metrics and goals are possible related to system productivity, such as system capacity, cost per mile, mean time to repair, etc. These are not included in the working group examples.

As CT technologies develop, performance enhancements are expected. The following metrics and goals are examples to promote discussion within the mining community. These long-term goals represent a view of an ideal CT world in the mine environment; it is likely that some of the long-term goals may not be realistically achievable. NIOSH continues to advocate the development of performance metrics and goals in collaboration with labor, industry, and regulatory agencies. Readers should refer to the latest MSHA and state regulations and policies to understand the minimum performance requirements expected by those agencies.

Table 3-2. Example Performance Goals and Metrics of CT Systems

General Category	System	Performance Metric	Long-Term Goal
Coverage & Range	Comm.	Wireless Coverage	Everywhere miners go
Coverage & Range	Track.	Tracking System Reporting Area	Everywhere miners go
Functionality	Comm.	Wireless Communications Capability	Voice & data with free-form texting
Functionality	Comm.	Peer-to-Peer Communications	All mobile radios should be capable of radio-to-radio communications without infrastructure
Functionality	Comm.	Paging Capability	Page all
Functionality	Track.	Tracking Data Storage Requirements	TBD
Functionality	Track.	Rescue Team Victim Locator	Audible alarm activated by proximity or radio
Functionality	Both	Remote Shutdown/Power Management	System can be turned off and on remotely for power conservation & safety
Functionality	Both	MOC (Surface) Requirements	Real time graphical display of miners, batteries, and faults/alarms
Functionality	Both	Interoperability	Voice & data communications to all devices & locations
Functionality	Both	Battery Maintenance and Monitoring	Reliable monitoring of battery conditions with alarms
Installation & Maintainability	Comm.	Coverage Verification	Monthly verification through “drive” tests
Functionality	Track.	Tracking System Update Interval	TBD
Functionality	Track.	Tracking System Resolution	TBD
Functionality	Track.	Miner Location Update Interval	TBD
Installation & Maintainability	Both	Maintenance & Monitoring	Real time monitoring of all elements with alarms, end-to-end automated test
Survivability	Comm.	Wireless Coverage Survivability (refers to access link)	Invulnerable infrastructure
Survivability	Comm.	Maximum Outage Area with a single element failure (worst case)	Invulnerable infrastructure
Survivability	Comm.	Communications Path Survivability (pertains to voice/data and tracking system backhaul)	Invulnerable infrastructure
Survivability	Comm.	Battery Life - Communications Mobile	TBD
Survivability	Comm.	Battery Life - Communications Fixed Infrastructure	96 hrs - indefinite with power management
Survivability	Track.	Tracking System Survivability	Invulnerable infrastructure
Survivability	Track.	Battery Life - Tracking Mobile	TBD
Survivability	Track.	Battery Life - Tracking Fixed Infrastructure	96 hrs - indefinite with power management
Survivability	Both	Battery Life - MOC	Unlimited
Post Accident Safety	Both	Battery System Safety	Invulnerable infrastructure
Post Accident Safety	Both	Permissibility or safe air validation post-disaster	Invulnerable infrastructure

Note: TBD indicates that the development of Long-Term goals are expected through consideration of on-going research efforts. These efforts include detailed analysis of the history, types, and duration of disasters in coal mines.

3.1.7 Wireless Systems Considerations

In wireless systems, the antenna performs a critical role in coupling the energy to and from the transmission medium. For an antenna to be effective, the antenna has to be a significant portion of the wavelength. This leads to the problem of the antenna becoming quite large for lower frequencies. Another issue with systems that operate at low frequencies is that they have very little throughput to support general operations where multiple users and significant data traffic is required.

Based on NIOSH research and discussions with focus groups, it has been determined that in order for the transceiver (including antenna) to be small enough for a miner to wear or carry the radio comfortably throughout a shift, the device necessarily needs to operate at conventional radio frequencies (VHF/UHF/SHF, where super high frequencies, SHF, range from 3 to 30 GHz). Systems that support these devices are called “primary communications” systems and they generally have the following attributes:

- Operate in conventional radio communications frequency bands.
- Use small antennas that allow the miner to have wearable devices with long battery life.
- Have sufficient throughput for general operations.

In contrast, secondary systems have the following attributes:

- Operate in non-conventional frequency bands.
- Use large antennas that are best suited for fixed locations or portable applications.
- Do not have sufficient throughput for general operations.

In the following sections, the leaky feeder and node-based systems are primary systems and the Medium Frequency (MF) and Through-the-Earth (TTE) systems are considered secondary systems. Within the medium frequency section there is an example of a hybrid system, which uses both UHF and MF, which may be usable as a primary system in exceptionally small mines. A hybrid system combines one or more types of systems to improve survivability or other desirable system characteristics.

3.2 Point-to-Point Communications

Throughout this tutorial, there is a distinction between a direct communications link between a sender and receiver and a communications path that requires a network (multiple links) to complete the connection. With *point-to-point* (P2P) communications there is a direct link between two devices. One example is an intercom system in which a sender presses a button on an electronic device to talk to a recipient who hears the message on a second electronic device. There is a wired connection linking the two devices. Another example is a pair of walkie-talkies or handheld radios. They operate similarly to the intercom system, but the connection between the sender and receiver is wireless.

Through-the-Earth communications is another example of P2P communications. A transmitting coil on the surface communicates directly to a receiving coil in the mine, with only the earth as a transmission medium. TTE communications provides an alternate communications link out of the mine at one specific location, but will not provide radio coverage at locations other than directly below the surface coil.

The discussions of the various communications technologies make it clear that P2P communications has limited usefulness in the mine environment. Other than Through-the-Earth, the P2P communications range is too small to be of practical use. To extend the communications range requires additional components in the path, i.e., some type of network or a large distributed antenna system (e.g., leaky feeder).

3.3 Wired Communications

Wireless radios have been described as “untethered,” i.e., no wires are connected to the handheld communications device. Most mines use some type of wired communications systems, where “wired” communications means the miner has to use a device that is in a stationary or fixed location. Many of these wired systems communicate data rather than voice. Examples of wired data communications are atmospheric sensor monitoring, conveyer monitoring and control, and monitoring of pumps. The systems use different types of wiring, cables, or media depending on the amount of data, the susceptibility of the wiring and the data to EMI, and the cost.

3.3.1 Twisted Pair

Twisted pair is two insulated copper wires twisted around each other. Each connection to twisted pair requires both wires. Sometimes the installation uses multiple wire pairs grouped into a single cable. Home telephones are connected using twisted pair. Twisted pair is the least expensive hardwire connection medium.

Standard pager telephones used in coal mines use twisted pair to communicate between the surface and miners underground. Several phones are connected in parallel to provide additional communications within the mine, yielding a “party line.” Pushing a handset switch activates the amplifiers in all the phones so that the message broadcasts to anyone within hearing range of a phone.

3.3.2 Ethernet Cable

Ethernet cable is generally an 8-wire cable terminating on a RJ-45 connector as used for Local Area Networks (LANs) and at the output of cable and digital subscriber line (DSL) modems for

Internet service. Called CAT5E and CAT6, computers are frequently interconnected using this type of cable. Mine sensor data or control data may use Ethernet cable as the medium for transferring information, but the distance supported is limited. As a result, several mediation devices allow Ethernet and other signal support over coaxial cable or fiber optic cable. Coaxial cable has lower signal losses and generally better shielding than CAT5E/6 or twisted pair, and therefore is less susceptible to EM interference. It is also more expensive than twisted pair.

3.3.3 Fiber Optic Cable

Fiber optic cables can transfer data at much higher data rates compared to metallic cables. Fiber optic cable is composed of continuous optical fibers bundled into a flexible cable. The cable can replace copper communications cables. Fiber optics use light pulses to transmit information down fiber lines instead of using electronic pulses to transmit information down copper lines. The cable is much less susceptible to EMI since it uses light pulses rather than electrical pulses. In addition, there is less attenuation than in copper, so the cable can transmit data over very large distances.

The fiber optic cable requires a translator. The translator accepts coded electronic pulse information coming from copper wire. It then processes and translates that information into equivalently coded light pulses. The process reverses at the other end of the cable, where the translator converts light pulses back to electronic pulses.

Fiber optic cables are generally more expensive than copper cables. If a fiber optic cable breaks, it requires more than a simple splice to reconnect it. Manufacturers are continually improving the fiber cable designs, making them more robust and more cost competitive.

3.4 LEAKY FEEDER

3.4.1 Description

A leaky feeder communications system uses handheld radios that communicate with a radio transceiver (base station), usually on the surface, and other handheld radios. Specially designed cable greatly extends the effective range of the base station. The link from the handheld radio to the cable is wireless. Figure 3-8 shows one type of leaky feeder cable. The cable acts as a distributed antenna, able to receive and transmit radio signals. The holes in the outer conductor allow EM waves to penetrate into, or leak out of, the coaxial cable. The cable also acts as a low-loss transmission medium, transporting RF signals over distances many times larger than would be possible without the cable present.

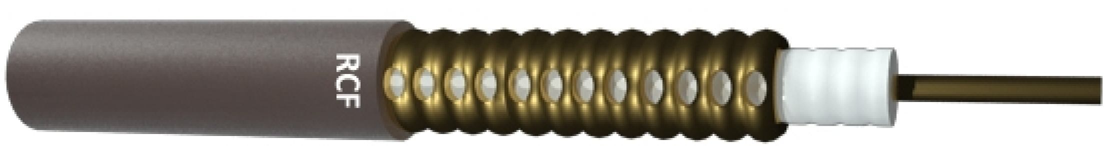

Figure 3-8. Cut-Away View of a Leaky Feeder Cable

Leaky feeder systems typically operate in either the VHF band at around 150 MHz or the UHF band at around 450 MHz.

VHF leaky feeder systems are very common in mines, and UHF leaky feeders are becoming more prevalent. VHF frequencies tend to experience lower line attenuation and coupling losses than UHF systems. UHF leaky feeders have requirements that are more stringent for installation and operation than VHF, and cost more. Because of their higher frequency, UHF systems can accommodate larger bandwidths and, therefore, handle more data and at higher speeds for a communications system. UHF signals from the handset propagate better than VHF around corners and into crosscuts in the mine. Thus, UHF systems allow the user to maintain communications when further away from the leaky feeder cable than do VHF systems.

Figure 3-9 shows a cut-away view of a mine with a leaky feeder system installed. Miners 1 and 2 are able to communicate with each other if they are within RF range of the leaky feeder cable.

3.4.2 Components

A leaky feeder system comprises a number of different components: head end, base station, power coupler, leaky feeder cable, line amplifiers, barriers, splitters, mobile radios, auxiliary antennas, and terminators.

A *base station* is the main hub of a leaky feeder system. The base station handles communications originating from the Mine Operations Center (MOC) and traveling into the

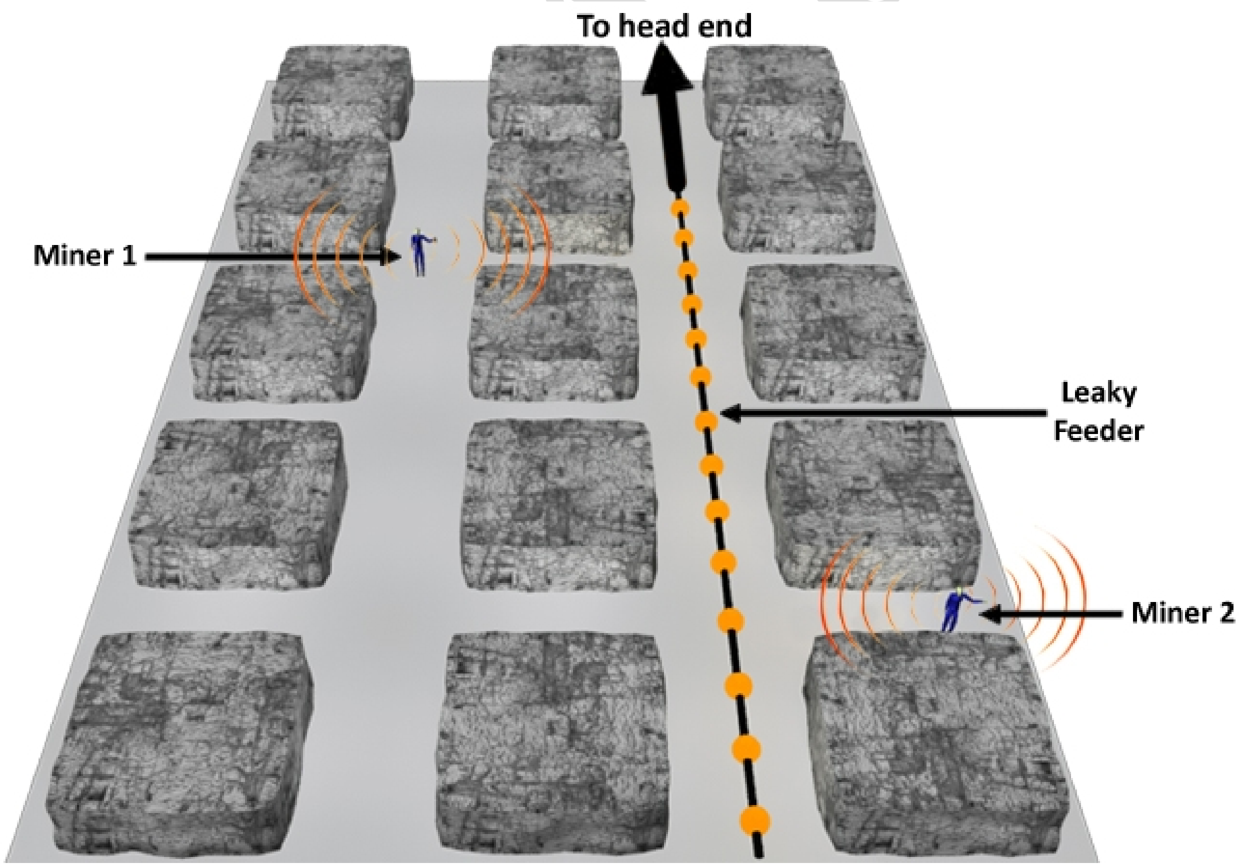

Figure 3-9. Leaky Feeder Communications System

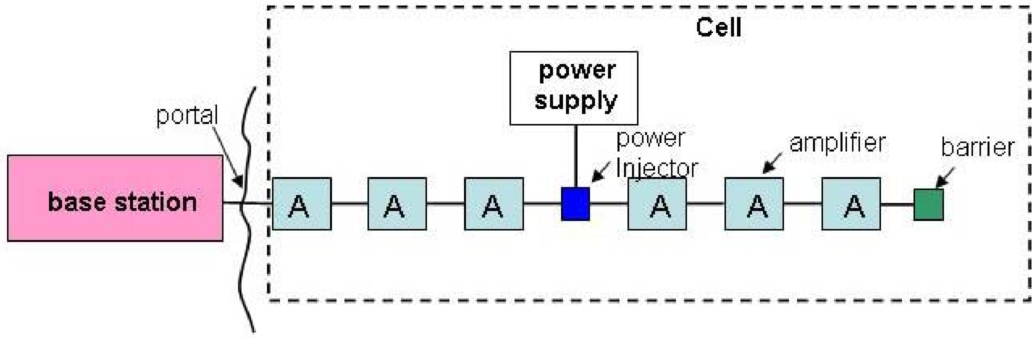

Figure 3-10. Main Components of a Leaky Feeder System

mine, and relays information between different branches of the leaky feeder system. A typical base station setup may include a head end, radio repeaters, power supplies, phone interconnect, data servers, and Ethernet (for communications systems configured for high-speed data). Components are usually organized and stored in rack-mounts. Communications into the mine feed into the head end, which then transmits signals down the feeder (see Figure 3-10).

Radio communications originating within the mine travel along the feeder cable to the base station, referred to as *uplink* or *upstream* travel. *Downlink* or *downstream* refers to messages from the base station to a handheld device. The uplink and downlink frequencies are not the same because the head end performs a frequency shift before retransmitting the message. Hence, the handheld radio transmits at one frequency and receives at another. As an example, a VHF radio might transmit at 170 MHz and receive at 150 MHz.

Communication signals between the MOC and the portal use a non-radiating cable. Once underground, this cable splices into the leaky feeder cable. DC power is injected into the cable at the head end to power the first few aboveground components located along the leaky feeder.

RF signals on a leaky feeder cable experience a loss in power as the signals propagate down the cable. This is because much of the signal intentionally leaks from the cable along its length. Significant power loss also occurs at junction points where the signal power may split among two or more feeder branches. To combat this loss, *line amplifiers* inserted at intervals along the run of the cable boost the signal strength. In most industry applications, these amplifiers are unidirectional, meaning signals can travel in one direction only. A modification that some manufacturers have made for the coal industry is to provide an option for bi-directional (two-way) amplifiers, meaning amplification occurs on signals traveling in either direction. Bi-directional amplifiers become important when considering the survivability of the system. Section 3.4.5 discusses this issue in more detail.

The feeder cable itself, using DC power injected at the head end, powers line amplifiers that are close to the MOC. Underground power supplies handle amplifiers further down in the mine. A typical setup will have line amps spaced approximately 1,500 to 1,800 feet apart along straight segments, depending on the frequency and any insertion losses caused by hardware on the line. Figure 3-10 illustrates an example of the periodic placement of line amplifiers in a leaky feeder cable.

Many amplifiers utilize Automatic Gain Control (AGC). AGC ensures that the power level of the output signal of an amplifier remains constant no matter the level of the input signal power. This helps to balance the overall power levels along the system and to smooth out any surges or irregularities.

Barriers are devices used to separate "cells," which are the building blocks of a leaky feeder system. These barriers pass RF signals between sections while also isolating the DC power between them. This ensures favorable power characteristics across the leaky feeder system by confining any electrical power imbalances to a single cell. Dividing the leaky feeder system into power "cells" is a necessary modification made for the coal industry to allow the systems to operate in a possibly explosive atmosphere. The requirement is related to the stored energy in the lines, and operators need to ensure that the length of the lines and the size of the "cells" do not exceed what was approved for the system.

Junctions are points where the leaky feeder cable branches off into separate directions. At junctions, the leaky-feeder cable divides into two or more cables by the use of splitters. *Splitters* maintain proper impedance matching between branches. They can also determine how the signal power divides among each branch in the event that one branch requires more or less power, which is important when designing an efficient communications system.

Mobile radios are the most common devices used to link to the leaky feeder cable. Other devices eliminate the need to communicate wirelessly through direct wiring into the cable. For example, a Radio Frequency Identification (RFID) tag reader wired to a leaky feeder cable relays information back through the cable to the base station in the MOC every time it scans an RFID tag.

It is possible to extend the range of a leaky feeder cable by using an *auxiliary* or *coverage antenna*. These antennas usually attach to a branch of the cable to provide coverage in a crosscut or portion of a parallel entry. Auxiliary antennas come in a variety of shapes and sizes that can address a number of coverage requirements. Termination antennas on the end of the feeder cable (sometimes called stope antennas) extend the range of the cable beyond the cable length.

Lengths of lower-quality leaky feeder cable can extend coverage into areas off the main feeder cable. It can be advantageous if this is done in areas where a cable is more likely to be damaged to avoid harming a higher quality (and more expensive) cable. Since a leaky feeder cable installs practically anywhere, this is a good solution for areas where obstructions may prevent adequate coverage by an antenna.

As the name implies, a *terminator* is at the end of a leaky feeder cable. A terminator unit is a component attached to the end of the leaky feeder cable to minimize reflections or undesirable effects due to abrupt change in cable impedance at its ends.

3.4.3 Transmission Media

The communications between two miners talking over their handheld radios incorporates two intermediate physical links, each with two parts as shown in Figure 3-11. The first link, typically called the *uplink*, is from the sender's radio to the base station consisting of the parts 1 and 2 in the diagram below. The part labeled with a 1 in a circle is through the air from the sender's radio to the leaky feeder cable. The part 2 of the link is along the cable to the base station. The second communications link, called the *downlink*, is from the base station to the receiver radio and it

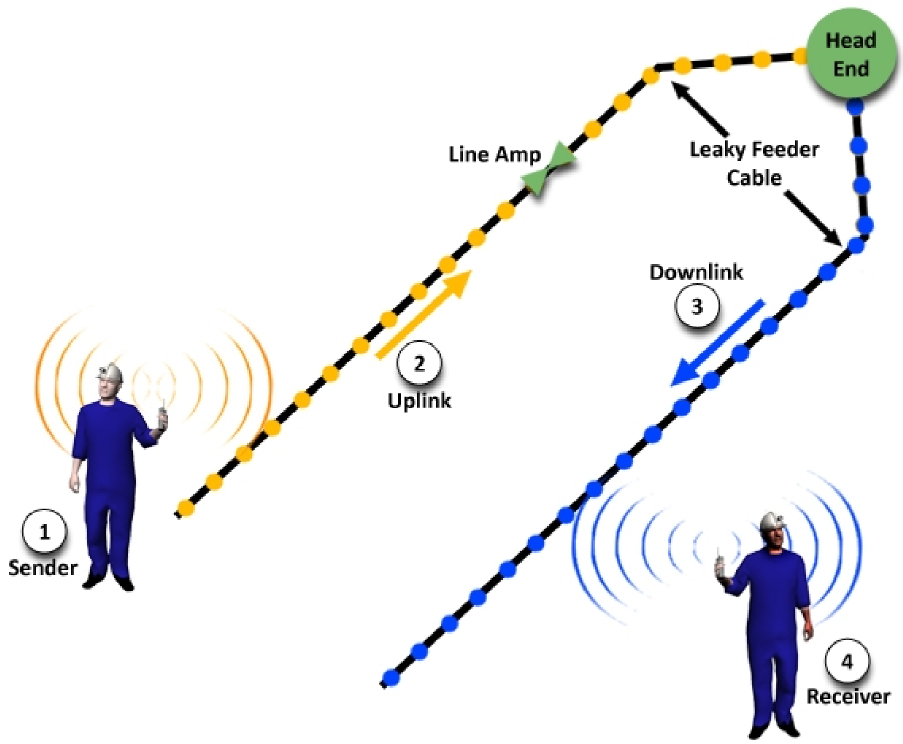

Figure 3-11. Communications Link between Sender and Receiver

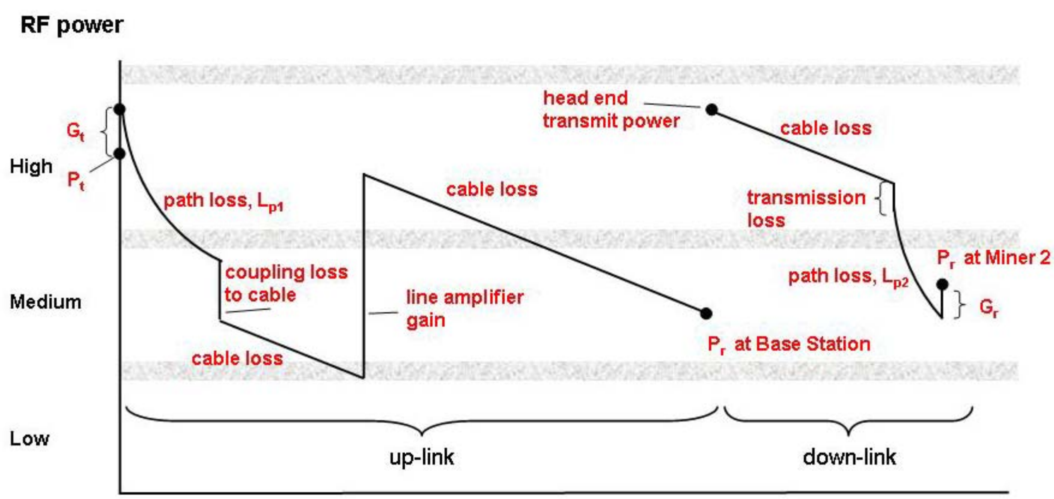

Figure 3-12. Conceptual Link Budget Analysis for Leaky Feeder

also consists of two parts. The first part of the link, indicated as 3 in the diagram, is down a different branch (although, depending on the receiver location, it could be the same branch) of cable to where the radiated signal travels through air (part 4) to the receiver.

Each of the four segments can have link budget analyses, which, when combined, determine if the entire physical link is feasible. Figure 3-12 is a graphical illustration of the link budget analysis. Starting the uplink analysis at the left-most side of the graph is the sender's radio transmit power, P_t, and an immediate jump to account for his radio's antenna gain, G_t, assumed to be positive. The free-space path loss of the RF signal traveling through the air follows. There is a coupling loss as the leaky feeder cable intercepts part of the RF signal. As the signal travels down the cable, there is a cable loss.

When the signal reaches the line amplifier, the signal level is increased. Further line losses occur until the signal reaches the base station. The base station amplifies the signal and retransmits it (at a different frequency) to begin the downlink portion of the analysis. There are losses in the cable until the signal reaches the location where it is nearest to the receiver radio. In converting from a signal in the cable to a signal in the air, there is a transmission or coupling loss. As before, there is further loss as the RF signal travels through the air. However, there is an increase in RF power due to the receiving antenna gain (assuming it is a positive number). The final number is the received power P_r, in the receiver's radio. P_r has to be above the receiver signal-level threshold of this radio for the link to be viable.

The manufacturer can supply most of the values used in a link budget analysis. The sender and receiver can affect the free-space path loss through the air by their actions. If the sender or receiver moves further from the leaky feeder cable, the path loss through the air will increase, resulting in a decrease in P_r. At some distance from the cable, the link is no longer viable.

3.4.4 Network Operations

Figure 3-10 introduced the cell as the building block of a leaky feeder system. Cells combine through the barrier component, which brings the ends of two leaky feeder cables from adjacent cells close together, so that RF signals can jump the gap between them. The gap provides direct current isolation between the cells so that powering the line amplifiers in one cell is independent of another cell. The network thus assembled is linear, with the head end at one end. This topology is especially compatible with the long entries of many mines. Figure 3-13 shows the topology schematically.

It may be desirable to have communications in parallel entries, in which case a tree topology is used. Because all communications travel through the head end, it acts as the base of the tree. Figure 3-14 shows the tree topology.

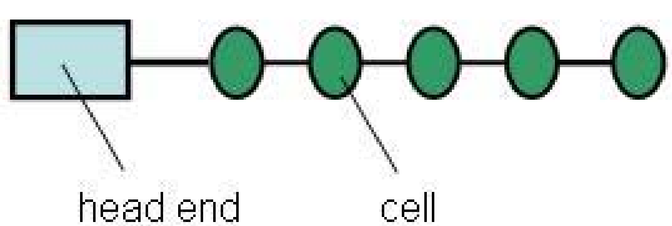

Figure 3-13. A Leaky Feeder System Using a Linear Topology

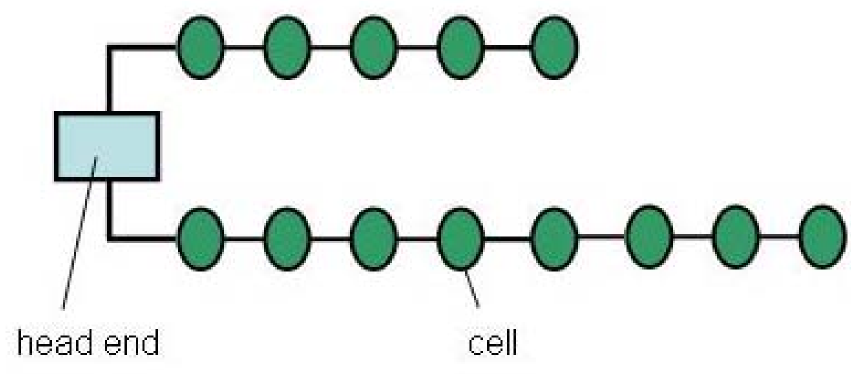

Figure 3-14. A Leaky Feeder System Using a Tree Topology

More elaborate topologies can be used to enhance the survivability of the leaky feeder system, or to increase the area of coverage. The next section discusses some of these options.

3.4.5 System Implementation

The inherent linear nature of the leaky feeder system makes it especially suited for providing radio coverage in long entries. Figure 3-14 demonstrates how radio coverage is readily extendable down parallel entries.

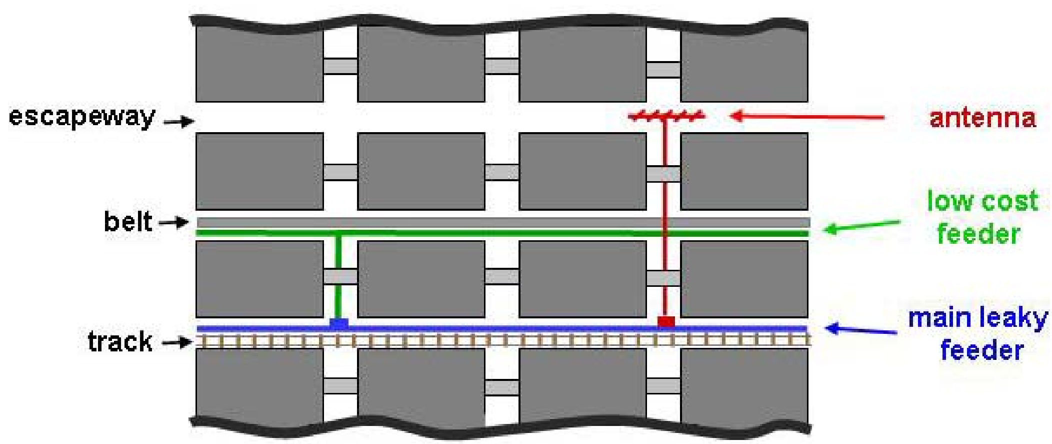

Figure 3-15. Ways to Expand Radio Coverage of Leaky Feeder

Figure 3-15 illustrates additional ways to extend the main leaky feeder radio coverage. One method is to splice a lower cost, lower performance cable into the main feeder cable rather than running a new cable all the way to the head end. An antenna spliced into the main cable can extend radio coverage to strategic areas.

The linear nature of the leaky feeder also makes it vulnerable to certain failures. If a roof fall damages or breaks the cable, all communications inby the break will cease.

Building in redundancy increases the survivability of communications. If an independent, redundant, leaky feeder cable exists in a parallel entry, it might remain operational in the case of a localized roof fall that breaks the main cable. In this case, miners cut off from communications could move to another entry to re-establish communications with the surface.

Providing an alternate communications path carries the idea of a redundant path to enhance communications survivability one step further. An alternate communications path reaches the surface at a point separated by a significant distance from the normal communications exit point. Figure 3-16 shows an example where the main leaky feeder exits the mine at an elevator shaft. An accident breaks the main communications link. An alternate communications path provides a leaky feeder exit to the surface through an air-shaft or bore hole. A surface connection re-establishes communications between the miners inby the accident and the operations center where the primary base station is located.

An RF message on the main leaky feeder cable inby the accident may need to change its direction of travel on the cable. For example, in Figure 3-16, if the sender were inby the accident but outby the alternate communications path to the surface, his message would have to change its propagation direction. Special bi-directional amplifiers in the cable permit this reversal of direction.

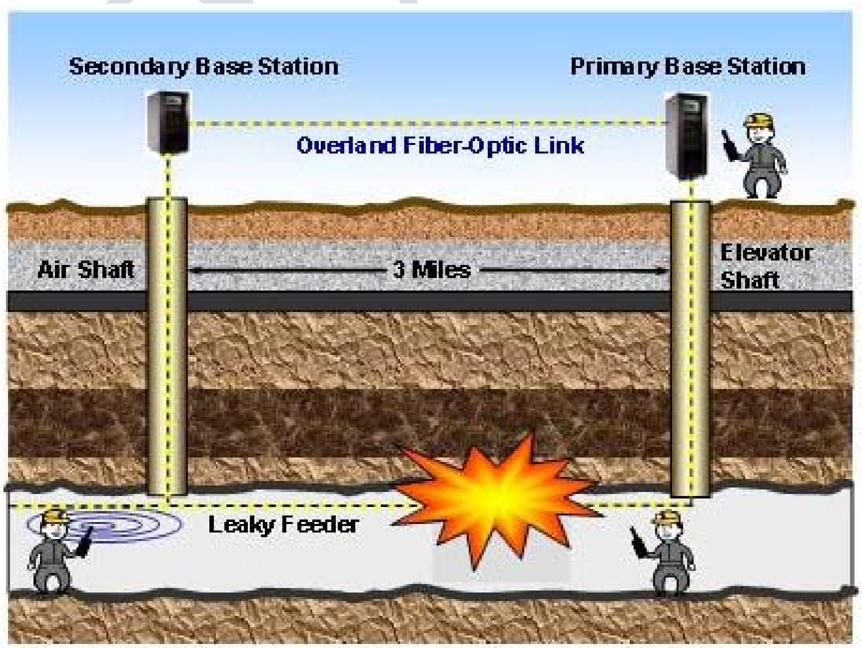

Figure 3-16. Example of an Alternate Communications Path

There are additional protective measures that can be taken to increase survivability, or "*harden*" the system. For example, there are measures to harden the leaky feeder cable against roof falls, such as encasing the cable in pipe or conduit made of a non-conducting material like PVC, which permits the penetration of RF signals. Burying the encasement at a shallow depth or coating it in protective material such as shotcrete also protects the cable.

For safety reasons, the mine may shut off electrical power following a major accident. Because each cell of the leaky feeder requires electrical power for the line amplifiers, the system would become inoperable. Therefore, each cell should have MSHA-approved backup batteries.

3.4.6 Maintenance and Inspection

The first indication that a leaky feeder communications system is not functioning is typically the inability to communicate between the dispatcher and a worker in the mine with a mobile handset. Leaky feeder systems come with different built-in diagnostic capabilities that help troubleshoot a problem. This varies from manufacturer to manufacturer, and may be in the form of an upgrade or option. For example, amplifiers may have a number of light emitting diodes, LEDs on their outer case that indicate the condition of the amplifier or the system, or even displays that provide status information. In addition, a diagnostic head-end capability may be available that requests and stores diagnostic information (such as voltage, current, and signal strength levels from the amplifiers), and displays the information in tabular or trend form or as graphical information in a map system. The main arterial of a leaky feeder system is typically in the track or main haulage entry, and the amplifiers with diagnostic LEDs would be in that entry. It would therefore be simple for a maintenance worker to ride in a man haulage vehicle in that entry to reach the amplifier that indicates a system problem.

In the case where a leaky feeder system has enhancements to increase its survivability, there may be components of the system only utilized in the emergency mode. The functional status of these components may not be readily apparent at all times as with the main arterial system. This may include branches off the main arterial to provide radio coverage in other entries, or antennas used to extend coverage in other entries. When utilizing a redundant loop for survivability, testing indicates the operational status of the loop function. All enhancements and their components can periodically be tested and inspected visually to make sure they are functioning correctly when needed.

For communications system components that are installed in XP enclosures for MSHA approvals, the gap of the enclosure lid must be checked on a regular basis with a feeler gauge as required by Code of Federal Regulations (CFR) regulations. In addition, if a hydrogen sensor is required (for MSHA approval) in enclosures with batteries, the hydrogen sensor has regular required maintenance. The batteries themselves must be checked periodically for state-of-charge and state-of-health and replaced as needed.

For leaky feeder systems installed in shafts of deep mines, special care is needed to make sure the tensile strength of the cable dropped down the shaft is great enough for a single point of attachment at the top of the shaft. Another concern is the high velocity air in the shaft whipping around a cable not securely fastened or placed in a conduit. The cable must be checked periodically for integrity. In the wintertime, leaky feeder components in intake air must function in temperatures well below 0° F. The components must be checked periodically for functionality.

3.4.7 Performance & Limitations

The primary arterial cable of the leaky feeder system is typically in the main access entry to the mine. In the case of a mine with a track for miner and supply transport, it is in the track entry. The cable is either attached to the rib near the roof or to the roof to one side toward the rib, to be out of the way of haulage vehicles and miners walking the entry. Both VHF and UHF leaky feeder systems provide good communications within the entry with the main arterial cable. As a miner travels into a crosscut walking away from the leaky feeder cable, UHF systems provide good communications all the way into the adjacent parallel entry (for open crosscuts). As the miner turns the corner around a pillar, communications will typically be lost by the time the center of the pillar is reached. VHF systems will lose communications midway into the crosscut. When there is a concrete block stopping in a crosscut, UHF systems may provide communications in the crosscut on the other side of the stopping from the main arterial cable, although it will be degraded. Performance can vary depending on whether there is equipment or materials filling the crosscut.

There are various techniques for enhancing coverage of leaky feeder systems to parallel entries or other points in the mine away from the main arterial cable. Low-cost radiating cable coupled to the main arterial cable can achieve communications over 2200 feet along the cable (in the belt entry). In addition, antennas (including yagi, a highly directional antenna, and helical antennas) can extend coverage 1000 feet in an open entry.

Installing independent arterials in separate parallel entries to provide redundancy is one approach to increase system survivability. This approach may allow for continued communications after a localized mine event (roof fall or explosion) as long as the mine damage from the event is limited to one entry. However, if the event involves multiple entries, the communications system may not survive. In the approach of using a redundant loop to increase system survivability, if a major event takes out multiple entries, including some of the leaky feeder infrastructure, the leaky feeder system would still be operational on either side of the event and to the surface. However, the miners might need to walk a short distance to re-establish communications, depending on what components the event affected, and where those components are located in the leaky feeder cell structure.

Mined out areas are often sealed to isolate the area from the rest of the mine. Before the area is sealed, miners should remove the leaky feeder components and cable. Similarly, in the case of longwall mining, miners should remove the leaky feeder components and cable as the panel retreats back toward the mains.

Leaky feeder systems can interoperate with other communications and tracking systems. For example, they can interface with mesh communications systems through a gateway node to provide an alternate communications path out of the mine. Similarly, they can work with tracking and tagging systems to transmit miner location information out of the mine. Tests have been conducted interfacing medium frequency communications systems with a leaky feeder system, where the medium frequency system was used to bridge a gap for a simulated leaky feeder cable break.

It is difficult to provide complete mine-wide communications coverage with leaky feeder systems. However, with redundant approaches and coverage extension schemes, most areas where workers are located and travel can have good quality communications signals, with a good level of survivability.

3.5 Medium Frequency

3.5.1 Description

Medium Frequency (MF) communications systems are so named because they operate in the MF band (300 kHz to 3 MHz), more specifically around 500 kHz. Their method of EM wave propagation characterizes MF systems. The MF radio waves attach themselves, i.e., they *parasitically couple*, to nearby continuous metallic conductors within the mine entry. The signals can propagate on the conductors for a few miles before they become too weak to be picked up by another MF radio. The conductors can be pre-existing phone lines, conducting life-lines, power cables, data cables, conveyor structures, piping, or inexpensive wiring specifically installed for MF communications. The signal radiates off the conductor as it propagates, so essentially the conductor behaves as a very inexpensive leaky feeder cable. In other words, the conductor acts as a distributed antenna, able to receive and transmit MF signals. In addition, the conductor acts as a transport medium for the signals. Figure 3-17 gives a simple example of MF radios used to communicate between two miners.

An MF radio is more accurately described as a man-portable radio, because it is significantly bigger and heavier than a typical handheld radio. An example of an MF radio could be a handheld microphone with a connecting cord to the transceiver. The transceiver might be connected to either an external ferrite or a bandolier loop antenna, or be in an integrated package with the antenna and batteries. The bandolier loop antenna might be on the order of a couple feet in diameter. Given the size and weight, a miner will not likely wear the MF radio continuously. One option is carrying MF radios to a working area and placing them nearby so workers have ready access to them. Alternatively, the MF radio might be used as a redundant communications system or a system used mainly for emergencies, perhaps stored in rescue chambers. Thus, MF systems are considered secondary communication systems, except possibly in small mines.

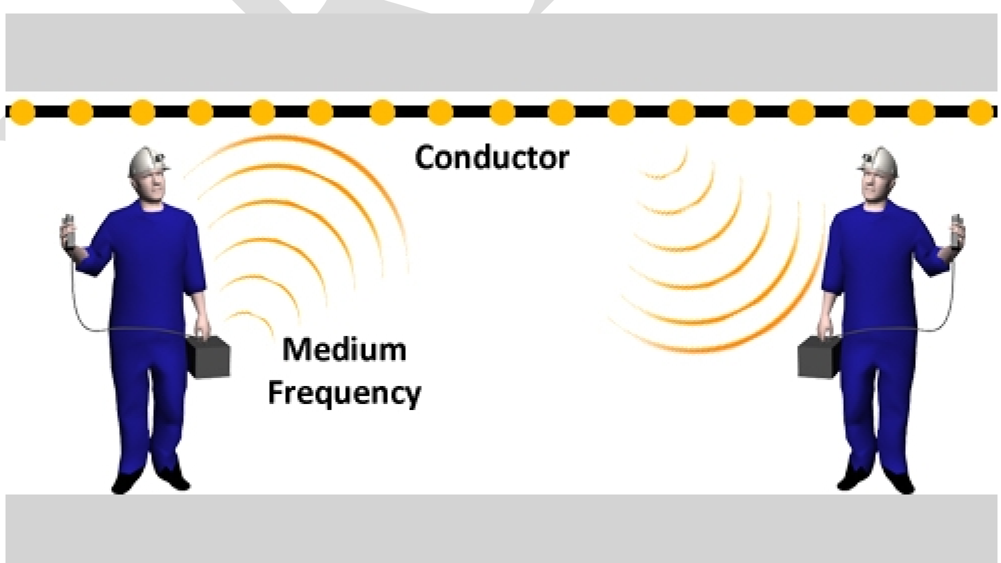

Figure 3-17. A Simple MF Communications System

A device exists that is able to interconnect MF and higher frequency systems like UHF or VHF. The device is called an up/down frequency converter, cross-band repeater, or bridge node. It can convert RF signals received in one frequency band to RF signals transmitted in a higher or lower frequency band. For example, the bridge node can down-convert signals received in UHF to signals transmitted at MF, or conversely, received in MF and transmitted at UHF. Thus, the bridge node acts somewhat like a repeater, except that it re-transmits the signal it receives at a different frequency.

Figure 3-18 is an example how the bridge node is used. The sender on the left communicates with the bridge node using a handheld UHF radio. The bridge node converts the RF message to MF, which couples to a nearby conductor. Another bridge node picks up the MF message and then re-transmits the message at UHF for the UHF receiver radio on the right.

MF systems that are currently available for coal mine applications are analog systems that support voice communications. As discussed in Section 3.1.1, a key advantage of digital systems is that digital signals can be copied an unlimited number of times and transmitted long distances without corrupting the information being sent. This is accomplished by the information being extracted from the radio signal, then re-modulated on a new radio signal at each node, whereas analog amplifiers amplify the entire signal, noise included. The digital approach eliminates the cumulative effect of noise. Noise can significantly limit the range of MF (and lower frequency) devices; therefore, it would be advantageous to have an MF system to extend the service area of MF systems.

Due to the lower frequency, the bandwidth, and hence, the bit rate, available for digital communications on a MF system is much lower than that of conventional UHF systems. This lower available bit rate creates technical challenges of introducing a MF system that can support voice. Despite these challenges, there are MF systems that support digital voice transmissions.

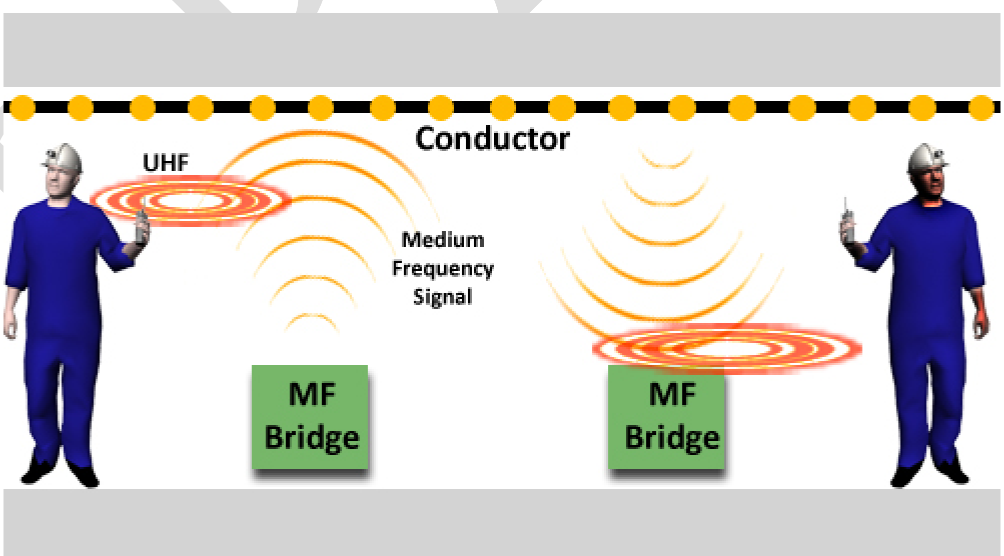

Figure 3-18. An Example Using MF Bridge Nodes

3.5.2 Components

The assembly of an MF radio system requires very few components. Man-portable MF radios and existing continuous conductors are all that is necessary to establish a communications system. Installing inexpensive twin-lead or twisted pair wire ensures a good propagation path for MF signals. Unlike with leaky feeder systems, there are no line amplifiers for the MF system, and hence, there is a limit to the maximum separation of a sender and receiver. A representative maximum separation distance is in the range of 2 to 4 miles. Figure 3-19 illustrates the simplest MF communications system.

MF signal will propagate along many different types of conductors (conducting medium). The best propagation is achieved with multiple insulated conductors in the entry, with a single end of one of the conductors tied to ground. This ground allows for a potential difference along the wire allowing signal to flow from one end to another. Properly resistance-terminated and grounded solid copper or other low resistance wires increase the distance a MF signal will propagate.

Some common types of wires that can be used for MF transmission are solid and stranded twisted pair, TV twin-lead, single conductor, and three conductor wire.

Conducting mine life-lines are another option for allowing MF signals to propagate along an escape route. Life-lines offer an advantage in that the user with his MF radio is likely to be extremely close to the conductor most of the time, which enhances the radio performance.

Three phase power cable and shielded power cable can be used to transmit signal as well, although electrical noise can interfere with the MF signal while power is on. Power cable can be used since MF has a fairly strong magnetic component to its wireless propagation. The magnetic component (often referred as the H-field) simply passes through many types of obstructions, seeking out conductive material, and propagates alongside them. The copper core of power cables has been known to remain intact in many mine disasters due to the large diameter of these conductors.

