



NIOSH Mining Safety and Health Content

Tutorial on Wireless Communications and Electronic Tracking Part 2: Advanced

1.0 Introduction

In 2006, three major underground coal mine accidents in the United States claimed the lives of 19 miners and prompted lawmakers to pass the Mine Improvement and New Emergency Response Act (MINER Act) of 2006. One of the requirements of the MINER Act is to provide wireless [two-way communications](#) and location information between underground workers and surface personnel following an underground accident. At the time of the accidents in 2006, most coal mine communications systems consisted of either leaky feeder systems or pager phones. A few mines had electronic [brass-in/brass-out](#) systems or zone-based tracking, but location tracking throughout the entire mine was not a common practice. Since then, efforts to develop new [radio](#) communications and personnel tracking technology have resulted in many new systems on the market for underground mine applications, and new systems continue to be introduced. New communications technologies include radio node [network](#) systems, such as [mesh](#) and [Wi-Fi](#); improved [leaky feeder systems](#); low-frequency, [through-the-earth systems](#); [medium frequency radios](#); and combinations of these technologies. New personnel electronic tracking technologies include [radio frequency identification \(RFID\)](#) and radio ranging techniques. Due to the increasing availability of new systems, the Mine Safety and Health Administration (MSHA) requires underground coal mines to have compliant communications and electronic tracking (CT) systems installed by June 15, 2011.



The new CT technology that is available may be unfamiliar to mining professionals who need to purchase, install, and use this technology. To provide a better understanding of CT technology, a two-part tutorial has been developed by the Office of Mine Safety and Health Research (OMSHR), a division of the National Institute for Occupational Safety and Health (NIOSH), which consists of an overview of the available technologies (Part 1) and advanced details on how available systems operate (Part 2). The reader should review the [Tutorial on Wireless Communication and Electronic Tracking - Part 1: Technology Overview](#) online before studying this document - Part 2: Advanced.

Readers of this tutorial are assumed to be associated with coal mining, and therefore familiar with coal mining operations and terminology, and to have a technical background in electronics and/or communications systems. This tutorial is meant for those who need detailed information to compare systems and whose job responsibilities require advanced knowledge. For example, the mine's communications expert will need to understand how the underground environment influences the performance of CT systems, how different CT systems work, and their advantages and disadvantages.

This tutorial provides an advanced discussion of the available CT technologies and operating characteristics starting with general communications system performance considerations in Section 2.1. This is followed by descriptions of specific technologies used for both [primary communications](#) (daily use, high bandwidth) and [secondary communications](#) (emergency use, low bandwidth). A comparison of the available technologies is presented in Section 2.6. Chapter 3 provides details on the operation and performance of the available miner tracking systems.

A critical question related to CT technology is, "What happens after a major accident?" Chapter 4 discusses issues related to survivability and reliability. Chapter 5 discusses safety issues such as MSHA certification of electronics used in explosive atmospheres, safe battery designs, and concerns related to electromagnetic fields. Chapter 6 discusses considerations related to the [mine operations center \(MOC\)](#) on the surface. There are also two appendices; Appendix A provides CT systems engineering specifications, and Appendix B gives basic wireless CT theory including link budget analysis and [electromagnetic interference \(EMI\)](#). A list of technical references and standards are also included at the end of this tutorial for further information. The italicized words in the text of this document are hyperlinked directly to the [Mine Communications and Tracking Glossary](#).

2.0 Communications System Performance

2.1 General Performance Considerations

The discussion of [wireless communications systems](#) begins by considering the general characteristics of the systems and addressing the following questions:

- What is necessary to establish communications between two radios?
- What [frequency](#) or frequencies are appropriate for use in a mine?
- What frequency or frequencies must not be used to avoid potential interference?
- How much [radio frequency \(RF\)](#) power is allowable for use in underground coal mines?
- How much bandwidth is needed?
- What is [bit error rate \(BER\)](#), and how is it related to reliability?
- 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?

Another important consideration is the basic type of wireless communications system, i.e., primary or secondary. [Primary communications systems](#) are those used by miners for providing daily underground and surface communications throughout their shift. These systems are typically hand-held devices operating in the conventional radio bands (e.g., [very high frequency \(VHF\)](#), [ultrahigh frequency \(UHF\)](#), 2.4 GHz, 5.8 GHz). [Leaky feeder](#) and [node-based systems](#) are examples of such primary systems. [Secondary communications systems](#) are those which operate in nonconventional frequency bands (100 Hz to 1 MHz) and are not readily portable, but they may be more likely to remain operational following a mine accident or disaster. [Medium frequency \(MF\)](#) and [through-the-earth \(TTE\)](#) systems are examples of secondary systems that may provide survivable [alternative paths](#) to primary communication systems. All of these systems will be discussed in more detail in the following sections of this chapter.

2.1.1 Physical Communications Link

The essence of communications between two radios is the establishment of a [physical communications link](#) between the devices. Figure 2-1 shows the factors that contribute to the simplest communications link between a [transmitter](#) (Tx) and a [receiver](#) (Rx). The radio frequency (RF) power flows from the sender (transmitter) 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.

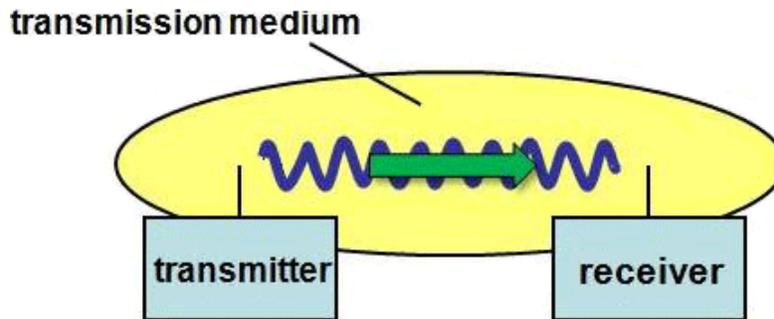


Figure 2-1. Components of a simple wireless communications link.

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. Because the path loss increases with distance, the maximum allowable path loss can be used to estimate the maximum possible separation distance 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 path loss is calculated as follows:

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

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 Rx antenna gain (G_r). Any additional losses, such as cable losses, are categorized as a miscellaneous term (L_{misc}). All terms are in [decibel \(dB\)](#) units; the antenna gains are in [Decibel \(dBi\)](#); 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, which means that 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 (mine-specific) consideration. The equation yields the [allowable 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 2.1.4.

At very low frequencies (less than about 10,000 Hz), EM waves can propagate directly through the earth. At somewhat higher frequencies (100-1,000 kHz), EM waves couple to, and are transported by, metallic conductors. At even higher frequencies (greater than about 100 MHz), 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 (Equation 1) 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 communications link, the primary information transferred is either voice or text messages, or data messages from a sensor. 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), but 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 contains a speaker or piezoelectric crystal, and oscillations of the speaker diaphragm or crystal convert the pressure waves into electrical signals.

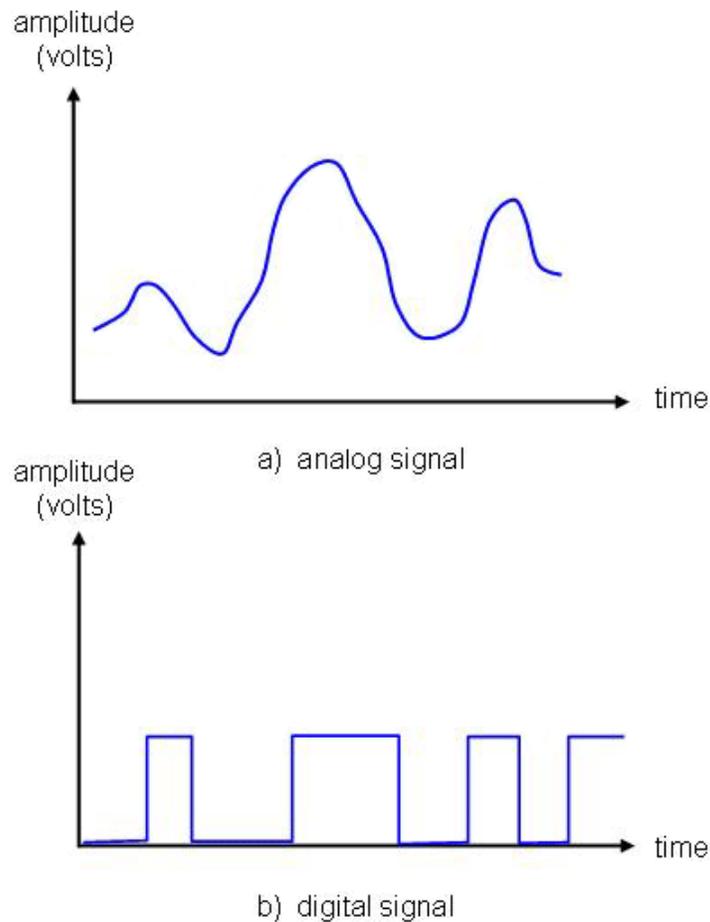


Figure 2-2. Analog and digital signals.

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 2-2a. 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 2-2b.

Current CT systems can 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 of being able to be read, stored, and manipulated by computers. 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 2-3a shows a simplified analog transmission model (the message transmits as an analog signal). The source (transmitted) message, which might be voice or data, can be in analog or digital format. A device called a [modulator](#) combines the analog or digital signal with the [carrier frequency](#) (the assigned or advertised frequency of operation); i.e., the modulator varies the carrier frequency along with the analog or digital signal. The modulated signal travels to the transmitter, where the analog message is sent out over the medium. When an analog signal arrives, the process repeats in reverse order, or [demodulates](#), to recover the analog message.

Figure 2-3b shows a digital transmission system. The [Encoder/decoder\(codec\)](#), also called a [codec](#) when applied to analog signals, digitizes the analog signal by sampling it at certain time intervals as shown in Figure 2-4. There are several methods of digitizing analog signals; one is discussed briefly below.

Figure 2-4a illustrates the digitization of an analog signal. Figure 2-4b 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, $(1 - (-1)) / 256 \sim 7.8$ 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 2-4c shows what a reconstructed signal might look like.

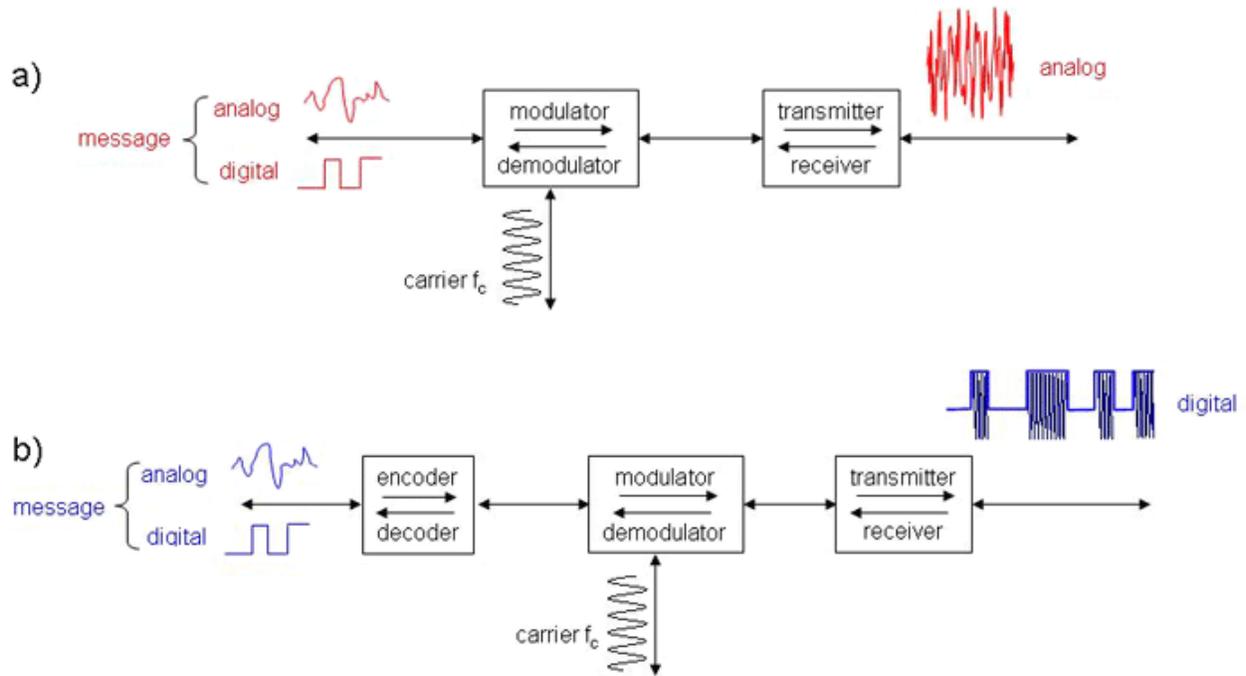


Figure 2-3. Simplified analog and digital communications models.

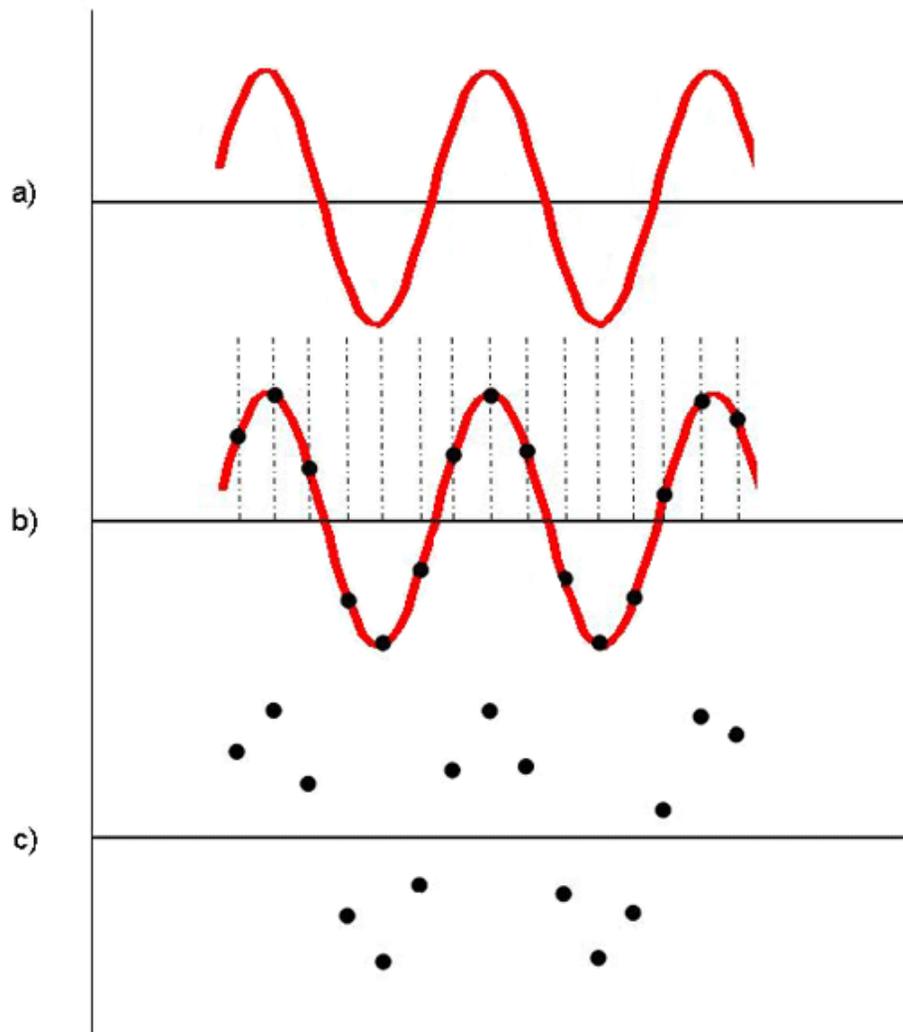


Figure 2-4. Digitization of an analog signal.

The data rate, 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]:

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

(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 [signal-to-noise ratio](#) (SNR) (S/N in Equation 2) increases, the channel capacity (C) also increases. If the noise power (N) increases but the signal level remains fixed, S/N decreases as does the channel capacity (C). 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 (*noise*) inserted somewhere between the transmission and reception process. 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 following formula (Equation 3):

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

where

- N = noise power (watts),
- k_B = Boltzman's constant (1.38×10^{-23} J/K),
- T = system temperature (Kelvin scale), 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 shown in Equation 4 as follows:

$$N = (1.38 \cdot 10^{-23} \text{ J / K})(290\text{K})(80,000\text{Hz})$$

$$N = 3.2 \cdot 10^{-13} \text{ mW}$$

$$N = -125 \text{ dBm}$$

$$\text{Receiver noise floor} = -125 + 7 = -118 \text{ dBm}$$

(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 are frequency shift keying (FSK), phase shift keying (PSK), and orthogonal frequency shift keying (OFSK) [Stallings 2007]. 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* (SNR) which is 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 each bit is associated with a distinct waveform. Consequently, bits have several properties that derive from their waveform representation:

- The bit duration T_b (sec) 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:

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

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.

If the value of E_b/N_o is known, the SNR is:

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

where

R = data rate,
 B = channel bandwidth (Hz).

Equation 8 suggests that if the data rate (R) increases, the SNR must also increase. If a larger bandwidth signal is used, the required SNR decreases.

Figure 2-5 shows BER plots for PSK and OFSK modulation schemes. Acceptable BER values typically range from 10^{-3} to 10^{-6} [Freeman 2005]. As an example in applying the equations above, if the acceptable BER is given as 10^{-6} , the required data rate is assumed to be $R = 40$ kilobits per second (kbps) for digital voice channel communications, and the modulation technique is PSK, then Figure 2-5 gives the corresponding E_b/N_o value of about 10.4 dB or a numeric value of 11, and the following Equation 9 is derived from Equation 8:

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

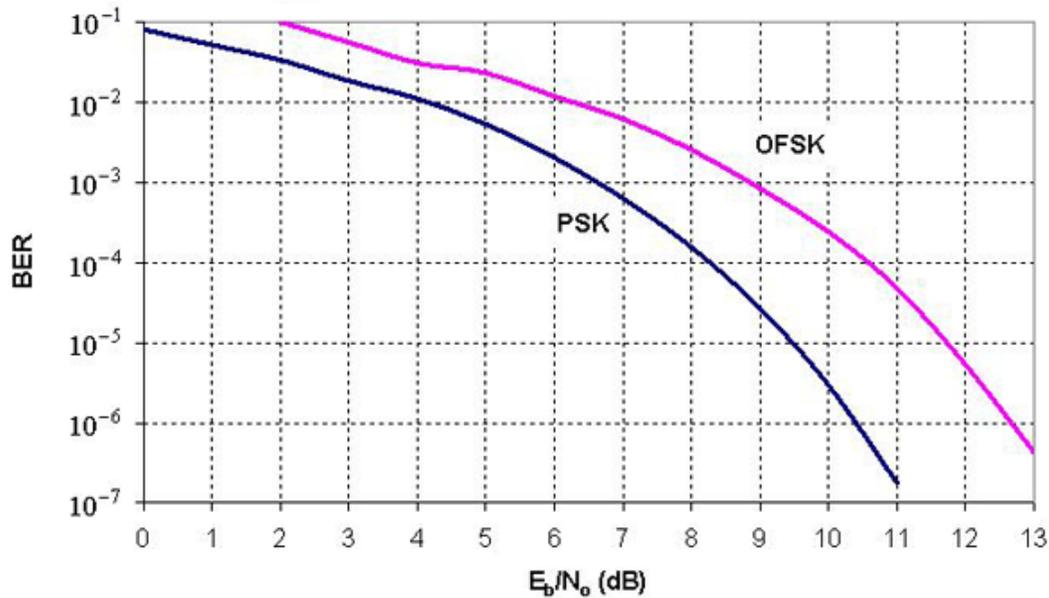


Figure 2-5. Probability of bit error rate (BER) for two modulation methods [Freeman 2005].

For this example, the receiver signal must be 7.4 dB above the receiver noise floor, therefore:

$$P_r = \frac{\text{receiver signal}}{\text{level threshold}} = -118 \text{ dBm} + 7.4 \text{ dB} = -110.6 \text{ dBm}$$

(10)

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 minimum receiver power is increasing. This increasing power affects the path loss of Equation 1. The maximum path loss depends on the magnitude of P_r ; as the magnitude of the minimum P_r increases (as in the example above), 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 2-6 illustrates a more complicated communications path between the sender (transmitter) and receiver, but one that is also more common. The Tx and Rx access a network (inside the dashed line in this figure) 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.

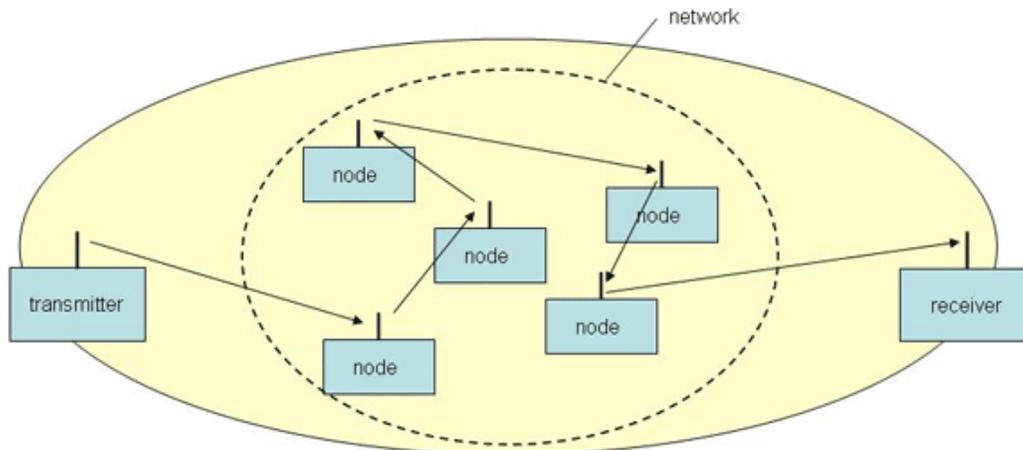


Figure 2-6. Communications via a network.

2.1.2 Networks

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, i.e., < 600 m (2,000 ft) 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 2-7 shows several basic types of 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 links.

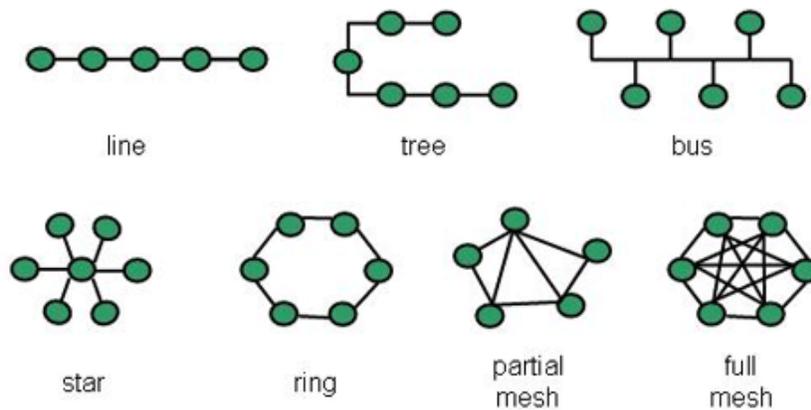


Figure 2-7. Examples of standard network topologies.

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 *working face*) of 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 accesses one of the nodes with his radio link, but the signal could take multiple paths to reach the intended receiver. In addition, if one node fails, there are multiple paths around the failed node. However, it is unlikely that the full-mesh topology would ever be implemented in an underground 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.

2.1.3 Management of the Electromagnetic Spectrum

The MINER Act of 2006 requires mine operators to install wireless, or partially wireless (see MSHA Program Policy Letter No. P11-V13, April 28, 2011), communications and tracking systems into a mine environment that previously has had a very limited number of intentional RF emitters (transmitters, wireless remote controls, etc.). Consequently, there is the potential for electromagnetic interference (EMI). EMI occurs in a system when undesired electromagnetic (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 or being the victim of RF radiation which causes unacceptable degradation in the system itself. EMC is established when any potential EMI between systems has been eliminated or reduced to an acceptable level. EMC has two aspects: (a) a system should not generate EM disturbances that causes a malfunction in another system (usually referred to as the emission aspect) and (b) 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 the frequencies at which these devices work. [Spectrum management](#) is the term that indicates the management of the use of radio frequencies. Table 2-1 lists possible radio frequency emitters in a coal mine.

Table 2-1. Potential RF emitters in a coal mine

Frequency	Application	Comments
300-10,000 Hz	Personal emergency devices	Through-the-earth communications
70-500 kHz	Proximity detection devices	Audible and visual warning
300-800 kHz	Medium frequency radios	Voice, text
150-175 MHz	VHF leaky feeder systems	Voice and low bandwidth data
400-410 MHz	Miner or asset tracking systems	Radio frequency identification (RFID)
450-470 MHz	UHF leaky feeder systems	Voice and low bandwidth data
490 MHz	Remote-operated continuous miner	Remote control of continuous miner
900 MHz	Active radio frequency identification (RFID) tags	RFID to track miner's location
900 MHz	Line-of-sight radios	Voice, text
900 MHz	Rescue robots	Robot control
2.4 GHz	Rescue robots	Video
2.4 GHz	Line-of-sight radios	Voice, text

Another source of interference is noise, which consists of random electrical voltages. EM noise can originate within a radio receiver as discussed previously, or it can be external in origin. External noise can be classified as either manmade noise or as natural noise. In a coal mine, manmade EM noise can 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 the mine.

2.1.4 Modeling and Analysis

The link budget analysis, 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.

Aboveground, hand-held radios can achieve 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 waves radiated by the Tx antenna travel through the surrounding medium, losing energy as they travel. This process is called EM wave propagation, and results in a propagation loss (path loss). As an example, consider the EM propagation of [ultrahigh frequency \(UHF\)](#) waves in a mine entry. It is possible to describe the path loss by modeling the tunnel as a waveguide [Emslie et al. 1975]. EM waves can propagate only if the [wavelength](#) is less than 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 (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 ($L_{\text{insertion}}$) 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 mentions 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 (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 crosscut, but these losses will not be discussed further here. Equation 11 gives the *line-of-sight (LOS)* path loss for UHF propagation down an entry for the effects previously discussed. Each of the constants (C) may depend on the wavelength of the UHF wave, the height and width of the entry, and the electrical properties (relative dielectric constants) of the walls, floor, and roof.

$$L_p (dB) = 2L_{insertion} + (C_{mode} + C_{wall} + C_{tilt}) \left(\frac{z}{100} \right) \quad (11)$$

Representative values of the terms on the right side of the equation are (assuming a 14-ft-wide by 7-ft-high entry, frequency of 900 MHz, wall roughness of 4 in, 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 1,000 ft is 72 dB. Equation 11 indicates that as the distance z increases, the path loss increases as expected. The dependence of L_p on mine-specific features illuminates the difficulty in applying generic CT performance statements to all mines.

As seen above, the propagation loss may depend on the surrounding medium (wall, roof, floor roughness), any blockages along the path (e.g., mining equipment), 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 may also be necessary to determine the required spacing between antennas or an alteration of the frequency used by the source and victim (receiver).

2.1.5 Maintenance and Testing

Coal mine communications and tracking systems require periodic maintenance for optimum performance. 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 backups. These batteries need to be checked periodically to ensure they are operational. Even rechargeable batteries in hand-held devices have a terminable lifetime associated with them, requiring periodic replacement.

To verify that the coverage is fully functional, periodic testing of CT systems is a necessary routine in the mine. 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 will likely involve spot checks of communications links using a series of "Can you hear me now?" interchanges between underground and surface users.

2.1.6 Performance Metrics and Goals

Performance metrics and *performance goals* 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 in relation to the 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 in troubleshooting. Quantitative metrics are directly measured or involve numbers that can be explicitly assigned—for example, [bit error rates \(BERs\)](#), [received signal strength indications \(RSSI\)](#), 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:

- Able to provide two-way communications.
- Able to determine a miner's location.
- Easy to use.
- Easy to install and maintain.
- Safely operable in both pre- and post-accident scenarios.
- Reliable in both normal and emergency situations.
- Survivable in being able to remain operational post-accident.

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

- What mechanical and explosive forces and extent of damage must the system survive?
- How often should the system be tested, and how is it verified to be properly functioning?
- How long does a system have to remain operational post-accident?
- What percentage [reliability](#) or [availability](#) is required of a system?
- What is the maximum acceptable time for routine maintenance and repairs?
- What is the maximum acceptable delay for a miner's message to reach the surface (during normal operations and/or post-accident)?
- What constitutes sufficiently safe operation of battery-powered devices in a potentially explosive (methane and/or coal dust) 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 linear parameter measured in feet or miles. Aboveground coverage 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 survivability and reliability are not well suited to underground applications.

2. **The underlying system requirements 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 of 2006. Aboveground, 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 tradeoffs 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 (potential ignition sources).
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 aboveground. In addition, aboveground companies have ready access to service 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. Suitable tools to measure and predict performance in an underground mine environment are limited.
- b. Personnel expertise, experience, and historical data to formulate performance metrics in the underground mine environment are limited.
- c. At this time there is very little information relevant to CT systems in any underground mine disaster scenarios that are usable for determining system requirements.

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

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 NIOSH 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.
- **Communications and tracking 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 possibly related to system productivity, such as system capacity, cost per foot or 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 in Table 2-2 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 2-2. Example performance goals and metrics of CT systems

General Category	System	Performance Metric	Long-Term Goal
Coverage and range	Comm.	Wireless coverage	Everywhere miners go
Coverage range	Tracking	Tracking system reporting area	Everywhere miners go
Functionality	Comm.	Wireless communications capability	Voice and 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	Tracking	Tracking data storage requirements	To be developed*
Functionality	Tracking	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 and safety
Functionality	Both	Mine operations center (MOC) surface requirements	Real-time graphical display of miners, batteries, and faults/alerts
Functionality	Both	Interoperability	Voice and data communications to all devices and locations
Functionality	Both	Battery maintenance and monitoring	Reliable monitoring of battery conditions with alarms
Installation and maintainability	Comm.	Coverage verification	Monthly verification through "drive" tests
Functionality	Tracking	Tracking system update interval	To be developed*

Functionality	Tracking	Tracking system resolution	To be developed*
Functionality	Tracking	Miner location update interval	To be developed*
Installation and maintainability	Both	Maintenance and 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	MSHA Program Policy Letters (PPL)
Survivability	Comm.	Battery life - communications fixed infrastructure	96 hrs - indefinite with power management
Survivability	Tracking	Tracking system survivability	Invulnerable infrastructure
Survivability	Tracking	Battery life - tracking mobile	To be developed*
Survivability	Tracking	Battery life - tracking fixed infrastructure	96 hrs - indefinite with power management
Survivability	Both	Battery life	Unlimited
Post-accident safety	Both	Battery system safety	Invulnerable infrastructure
Post-accident safety	Both	Permissibility or safe air validation post-disaster	Invulnerable infrastructure

***Note:** "To be developed" indicates that the development of long-term goals is expected through consideration of ongoing research efforts. These efforts include detailed analysis of the history, types, and duration of disasters in coal mines.

2.1.7 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 are typical.

2.1.8 Point-to-Point Communications

Throughout this tutorial, there is a distinction between a direct [communications link](#) between a sender and receiver (one link) 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. A wired connection links the two devices. Another example is a pair of walkie-talkies (i.e., hand-held radios). They operate similarly to the intercom system, but the connection between the sender and receiver is wireless. [Through-the-earth \(TTE\)](#) communications is another example of P2P communications. An antenna on the surface communicates directly to an antenna in the mine, with only the earth strata 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 underground at locations far from the area directly below the surface antenna. P2P provides limited communications between two devices, but to extend the communications range requires additional components in the path (i.e., some type of network or a large distributed antenna system such as a leaky feeder).

2.1.9 Wired Communications

Most mines use some type of wired communications system, 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 conveyor monitoring and control, [ethernet](#) networks, and pager phones.

2.1.9.1 Twisted Pair

A [twisted pair](#) consists of two insulated copper wires twisted around each other. Sometimes the installation uses multiple wire pairs grouped into a single cable. For example, home telephones are connected using a twisted pair. A twisted pair is the least expensive hardwire connection medium.

Standard pager telephones 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 on the phone activates the amplifiers in all the phones so that the message broadcasts to anyone within hearing range of a phone.

2.1.9.2 Ethernet Cable

Ethernet cable is generally an eight-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. These kinds of Ethernet cable are referred to as CAT5E (for LANs) and CAT6 (for Internet) cable; computers are frequently interconnected using this type of cable. Mine sensor data and/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 in place of coaxial cable or fiber-optic cable. Coaxial cable has lower signal losses and generally better shielding than CAT5E/CAT6 or twisted pair connections, and therefore is less susceptible to electromagnetic interference (EMI). However, coaxial cable is also more expensive than twisted pair.

2.1.9.3 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. This type of cable can replace copper communications cables. Fiber-optic cable uses 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 because 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. Fortunately, manufacturers are continually improving the fiber-optic cable designs, making them more robust and more cost-competitive.

2.1.10 Primary and Secondary Communications

Primary communications systems are those used by miners throughout their shifts that provide normal daily underground and surface communications. These systems operate in the conventional radio bands (e.g., VHF, UHF, 2.4 GHz, 5.8 GHz). They use small antennas that allow miners to have wearable devices with long battery life (lasting longer than one shift), and have sufficient throughput for general mining operations. Leaky feeder and node-based systems are examples of primary communications systems.

Secondary communications systems are those which operate in nonconventional frequency bands (100 Hz to 1 MHz). At such low frequencies they require large antennas which are not readily portable or are installed at fixed locations. Also, because of the low frequencies, they do not have sufficient throughput for communicating during general mining operations. Secondary systems have very few active components and appear to have a high potential for surviving a disaster. Medium frequency (MF) and through-the-earth (TTE) systems are examples of secondary systems that may provide survivable alternative paths to primary systems. It should be noted that primary communications systems are potentially vulnerable to a mine emergency or disaster (methane and/or coal dust explosion, roof or rib fall, water inundation, etc.). Survivability of primary systems to these events can be questionable, depending upon the severity and location of the incident.

One approach is to provide an alternate communications path which is truly diverse and highly reliable. It would not have any shared components between the primary and alternate paths that would fail from a common event. A borehole directly to the miner would be the ideal alternate communications path, but a moving borehole is not very practical. Secondary systems with their limited infrastructure needs offer a great potential for an alternate communications path, particularly near the face.

One other possible option is to consider a hybrid system that assumes interoperability between the primary and secondary systems—that is, design the systems in such a way that a low bandwidth secondary communications system would be used as a [backup system](#) for the primary communications system. A key goal would be to ensure that miners would still be able to communicate using the same wearable device as used for day-to-day operations.

2.2 Primary Communications: Leaky Feeder Systems

2.2.1 Description

A [leaky feeder](#) communications system uses underground hand-held radios that communicate with a radio [transceiver](#) (base station), which is usually located on the surface at the [mine operations center \(MOC\)](#), and other hand-held radios carried by the miners underground. Specially designed leaky feeder cable greatly extends the effective range of the base station. The link from the hand-held radio to the cable is wireless. Figure 2-8 shows one type of leaky feeder cable. The cable acts as a distributed antenna, able to receive and transmit radio signals along its entire length. 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 2-8. Cutaway 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; however, UHF leaky feeder systems are becoming more prevalent. VHF frequencies typically 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 are also more costly. However, because of their higher frequency, UHF systems can accommodate larger bandwidths and, therefore, handle more data at higher speeds. In addition, UHF signals from the hand-held radios propagate more efficiently than VHF signals around corners and into crosscuts in the mine. Thus, UHF systems allow the miner to maintain communications when further away from the leaky feeder cable than do VHF systems.

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

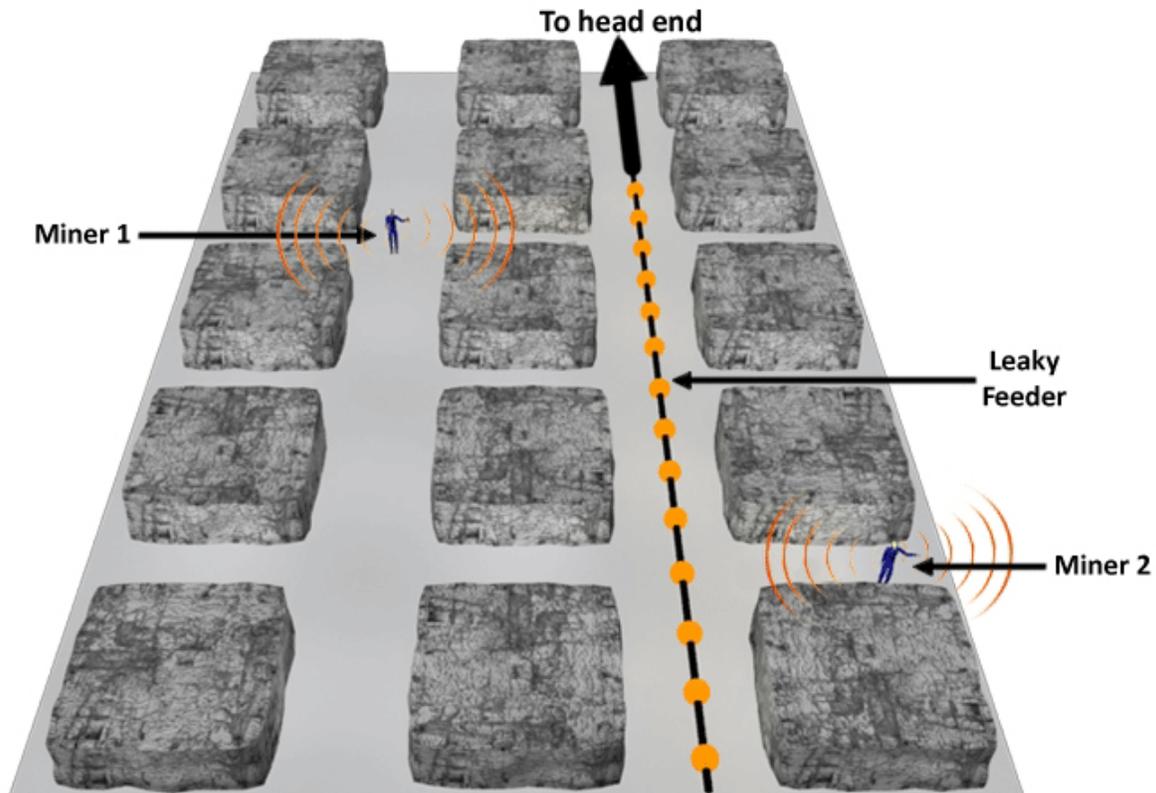


Figure 2-9. Leaky feeder communications system.

2.2.2 Components

A leaky feeder system consists of 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 MOC and traveling into the 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 (see Figure 2-10). 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 2-11 in Section 2.2.3) and are referred to as [downlink](#) or [downstream](#) transmissions. Radio communications originating within the mine travel along the feeder cable "up" to the base station, and are referred to as [uplink](#) or [upstream](#) transmissions. The uplink and downlink frequencies are not the same because the head end performs a frequency shift before retransmitting the message. Hence, the hand-held 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. Likewise, a UHF radio might transmit at 470 MHz and receive at 450 MHz.

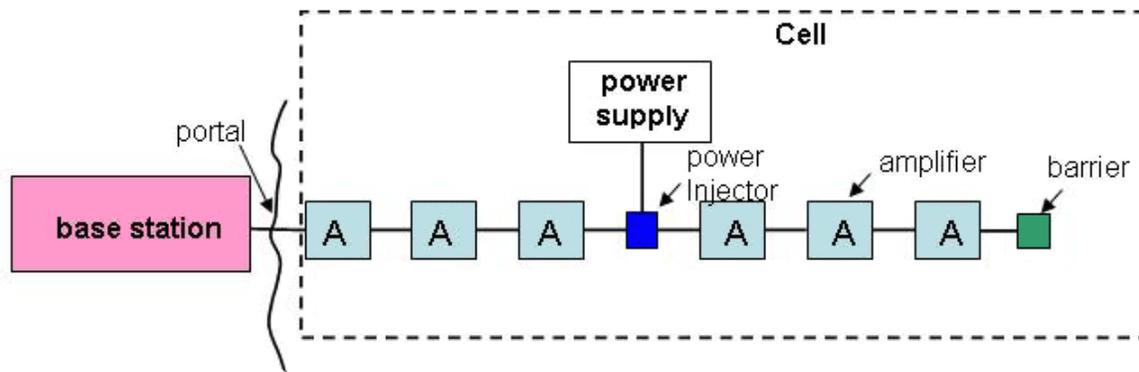


Figure 2-10. Main components of a leaky feeder system.

Note that communications signals between the MOC and the mine portal use a nonradiating cable so that the signals do not radiate from the cable on the surface. However, once underground, this nonradiating 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 that amplification can occur on signals traveling in either direction. Bidirectional amplifiers become particularly important when considering the survivability of the system. Section 2.2.5 discusses this issue in more detail.

The leaky 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 amplifiers spaced approximately 450-550 meters (1,500-1,800 feet) apart along straight segments, depending on the frequency and any insertion losses caused by hardware on the line. Figure 2-10 illustrates an example of the periodic placement of line amplifiers in a leaky feeder cable.

Many amplifiers use [automatic gain control \(AGC\)](#). AGC ensures that the power level of the output signal of an amplifier remains constant and independent of 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 [power cells](#) or 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 mining industry to allow the systems to operate in a possibly explosive atmosphere (e.g., methane, coal dust). The requirement is related to the stored energy in the leaky feeder cable, and operators need to ensure that the length of the leaky feeder cable and the size of the "cells" do not exceed what was approved by both the manufacturer and MSHA 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 hand-held 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 [hardwired](#) 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 that does not have leaky feeder cable. Auxiliary antennas come in a variety of shapes and sizes and can address a number of radio coverage requirements. [Termination antennas](#) on the end of the feeder cable (sometimes called [slope antennas](#)) also 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, thereby avoiding harm to a higher-quality (and more expensive) cable. Because a leaky feeder cable can be installed practically anywhere, this is a good solution for areas where obstructions may prevent adequate coverage by an auxiliary antenna.

As the name implies, a [terminator unit](#) is at the end of a leaky feeder cable. A terminator unit is a component attached to the end of the leaky feeder cable and minimizes reflections or undesirable effects due to abrupt changes in cable impedance at its ends.

2.2.3 Transmission Media

Figure 2-11 illustrates the communications between two miners talking over their hand-held radios, incorporating two intermediate physical links, each with two parts. The first link, typically called the [uplink](#), is from the sender's radio to the head end in the base station, consisting of the circled parts 1 and 2 in the diagram (Figure 2-11). The circled part 1 is through the air from the sender's radio to the leaky feeder cable. 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 also consists of two parts. The first part of the link, indicated as part 3 in the diagram, follows 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 to the receiver (part 4).

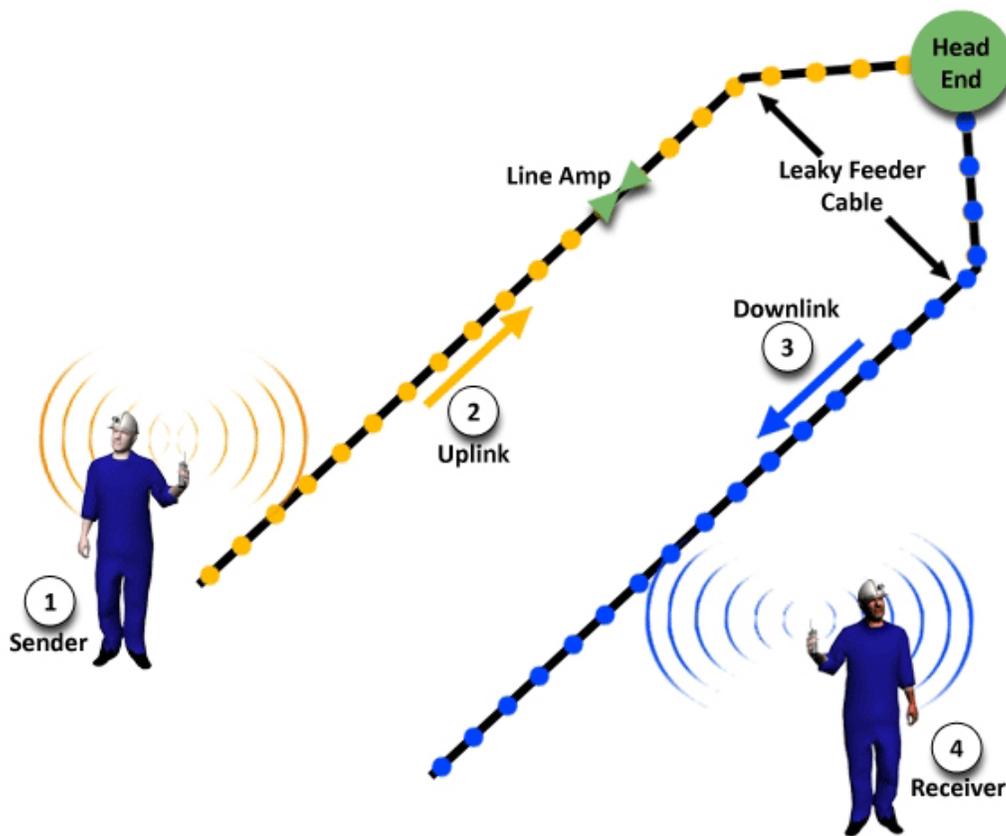


Figure 2-11. Communications link between sender and receiver.

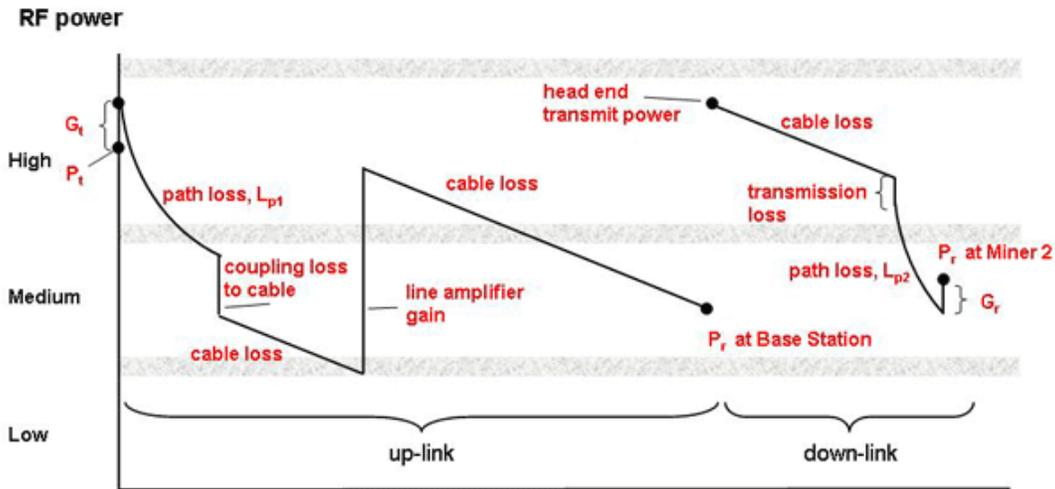


Figure 2-12. Conceptual link budget analysis for leaky feeder system.

Each of the four parts can have individual link budget analysis which, when combined, determine if the entire physical link is feasible. Figure 2-12 is a graphical illustration of the link budget analysis. Starting the uplink analysis at the left side of the graph is the sender's radio transmit power (P_t) and an immediate jump to account for the radio's transmit antenna gain (G_t) which is assumed to be positive. The next link is the free-space path loss of the RF signal traveling through the air. Next, 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 by the gain of the line amplifier. 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 link budget 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 mentioned before, there is further loss as the RF signal travels through the air. However, there can be an increase in RF power assuming that the receiving antenna has positive gain. The final number is the received power (P_r) in the receiver's radio. The 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/or the receiver can affect the free-space path loss through the air by their actions. For example, 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 leaky feeder cable, the physical link ceases to be viable.

2.2.4 Network Operations

Figure 2-10 introduced the *power 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 2-13 shows the linear topology schematically.

It may be desirable to have communications in parallel entries, in which case a tree topology (Figure 2-14) is used. Because all communications must travel through the head end, it acts as the base of the tree.

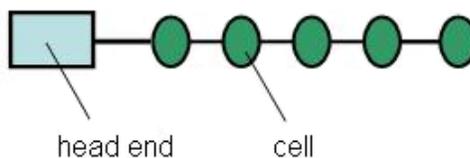


Figure 2-13. A leaky feeder system using a linear topology.

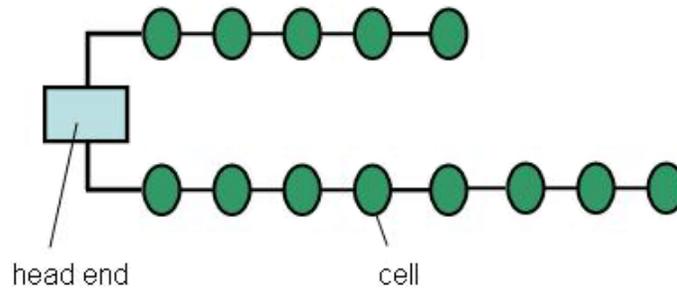


Figure 2-14. A leaky feeder system using a tree topology.

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.