Other types of conductive material can be used to enhance or bridge MF signals. Solid and properly bonded steel rails provide a source for MF propagation. Trolley wire can offer a good low resistance path. Metal belt structure, continuous roof mesh, and water pipes allow for propagation in the entry in which they reside, but these conductors will not work as well as insulated conductors. Although these types of infrastructure can allow for MF signal to propagate, it is recommended that they are not solely relied on as the only medium through which to pass signal. This recommendation is due largely to the ability to ensure the proper continuous path. Repairs and use of belt structures, roof mesh, and water pipes could impede propagation since their main purpose is not to provide communication. These conductors should only be used as a last resort or as an alternate or redundant MF communications path.

Finding and installing suitable conductors in a mine involves mine-specific considerations. The best way to determine whether a conductor will work is to simply try communicating some significant distance using the conductor and two portable MF radios.

A portable MF transceiver produces high power MF signals that directly couple to a conductor. Another component, the up/down converter, was introduced in the previous section, and an example of a system using the bridge node was shown in Figure 3-18. Hybrid systems that combine MF capabilities with components that operate in different bands (VHF or UHF) use the bridge node. The bridge node operates between MF and VHF or MF and UHF. The VHF and UHF are compatible with VHF and UHF leaky feeder systems and handsets like the Kenwood TK 290/390. The MF side of the bridge node is available as analog or digital (pending MSHA approval). Forming ad-hoc networks requires the digital version, as discussed in Section 3.5.4.

3.5.3 Transmission Media

Figure 3-19 shows the three parts of a physical link involved in establishing communications between a sender on the left and a receiver on the right using an MF communications system. There are three different media successively involved in the RF propagation: air, conductor, and air again.

Part 1 includes the losses from the transmitter, through the transmit antenna, propagation through the air, and coupling to the conductor. Figure 3-20 shows schematically the power losses or gains, in dB, starting with the transmitter power P_t. The transmit antenna gain G_t is shown as a power decrease or negative gain because the antenna dimensions are comparable to the largest dimension of the briefcase shown in Figure 3-19; hence, the antenna is much smaller than the wavelength in the MF band. Therefore, the antenna is very inefficient. L_{p1} shows the path loss through the air. Also shown is the RF coupling loss to the conductor.

Part 2 involves the RF propagation on the conductor. As in the leaky feeder cable, there is an attenuation of the power of the RF signal as it progresses on the conductor, although the attenuation is typically much less for MF propagation.

Part 3 accounts for a potential loss in power in coupling the RF signal from the conductor to the air. There is then the path loss through the air, L_{p2}, and the negative gain of the receiving antenna, G_r. P_r is the power at the receiver, which must exceed the receiver signal-level threshold to create a viable communications connection. The communications equipment manufacturer can provide the actual values for the various link budget parameters.

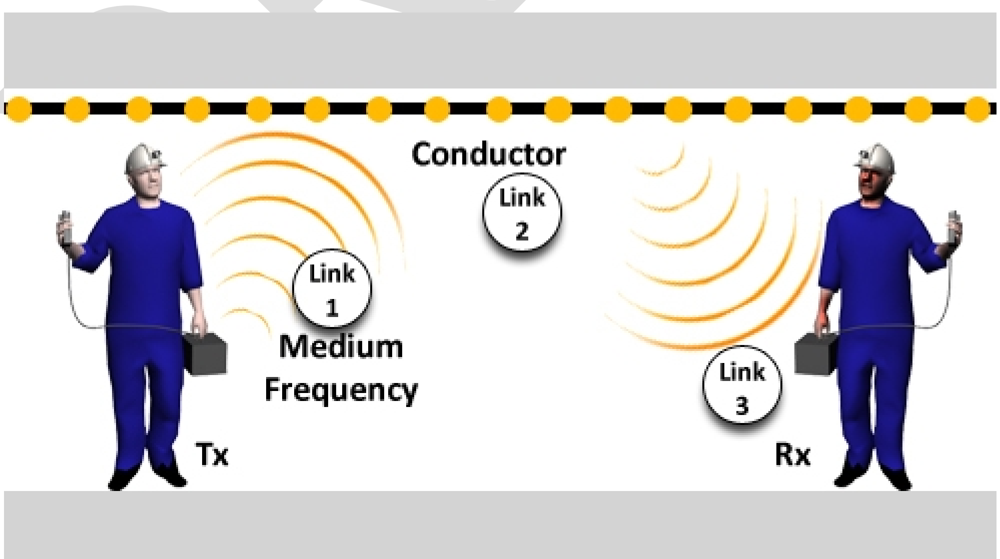

Figure 3-19. Three Parts of Physical Link in MF Communications Between Sender (Tx) and Receiver (Rx)

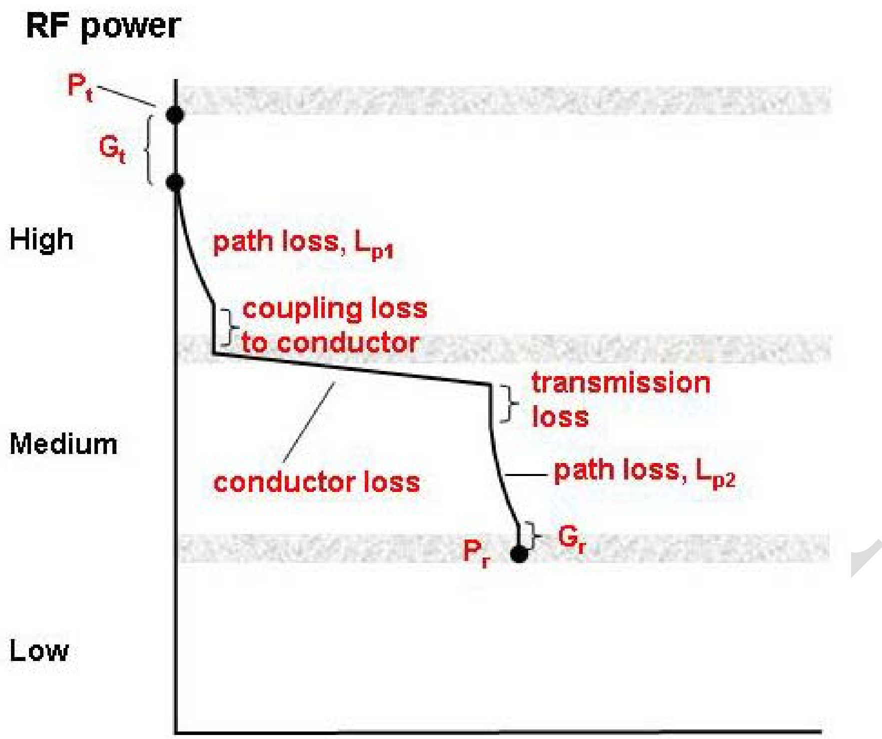

Figure 3-20. Conceptual Link Budget Analysis for MF Communications System

3.5.4 Network Operations

The analog MF systems that are available for purchase transmit using a very narrow bandwidth that only allows one channel for communications. When a sender keys his microphone to talk, he is broadcasting to all radios within RF range. Even though many users can communicate using this system, it is not a network. There are no programmable components to control the routing of message traffic. Further, there are no analog repeaters to extend the range necessary in large mines.

In contrast, digital MF systems, which are under development, will have the intelligence, control, and switching capability built into the nodes to perform message routing similar to node-based system networks discussed in Section 3.6. The MF/UHF or MF/VHF bridge node introduced in Section 3.5.2 is one of the first components offered in support of the MF network development path.

3.5.5 System Implementation

The principal use for MF communications systems is most likely to be for secondary communications systems and alternate communications paths. MF radios may have uses as primary communications systems for exceptionally small mines. Either conductors that already exist in entries could be used or inexpensive conductors could be installed specifically for the MF communications. It is possible to build in redundancy using conductors in parallel entries.

Workers would carry MF radios to their working areas to provide their communications connection to other workers and to the surface. MF signals will couple to conductors that have been buried in a trench to increase the survivability of the conductor. However, such a system would be cumbersome relative to the size of the equipment.

A less cumbersome variation on the above implementation is to replace the MF radios with analog MF/UHF bridge nodes and UHF handheld radios. To provide continuous coverage in an entry with a continuous conductor, the bridge nodes are placed so that a worker with a UHF handset is always within RF range of a bridge node. At the portal or some other exit point, a bridge node within RF range of the conductor receives and converts the MF message to UHF and transmits it to the MOC. Another option is to directly connect a MF base station near the portal to the conductor to receive the signal, and then use a hardwired connection to transfer the message to the MOC.

UHF radios and the MF/UHF bridge nodes can be used to extend leaky feeder coverage into a working section. Figure 3-21 shows a worker near the working face. He communicates with a UHF radio that links to the MF/UHF bridge node. The bridge node receives the UHF message, converts it to MF, and couples the signal to a nearby conductor. The MF signal travels down the conductor until a bridge node, which re-transmits the message in UHF to be linked to the leaky feeder cable, picks it up.

The miner at the working face could also be issued an MF radio. The power cable to a continuous miner is a good conductor for MF signals. The MF signals would be carried back towards the main entry where an up/down converter would capture the MF message and re-transmit a VHF or UHF signal to couple to a leaky feeder backbone. The rugged continuous miner power cable will frequently survive a roof collapse, providing an inherently hardened communications line.

Another concept that is being developed is the use of a digital MF converter, which can be used in forming an extended MF mesh network. The converters can be thought of as nodes that are linked by, but not hardwired to, continuous conductors. Voice and text are encoded into a digital

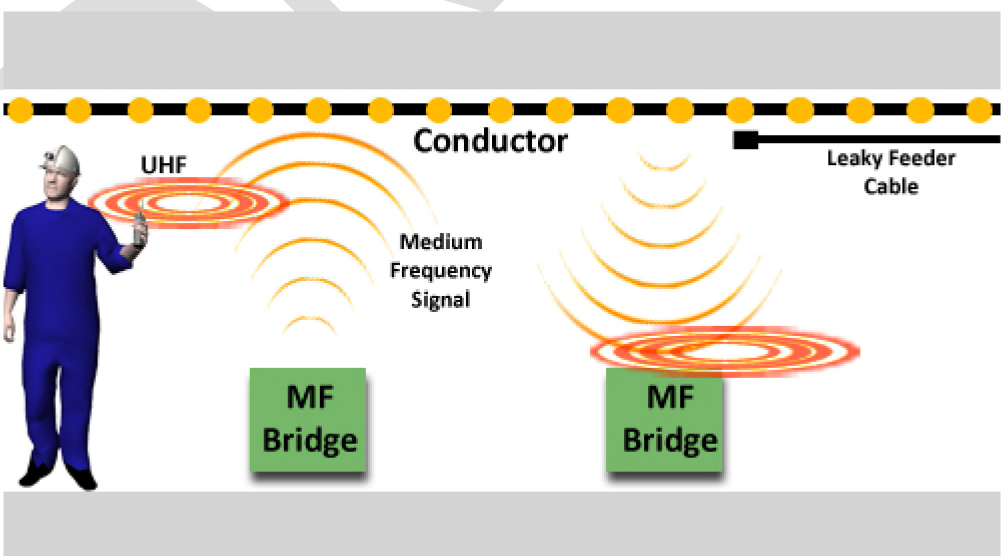

Figure 3-21. MF Bridge Node Used to Extend Leaky Feeder Coverage

sequence by computers within each node. The nodes communicate with other nodes to compute the route from the sender to the recipient through the interconnected nodes. A network in which the nodes are self-configuring is called an *ad-hoc network*. Some of the nodes could be portable, either because they are installed on mobile machinery or carried by workers to their work areas. Once a node is within RF range of the network, the network automatically accounts for the addition of that node in determining routes. Should one node fail or be carried out of range of a conductor, the other nodes are able to detect the loss and determine alternate communications routes if they are available. This is one advantage of mesh networks. Section 3.1.2 introduced mesh networks as networks that have multiple routes connecting pairs of nodes. The presence of multiple routes, i.e., redundancy, increases the survivability of the communications system.

There are also niche applications for MF radios. MF radios could be installed on a man trip to provide a redundant communications system if conductors are present in the entry. MF radios could be stored in caches in critical areas or stored in rescue chambers for use during emergencies. The assumption is that some conductors may survive the event and present a continuous path for MF signals.

The proximity of the MF antenna to the conductor is very important to maintain good communications. Often times a person can hear the MF signal, but may not have the ability to respond. This is due in part to the importance of the air gap between the MF antenna and the wire. It is highly recommended that the user place his radio as close as possible (although no hard-wired metallic connection is needed) to the conducting medium to achieve the greatest coupling of the signal to the conductor. Being close to the conductor results in the greatest distance the signal can travel. In addition, it is always recommended for the user to be as close to the conducting medium as possible because noise, distance, and breaks and inconsistencies in the conducting medium reduce the strength of the MF signal. MF signal strength is directly related to the maximum distance it will propagate.

Given the need for the MF antenna to be near the conductor, it is important not to place the conducting medium out of reach of the users. Strategic positioning of conductors in an entry is important to consider during installation, and maintenance checks should ensure access to the conductor. The access to the conducting medium varies depending on mine-specific conditions such as the mine roof, location of obstructions within the entry, water, trolley wire, floor and rib conditions.

It has been mentioned in the paragraphs above that noise sources can affect the ability to communicate using MF. RF noise sources that can generate frequencies in the MF range are: AC power harmonics, belt drive motors, power centers, pumps, continuous miners, and long-wall equipment. Other equipment that could interfere with MF communication could be power haulage vehicles, and very large DC drives, especially if they experience large changes in power demand. These types of equipment cause interference by producing current or voltage fluctuations at frequencies in the MF band which combine with the MF communication signals, making it difficult to separate out the communication information. The interference can introduce static, distortion, or completely overwhelm the MF signal. The interference typically occurs in the vicinity of the noise source as most low frequency noise sources do not propagate very far along the same conductor as the MF signal. The best solution to correct this problem is to add separation distance between the conductor, the MF radio, and these noise sources. In some cases, distances as short as a couple of feet may dramatically decrease the effects of the noise source.

In most cases with MF, mine-specific considerations are extremely important. Placement of the conductor has to be taken into consideration when installing an MF system both for reasons of coverage and access. In some cases, it may be better to run multiple conductors in strategic locations of each entry in order to have consistent coverage throughout.

It has also been found that the MF signal propagates best on the conductor if one end of the conductor is grounded. Typically, this is best done outside the mine on the surface where general maintenance and good contact are more easily achieved. An example of a good ground would be a three-foot long, copper-clad ground rod pounded into conductive earth. The ground can be tested the same way as ground bed measurements described in 30 CFR 77.700. It is important that the MF conducting medium is not tied into any part of a power system. Electrical ground can offer higher interference as well as possible electrical hazards to persons using the MF conducting medium.

Another important consideration is how to connect branch conductors. These tie points can be crucial to providing MF communications to off-shoots from the main line, down a cross-cut, for example. It is recommended to connect branch circuits by forming a series loop in the conductor in order to pass the maximum amount of signal. The performance of this configuration depends on how long the branch is compared to the main line and how close the branch is to the MF source.

Directly shorting or tying the conductor in a “T” fashion is not desirable. This short-circuits the MF signal, forcing it to propagate more down the main line and bypassing most if not all of the branch conductor.

Having the ends of the conducting medium properly terminated is beneficial. In some cases, two-conductor medium are slightly imbalanced, offering some loss in signal propagation. This can be due to several factors including different distances, shapes, manufacturer variances, temperature, and partial physical damage. Often times a reasonably well-conductive two-conductor medium will only require both ends to be tied to each other. This should be tried as a first option. In most cases, it is undesirable to have open-ended terminations, unless dealing with a single conductor medium.

In the case of a single or floating end termination, it is desired to have more cable beyond the end of where the furthest communication is planned. This can be easily done by leaving a spool of extra wire at the end (see Figure 3-22). This is also convenient when one has to expand coverage from the end of the conductor. Dead-end or floating terminations create end effects that are not desirable for MF communications.

MF conductors used as the transmission medium should be protected against damage. Breaks and kinks in the conductor may be tolerated to some extent, but they attenuate the signal.

When installing new conductors, it preferred to take basic steps during the installation to ensure the conductors are hardened to damage. The best protection against damage is to bury the conductors in the floor. This protects them from perpendicular explosion forces as well as roof falls. The cable only needs to be buried under a few inches of semi-fine material in order to prevent it from blast forces and basic roof falls.

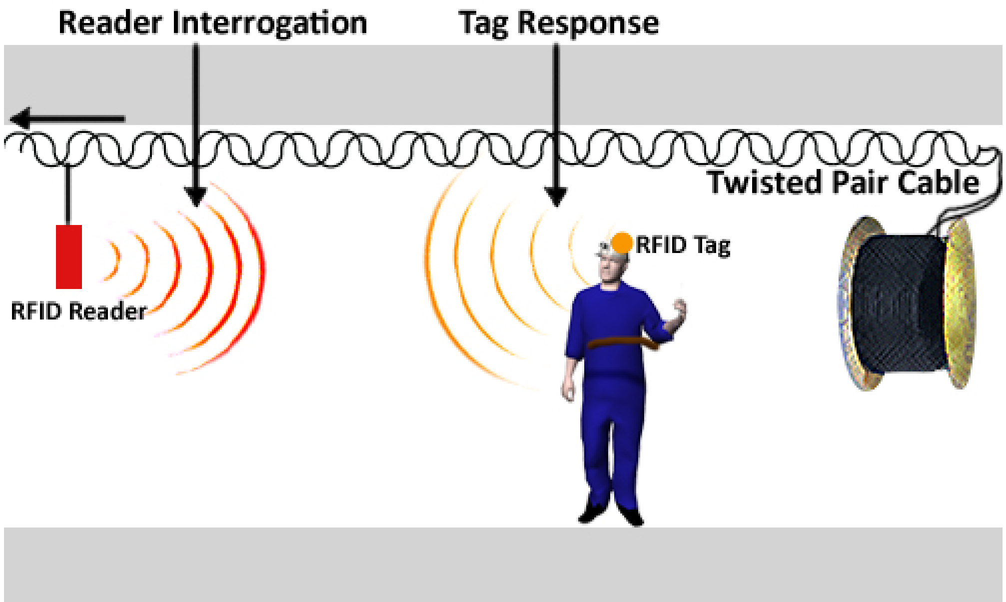

Figure 3-22. MF Communications Recommended End Configuration

Another option is to bury the cable only at the intersections of cross cuts. This general area of the mine is prone to roof falls and also holds the greatest chance for perpendicular forces to damage MF conductors. Conductors in trenches, even if covered in water or mud, will still propagate MF signals. Even conductors installed in simple conduit on the floor have some protection against daily stress.

Other options for cable installation include hanging the cable tight to the corners of the mine rib on either the floor or the roof. Roof falls frequently have the thickest portion of material towards the center of the entry, which forms an arch there; hence, the conductors will be more protected near the corner. Steps need to be taken to ensure the installation approach at intersections is consistent with the main run of MF conductors and that they are protected from the largest forces possible in the mine entry. Multiple pathways for the MF signal will reduce bottleneck weak points, while a single large break could prevent communications from propagating down the main path.

Existing components of a communications system play a part in MF signal propagation. Since MF is typically used as a secondary, emergency communications system, it is likely that a mine would have a primary communications system. MF can use any type of continuous conductor as a means to communicate. Twisted pair for page phones, leaky feeder cable, and other metal conductors are good examples of existing infrastructure that could be used by an MF communications system. These conductors can be easily controlled and followed to ensure propagation. Other types of conductors such as rail and power cable can be used also, but they might require more extensive testing to verify the MF communications link.

The MF bridge, if used, also needs to be protected. The MF antenna needs to be close to the conductor for good MF coupling. Some form of non-conductive enclosure should be used to both protect the MF unit and not impede the transmission signal. Although MF signal can pass through metal to some degree, it is not desirable to have coupling to the MF bridge housing itself. A good option is a Lexan enclosure with a metal cage guard. This allows most of the MF signal to penetrate the enclosure and couple to the conductors in the mine. This option will also allow the unit to operate near a given conductor even if that location is prone to physical damage.

If a stationary MF component has exposed connectors, they should be protected against damage. Also, fixed components should not be installed at cross cuts, if possible, to avoid potentially large perpendicular forces from explosions.

As mentioned earlier in this section, MF radios are considered a secondary communication source, except possibly in small mines. MF systems are useful for providing alternate communication paths or more survivable communications from a working section. The most diverse paths would be through existing boreholes or separate entries other than the main entry. Boreholes offer a direct path to the surface in which a conductor can pass and provide communications to the surface. Continuous metal-cased boreholes can be used to carry an MF signal. At the surface, MF signals can be converted to UHF using a bridge to link to a handheld radio, or the MF signal can conducted directly to the MOC.

A lifeline made of a metal conductor could also serve as an MF communications medium. Since a lifeline may be used in an emergency and would be in close proximity to a miner carrying an MF source, signal attenuation would be minimal. Additional conductors could be placed on the ground or buried to enhance the MF signal in entries with no pre-existing conductors, including in returns and other areas of the mine which may not necessarily need communications except in an emergency. Power cables are thick, sometimes armored cables that can serve as an MF path to different areas of the mine if not to the surface. Mine pager-phone wire, solid copper twisted pair, serves as an excellent medium for propagation of MF signals. Mine pager-phone wire is continuous; it provides for a better signal coverage if it is configured in a manner described in Figure 3-22.

As to spare parts, an MF system is inherently simple. It has few components and uses a large variety of conductors, including those that are already installed in the mine. An MF system needs to be planned out in advance. Throughout the mine, existing conductors should be located, mapped and analyzed. This will determine where coverage potentially requires additional conductors. Spare or additional conductor needs to be located in areas of rapid expansion, such as the face area, to extend coverage. This can be accomplished by keeping a spool of extra conductor on the expanding end at all times. This spool of conductor may also act as a higher gain antenna than the conductor alone, enhancing MF communications in that area of the mine.

It is also important to provide a cache of spare batteries (assuming MSHA approves of battery replacement underground) in key locations underground to allow MF communications for a prolonged duration.

3.5.6 Maintenance and Inspection

Due to the few components needed to operate a MF system, the system is not very complex. The factors that most influence performance are the conductor configuration and the proximity to that conductor. Because all conductors in an entry near an MF radio can possibly propagate the signal, some trial and error testing is needed to determine signal strength at strategic locations throughout the mine. One basic method of determining signal propagation is to periodically check the quality of the communications. If conductors or conductor connections have been changed, the system may not work as originally intended. If the mine has miles of conductors, there is a reasonable chance that a conductor path will be altered or removed.

An example of a simple hybrid analog MF system would most likely consist of each miner having a UHF handheld radio, an MF to UHF Bridge installed in strategic locations, a near-by preinstalled-preconfigured conductor, and an emergency MF-only portable radio. MF radio antennas are significantly larger and heavier than UHF radios, hence, the use of the MF bridge allows the miners to use UHF radios. The MF system would likely be installed at the working area and in other strategic areas. If it is necessary for a miner to leave the UHF range of the MF bridge, he would have to take a portable MF-only radio to maintain radio coverage. Of course, the extended MF radio coverage only works if there is a properly configured conductor present to transfer the signals. If there are no conductors, or the conductors are not configured correctly, there will be no MF communications.

The only inspections of the same hybrid MF system are the MF bridges, handhelds, and the conductors being used as the transmission medium. Spot checks will need to be made at strategic locations to ensure the radios and conductors are properly working. A simple voice-analog MF system will have to be checked in person. This could be done at the beginning of each shift. More complex digital MF systems may be able to diagnose problems related to coverage and unit functionality, but the limited bandwidth of the system may restrict this operation. Analog-voice systems are easier to install and use, but do not offer much capability in troubleshooting.

The only inspections of a simple MF system are the MF bridges, handhelds, and the conductors between them. Spot checks should be performed at strategic locations to ensure that the radios and conductors are properly working, preferably at the beginning of each shift. Battery maintenance is similar to other battery operated systems. The battery charge and health of the portable MF radios can be verified each shift before taking them below ground. The fixed position MF bridges will be powered by mine power until an emergency, in which case, they may revert to battery backup power if the main power is shut down. It is recommended that the fixed position bridge have some indication of the health of the battery.

3.5.7 Performance & Limitations

The coverage of an MF system depends on a number of factors. The RF communication range of two MF radios in free-space can vary with the transmitted power level, but typical surface ranges are on the order of tens of feet. However, this range is misleading because once the signal couples to a metallic conductor it can propagate for several miles. This phenomenon is the result of the magnetic field parasitically coupling to a metallic conductor. If conductors are properly configured, MF signals can travel on many different conductors throughout the entire mine.

There are two main factors that strongly influence the communications range of an MF system. The first is the overall conductor transmission range, which is the distance that the MF signal propagates along the conductors. In order to ensure the maximum coverage along a conductor, proper grounding and terminating are important.

The second range consideration is the separation distance between the MF radio and the nearest conductor. Since MF needs to couple magnetically to a conductor, the transmitter must be within a few feet of the conductor to effectively couple the MF signal. The closer the MF radio is to the conductor, the stronger the coupling to the conductor. Stronger coupling increases range and the ability of the MF signal to pass through smaller or slightly damaged conductors.

It has been observed that to receive an MF signal, an MF radio may be able to be further from the conductor than to send a return signal. In general, it is best to transmit as close to the conductor as possible in all cases.

It is difficult to determine which conductors are propagating the MF signal. A spectrum analyzer or other RF analysis equipment that measures the signal strength can be used to assess which conductors are participating in providing MF coverage. Since MF is highly dependent on conductors for propagation, being able to measure the signal drop along the conductor can be helpful. If an MF bridge is used, the UHF or VHF coverage will need to be verified as well to ensure the expected performance.

Extending the range of an MF system is highly dependent on the number of conductors in an entry. Adding another conductor on the opposite rib will ensure better coverage. This will also allow the recipient with access to the closer conductor to respond back. Receive distances are relatively short from any conductor so placement becomes challenging. Coverage can be extended to crosscuts along the mainline by installing loop paths. Looping a conductor around a pillar will offer the extra coverage needed in adjacent entries while also offering coverage to those entries nearby which do not have conductors in them.

The simplest MF system uses analog voice. Peer-to-Peer communications is standard, where paging persons is possible over an all-call function. The system incorporates no remote shutdown or power management. Only MF users within RF range and on the same frequency will be able to hear the original sender.

The MF system can be used to extend the range of a UHF or VHF leaky feeder system. Miners in a working section could use UHF or VHF radios to communicate to an MF bridge which would couple MF to a conductor (possibly a power cable for a continuous miner, for example) which would carry the MF signal to the main entry. Another MF bridge would then re-transmit the signal in UHF or VHF to couple to the leaky feeder cable frequencies.

The stationary MF bridges may be designed to further increase the chances of survival. Since they do not depend on line-of-sight proximity to the conductor, they can be better protected in the event of a disaster. It is important to protect the conductors, which are the transmission medium. Installing more than one conductor is helpful to withstand damage caused by perpendicular forces. Mine seals and crosscut intersections are key areas which could use better protection against environmental forces.

The battery life for MF systems is less per amp-hour of use than higher frequency communications systems, because higher currents are needed to generate the magnetic field through a loop or ferrite antennas in the MF system. The entire unit is not wearable on a belt. Loop and/or ferrite antennas can be adapted to be separate and wearable. Batteries for stationary MF bridges are less important as they can be larger and heavier because portability is not a concern. MF systems may use fewer batteries than UHF or VHF systems because there are generally fewer battery powered components. Batteries in fewer locations result in less chance to damage critical components, and hence, increased reliability. If an accident occurs, the primary communications system may become inoperable. If the miners inby the accident have an MF portable radio, it may provide an alternate communications mechanism. If the accident occurs between the escape route and the face, it is best to try the MF radio using whatever conductors are near by. On the surface or outby the accident, it is best to have all conductors properly tied to the same point; this way personnel outby the accident should not miss any MF signal coming from inby the accident. Emergency procedures must be established and miners properly trained to describe the order and process for re-establishing communications.

As part of the emergency communications procedures, miners may have to use power management techniques to extend the life of the MF radio batteries. Power management techniques may require a short test message to verify the communications link and then engaging in radio silence for some time to conserve power. Backup batteries may be cached at the rescue chamber. An advantage of a basic MF system is that the conductors do not need any power source. As long as the conductors are intact and properly configured, they should be able to carry MF communications. Repair of damaged sections of conductors is possible by properly reconnecting the wire.

Rescue teams may be able to take advantage of a basic MF system in communicating with trapped miners if the miners have an MF radio. Also, the rescuers may be able to communicate with the surface from long distances using an MF radio. It will be important for rescuers to be trained on the use of MF radios and to be able to quickly assess the location of conductors that may facilitate MF communications during rescue operations.

3.6 NODE-BASED SYSTEMS

3.6.1 Description

The concept of node-based networks was introduced in Section 3.1.2. In this section, the focus will be on RF node-based systems, where RF is defined to cover the frequency band from 3 MHz to 30 GHz.

The digital MF converter/repeater was discussed in Section 3.5 and the repeater was called a bridge node. It may be possible to assemble a self-configuring, self-healing, ad hoc partial-mesh network using digital MF repeaters. The digital MF system could have been included in this section as a node-based system, but the frequency of operation is below the RF range being considered. Part of the reasoning for excluding the digital MF networks is the unusual dependence of MF waves on parasitic coupling for propagation; conductors have to be present to achieve any significant propagation distance. It was decided that MF systems would be easier to understand, both analog and digital, if they were discussed together in a separate section.

In node-based systems, the first communications link, which is from the miner’s handheld radio to a node, is through the air and is called the *access link*. The node providing the service to the miner is called the *access node*. The communications path from the access node to the surface is called the *backhaul*. The connection between nodes and other links that are involved in getting the information to the surface are called the *backhaul links*, and these links can be made through wires, or the air, or both. Thus, node-based systems come in many forms.

The nodes discussed in this section are also *digital routers* which can transmit, receive, act as a signal repeater, and route traffic to other nodes within their RF range. The traffic on a wireless mesh network may be voice, data, video, or tracking information. The information is sent as data packets that are addressed to the desired recipients. In contrast to a conventional leaky-feeder analog VHF or UHF radio system where all the mobile radios tuned to a given frequency may hear the messages in broadcast fashion, the addressed packets of the mesh system enable person-to-person calling and text messaging.

Further, for the types of systems discussed here, the physical link between two communicating devices uses only a portion of the full band of assigned frequencies. The band is divided into channels. When two devices are communicating, they are using one channel. Depending on the system, the channel may have different frequencies used for the uplink and downlink. Channels can have fixed frequency ranges assigned, or they can have a dynamic assignment in which frequencies are automatically allocated based on their availability at the time of a request.

The type of network formed by interconnecting the nodes, i.e., the topology, is purely a function of how the system is designed for a given mine, assuming the hardware can support the chosen topology. Common topologies are line, bus, tree, ring, star, and mesh. (See Section 3.1.2 for more detail.) Mesh networks can be either partial or full, but in a typical mine layout, it is not practical to link each node to every other node. Therefore, partial meshes are common. This may be one reason why manufacturers implementing a node-based mesh network seldom use the term "partial" to describe their mesh; they are all partial meshes. Mesh networks have attracted considerable interest in to the mining community because of the ease of building in redundant routes.

A mobile device such as handheld radio can access the network if it is within RF range of a *wireless access point* (WAP), another term for a fixed-position node. When a miner talks or sends a text message using his handset, a physical link is established with a nearby WAP. Using either wired or wireless links between nodes, the network routes the miner's communication to the desired destination (address), either inside or outside the mine. A sample wireless mesh in a coal mine is depicted in Figure 3-23.

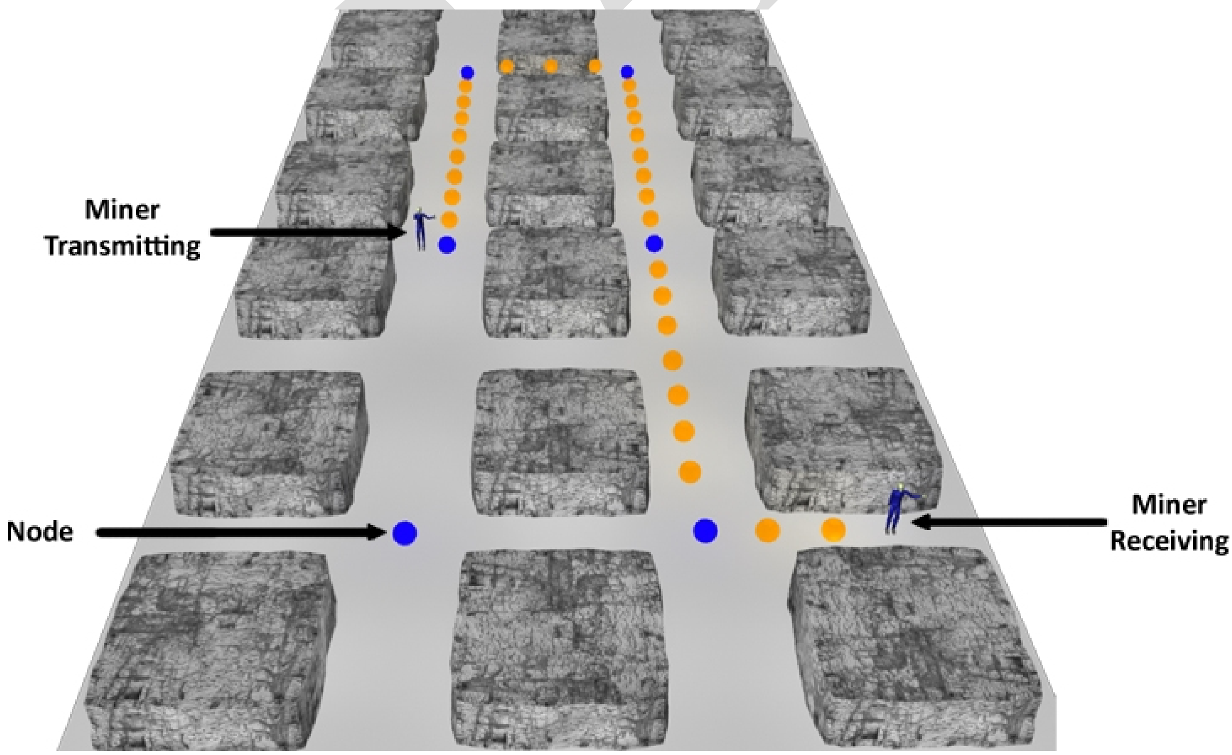

Figure 3-23. Cut-Away View of Mine with Node-Based Communications

Node-based systems generally operate in frequency bands that do not require the devices to be licensed by the Federal Communications Commission, FCC [30 CFR 15]. Being unlicensed though does not mean un-regulated. The FCC has established rules which attempt to minimize the potential of the unlicensed devices from interfering with licensed operations, such as TV broadcasts. Because of the numerous devices that operate in the unlicensed bands, standards have been developed to increase the compatibility between systems operating in the same band. One organization that develops many of the communications standards is the Institute of Electrical and Electronics Engineers, or what is more commonly called the IEEE.

Three types of node-based systems are being proposed for use in underground mines by various manufacturers: wireless local area network (WLAN), wireless fidelity (Wi-Fi) mesh, and ad hoc mesh. All of these systems operate by taking information from the sender's radio, receiving it at an access node, routing it through the network, and retransmitting it to a recipient radio. How these actions are accomplished varies considerably among the systems.

The first system to be discussed is a wireless LAN or WLAN. WLANs are familiar as systems used in the home or office to allow a computer to wirelessly connect to the Internet as shown in Figure 3-24.

WLANs identify each computer on the network by a unique identifier called the Internet Protocol address or IP address. In a large network, the IP address is assigned by a centralized server. Each message contains two addresses: the sending (source) node, and the intended recipient (destination). The source node sends the information to the gateway node and the gateway node then sends it to the recipient as shown in Figure 3-24.

Wireless LANs typically use technology based on the IEEE 802.11b/g technology standard. This open standard allows equipment manufacturers to build devices that will be compatible with systems built to the standard, resulting in a proliferation of devices. In a normal configuration,

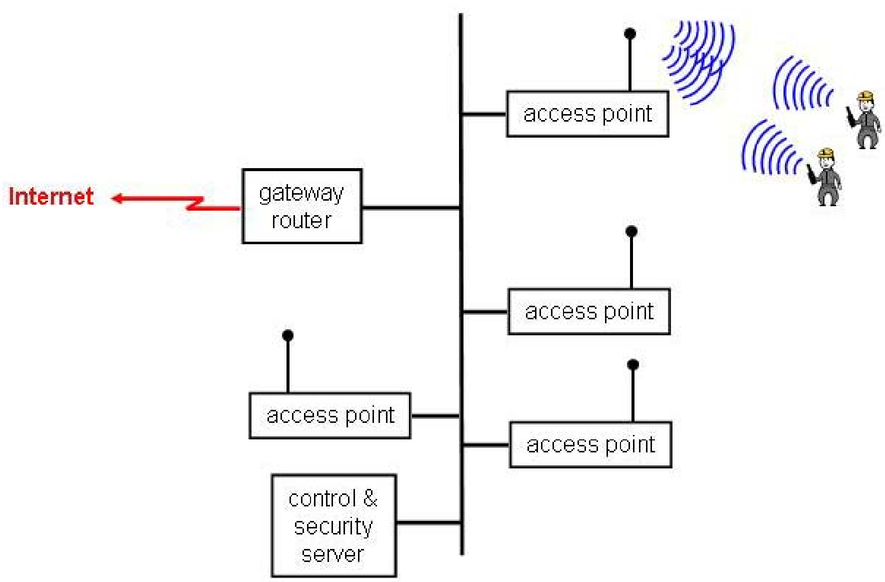

Figure 3-24. Example of WLAN Interface to Internet.

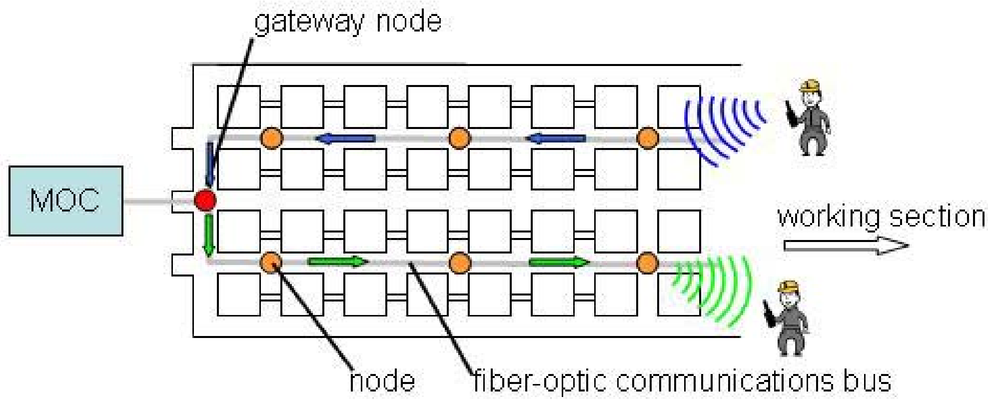

Figure 3-25. WLAN with Fiber-Optic Backhaul

WLAN uses standard Ethernet *protocol* (rules for sending messages) with wired connections between the nodes as shown in Figure 3-25. Thus the access link is wireless, and the backhaul links are wired.

With the network arrangement shown in Figure 3-25, if one of the nodes should become inoperable, the remaining network should remain functional. Of course, if the communications bus is damaged, the whole network could be disabled. WLAN systems are not inherently robust, but can be made to be quite survivable if a fiber-optic ring topology is used as discussed in Section 5. Additionally, the standard provides methods to limit dependency on a central server for data applications; however, for voice applications a central server is required.

Another limitation of a WLAN system is the ability of the system to handle the mobility of a user. As the miner moves from the coverage area of one node to another node, the system has to be able to recognize that the source node has changed and re-direct traffic accordingly. This process is sometimes referred to as *handoff*, with the system handing off the responsibility for a miner's radio call or text message from one node to another as the miner moves. WLAN systems generally have difficulty properly handling mobility, particularly at speeds greater than walking, such as in miners riding in transport vehicles in the mine.

In order to improve the survivability of these systems and to overcome some of the limitations, various manufacturers have implemented proprietary features as in Wi-Fi mesh systems, which will be discussed next.

The second node-based system to be discussed is the Wi-Fi mesh system, which is a variation of the WLAN system. As with the WLAN system, Wi-Fi mesh systems use the same IEEE 802.11b/g standard for the access link, which allows the use of standardized devices; however, the backhaul links can be either wired or wireless. Another important difference is that the routing of traffic through the network is not dependant on a central server but is handled by the individual nodes. These improvements are accomplished using proprietary techniques unique to each manufacturer, although standards have been proposed. Figure 3-26 shows a Wi-Fi mesh system with a fiber-optic backhaul. Notice that the communication from one miner to the other no longer has to pass through a gateway node.

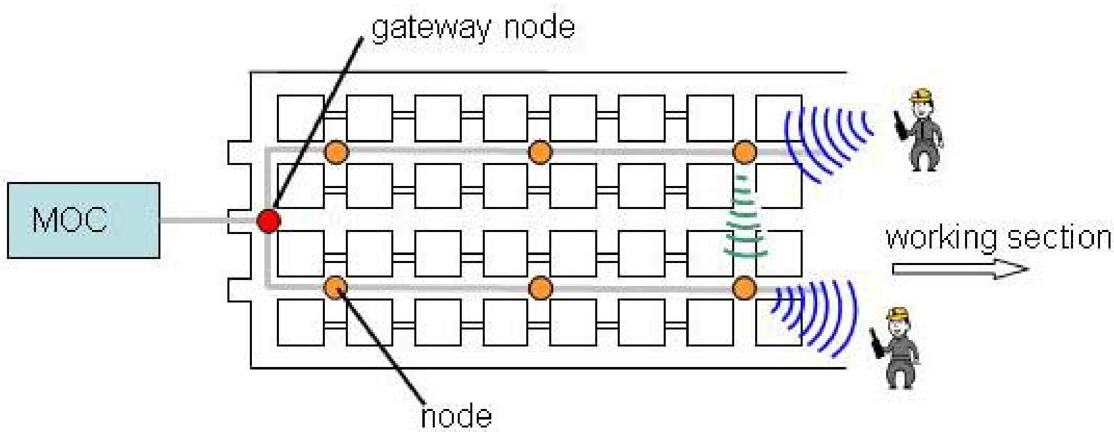

Figure 3-26. Wi-Fi Mesh with Fiber-Optic Backhaul

Many of these Wi-Fi mesh systems rely on proprietary routing protocols that allow a given node to communicate through a particular subset of nodes, which allows the system to reconfigure itself if one node fails. However, in the event that the bus is cut or otherwise disrupted, the ability of the system to reconfigure itself is limited by the wireless range of the node. For the system to reconfigure itself any given node has to be in radio range of multiple other nodes, so a high *node density* or high degree of coverage overlap between nodes has to exist for this redundancy to be implemented.

Neither the WLAN nor Wi-Fi mesh systems are considered ad hoc mesh systems. The WLAN or Wi-Fi systems can be quite survivable if the system is designed with some overlapping radio coverage and the software that controls the nodes permits autonomous reconfiguration. Additionally, because of the operating frequencies for 802.11b/g systems, the range of the access link is typically limited to line-of-sight. Assuming comparable transmitter power, this leads to the need for more infrastructure in the mine for the same level of radio coverage as compared to some of the ad hoc mesh systems.

The third node-based communications system to be discussed is the ad hoc mesh system, which communicates node-to-node through a network similar to Wi-Fi mesh systems but with a few key differences.

Some of the characteristics that distinguish an ad hoc from a Wi-Fi mesh system are:

1) The end user device (mobile radio) can serve as a mesh node, relaying network traffic from other radios on the network.

2) Any node in the network can autonomously communicate with any other node that is within radio range and is not limited to a pre-defined subset of nodes within its range.

3) Any group of nodes that are within direct radio range of each other can autonomously form a network without any dependency on a central server.

One example of an ad hoc mesh system is commonly referred to as Zigbee, which refers to the IEEE 802.15.4 standard. Zigbee is a true ad hoc mesh protocol and has the additional advantage of being able to operate in the 900 MHz range, which is the frequency for maximum radio range in most underground coal mines. However, Zigbee operates at low power and does not support voice communications.

NIOSH has funded the modification of a Zigbee-based mesh system so that *compressed voice* (modification of a voice message to reduce the required bandwidth) could be supported over the network while continuing to have the advantages of an ad hoc mesh. Compressed voice is a low bit rate form of voice communications that can be used over bandwidth-constrained systems. The advantages of this approach are:

- Full ad hoc mesh capabilities, which maximizes the flexibility of extending and/or repairing networks.
- Low bit rate voice can result in an increased communications range, as discussed in Section 3.1.1.
- 900 MHz operational frequency to improve the communications range of the nodes.
- Compressed voice may support future interoperability with Through-the-Earth and MF systems, which may use the same approach.

3.6.2 Components

The primary component in a node-based network is, of course, the nodes deployed throughout the mine to provide wireless coverage. The nodes send and receive radio signals to extend the communications range between handheld devices, which are another component of the system. The mesh network uses a variety of mobile devices such as handheld Voice-over-Internet Protocol (VoIP) phones or computers, laptop computers, tracking tags, and text communicators. The nodes link with other nodes to form a wireless or wired network throughout the mine.

Nodes may be called by other names such as mesh points (MPs), access points (APs), or WAPs. Figure 3-27 shows an example of a wireless node. Under normal operation, the nodes require power from an external supply. Thus, they must be located near existing or new electrical wiring. In an emergency, when base power is unavailable, the nodes can operate from a backup battery. A node may be about the size of a lunch box and has an external antenna.

Figure 3-27. An Example of a Wireless Node

In the MOC, there would likely be a computer server and display monitor to show information on the network performance and system diagnostics. On the monitor, there might be a display of a mine map showing the node locations and operational status of each.

Figure 3-28 depicts a sample block diagram for a wireless mesh network. Solid lines indicate wired communications paths, and broken lines indicate wireless communications paths. In the diagram, the nodes have wireless interconnections, but they could also have wired connections to other nodes.

Some mesh networks identify one node as the gateway or root node. This is the point where the wireless network transitions to a wired connection to the MOC above ground. Thus, all of the network traffic into or out of the mine flows through the gateway node.