2.2.5 System Implementation

The inherent linear nature of the leaky feeder system makes it especially suited for providing radio coverage in long entries. Figure 2-15 demonstrates one method in which radio coverage is extended down parallel entries.

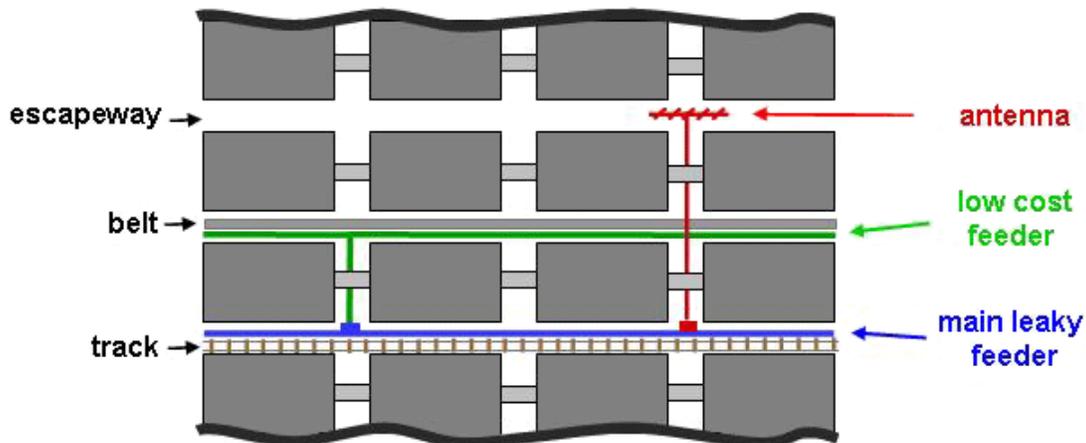


Figure 2-15. Ways to expand radio coverage of a leaky feeder system.

Figure 2-15 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 also be used to extend radio coverage to strategic areas.

However, it should be noted that the linear nature of the leaky feeder makes it vulnerable to certain failures. For example, if a roof fall either 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 may remain operational in the case of a localized roof fall that breaks the main cable. In this case, any miners cut off from the main communications could move to another entry to re-establish communications with the surface.

Providing an *alternate communications path (ACP)* carries the idea of a *redundant path* to enhance communications survivability one step further. An ACP reaches the surface at a point separated by a significant distance from the normal communications exit point. Figure 2-16 shows an example where the main leaky feeder exits the mine at an elevator shaft. An accident such as a methane or coal dust explosion breaks the main communications link. An ACP provides a leaky feeder exit to the surface through an airshaft or borehole. A surface connection re-establishes communications between the miners inby the accident and the MOC 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, as shown in Figure 2-16, if the sender is inby the accident but *outby* the ACP to the surface, the sender's message

would have to change its propagation direction. Special bidirectional leaky feeder amplifiers in the cable will permit this reversal of direction.

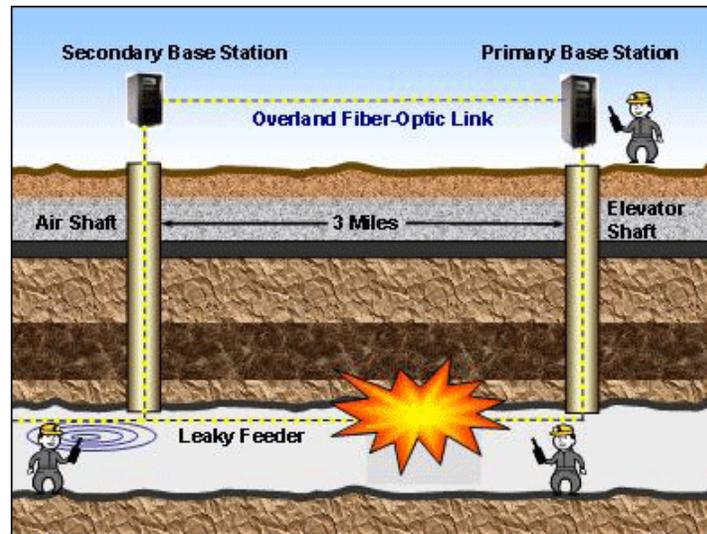


Figure 2-16. Example of an alternate communications path (ACP).

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 nonconducting 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 can also help to protect the cable.

For safety reasons, the mine may shut off electrical power following a major mining accident. Because each cell of the leaky feeder requires electrical power for the line amplifiers, the leaky feeder system would become inoperable unless each cell has MSHA-approved backup batteries or battery packs.

2.2.6 Maintenance and Inspection

The first indication that a leaky feeder communications system is not functioning is typically the inability to communicate between the MOC dispatcher and a worker in the mine with a hand-held radio. Modern leaky feeder systems come with built-in diagnostic capabilities that help troubleshoot a problem. The diagnostics vary from manufacturer to manufacturer and may be available in the form of an upgrade or option. For example, line 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 text or graphical 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 line amplifiers), and displays the information in tabular or trend form or as graphical information in a mine map system. The main *arterial cable* of a leaky feeder system is typically in the track or main haulage entry, and the line amplifiers with diagnostic LEDs would also be in that entry. It would therefore be relatively simple for a maintenance worker to ride in a vehicle in that entry to locate and reset or replace the line 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 used 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 cable to provide radio coverage in other entries, or antennas used to extend coverage in other entries. When using a redundant loop for survivability, periodic testing is needed to check the operational status of the loop function. All enhancements and their components can and must periodically be tested and inspected visually to make sure they are functioning correctly when needed.

For communications system components that are installed in *explosion-proof (XP) enclosures* as per MSHA directives, 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) Part 30 regulations [30 CFR Part 18.31] [1]. In addition, if a hydrogen sensor is required (for MSHA approval) in enclosures with batteries, the hydrogen sensor requires periodic scheduled maintenance. Also, the batteries themselves must be checked periodically for *state-of-charge (SOC)* and *state-of-health (SOH)* 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, and whether the cable should be placed in a metal or plastic conduit. Obviously, the cable must be checked periodically for integrity. In the wintertime, leaky feeder components near the intake air must be capable of functioning in temperatures well below 0°F. All leaky feeder components must be

checked periodically for functionality.

2.2.7 Performance and 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 both 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 near the rib, so that it is out of the way of haulage vehicles and miners walking through 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 generally 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. However, VHF systems will lose radio 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 mining equipment or material obstructing the crosscut.

There are various techniques for extending 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 often achieve communications over 670 m (2,200 ft) along the cable in the belt entry. In addition, antennas (including [yagi antennas](#), a highly directional antenna, and [helical antennas](#)) can extend coverage 300 m (1,000 ft) in an open entry.

Installing independent arterial cables 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.

When using a redundant loop to increase system survivability, if a major event takes out multiple entries that include 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 may need to walk a short distance to re-establish communications, depending on what leaky feeder components were affected by the event, and where those components were located in the leaky feeder cell structure.

Mined-out areas are often sealed off in order 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 interface with other types of communications and tracking systems. For example, they can interface with UHF 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 successfully conducted interfacing medium-frequency (MF) communications systems (e.g., 500 kHz) with a leaky feeder system, where the MF system was used to bridge a gap for a simulated leaky feeder cable break [Damiano 2011].

It is important to note that it is difficult to provide complete mine-wide communications coverage with leaky feeder systems. However, with proper coverage extension schemes and redundant or alternative communications approaches, most areas where miners work and travel can have high-quality communications signals, with a good chance of survivability in the event of a mine emergency.

2.3 Primary Communications: Node-Based Systems

2.3.1 Description

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 this section, the focus will be on wireless node-based systems in the frequency range from 0.5 GHz to 6 GHz. Although this range extends beyond the conventional UHF band (300 MHz - 3 GHz), for simplicity, it will be referred to as UHF in this tutorial.

In node-based systems, the first communications link is through the air, which is from the miner's hand-held radio to a wireless node, 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 connections 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, 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, and/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 UHF or VHF 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 include line, bus, tree, ring, star, and mesh (See Section 2.1.2 for more detail on topologies). 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 from the mining community because of the ease of building in redundant routes.

A [mobile device](#), such as a hand-held 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 2-17; the orange dots indicate the propagation of the signal between blue WAPs and finally to the hand-held radio receiver.

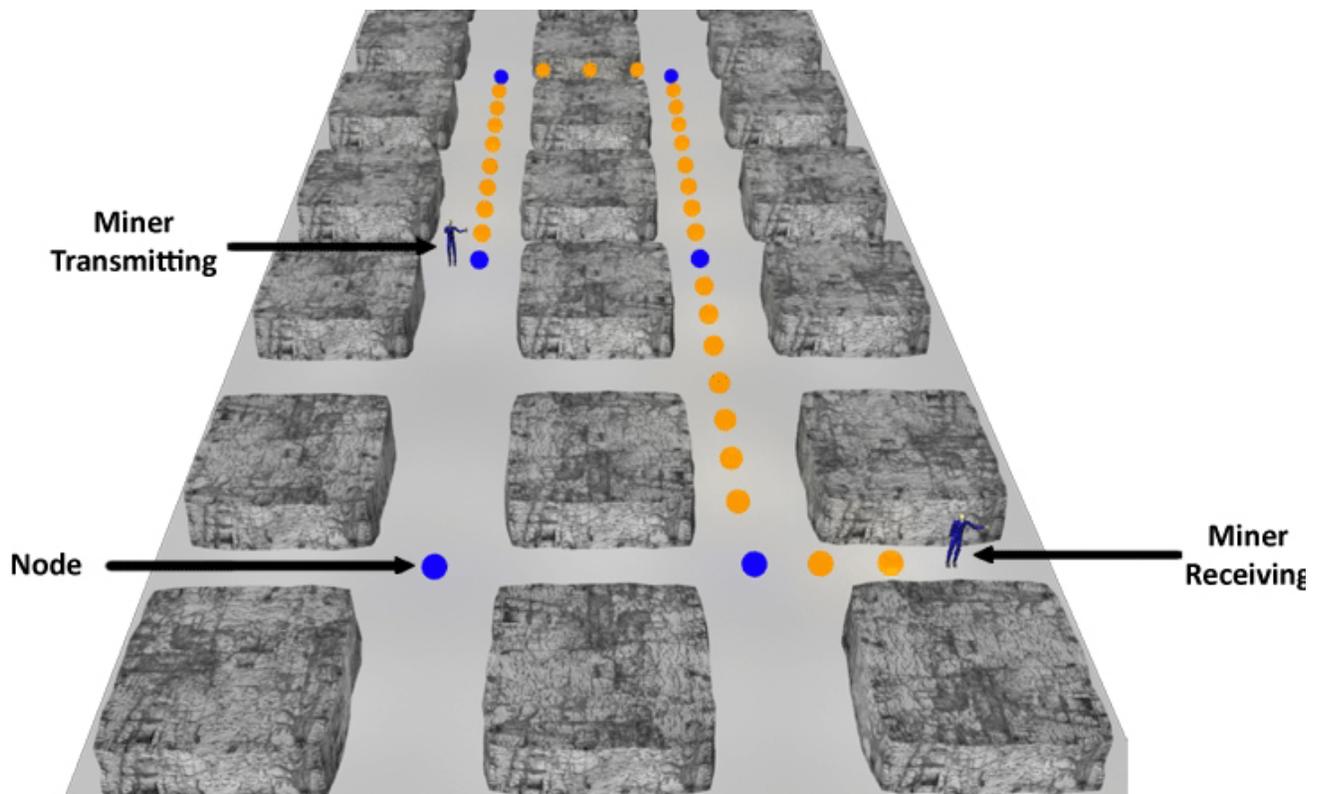


Figure 2-17. Cutaway view of mine with a wireless mesh node-based communications system.

Node-based systems generally operate in frequency bands that do not require the devices to be licensed by the Federal Communications Commission (FCC) [47 CFR 15]. Being unlicensed though does not mean unregulated. 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 (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.

2.3.1.1 WLAN Mesh 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 2-18.

WLANs identify each computer on the network by a unique identifier called the *Internet Protocol address* (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 2-18.

WLANs 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, WLAN uses standard *Ethernet protocol* (rules for sending messages) with wired connections between the nodes as shown in Figure 2-19. Thus the access link is wireless, and the backhaul links are wired.

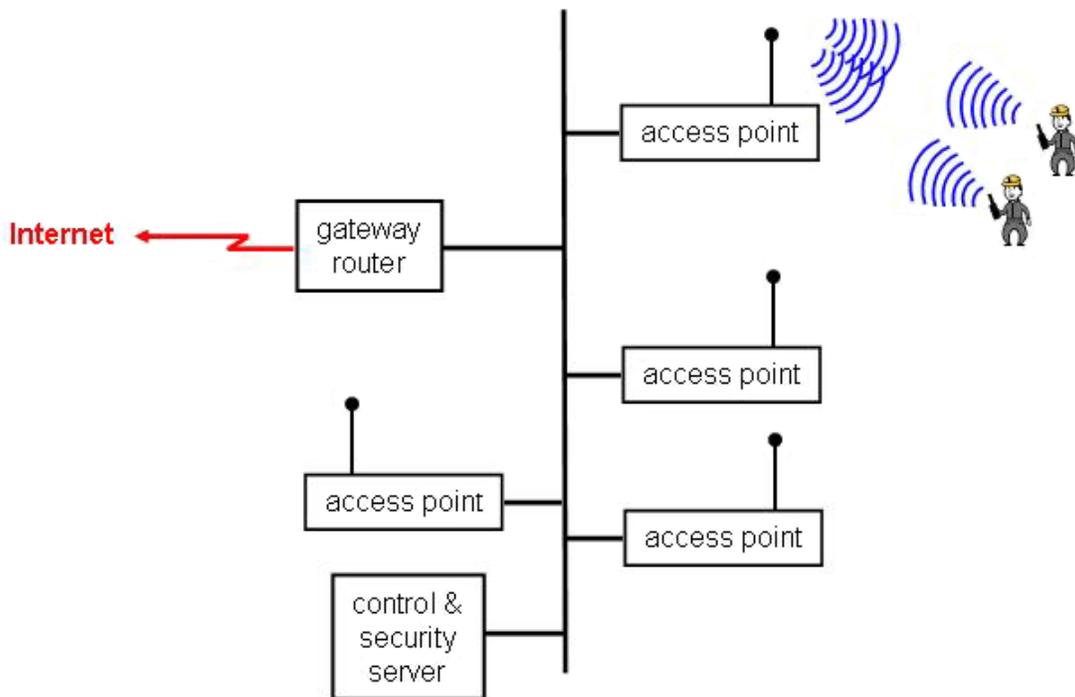


Figure 2-18. Example of WLAN interface to Internet.

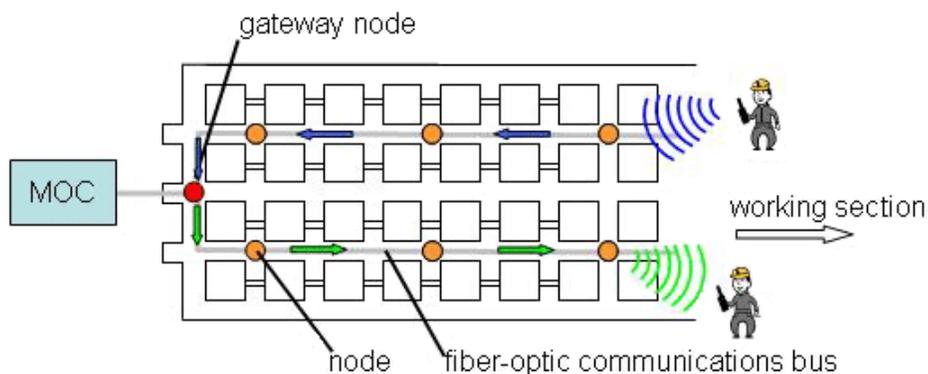


Figure 2-19. WLAN with fiber-optic backhaul links.

With the network arrangement shown in Figure 2-19, 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 Chapter 4. Additionally, the WLAN 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 must recognize that the source node has changed and redirect 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 miners riding in 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 in Wi-Fi mesh systems, discussed next.

2.3.1.2 Wi-Fi Mesh Systems

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 dependent 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 2-20 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.

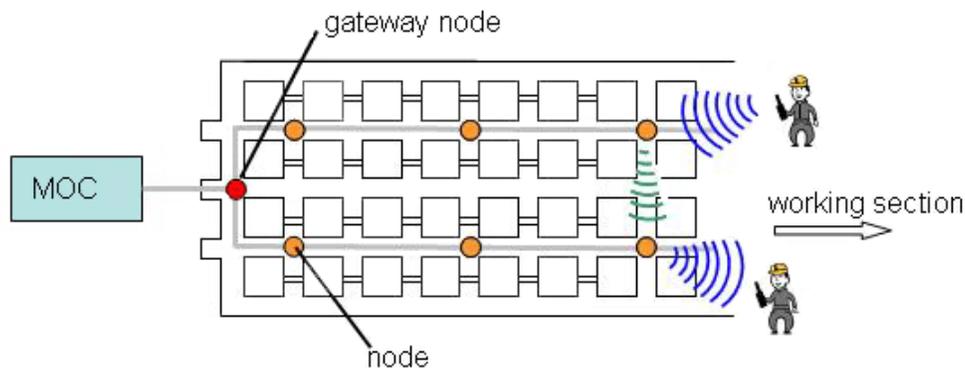


Figure 2-20. Wi-Fi mesh with fiber-optic backhaul links.

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 must be in radio range of multiple other nodes, so a high node density (high degree of coverage overlap between nodes) has to exist for this type of redundancy to be implemented.

Neither the WLAN nor Wi-Fi mesh systems are considered *ad hoc mesh* systems (discussed next). 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.

2.3.1.3 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 mesh system from a Wi-Fi mesh system are:

- The end user device (mobile radio) can serve as a mesh node, relaying network traffic from other radios on the network.
- Any node in the network can autonomously communicate with any other node that is within radio range and is not limited to a predefined subset of nodes within its range.
- 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 maximize the flexibility of extending and/or repairing networks.
- Low-bit-rate voice can result in an increased communications range, as was discussed in Section 2.1.1.
- 900 MHz operational frequency to improve the communications range of the nodes.
- Compressed voice may support future interoperability with TTE and MF systems, which may use the same approach.

2.3.2 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 hand-held devices, which are another component of the system. The mesh network uses a variety of [mobile devices](#) such as hand-held [voice-over-Internet-Protocol \(VoIP\)](#) phones, 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 [wireless access points \(WAPs\)](#). Figure 2-21 shows an example of a wireless node. Under normal operation, the nodes require power from an external supply. Thus, they must be located near electrical power wiring. In an emergency, when main 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 2-21. An example of a wireless node with external antenna.

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

Figure 2-22 depicts an example of a 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 aboveground. Thus, all of the network traffic into or out of the mine flows through the gateway node.

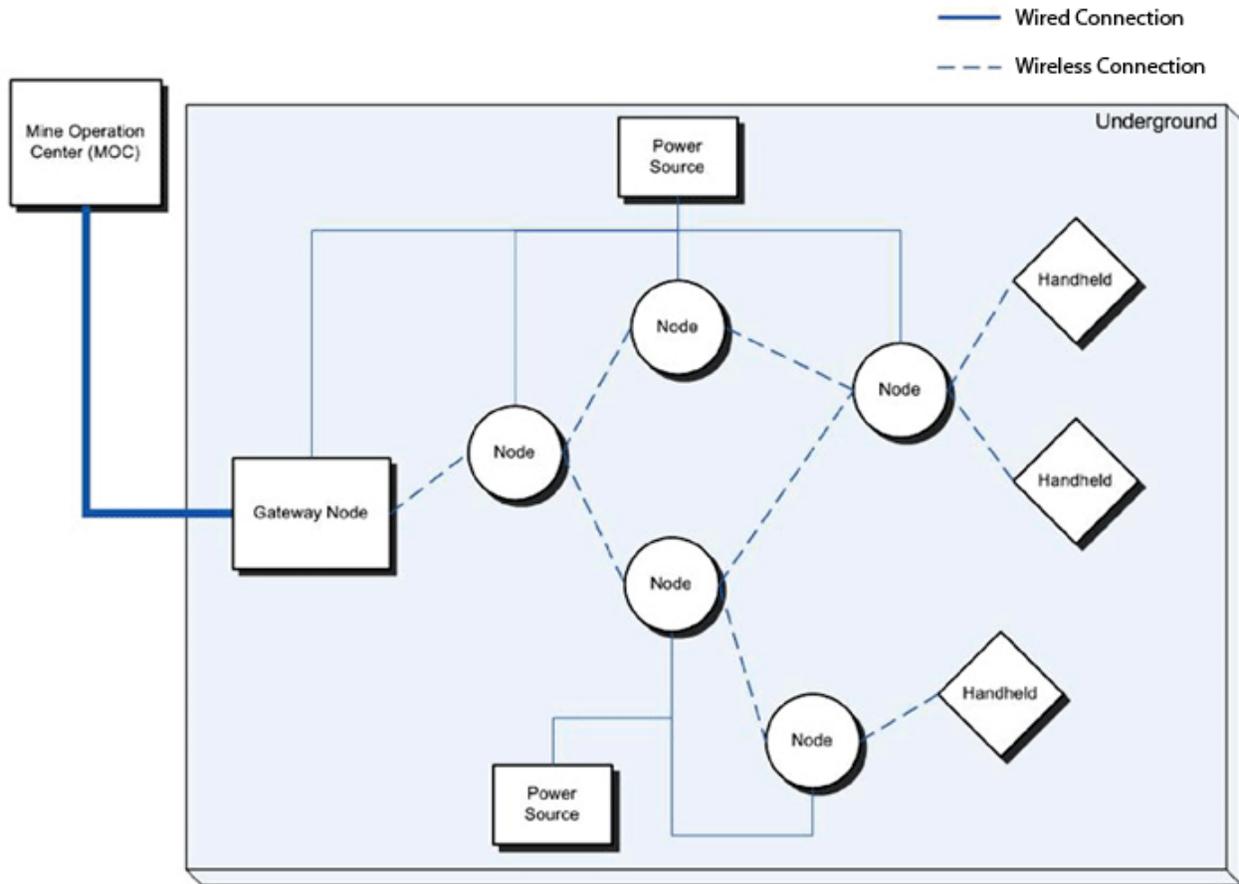


Figure 2-22. Block diagram of a node-based system.

2.3.3 Transmission Media

The communications between two miners talking over their hand-held radios involves a number of intermediate physical links depending on how many nodes are included in the route, as shown in Figure 2-23. 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 (nodes).

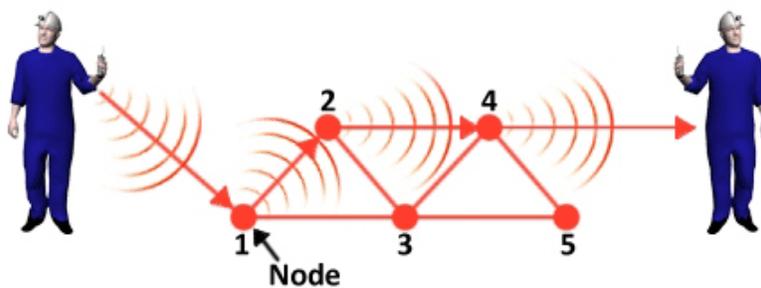


Figure 2-23. Links in a node-based system.

The link budget analysis is applied only to the access link of Figure 2-23. The analysis begins with the transmit power of the sending radio (P_t) on the left axis in Figure 2-24. G_t represents the antenna gain (assuming it is positive) of the sending radio (transmitter), 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_{node} , which adds to the received power, resulting in P_r at the receiver. The manufacturer should be able to supply most of the values used in this link budget analysis.

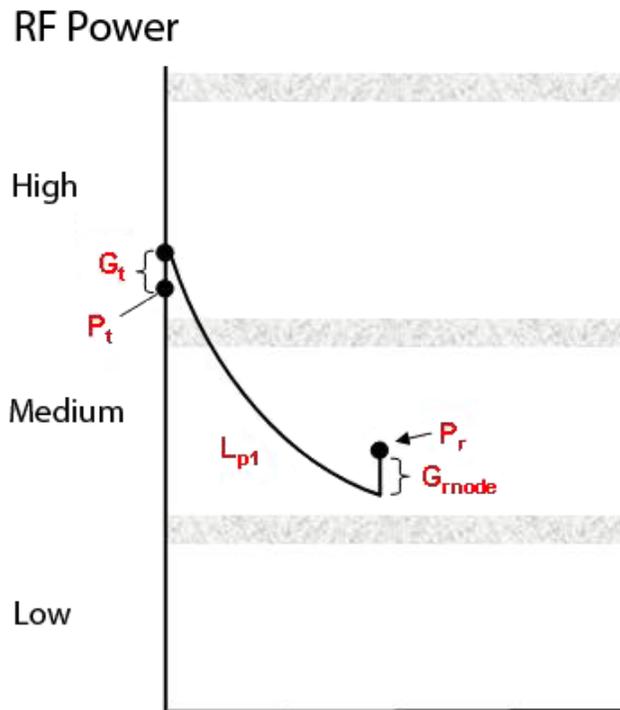


Figure 2-24. Conceptual link budget analysis for a node-based system.

2.3.4 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 2-25 shows a node-based linear network. Such a network could provide continuous coverage in an entry.

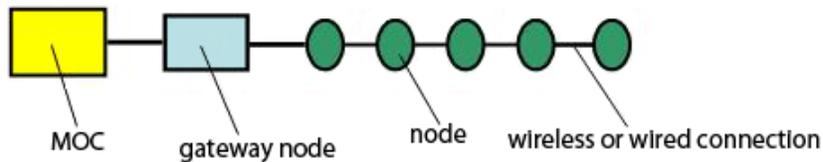


Figure 2-25. A node-based linear network.

Should one of the nodes in Figure 2-25 fail, all communications in by the failed node would be lost. One way to increase the system survivability would be to have the nodes close enough so 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 of entry. It is a viable method for adding redundancy to the system, although if the node failure is due to a roof collapse, the RF signal is unlikely to propagate around or through the debris.

Figure 2-26 shows a partial mesh network in which radio coverage is provided in two parallel entries and the nodes (blue dots) can communicate down crosscuts.

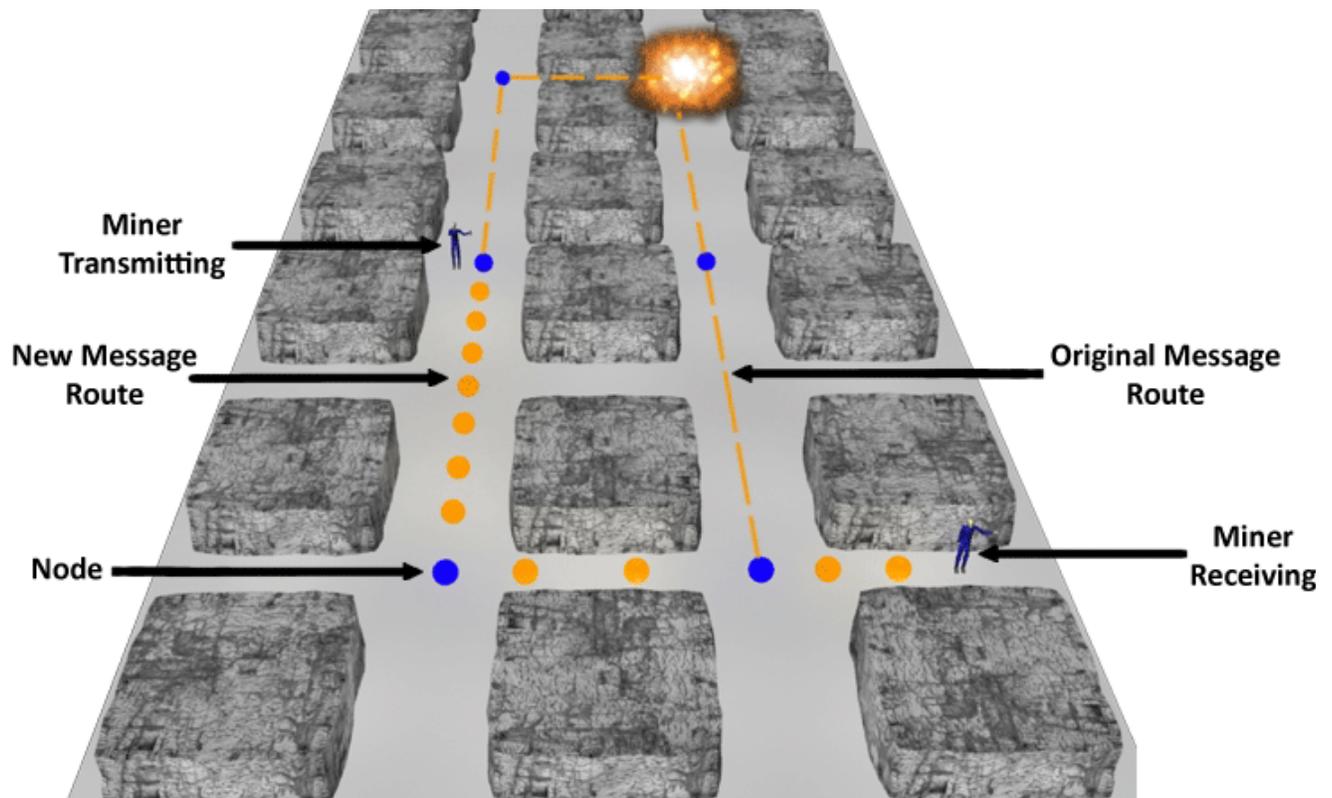


Figure 2-26. Cutaway view of a mine with a redundant communications path.

The original message route in Figure 2-26 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 mesh 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 manufacturers' nodes require that each node preprogram the allowable backhaul links that form the network topology. This is sometimes termed a [constrained mesh network](#). The nodes autonomously detect network failures and switch traffic through predetermined backup routes. Because the routes are predefined, the fail-switch-over dead time (outage time) can be very short.

In contrast, some manufacturers' 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 hand-held 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 will cause the network to reconnect 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 mesh 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 data packets. This added delay, called [latency](#), defined as the amount of time it takes a data packet to be transmitted end-to-end across the network, 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-optic 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.

2.3.5 System Implementation

Node-based communications systems offer the potential of easy-to-implement, redundant 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 adjoining crosscuts. Such a scheme permits redundant communications routes by providing a route that can bypass a failed node and still reach the MOC or other hand-held or portable radios.

As discussed in Section 2.3.1, 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 2-27 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 without interruption of service - a possible advantage of having wired connections of nodes.

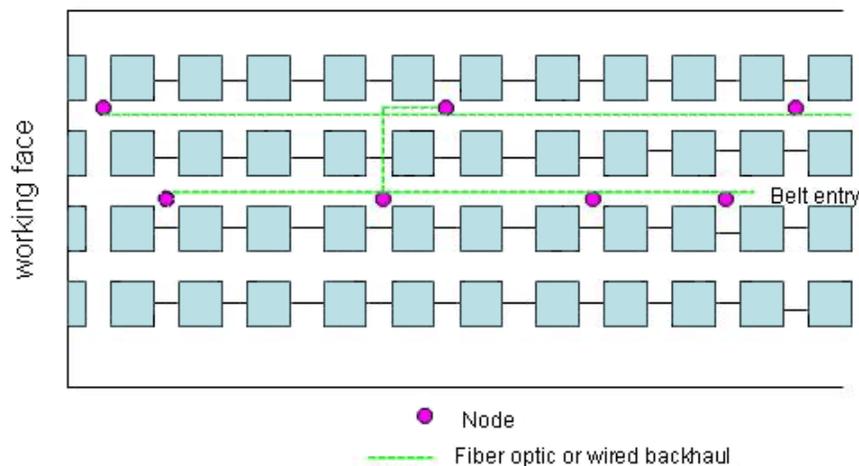


Figure 2-27. Network with fiber-optic backhaul in working section.

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 2-28). Node-based systems can also provide electronic tracking information, which is required in the working sections (see Section 3.3). 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 communications system, such as a leaky feeder system, but the backhaul could also be node-based.

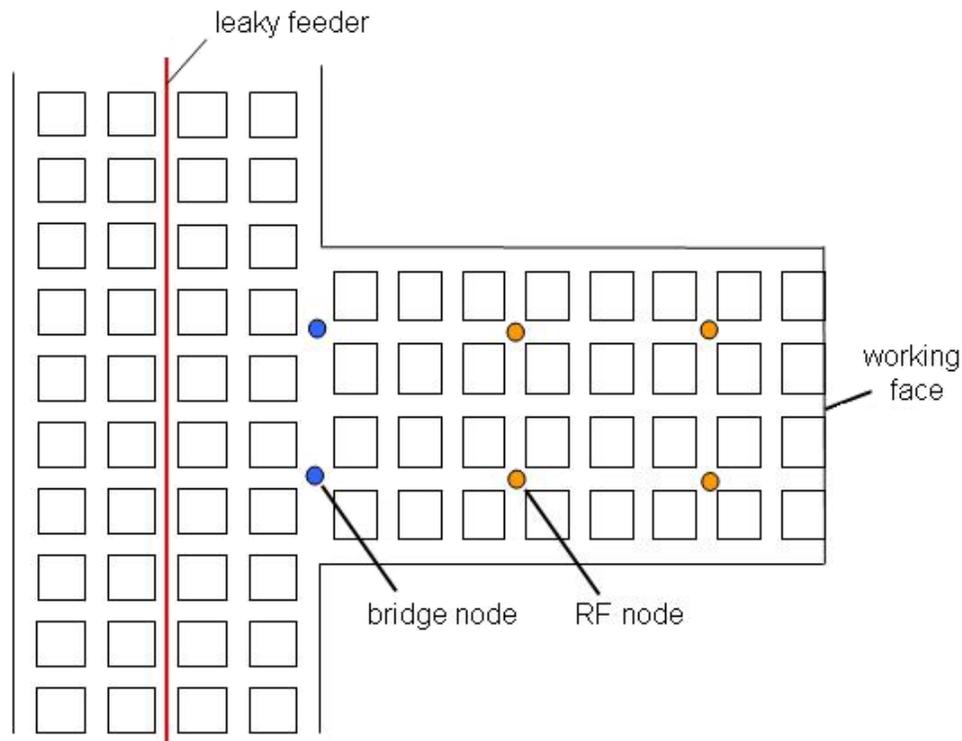


Figure 2-28. Leaky feeder backhaul with node-based system in working section.

Each node does not require mine AC power for normal long-term operation. When the mine power is either disrupted or turned 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 MSHA requirements.

2.3.6 Maintainability and Inspection

Maintenance for the node-based system's central computer will be similar to normal maintenance provided for all computer-type functions (e.g., cleaning, antivirus, security, memory and file backup, software updates). Some system providers will provide network software updates that are downloadable directly through an Internet connection. Because mine maps will have to be updated regularly, systems that provide map displays should provide utility programs to allow mine personnel to easily load updated maps. The system will run initialization, diagnostic, and database applications for adding and monitoring underground components, and will typically provide offsite 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. However, failed backhaul cabling may require replacement of long lengths of cable or careful repair procedures. Node backup batteries have a limited lifetime; therefore, 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.

2.3.7 Performance and Limitations

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

The U.S. Bureau of Mines (USBM) sponsored several radio propagation studies during the 1970s. NIOSH has made these studies available for download through the NIOSH Mining internet site on the [Downloadable Mining Publications](#) page.

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 2-29 was adapted from a figure in Emslie et al.'s paper, and is based on a coal mine entry 4.3 m wide by 2.1 m high (14 ft wide by 7 ft high).

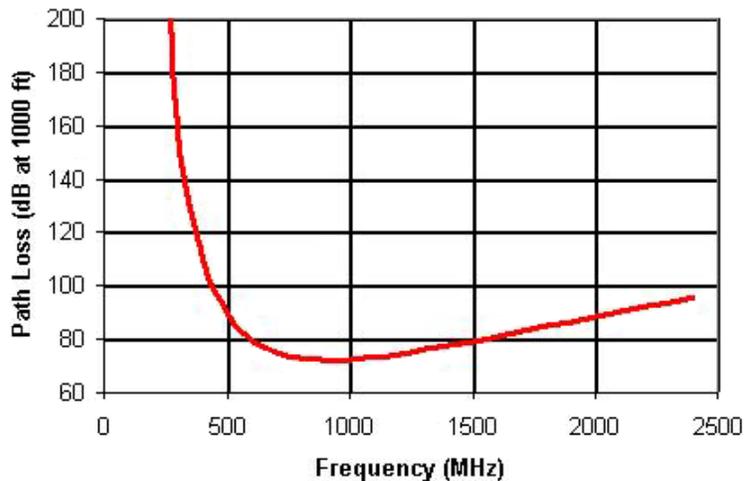


Figure 2-29. UHF propagation path loss modeling [adapted from Emslie et al. 1975].

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 waveguide (mine entry). The increase in path losses as the frequency increases is due to energy lost in the interaction of the UHF 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 UHF propagation more difficult. The minimum in the propagation loss in the 800 to 1,000 MHz range is sometimes referred to as the UHF propagation "sweet spot" for typical underground coal mine entries.

Systems operating at 900 MHz have demonstrated coverage that is not line-of-sight down a parallel entry for several crosscuts. Entry obstructions will absorb or reflect UHF signals, diminishing wireless coverage. Coverage distances in conveyor 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 also generally reduce wireless coverage range. Large vehicles will partially block UHF signals, and adequate [fade margin](#) should be factored into UHF 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 that transmissions through metallic stoppings will have large attenuations. In contrast, metallic surfaces can be used as reflectors to direct UHF signals around corners.

Overall network coverage will be limited by the total latency of the system. Latency increases with the number of hops through a network of nodes. Video or voice transmission requires that the delay (latency) through the network be consistent for the duration of the transmission, but 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 transmitting text [Emslie et al. 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 communications](#)). 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 networks are currently MSHA-permissible. This presents a safety concern even in intake air courses during a fan stoppage or mine 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 system 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 specific 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 to 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 2.3.2, the backhaul connections can be either wireless or wired. Segments of communications systems can be installed between multiple portals to the surface. For these situations, a linear topology (either wireless 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 in by 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 backhaul links.

Figure 2-30 shows a partial mesh network with wireless backhaul links. Dashed lines indicate the wireless links. The node layout (depicted as blue dots) is such that failure of any one node will not cut off communications to the surface in by 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 cables 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.

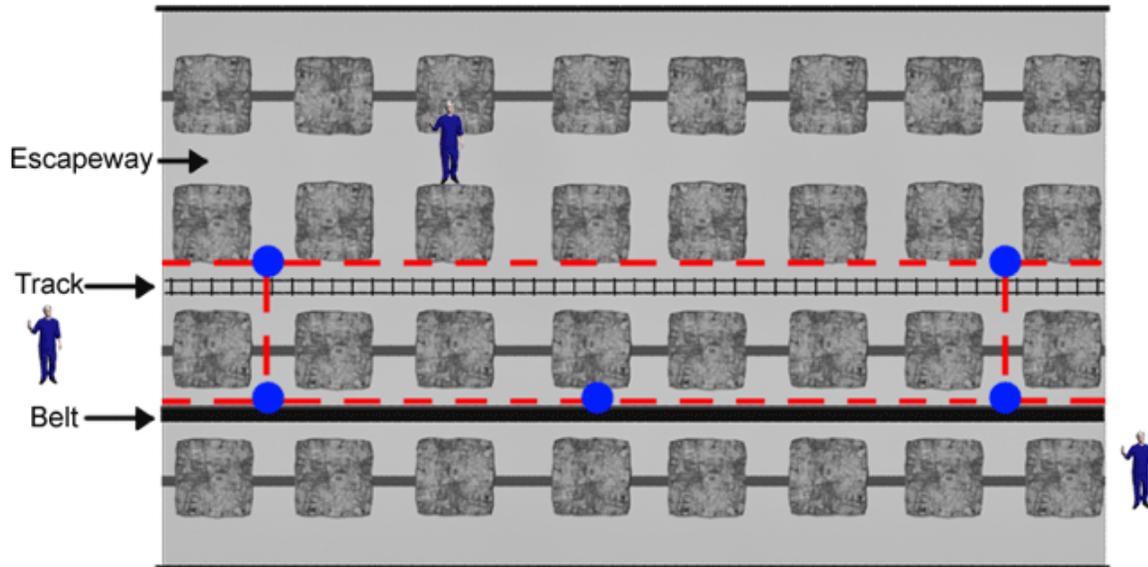


Figure 2-30. Partial mesh network with wireless backhaul links in a working section.

Figure 2-31 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 bidirectional 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 help to enhance network survivability. An ad hoc mesh implementation may allow isolated nodes to reform a network.

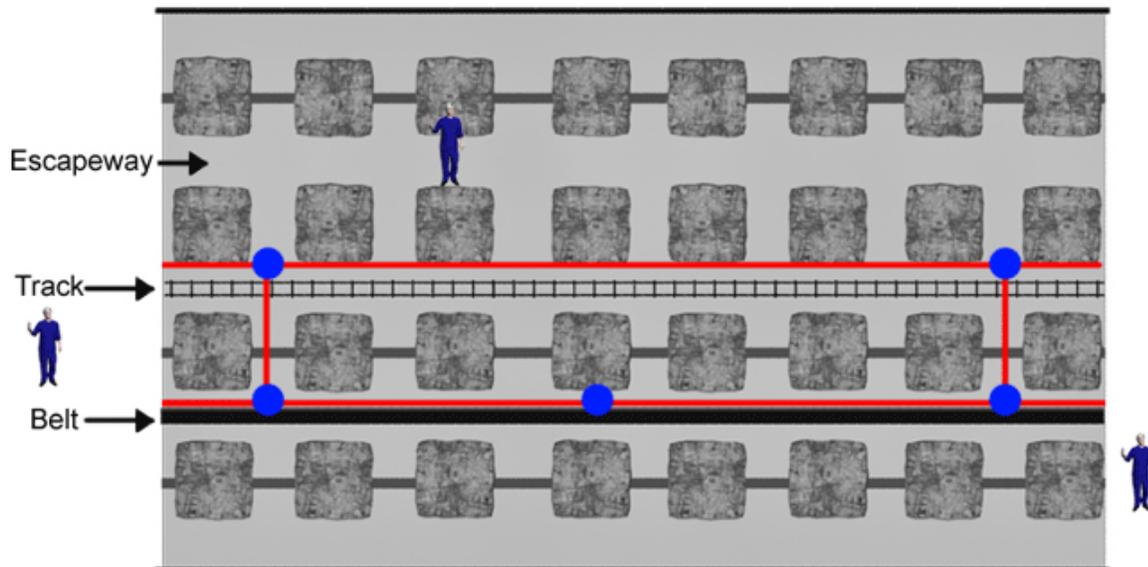


Figure 2-31. Fiber-optic or wired backhaul node network in a working section.

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 typically operate for at least 12 hours. If an emergency

occurs at the end of the shift, there may be only 4 hours or less of battery reserve. Manual shutoff or spare handsets can extend operation over a longer period. MSHA permissibility requirements for some types of handsets may prohibit battery replacement where excess methane is present.

2.4 Secondary Communications Systems: Medium Frequency Systems

2.4.1 Medium Frequency (MF) Description

Medium frequency (MF) communications systems are so named because they operate in the 300 kHz to 3 MHz band, most typically around 500 kHz. MF systems are characterized by their particular method of electromagnetic wave propagation. The MF radio waves parasitically couple (i.e., they attach themselves) to nearby existing metallic conductors within the mine entry. In other words, the conductors act as distributed antennas, able to receive and transmit MF signals as shown in Figure 2-32. The conductor also acts as part of a transmission line to transport the MF signal. The signal radiates off the conductor as it propagates, so essentially the conductor behaves as a very inexpensive leaky feeder cable. The conductors, for example, can be pre-existing mine telephone wire, water pipes, or leaky feeder cable. Both solid copper twisted-pair phone wire and leaky feeder cable serve as excellent conductors for propagation of MF signals because they are continuous. Other possible conductors include power cables, armored cables, data cables, conveyor structures, metal piping, wire-core lifelines, or inexpensive wiring specifically installed for MF communications.

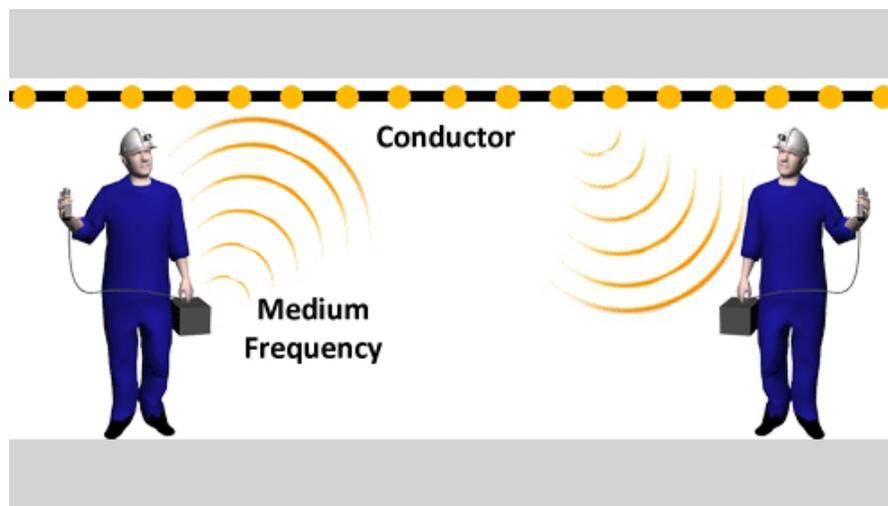


Figure 2-32. A simple MF communications system.

An example of an MF radio consists of a hand-held speaker/microphone with a connecting cord to the transceiver, which is connected to either an external ferrite or a bandolier-style loop antenna, or an integrated package that includes the antenna and batteries (Figure 2-33). An MF radio is generally considered to be a secondary communications system, except possibly when used in small mines. It is more accurately described as a man-portable radio because it is significantly bigger and heavier than a typical hand-held UHF or VHF radio. Given the size and weight of the MF radio, a miner will likely not wear it continuously. One option is to carry the MF radios to a working area and place them nearby so miners have ready access to them. Alternatively, the MF radio might be used mainly for emergencies, perhaps stored in mine rescue chambers.



Figure 2-33. Miner carrying a medium frequency (MF) radio. [Kutta Radios 2011]

MF systems are useful for providing alternate, and what are more likely, survivable communications paths 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. The MF signal can either travel directly to the mine operations center (MOC) or be converted to UHF or VHF using a [bridge node](#) (discussed later in this section) link to a hand-held radio. MSHA-approved MF systems (e.g., Kutta Radios DRUM™ Mine Radio 100P and Mine Radio Repeater 100R) that are currently available for coal mine applications are analog voice communications systems. An MF bridging device exists that is able to interconnect MF with higher frequency systems like UHF or VHF. The device is called a [bridge repeater](#), [up-down frequency converter](#), [cross-band repeater](#), or bridge node. It can convert RF signals received in one frequency band to RF signals in a different 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 conventional [radio repeater](#), except that it retransmits the signal it receives at a different frequency.

The band conversion repeater can be used to create a hybrid system of unique capabilities. Figure 2-34 is an example of how the bridge node is used. The sender on the left communicates with the bridge node using a hand-held UHF radio. The bridge node converts the UHF message to MF, which couples to a nearby metallic conductor. Another bridge node picks up the MF message from the conductor and then retransmits the message at UHF for the UHF receiver radio on the right. Thus, the UHF radios plus the MF repeaters permit communications between UHF radios, like the Kenwood TK 290/390 or the Motorola HT750, without any of the usual UHF infrastructure. The two UHF/VHF radios do need to be tuned to the same channel.

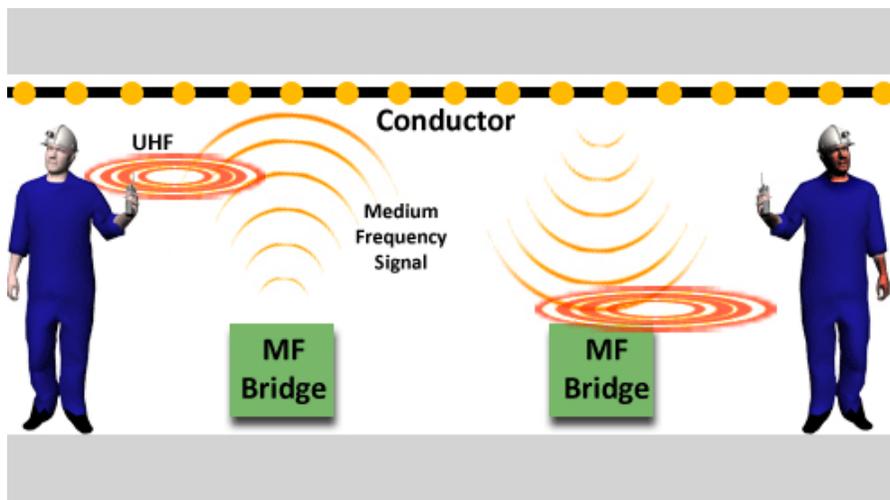


Figure 2-34. An example using MF bridge nodes.