3.6.3 Transmission Media

The communications between two miners talking over their handheld radios involves a number of intermediate physical links depending on how many nodes are included in the route, as shown in Figure 3-29. The first link is through the air from the sender's radio on the left to the node labeled 1. The second link is through the air from node 1 to node 2. The third link is through the air from node 2 to node 4. The final link is through the air from node 4 to the radio on the right. The signal has undergone three *hops*, i.e., the signal has passed through three intermediate devices.

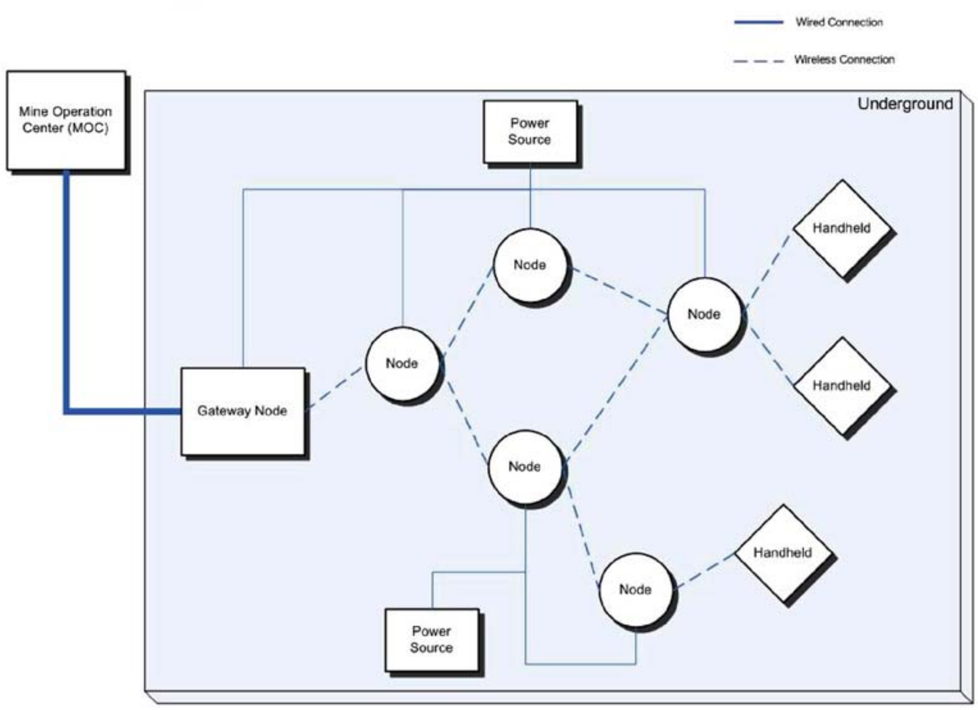

Figure 3-28. Block Diagram of Node-Based System

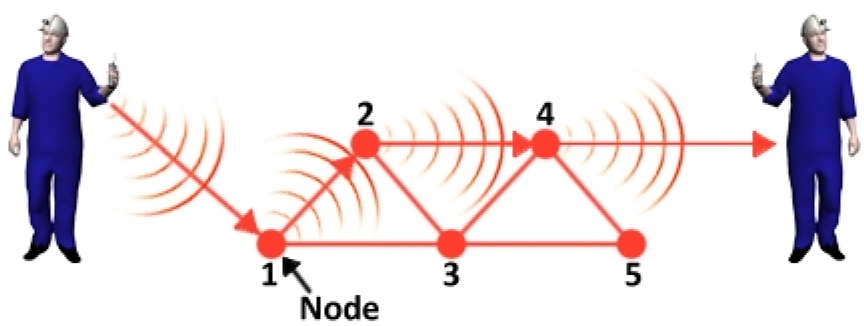

Figure 3-29. Links in a Node-Based System

The link budget analysis is applied only to the access link of Figure 3-29. The analysis begins with the transmit power of the sending radio, P_t, on the left axis in Figure 3-30. G_t represents the antenna gain (assuming it is positive) of the sending radio, which adds to the transmit power. There is a path loss, L_{p1}, as the RF signal propagates through the air to node 1. The node has a receiving antenna gain of G_{rnode}, which adds to the received power, resulting in P_r at the receiver. The manufacturer could supply most of the values used in this link budget analysis.

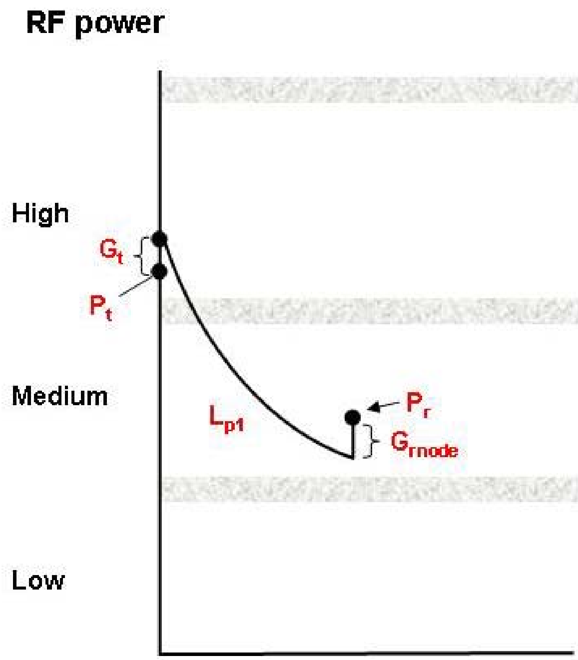

Figure 3-30. Conceptual Link Budget Analysis for Node-Based System

3.6.4 Network Operations

One of the advantages of a node-based communications system is its flexibility - it can use any of the network topologies available. To obtain continuous radio coverage in the long entries that are typical in a coal mine, certain topologies become more practical than others. Figure 3-31 shows a node-based linear network. Such a network could provide continuous coverage in an entry.

Should one of the nodes in Figure 3-31 fail, all communications inby the failed node would be lost. One way to increase the system survivability would be to have the nodes close enough that the RF range of each node extended beyond its upstream and downstream adjacent nodes to the node beyond. This approach increases the system cost, because more nodes would be required to cover the same length entry. It is a viable method to add redundancy to the system, although if the node failure is due to a roof collapse, the RF signal is unlikely to propagate around the debris.

Figure 3-32 shows a partial mesh network in which radio coverage is provided in two parallel entries and the nodes (blue dots) can communicate down cross-cuts.

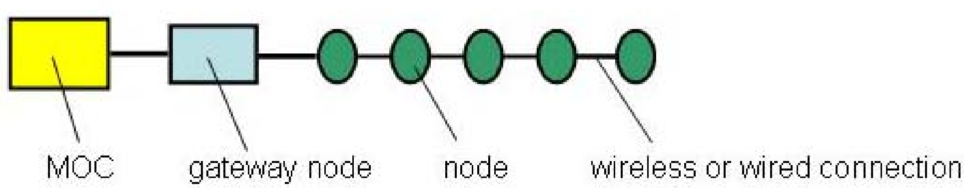

Figure 3-31. Node-Based Linear Network

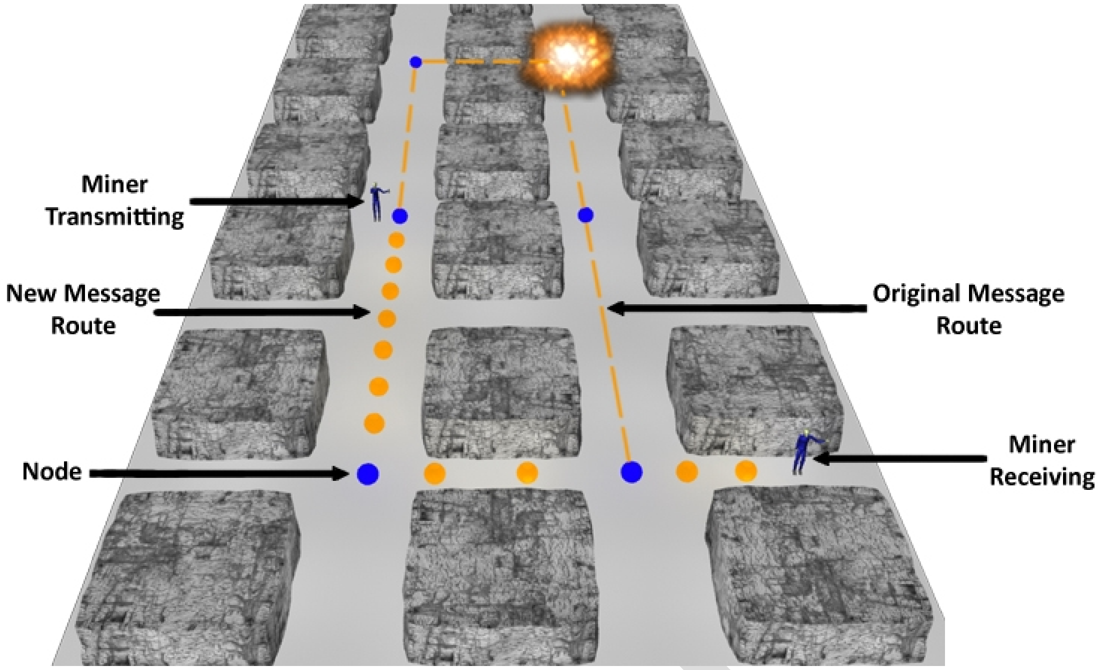

Figure 3-32. Cut-Away View of Mine with Redundant Communications Path

The original message route in Figure 3-32 followed the dashed line through the node in the upper right corner. An accident caused the node in the upper right corner to fail. In a *self-healing* network, an alternate route (assuming one exists) will be determined as shown by the orange dots. This redundant path increases the survivability of the network.

Some manufacturer's nodes require that each node pre-program the allowable backhaul links that form the network topology. This is sometimes termed a *constrained* network or constrained mesh. The nodes autonomously detect network failures and switch traffic through pre-determined backup routes. Since the routes are pre-defined, the fail-switch-over dead time or outage time can be very short.

In contrast, some manufacturer's nodes automatically and autonomously establish the network, because the equipment has the capability for self-configuring and self-healing. An ad-hoc or self-configuring network will detect the presence of a mobile node, possibly a handheld radio, as it comes within RF range of the network, and it will incorporate it automatically as part of the network. A self-configuring network automatically identifies the links that are available from each node and uses an algorithm to connect each node to the network using a subset of the available links. If an accident should disable a node or nodes, the self-healing feature would cause the network to re-connect all possible surviving nodes by other available links. There is a delay associated with the node switching over to other routes that is longer than in the constrained network case. Another possible delay occurs when traffic in a mesh network travels over multiple wireless hops to reach its destination; the throughput may be severely reduced compared to the rate of each hop alone. In addition, passing through multiple nodes may delay packets. This added delay, called latency, can be especially harmful to real-time communications such as voice.

Products are available that link some or all of the fixed nodes of the network with wired or fiber-optic cable connections. To the extent that wire or fiber connections are used, these networks may have limited or no ability to self-configure and self-heal and must be treated differently when analyzed for survivability.

3.6.5 System Implementation

Node-based communications systems offer the potential of easy-to-implement, redundant RF message routes, which increase the survivability of the system. One way to achieve redundancy is with a wireless mesh network with nodes installed in parallel entries such that there are backhaul links connecting nodes in different entries through crosscuts joining the entries. Such a scheme permits redundant communications routes by providing a route that can bypass a failed node and still reach the MOC or other radios.

As discussed in Section 3.6.2, the backhaul connections can be wireless or wired. Although wired connections increase the amount of infrastructure for the system, burying the connecting cables protects them from roof falls and explosive forces. Figure 3-33 shows a working section where a roof fall could block a passageway sufficiently that an RF signal could not pass, even though there is no damage to the nodes on either side of the fall. A buried cable might survive the roof fall and there would be no interruption of service.

There are other approaches to providing redundancy with node-based systems. Many mines have existing leaky feeder systems. Bridge nodes can couple node-based RF communications installed in a separate entry to the leaky feeder cable. The bridge node converts the RF signal of the mesh to frequencies that are compatible with the leaky feeder system. There is hardware and software in the MOC that recovers and interprets the mesh digital signal as received on the leaky feeder.

It may be useful to implement a node-based system in a working section. It is relatively easy to extend the coverage of the node-based system as the face advances (Figure 3-34). Node-based systems can also provide electronic tracking information, which may be required in the working sections (Section 4.3). A bridge node can interconnect the node-based system in the working section to the system in the main entry. The bridge node permits the two systems to communicate with each other. In this case, the backhaul to the MOC is through some other

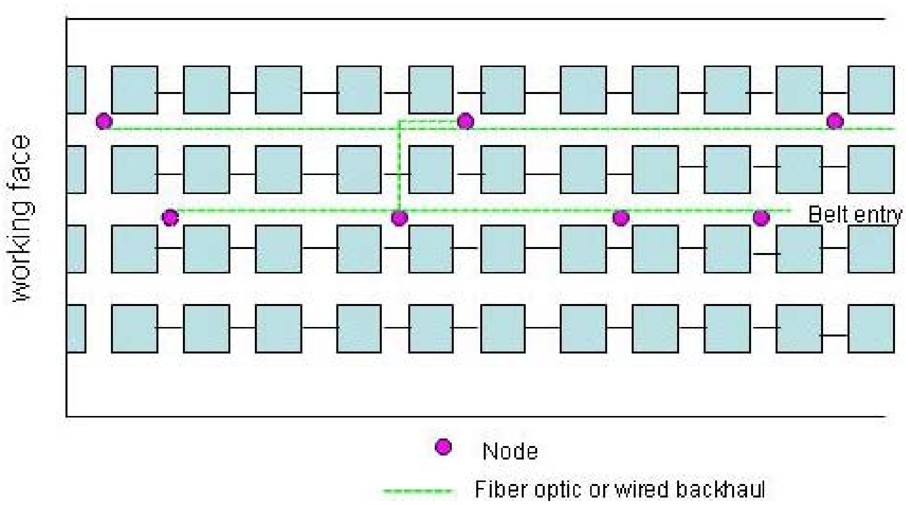

Figure 3-33. Network with Fiber-Optic Backhaul in Working Section

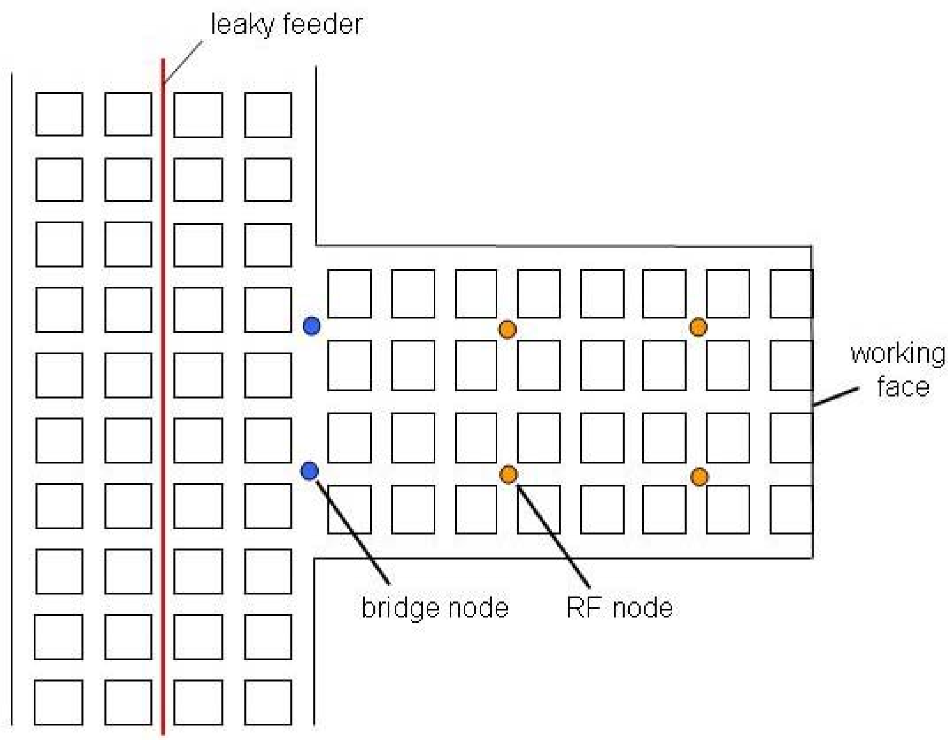

Figure 3-34. Leaky Feeder Backhaul with Node-Based System in Working Section

communications system, such as a leaky feeder system, but the backhaul could also be node-based.

Each node does require mine AC power for normal long-term operation. When the mine power is off (as during an emergency), each node needs a backup battery to provide power for continued operations. Typically, the battery might provide power for 24, 48, or 96 hours, depending on the requirements.

3.6.6 Maintainability and Inspection

Maintenance for the system's central computer will be similar to normal maintenance provided for all computer-type equipment (e.g., cleaning, anti-virus, memory backup, software updates). Some system providers will provide network software updates that are downloadable directly through an internet connection. Since mine maps will have to be updated regularly, systems that provide map displays should provide utility programs to allow mine personnel to load updated maps easily. The system will run initialization, diagnostic, and database applications for adding and monitoring underground components, and will typically provide off-site remote monitoring capabilities through an internet connection. To allow for quick identification and replacement of failed underground components, network monitoring should be continuous. Node and antenna replacement is easy. Failed backhaul cabling may require replacement of long lengths of cable or careful repair procedures. Node backup batteries have a limited lifetime; network diagnostic capabilities should include battery status monitoring. Periodic battery capacity tests ensure that the batteries will function during emergencies. Power supplies must be disconnected to check battery backup switchover and capacity, and redundant communications paths should be periodically tested by powering down nodes to test the network reconfiguration capability.

3.6.7 Performance and Limitations

A number of equipment and environmental factors influences wireless coverage distance or range. Transmitter power, antenna gain, receiver sensitivity, data rate, and frequency are the primary factors related to the equipment, and the link loss budgets account for these factors. Entry dimensions, bends, elevation changes, and obstructions will further limit wireless coverage.

The US Bureau of Mines sponsored several radio propagation studies during the 1970s. NIOSH has made these studies available for download through the NIOSH mining internet site (http://www.cdc.gov/niosh/mining/). One study that is particularly relevant to modern node systems involves a theory of propagation of UHF radio waves in coal mine tunnels [Emslie et al. 1975]. This study proposed that mine entries act as waveguides for frequencies in the UHF range. Figure 3-35 was adapted from a figure in [Emslie et al. 1975], and is based on a coal mine entry 14 ft wide and 7 feet high. The curve includes the insertion losses for the transmitter and receiver antennas, which result from the mismatch of the antennas to the fundamental mode of the wave guide (tunnel). The increase in path losses as the frequency increases is due to energy lost in the interaction of the EM wave with the walls, floor, and roof. The increase in path loss at the low frequency end of the curve is due to the wavelength approaching the dimensions of the entry, making EM propagation more difficult. The minimum in the propagation loss in the 800 to 1000 MHz range is sometimes referred to as the UHF propagation “sweet spot” for open coal mine entries.

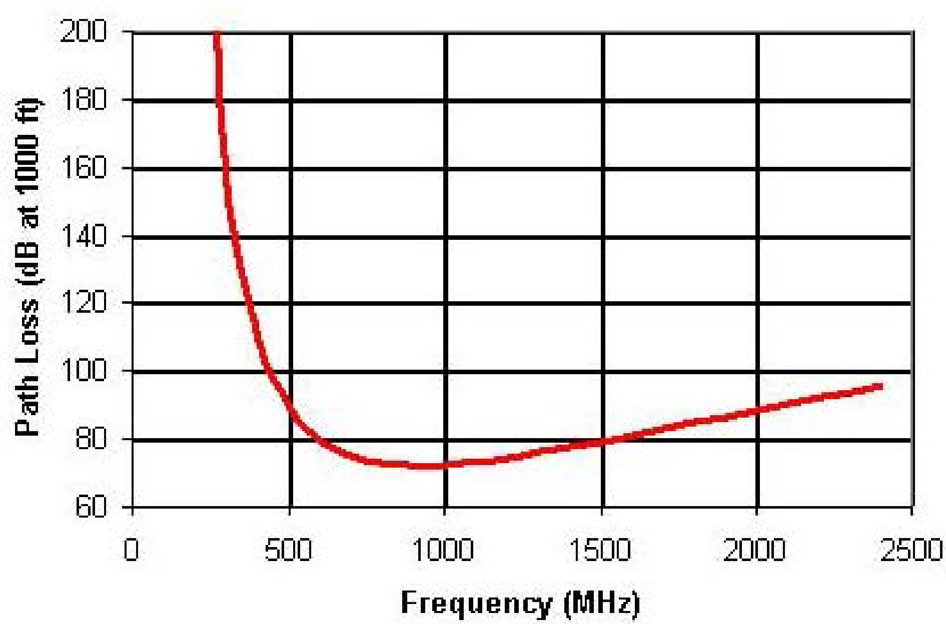

Figure 3-35. UHF Propagation Path Loss Modeling

Systems operating at 900 MHz have demonstrated non-line-of-sight coverage down a parallel entry for several cross cuts. (line-of-sight refers to an unobstructed straight-line path between the transmitter and receiver.) Entry obstructions will absorb or reflect radio signals, diminishing wireless coverage. Coverage distances in belt entries will generally be less than coverage in open entries due to the belt structure. Bends or changes in elevation that block the line-of-sight will generally reduce wireless coverage range. Large vehicles will partially block radio signals; adequate fade margin should be factored into RF backhaul link budgets to minimize the impact. Observations of concrete stoppings have shown they will attenuate UHF signals somewhat, approximately 10 to 15 dB in the 900 MHz range. Temporary metallic stoppings will reflect much of the incident signal, so transmissions through metallic stoppings will have large attenuations. In contrast, metallic surfaces can be used as reflectors to guide radio signals around corners.

Overall network coverage will be limited by latency, defined as the amount of time it takes a packet to be transmitted end-to-end across the network. Latency increases with the number of hops through a network of nodes. Video or voice transmission requires that the delay or latency through the network be consistent for the duration of the transmission and short enough so that it is not a nuisance. Main entries of large mines can use long distance fiber optic links to reduce the number of hops and associated latency. Latency is much less of an issue for low bandwidth data transmissions such as text [Emslie 1975].

WLAN or Wi-Fi systems support commonly available VoIP phones. VoIP phones require an intermediate node; they do not support phone-to-phone (i.e. peer-to-peer) operation. True ad hoc ZigBee mesh networks will not support VoIP phones; however, they may support communications devices that can also communicate independently of the network (peer-to-peer). As mentioned previously, these ad hoc mesh communications devices may also function as nodes, relaying messages from other communications devices that may be out of network coverage. One advantage of WLAN or Wi-Fi networks is interoperability with a wide variety of commercially available equipment. However, very few of these are permissible. This presents a safety concern even in intake air courses during fan out or emergencies when the ventilation system is compromised.

Node-based user communications devices can also serve as tracking devices. The system can identify which node is the access node for a particular user device. The system functions much like an RFID tracking systems in this respect, with the communications device acting as a tag and the access node acting as the reader. If a communications device is in contact with one node, the location accuracy is generally the radio range of the device or node, whichever is less. Techniques such as received signal strength indicator (RSSI), time difference of arrival (TDOA), or time of flight (TOF) can estimate a more accurate location, but may require the radio be in contact with multiple nodes simultaneously.

Node-based communications systems offer the potential of easy-to-implement, redundant RF message routes, which can increase the survivability of the system. As discussed in Section 3.6.2, the backhaul connections can be wireless or wired. Segments of communications systems can be installed between multiple portals to the surface. For these situations, a linear topology (either RF or cabled) may be implemented with both ends of the segment installed in separate portals to provide a redundant backhaul link to the surface. Segments of communications systems inby the last access to the surface may employ different topologies to achieve full redundancy. The following discussion considers two inby cases: wired (or fiber optic) and wireless RF backhaul links.

Figure 3-36 shows a partial mesh network with wireless RF backhaul links. Arrows indicate RF links. The node layout is such that failure of any one node will not cut off communications to the surface inby the failed node. Node placement in different crosscuts of adjacent entries may enhance survivability during emergencies. Node-based systems operating at 900 MHz have been observed to provide non-line-of-sight connectivity between nodes in adjacent entries to within a few crosscuts. Antenna cable can be used to place antennas in adjacent entries, such as those separated by metallic stoppings. Catastrophic events may disable multiple nodes in adjacent entries, isolating clusters of inby nodes. True ad-hoc mesh networks allow for automatic reconfiguration of isolated node clusters, establishing a new network within the isolated cluster.

Figure 3-37 shows a WLAN or Wi-Fi network with fiber optic backhaul links in a working section. A modified ring topology formed from two adjacent linear spurs supports bi-directional backhaul links for redundancy. The connection forming the loop between two spurs can advance as the face advances to prevent isolation of multiple nodes extending to the face area. The connection forming the loop may be wireless. Protecting the wire or fiber optic cable in damage-prone areas such as in front of seals may enhance network survivability. An ad-hoc mesh implementation may allow isolated nodes to re-form a network.

Each node does require mine AC power for normal long-term operation. When the mine power is off (as during an emergency), each node needs a backup battery. User communications devices will operate for at least 12 hours. If an emergency occurs at the end of the shift there may be only be 4 hours or less of battery reserve. Manual shutoff or spare handsets can extend operation over a longer period. Permissibility requirements for some types of handsets may prohibit battery replacement where excess methane is present.

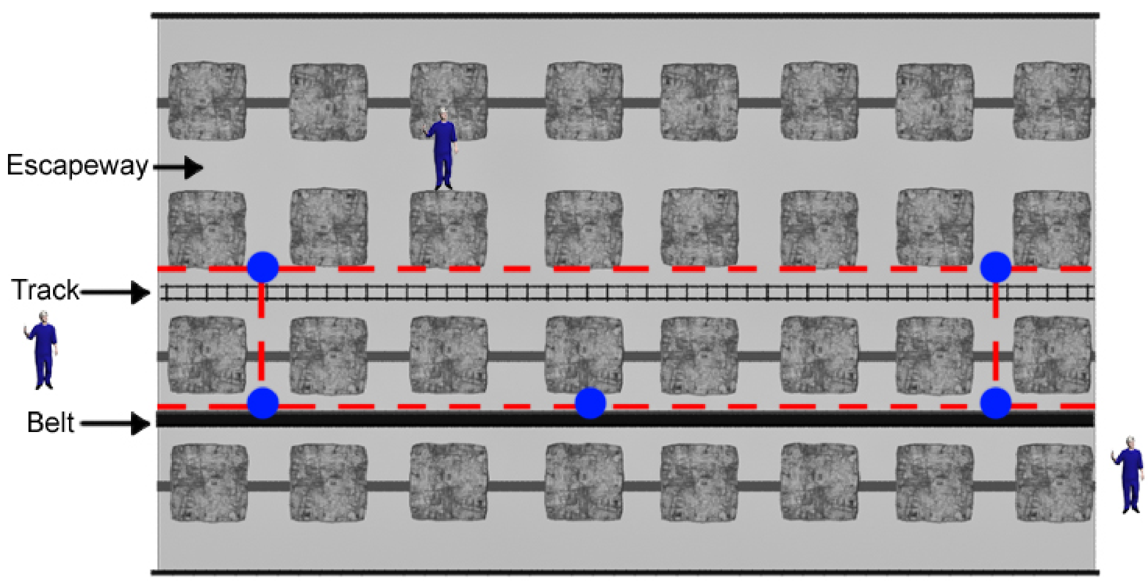

Figure 3-36. Partial Mesh Network with Wireless Backhaul in a Working Section

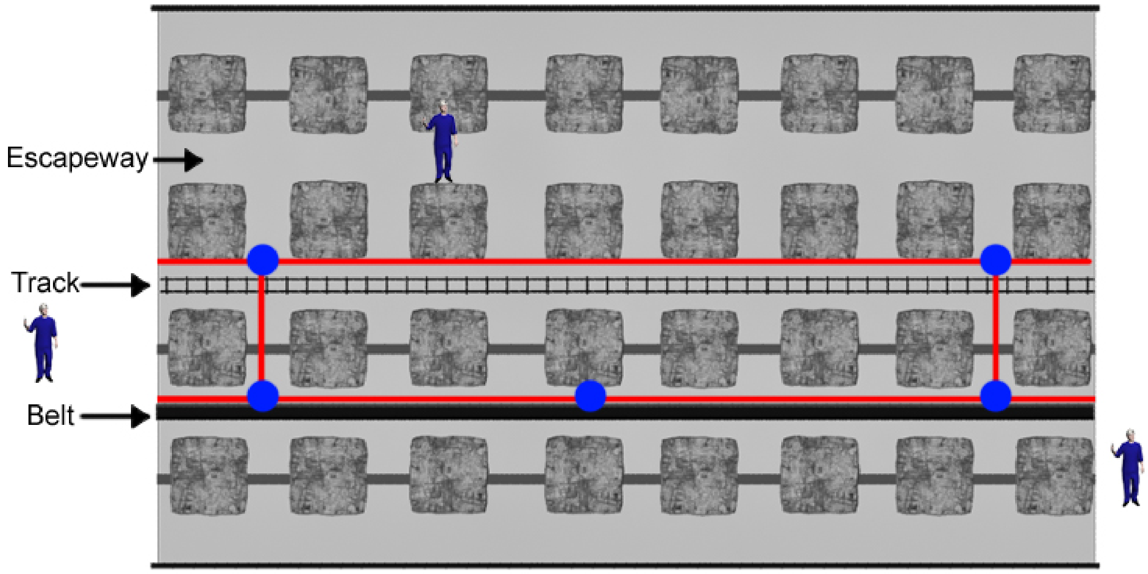

Figure 3-37 Fiber-Optic or Wired Backhaul Node Network in a Working Section

3.7 THROUGH-THE-EARTH SYSTEMS

3.7.1 Description

Most electromagnetic waves can only penetrate short distances into or through the earth. It is possible for very low frequency, long-wavelength EM waves to penetrate several thousand feet into the earth's strata. Through-the-Earth (TTE) communications systems are characterized by their ability to transmit directly through the earth, the overburden of a mine, either by sending a signal from the surface into a coal mine, or sending a signal from one part of a coal mine to another.

TTE systems typically operate between 90 Hz and 4000 Hz. These frequencies result in wavelengths between 45 and 1980 miles in free space. Portable communications systems operating in the VHF or UHF band often use ½-wavelength dipole or ¼-wavelength whip antennas to achieve high transmission efficiency. The transmission efficiency is high for antennas with linear dimensions that are a major fraction of a wavelength. However, this is not feasible for TTE systems, because of the extremely long wavelengths.

For TTE systems, the antenna on the surface may have fewer constraints and can be physically large compared to an antenna in the mine. A TTE surface antenna is usually a large loop of conducting wire, which may have multiple turns, and with a circumference measured in thousands of feet. Generally, the antenna should be directly over and encompass the areas of the mine needing coverage (see Figure 3-38). The surface transmit power can be over a kilowatt. Some TTE systems under development have significantly smaller diameter loops that use multiple turns of conductor and operate at lower powers.

The underground antenna is typically smaller for portability and operates at much less power in order to be permissible. In some TTE systems, the receive antenna is worn by the miner and

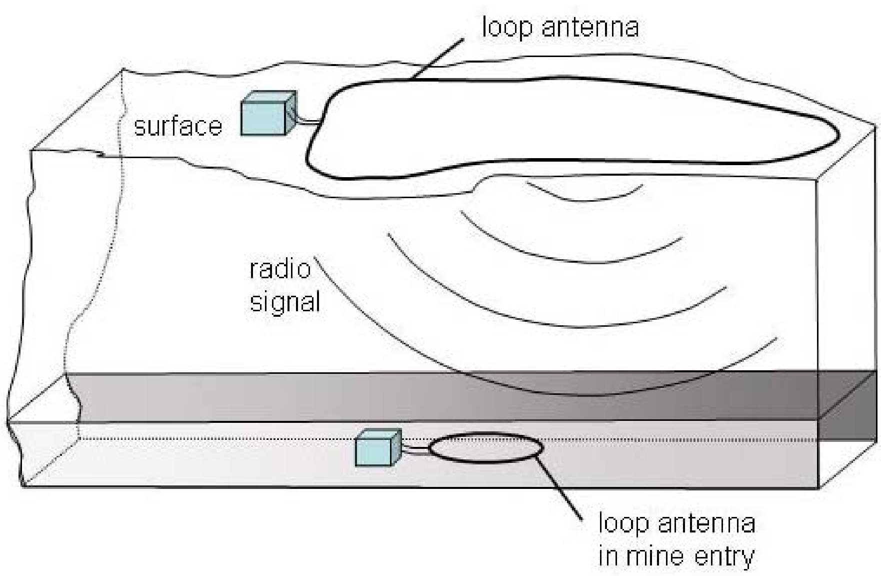

Figure 3-38. Surface and Underground Antennas for TTE System

integrated with his cap lamp. When a message arrives, the lamp will flash. The communications are typically text only and generally in one direction only, from the surface to the underground miner. Personnel on the surface receive no indication that the miners have received a message.

In other TTE systems, the miners establish the underground antenna only when there is an emergency. The wire and associated transceiver equipment is worn on the belt of the miner or stored in a cache in a suitcase-sized enclosure. During an emergency, the miner may wrap the wire around a coal pillar to form an antenna. The structure of a rescue chamber may also incorporate the antenna. Two-way communication is possible with both text and voice messaging at limited depths.

In an alternate system configuration, both TTE communication systems are underground. Similar to the concept shown in Figure 3-28, the trapped miners establish one TTE system. The rescue workers bring in a second TTE system to establish communications with the trapped miners. Figure 3-39 demonstrates the concept.

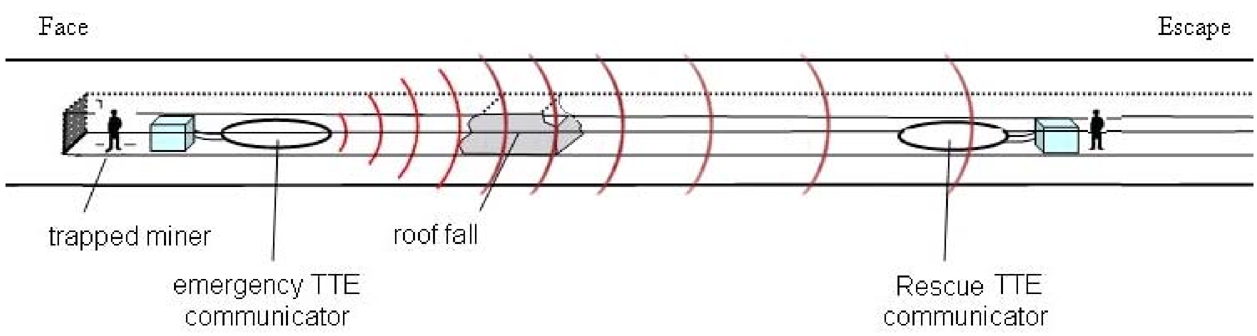

Figure 3-39. Rescue TTE System

TTE communications technology is the only technology that can transmit an electromagnetic signal between a sender and receiver with one underground and the other on the surface without relying on a network or other additional infrastructure. The communication can be either two-way or one-way (surface to underground). In the two-way mode, analog voice, voice messaging, text messaging, or pre-recorded messages are possible.

It is unlikely that a TTE system will be used for normal mine operations due to coverage and portability constraints, and low data transfer rates. At the low frequencies of operation, it can take several minutes to transfer a text message. In addition, there are many sources of RF noise, e.g. spurious voltage signals, at low frequencies that make it difficult to separate out the message. In an emergency in which the power is off, the RF noise underground is decreased dramatically. The same is not true on the surface though, making it difficult to extract the message received from underground from the RF noise at the surface. However, the advantage of a TTE communications link is that it is highly survivable and therefore is likely to play a significant role as an emergency alternate communications path as these systems become more available.

3.7.2 Components

TTE systems can consist of very few components. The simplest system, which would only deliver messages from the surface to the underground miners, consists of a surface transmitter and one or more underground receivers. The surface transmitter has a power source, a *modulator* (a device for encoding the message into an RF signal), antenna, connecting cables, and a computer for entering messages. The TTE receiver has an antenna, electronics to decode and display the message, and a power source (typically a battery) to power the electronics. The antenna could be just a spool of wire the miner distributes on the mine floor to form a loop.

If the system provides two-way communications, the surface and underground units would both be transceivers (a combination of transmitter and receiver). Transmitting and receiving uses the same antenna. The electronics must be capable of encoding and decoding messages.

3.7.3 Transmission Media

The earth is the main transmission medium for TTE systems. The electrical properties of the intervening earth strongly affect the propagation of EM waves through the overburden of a mine. The electrical properties can change rather dramatically as an EM wave passes through successive strata. Dramatic changes in electrical properties between consecutive strata cause a portion of the propagating EM energy to reflect at the interface, decreasing the strength of the signal that ultimately reaches the receiver.

The link budget analysis begins with the transmitter power, P_t, which could be on the surface or underground. The qualitative analysis in Figure 3-40 is the same whether the transmitter is on the surface or underground, but the quantitative analysis would have different numbers for the transmit power on the surface compared to that underground. There is a decrease in power for the negative gain of the transmit antenna, G_t, followed by the path loss through the earth, L_p. This is then followed by the loss of the receiving antenna gain, G_r, to arrive at the received power, P_r. If there are cables connecting the transmit and receive antennas to their respective electronics, these losses would be in addition to the antenna gain losses. The communications equipment manufacturer can supply the actual values for the various link budget parameters.

3.7.4 Network Operations

Based on discussions in the previous sections on TTE, it is clear that the TTE system does not require network infrastructure to extend the communications range. Only one link through the earth is necessary between the sender and receiver. As is shown in Figure 3-39, there may be instances when an additional TTE system underground, acting as a repeater, would be helpful — if, for example, the mine operators did not have access to all surface areas directly above the working sections to locate the surface TTE system. It would be advantageous to put the surface TTE system in a fixed location, with another TTE system directly under it within the mine. The underground system could act as a repeater for any other underground TTE system that the miners might set up during an emergency.

3.7.5 System Implementation

The most likely use for TTE systems is in emergencies only, with other technologies providing the communications for daily operations.

One manufacturer's system requires a very large loop on the surface for the transmit antenna. The projection of the surface loop onto the mine workings encloses the area covered by the system. Since the surface loop would be very large, it may be prudent to install it ahead of time,

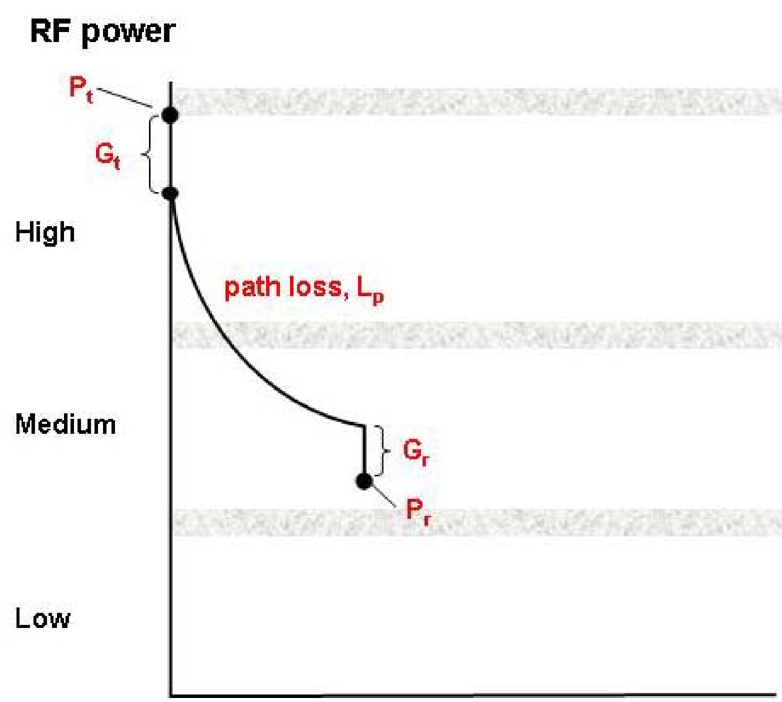

Figure 3-40. Conceptual Link Budget Analysis for the TTE System

rather than immediately after an emergency. This system provides one-way communications, typically text messages, from the surface to miners. The miners receive the message in a personal receiver that they wear, possibly powered by the miner's cap lamp battery.

Other TTE systems under development use transportable antennas possibly situated on the surface after an emergency occurs. The underground TTE antenna system is typically larger, and would be carried in each day by the miner to the working section, or cached nearby. Another option is to integrate the TTE antenna into a rescue chamber.

As indicated in Figure 3-39, it is possible to create a TTE network, with one or several units acting as repeaters. This is another approach to creating an alternate communications path with TTE systems. An advantage of the repeater approach is that the link from underground to the surface can have a fixed location. The miners could periodically move their TTE units as the face advanced or if operations moved to a different area of the mine. The repeater and surface TTE units would remain in fixed locations.

Regardless of the approach, the TTE communications link appears to be highly survivable and therefore is likely to play a significant role as an emergency alternate communications path as these systems become more available.

TTE communications system components should also be sufficiently rugged to withstand rough handling that may result during an emergency. As stated previously, underground components may be worn by personnel, contained in a suitcase style enclosure, or integrated into the design of a refuge chamber. During escape, should a loop antenna need to be deployed, the wire gauge should be of sufficient size to withstand bending and be jacketed to resist abrasion. Portable transceivers must be resistant to the mechanical shocks anticipated during escape. Underground system components must be protected in storage from moisture and dust. Refuge chamber components should be sufficiently rugged to withstand the repeated chamber movement as the working section advances and retreats. The surface antenna must exhibit similar qualities of mechanical strength. Permanent surface installations should be resistant to weather and rodents.

As stated previously, low data rates and electrical noise underground would preclude using a TTE system, as currently envisioned, for routine communications. However, future enhancements may allow TTE systems to bridge to medium frequency, node-based, or leaky feeder systems. Under those circumstances, the TTE system may be an alternate communications path out of the mine. With multiple transceivers underground, the TTE system may have applications for point-to-point underground communications and overlap with existing medium frequency, node-based, or leaky feeder systems.

3.7.6 Maintenance and Inspection

Underground caches can store multiple portable units that miners can use during an escape. Routine inspections underground should detect system component failures. The systems as presently envisioned are relatively complex and may require replacement of modules or entire units underground. Periodic checks of the batteries contained in both the portable and stationary units are necessary. Regular functional communications tests are necessary between the portable and stationary units underground. Each time the refuge chamber moves, tests should confirm communications with the surface. A troubleshooting manual should have a checklist in the event that the units do not operate during routine inspections.

3.7.7 Performance and Limitations

TTE communications are typically half-duplex, meaning that a transceiver cannot send and receive messages simultaneously. The signal transmission rate, usually expressed in bits per second, governs the transmission mode. The most desirable mode is real time digitized voice. It requires a data rate of ~2.5 kbps, which is practically achievable in the kHz frequency range. However, at those frequencies, transmission through the earth is more likely in shallow overburdens with relatively low conductivity. Greater depths and higher conductivities necessitate lower frequencies to facilitate transmission with less loss. The reduced bandwidth associated with lower frequencies will restrict the amount of information transferred and/or the time required to transmit the information. Consequently, this may limit communication to voice mail with data and text (~500 bps) or data/text messages (~100 bps). Depths greater than 2,000 feet may dictate that communications be limited to text input at one keystroke per second (~ 10 bps).

Fires, inundations, roof falls, and explosions near where the underground transceivers are located may damage and render inoperable components of the TTE system. These systems will be in areas where the likelihood of these events is highest. Accordingly, portable units used in escape should be stored with self-contained self-rescuers.

For the stationary transceiver, battery life should equate with that of the rescue chamber; for the portable transceivers, the weight of the battery may govern battery life. A battery meter should indicate if batteries are within the proper operating range. Underground components need to include an intrinsically safe design.

Following an incident, workers should attempt to ascertain mine conditions by using the primary mine communications system. Escaping from the mine is the highest priority. Several portable TTE transceivers should be available on the working section with charged batteries. During escape, should the primary system be inoperative, miners can deploy the TTE units to attempt communications with the surface, other workers in the mine, or with rescue teams. Deployment may involve looping a wire around a pillar for transmission. For reception, the units may feature two ferrite-core antennas in an orthogonal arrangement. The ferrite cores enhance the magnetic field strength while permitting a compact design. Multiple antennas ensure that reception is independent of the antenna orientation. Software can add the vector signals from each antenna to obtain a resultant signal. For power management, the transceiver can be set to beacon mode to send periodic signals during escape. The portable units should have multiple frequency and data rate capability to optimize communications at any particular location underground. Should escape not be feasible, workers can access a TTE transceiver with similar beacon and multiple frequency capability within the refuge chamber.

There are no size or power restrictions for surface antennas; only the terrain may limit deployment. It is possible with a very large loop to encompass most of the underground mine with a transmitted signal. Reception on the surface of magnetic field-based signals may be limited to an area directly above the underground location. Therefore, on the surface a transceiver may be located above refuge chambers. Signal strength generally will decline as the surface receiver moves away from the vertical axis directly above the underground transmitter. Consequently, it may be difficult to pinpoint underground transmissions during escape, since the transceivers will be moving along with the miners. In these cases, it may be possible to scan for signals with a receiver in a helicopter.

A number of factors can affect the performance, coverage, and range of TTE communications systems. Transmitter power is limited underground due to concerns with operating in potentially methane-laden atmospheres. Thus, loop antennas should encompass a large area to enhance transmission efficiency. However, surface transmitters have no such limitations.

Lower values of transmission path conductivity have reduced loss. Generally, transmission through relatively low conductance media such as air or certain geologies such as limestone (~0.001 mho/m) maximizes the range. The conductance of coal (~0.25 mho/m) may be as much as 250 times higher than dry limestone and can impede signal penetration. The conductance of salt water (~5 mho/m) is as much as 20 times that of coal; this may be of importance in certain areas of the U.S. where salt deposits exist in the overburden. It is unknown how certain geological features and anomalies such as mined-out seams and aquifers may affect transmission though the earth. Signal reflections at an air or water interface may reduce the range.

Obviously, the shorter the distance between transmitter and receiver, the more likely communications can be established, all other factors being equal. Therefore, deep mines with significant overburdens present a challenge to TTE communications. Unfortunately, underground mining is trending toward deeper seams. Thirty years ago, mines with overburdens less than 500 feet were common. Today, most mines are deeper, 1000 feet and greater. Sending a signal from underground through these overburdens is challenging, since once it reaches the surface it may be too weak in magnitude for detection.