2.4.2 MF Components

The assembly of an MF radio system requires very few components (Figure 2-33). Man-portable MF radios (speaker/microphone, radio, batteries, antenna) and continuous metallic conductors are all that is necessary to establish a communications system. Unlike leaky feeder systems, there are no line amplifiers for the analog MF system, and hence, there is a limit to the maximum separation between sender and receiver. A representative maximum separation distance is in the range of 3 to 6 kilometers (about 2 to 4 miles), but distances exceeding 8 kilometers (about 5 miles) have been observed. Finding or 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. The best propagation is achieved with multiple insulated conductors in the entry, with a single end of one of the conductors tied to an appropriate electrical ground. Properly resistance-terminated and grounded solid copper or other low-resistance wires will help to increase the distance an MF signal can propagate. Three-phase power cable and shielded power cable can be used to transmit the signal as well, although electrical noise can interfere with the MF signal while the power is on.

One advantage of transmitting MF signals on the copper core of power cables is that they frequently remain intact after a mine disaster due to the large diameter of the conductors, thus enhancing the survivability of the communications system. Wire-core lifelines are another option for allowing MF signals to propagate along an escape route. Lifelines offer a definite advantage in that the miner and/or rescuer are likely to be extremely close to the conductor most of the time, which will enhance the MF radio performance.

2.4.3 MF Transmission Media and Link Budget Analysis

Figure 2-35 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 - namely air, conductor, and air again.

Link 1 includes the losses from the transmitter, through the transmit antenna, propagation through the air, and coupling to the conductor. Figure 2-36 schematically shows 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 2-35; hence, the antenna is much smaller than the wavelength in the MF band. Therefore, the antenna is very inefficient. Path loss through the air (L_{p1}) and the RF coupling loss from the air into the conductor are shown in Figure 2.36.

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

Link 3 accounts for a potential loss in power in coupling the RF signal from the conductor to the air. Then there is the path loss through the air (L_{p2}) and the negative gain of the receiving antenna (G_R). The power at the receiver (P_R) 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.

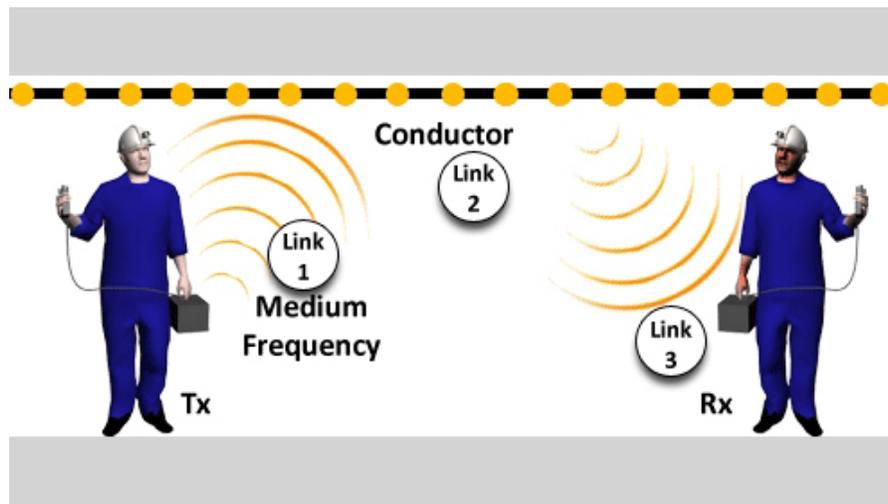


Figure 2-35. Three parts of the physical Link in MF communications between sender (Tx) and receiver (Rx).

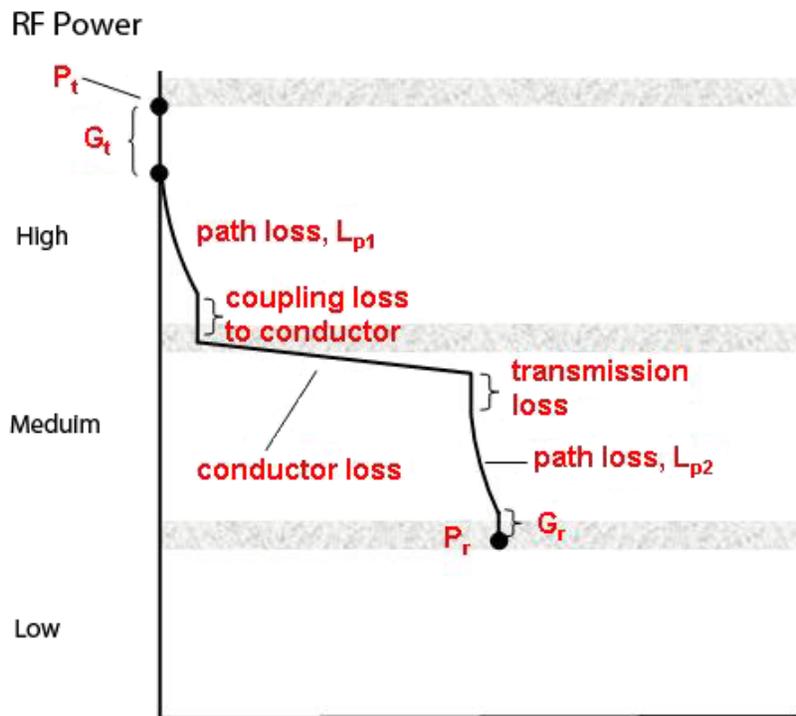


Figure 2-36. Conceptual link budget analysis for an MF communications system.

2.4.4 MF Network Operations

The analog MF systems that are commercially available transmit using a very narrow bandwidth that typically allows only one channel for communications. When a sender keys his/her microphone to talk, the sender is broadcasting to all radios within MF 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 presently under development will have the intelligence, control, and switching capability built into the bridge nodes (i.e., MF/UHF or MF/VHF nodes), as discussed in Section 2.4.1, to perform message routing similar to node-based system networks, as discussed in Section 2.3.

2.4.5 MF System Implementation

As mentioned in Section 2.4.1 the principal use for MF communications systems is most likely to be for secondary communications systems and/or alternate communications paths. MF radios can be a primary communications system for [small mines](#). Either metallic conductors that already exist in mine entries could be used, or inexpensive conductors could be installed specifically for MF communications. In addition, it is also possible to build in redundancy using conductors in parallel entries.

Miners would carry MF radios to their working areas to provide their communications connections to other miners and to the surface. MF signals will couple to conductors that have been buried in a trench to increase the survivability of the conductor.

UHF radios and the MF/UHF bridge nodes can be used to extend leaky feeder coverage into a working section. Figure 2-37 shows a worker near the working face. The worker 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 picks up the signal and then retransmits the message in UHF to be linked to the leaky feeder cable.

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 a bridge node would capture the MF message and retransmit a UHF signal to couple to a leaky feeder [backbone system](#). The rugged continuous miner power cable will frequently survive a roof collapse, thereby providing an inherently hardened communications line.

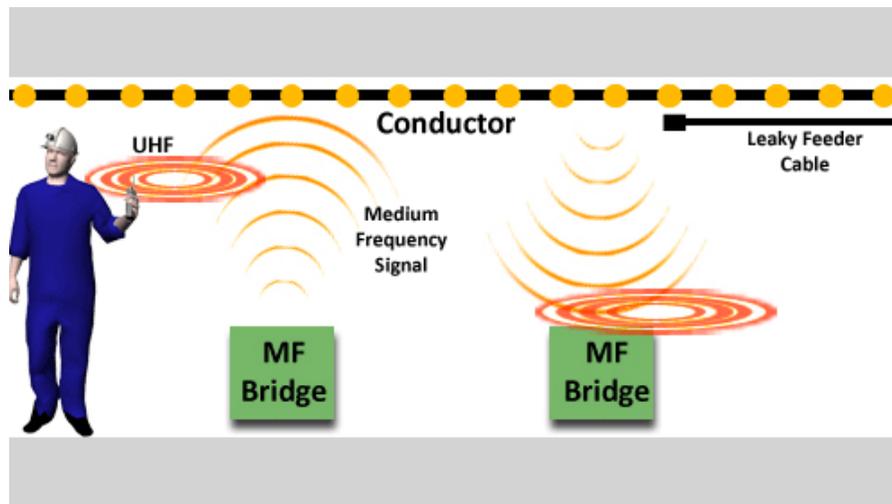


Figure 2-37. MF bridge node used to extend leaky feeder coverage.

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. A person, located relatively far from the conductor, can often receive the MF signal, but may not have the ability to respond, i.e., because a communications link cannot be established in the reverse direction. This appears to be due to the difference in signal-to-noise ratio (SNR) on the conductor when the transmitter is close to the conductor (high SNR) compared to the return communication from the MF radio that is further from the conductor, and hence has a low SNR on the conductor. 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 best coupling of the signal to the conductor.

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 include 60-Hz power harmonics, belt-drive motors, power centers, pumps, continuous miners, and longwall equipment. Other equipment that could interfere with MF communications could be powered 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 communications signals, making it difficult to separate out the communications 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 meter may dramatically decrease the effects of the noise source.

2.4.6 MF Maintenance and Inspection

Because only a few components are needed to operate an MF system, the system is not very complex. The factors that most influence performance are the conductor configuration and the proximity of the radio to the conductor. Because all conductors in an entry near an MF radio can participate in propagating 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 characteristics](#) 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 many miles (kilometers) of conductors, there is a reasonable chance that a conductor path will be altered or removed.

Inspections that should be routinely made of a simple MF system are the MF [bridges](#), hand-held radios, and the conductors between them. Simple voice spot checks should be performed at strategic locations to ensure that the radios, bridges, and conductors are properly working, preferably 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 than digital-based systems, but do not offer much capability in troubleshooting.

Battery maintenance is similar to other battery-operated systems. The battery charge and health of the portable MF radios can be verified at the start of each shift before taking the radios underground. 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 mine power is shut down. It is recommended that the fixed position bridge includes some type of indicator that shows the status of the battery's charge.

2.4.7 MF Performance and Limitations

The radio signal coverage of an MF system depends on a number of factors. The communication range of two MF radios in free space can vary with the transmitted power level, but typical surface ranges are usually up to 30 meters (100 feet). However, in the presence of a metallic conductor, the MF signal can propagate for 3 to 6 kilometers (2 to 4 miles) due to parasitic coupling. 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. Note that for existing conductors like power cables, this may not be possible.

The second consideration is the separation distance between the MF radio and the nearest conductor. The coupling between the radio and the conductor decreases dramatically with an increase in separation distance. The closer the MF radio is to the conductor, the stronger the coupling to the conductor. Stronger coupling results in a larger signal on the conductor, hence a greater SNR and a greater likelihood of a signal of adequate amplitude reaching the intended radio receiver.

Due to the higher power requirements needed to generate a magnetic field through the antennas (loop or ferrite core coil), the battery life for an MF radio is less than that of a UHF or VHF radio. Batteries for stationary MF bridges can be larger and heavier because portability is not a concern. If a mine accident occurs, the primary communications system may become inoperable. If the miners in by the accident have an MF portable radio, it may provide an alternate, secondary communications mechanism by using whatever conductors are nearby. If the accident occurs between the escape route and the working face, it would be best to try the MF radio using whatever conductors are nearby.

2.5 Secondary Communications: Through-the-Earth Systems

2.5.1 Description of Through-the-Earth Systems

Most electromagnetic waves can only penetrate short distances into or through the earth. However, it is possible for ultralow-frequency (ULF), long-wavelength EM waves to penetrate several thousand feet through the earth's strata. Such ULF systems are called *through-the-earth (TTE) systems* because they have the potential to provide wireless communications between underground and surface personnel without intervening infrastructure, perhaps more closely meeting the intent of the MINER Act of 2006. With less infrastructure than traditional communications systems require, TTE systems are more likely to survive an underground explosion and to provide a communications link to the surface for trapped or escaping miners.

TTE systems typically operate between 72 Hz and 4,000 Hz. These frequencies result in wavelengths between 70 and 3,200 km (45 and 2,000 miles) in free space. Portable communications systems operating in the VHF or UHF band often use half-wavelength dipole or quarter-wavelength whip antennas to achieve high transmission efficiency. Note that the transmission efficiency is high for antennas with linear dimensions that are a major fraction of a wavelength. In contrast, TTE antennas are very inefficient because of their extremely long wavelengths. This means that only a small fraction of the transmitter power is actually radiated from the antenna.

The path for the TTE transmitted signals can be either vertical (through the earth or overburden) or horizontal (through the coal seam). TTE systems generally operate as *half duplex* systems which provide communications in both directions, but in only one direction at a time (not simultaneously). They may provide voice in real time, voice or text messages, or emit a periodic beacon signal, which can be detected on the surface and which allows rescuers, typically on the surface, to estimate the underground location of the transmitter. Each of these modes is characterized by different signal transmission rates. For example, data rates as high as 2.5 kbps permit real-time digitized voice, but rates as slow as 10 bps only allow text at one keystroke per second. Obviously, real-time voice is desirable, but TTE transmission range is affected and limited by data rate, as well as by other factors discussed below.

Factors that affect TTE signal transmission include the frequency, transmitter power, and nature of the overburden strata such as electrical conductivity, depth, and any geological variations that can alter the overburden electrical properties. The reception of a transmitted signal is also affected by the presence of electrical noise, both underground and on the surface, both natural and manmade. The ability of the system to communicate is dependent upon the remaining energy of the transmitted signal, after attenuation through the earth, being sufficient to be distinguished from the noise at the receiver location. Finally, the antenna configuration, e.g., wire loop, ferrite core coil, or linear wire line, can impact transmission and reception.

It is known that the lower the frequency of a transmitted signal, the lower the signal attenuation through the earth. However, at ultralow frequencies, data transmission rates are limited and only text messages or preprogrammed messages may be possible. The lowest practical rates generally allow the greatest depth penetration and are typically used to generate beacon signals underground. TTE beacon signals can be detected by rescuers on the surface at long ranges for which data and voice transmissions are not possible. The beacon signals help determine the approximate location of the transceiver underground.

Given these performance limitations, it may be desirable to have multiple transmission frequency capabilities to optimize TTE

range and mode for a given set of geological conditions. Transmission range is proportional to transmitter power. However, when the transmitter is used underground, consideration must first be given to the safe use of electrical equipment in potentially explosive atmospheres. Consequently, transmitter power underground must be limited as required by MSHA approval regulations.

Surface TTE antennas are generally not restricted in their physical size or transmitting power. They may theoretically consist of large loops of wire, thousands of feet in circumference, which encompass most of the mine. Generally, the surface antenna should be directly over and encompass the areas of the mine needing coverage, such as mine refuge chambers. However, from a practical standpoint, they may likely be limited in size by the terrain and by limited access to property above the mine. Note that over a kilowatt of transmitting power may be used on the surface in order to transmit a strong signal to the underground environment. Some TTE systems currently under development have significantly smaller diameter loops that use multiple turns of conductor and transmit at much lower powers, some as low as a few watts.

The TTE receiving antenna may incorporate ferrite-core windings to conserve space for portability. To optimize antenna coupling, and consequently signal transmission, both sending and receiving loops (or windings) should be oriented in the same direction (Figure 2-38). Multiple ferrite windings may be placed in an X-Y-Z axes orientation for receiving antennas. Antenna outputs can then be added vectorially to obtain a resultant signal. Underground TTE transceivers can be used for communications to the surface or underground and from point-to-point (horizontally) within the mine. The transceivers may be transportable or in a fixed location, however they must be limited in power (MSHA [intrinsically safe](#) or [permissible](#) requirement) to ensure safe operation in potentially explosive atmospheres.

NIOSH funded multiple industrial TTE development projects to investigate the feasibility of applying various types of TTE technology to mining. All contracts resulted in the development of prototype or preprototype systems. Varying system features include both magnetic and electric field sensing, loop and line antennas, digital and analog processing, noise filtering and cancellation, and direction finding. All systems have been evaluated at various commercial underground mine sites during development.

As mentioned earlier, the underground antenna may be smaller for portability and may operate at less power to be MSHA-permissible. In one TTE system, the receive antenna is worn by the miner and is integrated with the miner's cap lamp. When a message arrives, the miner's lamp will flash. In this system, the communications are text only and travel in one direction only—from the surface to the underground miner. Unfortunately, personnel on the surface receive no indication that the miners have received their message.

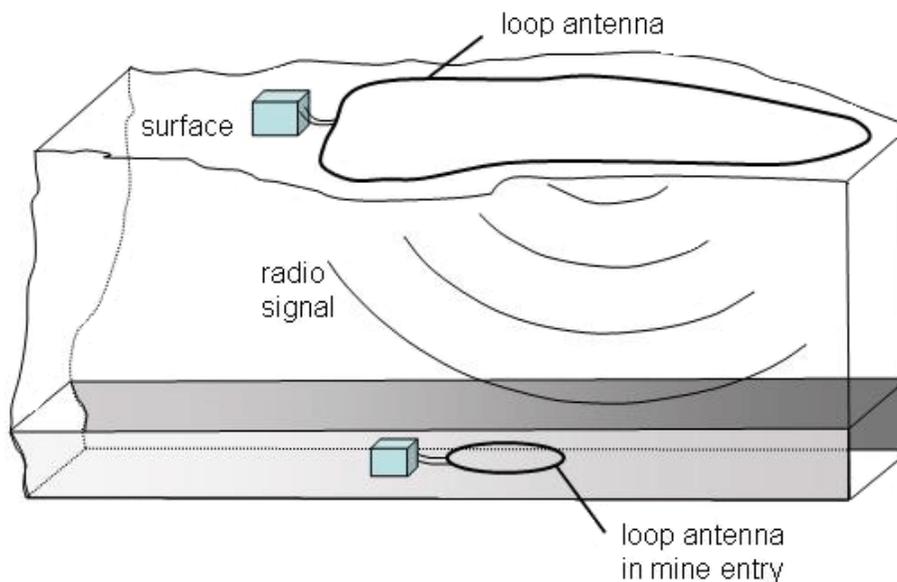


Figure 2-38. Surface and underground antennas for a TTE system.

In another TTE system concept of operations, the miners deploy the underground antenna only when there is an actual 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 mine pillar to form an antenna. The structure of a rescue chamber can also incorporate the antenna. Two-way communications are possible with both text and voice messaging at depths exceeding 300 m (1,000 ft). Greater depths are generally associated with lower data rate communications such as text (compared to voice).

In another concept of operations, both TTE communications systems are underground. Similar to the concept shown in Figure

2-38, the trapped miners deploy one TTE system. The rescue workers bring in a second TTE system to establish communications horizontally with the trapped miners. Figure 2-39 demonstrates the concept.

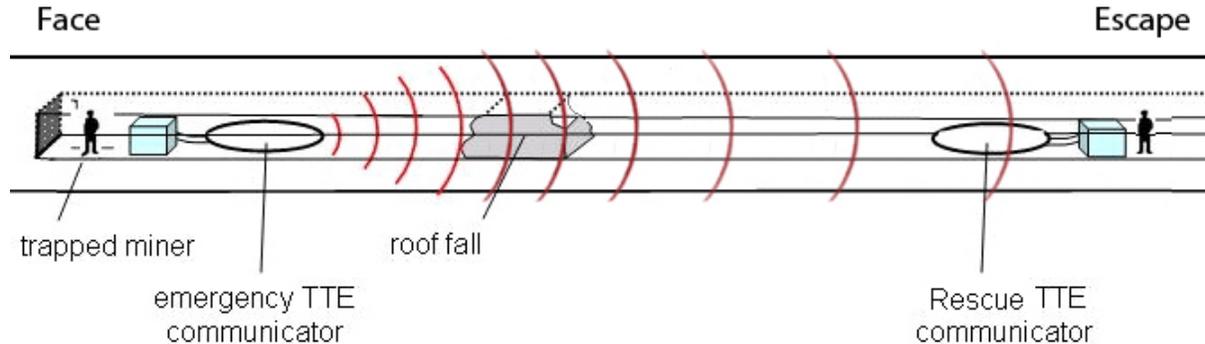


Figure 2-39. An in-mine rescue TTE system.

As was mentioned earlier, a TTE system cannot be used as a primary communications system for normal mine operations due to limited coverage and portability constraints, and low data transfer rates. At the ultralow frequencies of operation, it can take several minutes to transfer a text message. In addition, there are many sources of EMI and/or RF noise, e.g. spurious voltage signals, at low frequencies that make it difficult to separate out the message. Fortunately, in an emergency in which the underground power is off, the EM 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 EM noise at the surface. However, the main 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 or secondary communications path.

2.5.2 Components

TTE systems consist of very few components. The simplest system, which only delivers 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), loop antenna, connecting cables, and a computer for entering messages. The TTE underground receiver has a loop or ferrite-core antenna, a [demodulator](#) to decode and display the message, and a power source (typically a battery) to power the system. The antenna could be just a spool of wire the miner lays 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). Typically, different antennas are used for transmitting and receiving. The TTE electronics must be capable of both encoding and decoding messages.

2.5.3 Transmission Media

The earth (overburden) 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. Significant changes in electrical properties between consecutive strata may cause a portion of the propagating RF 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 2-40 is the same whether the transmitter is on the surface or underground, but the quantitative analysis may have different numbers for the transmit power on the surface compared to transmitter power used 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 cable 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.

2.5.4 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 2-39, there may be instances when an additional TTE system underground, acting as a repeater, would be helpful. For example, if the mine operators did not have access to all surface areas directly above the working sections, it may be advantageous to put the surface TTE system in a fixed location with another TTE system directly under it within the mine. The underground TTE system could then act as a repeater for any other underground TTE system that the miners might set up

during an emergency.

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. Some preplanning is required to coordinate the use of multiple TTE devices to avoid signal collisions. Most TTE devices do not detect whether another device is transmitting at the same time they are trying to transmit; this is called collision avoidance or blocking. TTE devices can only transmit or only receive at any given time and hence, if a TTE device is transmitting, it cannot detect or receive an incoming signal.

2.5.5 System Implementation

The most likely use for TTE systems is in mine emergency situations only, with other technologies providing the primary communications for daily operations. Even though the system is intended for emergency operation only, it would be prudent to periodically check that TTE communications can be established between two locations.

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. Because the surface loop can be very large, up to 12 km (7.5 miles) in length, it would be prudent to install it ahead of time, 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, usually powered by the miner's cap lamp battery.

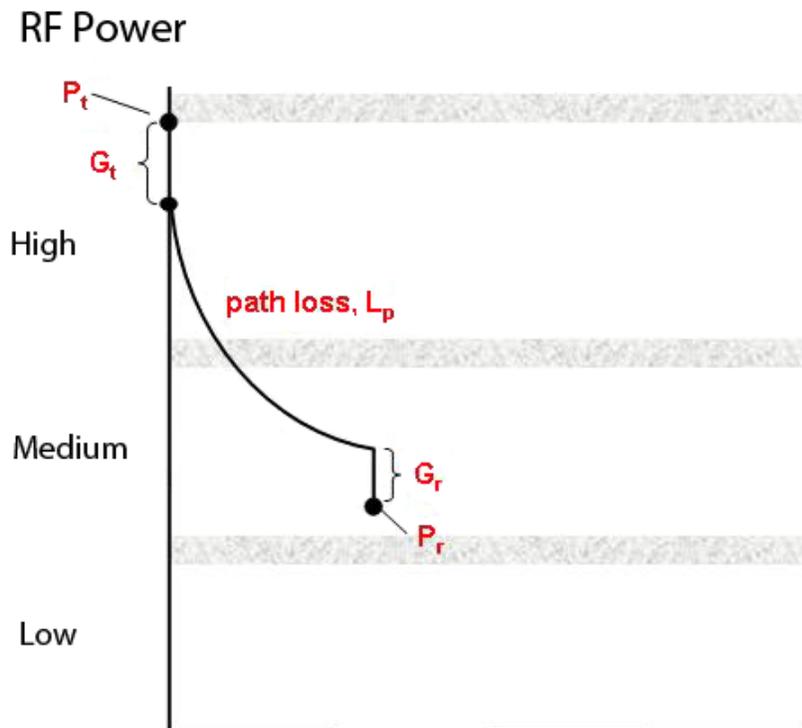


Figure 2-40. Conceptual link budget analysis for a TTE system.

Other two-way TTE communications systems under development use a large transportable loop for transmitting and a ferrite rod antenna for receiving. The underground TTE antenna system could be carried into the working section each day by the miner or cached nearby. It would be prudent to check the TTE communications link regularly, in which case, the TTE should always remain deployed. 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 secondary or alternate communications path.

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 robust 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 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.

2.5.6 Maintenance and Inspection

Underground caches can store multiple TTE portable units that miners can use during an escape. Routine inspections of these systems underground should detect system component failures. The present TTE systems 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 TTE units are necessary. Regular functional communications tests are necessary between the portable and stationary units underground. Each time the refuge chamber moves, tests should reconfirm TTE communications with the surface. A troubleshooting manual in the nearest refuge chamber should have a checklist in the event that the TTE units do not operate during routine inspections.