As stated previously, once power is off underground in an emergency, low frequency noise levels diminish significantly. Environmental noise on the surface will continue to interfere with signals received from underground. Electrical storms and nearby substations and power lines are common sources of noise which may be of the same magnitude or greater than the desired communications signal. There are techniques available to nullify much of the ambient noise. A common method is to use more than one antenna, one to detect all electrical signals and one tuned to receive noise only. The noise signals are then subtracted from the combined signals, enhancing signal-to-noise ratios. More sophisticated (and more expensive) techniques can further improve signal quality.

3.8. Communications Technology Comparisons

Currently there are four commercial techniques for communicating with personnel in underground coal mines. While the hardware and software will differ from different vendors, there are some general capabilities and limitations that are inherent in the technologies used. The Comparison Matrix in Section 3.8.1 compares the four technologies for a variety of attributes. Discussion of some of the table entries are given below. It is important to note that TTE systems and MF systems are still under development and may have limited commercial availability at this time (Spring, 2009). TTE systems are particularly useful because they do not need fixed structures underground which could be damaged. MF systems can use whatever continuous conductors already exist and hence, are less reliant on special cables or equipment than more conventional techniques, although they are not totally immune to disruption. The inherent bandwidth limitations of both technologies restrict their use to either emergency only situations (TTE in particular) or as an adjunct to more conventional technologies. Leaky feeder and node-based UHF systems are the most commonly installed systems to date, with leaky feeder technology having the longest successful history of usage in coal mines and tunnels.

3.8.1 Comparison Matrix

Table 3-1 Comparison of Communication Systems

		Communication Systems			
Category	**Feature**	**System Description**			
		Leaky Feeder[2]	**Medium Frequency[3]**	**Through-the-Earth**	**UHF Node Based**
Coverage & Range	Coverage Range - Access Link	< 150' / <400'	< 2 miles	< 2000' of cover	<1000'[4]
Coverage & Range	Expandibility (adding components)	Moderate	N/A1	N/A[1]	Easy/Moderate[5]
Installation	Design[19]	Low	High	Moderate	High
Installation	Labor Intensity	Moderate	Low	Low	Low
Installation	Infrastructure Recovery	Difficult	Easy	Easy	Moderate
Functionality	High Speed Data	Yes[6]	No	No	Yes
Functionality	Paging	Yes	No[7]	Yes[8]	Yes
Functionality	Peer to Peer	Yes[9]	Yes	N/A	Yes[6]
Functionality	Text - Low Speed Data	Yes	Yes[6]	Yes	Yes
Functionality	Voice	Yes	Yes	Yes[10]	Yes[6]
Functionality	Troubleshooting via centralized test diagnostics[11]	Moderate	Low	Low	High
Functionality	Interoperability[12]	Open	Proprietary	Proprietary	Proprietary
Survivability	Battery Load - Fixed Infrastructure[13]	High/Moderate	High/Low	Very High/Low	High
Survivability	Battery Life - Mobile	>24 hours	N/A	N/A	>24 hours
Survivability	Battery Locations	Low	Low	Low	High
Survivability	Fault Tolerant - Hardware	Moderate	Low	Low	High[14]
Survivability	System Survivability[15,16]	Moderate	High	High	Moderate
Footnotes to Comm Table					
1	N/A Not Applicable or Not Available				
2	When two values are shown, they represent VHF/UHF systems respectively				
3	Data for analog systems only				
4	Varies with frequency and entry dimensions if nodes are LOS. Stoppings and other obstacles will decrease range.				
5	May require a system redesign to expand				
6	Vendor specific				
7	Current technology				
8	Currently available system has paging + text for downlink only				
9	If handhelds allow F1/F2 switching				
10	Depth limited - system under development				
11	Describes system requirement for effective troubleshooting				
12	Does system use standard vs proprietary interface protocols				
13	Values for Transmit/Standby modes				
14	Depends on installation details				
15	System resistance to major disruptive events (fire, explosion, roof collapse, inundation) when properly implemented				
16	Based on the number of components needed and/or complexity of setup				

4. ELECTRONIC TRACKING SYSTEM PERFORMANCE

The MINER Act requires that electronic tracking systems be in place at coal mines to facilitate rescue operations in case of an emergency. Electronic tracking systems provide a mechanism for surface personnel to know which workers are in the mine and in which area they are working.

Many mines use manual tracking to monitor which miners are underground and their general location. When using manual tracking, at the beginning of each shift, the mine foreman provides the dispatcher with a list of names of people and where they are going within the mine. Once in the mine, if a miner needs to go to a different area to work, he notifies the dispatcher using the dial phone in the mine. The dispatcher then updates his list.

Manual tracking has a number of limitations. A miner's location may be given as within a working section that can be quite large. Occasionally a mine worker will forget to notify the dispatcher when he changes work locations.

There are several technologies available that can be used for electronic tracking. One technique uses *radio frequency identification* or *RFID* technology. RFID technology is used in commercial stores to prevent merchandise from being stolen. There is a small electronic circuit called a *tag* attached to the merchandise. At the exit to the store, there are two vertical gates that periodically emit an RF signal. The signal is received by the tag attached to the merchandise and the circuit emits a return RF signal if the tag has not been deactivated at the cash register. The return signal from the tag is picked up by the vertical gates and a warning is sounded.

Several technologies use the tag and reader approach for tracking just described. Another tracking technology uses the communications link between a radio and a node. The node analyzes radio signals from a miner's radio to determine how far away the radio is from a node or multiple nodes to infer the miner's location.

Another technology that has been proposed for use is called *inertial navigation* or inertial guidance. The system measures accelerations and other motion characteristics of the miner and changes in the magnetic environment to calculate changes in location.

In addition to determining location, there are other characteristics of interest for tracking systems. The system must have the *capacity* to track the maximum number of people that may be in a coverage area. It must also be able to distinguish each individual in a group of workers traveling in an area of the mine. In addition, there may be a requirement as to how often the tracking system needs to update each miner's location, referred to as the *scan rate*. These features should be discussed with a vendor when considering the purchase of a tracking system.

4.1 Tracking Techniques

Several tracking technologies are available for use in the coal mine environment. One technology, reader-based tracking, is similar to what is used in commercial stores. It has two major components: a device called a reader for detecting the presence of tags and the tags themselves. In mines, there are two variations within the reader-based technique. One approach places a tag on each miner and the readers are installed at specific locations within the mine. This approach is called *zone-based RFID*. In the other approach, called *reverse-RFID*, each miner wears a small reader and the tags are installed at known locations within the mine.

Another technology, called *node-based electronic tracking*, does not use tags. It relies on a sophisticated analysis of the RF signals passing between a radio and one or more nodes to determine the distance of the radio from the nodes.

The last tracking technology to be discussed is called *inertial tracking*, which uses sensors worn by a miner to monitor accelerations, changes in the earth's magnetic field, and changes in angular orientation, to calculate the change in the miner's location. The miner's location would be calculated from these changes, either by a small computer worn by the miner, or the change information can be transferred to a central computer at the mine operations center. In either case, a link to the communications system would be required to report the location information to the surface. As of this writing, inertial tracking systems are still under development and thus the discussion of this technology is limited.

In the following sections, each of these tracking technologies is discussed in more detail.

4.2 Reader-Based

Reader-based tracking is implemented in one of two forms: 1) zone-based RFID, in which case the miner wears the tag and the readers are in pre-determined, fixed locations; or 2) reverse-RFID, in which case the miner wears the reader and the tags are in pre-determined, fixed locations.

Reader-based tracking systems merely detect when a tag and a reader are within RF range of each other. When a tag is recognized by a reader, the miner's position becomes associated with the location of the fixed component (tag or reader). The *resolution* or distance within which the miner is located is determined by the spacing between fixed-position components. In some systems, a *received signal strength indicator* (RSSI) is used to further increase accuracy. These topics will be explained in more detail below.

4.2.1 Zone-Based RFID

4.2.1.1 Description

Zone-based RFID is based on readers positioned in known locations within the entries, and each miner wearing an RFID tag. Each miner wears a tag that transmits a unique identifier that has been assigned to that miner. The tag is read whenever the miner passes within the RF range of a reader. The reader transmits an RF signal to which the tag responds. The reader is said to *interrogate* the tag. Upon receiving the return signal from the tag, the reader must relay the detection information to a central location, usually the Mine Operations Center, or MOC. The information can be relayed over a pair of wires, through fiber optic cable, wirelessly, or through an interface to the communications system backhaul.

Each RFID reader has a unique identification and a location associated with that identification, so that when a tag is read by a given reader, and the information is forwarded to the operations center, personnel at the center know that the miner is within a certain distance, the RF range, of that readers' location. Because the miner's location is determined to be within the RF range of the reader, this is referred to as zone-based RFID.

Figure 4-1 shows two miners wearing tags whose RF range is indicated in red. The fixed position readers have an RF range indicated by the blue ovals. Miner A is within RF range of the reader located at survey marker 58301. A representative RF range is 300 feet. Thus, miner A is known

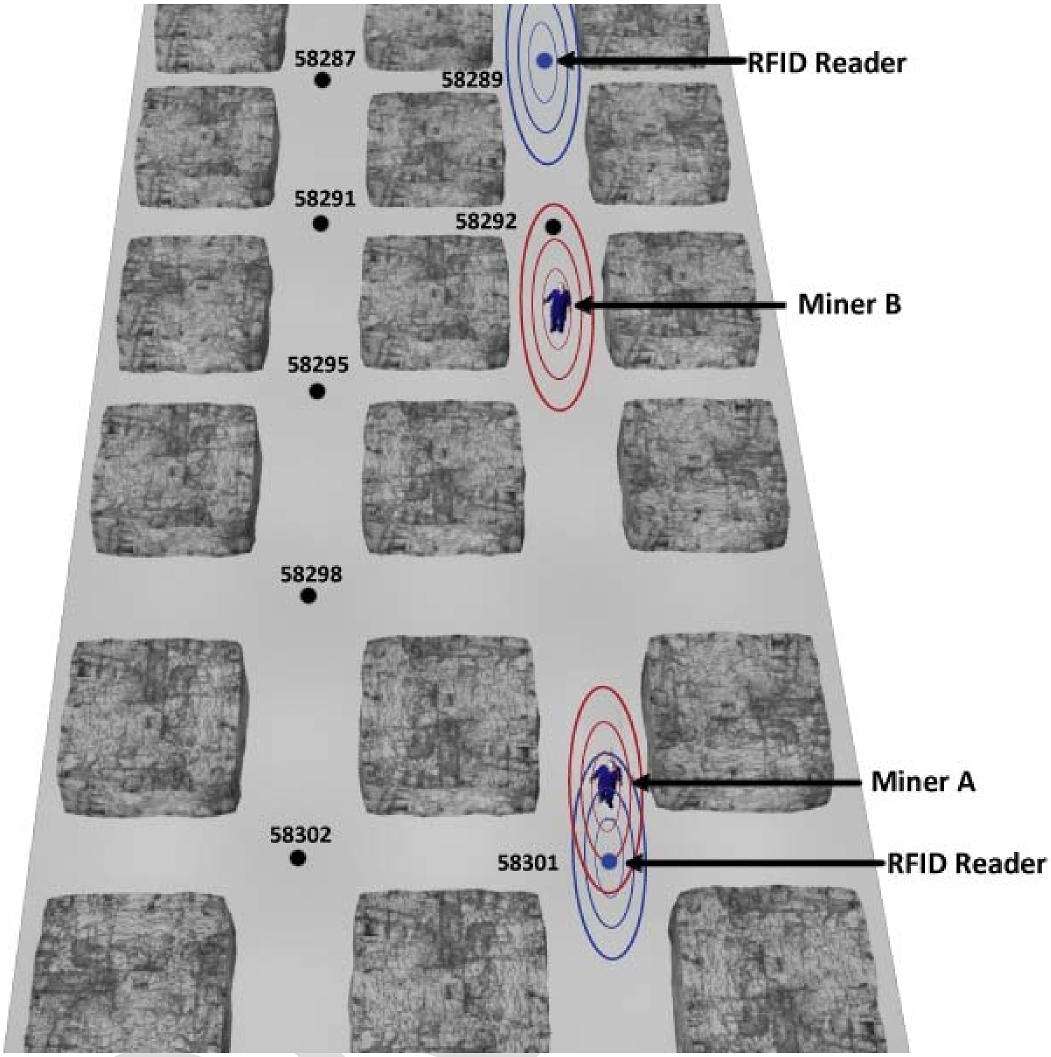

Figure 4-1. Example of Zone-Based RFID Tracking

to be within 300 feet of survey point 58301. This could be displayed as text or on a mine map on a computer terminal in the MOC.

Miner B who is walking toward miner A, is not within RF range of any reader. With zone-based RFID, unless the zones overlap, there are situations in which a miner's location is not known for certain. If miner B had recently been within range of the reader at survey point 58289, then the display in the MOC might have a special indication that miner B had been at 58289, but was not within range at this time. It could also display the last time and location that a reading had been recorded for that miner.

Notice that miner A could go down the left or right cross-cut at survey point 58301, and he would still be considered to be within 300 feet of point 58301. Miner A might be part way down a parallel entry and still within 300 feet of 58301, except that the RFID readers generally require an line-of-sight to read a tag. To resolve the miner's position and know his location more precisely, more readers are needed, which increases the cost of the system.

There are other performance factors for RFID tags and readers that should be evaluated. In reading a tag, there is a certain probability that an incorrect reading or no reading will occur. The uncertainty in reading the tag can be due to several factors:

- The distance between the tag and reader (greater distance yields a weaker signal making it more difficult to interpret).
- Orientation of the tag relative to the reader (e.g., if the plane of the tag is normal to the reader, it receives no interrogating pulse).
- The presence of metal objects (metal may reflect incident RF signals confusing the reader or the tag).
- The presence of multiple tags close together (multiple tags on a group of miners may confuse the reader because of multiple superimposed signals).

Another performance feature is the frequency of the reads - i.e., how often the system updates the readings. The frequency of updates can also affect the power requirements for the system and the life of the battery backup.

4.2.1.2 Components

The main components of the zone-based tracking system are the tags and the readers. The tags are inexpensive; the readers are considerably more expensive than the tags. The tags are battery operated, but are low power devices. The batteries are expected to last for several years before needing to be replaced.

The readers operate on mine AC power under normal conditions. In case of an emergency, they would use battery backup power. The readers also need a mechanism to get their information back to the surface, with the most likely location on the surface being the MOC. The information from the readers can be transferred to the MOC over wired or wireless links dedicated to the readers. Another alternative is to link the reader into the communications backbone to get the information to the MOC. Appropriate software and a computer with a display monitor are required at the MOC to interpret the information being sent by the readers.

Figure 4-2 illustrates a block diagram of a zone-based tracking system with a hardwired backhaul to the MOC. The tag might be worn on the miner’s helmet. A twisted pair cable is used to transfer the RFID reader information to the MOC.

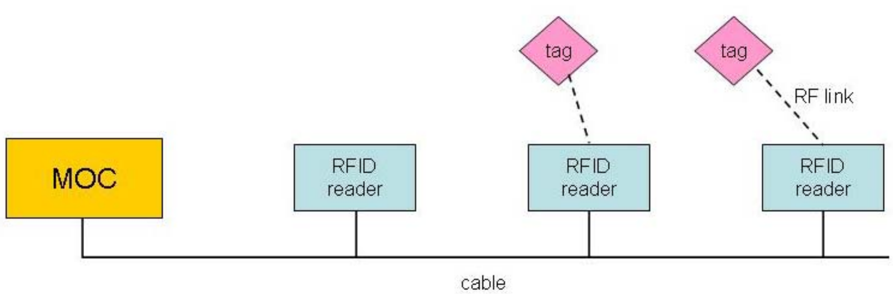

Figure 4-2. Sample Block Diagram of a Zone-Based Tracking System

4.2.1.3 Transmission Media

Reader-based tracking systems have to establish a physical RF link between the tag and reader similar to a communications link. The tag and the reader are exchanging RF messages. A link budget analysis can be performed.

Figure 4-3 shows a miner wearing an RFID tag on his helmet. An RFID reader is mounted in the entry. There is a downlink from the reader to the tag, and an uplink from the tag to the reader. A link budget analysis should be performed on both the downlink and uplink to ensure the received power in each case is above the receiver signal level threshold of the tag and reader, respectively. The other difference in analysis between the up- and down-links is in the transmit powers. The reader and the tag will have different transmit powers.

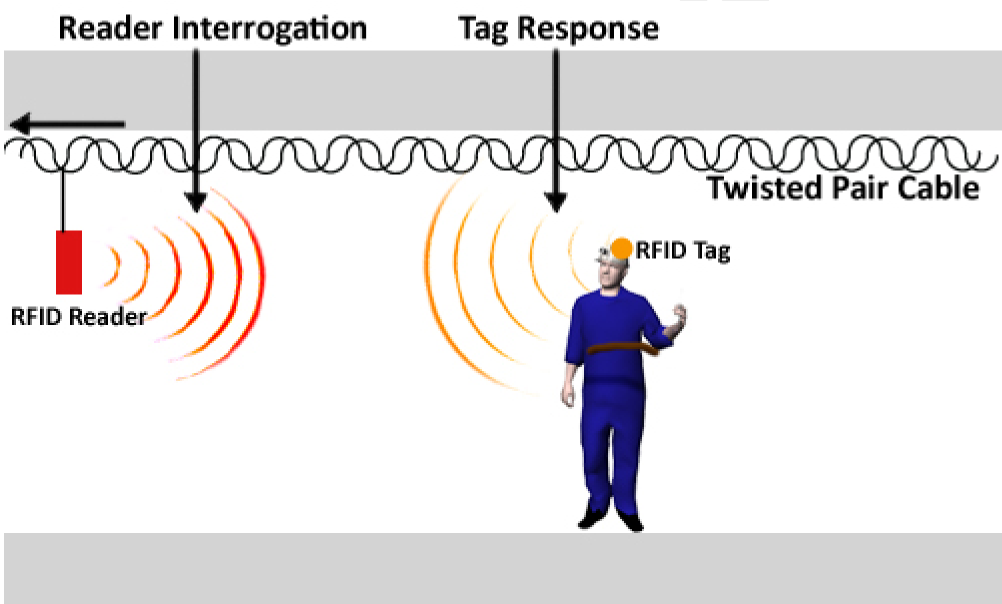

Figure 4-3. The Physical Link between a Reader and a Miner's RFID Tag

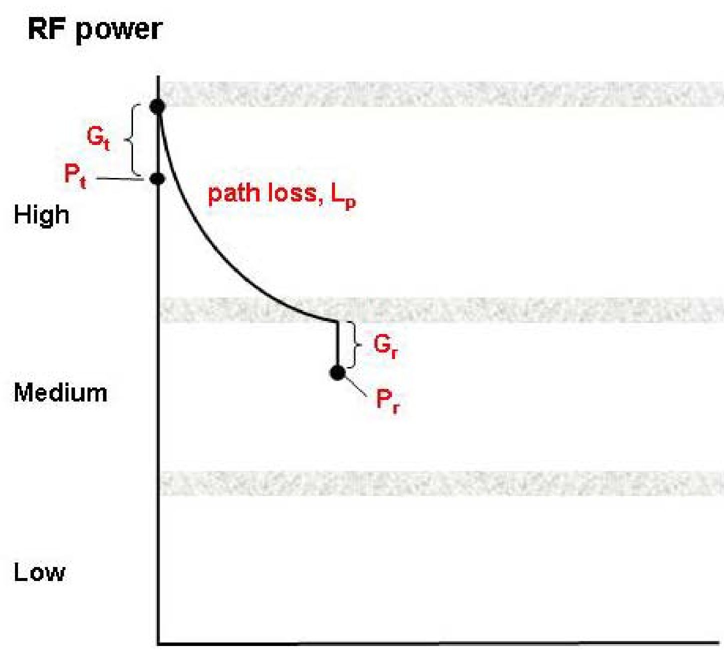

Figure 4-4. Conceptual Link Budget Analysis for Zone-Based Tracking

The downlink analysis will be presented. The uplink analysis can be done in a similar manner. In Figure 4-4, the link budget analysis begins with the reader transmit power P_t at the left of the graph. The reader is assumed to have an antenna with positive gain G_t adding to the transmitted power. The transmission medium is air and the associated path loss is L_p. The RF signal is picked up by the tag antenna which has a gain G_r, assumed to be negative, and thus the power is reduced. The resulting received power is P_r. Most of the values used in this link budget analysis could be obtained from the manufacturer.

4.2.1.4 Network Operations

Similar to communications networks, there are two aspects to the electronic tracking network: access and transport. The tags access the network through a reader, using the air as the medium for the RF signal. The reader transports the information to the MOC. There are a variety of ways that the reader information can be transferred to the MOC.

Figure 4-3 uses a twisted wire pair to form the backhaul to the MOC. In this case, the readers are likely to be in a linear topology, or if multiple entries are wired, a tree topology might be used, as shown in Figure 4-5. However, a more survivable approach would be to use a ring configuration or an alternate communications path out of the mine.

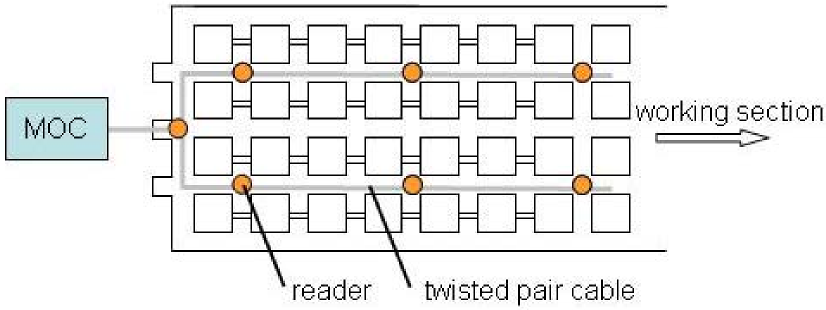

Figure 4-5. Sample Network for Zone-Based RFID System

The readers can also be integrated into the communications backhaul if the systems are compatible. For example, if there is a leaky feeder system in use for the backhaul, the RFID readers can use the leaky feeder cable to get the location information to the MOC by performing as a repeater and establishing an RF link with the leaky feeder cable. The tracking network topology would then be the same as the communications system topology.

It is unlikely that the RFID readers would be integrated into a node-based communications system network. As will be seen in Section 4.3, node-based communications have an inherent ability to perform tracking; there is no need for RFID readers or tags.

4.2.1.5 System Implementation

The tracking system can be implemented independently of the communications system. Both the tracking and communications systems could have separate links to the surface, but it may make sense to integrate the two systems. It is likely that tracking will be required in the same entries and strategic locations as communications.

Zone RFID tracking systems differ primarily by:

a) The method used to transmit tag data back to the MOC.

b) The method used to transmit data between the reader and the tag.

c) The location of the tag on the miner.

To transmit data back to the MOC (a), some tracking systems will use a dedicated communications system while others will utilize whatever communications system is already installed. Whether or not the tracking system is integrated into the communications system, implementation recommendations are dependent on the specific communications technology and are covered in Chapter 3. Only specific components related to (b) and (c) will be covered in this section.

Tags that are integrated into another piece of equipment, such as a cap lamp battery, do not need any special attention. Tags that are separate units need to be worn so as to be detected by the reader. The manufacturer of the system is the best source of guidance for protection of their hardware. The only caution is that active tags (the usual type) are miniature transmitters. While their power output is small, they can be worn very close to vital organs and are likely to be worn for long periods of time. Output power and distance should conform to safe distance recommendations (see section 6.3.1).

Readers are complex electronic devices that must be protected from damage by mounting them out of the way of moving equipment. At the same time they must be able to “see” the tags to operate correctly. It is possible to recess readers into the ribs to protect them from blast forces, but this will likely reduce their RF range. Generally, the readers require line-of-sight to the tags, and recessing a reader will reduce its field of view. A reader may be located at a cross-cut to increase its coverage, but such a location may be more susceptible to blast forces and roof falls. As discussed below, installation at a cross-cut can also cause location errors under some circumstances. Attention should be paid to protecting connecting cables and connectors. The manufacturer is the best source of information on how the reader must be installed.

The loss of a single reader does not result in the failure of the system. Since the last known location of the miner is always stored by the system, a location estimate can still be made even though the miner is not within range of a functional reader.

Spare tags should be readily available for quick replacement of damaged units since a failed tag means a miner cannot be tracked. The tracking software at the surface should allow for quick reassignment of tag IDs. If the tag is integrated into the cap lamp battery enclosure, then the complete unit may have to be replaced. If tags use replaceable batteries, spares should be readily available.

4.2.1.6 Maintenance and Inspection

RFID systems are in common use above ground and their operating characteristics are well understood. However, the underground environment adds an important complication – the tag to reader detection range. The nominal tag-reader detection range will depend on its position in the tunnel as well as the tunnel geometry. It is unlikely that the range will be the same for all readers. In addition, equipment can block the line-of-sight between a reader and a tag, exposed antennas can be damaged, batteries can discharge, and electronic components can age. All of these factors can affect the tag-reader detection range. The system may have the ability to detect the battery condition of its components, but other factors are not as easily assessed. As a result, the system performance, in particular the detection range, can only be verified by periodically testing critical underground locations.

Tag readers usually have indicator lights on the units which provide information about their health status. Some may signal the MOC when an error is detected. The only certain way to know if the system is working is to periodically test each reader by allowing it to read a tag and cross-check the result at the MOC. A good test would be to have a miner walk a predetermined route and record the time at certain points of the route. Comparing the known route and time data to the recorded data provides the check. The tests also need to be carried out as required by regulations or manufacturer’s guidance. Since readers are designed to read multiple tags in rapid succession to accommodate groups of miners or miners riding a man trip, the more advanced features cannot be easily checked unless there are built-in diagnostics. These tests, if available, should be run as recommended by the manufacturer.

The tag may also have an indicator light to alert the user of a malfunction. However, the simplest test is to allow a reader to read the tag and see if it was detected correctly. Replacing tags that have failed requires reprogramming the tracking software to connect the new tag ID with a particular person. Maintaining the system's database to reflect tag replacement is critical to performance and a standard routine should be followed.

4.2.1.7 Performance & Limitations

In this discussion, coverage area refers to the area of the mine in which the tracking system can provide location information about a miner. While tracking systems are limited by their dependence on a backhaul system to send data to the MOC, RFID systems are further limited by the reader-tag detection range and the distribution of readers.

The usual definition for accuracy gives the location error in feet for a detected tag. A reader knows whether or not a tag is within its detection zone, but not where it is within its zone. Figure 4-6 provides a demonstration. The reader spacing is S and the reader can detect a tag within a radius of R. For a miner in position M1, the system reports his position to be within ±R of reader R3. So the location accuracy of M1 is ±R. In contrast, a miner in position M2 is not detected by any reader, but if he were previously detected by reader R3, then there are four areas he could have walked into (a, b, c, or d). If he were last detected by reader R2, he could be in areas (b) or (e). In both cases, he is within a circle of radius S-R, which, depending on the reader spacing, may be much greater than R. For widely spaced readers, accuracy varies greatly between detected and non-detected miners.

When the reader detection ranges overlap (Figure 4-7), this problem does not occur. The accuracy depends only on the distance between readers and is no worse than ±S/2 at the time of detection. The tracking software must be able to calculate the miner's position based on detection by multiple readers. However, accuracy is still limited by the interval between system updates. For example, a miner walking at 2 miles per hour would travel 176 feet in one minute. So one minute after detection, the miner could be 176 feet from the last known reader detection zone in either direction. To meet a given accuracy requirement, reader spacing, detection range, and update interval must all be considered.

As mining progresses, the system will need to be expanded to allow coverage in new areas. For a typical system, this will involve installing new readers in the mine and associating them with survey markers or landmarks, such as an intersection. The new reader information is then input into the tracking software database. New miners must be issued tags and the tag ID entered into the tracking database. Maintaining an accurate database of readers and tags is a critical consideration.

Critical functions include tracking the location (with time stamp) of all miners while underground, providing data storage capabilities so location history for each miner is available, providing diagnostics so damaged units can be identified, and battery condition monitoring for the tags. The surface portion of the tracking system should be equipped with standby power to ensure continuous operation in the event the line power is interrupted. The tracking system should be configured to allow monitoring of the location of miners underground from the communications facility required under 30 C.F.R. § 75.1600-1 where a person is always on duty when miners are underground and should include the capability to display the location of all miners underground. The tracking system interface should display the last known location of a miner when the tracking device is not communicating with the system.

Survivability of the tracking system after an accident is a key requirement of the MINER Act. RFID systems may use the existing mine communications system or a dedicated system to transmit location information to the surface. In either case, the survivability of the tracking system is tied to the survivability of the backhaul system. If the backhaul system is damaged during an accident and cannot be restored during rescue efforts, the tracking system will not provide updated miner location information. Only the last known position of each miner before the accident will be available. If system components must be installed in areas vulnerable to damage (such as in front of seals), protection should be provided against forces that could cause damage. Protection could be provided by installing enclosures in recessed areas, around corners, or other areas that reduce potential for damage.

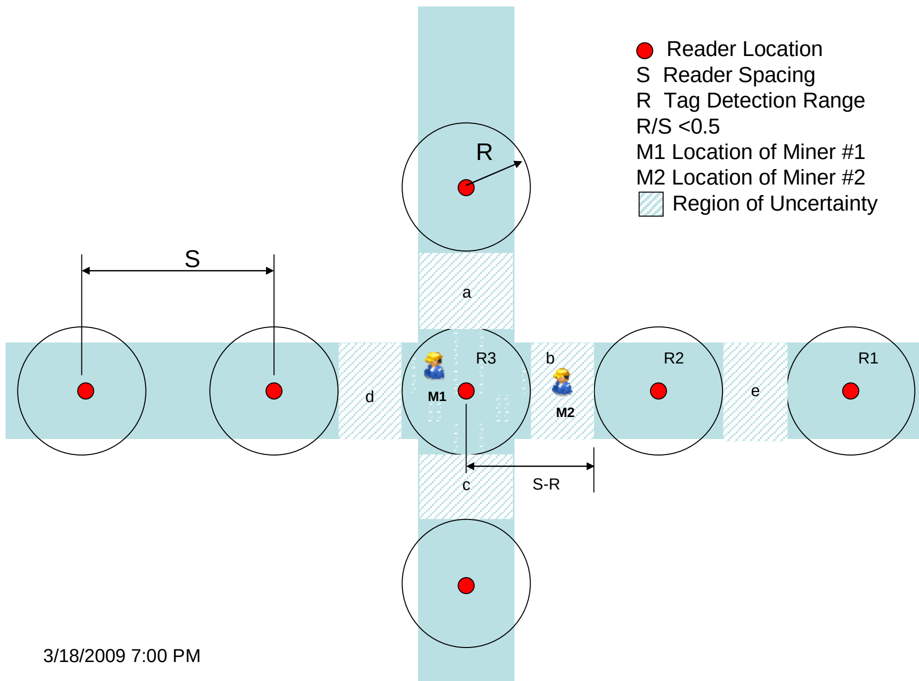

Figure 4-6. RFID system layout – readers do not overlap.

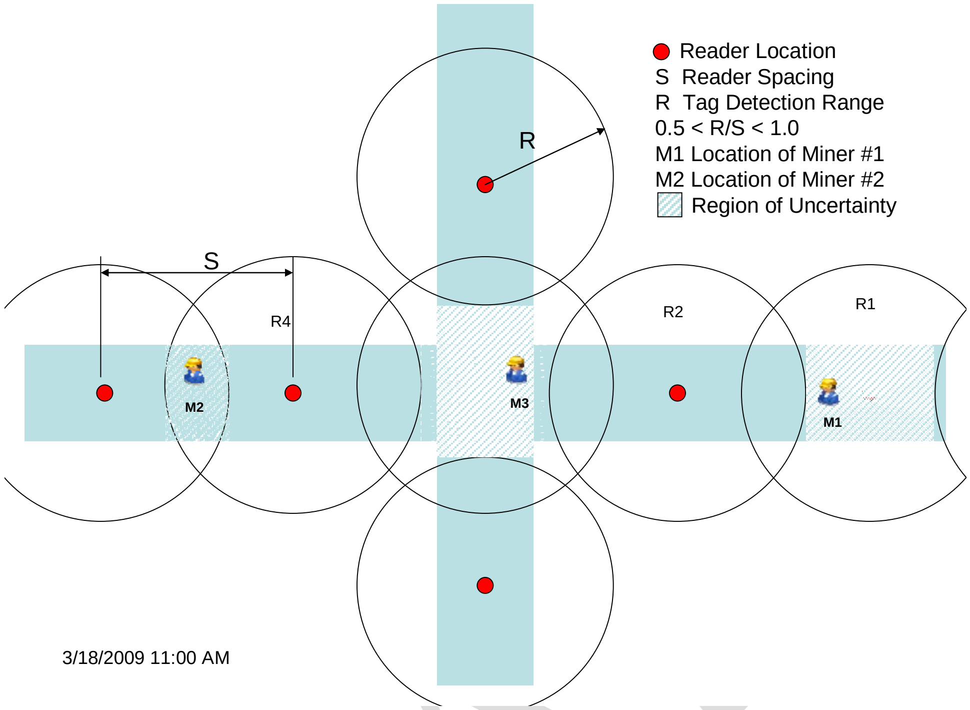

Figure 4-7. RFID system layout – readers overlap.

In the event that mine power is lost during an accident, it will not affect the operation of the tags, since tags normally operate on long life batteries or are integrated into the miner's cap lamp assembly. Readers are required to have battery backup capability and are expected to operate for more than 24 hours if properly maintained. Currently available systems exceed this requirement.

Miner location data is generally only available on the surface tracking computer, but the tag worn by the miner is continuously sending out its ID. While this signal has a limited range (<500 feet), a rescuer with a portable version of the reader might be able to use the signal to further aid in finding trapped miners.

4.2.2 Reverse RFID

4.2.2.1 Description

Zone-based RFID tracking has been described in Section 4.2.1. In zone-based RFID, each miner wears an RFID tag and the readers are in fixed, known locations. In Reverse RFID tracking, the miner wears the reader and the tags are in fixed, known locations. An advantage of this approach is that RFID tags are inexpensive. Tags can be located close together to achieve greater precision in locating the miner compared to zone-based systems, where the readers may be located fairly far apart to keep costs down.

The location information obtained by the RFID reader, which the miner is wearing, must still reach the MOC. To accomplish this, the reader has a radio transmitter that periodically transmits the miner's location data to the mine's backhaul communications system. Figure 4-8 illustrates a Reverse RFID system in which the backhaul is a UHF leaky feeder system.

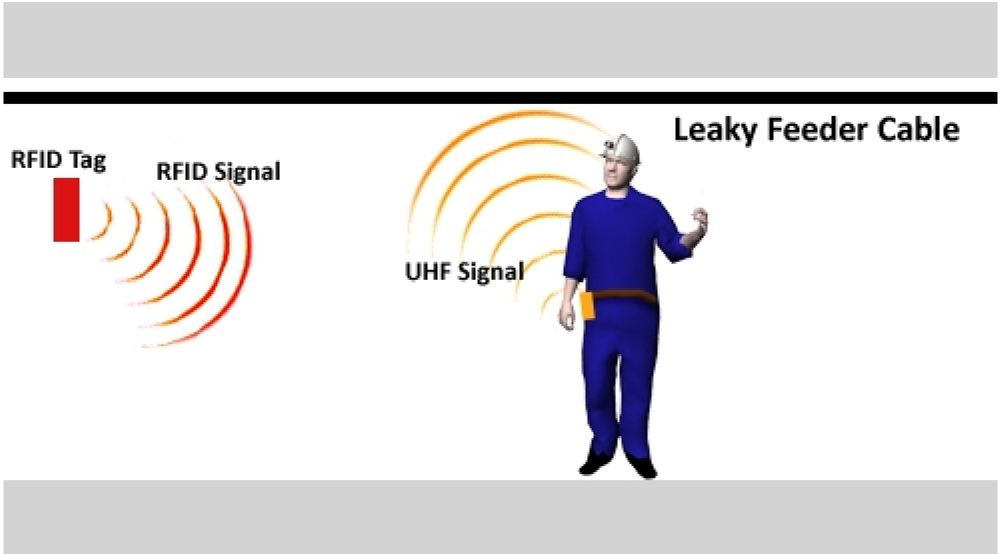

Figure 4-8. Reverse RFID Tracking System Coupled to a Leaky Feeder

The RFID tag is programmed to periodically emit its identification information, shown in red in Figure 4-8. A separate antenna might be mounted on the miner's cap to receive the RFID tag signal. The RFID information is then transferred to the transmitter on the miner's belt to be relayed to the leaky feeder cable and ultimately the MOC. A UHF transmitter mounted on the miner's belt transmits the location information to the leaky feeder cable.

4.2.2.2 Components

The Reverse RFID tracking system has the same components as the zone-based system: tags, readers, some type of backhaul to the MOC, software, and a computer with a monitor. In the Reverse RFID system, the RFID reader must have an RF transmitter to relay information from the miner to a network that acts as the backhaul to the MOC. Although the components are similar to the zone-based RFID system, the block diagram of the Reverse RFID is quite different (see Figure 4-9).

Each tag has a unique identification number and a unique location within the mine. The tags are battery operated, but battery life is estimated at several years. The readers are worn by the mine workers. Each reader is unique and assigned to a specific miner. The readers are battery operated, but can be recharged when the miner is not working.

Because a leaky feeder cable provides communications coverage essentially in the entry in which it is located, the tags and the RFID readers (miners) would also have to be in the same entry for the system to provide useful location information. Leaky feeder coverage, and hence, Reverse RFID tracking coverage, can be extended into parallel entries or isolated locations though through the use of an antenna that is spliced into the leaky feeder cable (see Figure 3-15).

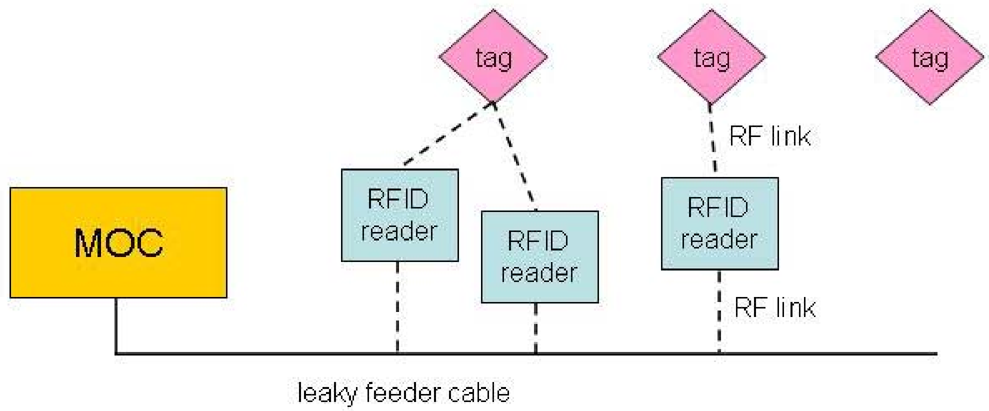

Figure 4-9. Block Diagram of Reverse RFID Tracking System Linked to Leaky Feeder System

4.2.2.3 Transmission Media

As seen in Figs. 4-8 and 4-9, two physical RF links must be established for the Reverse RFID connection, although the links need not be established simultaneously. One link is between the tag and the reader, and the second link is between the reader and the backhaul network. Both these links are through the air and both could have uplinks and downlinks.

Consider the physical link between the tag and the reader. The reader may send an interrogating signal to the tag and the tag will respond. Thus, there is an uplink and a downlink. Alternatively, the tag may periodically transmit its location information which is received only when a reader is within range and not require an interrogating signal. Then only a link in one direction is required. The disadvantage of the single-link approach is that the tag is continually emitting, which requires power from the internal battery. In the first approach, the tag is inactive until it receives an interrogating pulse. It should use less energy in the latter case and the batteries should last longer between replacements.

It is required that the reader link with the backhaul to be able to send its location information to the MOC. There is no requirement to establish a link in the opposite direction (backhaul to reader). It may be a good safety measure though to have the MOC periodically send a signal to the reader indicating that there is a connection to the MOC. The miner's reader could have a reassuring light to indicate if a link to the MOC is present. The link could also be used for the MOC to verify that a connection to the miner is present.

A link budget analysis would normally be performed for all uplinks and downlinks to verify that the receiver signal level threshold was met for each receiver. For simplicity, the analysis below only considers the links from the tag to the reader and from the reader to a leaky feeder cable. Figure 4-10 illustrates the link budget analysis beginning with the tag transmitter power P_t of the tag at the far left of the graph. The gain of the tag antenna G_{tag}, is assumed to be negative. The path loss for the RF signal through the air is L_{p1}. The negative gain of the reader's receive antenna is G_{r1}, resulting in a received power in the reader of $P_{r\ reader}$.

The reader may change the frequency before re-transmitting the location information at power $P_{t\ reader}$ from its antenna of gain $G_{t\ reader}$. There is the path loss of this signal through air L_{p2} as it is received by the leaky feeder cable which has an assumed gain of $G_{r\ cable}$. The received power in

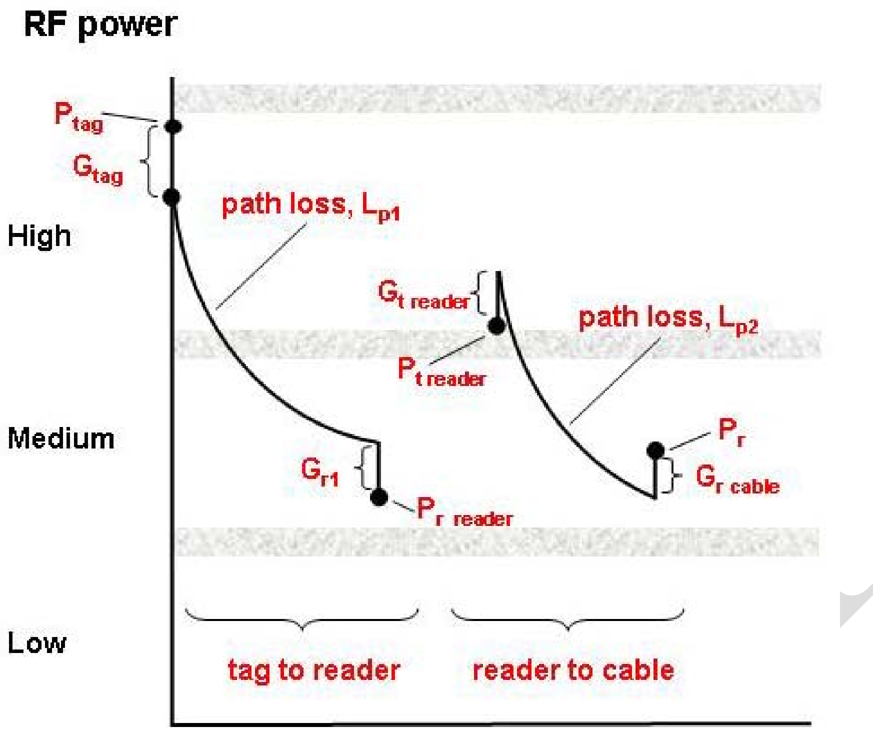

Figure 4-10. Conceptual Link Budget Analysis for Reverse RIFD Tracking

the cable is $P_{r\ cable}$. Most the values used in this link budget analysis could be obtained from the manufacturer.

4.2.2.4 Network Operations

As discussed in previous sections, the Reverse RFID system uses RFID tags distributed throughout the mine at specified locations. Each miner wears his assigned RFID reader. The Reverse RFID system requires an existing backhaul communications system to get the location information to the surface and ultimately, the MOC. The Reverse RFID reader must transmit location messages that are compatible with the communications backhaul system.

All the communications systems have been discussed in Chapter 3. The Reverse RFID reader is not compatible with wired communications. An interface to a wired communications backhaul would have to be wired, and the reader must be un-tethered to meet the goals of the MINER Act. The reader could be designed to communicate with a VHF or UHF leaky feeder. A leaky feeder backhaul has been used in most of the examples in the earlier sections on Reverse RFID. The reader could be similarly interfaced with a UHF node-based communications system. It is unlikely that the reader would transmit MF to couple to an MF network, because the MF antenna and transmitter are too bulky. The reader could transmit VHF or UHF and couple to an MF/VHF or MF/UHF converter and ultimately a digital MF network. Regardless of the technology used, the network backbone will be that of the communications system. The Reverse RFID reader would represent an additional access to that network.

4.2.2.5 System Implementation

The Reverse RFID tracking system requires a communications backhaul system to relay location information to the MOC. Figure 4-11 shows a leaky feeder system providing the backhaul to the surface of the mine. In this example, there is an RFID tag on each pillar in the entry with the leaky feeder cable. If miner A is within RF range of an RFID tag, his position can be read and transmitted to the leaky feeder cable by the reader. In the MOC, the miner’s location would be associated with the known location of that tag. Therefore, if the crosscuts are separated by 100 feet, then his location would be known to within 100 feet, provided the miner remains in the entry with the leaky feeder cable. Signal strength measurement techniques, such as RSSI, can further improve accuracy by estimating distance from a tag based on the strength of the received tag signal.

For the Reverse RFID system to remain viable after an accident, the backhaul, RFID readers, and tags need to be operational. Because the Reverse RFID system is dependent on the communications backhaul, the survivability of the RFID system will depend on the survivability of the backhaul. Thus, any provisions to harden the backhaul or accommodate alternate communications paths will also increase the survivability of the tracking system.

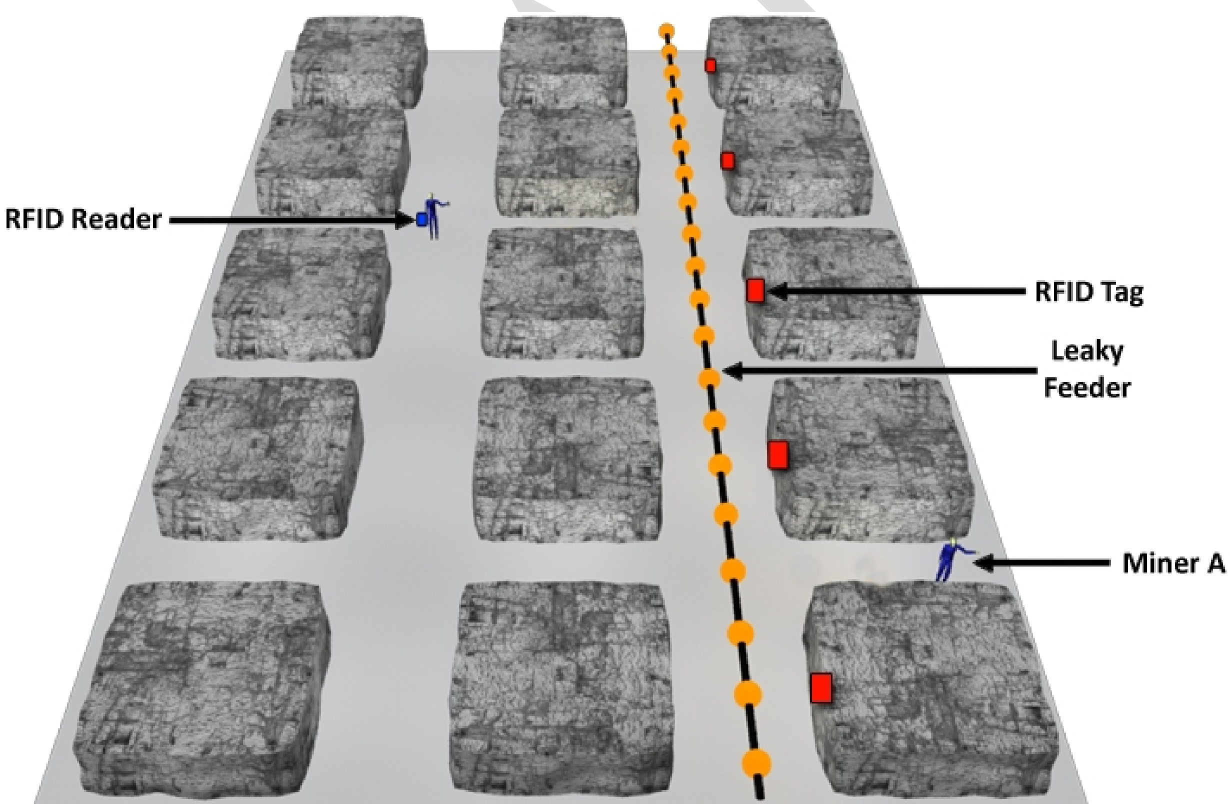

Figure 4-11. Reverse RFID with Leaky Feeder Backhaul

If the miner survives an accident, there is a good chance his RFID reader also survived. However, after an accident involving an explosion, fire, or a fall of ground, one or more tags may be damaged. The failure of a tag will result in less tracking accuracy in the immediate area of that tag. As soon as the miner reaches the next operational tag, the accuracy is then restored to normal. If multiple adjacent tags are not functioning in an area, tracking may not be possible until the miner reaches the transmit range of the next functioning tag. The last known location of the miner is always stored by the system so that a location estimate can still be maintained.

RFID tags may be recessed into an entry wall or covered with a non-conducting shield to protect them against blast forces. Recessing a tag may decrease its field of view and thus, reduce its RF transmit range. To minimize the chances of being struck by equipment, tags may need to be hung near a wall rather than the center of an entry or in the middle of an intersection. Each manufacturer will list minimum clearance distances between tags and other structures.

For the highest resolution and redundancy, tags should be attached to the roof with a spacing between the tags less than or equal to the maximum transmit range of each tag. This provides 100% overlap of the tag signals. In areas where less resolution is needed, greater spacing can be used. Tags can be hung at intersections to allow tag detection in crosscuts; although the detection range and ability to communicate with the backhaul system will limit the distance a miner can travel into a crosscut and still be tracked. Tag density may need to be increased in working sections to increase accuracy and redundancy.

Hardening of the reader electronics is maximized when the reader and backhaul radio are integrated into the cap lamp battery enclosure and existing cables. In some systems, the reader electronics and radio may be in separate enclosures and worn on the belt. This presents more failure modes as cabling, separate power supplies, and an extra enclosure all add complexity to the system. Hardening of the cables, connectors, and enclosures is critical and methods should be employed to route and bundle cables so that they are not a hazard to miners.

It is recommended that spare tags be readily available for quick replacement of damaged or failed tags. The tracking software at the MOC should allow for quick reassignment of tag IDs. If the tag reader and radio electronics are integrated into the cap lamp battery enclosure, then the same policy for spare cap lamps located underground should apply. If the reader electronics are in a separate enclosure, spare units should be available underground. If a miner replaces his reader unit while underground, surface personnel must be notified so that the tracking software is updated. The new reader ID must be entered and its operation verified, and the old reader ID must be removed from the tracking system database. Bookkeeping procedures must be well-established to prevent errors that could result from reader or tag replacement.

4.2.2.6 Maintainability and Inspection

The complexity of Reverse RFID systems is generally considered high due to the number of tags required throughout the mine, the addition of a tag reader device that must be worn by each miner, and the required interface to the existing mine communications system. The system's tracking computer should be self-monitoring and have a maintenance display that will automatically run self-diagnostics at predetermined intervals as well as have the option to initiate diagnostic scanning manually. Maintenance for the tracking computer will be similar to normal maintenance provided for all PC and IT equipment (e.g. cleaning, anti-virus updates, software updates).

Tags can fail during day-to-day operations due to low batteries, damage from passing equipment, and harsh environmental conditions. For these reasons, tags must be visually inspected at regular intervals. This can be accomplished during other mine inspections and safety checks and should occur at least quarterly. Along with a visual inspection, the functionality of each tag should be checked periodically by verifying that the software is correctly updating the inspector's location as the system is being inspected. In addition, some systems will flag a particular tag if it has not been detected by a reader in a predetermined amount of time. It may be useful to have a test station at the entrance to the mine to verify the miner's reader is working properly before the miner goes underground. Also, a portion of the message stream that is transmitted to the reader from the tag should include tag battery status. Maintenance personnel can then be alerted by the software to investigate the operation of a particular tag.

4.2.2.7 Performance and Limitations

The performance of a particular Reverse RFID system depends on many factors and will vary with each manufacturer. The main performance metric for tracking systems is the system's accuracy in determining and displaying a miner's location in the mine. In Reverse RFID, this is highly dependent on the characteristics of the tags. Transmit range, update rate, RSSI methodology if used, and other technical factors all affect the resolution and accuracy capabilities of a particular tag. Resolution is the smallest change in the miner's location that the system can detect. For systems that use RSSI, resolution will depend on the smallest signal strength change that can be detected. Systems that do not use RSSI will have poorer resolution numbers because resolution will be determined strictly by the spacing of the tags. Location accuracy is a measure of the difference between the miner's actual location and the location that is displayed on the tracking computer. Accuracy is influenced by the miner's travel speed, system update rates, backhaul communications delays, and signal propagation errors. Generally, accuracy is not as precisely determined as resolution.

For systems that compare the signal strengths (RSSI) of tags, the best accuracy is achieved when at least two tags are detected by the miner's reader. A comparison can be made between the received power of the two tag signals, which allows the miner's position between the two tags to be more accurately estimated (See Figure 4-15A). The accuracy is decreased when only one tag is detected, as shown in Figure 4-15B. For systems that do not use RSSI techniques, accuracy is similar to zone-based systems. A miner can be anywhere within a circle centered at a tag with a radius equal to the transmit range of the tag (Figure 4-15C). Accuracy can be improved in both types of systems if some intelligence is added to the tracking software to eliminate the possibility of a miner standing inside a pillar, for example. Update rate, or how often the location information is sent to the tracking computer, greatly affects accuracy. For example, if a miner moves after the last update, then his actual location will differ from the last known location by some distance that is dependent on travel speed and the time to the next update.

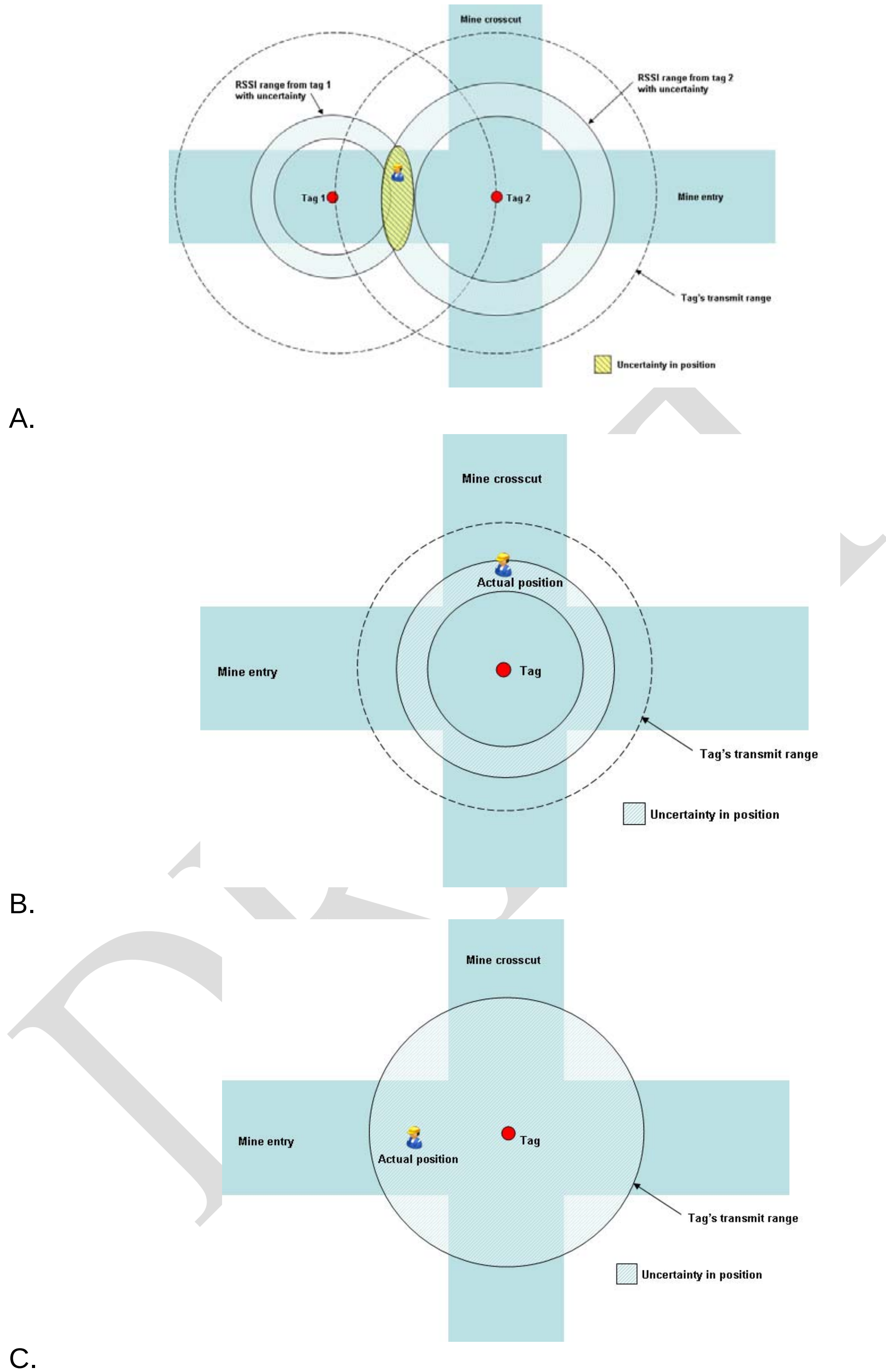

Figure 4-15. A.) System using RSSI with ability to compare at least two tags. B.) System using RSSI with only one tag in range. C.) System that does not use RSSI.

The ability of a reader to detect tags depends on the sensitivity of the reader and the transmit power of the tags. Generally, if a tag is mounted at an intersection, tag detection will occur as long as there is line-of-sight to the reader and it is within the transmit range of the tag. Tag signals may penetrate some materials — e.g. wood, concrete blocks — but the signal will be attenuated, which limits the detection range.

The reader electronics worn by the miner will contain some device to communicate the location information through the mine's existing radio backhaul communications system. The communications system will then transmit the information to the tracking computer in the MOC. Each manufacturer will have a unique way of doing this. For a discussion of the methods and limitations of a particular communications scheme, see the preceding sections. An important consideration is the transmission characteristics of the radio link between the reader and existing communications, with the accuracy of tracking affected by the ability of the system to reliably transmit location information. For example, if the tracking system uses the mine's leaky feeder system to transmit location information to the surface and the miner is not within communications range of the leaky feeder cable, then current location information will not be available for that miner. Also, because of power limitations, the reader will not transmit location information to the backhaul communications system continuously. The update rate can be as low as once every minute, affecting accuracy as described earlier.

As mining progresses, the system will need to be expanded to allow coverage in new areas. For a typical system, this will involve installing new tags in the mine and associating those new tags with survey markers or landmarks, such as an intersection. The new tag ID and location are then input into the tracking software database. The communications backhaul will need to be installed in the new areas also. New readers will need to be added to the system if employment size increases.

Each manufacturer will have their own protocol for information sent from the reader to the surface tracking computer. For example, some systems send the ID of the two nearest tags and the signal strength of those tags. The tracking computer then uses this information to calculate the location of the miner in relation to the mine map. The reader itself typically does not calculate location. The location information of a miner is only available at the surface tracking computer. It may be possible to send the calculated position of the miner back through the mine's communications system to the reader, but this is not currently done in available systems. Thus, location information is not available to each individual miner. As a miner travels through the mine, the latest tag IDs and signal strengths (if used) are stored by the reader and transmitted to the mine's backhaul communications system when it is available. Also, miner location information that is calculated by the tracking computer can be stored at the surface for days or weeks or more, depending on the storage media.

The available Reverse RFID systems are typically stand-alone systems and cannot interface with other tracking systems. For example, Reverse RFID tags are not compatible with conventional zone-based RFID systems. However, in the future, Reverse RFID may be integrated into node-based communications systems to provide better tracking accuracy to those systems. As discussed, current Reverse RFID systems will likely use the existing radio communications system to transmit tracking information to the surface. Thus the radio link for the reader must be compatible with the existing communications system, not cause interference with other radio devices, and not require excessive bandwidth as to limit other radio communications functions.

In a typical system, tag batteries may not be replaceable due to long expected battery life and the low overall cost of each tag. The entire tag should be replaced according to the manufacturer's replacement schedule, which should be well before the tag battery is expected to fail. As discussed earlier, the system should be designed to monitor the tag battery voltage level and provide either a visual indicator on the tag, a warning within the tracking software, or both, when a tag's battery power level is low. Battery voltage level for the reader should also be monitored within the reader electronics and a visual indication should be provided when the reader power levels are low. Spare reader units or batteries should be accessible underground.

Because it is critical that tracking systems operate after an accident, survivability should be a major consideration (see section 5.2). Tags are the component most susceptible to damage. Failure of multiple tags is likely in the event of a fire or explosion, making tracking impossible in the affected area. However, once a miner has reentered an area with functioning tags, tracking can resume provided the communications infrastructure is functioning. For Reverse RFID systems that use the existing mine communications system to transmit location information to the surface, the survivability of the tracking system is closely tied to the survivability of the communications system. If the communications system is damaged during an accident and cannot be restored during rescue efforts, the tracking system will not provide updated miner location information.

In the event that mine power is lost during an accident, it will not affect the operation of the tags and readers. Both operate on battery power normally. Battery life of a tag is typically measured in years. Battery life of a reader depends on the power source. Some readers are integrated into the cap lamp battery. Others are mounted in a separate enclosure and require another battery. In either case, the reader must function for a minimum of 12 hours on battery power according to MSHA guidelines. Available systems exceed this requirement. If loss of mine power affects the communications system that the tracking system uses to transmit location information to the surface, then updated location information will not be available until main power is restored or the communications system is switched to backup power.

4.3 Node-Based Communications with Integrated Tracking

4.3.1 Description

Node-based electronic tracking is an extension of the functionality or capability of a node-based communications system. The tracking capability is often integrated into the node-based system such that the miner radio acts as the tracking device and no additional components are added to the communications system, although there are possible changes to software or hardware within the radio or node. It is also possible that a node-based system could be designed primarily for the purposes of tracking, which allows the size of the radio to be reduced.

In either approach, each miner is assigned a communications device with a unique identifier. The identifier is similar to a phone number, which is assigned to a specific mine worker. If a link is established from the miner's radio to a node, then the miner must be within RF range of that node. Each node has a unique identifier and specified location associated with it. This information is sent to the MOC computer via the communications backhaul. Software on the MOC computer interprets the information. The location of the node can be displayed on a mine map. The miner's location is associated with that node on the map.

Wireless nodes may be located 2000 feet apart and still provide continuous communications coverage. Based on the approach just introduced, the miner's location would only be known within 2000 feet. In addition, the RF ranges of neighboring nodes frequently overlap in order to provide continuous coverage. The overlap implies that a method is required to resolve the location of radios that are within the overlap region.

Several techniques are available to obtain greater resolution in determining a miner's location. One technique uses RSSI to determine how far away the radio is.

Another technique to determine a radio location in a node-based system is based on *time distance of arrival (TDOA)*. The TDOA approach measures the difference in the time of arrival of a radio's signals to different nodes. The greater the distance a radio's RF signal travels to reach a node, the more time that is required. The difference in the travel times to different nodes is a measure of the difference in the travel distances. If the miner's radio is known to be between two nodes, the difference in distances will isolate his location. As in the RSSI technique, sometimes the information from three nodes is used to reduce uncertainties in the analysis.

Unfortunately, there are many sources of error or uncertainty introduced in the RF environment of a mine. RF signals interact with, and reflect off of, rough walls, people, equipment, and other obstructions. People and equipment are constantly moving in a dynamic mine environment, which introduces time-varying effects on RF signals. There are other sources of electromagnetic disturbance or interference present in the mine that combine with the true signal. The result is that the resolution in the location is not as good as what would be expected if these confounding effects were not present or were properly resolved.

4.3.2 Components

Because of the very strong inter-relationship between node-based communications and node-based tracking, it is unlikely that a node-based tracking system would be implemented unless a node-based communications system was also implemented. A node-based tracking system requires no additional components over what is necessary in a node-based communications system. To accomplish the tracking capability, there may be additional internal hardware added to the radios and nodes to generate the periodic and automatic location information exchange between a radio and the nodes. There will also be additional software control and software analysis required to interpret the location data. The tracking block diagram and component discussion is unchanged from the communications block diagram of Figure 3-28 and discussion in Section 3.6.2.

4.3.3 Transmission Media

The node-based tracking transmission media discussion is the same as the node-based communications discussed in Section 3.6.3. The physical link from the radio to a node is through the air. The node-to-node backhaul link can be wireless or wired. The link budget analysis shown in Figure 3-30 is unchanged.

4.3.4 Network Operations

As might be expected, the network operations of the node-based tracking system are similar to those of the node-based communications presented in Section 3.6.4. One difference in network operations is that the MOC will need to have the capability to capture, process, and display the information from the network required for the location determination. There will be increased message traffic on the network because of the periodic passage of location information from each radio to the MOC. Even when miners are not talking on their radios, the radios are periodically exchanging location information with the network and the MOC to keep the location information current. For most systems, this information is not a large part of the total network traffic, but it should not be overlooked in the system design.

4.3.5 System Implementation

In terms of survivability, the tracking and communications systems are essentially the same system. Any activities or accommodations aimed at enhancing the survivability of the node-based communications system will similarly extend the survivability of the tracking system. The discussion in Section 3.6.5 introduced redundant paths that can be achieved with a mesh network, the possible benefits of wired connections between nodes, and creating alternate communications routes by interfacing to other communications technologies such as leaky feeder, as approaches to increasing the survivability of the communications system. The same approaches and discussion applies to the survivability of the node-based tracking system.

Adding the tracking functionality to the node-based communications system does make the combined system more complicated. As mentioned in the previous sections, there is additional hardware and software required which decrease the system's *reliability*, i.e. the ability of the system to perform its specified function or perform without failure. How much the increase in complexity affects the reliability may only be known after these systems have been in use for several years.

4.3.6 Maintainability and Inspection

Integrated node-based communications/tracking systems require less underground infrastructure than separate systems, but are complex from a network management perspective. Network maintenance will involve all the processes described in Section 3.6. Communications devices that double as tracking devices must be assigned to individual miners and logged into a database as would be any tracking device. Communications devices consume considerably more power than RFID tags. Where RFID tags may use non-rechargeable (primary) batteries that can last for years, communications devices will typically use rechargeable secondary batteries that need to be recharged often. Text communications devices may use primary batteries, but these batteries will typically need to provide much more capacity or be replaced more often than RFID tag batteries. Communications devices will typically provide battery status information to the user and network; whereas RFID tags will often require periodic inspection to ensure that they are operable.

4.3.7 Performance and Limitations

As discussed in Section 3.6, if a simple communications device is in contact with one access node, the location accuracy will be based on the location of the node and will be the radio range of the device or node, whichever is less. Techniques such as RSSI, TDOA, or time of flight (TOF) can be used to estimate a more accurate location. The device can be located even more accurately using the RSSI or TOF techniques if the device is in radio range of multiple nodes. These techniques are especially useful for high power nodes and communications devices with long distance coverage.

The accuracy, resolution and range of RSSI techniques were discussed in section 4.2.2.7. Although RSSI and TOF techniques offer enhanced tracking capabilities compared to simple RFID systems, they do require sophisticated algorithms to estimate the communications device's location. Location accuracy will be highly dependent on the number of nodes in radio range of the user device at any given time. Entry dimensions, bends, elevation changes, and obstructions can also impact system-reported location accuracy. The situation may be exacerbated during emergencies if one or more nodes are disabled. Detailed information about the network from the network monitoring software needs to be easily accessible, especially during emergencies, to allow surface personnel to assess the accuracy of system-reported locations using these techniques. Communications devices may offer "man down" signaling features for rescue/recovery situations that are not available with simple RFID tags.

4.4 Inertial Navigation

Inertial navigation has been used for many years to provide location and guidance information to aircraft, submarines, spacecraft, and missiles. In some cases, the Global Positioning System or GPS has replaced inertial navigation. GPS uses RF signals from orbiting satellites to generate location information. Unfortunately, GPS signals do not penetrate the earth and cannot be used in mines.

Unlike some electronic location systems, inertial navigation does not use RFID tags or RF signals to determine location. Instead, the system uses sensors to detect various types of motion, such as accelerations, rotations, or changes in the earth's magnetic field because of changes in position. Separate sensors for each type of motion are used to monitor each of the three coordinate axes. Modern sensors are based on micro-electromechanical systems (MEMS) which are quite small. MEMS technology has greatly reduced the size and power consumption of the system compared to previous large-scale mechanical systems. The small size has made wearable Inertial Navigation Units (INUs) a possibility.

The MEMS sensors monitor changes in parameter values, not the actual or absolute values. Hence, the system must be initialized and oriented at some starting location. As the miner moves from the starting location, the INU interprets the sensor readings, which must be integrated over time to determine the change in location.

Unlike reader-based or node-based tracking, an inertial navigation system provides a tracking capability that is independent of the infrastructure, such as fixed-location tags or nodes inside the mine. The concept is that a miner's location is determined solely by position changes relative to his starting location. However, the location data is in the INU worn by the miner. The information needs to be relayed to the surface and the MOC. Hence, the INU needs its own transmitter or it needs to have an interface to the miner's radio to be able to link into the backhaul system. The situation is similar to the Reverse RFID system (see Section 4.2.2) in that the location data is on the miner and needs to be transferred to the MOC via the communications backhaul system.

A number of issues must be resolved before INU technology can be used in the mine environment. INUs have difficulty maintaining accuracy for extended periods of use, such as a complete work shift. Small errors in measurement, known as "drift," accumulate over time and become a significant error after an extended period of use. The rates at which errors accumulate vary with the type of movement a miner performs. For example, walking and crawling produce errors at different rates. It is possible that in some cases, errors can be reduced or corrected by correlating the INU data with a mine map. In the mine environment, the miner's location is known to be restricted to entries and cross-cuts; he cannot be inside a pillar, for example, even though INU data may indicate that possibility.

Another issue for INUs is that vibrations due to mining machinery can couple to a miner; i.e., the miner shakes slightly because of the dynamic environment. The INU can misinterpret the shaking as changes in his position. The errors can accumulate over time and distort the miner's true location. With further technology development, it may be possible to greatly reduce these errors.

4.5 Tracking Technology Comparison

Currently there are three commercial technologies for tracking personnel in underground coal mines. While the hardware and software will differ from different vendors, there are some general capabilities and limitations that are inherent in the techniques used. The Table 4-1 compares the three techniques (RFID, Reverse RFID, and Node-Based) for a variety of attributes. Discussion of some of the table entries is given below.

Range values are approximate because radio propagation distances underground vary too much to categorize. However, node-based systems using handheld radios are not limited in transmit power to the same extent as systems which use tags and so are likely to have greater ranges than either RFID or Reverse RFID systems.

Installation complexity was judged on the need to access AC power and/or other engineering effort. Node-based systems rely on node spacing to form a continuous communications link to the surface and require more engineering effort to install.

A desirable feature of any tracking system would be a direct means to locate a miner by rescue team personnel. All three systems employ a transmitting device on the miner and could theoretically be used by a rescue team member to find a victim. At this time, only the node-based system has the necessary hardware.

Accuracy ranges for RFID systems are limited by the spacing of the fixed component. Reverse RFID systems have an advantage in this respect because tags are much less expensive and easier to install than readers (even though there is no theoretical reason why the two methods differ in accuracy). The accuracy of node-based systems that do not use RSSI or TOF technology is similar to RFID systems. The figure quoted in Table 4-1 assumes the nodes use RSSI and the miner is within range of two nodes.

System survivability is based on the vulnerability of the infrastructure components. The destruction of tags in a reverse RFID system does not impact the system as a whole.

4.5.1 Comparison Matrix

Table 4-1. Electronic Tracking System Comparison

Tracking Systems

Category	Feature	System Description		
		RFID	Reverse RFID	Radio Node-based[11]
Coverage & Range	Range[1]	500	500	1000
Coverage & Range	Expandibility[8]	Difficult	Easy	Medium
Coverage & Range	Density of AC powered devices in mine[2]	High	N/A	Medium
Coverage & Range	Density of tags(mobile or fixed)	Low	High	N/A
Coverage & Range	Data transmission method to surface[3]	Manufacturer specific	Existing comm system	Dedicated system
Installation	Design Complexity[4]	Moderate	Low	High
Installation	Labor intensity	Moderate	Low	High
Functionality	Centralized diagnostics	Yes	Yes	Yes
Functionality	Rescue team victim locator	Yes[10]	Yes[10]	Yes
Functionality	Tracking system accuracy[5]	500 feet	50 feet	100[12] feet
Functionality	Tracking system update interval	<60 seconds	<60 seconds	<60 seconds
Functionality	Component worn by miner	Tag	Reader	Radio handset
Survivability	Tracking system survivability[7]	Medium	High	Medium
Survivability	Battery life - Tracking fixed infrastructure	>24 hours	> 1 year	>24 hours
Survivability	Battery Life - Mobile component	> 1 year	>12 hours	>12 hours
Survivability	Number of battery locations[9]	High	High	Medium

Footnotes to Tracking Table

1. Line of sight transmit range. Estimates only and may vary with manufacturer and installation.
2. Density of AC powered tracking devices to achieve highest practical accuracy.
3. Method used to transmit location information to the surface.
4. Based on number of fixed components and difficulty of installation.
5. Accuracy is dependent on spacing of the infrastructure tracking devices - values are typical.
6. Depends on manufacturer.
7. Probability that tracking system components would survive a disaster.
8. Tracking system only.
9. Device batteries for normal operation or backup power.
10. Possible but not yet available.
11. Values assume system uses RSSI
12. Handset in contact with two nodes else accuracy is the same as node spacing

5. CT SYSTEM SURVIVABILITY, RELIABILITY, AND AVAILABILITY

5.1 General Considerations

Ideally, mines should install CT systems that can survive and remain operational, or can be quickly made operational following an emergency event to meet the requirements of the MINER Act. Examples of major emergency events are explosions, fires, roof falls, and inundations. The key requirement is to improve emergency response in the event of a crisis by having the communications system survive, or at least be quickly reconfigurable or repairable, so that there can be communications between miners and surface personnel. Failure of the system could be a result of the emergency event or a random failure of a critical component of the system.

Immediately following a significant emergency event in the mine, the power is shut down to prevent possible sparking or heating that might initiate a fire or explosion due to a possible buildup of flammable gases after the incident. Therefore, if CT systems are to remain operational, they will need to have a permissible backup power source.

In discussing the quality of a system, as opposed to its technical performance, the terms *survivability*, *reliability*, and *availability* are frequently used. In this tutorial, they are used in the context of systems engineering, i.e., the engineering discipline that considers complex systems in an organized, systematic manner. Each of these terms is discussed below.

Survivability is the ability of a system to provide essential services in spite of an accident. The definition does not require that the system perform exactly as it did before an accident, but that it does provide essential services after an accident.

Reliability can be defined in several ways depending on what the objectives are for the system. Reliability is frequently represented as a probability or as a percentage. Examples of reliability objectives are:

- The ability of a system to perform its specified functions.
- The ability of a system to perform without failures.
- The ability of a system to perform without repairs or maintenance.

Reliability has two aspects. *Basic reliability* refers to the ability of a system to operate without repairs or adjustments. *Operational reliability* refers to the ability of a system to perform and complete its functions satisfactorily.

Availability is the proportion of time a system is in a functioning state and able to provide its services. Availability also takes into account the time needed to repair a system, because while undergoing repair the system is assumed to be unavailable.

Survivability, reliability, and availability are measures of the quality of a system. They measure different but interrelated qualities that pertain to keeping a system useful. For example, redundant communications paths have been introduced as a technique to increase the survivability of a communications system. Adding a redundant path means adding components and complexity to a system which would increase the operational reliability, but may cause the basic reliability to decrease because of the increase in the number of components that could potentially fail. The availability could increase, decrease, or stay the same, depending on the impact on the time to repair and time between repairs.

Survivability and reliability will be discussed in Section 5.2. Availability is discussed in more detail in Section 5.3.

5.1.1 Objectives and Approaches

In consumer products, there may not be any specific requirements regarding survivability, reliability, and availability. Nevertheless, market forces will frequently drive the manufacturers to improve these qualities. For example, people will not intentionally purchase a car known to be unreliable. Or a consumer may be interested in purchasing a car known to have more safety features, making it more likely for a driver to survive an accident. Products that are considered life-critical, where the failure of the system may cause death or serious injury to people, will generally have specific quantitative requirements on survivability, reliability, and availability.

In the UG coal mining industry, the importance of CT systems has long been recognized. In particular, their importance in being operational following an emergency event has been recognized and is being mandated by MSHA. CT technologies used in surface applications are being adapted to the mine environment and new technologies are being developed. Methods to enhance survivability are being proposed and evaluated, such as combining different technologies, installing alternate communication paths, providing protection or hardening of components, and developing permissible batteries to serve as backup power supplies.

These topics are covered in more detail below. Section 5.2 begins with a discussion of anticipated emergency events; how CT systems might fail based on these events; how CT systems can be improved to potentially overcome failures from these events; and finally, how CT systems can be modeled to assess the benefits of various system options.

5.2 Survivability and Reliability

Examples of major emergency conditions likely to be encountered by CT systems in a coal mine fall into four overall categories:

- Explosions—Includes methane-only explosions and those aided by suspended or disturbed coal dust generally following an initial methane explosion.
- Fires—Includes the ignition of various types of fires, their progress and intensification, and likely distribution within and through mine passages. These fires can comprise those following mine explosions, those due to faulty equipment and those initiated through inadvertent human action.
- Roof falls, pillar bursts, and related ground control accidents—Includes situations involving falls or expulsion of significant amounts of debris from mine passage surfaces, such as roofs, pillars, ribs and other excavated underground areas.
- Inundations—Includes sudden inundation with high water depths and long-term, chronically wet mine passage surface conditions.

The associated environmental conditions produced can include high temperatures, high pressure waves and air velocities, collisions with rapidly moving or heavy objects, stress or load concentrations, and water damage. Cables and connectors, components, antennas, and external power supply or battery-charging systems are all susceptible to damage.

Based on NIOSH-sponsored contract work [Foster-Miller 2008], it was found that the majority of recent major coal mine accidents (1990-2008) were mine gas ignitions or explosions. Such explosions have resulted in the most significant instances of damage to CT systems and are being used to provide the basis for rigorous suggestions for hardening and redundancy improvements.

In most of the studied cases, at least some if not most miners underground were in their working sections when an accident occurred, though they were not always the victims of the events. In numerous cases, accidents were triggered in outby or remote areas and the victims at those locations were often killed instantly.

It should be noted that in no cases studied to date did communications or monitoring systems cause the initial ignition or explosion. Rarely were there secondary explosions and even when they did occur, there was no data found to indicate that the additional explosions were caused by these systems. It is fair to assume that the likelihood of these systems causing ignitions or explosions is small.

The study concludes that the forces likely to be encountered during coal mine accidents include:

- Explosions where peak blast pressures range from 45 psi down to 8 psi depending on distance from the blast and whether the exposure is direct or indirect. Peaks from methane-only explosions are typically on the order of 1/3 second. With coal dust involved, these peaks will last longer. The resultant explosive forces leave very little equipment intact in the path of the explosion.
- Fires, when fully developed, can range up to 2000-2500+°F. In addition, roof temperatures above localized fires can range up to 400-1000°F.
- Roof falls, pillar bursts and related ground control accidents can leave a mass of debris. Each 1000 cubic feet of rock debris can weigh as much as 40-80 tons. Depending upon the size and shape of the fallen debris, a floor load impact of 1500-3000 lb/sq ft (10-20 psi) may result; in fact, if the load is concentrated the impact can be as great as 250-500 psi.
- Water inundations, assuming a water depth of 200 ft can result in a 100 psi pressure for up to 200 hours.

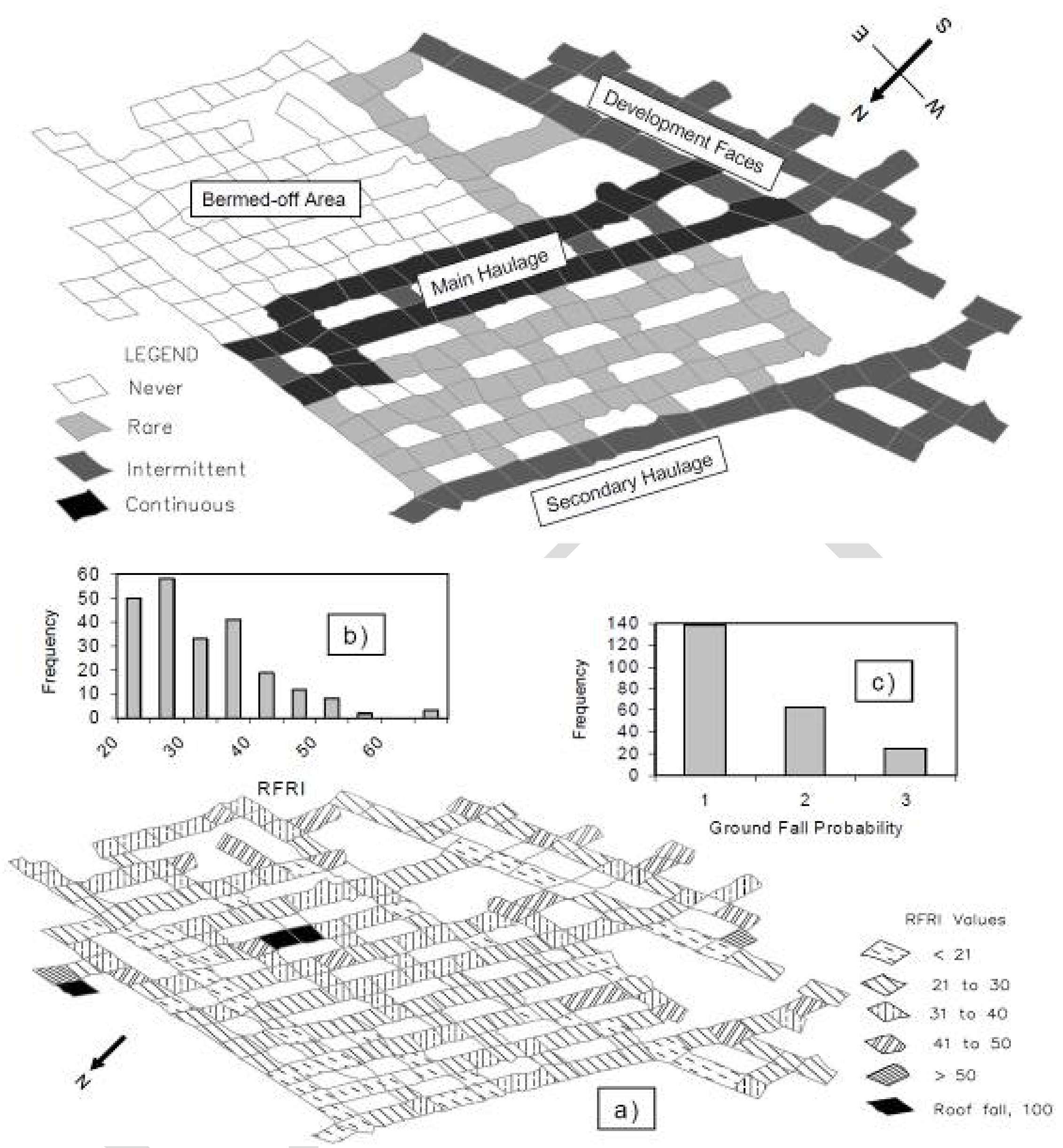

Figure 5-1. Example of a Miner Activity/Travel and Roof Fall Probability Map

To address some of these issues, the [Foster-Miller 2008] study notes that it may be possible to mount pagers and other smaller equipment in the rib. It is also possible to locally protect cables in crosscuts by fixing protective plates over the cables and into the roof. The probability of roof falls for specific areas of the mine should be determined using a roof fall rating index along with a probability map showing the areas where the miners are working and traveling throughout the mine as shown in the example in Figure 5-1.

5.2.1 Survivability of CT Systems

It should be noted that it is highly impractical, if not impossible, to design a CT system such that the entire system could survive any and every imaginable emergency event. There will always be an event that is too large, too energetic, or too devastating for the parts of the CT system in the immediate vicinity of the event to survive. The goal of the system design should be to ensure that the parts of the CT system that are not in the direct vicinity of the event remain operational. Given the linear nature of coal mines, systems that can use alternate communications paths out of the mine can help ensure this type of survivability. The objective of this discussion is to provide a knowledge base and tools that can be used to consider tradeoffs to determine the best CT approach for the constraints of a given mine.

Survivability is defined as a system's (component, cable, antenna) ability to continue to provide services considered essential and operations-critical in spite of either accidental or malicious harm. For coal mining CT systems, survivability may be considered the ability of the system to provide coverage in critical areas of the mine after an emergency event such as an explosion, fire, roof fall, or water inundation.

The key questions a mine operator must be concerned with when considering system survivability are:

- With respect to the origination point of the event, which parts or components of the system are most likely to survive and continue to function post-event?
- Assuming that some components will be damaged and non-functional, how will the loss of those components affect the coverage of the system?
- Post-event, will the system still provide coverage to critical areas of the mine?
- How may system coverage in critical areas be better protected and preserved post-event?

A survivability assessment will also take into account the configuration of the system, including the proximity of those components to potential origination points of an explosion, fire, roof fall, or water inundation.

The survivability of the system also depends upon which components are still functional after the emergency event and which are not functional. In the mining environment, the survivability of the individual components will be dependant upon the locations of the components with respect to where the event originates. For example, components located directly next to an explosion site will most likely not survive. However, components that are at a very great distance from the explosion site will most likely survive, especially if they are not located directly in the line of the pressure wave. Components not directly next to the explosion site, but that are in line with the direction of travel of the blast pressure wave may or may not survive, depending upon the proximal distance, how that component is installed, and whether the component has been hardened or otherwise protected.

The ability of a component to survive an event will increase if the appropriate protection has been implemented. The extent to which the component is protected from adverse harm will help determine whether or not that component is likely to survive. Also, components that are at higher risk to damage will benefit from additional protection. For example, a coal mine operator may consider implementing additional protections for components located close to the working face, where risks for explosions are greater than in a travelway. Also, the degree to which the component is protected against an emergency event (i.e., heat from fire, pressure from explosion, crushing from roof fall) should be considered during the installation of the system.

The metric that is most useful for determining survivability of a communications, tracking, or atmospheric monitoring system is coverage. Therefore, a coal mine operator should take into consideration how much system coverage would be potentially lost if the more vulnerable components of the system were to become non-functional. The result of this analysis may determine the system configuration and component placement in the mine.

The ability of a component to survive an event is based upon several factors. Examples of these are:

- Amount of hardening of the cable or component.
- Whether the component is in a fireproof/crushproof box.
- Mounting techniques used on the cable or component.
- Orientation of the cable or component with respect to the expected line of force from a blast.
- Burial of the cable or component.
- Whether the cable or component is protected with sandbags.
- Whether the cable or component is recessed into the rib.

In addition to improving survivability of system components, there are also other methods to improve survivability of system coverage. For example, a mine operator should try to place more critical components of the CT system away from areas that are at higher risk of experiencing an event. By doing this, the critical components will be more likely to survive an emergency event and preserve overall system coverage. Also, having redundant communications in less vulnerable areas of the mine (an adjacent entry, for example), may preserve paths of communication.

5.2.2 Reliability of CT Systems

As an engineering discipline, reliability is known as an area of study aimed at determining, evaluating, and modeling the ability of a system to perform its function or functions under specified conditions and parameters. In standard applications, reliability is expressed as a probability that the system will perform its expected functions within certain operating environments and times.

However, for UG coal mining CT systems, the mine operator has additional considerations besides the ability of the system to function as specified. The mine operator needs to know the likelihood that a system will function in critical areas of the mine (e.g., the working face, the travelways). If the system experiences any failures, the mine operator needs assurance that those failures will have minimal impact on coverage in critical areas. This issue is best summarized as a “coverage” assessment. Therefore, the mine operator is most interested in knowing the following:

- Where is there system coverage?
- How reliably will the system provide that coverage?
- Due to the configuration of the system or reliability of the components, how reliably will the system provide coverage in critical areas of the mine?

A system coverage assessment will take into account the reliability of each section of the system. Reliability of each section is determined by the Mean Time Between Failures (MTBF) data of the section's components and the component configuration. A mine operator should collect this data from the system's manufacturer.

The communications coverage responsibility of each section is determined by the components and configuration within that section. In some systems, losing functionality of an outby section of the system means that all sections inby that lost section are also useless for communications. Therefore, during an assessment, the more coverage the section is responsible for, the more critical that section is to the overall ability of the system to provide coverage.

Some areas of the mine are critical for communications, and the ability of the system to provide reliable post-accident communications coverage in those areas is paramount. In certain areas of the mine, such as the working face, having coverage is much more critical than seldom used areas of the mine. A coverage assessment of the mine would include determining where these critical areas are located and configuring the system to have highly reliable coverage performance in those locations.

The reliability of the system is determined by:

- Reliability of each of the components.
- Reliability of each component's interconnections (cables, connectors).
- Configuration of the components, especially when considering series (in line) or parallel (redundant) configurations.

Reliability of the system and components are measured in terms of MTBF data, which assesses the ability of the system to perform without failure, within specified times and under specified conditions. MTBF is expressed in units of time and should be available from the system manufacturer.

The system manufacturer determines MTBF in several different ways, including testing, analysis of historical data, theoretical modeling or simulation, and comparison to similar systems or components. Whatever the means of collecting the data, the methods used by the manufacturer should result in data representative of the system's ability to perform its desired function (i.e. voice communications, tracking information, data transfer, atmospheric monitoring) in the operating environments and conditions expected in actual use. Therefore, MTBF data collected from testing the component on a bench in a lab might not be necessarily representative of the component's performance in the mine, which, in some cases, may be a much more caustic, humid, and/or hot environment.

For systems lacking sufficient historical data or comparisons against which to evaluate, testing is a popular method by which manufacturers determine reliability. Reliability tests are commonly divided into various categories, including environmental (i.e. humidity, resistance to chemicals, salt spray), mechanical (i.e. vibration, mechanical shock, pressure), and electrical (i.e. overvoltage, reserve voltage, electric static discharge).

To a certain point, the reliability of the components and system is limited by the system's design. However, through *path redundancy*, *coverage redundancy*, and careful consideration of the *system configuration*, mine operators can improve the ability of the system to reliably cover critical areas.

Path redundancy of components or sections of the system allows for alternate success paths for communication. For single-path systems, one break in that path will render the rest of the system inoperable. However, when multiple redundant paths exist, then communication signals may travel along an alternate parallel path to reach their intended endpoint even though the main path may be cut. *Coverage redundancy* refers to overlapping coverage sections, so that if one component or portion of a system becomes non-functional, that area will still be covered by another component or portion of the system. Lastly, the *system configuration* may help to increase reliability. Certain areas of the mine may be more active and equipment may be more likely to be damaged in those highly active areas when compared to less active areas of the mine. It would therefore be wise to place critical sections of a system away from these highly active areas.

A pre-event coverage reliability assessment allows the mining operator to determine overall, day-to-day, system coverage based upon the reliability of each section. Due to the probabilistic nature of MTBF, the pre-event reliability assessment determines the likelihood that the system will provide the required coverage over a given amount of time. However, it is not assumed during this type of assessment that more than one component or portion of a system will be non-functional at a time.

5.2.4 Techniques to Enhance Survivability and Reliability

There are several approaches to consider when increasing the survivability and/or reliability of a CT system. Three different techniques are discussed in this section: hardening, redundancy, and reconfiguration.

5.2.4.1 Hardening Techniques

Hardening is a technique to protect equipment from explosive forces, inadvertent collisions, rock falls, and possibly fires. Hardening reduces the potential for damage to the CT system, which thereby increases its survivability. Hardening may also increase the time required to repair inaccessible parts, which would decrease the basic reliability. However, the parts may become less susceptible to certain types of failure, which would help to increase reliability.

Cables and Connectors

Use of reinforced cables, conduit, supplementary cable shielding, and/or in-floor trenching for cabling is a technique to help protect the cable from pressure waves and flying debris. Encasement, shielding, or recessing of component enclosures may also help minimize damage from explosive blast forces and flying debris.