2.5.7 Performance and Limitations

The feasibility of two-way TTE communications in underground mines has been demonstrated in several NIOSH-sponsored research contracts. These projects involved development of TTE prototype units which were evaluated at commercial mines. The systems used varied approaches to establish communications through the earth. Most systems featured magnetic field sensing, with one design based upon electric field propagation. Both digital and analog signal processing techniques were employed. Loop or line antennas were used for transmission. Noise filters or noise cancellation techniques were found to be necessary for signal reception. Underground-to-surface as well as underground point-to-point communications for voice and text were demonstrated at ranges exceeding 300 m (1,000 ft). The range generally increased with increasing transmit power levels. Prototype systems were often evaluated at power levels exceeding MSHA permissibility limits on the underground transmitter and will require further field evaluations to determine their range when operating at [permissible](#) power levels.

Through these research contracts, NIOSH provided companies an opportunity to demonstrate and develop technology solutions that they believe can help solve underground mine communications problems. There was considerable research conducted by the U.S. Bureau of Mines (USBM) in the early 1970s through the mid 1980s that documented the challenges and potential solutions to TTE communications. Based on their initial understanding of these challenges, most companies were initially very confident that they could readily achieve depths in excess of 300 m (1,000 ft) for voice and up to 600 m (2,000 ft) for text. In all cases, the manufacturers found the challenges to be much more difficult than they had expected. There are several possible explanations. First, the digital signal processing and noise cancellation techniques used for radio, radar, and sonar applications were not designed to be effective on the type of signals and noise experienced at these ultralow frequencies. Second, mining equipment typically operated at lower utilization voltages and horsepower in the 1970s and 1980s than at present (2011). Today's equipment would be expected to generate a different electromagnetic noise profile. Lastly, as a result of continued development, the noise levels due to aboveground transmission lines and other manmade sources most likely have increased substantially in the last 30 to 40 years. Before this technology can be fully used by the mining industry, there are questions that remain to be answered. These questions relate to communications format, time delays, portability, deployment, noise characterization, interaction with other systems, and permissibility, which are briefly detailed below.

One question revolves around the choice of TTE communications format—specifically, text versus voice. From a technological standpoint, the signal range for text can be greater than for voice. Text can be transmitted at lower bit rates and lower frequencies, with preprogrammed canned messages having the greatest potential range. Text also has the advantage of being a familiar and well-accepted communications format for a workforce becoming more comfortable with computers. There are concerns over the ability to text under stressful, adverse, emergency conditions especially when smoke hinders visibility. Those same conditions, however, may also hinder voice communications when self-contained breathing apparatus are in use. The solution may lie in software which can convert voice input into text, and text into synthesized voice.

Another question focuses on what is an acceptable time delay for a message. Real-time communications without functional delays, as with conventional telephones, is a goal which may not be practically achievable or necessary. It is conceivable that a message can be transmitted and received, and a response made over several minutes without adversely affecting rescue or escape. As with message format, message delay times and range are impacted by bit rate.

Further questions revolve around the TTE hardware and its deployment. It could be stationary while in use, or it may need to be transportable. It may be used while workers are awaiting rescue or during their escape. Some systems may feature components in heavy explosion-proof enclosures, which could only be moved by equipment. Underground antennas could be predeployed by integration into the design of refuge chambers or be carried and deployed as needed by an escaping miner who might also have donned a self-contained self-rescuer (SCSR). On the surface, antennas may be permanently deployed directly above dedicated, hardened transceivers installed underground, or may be installed following an emergency on the surface above a rescue chamber.

Finally, it is known that the geology of the earth transmission path poses further challenges for the designer and users of TTE communications systems. The electrical conductance of the overburden has a great impact on the efficiency of transmission and can vary by orders of magnitude from mine to mine. For example, lower values of transmission path conductivity have

reduced loss. Signal transmission with minimal loss is most easily achieved through materials with relatively low conductivity, such as air, granite, or sandstone. Higher conductivity materials such as salt or coal can impede transmission. The conductance of formation salt water (~5 S/m or ~0.2 ohms/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 through the earth. Signal reflections at strata interfaces (for example, air-rock, water-rock, or coal-shale) will also likely reduce the effective coverage range. Maximum TTE system ranges can be simplistically extrapolated assuming a homogeneous overburden with uniform conductivity. For a point-to-point underground transmission, multiple entries, solid coal blocks, roof mesh, and/or gob could significantly alter the range.

Batteries will be required for emergencies when the power is off. A battery meter should indicate if batteries are within the proper operating voltage range. Underground components need to include an MSHA-approved intrinsically safe design.

For reception, the units may feature two or three ferrite-core antennas in an orthogonal arrangement. The ferrite cores enhance the magnetic field strength while permitting a compact design. Multiple, orthogonally arranged antennas ensure that reception is independent of the antenna orientation. Software can add the component signals from each antenna to obtain a resultant vector signal.

2.6 Communications Technology Comparisons

Currently there are four types of commercially available systems for underground coal mine wireless (or partially wireless) communications systems: node-based, leaky feeder, MF, and TTE. Although the hardware and software will differ from different vendors, there are some general capabilities and limitations that are inherent in these communications technologies. The comparison matrix in Table 2-3 compares the four technologies for a variety of attributes. Discussion of some of the table entries is given below.

It is important to note that MF systems and especially TTE systems are still under development and may have limited commercial availability at this time (as of Fall 2011). MF systems can use whatever continuous conductors already exist in the mine entries and hence are less reliant on special cables or equipment than more conventional techniques, although they are not totally immune to disruption. TTE systems are particularly useful because they do not need fixed structures underground which could be damaged. The inherent bandwidth limitations of both MF and TTE technologies restrict their use to either secondary or emergency-only situations (TTE in particular) or as an adjunct to more conventional technologies such as leaky feeder and node-based UHF systems. Leaky feeder and node-based technologies are the most commonly installed wireless systems to date. Leaky feeder technology has the longest successful history of usage in coal mines and tunnels, having been used since the early 1980s.

Table 2-3. Comparison matrix of communications systems

Category	Feature	Communications Systems			
		System Description			
		Leaky Feeder ¹	UHF Node Based	Medium Frequency ²	Through-the-Earth
Coverage and Range	Coverage range - access link	< 50 m (150 ft) < 120 m (400 ft)	< 300 m (1,000 ft) ³	< 3.2 km (2 miles)	< 600 m (2,000 ft) of cover
Coverage and Range	Expandability (adding components)	Moderate	Easy/Moderate ⁴	N/A ⁵	N/A
Installation	Design	Low	High	High	Moderate
Installation	Labor intensity	Moderate	Low	Low	Low
Installation	Infrastructure recovery	Difficult	Moderate	Easy	Easy
Functionality	High speed data	Yes ⁶	Yes	No	No
Functionality	Paging	Yes	Yes	No ⁷	Yes ⁸
Functionality	Peer to peer	Yes ⁹	Yes ⁶	Yes	N/A
Functionality	Text - low speed data	Yes	Yes	Yes	Yes
Functionality	Voice	Yes	Yes	Yes	Yes ¹⁰
Functionality	Troubleshooting via centralized test diagnostics ¹¹	Moderate	High	Low	Low
Functionality	Interoperability ¹²	Open	Open, Proprietary	Proprietary	Proprietary
Survivability	Battery load - fixed infrastructure ¹³	High/Moderate	High	High/Low	Very High/Low
Survivability	Battery life - mobile	> 24 hours	> 24 hours	N/A ⁵	N/A ⁵

Survivability	Number of battery locations	Low	High	Low	Low
Survivability	Fault tolerant - hardware	Moderate	High ¹⁴	Low	Low
Survivability	System survivability ^{15,16}	Moderate	Moderate	High	High

- . When two values are shown, they represent VHF/UHF systems respectively.
- . Data for analog systems only.
- . Varies with frequency and entry dimensions if nodes are line-of-sight (LOS). Mine stoppings and other obstacles will decrease range.
- . May require a system redesign to expand.
- . N/A - Not Applicable or Not Available.
- . Vendor specific.
- . Current technology.
- . Currently available system has paging + text for downlink only.
- . If hand-helds allow F1/F2 switching.
- . Depth limited, system under development.
- . Describes system requirement for effective troubleshooting.
- . Does system use standard vs. proprietary interface protocols.
- . Values for Transmit/Standby modes.
- . Depends on installation details.
- . System resistance to major disruptive events (fire, explosion, roof collapse, inundation) when properly implemented.
- . Based on the number of components needed and/or complexity of setup.

3.0 Electronic Tracking System Performance

The 2006 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 the list of miners' current locations.

Manual tracking has a number of limitations. A miner's location may be given as being within a working section that can be quite large and therefore difficult to pinpoint a miner's exact location. Occasionally a mine worker will forget to notify the dispatcher when moving to another work location.

Several electronic tracking technologies that overcome the limitations of manual tracking are currently available. One technique uses a reader-based technique called [radio frequency identification \(RFID\)](#) technology. One common implementation of RFID technology can be found in retail stores to prevent merchandise from being stolen. In this type of system a small electronic circuit called a [tag](#) is attached to the merchandise. At the store's exit, two vertical gates periodically emit a radio frequency (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. These systems use ultralow-cost and very short read range tags. Many industries use the tag-and-reader approach for tracking items and equipment. There are many types of tag-and-reader systems. Each system is optimized to trade off parameters such as read range, cost, reliability, and robustness. Examples of RFID tags and readers are shown in Figures 3-1 and 3-2.

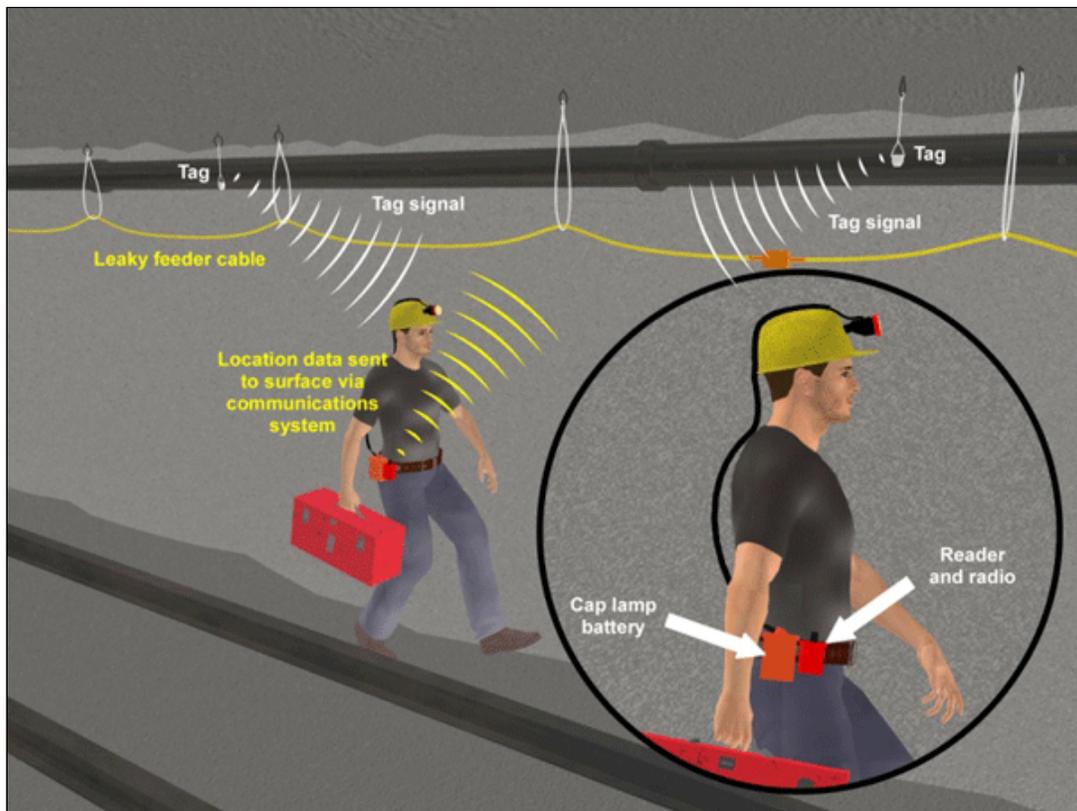


Figure 3-1. Example of RFID tags and readers.

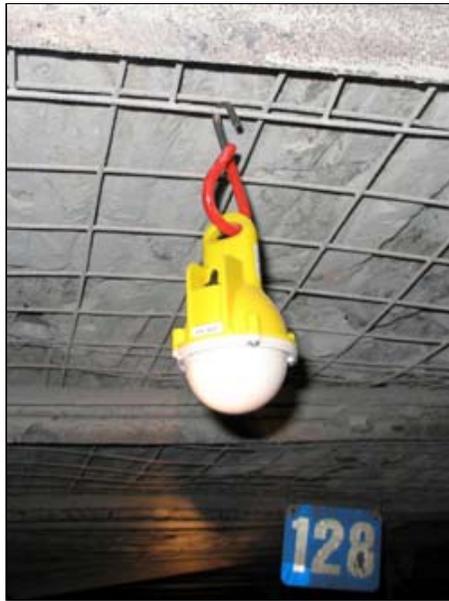


Figure 3-2. Example of an ultrawide band (UWB) tag in a mine.

A second type of tracking technology ([node-based electronic tracking](#)) uses the communications link between a radio and a node. The node analyzes the radio signal strength from a miner's radio to determine how far away the radio is from a node (or multiple nodes) to estimate the miner's location.

Another technology that has been proposed for use in mines is called [inertial navigation](#) (or inertial guidance). The system measures accelerations and other motion characteristics of the miner to determine how far the miner has moved from a known starting point.

In addition to determining location, there are other important characteristics for tracking systems. The system must have the system 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 at varying speeds, e.g. walking or riding in a vehicle. 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](#). All of these features should be discussed with a vendor when considering the purchase of a tracking system.

3.1 Tracking Techniques

As mentioned above, several tracking technologies are available for use in the coal mine environment. One technology, [reader-based tracking](#), is similar to what is used in retail stores. It has two major components: a device called a reader for detecting the presence of tags and the tags themselves. In a retail store the tag will be what is called [passive](#), in that it does not contain a battery. Typically, however, in mining the tag will be what is called [active](#), in that it contains a battery. In mines, there are two variations within the reader-based technique. In one approach, called zone-based RFID, a tag is placed on each miner and the readers are installed at specific locations within the mine. 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 technique ([node-based 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 rate of the miner 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 in this tutorial is limited.

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

3.2 Reader-Based Tracking

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 predetermined, fixed locations; or 2) reverse-RFID, in which case the miner wears the reader and the tags are in predetermined, 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.

3.2.1 Zone-Based RFID

3.2.1.1 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 (MOC). The information can be relayed a number of ways, e.g., over a pair of wires, through fiber-optic cable, via wireless communication, 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 MOC, personnel at the MOC know that the miner is within a certain radius (the RF range) of that reader's 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 3-3 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 about 100 m (300 ft). Thus, miner A is known to be within 100 m (300 ft) of survey point 58301. This could be displayed as text or on a mine map on a computer terminal in the MOC.

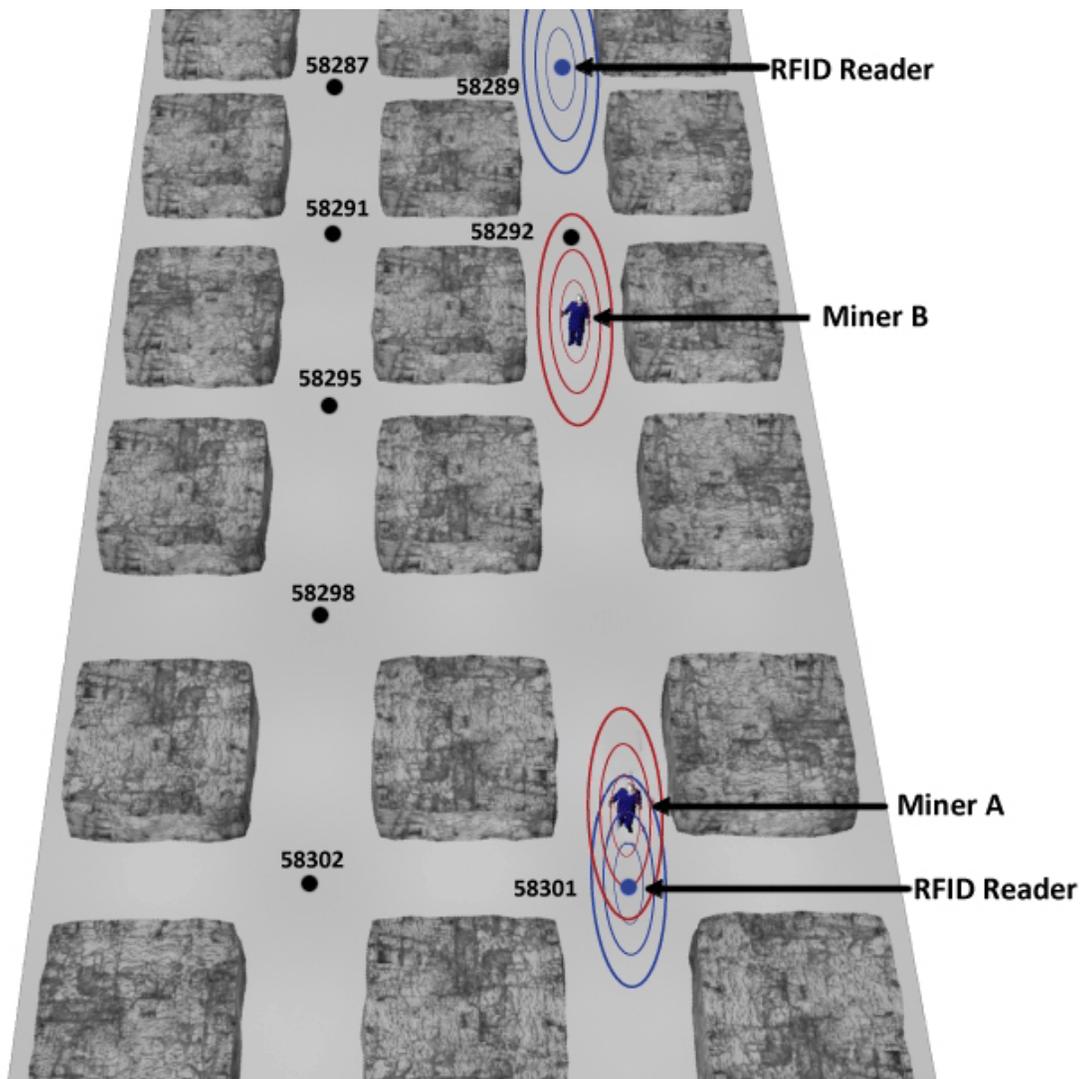


Figure 3-3. Example of zone-based RFID tracking.

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 crosscut at survey point 58301, and he would still be considered to be within 100 m (300 ft) of point 58301. Miner A might be part way down a parallel entry and still within 100 m (300 ft) of 58301, except that the RFID readers generally require a line-of-sight (LOS) 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 RFID 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 oriented normal to the reader, it does not receive an 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.

3.2.1.2 Components

The main components of a zone-based tracking system are the tags and the readers. The tags are typically inexpensive, but the readers are typically expensive. The tags are battery operated, but are low-power devices. The batteries should be 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 will 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 backhaul system](#) to send 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 3-4 illustrates a block diagram of a zone-based tracking system with a hardwired backhaul system 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.

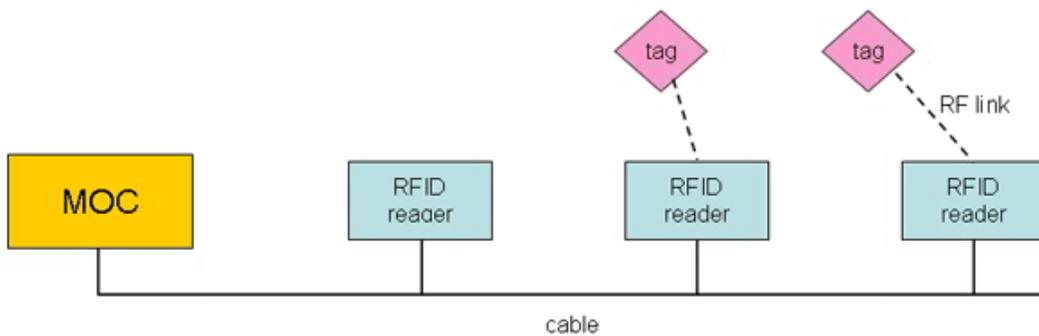


Figure 3-4. Sample block diagram of a zone-based tracking system.

3.2.1.3 Transmission Media

Reader-based tracking systems must establish a physical RF link between the tag and the reader similar to a communications link so that the tag and the reader can exchange RF messages. A link budget analysis can be performed on the system to verify that it will function as intended.

Figure 3-5 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 difference in analysis between the uplinks and downlinks is in the transmit powers of the reader. The reader and the tag have different transmit powers.

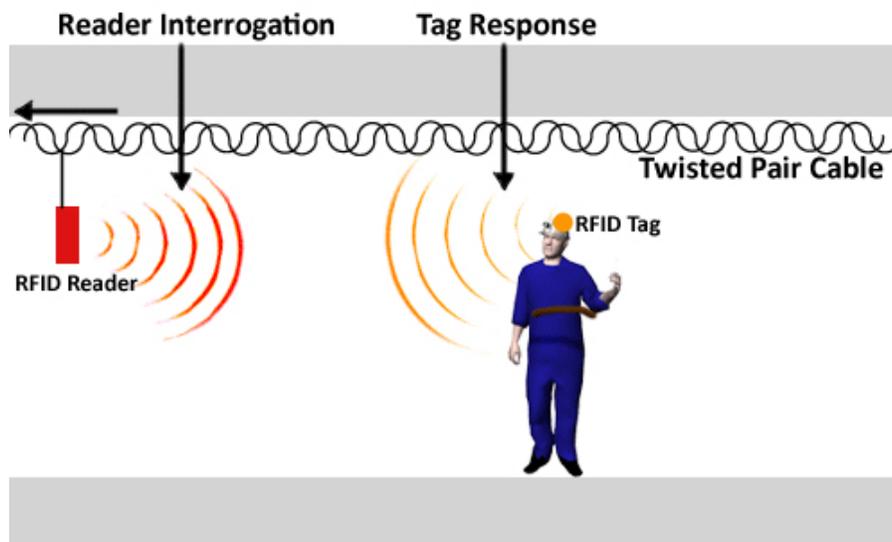


Figure 3-5. The physical link between a reader and a miner's RFID tag.

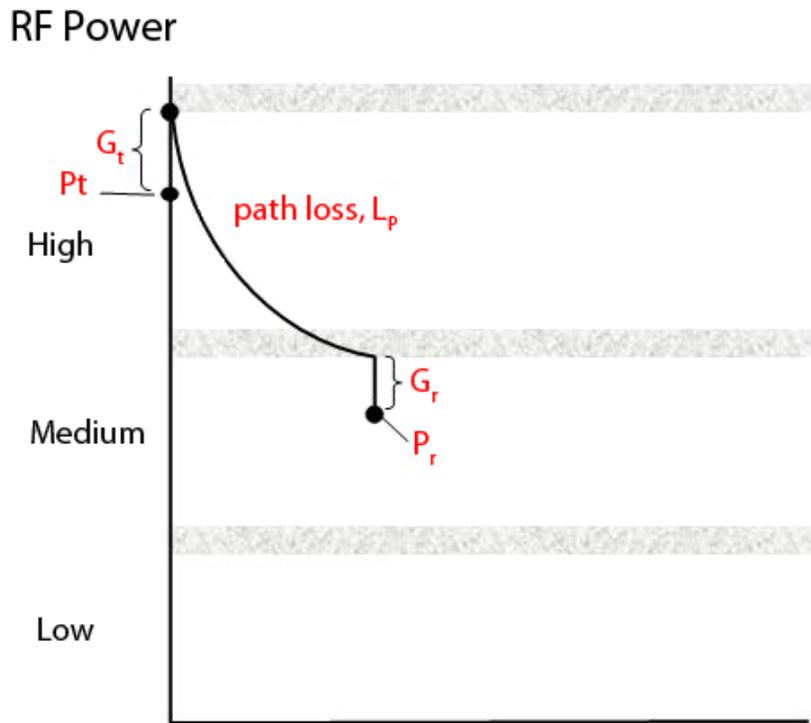


Figure 3-6. Conceptual RFID reader downlink budget analysis for zone-based tracking.

The downlink budget analysis is shown in Figure 3-6. (The uplink analysis can be done in a similar manner.) 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 can be obtained from the manufacturer.

3.2.1.4 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 3-5 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 3-7. However, a more survivable approach would be to use a ring configuration or an alternate communications path out of the mine.

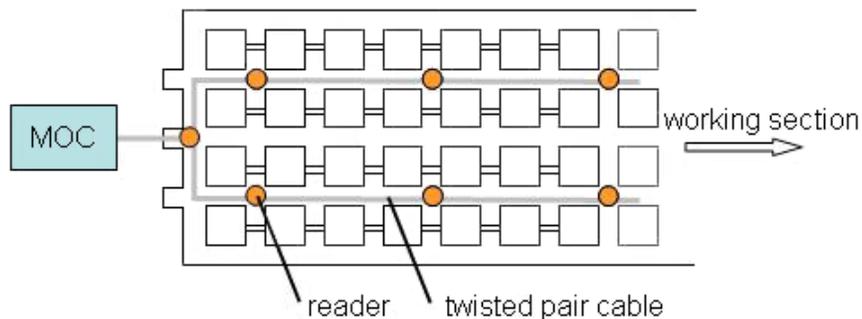


Figure 3-7. Sample network for zone-based RFID system.

The readers can also be integrated into the backhaul system if the systems are compatible. For example, if there is a leaky

feeder system is being used for the backhaul system, the RFID readers can use the leaky feeder cable to get the location information to the MOC by acting as a radio repeater and thereby 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 because, as will be seen in Section 3.3, node-based communications have an inherent ability to perform tracking; consequently there is no need for RFID readers or tags.

3.2.1.5 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 both systems. It is most likely that tracking will be required in the same entries and strategic locations as communications.

Zone-based RFID tracking systems differ primarily by:

- The method used to transmit tag data back to the MOC.
- The method used to transmit data between the reader and the tag.
- The location of the tag on the miner.

To transmit data back to the MOC some tracking systems use a dedicated communications system while others use 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 (as covered in Chapter 2). Tags that are integrated into another piece of equipment, such as a cap lamp battery, do not need any adjustments or special care of any kind to be detected by a reader. 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* (tags that require a battery supply) 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. The amount of output power and distance from the body should conform to safe distance recommendations (see Section 5.3.1).

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 mine's 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 crosscut to increase its coverage, but such a location may be more susceptible to blast forces and roof falls. As discussed below, installation at a crosscut can also cause location errors or uncertainty 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. Because 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 because 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.

3.2.1.6 Maintenance and Inspection

RFID systems are in common use in many fields outside of mining and their operating characteristics are well understood. However, the underground mining environment adds an important complication in regard to the tag-to-reader detection range. The nominal tag/reader detection range will depend on physical locations of the readers and the tags in the mine as well as the mine geometry. It is unlikely that the detection 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 monitor 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. Because 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.

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 replacement routine should be followed. Tests also need to be carried out as required by federal and state regulations in addition to the manufacturer's guidance.

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.

3.2.1.7 Performance & Limitations

In this section, [tracking 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 latter two limitations will be discussed in more detail.

The usual definition for accuracy gives the location uncertainty in meters (feet) for a detected tag. A reader can detect whether or not a tag is within its detection zone, but not where it is within its zone. Figure 3-8 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 $\pm R$ of reader R3. So the location accuracy of M1 is $\pm R$. 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 nondetected miners.

When the reader detection ranges overlap (Figure 3-8), this problem does not occur. The accuracy depends only on the distance between readers and is no worse than $\pm S/2$ 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 about 3 km/hr (2 miles/hr) would travel 50 m (175 ft) in one minute. Consequently, one minute after detection, the miner could be 50 m (175 ft) 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 individual tags and the tag ID must be entered into the tracking database. Maintaining an accurate database of readers and tags is a critical requirement.

Critical functions of the tracking system 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 for identifying damaged units, and monitoring the condition of the tags' batteries. Both the surface and underground portions of the tracking system should be equipped with standby power to ensure continuous operation in the event that 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 CFR. § 75.1600-1, which also requires that someone on the surface should always be on duty when miners are underground. The tracking system should also include the capability to display the location of all miners underground at all times. In addition, 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 another key requirement of the MINER Act of 2006. RFID systems may either 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 mine seals, protection should be provided against forces that could cause damage. Protection could be provided by installing hardened enclosures in recessed areas, around corners, or other areas that can help to reduce the potential for damage.

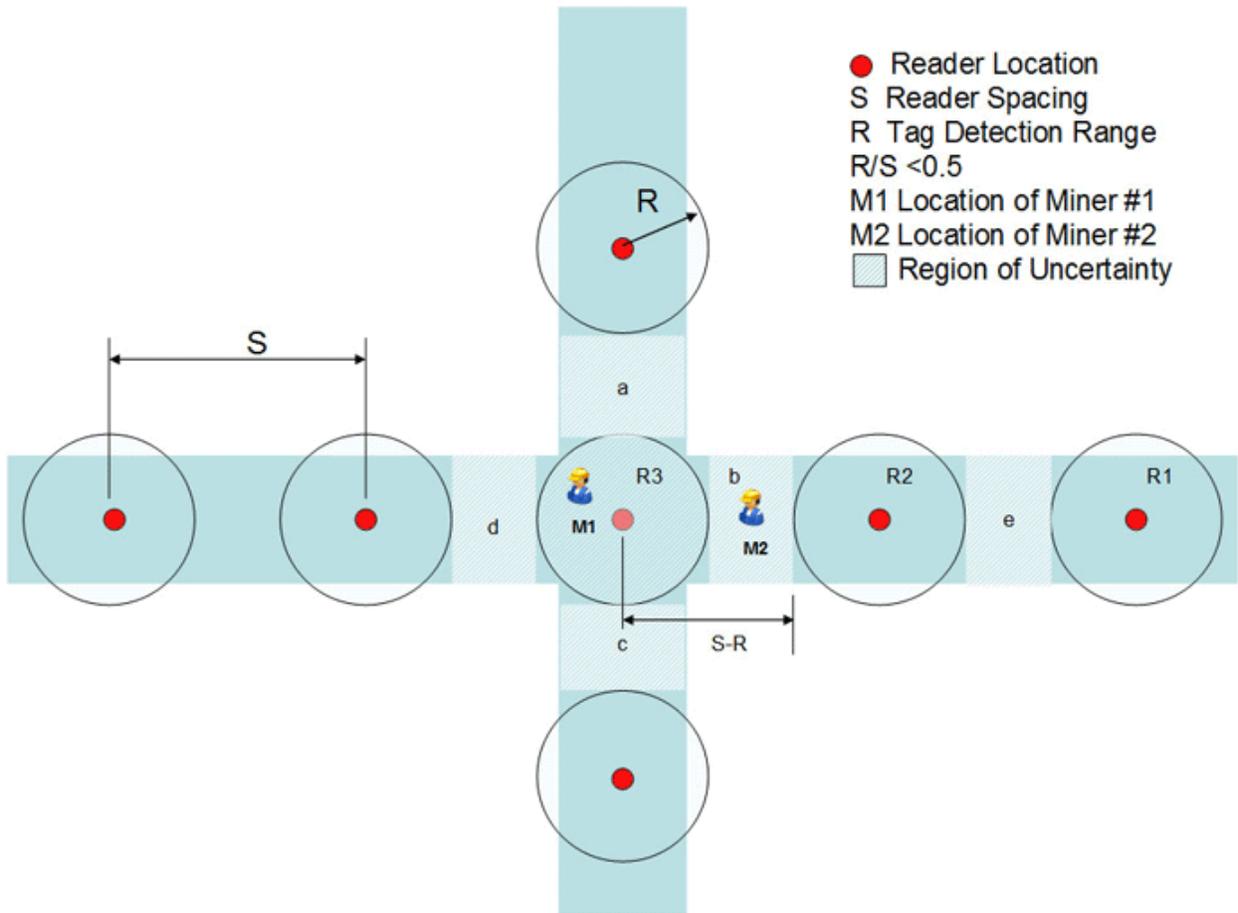


Figure 3-8. An RFID system layout showing readers with detection ranges that do not overlap.

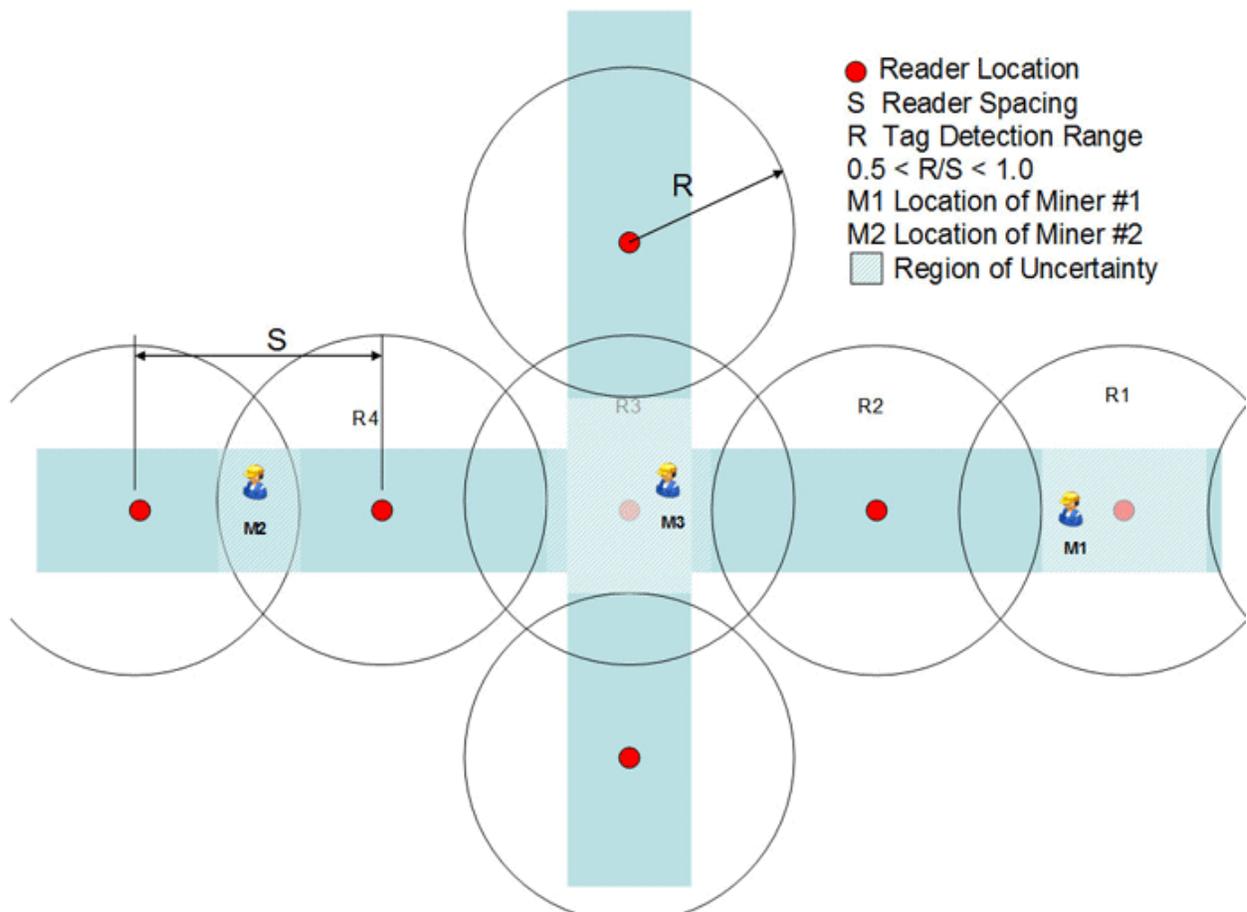


Figure 3-9. An RFID system layout showing readers whose detection ranges overlap.

In the event that mine power is lost during an accident, it will not affect the operation of the tags because tags normally operate on internal 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. Although this signal has a limited range, typically less than 150 m (500 ft), a rescuer with a portable version of the reader might be able to use the signal to further aid in finding trapped miners.

3.2.2 Reverse-RFID Tracking

3.2.2.1 Description

Zone-based RFID tracking has been described in Section 3.2.1. 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 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 3-10 illustrates a reverse-RFID system in which the backhaul is a UHF leaky feeder system.

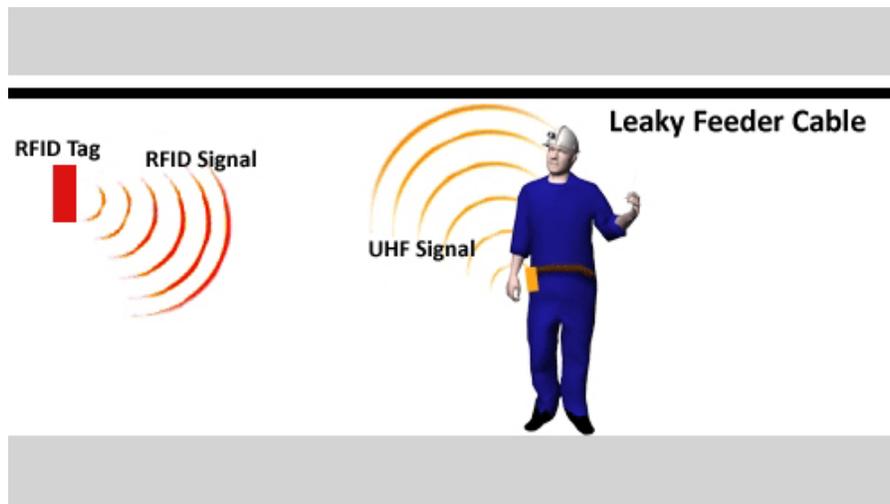


Figure 3-10. A reverse-RFID tracking system coupled to a leaky feeder cable.

The RFID tag is programmed to periodically transmit its identification information, shown in red in Figure 3-10. 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 to the MOC. A UHF transmitter mounted on the miner's belt transmits the location information to the leaky feeder cable.

3.2.2.2 Components

The reverse-RFID tracking system has the same components as the zone-based system: tags, readers, some type of backhaul communications 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 system is quite different (see Figure 3-11).

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 they 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 (on the 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 2-15).

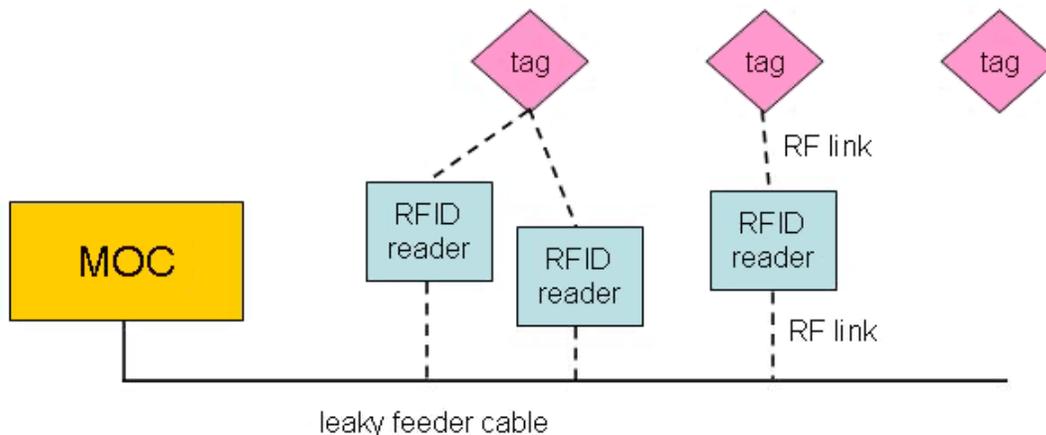


Figure 3-11. Block diagram of reverse-RFID tracking system linked to leaky feeder system.

3.2.2.3 Transmission Media

As seen in Figures 3-10 and 3-11, 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, in this case assumed to be leaky feeder. 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 required to have an interrogating signal. In this case only a link in one direction is required. The disadvantage of the single-link approach is that the tag is continually transmitting, which requires power from the internal battery. In the first approach, the tag is inactive until it receives an interrogating pulse. It should therefore use less energy as compared to 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 that 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 3-12 illustrates the link budget analysis beginning with the tag transmitter power $P_{t \text{ tag}}$ 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 $P_{r \text{ reader}}$.

The reader will change the frequency before retransmitting the location information at power $P_{t \text{ reader}}$ from its antenna of gain $G_{t \text{ reader}}$. 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 $G_{r \text{ cable}}$. The received power in the leaky feeder cable is $P_{r \text{ cable}}$. Most of the values used in this link budget analysis could be obtained from the manufacturer.

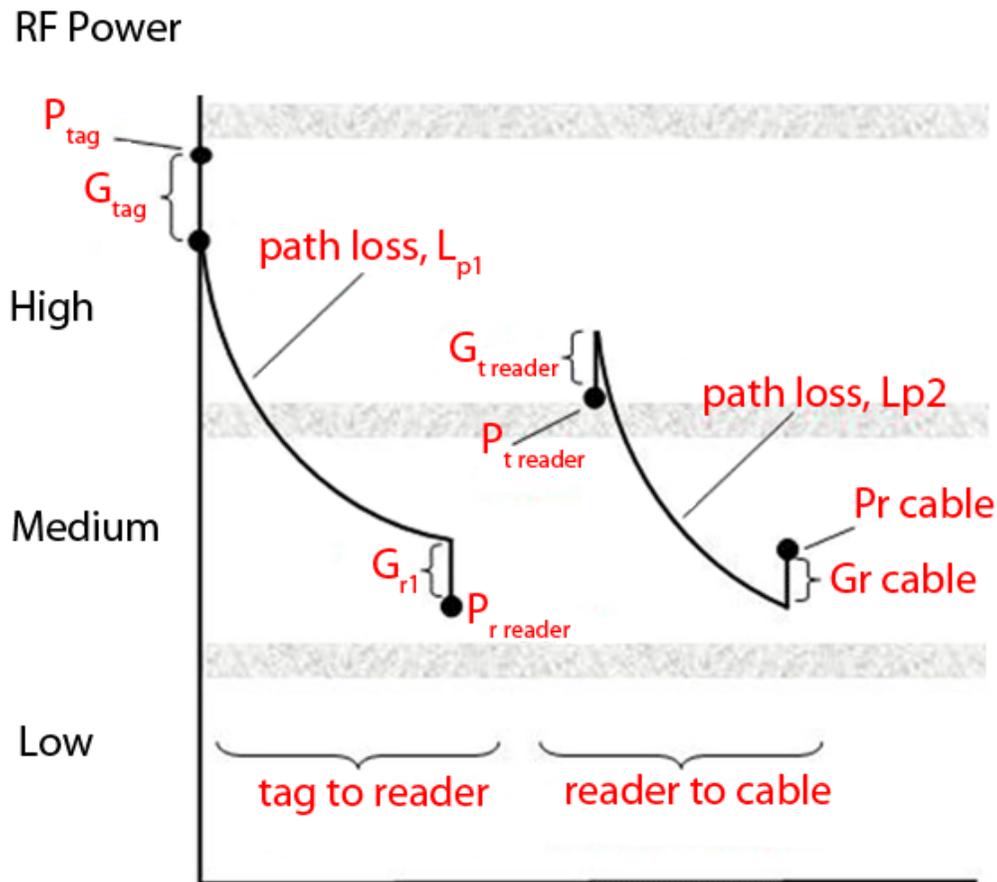


Figure 3-12. Conceptual link budget analysis for reverse-RFID tracking.

3.2.2.4 Network Operations

As discussed in the previous section, 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 transmit the location information to the surface, and ultimately to the MOC. The reverse-RFID reader must transmit location messages that are compatible with the backhaul system.

As included in the discussion of communications systems in Chapter 2, 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 untethered to meet the requirements of the MINER Act. The reader could be designed to communicate, for example, with a VHF or UHF leaky feeder or with a UHF node-based system. A leaky feeder backhaul has been used in most of the examples in the earlier sections on reverse-RFID, however that does not preclude the use of other technologies. It is unlikely that the reader would transmit medium frequency (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 to a digital MF network. Regardless of the technology used, the network backhaul will likely be that of the communications system. The reverse-RFID reader would represent an additional access to that network.

3.2.2.5 System Implementation

The reverse-RFID tracking system requires a communications backhaul system to relay location information to the MOC. Figure 3-13 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 30 m (100 ft), then the miner's location would be known to within 30 m (100 ft), 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 backhaul system, 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.

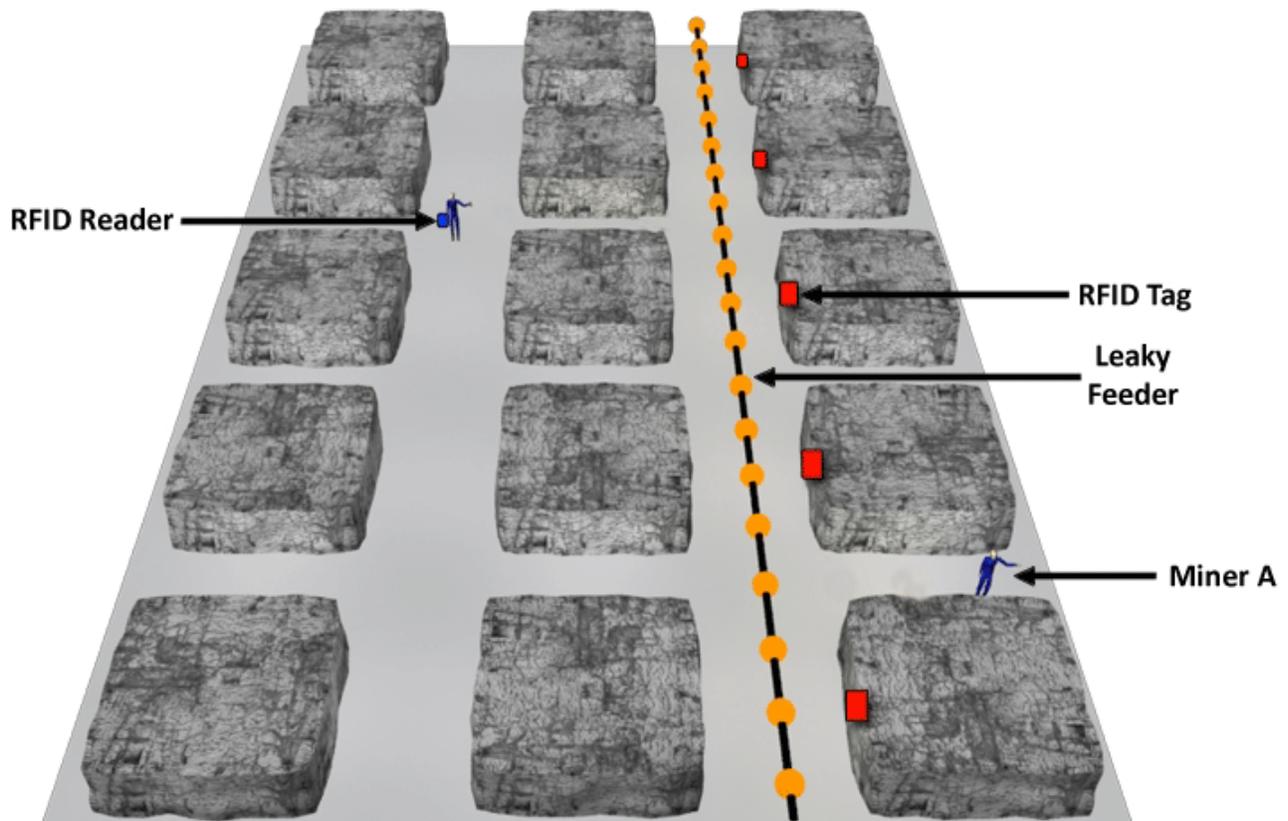


Figure 3-13. A reverse-RFID system with leaky feeder backhaul.

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 roof fall, 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 properly 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 nonconducting 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 both 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 recommendation for spare cap lamps located underground should apply. If the tag reader electronics are in a separate enclosure, spare reader 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 a tag reader being replaced with another reader unit.