The cabling and electrical components of typical CT systems are normally hung and strung through mine entries without special provisions for physical protection, other than mounting them as high as reasonably possible to reduce snagging by personnel, vehicles, or other equipment. While the cabling, wiring, or electrical “boxes” have some modest degree of strength, the combination of being the usual industrial configuration, plus a “hanging” style of installation, make them quite vulnerable to blast and debris damage.

Common wiring or cabling practices make hardening of these system components difficult to achieve. Often the wiring or cable is simply hung by a tie or wire hangar from a convenient roof bolt plate, light, or rib-mounted bracket, using substantial slack to prevent over-tensioning

Figure 5-2. Hanging Conductors from the Roof

through earth movements, thermal excursions, and repositioning of electrical components. Often manufacturers recommend slack in the 5-10% length range. This may result in a substantial droop between hangars, meaning that an air blast of over a few psi could sever the wire or cable. A typical installation seen in mines is shown in Figure 5-2.

Cables are highly susceptible to damage from forces and flying debris where they cross open areas such as where they pass in front of crosscuts. In fact, it may be more likely for the cables to fail than the devices connected to them. Sometimes the location that provides easiest access is the most exposed to destructive forces.

One installation consideration to improve the protection of the system is installing cables on an upper rib area rather than the roof. This is not optimal for coverage, but may be best for cable protection. When the cable is located in the center of the roof, there may be a greater chance for accidental damage from vehicles and other equipment. The upper rib area is considered to be better guarded by location.

Installing cables with slack and/or service loops is another installation consideration. This is a multipurpose practice. The slack promotes better communication coverage, and the service loops allow equipment placement to be adjusted without re-wiring. These practices also help the cable to be more compliant in the case of small rock falls and other incidental contact.

Cables can be inserted in a protective conduit. Mechanically reinforcing cables and the associated components (e.g., thicker, stronger covering, encasement in conduit or pipes, etc.) is especially important in critical areas of the mine. Investigating various grouting and encasement materials to protect interconnecting cabling may increase the chances that it will survive adverse conditions.

When installing a system, one should also consider hanging communication, data, and power cables on the roof or rib, laying the cables on the floor, or burying them using trenching techniques. For trenching, it is important to consider when the trench can be dug after mining, how deep and how wide the trench should be, the type of filler material to be used, the effect of the trench on the stability of the mine floor, and how to locate and repair or replace the buried cables if needed. Installing redundant cables in separate entries also enhances survivability.

Figure 5-3. Examples of Trenching Conductors

Replacing a trench with the material taken to construct it is the simplest design. However, using concrete, foam, or other types of material may allow for better propagation of radio signal depending on the system using it. Figure 5-3 provides a few examples of how to protect conductors using conduit and trenching cover techniques.

These are only a few examples of various kinds of trenches. These methods do not consider the wide variety of ground conditions in various mines, nor all types of floor material.

Burying the conductor at certain depths still allows for communication at both UHF and MF frequencies. Figures 5-4 and 5-5 show examples of how 450 MHz and 472 kHz signals propagate in a 1000-2000 foot long mine entry when conductors are buried versus conductors being hung in the center of the entry. Burying conductors in a trench with conduit may be very beneficial to the survivability of the conductor under vertical crushing forces and have minimal effect on the propagation of radio signals on the conductor.

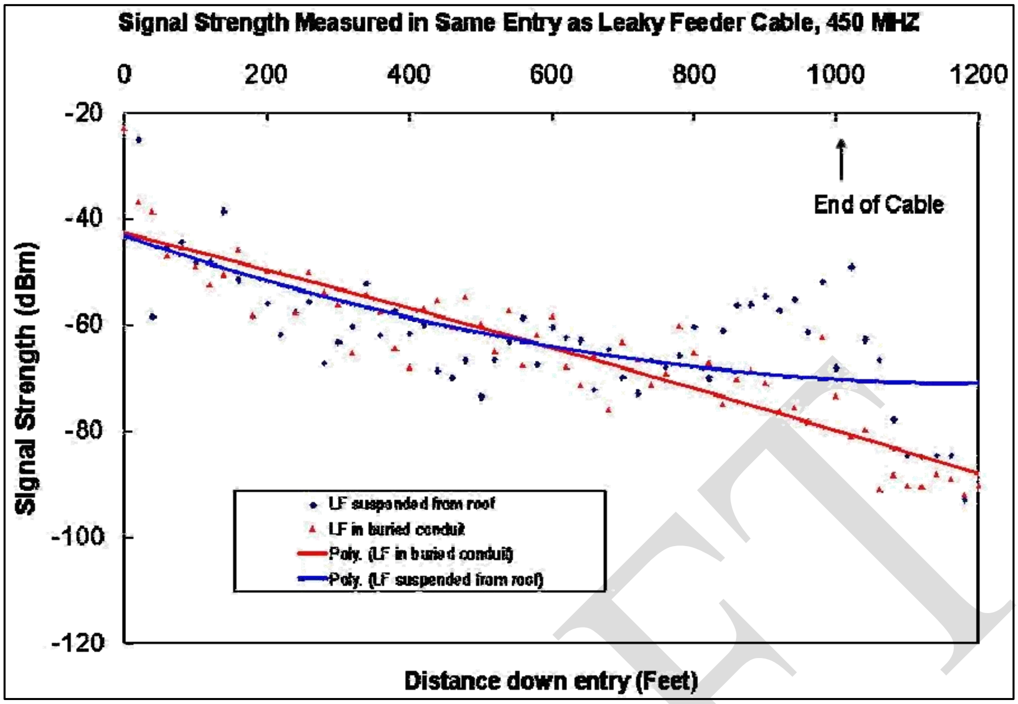

Figure 5-4. 450 MHz Signal Propagating Down a 1000 foot Leaky Feeder

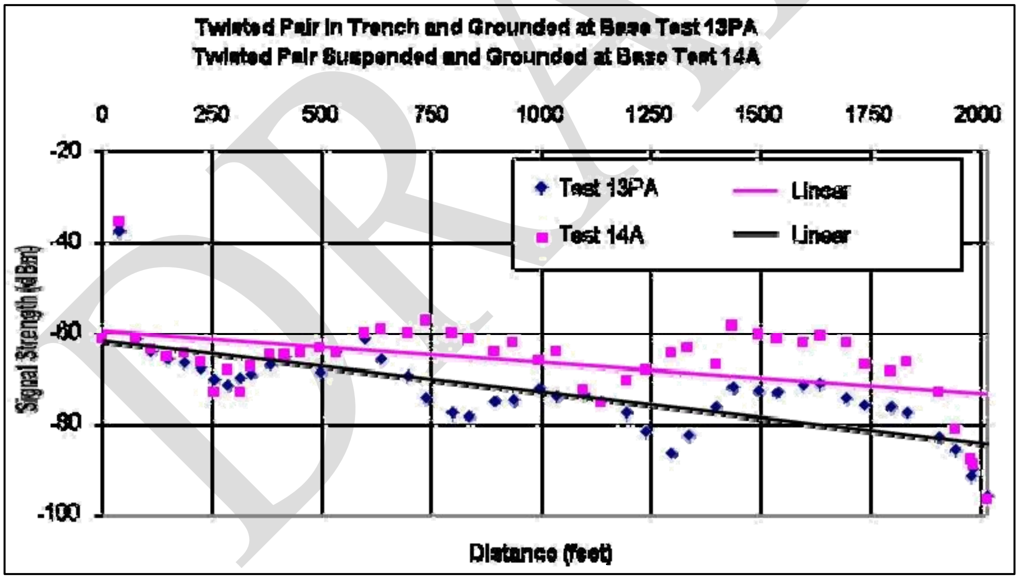

Figure 5-5. 472 kHz Signal Propagating Down a 2000 foot Twisted Pair

The results of this simulation are only examples of possible trenching depth that may be used to provide for extra protection for certain conductors. These examples are not exposed to the same dynamic loads over time that a mine environment may contain. In some cases, trenching may not be an option. Also, certain conditions may make hanging conductors the only feasible option.

Burying a conductor in key areas prone to damaging forces is another important consideration. This approach limits the amount of trenching while also guarding critical areas of the mine from perpendicular forces. When installing conductors, it is vital to understand the types of forces that may result from an event and their impact on those conductors.

Conductors can be protected a variety of different ways. They can be trenched in different types of conduit or placed in strategic locations along an entry depending of the type of communication system and trenching conditions. To demonstrate, Table 5-1 shows examples of how 14-guage solid twisted pair page phone wire reacts when subjected to different static pressures in various depths.

Table 5-1. Reaction of Twisted Pair Cable to Static Pressure

Test no.	Trench Cover Material	Depth of conductor in Trench	Load Pressure	Result (damage to insulation)
1	Minus 5/8" crushed gravel	3 inches	800 psi	Significant
2	Minus 5/8" crushed gravel	3 inches	375 psi	Minor dents
3	Minus 5/8" crushed gravel (wet)	3 inches	800 psi	Significant
4	Minus 5/8" crushed gravel	6 inches	800 psi	Minor abrasions
5	Minus 5/8" crushed gravel	6 inches	375 psi	No damage
6	1/16" sand	3 inches	800 psi	No damage
7	3/8" pea gravel	3 inches	800 psi	Minor dents
8	Minus 5/8" crushed gravel	3 inches	800 psi	Significant
9	Minus 1" water washed gravel	3 inches	800 psi	Minor dents
10	Minus 5/8" crushed gravel	1 inch	1340 psi	Wire failed

During an explosion or high pressure wave, forces propagate down the entry like a waveguide. At tunnel intersections, these forces come into contact with conductors strung either parallel or perpendicular to the entry. Perpendicular forces are capable of destroying almost any conductor, but when the same conductor is subject to the same forces parallel to it, the damage can be significantly reduced. Figure 5-6 shows an example of leaky feeder cables subjected to a more than 120 psi pressure wave and shows the effects on conductors that were parallel compared to perpendicular to the pressure wave.

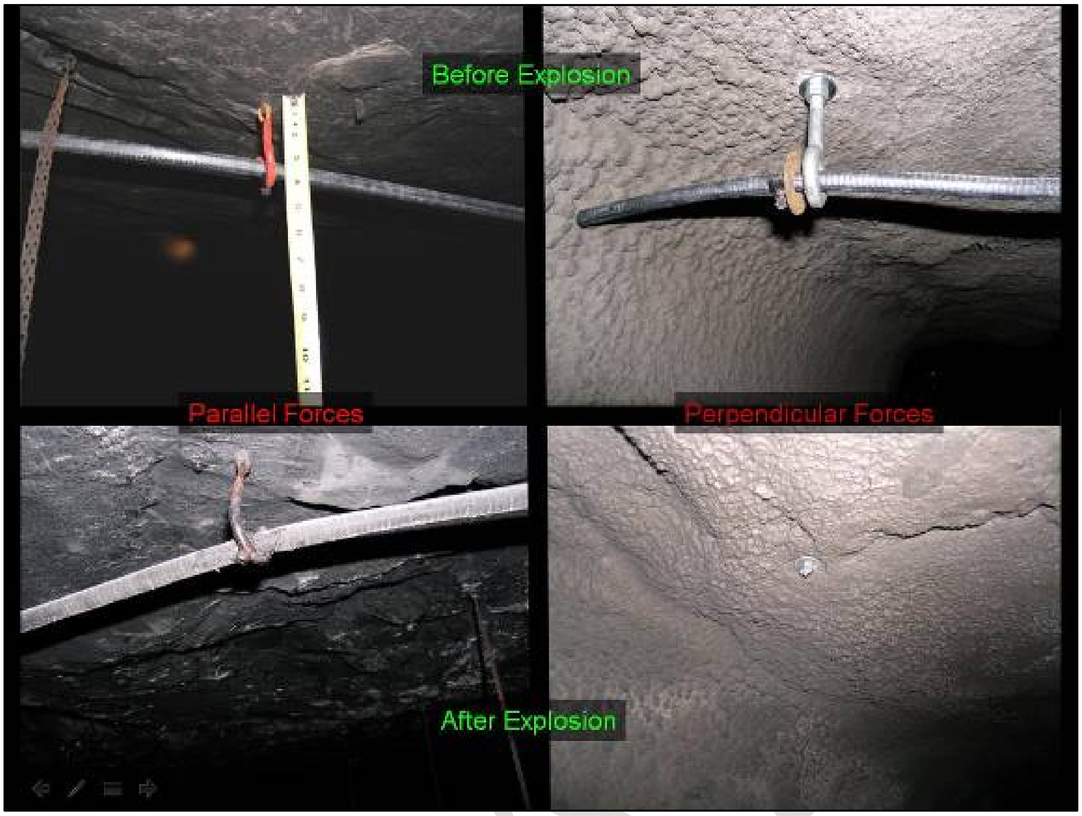

Figure 5-6. Examples of Parallel Versus Perpendicular Explosion Forces on a Conductor

Components

The primary communications system for most mines consist of hard-wired mine paging phones. Hence, these systems still dominate the industry and hardening of them will be important until other communications systems are more widely adopted. Communication equipment (pager phones) on longwall faces would likely be mounted in a similar location as the control box (hanging down from under the shield canopy) and would be vulnerable to impact from flying coal from face outbursts. Exact locations and mounting techniques should be explored with longwall equipment manufacturers.

Coal outbursts along longwall faces can inflict considerable damage to equipment along the face. As these accidents demonstrate, consideration must be given to hardening longwall face pager phones and any atmospheric monitoring system (AMS) equipment located along the shields.

Any communications equipment not directly under vertical roof or rib falls occurring along the ribline would likely not be vulnerable to damage. Rib and roof falls in longwall headgate entries near the faces are most likely to occur along the riblines rather than in the center of the entries due to loading from the retreating face.

Components are highly susceptible to damage from forces and flying debris where they cross open areas such as where they pass in front of crosscuts. Any device subjected to overpressures of at least 2 psi would be blown away from the source of the explosion unless securely fastened or anchored. At higher explosive pressures, hardening to withstand an explosion may be impractical both physically and in terms of cost. However, it may be feasible to harden critical equipment at the lower explosive pressures so that if the equipment resides on the fringes of the explosion it will survive. To better withstand the pressure waves it may be that all components should be pressure tested to 5 psi at a minimum. XP enclosures are typically very robust and there is little that can be physically hardened on these units. However, drop and vibration tests may be helpful at identifying potential weaknesses.

Components can also benefit from the same installation techniques as used with cables. They can be recessed in a wall, floor, or roof, and/or a protective shield can be installed over them. They can be placed in cut-outs and cross-cuts to avoid perpendicular forces. For example, amplifiers and power couplers can be located in blind cross cuts rather than open intersections. This moves the components out of the main path of travel to help prevent incidental damage. Also, being located in the cross cuts can reduce the level of blast pressure the equipment experiences during an explosive event.

Some wireless nodes may be installed in cross cuts; however, in some cases the antennas must be installed in intersections and travel tunnels to ensure proper propagation of the RF signals.

Wireless nodes should be protected in enclosures similar to NEMA4X/IP66 (dust tight, protected against jets of water, and corrosion resistant).

Coal outbursts along a longwall face can inflict considerable damage; hence, the CT antennas must be carefully located and mounted. Rib and roof falls in longwall headgate entries near the faces are most likely to occur along the riblines rather than in the center of the entries due to loading from the retreating face. This would suggest that antennas in headgate entries should be in the center of the entry away from the ribs. Small antennas used for frequencies greater than 900 MHz, could be enclosed in an RF-transparent dome of Lexan or some polycarbonate material.

Redundancy

Redundancy is one method of increasing survivability. An example of redundancy is installing an independent leaky feeder system in an entry parallel to one already having a leaky feeder system.

Redundancy methods can include one or more of the following techniques:

- An alternate communication path that consists of backhaul cabling that is looped back through another portal, shaft, or a borehole to the surface. This can be applied for leaky feeder and also with network systems utilizing backhaul cabling.
- Parallel paths assume that there are two independent conducting paths placed in two separate locations, i.e., cables and components running down two parallel entries, so that if one cable or component is severed or damaged the second system can maintain communications.
- Wireless mesh systems deploy a robust, self-configuring, self-healing capability of the nodes, enabling the system to reconfigure itself by rerouting (bypassing a damaged node) if one or more of the nodes fail. This can be accomplished by overlapping coverage of the nodes; however, this is often difficult to accomplish in the mine environment due to the room and pillar configuration.

Some hybrid systems are installed in a configuration so that wired and wireless systems co-exist in separate entries. Any weaknesses in one system may be compensated for by the other system.

Leaky feeder systems can also be installed to provide redundancy. This requires two systems and there is the cost of an interconnecting fiber optic cable; however, suppliers have found that even in normal operation, the increased reliability is sufficient to help offset the cost.

Power Supplies

It is imperative that CT emergency power systems work reliably when required. The reliability of emergency power systems may be analyzed using a methodology similar to that used for CT systems.

The first step of the methodology, is to define the system. The system engineer shall identify the parameters, specifications and requirements against which the performance of the emergency power system will be analyzed. While some of these parameters may be the same as in routine use CT systems, other parameters may be different. For example, in a routine use, certain components of the system may not need to be intrinsically safe. However, in emergency power systems, the entire mine may potentially be explosive and therefore the entire emergency power system must be intrinsically safe.

Just as is the case when analyzing other underground CT systems, batteries may also be evaluated using the proposed methodology. It is recommended that a common set of parameters and requirements be created to evaluate batteries. Once established, reliability and survivability of batteries may be determined through data collection of reliability and survivability against those parameters.

Communication Paths (Protection to the Surface)

Alternate communication paths (ACPs) involve communications and/or electronic tracking system links to the surface at locations that are remote from the MOC. ACPS may use a specially drilled bore hole, separate air shafts or any other method of access to the surface separate from the main entries. Ideally, there would be an RF communications path on the surface from an ACP back to the MOC, so that information between the ACP access point and the MOC would be relayed with a minimum of delay. In the optimum system, messages and information would be relayed automatically. However, the message relay could be done manually by operators stationed at the ACP surface egress point (i.e., any message to/from the ACP egress point is received and repeated by the operator). The link should only be required in a rare emergency in which the normal backhaul has become inoperable. Measures should be taken to ensure the ACP access point is easily reached and periodically verified that it is operational. CT systems that utilize an ACP must be capable of reversing the direction of message flow, at least, over a portion of the backhaul system.

Figure 5-7 shows an example of an ACP layout with the bi-directional area of communications. The green line shows the normal way that communications traffic will flow. The red line shows the alternative emergency communications way if the normal communications were disrupted by a blast, fire, or roof fall in the mine. There are two ACPs within this system. Depending on how far the miner is in the mine he can use either one of the ACPs. When the communications path reaches the open surface there is a common backhaul device (CBD) at each location.

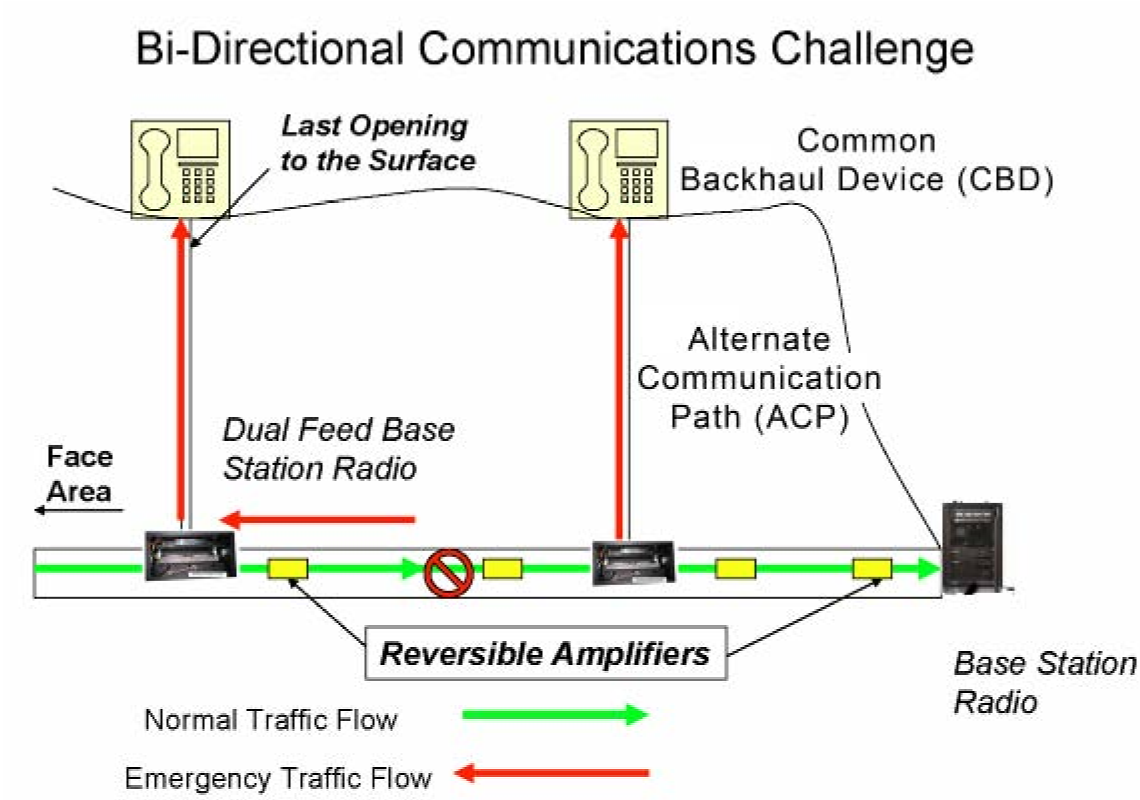

Figure 5-7. Bi-directional Communications Challenge

Hardening and Redundancy Considerations for Electronic Tracking Systems

Most tracking systems share the communication backbone with the communications system, so redundancy and hardening improvements made to the communications system also directly affect the tracking system

The tracking systems redundancy can be improved by adding more “reference points”. Depending on the type of tracking system this “reference point” may be an RFID reader, an RFID tag, or a Wireless Access Point. The more tracking “reference points” installed in mine, the more accurate the system, plus it allows the system to provide tracking information even if one of more of these “reference points” is lost.

Hardening and Redundancy Considerations for Atmospheric Monitoring System

Manufacturers have indicated that there are no industry requirements for a redundant AMS system. Therefore mine operators are not requesting redundancy. Most dedicated AMS manufacturers do not offer redundant “loop back” for their systems. Some leaky feeder and wireless systems do offer add-on AMS equipment which would then benefit from those systems redundancy.

AMS sensor manufacturers have indicated that it is difficult to harden sensors, as they need to be able to freely sample the air, and be placed in high use areas of the mine.

True mine-wide AMS systems do not yet exist in many mines so it will be important to protect those systems that detect fires and other hazardous, flammable, and noxious gases along beltlines until more complete systems are widely adopted.

Reconfiguration

Reconfiguration refers to the ability to create redundant routes in a network by adding nodes or changing to a different communications technology. An example of the latter is switching channels on a handheld radio after a leaky feeder becomes inoperable. The new channel would link the handheld radio to a media converter device interfaced to the hardwired pager phone. This action creates a redundant path, but only after some feature of the system is reconfigured. The redundant path increases the survivability of the system. Similar to the redundancy discussion earlier in this chapter, the increased number of components will decrease the basic reliability. However, the additional message routes will increase the operational reliability.

5.2.5 Calculation and Modeling

The military and automotive industries are examples of institutions that have well-established reliability programs and standards. Over the years, they have developed powerful methods and tools for calculating survivability and reliability of systems. These methods and tools must be tailored for use in the mining industry and CT systems in particular.

All the tools require developing a model to describe the CT system. For example, for each communications system discussed in Chapter 3, a block diagram was presented. The block diagram is one type of model of a system. It is possible to calculate reliability numbers that can be associated with each block of the system. A systems engineer can then evaluate how changes to a particular block can affect the overall system reliability.

For example, Figure 5-8 shows a block diagram of a leaky feeder system with a splitter, after which there are two leaky feeder cables in parallel, one terminated with an antenna and the other with a termination unit. Two separate radios are able to link to either of the two leaky feeder cables. The reliability of each component is shown as a percentage number below the block.

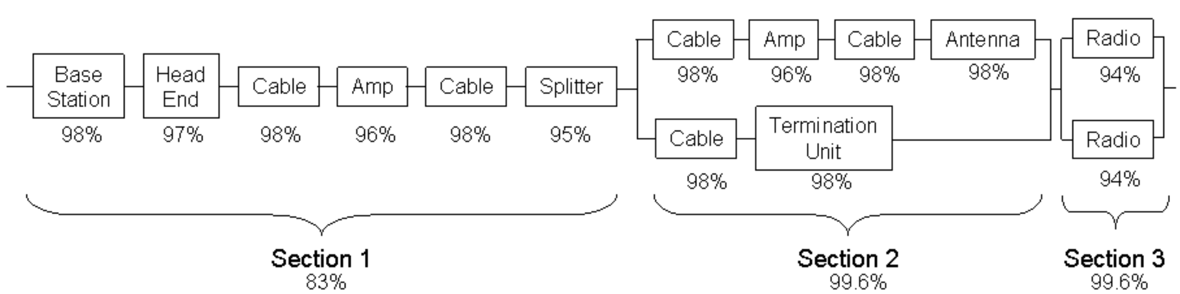

Figure 5-8. Block Diagram of Portion of Leaky Feeder.

All the components in Section 1 of Figure 5-8 are in series. Hence if one component fails, the entire system fails. The basic or, in this case, the operational reliability of Section 1 is found by multiplying together the reliability of the six components:

Section 1 reliability = 0.98 * 0.97 * 0.98 * 0.96 * 0.98 * 0.95 = 0.83 or 83%.

Notice that the reliability of a series system is less than any of the components.

Section 2, inby the splitter, shows the two leaky feeder cables as parallel components. As redundant cable systems, it assumes if one cable fails, the other will maintain the operations. The operational reliability of components in parallel is found by adding the reliabilities of the parallel systems and then subtracting the product of the reliabilities of the parallel systems.

Reliability of upper cable = 0.98 * 0.96 * 0.98 * 0.98 = 0.90

Reliability of lower cable = 0.98 * 0.98 = 0.96

Section 2 reliability = 0.90 + 0.96 – [0.90 * 0.96] = 0.996 or 99.6%.

Notice that the operational reliability of systems in parallel (upper cable is in parallel with lower cable of Figure 5-8) is greater than either system alone, i.e. 99.6% is greater than 90% or 96%.

A similar analysis can be performed to get a reliability percentage in Section 3 of 99.6%.

The total operational reliability for the system shown in Figure 5-8 is the product of the reliabilities of each section:

Total system reliability = 0.83 * 0.996 * 0.996 = 0.82 or 82%.

With this type of model, it is possible to perform “what if” types of analyses. For example, if the lower cable with the termination unit were not part of the total system, the reliability of the system would become:

The total system reliability without the lower cable = 0.83 * 0.90 * 0.996 = 0.74 or 74%.

The reliability with the redundant or parallel system has a higher operational reliability of 83% compared to the system without the redundant path, 75%. This quantitatively illustrates the benefit of having a redundant communications system.

Similar modeling and calculations can be established for determining survivability.

5.3 Availability

Reliability accounts for the time a system or component operates without failure; however it does not account for the time required to repair a failure. Availability is defined as the probability that a system is operating properly when it is needed. Thus, availability is the probability the system has not failed or is not undergoing repair when it needs to be used.

A simple equation for determining availability is:

$$availability = \frac{uptime}{(uptime + downtime)} \quad . \qquad (1)$$

In a more rigorous discussion, the Mean Time Between Failures (MTBF) is used by a manufacturer to describe the mean (average) time a system or component is expected to operate before a failure occurs. Similarly, the Mean Time To Repair (MTTR) is the average time taken to repair a failed system or component. With these definitions, the availability can be expressed as:

$$availability = \frac{MTBF}{(MTBF + MTTR)}. \quad (2)$$

From equation (2), it can be seen that a system could have a low reliability (MTBF) and still have a high availability, if the MTTR is small relative to the MTBF. The MTTR can be estimated from knowledge of the accessibility of spare parts, and how the repair of the system is manned. For example, is the repairman onsite 24 hours a day or only during regular working hours, or possibly only on-call?

Availability is easily understood by considering downtime. Availability is typically specified in nines notation; a 3-nines availability corresponds to a 99.9% availability. Table 5-2 shows the relationship between availability and downtime.

Table 5-2. Relationship between Downtime and Availability

Availability	Downtime
90% (1-nine)	50,000 minutes/year
99% (2-nines)	5,000 minutes/year
99.9% (3-nines)	500 minutes/year
99.99% (4-nines)	50 minutes/year

System availability may be calculated by modeling the system as an interconnection of parts in series and parallel. Figure 5-9a shows two systems or components in series. The parts are considered to be connected in series if a failure of either leads to the system becoming inoperable. Figure 5-9b shows two systems or components in parallel. The parts are considered to be connected in parallel if a failure of either leads to the other taking over the operations of the failed part.

The availability of a system composed of Parts X and Y in series is the product of the availabilities of the two parts. So if the availability of Part X is 99% (downtime = 5,000 minutes per year, or 83 hours) and Part Y is 99.9% (downtime = 500 minutes per year, or 8.3 hours), the overall availability for the series combination is 98.9% (downtime = 5,700 minutes per year, or

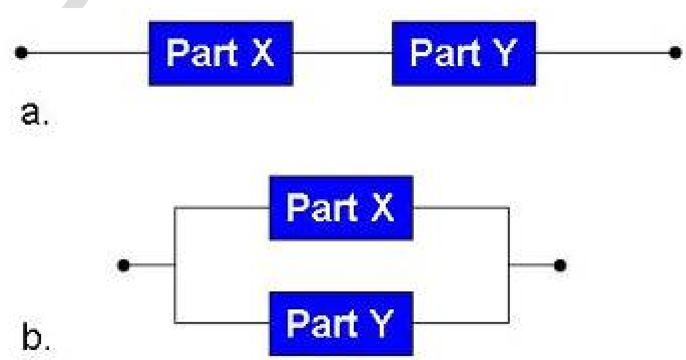

Figure 5-9. Components Connected in a) Series and in b) Parallel.

96.4 hours). When parts are combined in series, the overall availability of the combination is less than the smallest availability of the individual parts.

If a system is composed of Parts X and Y in parallel, the system is operational if either part is available. Hence, the combined availability is calculated as 1 – (the probability that both parts are unavailable). Using the availabilities given for the parts in the example above, the overall availability for the parallel combination becomes 99.999% or 5.2 minutes per year. When parts are combined in parallel, the overall availability is greater than the highest availability of the individual parts. This is a very powerful method making highly reliable systems, and illustrates why critical systems are designed with redundant components.

6. CT SYSTEM SAFETY

One of the goals of the MINER Act is to increase mine safety by providing two-way communications between miners and surface personnel, especially following an accident. In addition, electronic tracking is required to allow surface personnel to determine the current or, at least, immediately pre-accident, location of all underground mine personnel. The CT systems being proposed must be assessed to ensure they do not introduce new hazards. Some of the areas of concern are the permissibility in a potentially explosive atmosphere; radiation hazards to personnel, fuels, and blasting caps; and electromagnetic compatibility between RF emitting systems. These concerns are individually addressed in the sections below.

6.1 Permissibility

Ventilation is required in coal mines to prevent the build-up of methane gas and reduce coal dust levels. However, following certain emergency situations there is concern that the ventilation flow may have been compromised. For example, a roof fall or water inundation may obstruct air flow resulting in a build-up of methane or other flammable gases, creating a potentially explosive or flammable atmosphere. The electrical power to the mine is shut down for reasons of safety. Under such circumstances, CT systems can only be allowed to remain powered if they are MSHA approved as *permissible*, i.e., able to safely remain electrically powered in a methane-air or coal dust atmosphere.

There are two methods by which the MSHA permissible designation can be obtained. For the first method, the equipment is installed in an *explosion-proof enclosure*. For the second method, it has to be shown that the equipment, even if it fails, cannot release sufficient energy to initiate an explosion or fire. In the latter case, the equipment is classified as *intrinsically safe*. These two permissibility designations are discussed in detail below.

Gas or dust explosions and fires are some of the greatest hazards faced by underground coal mine workers. Methane gas is released during the mining process and accumulates in areas that are not well-ventilated. Coal dust accumulations pose a fire hazard, and coal dust can form explosive dust clouds when entrained into the air. Methane-air ignitions or explosives can disperse coal dust layers into the atmosphere that subsequently ignite and propagate as powerful explosions.

The term permissible refers to equipment that meets specifications for the construction and maintenance of such equipment, and ensures that such equipment will not cause a mine explosion or mine fire [30 CFR 75.2]. Electrical equipment that is normally exposed to methane or coal dust inby the last open crosscut [30 CFR 75.500], or within 150 feet of pillar workings or longwall faces [30 CFR 75.1002], or in return entries [30 CFR 75.507], must be permissible. 30 CFR 75.313 requirements for electrical equipment apply when main mine fan stoppage occurs with persons underground. 30 CFR 75.323 requirements for electrical equipment apply when excessive amounts of methane are present in a working place or in an intake air course, including an air course in which a belt conveyor is located.

Requirements for permissible CT equipment designs are governed by 30 CFR Part 23 - Telephones and signaling devices, and 30 CFR 18.68 - Tests for intrinsic safety. These 30 CFR requirements are supplemented by a number of MSHA policies and test procedures that may be obtained online through the MSHA website. The two primary methods of electrical equipment explosion protection recognized by MSHA are explosion-proof enclosures and intrinsic safety certification, described in the following sections.

6.1.1 Explosion-Proof Enclosures

Sparks, electrical arcs, or hot surfaces have the potential to ignite a mixture of coal dust or methane-air mixtures. One of the ways to mitigate these hazards is to house electrical and electronic devices in explosion-proof (XP) enclosures. Figure 6-1 shows an example of an XP enclosure. XP enclosures meet specific design criteria to ensure that should the device within the enclosure ignite a methane-air mixture, the ignition will not propagate outside of the enclosure. MSHA describes the design guidelines and testing procedures for the XP designation in 30 CFR Part 18. An example of the use of an XP enclosure might be for a backup battery which powers leaky feeder line amplifiers when the main power is shut off.

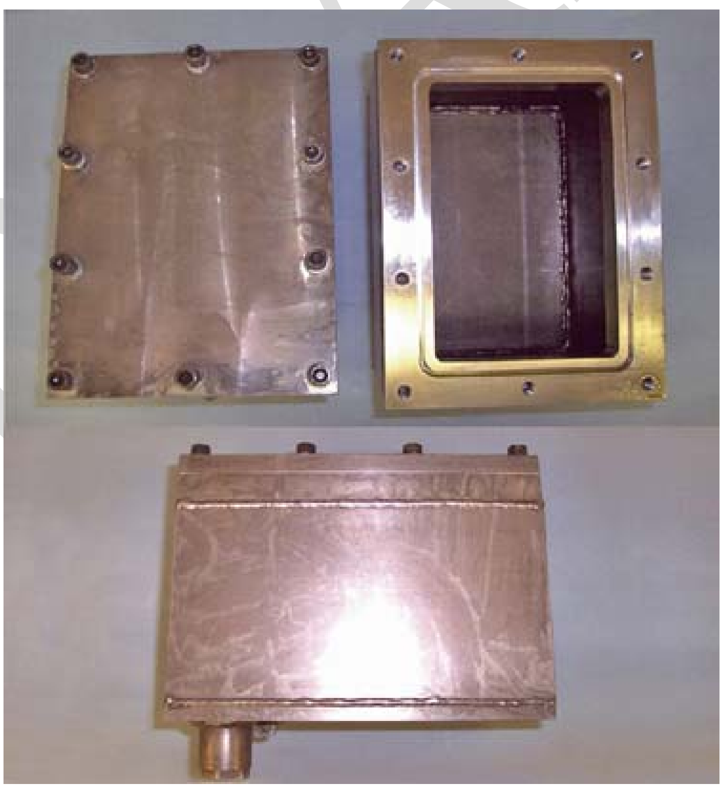

Figure 6-1. An Example of an XP Enclosure

6.1.2 Intrinsic Safety Certification

An alternative or additional approach to obtaining MSHA permissible equipment approval is through the intrinsic safety (IS) certification. The MSHA IS test requirements are specified in 30 CFR Part 18.68. There is further clarification of IS requirements in MSHA documents ACRI 2001 "Criteria for the Evaluation and Test of Intrinsically Safe Apparatus and Associated Apparatus," and ACRI 2011, "Intrinsically Safe Active Voltage/Current Power Source Criteria." A number of other policy and standardized test procedure documents pertaining to IS can be obtained online through the MSHA website (www.msha.gov).

Intrinsically safe equipment and wiring is designed to be incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a coal dust or a specific hazardous atmospheric mixture, even if the mixture is at its most easily ignited concentration. In many cases, where IS circuits are powered through the mine electrical system, an energy limiting barrier is required. Under fault conditions, the barrier prevents potentially dangerous voltage or current levels from reaching the hazardous area.

6.2 Battery Requirements

Batteries will be a necessary source of backup power for CT systems following an accident. MSHA is responsible for establishing the requirements for the operational duration of standby power. A representative requirement might be to provide at least 24 hours of standby power based on 5% transmit time, 5% receive time, and 90% idle time duty cycle (denoted as 5/5/90). The reader should verify the latest MSHA requirements for battery duty cycles. Additional MSHA battery requirements can be found in 30 CFR Part 7 Subpart C. Ideally, CT systems and devices should be designed to support easy, safe, underground battery replacement, even under extreme conditions (e.g., methane environment). Equipment users should be trained to prevent abuse or mishandling of batteries. There are many different battery-powered CT components; Mine operators should establish procedures to ensure that batteries are not lost or discarded underground.

Generally, batteries have too much stored energy to be considered intrinsically safe unless special design features, such as a current-limiting resistor, are integrated with the battery terminals to limit the energy delivery rate. High-energy storage batteries may be maintained in XP or 30 CFR Part 7 compliant enclosures. One concern is that the enclosure may not survive a roof collapse and therefore a hazardous situation could occur. Damage is also a concern for IS devices with lithium chemistry batteries, for example, which may be susceptible to thermal runaway. Lithium batteries are a subject of on-going research, but they appear to present greater risks to safe operation than other chemistries.

Stationary equipment will be on charge and unattended for long periods of time. If possible, stationary equipment containing batteries should not be located in return air entries. Lithium batteries used in stationary equipment present a greater risk than batteries of other chemistries because lithium batteries may undergo *thermal runaway.* (NIOSH has on-going research projects to investigate the various chemical types of batteries being suggested for stationary CT applications.) The state of charge and health of batteries should be visible on the batteries and/or displayed in the MOC.

Some of the areas of further investigation for batteries are listed below.

- What operation time (battery life) is needed? How does this compare to current battery technology and available CT system capabilities?
- What overall CT system designs and application strategies could help to increase available operation time?
- Battery-related issues in portable devices such as handheld radios include the following: capacity (operation time), size, weight, limitations on safe locations for recharging or battery change-out, potential failure modes and consequences, use of battery types that may present an increased hazard in explosive atmospheres or near flammable material (such as various lithium chemistries), and MSHA approval of new battery-powered equipment designs.
- Battery-related issues in fixed installations such as radio repeaters or wireless mesh nodes include the following: size and energy available, battery type, provisions for operation in an explosive atmosphere and near flammable material, protection afforded by an enclosure from physical/environmental damage (particularly from roof falls), charging safety, remote status/condition monitoring, meaningful condition testing, remote and/or local control of output (on/off), potential failure modes and consequences, and regular maintenance requirements.
- Development and acceptance of standard operating procedures for use of battery-powered CT systems under emergency conditions, when normal underground power distribution has been disconnected.

6.3 Hazards of Electromagnetic Radiation

Electromagnetic radiation is pervasive in our environment. It allows us to receive satellite TV stations, AM or FM radio stations, make and receive cell phone calls, and download emails to a Blackberry. Nevertheless, none of the radiation that allows these devices to work can penetrate the overburden of a mine. Hence, the EM environment in the mine will be determined largely by whatever radiation sources already exist within the mine, along with any new wireless devices being introduced. One required task is to ensure that the RF emitting devices not interfere with each other; this topic is covered in Section 6.4. Another required task is to identify and address any safety issues that might arise with the introduction of the CT systems. The safety issues and hazards are the topic of this section. In the mine environment, three areas may be adversely impacted by EM radiation or what is commonly called radiation hazards (RADHAZ): people, explosive atmospheres, and electrically initiated devices (e.g., blasting caps).

6.3.1 Personnel

When a communications or tracking system radiates RF energy, workers in proximity to the radiating system may suffer health effects if the radiation levels are too high. These negative effects are often referred to as hazards of EM radiation to personnel (HERP). There are well-recognized standards [IEEE C95.1 (2005); 47 CFR 1.1310] that describe the acceptable levels of radiation that do not pose a concern to humans. The acceptable radiation levels depend on the frequency, power levels and distance of the radiators from the person.

All the CT systems proposed for use in mines produce only non-ionizing radiation. This means that the RF radiation has insufficient energy to ionize atoms (strip off electrons), unlike x-rays, for example. The non-ionizing radiation can cause electro-stimulation (electrical shock) or thermal heating effects in humans. A HERP analysis on representative CT systems has been completed in a report sponsored by [JSC-WP-08-217 2008]. A broad summary of the findings is that no hazard exists except possibly in the highest power radiating devices — those with 4 or 5 watt power ratings. For high-power devices, there may be a concern with holding the transmitter against the head for extended periods of continuous transmission (greater than 6 minutes).

6.3.2 Explosive Atmosphere

Coal mine operations generate coal dust and methane gas that is released in the mining process. Within a concentration range of 5% to 15% of methane in air, the mixture is flammable and possibly explosive. Radiated RF energy can couple to conducting objects and possibly create a spark that ignites the methane/air mixture, causing a hazardous situation. This is sometimes referred to as hazards of EM radiation to fuels, or HERF.

There is an international standard [IEC 60079-0 2007] that assesses the risk of inadvertent ignition of flammable atmospheres by RF transmitting devices operating over a frequency range from 9 kHz to 60 GHz. Within the standard, threshold radiated power levels are defined, below which there is no hazard, and above which a potential hazard exists. Hazards of mine CT systems in an explosive atmosphere have been evaluated in a publication by the Joint Spectrum Center [JSC-WP-08-217 2008]. A broad summary of the conclusions within the document is that devices with power ratings under 6 watts should present no HERF hazard (including the presence of diesel fuel).

6.3.3 Electro-Explosive Devices

Electro-explosive device (EED) is a more general term for items such as electrically initiated blasting caps. A potential hazard is that radiated RF energy in the environment may couple into the leg wires (leads) of an EED and cause an unintended explosion. RF safety concerns with EEDs can be broken into transportation and deployment.

Regulations regarding transportation and packaging of EEDs from the manufacturer are specified by MSHA in 30 CRF 77 Subpart N; the Occupational Safety and Health Administration (OSHA) in 29 CFR Subparts H and U; and the Department of Transportation (DoT) in 49 CFR 173 and 176. What is not specifically addressed in these regulations is the underground transportation of EEDs that may have been removed from their original packaging and may be in the vicinity of RF radiating CT systems.

EEDs are shipped from the manufacturer with their leg wires coiled and the ends shorted together to minimize the potential for RF energy coupling to the wires. EED manufacturers have decades of experience (largely anecdotal) with shipping and handling of these devices, but not in the underground mine environment with new CT systems installed.

It is challenging to determine the RF environment experienced by an EED underground where RF energy can reflect off the walls, floor, and roof, then couple and be re-radiated from conductors within an entry. Quantitative analysis of this RF hazard in the mine environment is an area of ongoing research. In the near term, the safest recourse may be to use highly efficient RF shielding, such as shown in Figure 6-2. These enclosures or shielding blankets provide 50 to 60

Figure 6-2. Examples of RF Shielding Enclosures [TE3MI]

dB of attenuation of RF signals from 1 MHz to 3 GHz using only one layer of RF absorbing material. Such RF shielding should more than adequately protect EEDs from intercepting sufficient RF energy to fire.

Besides transportation, the other RF safety concern with EEDs occurs during deployment. During deployment, the leg wires of a blasting cap may be extended and the short removed from the ends of the leg wires, as shown in Figure 6-3. Thus, the leg wires can act as a conducting antenna. If the length of the leads L, is about half a wavelength or greater, the RF radiation will very effectively couple to the leads. The result is that significant RF energy can be deposited in the resistive heating element (or bridge wire) of the blasting cap causing the blasting cap to fire. The risk can be mitigated by observing a minimum distance of separation between RF emitters and the blasting cap leads.

There is an IEEE standard [IEEE C95.4 2002] to determine the required separation distance for various RF emitters from blasting caps. Unfortunately, the IEEE and other standards do not account for additional effects that occur in the mine environment. For example, UHF waves from an emitter can reflect off the floor, ceiling, and walls of an entry to substantially increase the energy incident on the blasting cap leg wires. At MF frequencies, longitudinal conductors in an entry can enhance the incident fields on a blasting cap by a factor of five [Thompson 1985]; these effects are not accounted for in the standards. This is an active area of research for NIOSH.

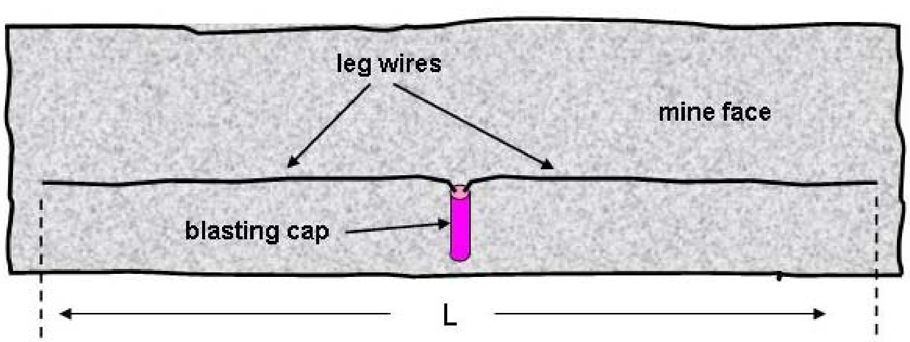

Figure 6-3. Blasting Cap Being Deployed

Based on the standards, if the RF power received by the blasting cap leads is below a threshold value of 40 mW [IEEE C95.4 2002] there should be no inadvertent firing of the cap due to receipt of RF energy. The received RF power of the blasting cap should be validated by measurements or by aid from a properly experienced consultant. Lacking either of these approaches, it is recommended that all UHF or higher frequency transmitters be kept at least 200 feet from electric blasting caps during deployment and all MF transmitters be turned off.

6.4 Electromagnetic Compatibility

Two terms that are often encountered when discussing the proper operation of electronic equipment in an RF environment are electromagnetic interference (EMI) and electromagnetic compatibility (EMC). EMI occurs in a system when undesired electromagnetic energy interferes with the reception or processing of a desired RF signal. EMC is a desired condition which prevails when electric systems are performing their particular desired functions while in the presence other systems. In effect, EMC is established when any potential EMI between systems has been eliminated or effectively managed. EMC has two aspects; a system under consideration can be a source of interference or it can be a victim of interference. More specifically, from the source of interference perspective, the system should not generate RF disturbances that cause a malfunction in another system (usually referred to as the *emission* aspect). From the victim of interference perspective, the system should be able to operate in its EM environment without risk of malfunction (usually referred to as the *immunity* or *susceptibility* aspect). These topics are discussed in greater detail in the following subsections.

6.4.1 Electromagnetic Interference

EMI is due to electromagnetic energy that either causes a malfunction in an electrical system or equipment or interferes with the reception or processing of a desired signal. EMI may result from intentional RF emission and proper operation of equipment, or it may be from unintentionally generated RF emissions. A handheld radio is an example of an intentional RF emitter, and a computer is an example of a device that emits RF signals (though this is not the intention or purpose of the device). EMI effects may be categorized as mild, medium, or severe, depending on the reaction of the victim equipment.

EMI of electrical equipment occurs because of inadvertent susceptibilities of the equipment. EMI is usually associated with coupling paths from one antenna to another antenna, although other types of coupling paths (e.g., from an antenna directly to the circuitry on the inside of a system cabinet) are possible.

Electrical and electronic systems or equipment can interfere with one another in many ways. Every RF interaction between a source and a victim requires four things to occur before it is determined that interference has occurred. First, there must be an emission of EM energy from the source (transmitting) system. Second, the emitted EM energy propagates along some path to the victim (receiving) system. Third, the EM energy incident on the victim system finds a low-loss path to the system's internal circuitry. This path may be through the victim's antenna or it may be through a gap or seam in the victim's housing. Fourth, when the undesired signal has sufficient strength to degrade the performance of the victim system, an interference situation is declared. This generally occurs when the strength of the undesired signal from the source exceeds a particular threshold level for the victim. The degradation could take the form of an undesirable or unacceptable response of the victim, an interruption in service, or a malfunction.

The major EMI concerns are as follows:

- co-channel interactions, where other systems operating on the same frequency interfere with each other;
- adjacent-channel interactions, where systems in the same frequency band, operating on nearby frequencies, interfere with each other;
- adjacent-band interactions, where systems in adjacent frequency bands operating on nearby frequencies interfere with each other;
- harmonic interactions, where systems operating on a harmonic frequency interfere with each other.

These concerns are discussed in further detail in Appendix B. Additional EMI concerns are discussed elsewhere [JSC-TR-08-120].

Methods to mitigate EMI address one or more of the four conditions required for EMI to exist. Changes can be made to the transmitting system, to the receiving system, to RF shielding, and possibly to the transmission medium to offset EMI effects. EMI mitigation techniques include frequency management, reduced transmitter power, increased antenna separation, antenna radiation control (directing the antenna radiation pattern), narrowed receiver selectivity, and filtering.

6.4.2 Standards and Regulations

Usage of the EM spectrum is regulated by two different agencies: the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). The FCC regulates commercial use and the NTIA regulates government use of the spectrum. Regulations stipulate what types of RF emitting or receiving devices are permitted to operate using a certain portion of the EM spectrum, and what transmission power levels are acceptable. FCC regulations are published in the CFR. For example, 47 CFR Part 15.211 presents FCC regulations regarding tunnel radios (radios for use in mine tunnels).

Traditionally, the FCC has largely focused on protecting commercial radio and TV broadcasts from interference. The FCC has very few regulations regarding the susceptibility of equipment to EMI, preferring to leave this quality feature to manufacturers to support—i.e., manufacturers making a device that is less susceptible to EMI will presumably sell more devices.

Standards, unlike regulations, are, in themselves, voluntary, although some regulations may require meeting a specific standard. Standards aimed at minimizing RF interference tend to address EMC rather than EMI. There are few commercial US standards that address EMC. The military, on the other hand, has very detailed standards on EMC.

Military equipment often contain multiple systems for communications with soldiers on the ground, aircraft, satellites, guided munitions, and may have RF systems for emitting and receiving radar information. In many cases, these systems are expected to operate simultaneously and without conflict, often in close proximity to each other. The military has developed detailed standards that can provide guidance for EMC in coal mine CT systems. For example, military equipment is often required to meet military standard 461F [MIL-STD-461F], which could be tailored for coal mine CT systems.

MIL-STD-461F establishes emission limits that are intended to control RF signals that may be conducted through external attached wiring or radiated from a source (transmitting) system.

MIL-STD-461F also establishes limits on the susceptibilities, also either conducted or radiated to a victim (receiving) system. The emissions from a source generally include out-of-band products such as harmonics and spurious emissions, whereas the susceptibilities of a victim include reactions such as spurious responses to out-of-band inputs. Conducted emissions and susceptibilities are conducted in or out of a box via wires such as power cords, whereas radiated emissions and susceptibilities are radiated from the box or from the antenna. The limits of MIL-STD-461 have been established at emission and susceptibility levels which result in a high likelihood that two systems, both meeting the limits and separated by a typical coupling path, will be compatible with each other.

MIL-STD-461F is designed for military electrical systems which can have very high-power radiating systems and many electrical systems compactly installed. The coal mine EM environment is quite different; hence, the limits on emissions and susceptibility have to be adjusted appropriately [JSC-TR-08-120 2008]. The intent is to achieve electromagnetic compatibility between systems at a reasonable cost.

6.4.3 Design and Construction Guidelines

One approach to mitigate EMI effects is through the use of shielding. Shielding is a design approach for keeping undesired EM noise and signals off susceptible equipment by strategic use of materials that reflect RF energy. One type of shielding is a metal barrier around electronic components, wires, or cables.

To demonstrate, twisted-pair wires are not shielded and hence signals from a nearby transmitter may be coupled onto the wires. Non-twisted wires are even more susceptible to RF coupling than twisted wires. The unintended signals could then be conducted into other equipment connected to the wires, possibly causing EMI. For this reason, coaxial cables can be important in reducing EMI. In a coaxial cable, the outer conductor is a shield that prevents most of the incident RF from reaching the internal conductors.

Electronic circuitry can also be shielded from radiated RF influence by packaging the circuits in conducting enclosures. It may be necessary to use specially designed RF seals at apertures, access points, and seams in the enclosure to reduce RF penetration into the enclosure. An example of such a consideration might be a carbon monoxide sensor that is mounted in a plastic enclosure. The sensor may give erroneous readings if a handheld radio is too close. The sensor could be hardened by using a metal enclosure.

Grounding is a design approach whereby all structures and equipment are maintained at the same electrical potential, usually physically connected to the earth through a low-resistance path. When this has been accomplished, the potential difference, or relative voltage, between any two points would be zero. In this way, electrical charges on equipment are carried away from the equipment without a chance to build up to the point where there could be an electrical discharge, potentially causing a fire or explosion. In addition, radiated noise due to the electrical charges and currents is minimized.

The enclosures (i.e., chassis, cabinets, boxes, cases, etc.) of electrical and electronic equipment should be installed to ensure a continuous low-impedance path between all adjoining or contacting surfaces. All exposed metal parts of equipment should be electrically grounded.

For any equipment connected to the mine’s electrical system, the power supply cable should include an extra conductor that is grounded inside a power panel, a connection box, or a receptacle. If it is not feasible to install a ground wire in the power supply cable, the enclosure may be grounded by means of a braid strap bolted to the enclosure.

7. MINE OPERATIONS CENTER

Wireless communications must be established between miners and surface personnel as required by the MINER Act. Similarly, for tracking systems, the electronic location information must also be available at the surface. A natural, central location on the surface to meet both these requirements is the mine operations center (MOC). A dispatcher is likely to be in the MOC, monitoring operations, directing needed resources, and checking the status of sensor readings. The MOC will have computer servers to monitor network performance and to implement diagnostic tests. There would likely be displays giving the status of the network, health of the various CT components and possibly atmospheric monitoring sensors, and mine maps showing locations of workers. The following sections describe how a mine operations center should function to ensure effective communications and worker safety.

7.1 Tracking Displays

The dispatcher in the MOC should have access to the tracking information. An electronic tracking system requires software to manage and process the data sent to the MOC from the readers or nodes in the mine. This software runs on a computer server in the MOC and should include graphical capabilities to display the locations of underground personnel on a representation of the mine map. The software should also include database capabilities to allow personnel in the MOC to pull up detailed information and track individual miners. Tracking information will have to be periodically stored so that in the event of an accident, the most recent pre-accident locations of mine personnel can be determined.

Ideally, displays in the MOC would indicate the locations of all miners by superimposing an icon representing the miner on a mine map. The icons would either have the miner’s name or some other unique identifier associated with each miner. The locations would be accurate to within a certain distance, which might vary depending on location (escapeway versus working section, for example). The required resolution will be stipulated by MSHA. Additionally, the locations would be updated at a regular interval, again specified by MSHA.

An example of a mine worker tracking display is shown in Figure 7-1.

Name	Location	Status
Brown, Al	6322	OK
Dean, John	6322	OK
Gibbins, Mike	6322	OK
Gibbs, Fred	5837	OK
Hickock, Bill	6322	OK
Hun, Chris	6322	OK
Jones, George	6322	OK
Sawyer, Mike	6322	OK
Sims, George	5837	OK
Stevens, Joe	6322	OK
Thompson, Tom	6322	OK
Williams, Jim	6322	OK

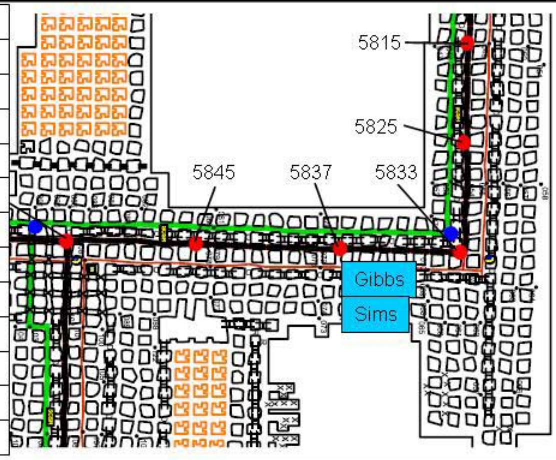

Figure 7-1. Example of Tracking Location Display

7.2 Surface Communications

As mentioned in Section 7, communications from underground will likely be centralized at the MOC. During normal operations, the CT backhaul will go directly to the MOC. Under emergency conditions, the CT system may be damaged and traffic may be routed through an alternate communications path (ACP).

ACPs involve communications and/or electronic tracking system links to the surface at locations that are remote from the MOC. Ideally, there would be an RF communications path on the surface from an ACP back to the MOC, so that information between the ACP access point and the MOC would be relayed with a minimum of delay. In the optimum system, messages and information would be relayed automatically. However, the message relay could be done manually by operators stationed at the ACP surface access point (i.e., any message to/from the ACP access point is received and repeated by the operator). The link should only be required in a rare emergency in which the normal backhaul has become inoperable. Measures should also be taken to ensure that the ACP access point is easily reached and periodically verified as operational.

Manual relay over an RF communications path could by accomplished by using commercial cellular phones or simple walkie-talkies. The use of cell phones requires the ACP access and MOC locations to be within the coverage area of a cellular base station. Walkie-talkies require relatively short distances between the ACP access point and the MOC. In the event that cell phones and walkie-talkies cannot be used, a wireless RF communications link could be established on the surface using high transmitter power, and/or high-gain antenna or a hardwired twisted-pair cable could be strung. It should be noted that any RF link on the surface would need to be approved by the FCC to avoid EMI with any existing radios or TVs in the area of the ACP access point and MOC.

Figure 7-2 presents three of the methods discussed for connecting the ACP access point to the MOC on the surface. Figure 7-2a shows an ACP for a leaky feeder system exiting an air shaft. At the surface, the ACP links to the MOC via a fiber-optic cable. Figure 7-2b shows a wireless transmission through the air used to link the ACP with the MOC. Figure 7-2c shows a manual link of the ACP with the MOC using miners with walkie-talkies, one at the ACP and the other at the MOC.

A fourth option (not shown in Figure 7-2), with widespread availability due to the proliferation of Internet Protocol (IP) capable devices and “broadband” networks, is to lease a connection that relies on the Internet. Such options include DSL modems through the telephone companies, cable modems through cable television companies, and satellite modems through satellite service providers. While not all mine communications natively support IP protocols, the equipment vendors will soon offer such an option and there are converters available that will allow mine communications through the Internet. An advantage of using the Internet-based approach is that mines can remotely monitor their communications links and other systems. Some equipment vendors and third party providers already offer services to monitor the systems, thus eliminating the burden of the local mine operations personnel of monitoring and troubleshooting the networks.

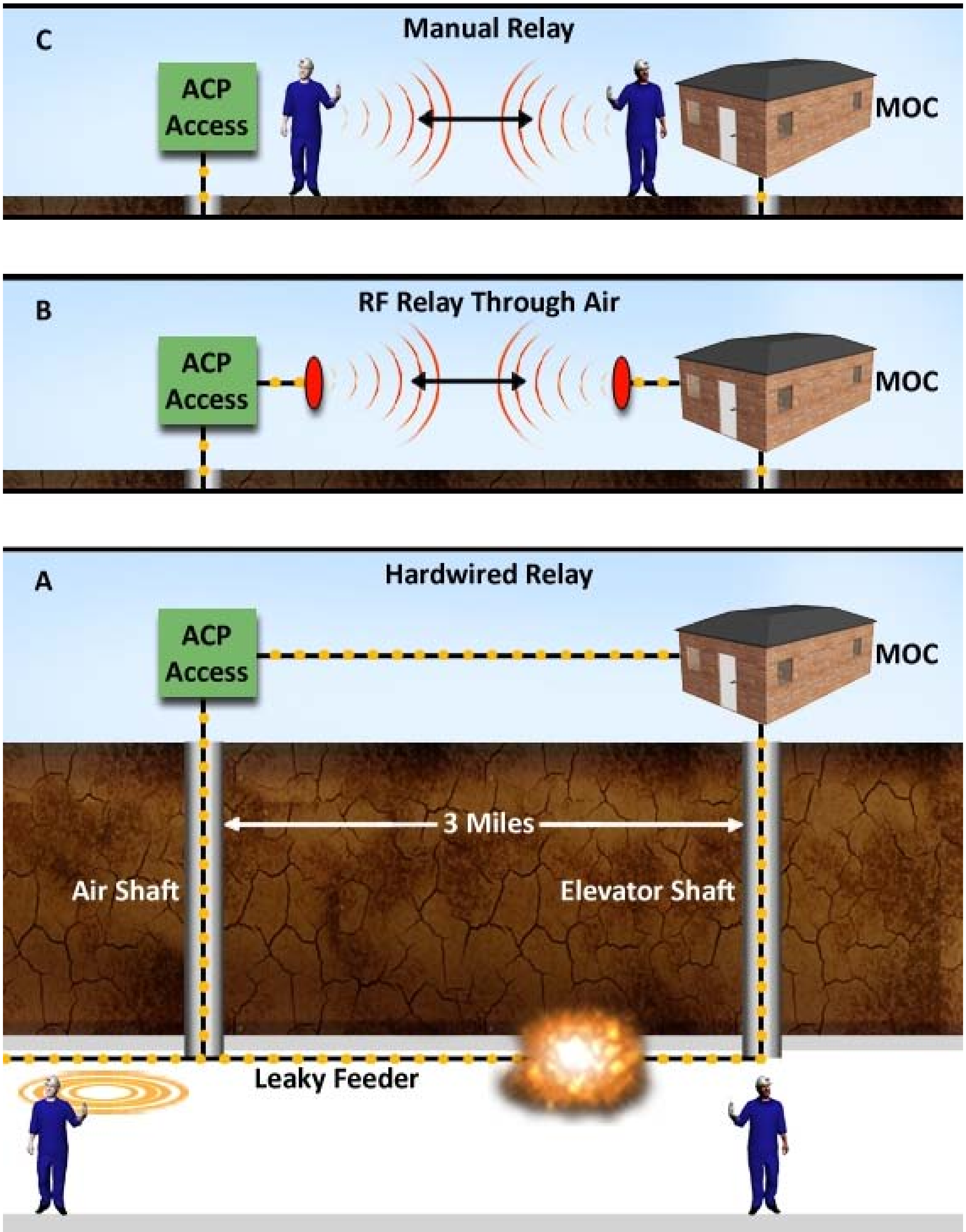

Figure 7-2. Several Approaches to Connecting ACP Access to MOC

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8.3 Acronyms

ACP	Alternate Communication Path
AGC	Automatic Gain Control
AP	Access Point
ARP	Accident Response Plan
BPS	Bits Per Second
BW	Bandwidth
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CT	Communications and Tracking
EED	Electro-Explosive Device
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EME	Electromagnetic Environment
EMI	Electromagnetic Interference
EMR	Electromagnetic Radiation
ERP	Emergency Response Plan
FCC	Federal Communications Commission
FM	Frequency Modulation
FSK	Frequency Shift Key
HERP	Hazards of Electromagnetic Radiation to Personnel
H-field	Magnetic Field
ID	Identification
IEC	International Electrotechnical Commission
INU	Inertial Navigation Unit

JSC	Joint Spectrum Center
LOS	Line-of-Sight
MEMS	Micro-Electro-Mechanical System
MF	Medium Frequency
MINER	Mine Improvement and New Emergency Response
MOC	Mine Operations Center
MP	Mesh Point
MSHA	Mine Safety and Health Administration
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NF	Noise Figure
NIOSH	National Institute for Occupational Safety and Health
NTIA	National Telecommunications and Information Administration
NTSC	National Television System Committee
OFSK	Orthogonal Frequency Shift Keying
PSK	Phase Shift Key
RADHAZ	Radiation Hazards
RF	Radio Frequency
RFI	Radio Frequency Interference
RFID	Radio-Frequency Identification
RSL	Received Signal Level
RSSI	Received Signal Strength Indication
Rx	Receiver
SCSR	Self-Contained Self-Rescuer
SHF	Super High Frequency

SNR	Signal-to-Noise Ratio
TDOA	Time Difference Of Arrival
TTE	Through-the-Earth
Tx	Transmitter
UG	Underground
UHF	Ultra High Frequency
ULF	Ultra Low Frequency
VHF	Very High Frequency
VoIP	Voice-over-Internet Protocol
WAP	Wireless Access Point
WLAN	Wireless Local Area Network
XP	Explosion-Proof

8.4 Glossary

Term	Definition
Access Link	In a node-based system, the first link, which is from the miner's handheld radio to a node, is through the air and is called the access link.
Access (Network)	Networks can be considered to have two responsibilities, one is to provide access and the other is to provide transport for data or voice.
Access Node	The node providing the service to the miner is called the access node.
Accuracy	Tracking system accuracy is the measure of error in the miner's reported location.
Active Tag	A tag that contains its own source of power for transmitting identification information.
Ad Hoc Network	A wireless ad hoc network is a decentralized wireless network. The network is ad hoc because each node is willing to forward data for other nodes, and so the determination of which nodes forward data is made dynamically based on the network connectivity.
Air Interface	See Access Link.
Alternate Communications Path	A communication path that may be used to continue communications in the event that a primary path is blocked. A communication cable routed through a borehole is an alternate communication path.
Amplitude	For an electromagnetic or radio wave, amplitude refers to the maximum value of the periodically varying wave.
Analog Signal	A signal whose amplitude varies continuously in time (see Digital Signal for comparison).
Attenuation	The reduction of a signal's amplitude or power is its attenuation.
Availability	The probability that a system is operating properly when it is needed (i.e., the probability that the system has not failed or is not undergoing repair when it needs to be used).
Backbone System	A system that ties together several diverse systems and provides a common path for the transfer of communications or data. A leaky feeder is a common type of backbone system.
Backhaul	The communications path from an access node to the surface.
Backhaul Link	The connection between nodes.
Backup System	A system that may be deployed in the event that a primary system fails. For example, an MF system may be used as a backup in the event of leaky feeder failure.

Term	Definition
Band	A specific range of frequencies in the electromagnetic spectrum.
Bi-Directional	A communications system that passes information in both directions along its connected paths.
Bit	A binary digit equal to either a 0 or 1.
Bridge	A device that provides interoperability between technologies.
Bridge Nodes	A node within a communications system that also acts as a bridge.
Bridge Repeater	A repeater within a communications system that also acts as a bridge.
Byte	A byte is an ordered collection of bits (0’s and 1’s). Although there is no standard, typically there are 8 bits per byte.
Capacity (Communications System)	The information carrying ability of a communications system.
Capacity (Tracking System)	The maximum number of people a tracking system can monitor in its coverage area.
Carrier Frequency	The nominal frequency of a radio transmission.
Channel Capacity	The upper bound on the amount of information that can be reliably transmitted over a communications channel.
Compressed Voice	Audio (voice) that has been encoded so as to reduce the number of bits required for storage or transmission.
Constrained Mesh Network	A network where the allowable backhaul links that form the network topology must be pre-programmed into each node.
Coverage	Refers to the region or area in which radio-based communications services are available.
Digital Router Or Router	A networking device whose software and hardware are usually tailored to the tasks of routing and forwarding information. For example, on the Internet, information is directed to various paths by routers.
Digital Signal	A signal in which the intensity maintains a constant amplitude for some period of time and then abruptly changes to another constant level where the different levels represent the binary digits 0 or 1.
Discrete Antenna	An localized arrangement of conductors to radiate or receive electromagnetic waves such as a whip or dipole.
Distributed Antenna	A dispersed antenna such as a leaky feeder cable when used in connection to a coal mine communications system.
Downlink	Pertaining to the transmission path from the base station to a mobile station.

Term	Definition
Dual Independent Communications Path	Communications paths to the surface that do not depend on or transgress a common set of entries. Generally this means that the two paths out of the mine differ in direction from the mine by at least 90 degrees.
Electromagnetic Compatibility	The condition which prevails when electronic/electrical systems or equipment are performing their individually designed functions without causing/suffering unacceptable EMI degradation to/from other equipment in the same environment.
Electromagnetic Energy	The energy carried by an electromagnetic wave.
Electromagnetic Environment (EME)	The radiated or conducted EM emission levels, in various frequency ranges that may be encountered by a system when performing its designed functions.
Electromagnetic Interference	Electromagnetic energy which causes a malfunction in an electronic/electrical system or equipment, or interferes with its reception or processing of a desired signal. EMI may result from intentional and proper operation of equipment, or it may be unintentionally generated. EMI can be categorized as mild, medium, or severe, depending on the reaction of the victim equipment.
Electromagnetic Spectrum	Electromagnetic (EM) spectrum refers to a range of electromagnetic radiation frequencies. The term is normally used when referring to the frequencies as a group.
Electromagnetic Wave	A form of radiated energy that travels in waves that are a combination of electric and magnetic fields.
Explosion Proof Enclosure	Explosion proof enclosures must meet three criteria. First, an enclosure that is rugged in construction and suitable for use in mining applications; second, the enclosure has a minimum structural yield pressure of at least 150 psig, without significant permanent distortion; third, there shall be no visible luminous flames or ignitions of a combustible methane-air atmosphere surrounding the enclosure during explosion testing.
Frequency	For an electromagnetic or radio wave, frequency refers to the number of oscillations per second, measured in Hertz.
Full Mesh	A mesh arrangement in which every node is connected to every other node.
Fully Wireless	See Through-the-Earth.
Hardened System	A system in which protective measures have been taken to ensure the system’s survivability. An example is enclosing a leaky feeder cable in a PVC pipe and burying it in a trench to enhance protection against roof falls.
Hardening	Increasing strength and ruggedness of system components to provide protection from damage.

Term	Definition
Hardwired	Connected by physical wiring or cabling.
Hard-Wired System	A communications system requiring physical wired connections between devices to operate.
Hertz	A unit of measure equivalent to cycles per second.
Hop	An intermediate network connection consisting of a leg from one router to another router and over which a packet travels to reach its destination.
Inertial Navigation	A navigation aid that uses a computer and motion sensors (accelerometers and gyroscopes) to continuously calculate via dead reckoning the position, orientation, and velocity of a moving object without the need for external references.
Inertial Tracking	A tracking system that uses inertial navigation.
Infrastructure	All fixed location equipment within the mine and in entries to the mine.
Intrinsically Safe	Describes electrical equipment and wiring which is incapable of releasing sufficient electrical or thermal energy under normal or abnormal opertions to cause ignition of an atmospheric mixture of methane in its most easily ignited concentration.
Interference	Stray electromagnetic energy (radiated, coupled, conducted, or induced) that causes undesirable or unacceptable responses, interruptions, malfunctions, or degradation of performance in a subsystem or equipment.
Intermodulation Interference	EMI caused by the mixing, in a nonlinear junction, of two or more signals. The mixing process creates new signals at frequencies that are sums and differences of integral multiples of the original signals.
Internet Protocol	A particular prescription or method used for communicating data across a packet-switched network.
Interoperability	The ability of different communications systems to communicate with one another.
Interrogate	Refers to the initial RF signal transmitted by an RFID tag reader to a tag, which begins the transfer of information between the two devices.
IP Address	An Internet Protocol (IP) address is a numerical identification (logical address) that is assigned to devices participating in a computer network utilizing the Internet Protocol for communication between its nodes. Although IP addresses are stored as binary numbers, they are usually displayed in human-readable notations, such as 208.77.188.166.
Latency	The time delay suffered by packets of information as they hop from node to node in a mesh network. More generally, the time it takes information to travel from one point to another in a communications network.

Term	Definition
Leaky Feeder	A communications device also known as “leaky coax,” which assists wireless transmission. A coaxial cable that has been modified to allow signals traveling within it to leak out over its entire length.
Line-of-Sight (LOS)	An unobstructed straight-line path between a transmitter and receiver.
Link Budget	The quantitative result of an evaluation of the factors that contribute to RF power gain or loss in establishing a communications link between two components. See Section 3.1.1.
Local Area Network (LAN)	A data communications system that (a) lies within a limited spatial area, (b) has a specific user group, (c) has a specific topology, and (d) is not a public switched telecommunications network, but may be connected to one.
MAC Address	In computer networking, a Media Access Control address (MAC address) is a quasi-unique identifier assigned to most network adapters or network interface cards (NICs) by the manufacturer for identification.
Medium Frequency (MF) System	Communications systems that operate in the range of 300-3000 KHz. MF systems have been shown to work well in tunnels where there are metallic structures such as power lines and pipes. The signals can couple onto conductors and travel long distances.
Mesh Network	A communications system where every node is connected to every other node and consequently has built in redundancy. In underground mines, this connectivity may be limited by the mine’s geometry and cost considerations.
Mesh or Node-Based System	A communications system which relies on multiple individual devices to establish a communications path.
Mesh Point	Another term for node in node-based communications network.
Modulator	A device by which analog or digital information is converted to signals at RF frequencies suitable for transmission.
Network	A system containing any combination of interconnected communications equipment used to transmit or receive information.
Node	A point of connection into a communications network.
Node-Based Tracking	A tracking system using node-based communications nodes to determine radio location.
Noise	A received signal consists of the transmitted signal plus additional undesirable voltage or current distortions, usually considered random, which tend to obscure the transmitted signal. All noise is interference, but not all interference is considered noise.

Term	Definition
Noise Figure (NF)	The ratio of actual output noise to that which would remain if the device itself did not introduce noise. NF is a number by which the performance of a radio receiver can be specified.
Partial Mesh	A mesh arrangement in which every node is connected to multiple other nodes.
Passive Tag	A tag that does not contain its own source of power (battery).
Peer To Peer Communications	A communications system in which every handset can communicate with every other handset without the aid of the infrastructure in the mine.
Permissible	Refers to electrically operated equipment designed, constructed, and installed to ensure that such equipment will not cause a mine explosion or mine fire and, to the greatest extent possible, other accidents when used inby the last open crosscut of an entry.
Physical Communications Link	The path connecting one transmitter and one receiver through the interconnecting transmission media.
Point of Presence	An artificial demarcation point or interface point between communications entities.
Propagation	The process whereby an EM wave travels through a surrounding medium, losing energy as it travels.
Protocol	The set of standard rules for data representation, signaling, authentication, and error detection required to send information over a communications channel.
Radio	A device used by individuals for voice or text communications.
Radio Frequency	The range of frequencies within which radio waves are typically transmitted, roughly 3 kHz to about 300 GHz.
Radio Frequency Interference (RFI)	An unwanted disturbance that affects an electrical circuit due to electromagnetic radiation emitted from an external source. See also the definition for EMI.
Reader	A tracking system component that interrogates a tag.
Received Signal Strength Indicator (RSSI)	RSSI is a technique in which the strength of the RF signal received is used to determine the distance of the transmitter from the receiver.
Receiver	An electrical device designed to receive electromagnetic energy.
Redundancy	Redundancy involves the duplication of system functions to ensure that those functions will survive some level of damage to the system; in the context of communications systems; it is used to describe a system that can maintain communications with the surface when a single communication path is disrupted.

Term	Definition
Redundant System	A system other than the normal operations system, designed to provide communications with the surface when the normal operations path is disrupted. A redundant system may be installed in a separate entry from the normal operating system provided that a failure in the normal operations system or path does not affect the redundant system or path.
Reliability (Basic)	Basic reliability is a measure of a system's ability to perform its functions without the need for repairs or adjustments. Basic reliability accounts for the time a system or component would be expected to operate without adjustments or repairs and only considers the reliability of the individual components; it does account for the arrangement of components (series versus parallel, for example). See Section 5.2.5.
Reliability (Operational)	The probability that a system can perform and complete its functions satisfactorily. The series or parallel arrangement of components is accounted for. For example, a redundant design reduces single points of failure and therefore raises the likelihood of the system completing its specified functions, raising the operational reliability. See Section 5.2.5.
Repeater	A device placed at intervals in a communications path to receive a signal and then re-transmit it at a higher power than received.
Resolution	Tracking system resolution is the smallest change in a miner's location that can be detected or displayed.
Reverse RFID	An RFID system where the locations of tag and reader are reversed; the tags are located at fixed, known positions within the mine and each miner wears an RFID reader.
RFID	A system that uses radio waves to communicate identification information between a tag and a reader. In a coal mine tracking system, the tag is worn by the miner and readers are placed throughout the mine.
Scan Rate	The frequency with which a tracking system updates location data.
Secondary System	Secondary communications systems operate in non-conventional frequency bands; use large antennas that are best suited for fixed locations or portable applications; and do not have sufficient throughput for general operations. Example are TTE or MF systems. (MF may perform as a primary system for a small mine.) See Section 3.1.7.
Self-Healing Mesh Architecture	A mesh network that automatically reconfigures itself if a node fails so that the maximum possible connectivity is maintained.
SHF System	System operating in the Super High Frequency range (3 GHz to 30 GHz).
Signal Propagation Characteristics	A technical description of the effects of the environment on the communications signal as it travels between devices.
Signal-to-Noise Ratio (SNR)	The ratio of a signal power to the noise power corrupting the signal. In less technical terms, signal-to-noise ratio compares the level of a desired signal (such as music) to the level of background noise.

Term	Definition
Single Communication Path Areas	Areas that do not have dual independent communications paths.
Spectrum	A range of electromagnetic waves.
Survivability	The measure of a system's ability to remain operational after an accident.
System	The working combination of communications or tracking components.
Tag	A component in an electronic location systems that transmits unique identification information via radio waves.
Thermal Noise	The electronic noise generated by the thermal agitation of the charge carriers (usually the electrons) inside an electrical conductor at equilibrium, which happens regardless of any applied voltage.
Thermal Runaway	A destructive process experienced by lithium chemistry batteries in which there is a chemical reaction producing a rapid increase in temperature leading to an intense fire and possibly an explosion.
Through-the-Earth System, TTE	A communications system that does not rely on any devices, wires, or structures between the transmitter and receiver.
Time Difference of Arrival (TDOA)	TDOA is a tracking system method based on the propagation time between a tag and a reader.
Tracking Reporting Area	The area where the system is capable of receiving an active reading from the miner's tracking device.
Transceiver	A device that functions as both transmitter and receiver.
Transmission Line	A material structure forming a continuous conducting path from one place to another, directing the transmission of electromagnetic energy with a relatively low loss. The term transmission line includes essentially all types of cables. Examples are telephone lines, power cables, twin lead, coaxial cables, and other similar items.
Transmission Medium	The intervening substance through which electromagnetic waves travel.
Transmitter	An electrical device designed to radiate electromagnetic energy.
Two-Way Communications	The ability of the miner's handset to receive and transmit information.
UHF System	A system operating in the Ultra High Frequency range (300 to 3000 MHz).
Untethered	A device is considered untethered if there are no cables or wires connected to the device, i.e., cordless.
Uplink	Pertaining to the transmission path from a mobile station to the base station.

Term	Definition
VHF system	A system operating in the Very High Frequency range (30 to 300 MHz).
Wave Length	The distance between two consecutive peaks of a wave.
Wi-Fi	Wireless Fidelity. The Wi-Fi Alliance (organization) owns the Wi-Fi (registered trademark) term and specifically defines Wi-Fi as any "wireless local area network (WLAN) products based on the IEEE 802.11 standards."
Wired System	Used to refer to systems whose components are connected using wires, cables, or fiber-optics. See also hardwired.
Wire Plant	The collection of conductors in a mine.
Wireless Access Point (WAP)	In computer networking, a wireless access point (WAP) is a device that allows wireless communications devices to connect to a wireless network using Wi-Fi, Bluetooth, or related standards. The WAP usually connects to a wired network, and can relay data from wireless devices.
Wireless (Communications System)	When used in this tutorial refers to a system where the link between the user and the system is wireless. A system that operates locally without wires. See Section 2.1.3.
Wireless Local Area Network (WLAN)	A network in which the mobile user can connect to a local area network through a wireless connection. See also Local Area Network (LAN).
ZigBee	A specification for a suite of high level communications protocols using small, low-power digital radios based on the IEEE 802.15.4-2006 standard for wireless personal area networks (WPANs), such as wireless headphones connecting with cell phones via short-range radio.
Zone-Based RFID	See RFID.

A. CT SYSTEMS ENGINEERING SPECIFICATIONS

A.1 DEFINITIONS OF EQUIPMENT PARAMETERS

Equipment parameters that are typically required for coverage and EMC analysis of communication and tracking systems and often specified in technical literature are explained in the following sections.

A.1.1 System

Equipment parameters generally applicable to an RF emitting system are listed in Table A-1.

Table A-1. System Characteristics

Parameter	Units
Frequency band, lower limit	MHz
Frequency band, upper limit	MHz
RF channelization start	MHz
RF channelization increment	MHz
Channel bandwidth	MHz
Duplex frequency offset	MHz
Modulation type	-
Data rate	Mbps

The frequency band consists of the lower (minimum) and upper (maximum) frequencies over which a system may be tuned. This frequency band is also called the fundamental frequency band. Within its tuning band, the system is usually tuned to specific frequencies (i.e., channel frequencies), but tuning to any frequency (i.e., continuous tuning) is generally possible.

For systems having a specific set of channels and uniform channel spacing, the RF channelization specifies the start frequency and the frequency increment. For example, a UHF radio may have a tuning band of 450 to 470 MHz with 25 kHz channel increments starting at 450 MHz. A specific channel frequency might be 464.025 MHz. If the channel spacing is not uniform, a list of the specific channels should be provided.

If the system is capable of duplex operation, the duplex frequency offset specifies the constant difference in frequencies between a transmit channel and a receive channel. For example, if the transmit channel is 464.25 MHz and the receive channel is 464.85 MHz, the frequency offset is 0.6 MHz.

The modulation type refers to how information is coded or blended onto a carrier frequency. Example modulation types include:

- FM
- single sideband (SSB) AM

- binary phase shift key (BPSK)
- quadrature phase shift key (QPSK)

The data rate is the number of bits per second (BPS) in a digital waveform. The units of kbps are also commonly used. This parameter is applicable only for digital modulation types and is assumed to be the same for both the transmitter and the receiver.

Note: the characteristics listed in Table A-1 are assumed to be the same for both the transmitter and the receiver. If, for some reason, this is not the case, then a list of the characteristics unique to the transmitter and the receiver should be provided.

A.1.2 Transmitter

Equipment parameters generally applicable to the transmitter are listed in Tables A-2 through A-4.

Table A-2. Transmitter General Characteristics

Parameter	Units
Peak power	dBm
Harmonic attenuation	dB

The peak power is also known as the peak envelope power. The unit dBm is power in decibels with respect to one milliwatt; see Sec B.1 for power conversions..

Harmonic frequencies occur at multiples of the fundamental tuned frequency. For instance, for a UHF radio having a fundamental tuning band of 450 to 470 MHz, the second harmonic frequency band occurs at 900 to 940 MHz, the third harmonic frequency band occurs at 1350 to 1410 MHz, etc. Note that the harmonic bands are wider than the fundamental band. Harmonic attenuation levels are generally provided for the second, third, and higher-order harmonics. The harmonic attenuation is relative to the in-band peak transmitter power. A typical harmonic level is -60 dB.

Table A-3. Transmitter Pulse Characteristics

Parameter	Units
Pulse width	μs
Pulse repetition frequency	pps or Hz
Duty cycle	dB
Mean power	dBm

Some systems have a waveform that is turned on and then turned off. Such a waveform is called a pulsed waveform, and is defined by its pulse width (PW) and pulse repetition frequency (PRF). The PW and PRF are only relevant for systems with a pulsed modulation type. Typical units are microseconds (μs) for the PW, and pulses per second (pps) or Hz for the PRF. The duty cycle (DC), in dB, is computed as 10 times the log of the product of the PW in seconds and the PRF in

Hz. In calculating DC, care should be taken to match the PW with the correct corresponding PRF. The mean power (i.e., average power) in dBm is computed by adding the DC in dB to the peak power in dBm.

Table A-4. Transmitter Emission Spectrum

Parameter	Units
Emission bandwidth	MHz
at attenuation level	dB
Rolloff	dB/decade
Broadband transmitter noise	dBc/Hz

The emission spectrum provides an indication of a transmitter's frequency-domain characteristics. An emission spectrum, which generally depends on the modulation type, is defined by the bandwidth (BW) of the spectrum at each of several attenuation levels. In general, these levels are the -3, -20, -40, and -60 dB points, although the -20, -40, and -60 dB points are sometimes not available. The BW and attenuation data points define an envelope for the spectrum. The minimum data required for an EMI analysis are the -3 dB BW and the rolloff.

For the analysis of a transmitter's frequency-domain characteristics, the midpoint of the -3 dB BW (and all other BWs) is usually assumed to be identical to the channel frequency. With this assumption, a modeled spectrum is symmetric with respect to the channel frequency. The channel BW is also usually assumed to be the same as the -3 dB BW. The frequency difference, Δf, to any arbitrary frequency (e.g., a receiver tuned frequency) is then the difference between that frequency and the channel frequency.

The spectrum rolloff defines the rate of attenuation of a spectrum's envelope skirt outside of the -60 dB points and is used in cases of a large frequency offset. This rate of attenuation is usually given in dB per decade of frequency offset. The rolloff may be computed from the emission spectrum data. In the event of missing emission spectrum data or an extraordinarily large computed rolloff, a default rolloff of -40 dB per decade may be assumed.

The spectrum of a transmitter at very large frequency offsets is dominated by broadband transmitter noise (BBTN). BBTN is generated within the transmitter components and radiated by the transmit antenna. A typical level for BBTN from solid-state components, -160 dBc/Hz, may be used as a default value. The unit dBc/Hz refers to the noise density with respect to the level of the carrier.

A.1.3 Receiver

Equipment parameters generally applicable to the receiver are listed in Tables A-5 and A-6.

Table A-5. Receiver General Characteristics

Parameter	Units
Sensitivity	dBm
Sensitivity criterion	
Sensitivity criterion type	
Noise figure	dB

The sensitivity is the power level in dBm required for some particular standard response for the receiver. The sensitivity criterion is usually either a required signal-to-noise power ratio (SNR) in dB for an analog system or a bit error rate (BER) for a digital system (other criterion types are encountered). Typical sensitivity criteria are 12 dB SNR for an analog system or a 10^{-4} BER for a digital system. Noise figure (NF) is a measure of degradation of the signal to noise ratio (SNR), caused by components in the RF signal chain. The noise figure is the ratio of the output noise power of a device to the portion thereof attributable to thermal noise in the input termination at standard noise temperature T_0 (usually 290 K). The noise figure is thus the ratio of actual output noise to that which would remain if the device itself did not introduce noise. It is a number by which the performance of a radio receiver can be specified. A typical value of 6 dB may be used for the receiver noise figure (NF).

Table A-6. Receiver Selectivity Characteristics

Parameter	Units
Selectivity bandwidth	MHz
At attenuation level	dB
Rolloff	dB/decade

The receiver selectivity provides an indication of the frequency-domain characteristics for the receiver. The selectivity is defined by the BW of the intermediate frequency (IF) stage at each of several attenuation levels. In general, these levels are the -3, -20, and -60 dB points. The BW and attenuation points define an envelope for the selectivity. The final IF stage is usually selected since it generally provides the most rejection to out-of-band (OOB) signals. In addition, the receiver noise level is usually computed using the -3 dB BW of the final IF stage. The minimum data required for an EMI analysis are the -3 dB BW and the rolloff.

For the analysis of a receiver's frequency-domain characteristics, the midpoint of the -3 dB BW is assumed to be identical to the channel frequency. The selectivity is then symmetric with respect to the channel frequency. The frequency difference, Δf, is the difference between any frequency and the channel frequency.

The rolloff defines the rate of attenuation, in dB per decade of frequency offset, of a selectivity's envelope skirt outside of the -60 dB points. The rolloff may be computed from available selectivity data. In the event of missing data or a large computed value of rolloff, a default rolloff of -80 dB per decade may be assumed.

A.1.4 Antenna

Equipment parameters generally applicable to the antenna and the transmission line are listed in Tables A-7 and A-8, respectively.

Table A-7. Antenna Characteristics

Parameter	Units
Antenna type	
Maximum gain	dBi
Pattern type	
Beamwidth, horizontal	deg
Beamwidth, vertical	deg

The maximum gain is sometimes called the mainbeam gain, although only directional antennas can be said to have a "beam".

The pattern type is a text data item, and typical values are:

- Omnidirectional
- Sector
- Directional

Other pattern types are possible.

An antenna beamwidth is obtained from a pattern for the antenna, and is the angular difference between the half-power (-3 dB) points on the pattern.

Table A-8. Transmission Line Characteristics

Parameter	Units
Line Type	
Line attenuation	dB/m
At frequency	MHz
Length	m

The line type is a text data item, and typical values are:

- Twin lead
- Coaxial cable

Other line types are possible.

The length of the transmission line is either from the transmitter to the antenna or from the receiver to the antenna. All transmission lines have some losses, and the line attenuation is a rating for the line. The loss along a particular section of line is then simply the line attenuation in dB per meter multiplied by the length in meters. Some line ratings are given in terms of dB per 100 feet, so to get dB per meter simply multiply the value in dB per 100 feet by 0.0328. Line ratings given in other units (e.g., dB per foot) may be converted to dB per meter by an appropriate scaling,

B. THEORY

B.1 BASICS

B.1.1 Power Conversions

Power values are expressed either in watts (W) or milliwatts (mW). The power in W may be converted to mW using the following:

$$p_{mW} = 1000\ p_W \qquad \text{(Equation B-1)}$$

where

p_{mW} = power, in mW.

p_W = power, in W.

The power in mW may be converted to W by solving the above equation for p_W.

Power values are often expressed in decibels with respect to a milliwatt, abbreviated dBm. The power in watts may be converted to dBm using the following:

$$P_{dBm} = 30 + 10 \log\ p_W \qquad \text{(Equation B-2)}$$

where

P_{dBm} = the power, in dBm.

p_W = the power, in watts.

A positive value indicates more than one milliwatt, whereas a negative value indicates less than one milliwatt.

The power in dBm may be converted to watts using the following:

$$p_W = 10^{\frac{P_{dBm} - 30}{10}} \qquad \text{(Equation B-3)}$$

where all terms were identified previously.

B.1.2 Antenna Gain Conversions

Antenna gain is often given in dBi units. To convert dBi to a numeric value, use the following:

$$g = 10^{\frac{G}{10}} \qquad \text{(Equation B-4)}$$

where

g = the numeric antenna gain, dimensionless

G = the antenna gain, in dBi

Given the numeric antenna gain, the gain in dBi may be computed as follows:

$$G = 10 \log g \quad \text{(Equation B-5)}$$

where all terms were identified previously.

Note: although less common, gain values are sometimes expressed in units relative to a half-wave dipole, commonly abbreviated as dBd. To convert dBd to dBi, add 2.15 to the value in dBd.

B.1.3 Wavelength

As indicated an EM signal has a frequency and a wavelength. Given the frequency, the wavelength may be computed using the following approximate equation.

$$\lambda = \frac{300}{f} \quad \text{(Equation B-6)}$$

where

λ = the wavelength, in meters

f = the frequency, in MHz.

B.2 NEAR-FIELD/FAR-FIELD DISTANCES

The radiation characteristics of an antenna vary with distance from the antenna. For instance, at large distances, referred to as the far-field region, some radiation characteristics are independent of distance, e.g., the gain is constant as the distance increases. On the other hand, at distances closer to the antenna, referred to as the near-field region, the gain changes with distance.

When two antennas are in the far-field of each other, the activation of one antenna has no effect on the performance characteristics (e.g., impedance, radiation pattern) of the other antenna. When the antennas are in the near-field of each other, on the other hand, the activation of one antenna could modify the performance characteristics of the other antenna.

For low-gain types of antennas (monopole, dipole, whip, rubber ducky), a common value for the distance to the far-field region is four wavelengths. For directive types of antennas (Yagi-Uda), the distance to the far-field region may be calculated using the following equation:

$$D_{FF} = \frac{2 D_{ant}^2}{\lambda} \quad \text{(Equation B-7)}$$

where

D_{ant} = the largest dimension of the antenna, in meters

λ = the wavelength at the system's frequency, in meters

B.3 INCIDENT RADIATION

An EM wave consists of an electric field (E-field) and a magnetic field (H-field). In general, the E-field and the H-field are perpendicular to each other and to the direction (the ray path) that the wave is traveling. The intensity of either field is referred to as field strength, where the intensity of the E-field is measured in volts per meter (V/m) and the intensity of the H-field is measured in amps per meter (A/m). The E-field and the H-field together carry power, where the power flow through space is called the power density, which is measured in watts per square meter.

B.3.1 Effective Isotropic Radiated Power

The effective isotropic radiated power (EIRP) is the defined as the amount of power leaving the antenna into the environment. The EIRP is measured at the output of the antenna and is computed as follows:

$$EIRP = P_t - LL_t + G_t \qquad \text{(Equation B-8)}$$

where

EIRP = the effective isotropic radiated power, in dBm

P_T = the transmitter power, in dBm

LL_T = the line loss, in dB

G_T = the transmit antenna gain, in dBi

If peak transmitter power is used in the above, the result will be peak EIRP; if average transmitter power is used in the above, the result will be average EIRP.

B.3.2 Power Density

The power density, in mW per square meter (mW/m^2) incident on a point may be computed using the following equation:

$$s = \frac{p_T g_T}{4\pi R^2} \qquad \text{(Equation B-9)}$$

where

s = the power density, in mW per square meter

p_T = the transmitter power, in mW

g_T = the transmit antenna gain (near-field or far-field), numeric

R = the distance from the antenna to the point of interest, in m

The power density in dBm per square meter (dBm/m^2) may be evaluated using the following equation:

$$S = 10 \log \left[\frac{p_T \, g_T}{4\pi R^2} \right] \quad \text{(Equation B-10)}$$

where

S = the power density, in dBm per square meter

and all other terms were defined previously.

The power density equations B-9 and B-10 assume that the EM wave radiated by a transmit antenna spreads as in a spherical wave. This is not strictly true in a tunnel, so the resulting values are estimates.

B.3.3 Electric Field Strength

Given a value for the power density incident on a point, the intensity of the electric field may be computed using the following equation:

$$E = \sqrt{120 \, \pi s} \quad \text{(Equation B-11)}$$

where

E = the root-mean-square (rms) E-field strength, in Volts per meter

s = the power density, in Watts per square meter

120π = the impedance of free space, dimensionless

B.3.4 Magnetic Field Strength

Given a value for the power density incident on a point, the intensity of the magnetic field may be computed using the following equation:

$$H = \sqrt{\frac{s}{120 \, \pi}} \quad \text{(Equation B-12)}$$

where

H = the rms H-field strength, in Amps per meter

and all other terms were defined previously.

B.4 ELECTROMAGNETIC PROPAGATION

B.4.1 Free-Space

In general, when two antennas are within line-of-sight of each other, and in the far-field of each other, the level of received power is related to the free-space propagation loss. This loss assumes the EM wave radiated by a transmit antenna spreads spherically. In the absence of a detailed propagation model, the free-space propagation loss may be used to provide an estimate of the loss. The free-space propagation loss along the straight-line path between two antennas may be calculated using the following equation:

$$L_{FS} = 20 \log \frac{\lambda}{4\pi D} \qquad \text{(Equation B-13)}$$

where

L_{FS} = the free-space propagation loss, in dB. Free-space propagation losses do not include any additional diffraction and reflection losses (e.g., reflection, multipath, refraction) along the ray path.

λ = the wavelength at the receive frequency, in meters

D = the distance between antennas, in meters

B.4.2 Tunnel Modeling

In general, the propagation loss should include all of the possible elements of loss associated with interactions between the propagating wave and any object between transmit and receive antennas inside of the mine. There are propagation models that predict the loss for a long or narrow rectangular mine tunnel. It is important to mention that the EM propagation model for mines should include the dimensions of the mine, the electric constants of the walls and roughness of the walls, and the model should be validated with measured data obtained from a mine.

B.4.2.1 Straight Rectangular Tunnel

Suppose a three-dimensional (3-D) straight rectangular tunnel has a width of *a* and a height of *b* (both *a* and *b* are in meters), as shown in Fig. B.4-1

The propagation loss can be modeled [JSC-TR-08-119 2008] as following free-space loss up to a break point distance, and then following a linear decay rate for distances beyond the break point. The propagation loss depends on the polarization of the wave. We are interested only in the EM wave polarization that experiences the least amount of attenuation as it propagates through the tunnel, because this is the wave that will travel the furthest. The polarization that is attenuated the least corresponds with the dimension of the tunnel which is greatest; if the width is greater than the

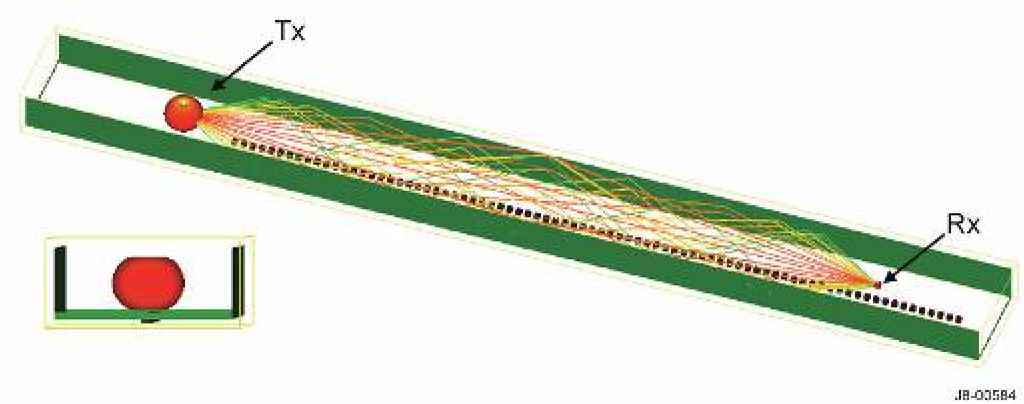

Figure B.4-1 Straight Rectangular Tunnel

height, then the attenuation of the horizontal polarization is lower than for the vertical polarization. The propagation loss and maximum propagation distance can be calculated as follows:

a. Find the break point distance, d_{FSL}, in meters using the following relation:

$$d_{FSL} = 2\left[\frac{b^2}{\lambda}\right] \qquad \text{(Equation B-14)}$$

where b and λ are in meters.

b. Find the free space loss, FSL_{bp}, in dB at the break point distance d_{FSL} using the following equation:

$$FSL_{bp} = 32.4 + 20\log\left[\frac{d_{FSL}}{1000}\right] + 20\log f_{MHz} \qquad \text{(Equation B-15)}$$

where
d_{FSL} = the break point distance, in meters
f_{MHz} = the frequency, in MHz.

c. Determine the far-zone linear decay rate, α_{spe}, in dB/m from:

$$\alpha_{spe} = 8.686\,\alpha_{mn} \qquad \text{(Equation B-16)}$$

where α_{mn} is given by:

$$\alpha_{mn} = \frac{2}{a}\left[\frac{m\lambda}{2a}\right]^2 \frac{1}{\sqrt{\varepsilon_r - 1}} + \frac{2}{b}\left[\frac{n\lambda}{2b}\right]^2 \frac{\varepsilon_r}{\sqrt{\varepsilon_r - 1}} \qquad \text{(Equation B-17)}$$

where:

ε_r = the relative dielectric constant of the wall (typical value is 6)
λ = the wavelength, in meters.
m,n = the mode numbers of the propagation loss inside of the mine. The least attenuated modes, also known as fundamental modes, are when m=1 and n=1.

Note: Equation B-17 is used when *b* > *a*. If *a* > *b* then the same equation is used but *a* and *b* are interchanged in the equation.

d. Find the median path loss as a function of the distance d, where d is in meters:

$$L = 32.4 + 20\log\left[\frac{d}{1000}\right] + 20\log f_{MHz};\ d \le d_{FSL}$$

$$L = FSL_{bp} + \alpha_{spe}(d - d_{FSL});\ d > d_{FSL}$$

(Equation B-18)

e. When the maximum allowable link path loss (L_{max}) is known from the radio and reliability parameters, the following relation may be used to find the corresponding maximum link distance d_{max} (assumed here to be greater than the break point distance $d_{FSL)}$:

$$d_{\max} = \frac{L_{\max} - FSL_{bp}}{\alpha_{spe}} + d_{FSL}$$

(Equation B-19)

B.5 LINK BUDGET ANALYSIS

The objective of a link budget analysis is to catalog all the losses and gains between the two ends of a communication link, thus obtaining the maximum loss in signal strength that can be tolerated between a transmitter and receiver. This maximum allowable loss in signal strength is also known as the available path loss. It is specified in logarithmic units (decibels) and can in turn be translated into the greatest spatial distance between transmitting and receiving antennas, at which reliable communication of the desired quality can still take place. In the context of wireless mobile communication systems, link budgets are a prerequisite to determining the location of, as well as spacing between, antennas or nodes in order to ensure reliable and uninterrupted communication as mobiles move through an area of intended radio coverage.

This subsection describes the method for computing a link budget when a transmitter is attempting to communicate with a receiver.

B.5.1 Desired Received Power

B.5.1.1 Far-Field

When two antennas are in the far-field of each other, the level of desired received power may be computed using the following equation:

$$P_R = P_T + G_T - L_P + G_R - L_{Misc} \qquad \text{(Equation B-20)}$$

where

P_R = the received desired signal power, in dBm.

P_T = the transmitter power, in dBm.

G_T = the transmit antenna gain, in dBi. G_T is the gain in the direction of the propagation ray path.

L_P = the total propagation loss between antennas, in dB. L_P is evaluated at the receive frequency, and includes any additional losses (diffraction, reflection, absorption, etc.) along the ray path between antennas.

G_R = the receive antenna gain, in dBi. G_R is the gain in the direction of the propagation ray path.

L_{misc} = the total of any additional miscellaneous losses, in dB. L_{misc} could include losses either at the transmitter or at the receiver. Examples of such terms are transmission line loss, insertion loss, filtering loss, or any other miscellaneous system loss.

The above equation is the general equation to be used for desired-signal link analysis.

B.5.1.2 Near-Field

In general, when two antennas are within line-of-sight to each other, and in the near-field of each other, it is not possible to separate the propagation loss and the antenna gains into individual terms as in the received power equation (Equation B-20). In this case, ignoring any miscellaneous losses, the level of received power may be computed using the following equation:

$$P_R = P_T + C \qquad \text{(Equation B-21)}$$

where

P_R = the received signal power, in dBm.

P_T = the transmitter power, in dBm.

C = the coupling evaluated at the receive frequency, in dB.

The coupling term, C, must be evaluated using numerical EM software, the details of which are beyond the scope of this tutorial.

B.5.2 Receiver Effective Noise

Many communication receivers are of the superheterodyne type, where the receiver includes several stages, namely, a radio frequency (RF) stage, and one or more IF stages. Analysis is often performed using the level of desired signal at the IF stage having the narrowest bandwidth. This is usually the final IF stage, although this is not always the case.

Electronic circuits, such as in a receiver, generate electrical noise which is referred to as thermal noise. The thermal noise is present at each stage of the receiver. Ignoring any external noise sources, the effective input noise power level at an IF stage is given by:

$$N_T = 10\log\left(kTBf_n\right) + 30 \qquad \text{(Equation B-22)}$$

where

N_T = the receiver's effective input noise power ignoring any external noise, in dBm

k = Boltzmann's constant, which is 1.38×10^{-23} J/K

T = the absolute temperature, in degrees Kelvin. The standard value is 290K (62.3 degrees Fahrenheit).

B = the BW of the IF-stage, in Hertz

f_n = the receiver's noise factor, unitless

The noise factor accounts for additional noise contributions from other stages of the receiver. The receiver noise figure (NF) is 10 times the log of the noise factor. A typical value of 6 dB may be used for the NF.

In an UG mine, electrical noise is generated by sources in the various pieces of mining equipment (e.g., electric motors, belt drives, breaks in power line insulation, etc.). This noise is referred to as man-made noise or environmental noise. Environmental noise in the passband of the receiver enters the receiving antenna, passes unattenuated through the stages of the receiver, and adds to the thermal noise. Including any environmental noise, the effective input noise power level at an IF stage of a receiver may be computed as follows:

$$N = 10\log\left(kTBf_n + n_e\right) + 30 \qquad \text{(Equation B-23)}$$

where

N = the receiver's effective input noise power including any external noise, in dBm

n_e = the environmental noise power in the mine, in W

and all other terms were defined previously.

Note in Equation B-23 that the total level of noise must be found by adding the individual noise contributions in Watts.

B.5.3 Signal-Noise Ratio

The SNR is useful in desired-signal analysis and may be found as follows:

$$SNR = S - N \quad \text{(Equation B-24)}$$

where

SNR = the available signal-to-noise power ratio, in dB

S = the signal power, in dBm.

N = the receiver effective noise power level (including any external noise), in dBm

When S is a measurement or prediction of the available received signal level under certain conditions, then SNR is the available SNR.

B.5.4 Sensitivity

Receiver sensitivity is defined in this subsection. The method for determining sensitivity depends on whether the receiver is designed for analog signals or for digital signals. As indicated previously, an analog signal is one where the signal is continuous over time, and a digital signal is one where the signal is discontinuous over time.

In order for a receiver to detect a desired signal, the signal needs to be higher than the level of the effective receiver noise. Receiver sensitivity is defined as the power level in dBm required for some particular standard response for the receiver. The sensitivity level for a receiver may be computed using the following:

$$S = N + SNR_{req} \quad \text{(Equation B-25)}$$

where

S = the receiver sensitivity, in dBm.

N = the receiver effective noise power level, in dBm

SNR_{req} = the required signal-to-noise power ratio, in dB

Note that the SNR in the above equation is a required SNR, which is different than the available SNR mentioned in the previous subsection.

The next two subsections define methods for determining the required SNRs for analog and digital receivers.

B.5.4.1 Analog Receivers

In an analog receiver, sensitivity is usually defined as the power level in dBm required for a certain level of signal intelligibility.

For voice communications, the articulation score (AS) is defined as the percentage of words, phrases, sentences, or other message elements that have been correctly identified. AS is usually evaluated by a listener panel [JSC-CR-06-072 2006]. The articulation index (AI) is a calculated quantity, ranging from 0.0 to 1.0, and is designed as a predictor of signal intelligibility. For daily working conditions, where the noise levels might be significantly raised due to the mine equipment, the minimum level for AI might be 0.8 or 0.9. In a rescue situation, the minimum AI level might be 0.95, but the mine equipment would likely be off, so the environmental noise levels would be lower.

The sensitivity criterion is the difference between the sensitivity and the effective receiver noise level. For an analog system, the sensitivity criterion is generally a required SNR in dB (other criteria are used, however).

The sensitivity criterion depends on the modulation type of the receiver. Curves of required SNR for various analog modulation types as a function of the AI are available in [JSC-CR-06-072 2006]. A value of 0.9 was selected for the minimum acceptable AI level. Approximate required SNR levels in the presence of noise only are listed in Table B.5-1. If the modulation type is unknown, the minimum typical required SNR for an analog system would be 12 dB.

Table B.5-1. Required SNR Values for Selected Analog Modulation Types

Modulation Description	Min AI	Required SNR (dB)
Double sideband AM voice	0.9	29
Single sideband AM voice	0.9	16
FM voice	0.9	13

B.5.4.2 Digital Receivers

In a digital receiver, sensitivity is usually defined as the power level in dBm required for a specified maximum fraction of errors in the detected pulses or data bits, i.e., the BER. Depending on the application, a typical required BER might be one error in ten thousand bits, or 10^{-4}.

For digital systems, an important parameter is E_b/N_o, which is the required energy per bit relative to the noise power. Curves of required E_b/N_o as a function of the required BER for various digital modulation types are available in [JSC-CR-06-072 2006]. To convert from E_b/N_o to SNR, use the following equation:

$$SNR_{req} = 10\log\left(\frac{E_b}{N_o}\frac{R_b}{B_R}\right) \quad \text{(Equation B-26)}$$

where

SNR_{req} = required SNR, in dB

E_b = energy required per bit of information, in Joules (or Watt-s)

N_o = thermal noise density in 1Hz of bandwidth, in Watts/Hz

R_b = system bit rate (data rate), in bits/s (or Hz)

B_R = receiver IF-stage bandwidth, in Hz

The parameter N_o may be found by using the following:

$$N_o = N / B_R \quad \text{(Equation B-27)}$$

where

N = receiver effective noise level, in dBm

B_R = receiver IF bandwidth, in Hz

If the IF-stage bandwidth, B_R, is not known, it may be estimated from the modulation type and the system bit rate. Table B.5-2 lists typical receiver bandwidths for selected digital modulation types. The receiver bandwidth is given in terms of a multiple of the system bit rate (R_b).

Table B.5-2. Receiver Bandwidths for Selected Digital Modulation Types

Modulation Type	Bandwidth B_R (Hz)
BPSK	$1*R_b$
QPSK	$0.5*R_b$
8-PSK	$0.333*R_b$
4-QAM	$0.5*R_b$
8-QAM	$0.333*R_b$
16-QAM	$.25*R_b$

As for analog systems, the sensitivity criterion depends on the modulation type of the receiver. Given a value of the BER, the required E_b/N_o may be determined from curves for various digital modulation types presented in [JSC-CR-06-072 2006]. A value of 10^{-4} was selected for the maximum acceptable BER level. Approximate required E_b/N_o levels in the presence of noise only are listed in Table B.5-3.

Table B.5-3. Required SNR Values for Selected Digital Modulation Types

Modulation Description	Max BER	Required E_b/N_o (dB)
PSK, 1 bit per symbol (BPSK)	10^{-4}	8.5
PSK, 2 bits per symbol (QPSK)	10^{-4}	8.5
PSK, 4 bits per symbol (8-ary PSK)	10^{-4}	11.5
Coherent FSK, 1 bit per symbol	10^{-4}	11.5
Non-coherent FSK, 1 bit per symbol	10^{-4}	11.5

B.5.5 Fade Margin

B.5.5.1 Analog Receivers

From [JSC-CR-06-072 2006], "the term *fading* applies to unexpectedly large variations in the desired signal power at the receiver. The cause of the variation may be understood, but may be impractical to model. For example, fading may be caused by multipath interference" due to different signal paths from the transmit antenna to the receive antenna. If two paths differ by approximately one-half wavelength, one signal could cancel, or significantly reduce, the other. For instance, as a miner with a hand-held radio moves through a mine, the result could be occasional periods of weak reception known as fades.

Since fading over time and with mobility inevitably introduces variability into the received signal strength, a signal at the receiver that is just equal to the sensitivity would be undetectable much of the time. To overcome the effect of fading, additional signal strength above the receiver sensitivity, called fade margin, must be included in the radio system design.

The minimum signal level required includes the necessary fade margin and may be determined using the following:

$$S_{\min} = S + M_F \qquad \text{(Equation B-28)}$$

where

S_{min} = the minimum signal level required to minimize fading, in dBm

S = the receiver sensitivity, in dBm

M_F = the fade margin, in dB

B.5.5.2 Digital Receivers

Because the path loss between a node and a mobile handheld or fixed subscriber has a random component, and the path loss predicts the median path loss, the fade margin allows taking random fading into consideration. The fade margin is related to the “edge reliability” percentage or also called the “rim coverage” probability. It represents the probability that the received signal level (RSL) at the input of the receiver is greater than the receiver signal threshold (RSL_{Th}) also measured at the input of the receiver. The equation used to determine the fading margin in dB corresponding to a particular value of edge reliability depends on the statistical definition of the fading environment and is given by:

$$P(RSL > RSL_{Th}) = P(x > x_0) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x_0} e^{-1/2(\frac{x-\mu}{\sigma})^2} dx$$

(Equation B-29)

where:

x = receiver signal level (RSL)

x_0 = receiver signal threshold (RSL_{Th})

μ = mean value representing the average received signal level

σ = the standard deviation

The standard deviation (σ) is estimated based on the probability distribution of RSL. For environments with severe attenuation, the number is between 6 and 10 dB. A value of 8 dB is used in the example shown in Table B.5-4. Only field testing can determine the exact value. In the example, the $P(RSL>RSL_{Th})$ for 74% rim coverage, the probability is 0.65.

Table B.5-4. Fade Margin Analysis

Morphology	Mine
Coverage Objective	Mine Coverage
Area Coverage Probability	90% (n=4)
Rim Coverage Probability	74%
Standard Deviation (dB)	8
Fade Margin (dB)	0.65 * 8 = 5.2

B.5.6 Maximum Separation Distance

Given the minimum signal level required to minimize fading, the maximum coverage distance may be computed using the following:

$$D_C = \frac{\lambda}{4\pi}\sqrt{\frac{p_T g_T g_R}{s_{\min}}} \qquad \text{(Equation B-30)}$$

where

D_C = the maximum coverage distance, m

p_T = the transmitter power, mW or W

g_T = the transmitting antenna gain, numeric

g_R = the receiving antenna gain, numeric

λ = the wavelength at the frequency of interest, m

s_{min} = the minimum signal level required to minimize fading, mW or W

Note that p_T and s_{min} must be in the same units. In addition, the coverage distance may be different if a propagation mode other than free space applies.

B.5.7 Passive Reflectors

Flat passive reflectors may be used in a mine to enhance the coverage into a cross tunnel. The reflector is arranged so that radiation from a transmitter reflects incident radiation into the cross tunnel. This configuration may have a lower path loss than a non-reflector configuration that is controlled by diffraction and scattering around the corner.

The effect of a passive reflector may be estimated by an approximate method where the reflector is modeled as if it is a receiving antenna [White 1975]. In this method, the gain of a passive reflector depends as follows on the frequency of the radio signal, the area of the reflector, and the included angle of the reflection:

$$G_{reflector} = 20\log_{10}\left[\frac{4\pi A\cos\alpha}{\lambda^2}\right] \qquad \text{(Equation B-31)}$$

Where:

$G_{reflector}$ = Passive reflector gain, dB

A = Reflector area, m^2

α = One-half the included angle of the reflection, degrees

λ = Wavelength of the radio signal, m

Note that the reflector dimensions and wavelength must be expressed in the same units in the above equation. The gain in Equation (B-31) may be re-written in convenient units as:

$$G_{reflector} = 22.2 + 40\log_{10} F_{GHz} + 20\log_{10} A_{sq.ft.} + 20\log_{10}\cos\alpha \qquad \text{(Equation B-32)}$$

Note that the area in the above equation is in square feet. For a link budget of a configuration that includes a passive reflector, first compute the propagation loss in dB along each leg of the complete path (i.e., transmitter-to-reflector and reflector-to-receiver). Parameter L_P in Equation B-20 is then the sum of the propagation losses along the two legs minus the reflector gain $G_{reflector}$.

The most typical use of a reflector in a mine would be to help re-direct a portion of a radio signal's power in a mine entry down a crosscut (or vice versa). As an example, for a right-angle crosscut, the included angle of the reflection in this geometry is 90º (α is 45º) and the gain of a 4-square-foot reflector at 2.45 GHz would be 46.8 dB.

B.5.8 Node Placement – Percentage of Coverage Overlap

The percentage of coverage is given by taking the total distance between nodes and multiplying by 100% minus the desired mobile unit overlap percentage to obtain the actual distance between nodes. For this tutorial, a desired mobile unit overlap of 25% is based on measurements of a typical cellular system. This approach ensures that the mobile unit has a 25% overlap between nodes. Higher overlapping area ensures reliable coverage but increases the cost. See B.5.9.3 for further discussion of coverage overlap.

B.5.9 Applications

B.5.9.1 Link Budget – Node-to-Node

The node-to-node link budget is calculated between two node units. The sample node-to-node link budget (Table B.5-5) calculates the maximum tolerable path loss between two adjacent nodes to obtain the maximum path distance between nodes to have acceptable and reliable communications.

Table B.5-5. Sample Node-to-Node Base Link Budget

Node-to-Node Link Parameters	Value	Basis	Source
Node Tx Power (dBm)	20.0	a	Manufacturer
Node Tx Power (Watts)	0.1	b	Manufacturer
Node Tx Antenna Gain (dBi)	8.0	c	Manufacturer
Node Cable Loss (dB)	1.0	d	Manufacturer
Node EIRP (dBm)	27.0	a+c-d	Section B.3.1
Fade Margin (FM) (dB)	5.2	e	Section B.5.5.2
Node Rx Antenna Gain (dBi)	8.0	f	Manufacturer
Node Cable Loss (dB)	1.0	g	Manufacturer Section A.1.4
kT (dBm/Hz)	-174	h	Constant* Section B.5.2
Node Noise Figure (dB)		i	Manufacturer
Baud rate (dBHz) (i.e. 10 Mbps)		j	Manufacturer

Average (Eb/No) (dB)		k	Section B.5.4.1
Node Rx Sensitivity (dBm)	-90	RSL=k+j+i+h or Given	Section B.5.4.1 or Given
Maximum Link Path Loss (dB)	118	L=a+c-d-e+f-g-RSL	B.4.2
Frequency (GHz)	2.4		Manufacturer
Maximum Distance (m)	400	Section B.4.2	Calculated

*kT = Boltzmann's Constant (1.38 * 10^{-23} Joules/ΔK) x Room Temperature (290K) = -174 dBm/Hz

B.5.9.2 Link Budget – Mobile-to-Node

The link budget calculates the maximum tolerable path loss for the reverse link and for the forward link, and then it takes the smaller of the two maximum loss values to determine the maximum distance of coverage.

The sample mobile-to-node reverse link budget (Table B.5-6) is calculated from the mobile unit to the node unit. The reverse link budget calculates the maximum tolerable path loss between the mobile and the node to obtain the maximum path distance that the node will cover to tolerate an acceptable and reliable communications.

Table B.5-6. Sample Mobile-to-Node Reverse Link Budget

Reverse Link Parameters	Value	Basis	Source
Mobile Tx Power (dBm)	15	a	Manufacture
Mobile Tx Power (Watts)	0.0316	b	Manufacture
Mobile Antenna Gain (dBi)	0.0	c	Manufacture
Mobile EIRP (dBm)	15	a+c	Section B.3.1
Body Loss (dB)	2.0	d	Manufacture
Fade Margin (FM) (dB)	5.2	e	Section B.5.5.2
Node Receiver Antenna Gain (dBi)	8.0	f	Manufacture
Node Cable Loss (dB)	1.0	g	Manufacturer Section A.1.4
kT (dBm/Hz)	-174	h	Constant* Section B.5.2
Node Noise Figure (dB)		i	Manufacture
Baud rate (dBHz) (i.e. 10 Mbps)		j	Manufacture
Mixed Mobility Average (Eb/N0) (dB)		k	Section B.5.4.1
Node Rx Sensitivity (dBm)	-90	RSL=k+j+i+h Given	Section B.5.4.1 or Given
Maximum Reverse Link Path Loss (dB)	104.8	L=a+c-d-e+f-g-RSL	Section B.4.2
Frequency (GHz)	2.4		Manufacture
Maximum Distance (m)	302	Section B.4.2	Calculated

*kT = Boltzmann's Constant (1.38 * 10^{-23} Joules/ΔK) x Room Temperature (290K) = -174 dBm/Hz

The sample node-to-mobile link budget (Table B.5-7) is calculated from the node unit to the mobile unit. The forward link budget calculates the maximum tolerable path loss between the node and the mobile to obtain the maximum path distance that the node will cover to tolerate an acceptable and reliable communications.

Table B.5-7. Sample Node-to-Mobile Forward Link Budget

Forward Link Parameters	Value	Basis	Source
Node Tx Power (dBm)	20	a	Manufacturer
Node Tx Power (Watts)	0.1	b	Manufacturer
Node Tx Antenna Gain (dBi)	8.0	c	Manufacturer
Node Cable Loss (dB)	1.0	d	Manufacturer Section A.1.4
Node EIRP (dBm)	28	a+c-d	Section B.3.1
Fade Margin (FM) (dB)	5.2	e	Section B.5.5.2
MS Rx Antenna Gain (dBi)	0.0	f	Manufacturer
Body Loss (dB)	2.0	g	Manufacturer
kT (dBm/Hz)	-174	h	Constant* Section B.5.2
Node Noise Figure (dB)		i	Manufacturer
Baud rate (dBHz) (i.e. 10 Mbps)		j	Manufacturer
Mixed Mobility Average (Eb/N0) (dB)		k	Section B.5.4.1
Mobile Rx Sensitivity (dBm)	-90	RSL=k+j+i+h Given	Section B.5.4.1 or Given
Maximum Link Path Loss (dB)	109.8	L=a+c-d-e+f-g-RSL	Section B.4.2
Frequency (GHz)	2.4		Manufacturer
Maximum Distance (m)	339	Section B.4.2	Calculated

*kT = Boltzmann's Constant (1.38 * 10-23 Joules/ΔK) x Room Temperature (290K)
= -174 dBm/Hz

B.5.9.3 Node Placement – Percentage of Coverage Overlap

Near the edge of a node's coverage, fading may cause reduced reliability of the communication link with mobile users. Designing the coverage of adjacent nodes to overlap increases the reliability of mobile connections in the edge region since it is less likely the link with both nodes will fade at the same time. For overlapping coverage, nodes are placed at a fraction (100% minus the desired mobile unit overlap percentage) of the maximum possible communication distance. For this tutorial, a mobile unit overlap of 25% is suggested based on measurements of a typical cellular system. This approach ensures that the mobile unit has a 25% overlap between nodes. Higher overlapping area increases reliability of coverage but also increases the cost.

From the example, the maximum distance between the mobile unit and the node is 302 m, therefore the distance between nodes is (2*302)*0.75 = 453 m to ensure 75% rim coverage probability with a coverage overlap of 25%.

B.6 ELECTROMAGNETIC INTERFERENCE ANALYSIS

The objective of an EMI analysis is to compute the level of undesired power received by a possible victim receiver. It is similar to a link budget, but all the losses and gains from a potential source system to the victim are catalogued.

This subsection describes the method for EMI analysis when an undesired signal from a transmitter is present at a receiver.

B.6.1 Frequency Coincidence

Major EMI interactions are based on the following cases of frequency coincidence between a transmitter and a victim receiver:

- Co-channel (CC) interference occurs when a transmitter and receiver share the same frequency band and their tuned frequencies are identical or very close to each other. Energy from the emission spectrum overlaps the receiver's passband.
- Adjacent-channel (AC) interference occurs when a transmitter and receiver share the same frequency band and their tuned frequencies are not identical but close to each other. Energy contained in the emission spectrum sidebands overlaps the receiver selectivity.
- Adjacent-band (AB) interference occurs when a transmitter and receiver are in different frequency bands and their tuned frequencies are close to each other. Energy contained in the emission spectrum sidebands overlaps the sidebands of the receiver selectivity.
- Harmonic (HR) interference occurs when a transmitter and receiver are generally in different frequency bands and the frequency of a transmitter harmonic is identical or very close to the receiver's tuned frequency. The undesired energy is at an integer multiple of the transmitter's fundamental frequency.

The CC, AC, and AB cases tend to be of most concern because of the high power involved at the fundamental frequency. HR cases are of less importance because of the reduced transmitter power and any antenna OOB effects, but still a concern.

Frequency coincidence for the four frequency coincidence cases may be determined by comparing the tuning bands of the two subsystems. Frequency coincidence definitions are given below.

B.6.2 Undesired Received Power

When two antennas are in the far-field of each other, the level of undesired received power may be computed using the following equation:

$$I = P_T - L_{OOB} + G_T - L_P + G_R - FDR - L_{Misc} \qquad \text{(Equation B-33)}$$

where

I	= the received undesired signal power, dBm.
P_T	= the transmitter power at the fundamental frequency, dBm.
L_{OOB}	= a correction factor to account for an interaction at an OOB frequency, dB. For a harmonic interaction, L_{OOB} is applied to the transmitter power.
G_T	= the transmit antenna gain, dBi. G_T is the gain in the direction of the propagation ray path.
L_P	= the total propagation loss between antennas, dB. L_P is evaluated at the receive frequency, and includes any additional losses (diffraction, reflection, absorption, etc.) along the ray path between antennas.
G_R	= the receive antenna gain, dBi. G_R is the gain in the direction of the propagation ray path.
FDR	= the frequency-dependent rejection (FDR), dB. See Section B.6.3 for a description of this parameter.
L_{misc}	= the total of any additional miscellaneous losses, dB. L_{misc} could include such terms as antenna loss at an OOB frequency, filtering loss, or miscellaneous system loss.

The above equation is the general equation to be used for EMI analysis. Since the undesired signal may be at a frequency different than the tuned frequency for the receiver, the above equation includes terms to account for OOB effects.

B.6.3 Frequency-Dependent Rejection

FDR consists of two components. The on-tune rejection (OTR) component is due to the difference in BWs between the selectivity and the emission spectrum, assuming that the receiver and transmitter are tuned to the same frequency (i.e., the difference in frequencies, Δf, is zero). The off-frequency rejection (OFR) component is due to any off-tuning between the transfer functions representing the selectivity and the emission spectrum. FDR is related to OTR and OFR by the following:

$$FDR = OTR + OFR \qquad \text{(Equation B-34)}$$

where FDR, OTR, and OFR are all in dB.

When the BW of the selectivity is greater than or equal to the BW of the emission spectrum, the receiver accepts all of the power of the undesired signal. Hence, the OTR term is zero for this case. On the other hand, when the BW of the selectivity is less than the BW of the emission spectrum, the receiver accepts only a portion of the power, and the magnitude of the OTR term is greater than zero. OTR is independent of Δf.

The OFR term is a function of Δf. The OFR term is zero when the receiver and the transmitter are tuned to the same frequency and its magnitude increases as Δf increases.

An approximate, conservative method, referred to as Quick FDR [JSC-CR-97-010 1997], may be used for the evaluation of FDR. Inputs to the calculation of Quick FDR are the -3 dB BW of the IF stage selectivity and the -3 dB BW of the emission spectrum. Other inputs are the rolloff of the selectivity and the spectrum. Each rolloff defines the rate of attenuation with respect to frequency. Rolloff values, in dB per decade of frequency, are computed from the IF selectivity and emission spectrum data. In the absence of data, typical rolloffs are -40 dB per decade and -80 dB per decade for the transmitter and the receiver, respectively.

B.6.4 Interference-Noise Ratio

The interference-to-noise power ratio (INR) is useful in undesired-signal analysis and may be found as follows:

$$INR = I - N \qquad \text{(Equation B-35)}$$

where

INR = the available interference-to-noise power ratio, dB

I = the undesired signal power, dBm.

N = the receiver effective noise power level (including any external noise), dBm.

When I is a measurement or prediction of the available undesired signal level under certain conditions, then INR is the available INR. As for the desired-signal analysis, N is the effective noise power in the -3 dB passband of the receiver's narrowest IF stage.

B.6.5 Undesired Signal Power Threshold

The undesired signal power threshold is the maximum allowable received power that a receiver can accept without degradation of its performance. The undesired signal power threshold, I_T, may be computed using the following:

$$I_T = N + INR_T \qquad \text{(Equation B-36)}$$

where

I_T = the undesired signal power threshold, dBm

N = the receiver effective noise power level (including any external noise), dBm

INR_T = the interference-to-noise threshold, dB

Note that the INR_T in the above equation is a threshold INR, which is different than the available INR mentioned in the previous subsection. A negative value of INR_T

is usually selected so that the threshold is below the receiver effective noise level. A typical value is -6 dB.

As a numerical example, suppose that the effective noise level, N, in a receiver's IF bandwidth is -120 dBm. Also, suppose that the interference threshold, INR_T, is -6 dB. The maximum allowable received power, I_T, to avoid receiver degradation would then be -126 dBm.

B.6.6 Interference Margin

A parameter referred to as the interference margin or EMI margin may be computed to quantify the level of EMI. The EMI margin may be computed using the following:

$$M = I - I_T \qquad \text{(Equation B-37)}$$

where

M = the EMI margin, dB

I = the received undesired power, dBm

I_T = the undesired signal power threshold, dBm

The EMI margin may be interpreted as the additional loss that would be required to reduce the undesired received power to a level below the threshold. Continuing the example from the previous subsection, if I is computed to be -100 dBm, the EMI margin would be 26 dB.

B.6.7 Required Frequency Separation

The required frequency separation (RFS) may be computed using a loss, L_{RFS}, that is similar to the EMI margin, but with FDR excluded. L_{RFS} would be the loss required for the received power to be equal to the receiver threshold given an off-tuning between the transmitter and the receiver. L_{RFS} may be computed using the following equation:

$$L_{RFS} = P_T - L_{OOB} + G_T - L_P + G_R - L_{Misc} - N - INR_T \qquad \text{(Equation B-38)}$$

where all terms were defined previously. Given a value for L_{RFS}, the RFS may be evaluated using multiple calls to Quick FDR where a search algorithm is employed to determine the frequency difference that would result in a loss approximately equal to L_{RFS}.

B.7 HAZARDS OF ELECTROMAGNETIC RADIATION

One of the concerns of introducing wireless systems in a coal mine is potentially hazardous EM radiation from transmitting systems. The concerns include hazards of EM radiation to:

- Personnel
- Blasting caps
- Explosive atmospheres.

B.7.1 Threshold Levels

B.7.1.1 Personnel

For HERP, levels of MPE were obtained from [IEEE C95.1 2005] and [47 CFR 1.1310]. Certain of the MPE levels of [47 CFR 1.1310] were determined to be lower than those of [IEEE C95.1 2005], and were used in the analyses. Reference [IEEE C95.1 2005] notes that the exposure limits in the frequency range from 100 MHz to 1500 MHz are generally based on guidelines from [47 CFR 1.1310].

Exposure of personnel to hazardous radiation is tiered based upon frequency. All of the following assume an external, sinusoidal-based, electromagnetic field in a controlled environment. A controlled environment is defined in [IEEE C95.6 2002] as "an area that is accessible to those who are aware of the potential for exposure as a concomitant of employment, to individuals cognizant of exposure and potential adverse effects, or where exposure is the incidental result of passage through areas posted with warnings, or where the environment is not accessible to the general public and those individuals having access are aware of the potential for adverse effects."

The following are from Table 1, Limits for Occupational/Controlled Exposures, of [47 CFR 1.1310]:

0.3-3.0 MHz

RMS electric field strength should not exceed 614 V/m averaged over 6 minutes.

RMS magnetic field strength should not exceed 1.63 A/m averaged over 6 minutes.

Note: for frequencies below 30 MHz, [IEEE C95.1 2005] mandates that both the E and the H fields be computed. [IEEE C95.1 2005] does not indicate the reason for this, but presumably it is to account for possible near-field effects. For any systems with frequencies in the range of 0.3 to 3.0 MHz, both fields were computed.

3.0-30 MHz

RMS electric field strength should not exceed $1842/f_{MHz}$ V/m averaged over 6 minutes, where f_{MHz} is the frequency in MHz. .

RMS magnetic field strength should not exceed $4.89/f_{MHz}$ A/m averaged over 6 minutes.

Note: for frequencies below 30 MHz, Reference 1 mandates that both the E and the H fields be computed. For any systems with frequencies in the range of 0.3 to 3.0 MHz, both fields were computed.

30 – 300 MHz

RMS electric field strength should not exceed 61.4 V/m averaged over 6 minutes.

RMS magnetic field strength should not exceed 0.163 A/m averaged over 6 minutes.

300 – 1500 MHz

Average power density should not exceed f_{MHz}/300 milliwatts per square centimeter (mW/cm^2) averaged over 6 minutes.

1.5 – 100 GHz

Average power density should not exceed 5 mW/cm^2 averaged over 6 minutes.

B.7.1.2 Blasting Caps

The applicable threshold for a blasting cap is its no-fire level of power. The threshold level was obtained from [IEEE C95.4 2002].

From [IEEE C95.4 2002], the specification or measured no-fire threshold of the blasting cap should be used, if known. If unknown, the typical no-fire threshold, 40 mW (16 dBm) average power, should be used.

B.7.1.3 Explosive Atmospheres

Applicable thresholds for an explosive atmosphere were obtained from [IEC 60079-0 2007]. [IEC 60079-0 2007] lists thresholds of radio frequency devices operating over a frequency range from 9 kHz to 60 GHz. The thresholds are presented for five different groups representing different environments. UG coal mines fall under Group 1.

The thresholds are defined with respect to a "thermal initiation time." From [IEC 60079-0 2007], the thermal initiation time is the time during which energy deposited by a spark accumulates in a small volume of gas around it without significant thermal dissipation. For times shorter than the thermal initiation time, whether or not ignition occurs depends on the total energy deposited by the spark. For times longer than the thermal initiation time, whether or not ignition occurs depends on the effective radiated power.

For systems capable of continuous transmissions, the threshold is given in terms of the "threshold power" in watts. This threshold also applies to systems capable of pulsed transmissions, where the pulse width exceeds the thermal initiation time. For Group 1, Table 4 of [IEC 60079-0 2007] defines the transmitter threshold power level to be 6 watts, and the thermal initiation time to be 200 μs.

From [IEC 60079-0 2007], threshold power is defined to be the effective output power of the transmitter multiplied by the antenna gain. In equation form, this is expressed as follows:

$$p_{thr} = p_T g_T$$ (Equation B-39)

where

p_{thr} = the transmitter's threshold power, W

p_T = the transmitter power at the input to the antenna, W

g_T = the maximum far-field transmit antenna gain, numeric.

Maximum transmitter power and maximum far-field transmit antenna gain were used in computing the threshold power. An antenna's gain value is most often relative to an isotropic antenna, a theoretical concept where radiation is equal in all directions. From the above, the threshold power is then identical to the EIRP.

For systems with a pulsed waveform, where the pulse width is less than the thermal initiation time (200 μs), the standard is defined in terms of the maximum threshold energy of the pulsed transmission in μJ. Table 5 of [IEC 60079-0 2007] defines the maximum threshold energy level to be 1500 μJ for Group 1.

The threshold energy may be computed using the following:

$$w_{thr} = p_T g_T \tau$$ (Equation B-40)

where

w_{thr} = the transmitter's threshold energy, μJ

τ = the transmitter's pulse width, μs

and other terms were defined previously.

B.7.2 Required Separation Distances, VHF Bands and Above

For systems having tuned frequencies in the VHF band and above, the RSDs were computed using transmitter power, far-field antenna gain, and free-space equations. Equations for computing the RSDs are presented in this subsection.

While antenna radiation is strongest in the near-field region, near-field antenna effects were not considered in the calculation of the RSDs because of time constraints and a lack of detailed antenna data. Nevertheless, for safety reasons, a field/power density multiplier was included in the calculation of the RSDs (see below).

For systems having tuned frequencies in the MF band, far-field antenna gain and free-space conditions are not applicable. Order-of-magnitude values of the fields and received power values were estimated using a manufacturer's data.

B.7.2.1 Power Density Threshold

The power density incident on a point may be computed using the following equation [Balanis 2005]

$$s = \frac{c^2 p_T g_T}{4\pi R^2} \qquad \text{(Equation B-41)}$$

where

s = the average power density, W/m^2

c = a constant multiplier to account for reflections

p_T = the transmitter power, W

g_T = the far-field transmit antenna gain, numeric.

R = the distance from the antenna to the point of interest, m.

In the analyses, maximum transmitter power and maximum far-field antenna gain were used. If p_T and g_T are maximum values for the system, then s is the maximum average power density.

As indicated, c is a multiplier that was included to account for reflections. For one perfect reflection, the constant c would have value 2.0, indicating that twice the field would be incident on some point in space. From Equation B-41, four times the power density would be incident. Similarly, for two perfect reflections, constant c would have value 3.0, indicating that three times the field, or nine times the power density, would be incident on the point.

For an MPE expressed in terms of threshold power density s, the RSD may be computed by solving Equation B-41 for R:

$$R = \sqrt{\frac{c^2 p_T g_T}{4\pi s}} \qquad \text{(Equation B-42)}$$

where

R = the RSD, m

s = the threshold power density, W/m^2

and all other terms have been defined previously.

B.7.2.2 Electric Field Threshold

For an MPE expressed in terms of electric field strength E, the electric field strength may be related to the power density. From [Kraus 1992], the relationship is as follows:

$$s = \frac{E^2}{120\pi}$$ (Equation B-43)

where E is the RMS electric field strength in Volts/m and s was defined previously.

The RSD may be computed by substituting Equation B-43 into Equation B-41 and simplifying:

$$R = \sqrt{\frac{30c^2 p_T g_T}{E^2}}$$ (Equation B-44)

where E is the threshold RMS electric field strength in V/m and all other terms have been defined previously.

B.7.2.3 Magnetic Field Threshold

For an MPE expressed in terms of threshold magnetic field strength H, the magnetic field strength may be related to the threshold power density. From [Kraus 1992], the relationship is as follows:

$$s = 120\pi H^2$$ (Equation B-45)

where H is the RMS magnetic field strength in Amps/m and s was defined previously.

The RSD may be computed by substituting Equation B-45 into Equation B-41 and simplifying:

$$R = \sqrt{\frac{c^2 p_T g_T}{480\pi^2 H^2}}$$ (Equation B-46)

where H is the threshold RMS magnetic field strength in A/m and all other terms have been defined previously.

B.7.2.4 Received Power Threshold

The power received by an antenna, or a wire acting as an antenna may be computed using the following equation [Balanis 2005]

$$p_R = p_T g_T g_R \left(\frac{\lambda}{4\pi R} \right)^2$$ (Equation B-47)

where

p_R = the received power at the output of the receiving antenna, W

p_T = the transmitter power, W

g_T = the transmitting antenna gain, numeric.

g_R = the receiving antenna gain, numeric.

λ = the wavelength at the frequency of interest, m

R = the distance between antennas, m

In the analyses, maximum transmitter power and maximum far-field antenna gains were used, so that p_R is the maximum average received power.

In the case of a blasting cap, it was assumed that a wire or a pair of wires connected to the cap is acting incidentally as a "receiving antenna." The wire or wires were assumed to be a half-wavelength long at the frequency of the transmitter, so the numeric gain [Balanis 2005] would be 1.64.

For a threshold, p_{thr}, expressed in terms of received power, the RSD may be computed by substituting p_{thr} for p_R and solving Equation B-47 for R:

$$R = \frac{\lambda}{4\pi}\sqrt{\frac{c^2 p_T g_T g_R}{p_{thr}}} \qquad \text{(Equation B-48)}$$

where R is the RSD in m.