3.2.2.6 Maintainability and Inspection

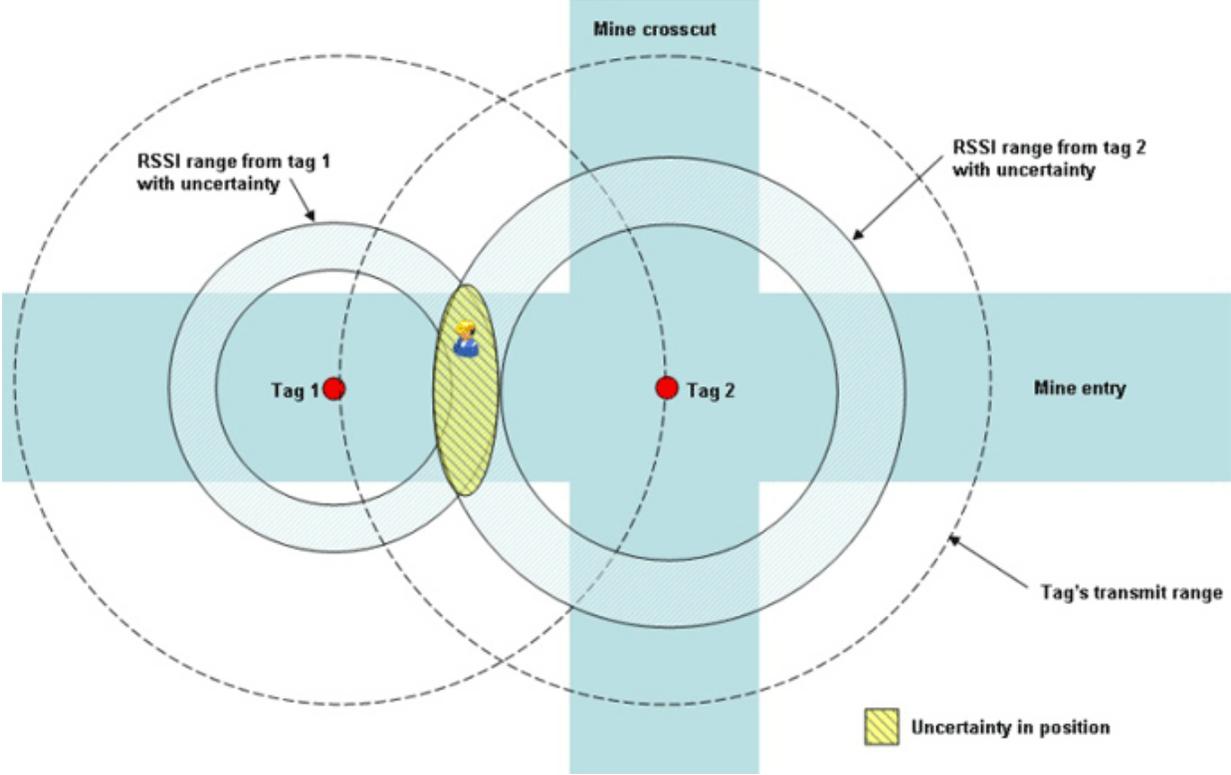
The complexity of reverse-RFID systems is generally considered high due to the number of tags required throughout the mine, the addition of a tag reader device that must be worn by each miner, and the required interface to the existing mine communications system. The system's tracking computer should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

Tags can fail during day-to-day operations due to low-voltage batteries, physical damage from passing equipment, and harsh environmental conditions (moisture, dust, humidity, etc.). 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 would be useful to have a test station at the entrance to the mine to verify that 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 and determine if it should be replaced with a new tag.

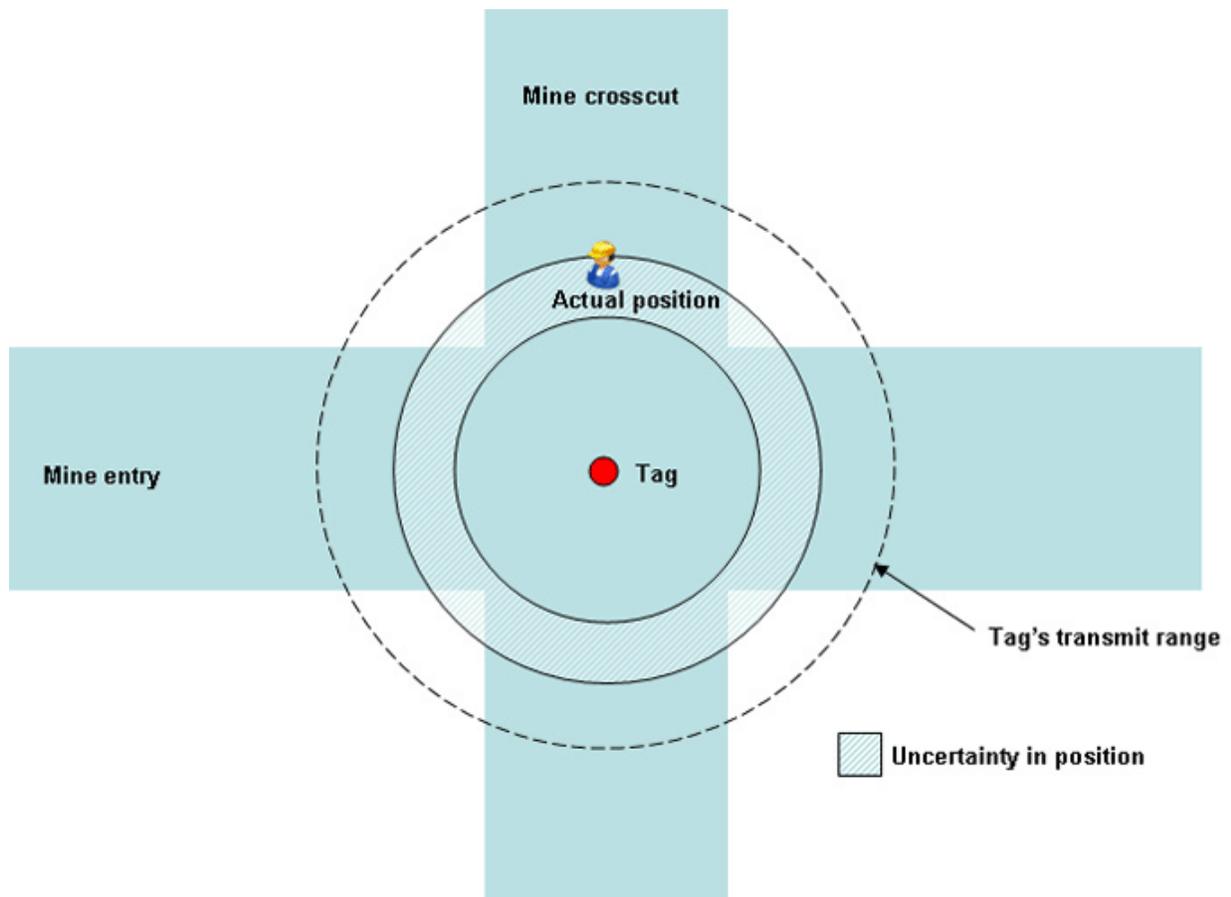
3.2.2.7 Performance and Limitations

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 systems, this is highly dependent on the characteristics of the tags. Technical factors such as transmit range, update rate, and RSSI methodology (if used), 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. 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 transmitted power of the two tag signals, which allows the miner's position between the two tags to be more accurately estimated (See Figure 3-14A). The accuracy is decreased when only one tag is detected, as shown in Figure 3-14B. 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 3-14C). Accuracy can be improved in both types of systems if some intelligence is added to the

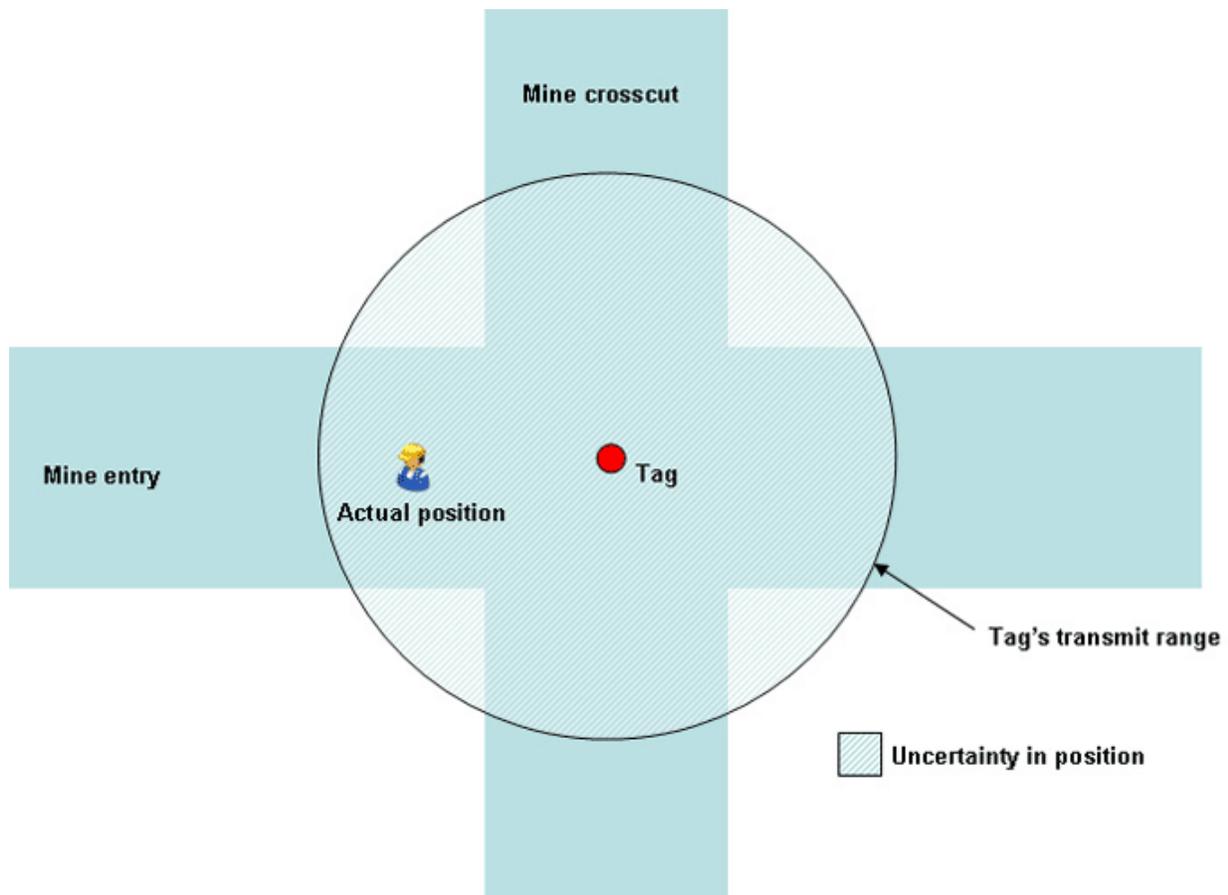
tracking software to eliminate the possibility of a miner standing inside a pillar, for example. Update rate, or how often the location information is sent to the tracking computer, greatly affects accuracy. For example, if a miner moves after the last update, then his actual location will differ from the last known location by some distance that is dependent on travel speed and the time to the next update.



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

Figure 3-14. Three possible received signal strength indicator (RSSI) configurations.

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 the reader is within the transmit range of the tag. Tag signals can penetrate some materials (such as wood or concrete blocks), but the signal will be attenuated, which therefore limits the detection range.

The reader electronics worn by the miner will contain some type of device to communicate the location information through the mine's existing radio backhaul system. The backhaul 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 Chapter 2. An important RFID tracking accuracy consideration is the transmission characteristics of the radio link between the RFID reader and the existing backhaul. The accuracy of the RFID tracking system is directly affected by the ability of the RFID system to reliably and accurately transmit location information. For example, if the tracking system uses the mine's leaky feeder system to transmit location information to the surface, but 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 reverse-RFID 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 backhaul system will need to be installed in the new areas also. New readers will also 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. 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 as well as on any federal, state, or local regulations.

The currently 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 it is anticipated that reverse-RFID will be integrated into node-based communications systems to provide better tracking accuracy to those systems. As discussed, reverse-RFID systems will likely use the existing radio communications system to transmit tracking information to the surface. Thus, the radio link for the RFID 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 reverse-RFID 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 tag reader units and/or replacement batteries should be available in fresh-air (permissible areas) underground.

Because it is critical that tracking systems operate after an accident, survivability should be a major consideration (see Section 4.2). 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 re-entered an area with functioning tags, tracking can resume provided the communications infrastructure is functioning. For reverse-RFID systems that use the existing mine backhaul 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 emergency, it will not affect the operation of the tags and readers. Both normally operate on battery power. 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. Other readers 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. Commercially available tracking 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 the main power is restored or the communications system is switched to backup power.

3.3 Node-Based Communications with Integrated Tracking

3.3.1 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 likely 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 may allow 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 link. Software on the MOC computer interprets the information. The location of the node can be displayed on a mine map and the miner's location is associated with that node on the map.

Wireless nodes may be located up to 600 m (2000 ft) apart and still provide continuous communications coverage. Based on the approach just introduced, the miner's location would only be known within 600 m (2000 ft). 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 [*received signal strength indication \(RSSI\)*](#) to determine how far away the handheld radio is from a node.

Another technique to determine a radio location in a node-based system is based on [*time difference 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 the more time that is required to reach a node. 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 help 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 also 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.

3.3.2 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 will likely 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 2-22 and discussion in Section 2.3.2.

3.3.3 Transmission Media

The node-based tracking transmission media discussion is the same as the node-based communications discussed in Section 2.3.3. The physical link from the radio to a node is through the air. The node-to-node backhaul link can be either wireless or wired. The link budget analysis is the same as shown in Figure 2-24.

3.3.4 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 2.3.4. 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.

3.3.5 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 2.3.5 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. 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 may 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.

3.3.6 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 2.3.6. 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 (both voice and/or text) 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. Communications devices will typically provide battery status information to the user and network; whereas RFID tag batteries will require periodic inspection to ensure that they have adequate stored energy.

3.3.7 Performance and Limitations

As discussed in Section 2.3, 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 3.2.2.7. Although RSSI and TDOA 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 miner's device at any given time. Entry dimensions, bends, elevation changes, and obstructions can also impact location accuracy. The situation may be exacerbated during mine 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, in order to allow surface personnel to assess the accuracy of system-reported locations using these techniques. Communications devices may also offer "man down" signaling features for rescue/recovery situations that are otherwise not available with simple RFID tags.

3.4 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, global navigation satellite systems (GNSS) have replaced inertial navigation. The NAVSTAR Global Positioning System (GPS) is a GNSS deployed by the U.S. Air Force. 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 motion in each of the three coordinate (X-Y-Z) axes and separately, rotations about the same 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 3.2.2) 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 over time. Small errors in measurement, known as "drift," accumulate within several minutes and can 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. Errors can also be reduced by periodically correcting the location data and re-initializing the INU at underground correction points. These could be surveyed locations and would require a secondary system to be interfaced with the INU, such as RFID.

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. However, with further hardware and software technology development, it should be possible to greatly reduce these errors.

3.5 Tracking Technology Comparison

Currently there are three commercially available 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. Table 3-1 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 quantify. However, node-based systems using handheld radios are not limited in transmit power to the same extent as systems which use RFID tags and so are likely to have greater read 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 consequently 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. This would require a handheld radio location device to pinpoint the location of a miner. At this time, some tracking system manufacturers were working on this capability.

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 3-1 assumes the nodes use RSSI and the miner is within range of two nodes.

Tracking system survivability is based on the vulnerability of the infrastructure components. For example, the destruction of tags in a reverse-RFID system does not impact the system as a whole but may reduce tracking accuracy in the affected area.

Table 3-1. Electronic Tracking System Comparison

TRACKING SYSTEMS				
Category	Feature	System Description		
		RFID	Reverse-RFID	Radio Node-based ¹¹
Coverage and Range	Range ¹	150 m (500 ft)	150 m (500 ft)	300 m (1000 ft)
	Expandability ⁸	Difficult	Easy	Medium
	Density of AC powered devices in mine ²	High	N/A	Medium
	Density of tags (mobile or fixed)	Low	High	N/A
	Data transmission method to surface ³	Manufacturer specific	Existing communications system	Integrated with the communications system
Installation	Design Complexity ⁴	Moderate	Low	High
	Labor intensity	Moderate	Low	High
Functionality	Centralized diagnostics	Yes	Yes	Yes
	Rescue team victim locator	Yes ¹⁰	Yes ¹⁰	Yes
	Tracking system accuracy ⁵	150 m (500 ft)	15 m (50 ft)	30 m (100 ft) ¹²
	Tracking system update interval	< 60 seconds	< 60 seconds	< 60 seconds
	Component worn by miner ⁶	Tag	Reader	Radio handset
Survivability	Tracking system survivability ⁷	Medium	High	Medium
	Battery life - Tracking fixed infrastructure	> 24 hours	> 1 year	> 24 hours
	Battery Life - Mobile component	>1 year	> 12 hours	> 12 hours
	Number of battery locations ⁹	High	High	Medium

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

4.0 CT System Survivability, Reliability, and Availability

4.1 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 of 2006. Examples of major emergency events are methane and coal dust explosions, fires, roof falls, and water 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 either a result of the emergency event or a random failure of a critical component of the system.

Frequently 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 the objectives of the CT system. Reliability is frequently represented as a probability or as a percentage. Examples of reliability objectives include:

- 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 assess different but interrelated qualities that measure the ability of a system to meet performance requirements. 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 4.2. Availability is discussed in more detail in Section 4.3.

4.1.1 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 underground 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 communications 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 4.2 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.

4.2 Survivability and Reliability

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

- Explosions. Includes methane-only explosions and coal dust explosions typically caused by suspended or disturbed coal dust 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 water inundation with potentially high water depths and long-term, chronically wet mine passage conditions.

The associated environmental conditions produced from these emergency conditions 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, electrical and electronic components, batteries, antennas, and external power supplies or battery-charging systems are all susceptible to damage.

Based on studies sponsored by NIOSH [QinetiQ 2008], it was found that the majority of recent major coal mine accidents (1990-2008) were methane and coal dust explosions. Such explosions have resulted in the most significant instances of damage to CT systems and are being used as the basis for recommendation for hardening and redundancy improvements.

In most of the studied cases, at least some if not most of the underground miners 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 none of the 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 [QinetiQ 2008] concludes that the forces likely to be encountered during coal mine accidents include:

- Explosions where peak blast pressures range from approximately 3.1 bars (45 psi) down to 0.6 bars (8 psi) depending on the distance from the blast and whether the exposure is direct (i.e., line-of-sight) or indirect (i.e., not line-of-sight). Peaks from methane-only explosions are typically on the order of 1/3 second in duration. 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 1,100°C-1,400°C (2,000°F-2,500°F). In addition, roof temperatures above localized fires (e.g., fires on or around a piece of mining equipment or a conveyor belt can range up to 200°C-550°C (400°F-1,000°F).
- Roof falls, pillar bursts and related ground control accidents can leave a mass of debris. Each 300 cubic meters (1,000 cubic feet) of rock debris can weigh as much as 36-72 metric tons (40-80 tons). Depending upon the size and shape of the fallen debris, a floor load impact could be 0.7-1.4 bars (10-20 psi). In fact, if the debris load is concentrated the impact can be as great as 17-35 bars (250-500 psi).
- Water inundations, assuming a water depth of 60 m (200 ft), can result in a 7-bars (100-psi) pressure for up to 200 hours.

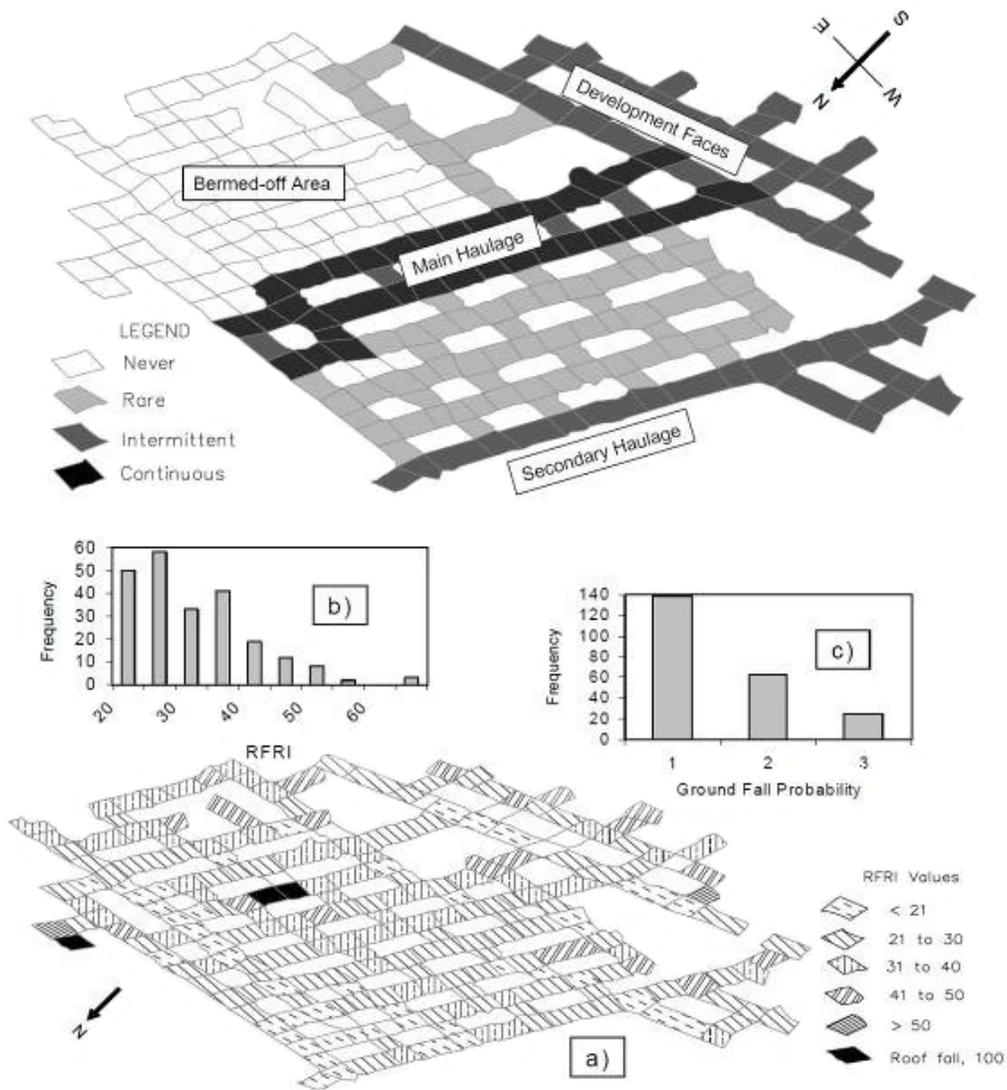


Figure 4-1. Example of a miner activity/travel and roof-fall probability map [Iannacchione et. al. 2007].

To address some of these issues, the QinetiQ [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 (RFRi) 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 4-1 [Iannacchione et al. 2007].

4.2.1 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.

As discussed above, 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 to the system. For underground coal mining CT systems, survivability may be considered the ability of the system to provide communications 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 nonfunctional, 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 depends upon which components are still functional and which are not functional after the emergency event. In the mining environment, the survivability of the individual components will depend upon the locations of the components with respect to the origin of the event. For example, components located directly next to an explosion site will probably not survive. Moreover, 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. 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.

The ability of a component to survive an event will increase if the appropriate protection has been implemented, i.e., 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 for being damaged 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 travel way. The metric that is most useful for determining survivability of a communications, tracking, or [atmospheric monitoring system \(AMS\)](#) is system coverage. Therefore, a coal mine operator should take into consideration how much coverage would be potentially lost if the more vulnerable components of the specific system were to become nonfunctional. 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, including the following:

- 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.
- Whether the cable or component is buried.
- 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 (for example, in an adjacent entry) may preserve paths of communications.

4.2.2 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 underground coal mining CT systems, the mine operator has additional considerations besides the ability of the system to function as specified by the manufacturer. The mine operator needs to know the likelihood that a system will function in critical areas of the mine, e.g., the working face, or the travel ways. If the system experiences any failures, the mine operator needs assurance that those failures will have minimal impact on communications coverage in critical areas. This issue is best summarized as a communications coverage assessment. Therefore, the mine operator is most interested in knowing the following:

- What areas in the mine have communications coverage?
- How reliably will the system provide communications coverage to those areas?

- Due to the configuration of the system or reliability of the components, how reliably will the system provide communications coverage in critical areas of the mine?

A communications 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 obtain 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 CT systems, losing functionality of an outby section of the system means that all sections inby that lost section also cease functioning. Therefore, during an assessment, the more coverage for which the section is responsible, 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 in seldom-used areas of the mine. A communications 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 areas.

The reliability of the CT system is determined by:

- Reliability of each of the system's components (electronics, battery, antenna).
- 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 its components is measured in terms of MTBF data, which assess 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's manufacturer.

The system's 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, 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., coal and rock dust, 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 CT system and its components 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 communications. For single-path systems, one break in that path will render the rest of the system inoperable. However, when redundant paths exist, communications signals can 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 nonfunctional, 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.

4.2.3 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.

4.2.3.1 Hardening Techniques

Hardening is a term used to describe the techniques that are used 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. However, hardening may increase the time required to repair such parts, which would decrease the basic reliability.

Cables and Connectors

Use of reinforced cables, conduit, supplementary cable shielding, and in-floor trenching for cabling are techniques 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 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 flying 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 hanger from a convenient roof bolt plate, light, or rib-mounted bracket, using substantial slack to prevent over-tensioning 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 hangers, meaning that an air blast of over a fraction of a bar (few psi) could sever the wire or cable. A typical cabling installation seen in mines is shown in Figure 4-2.



Figure 4-2. Hanging conductors from the roof.

Cables are highly susceptible to damage from blast 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 unfortunately the most exposed to destructive forces.

One installation consideration to help improve the protection of the system is installing cables on an upper rib area rather than the roof. This is not optimal for communications 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 physical location.

Installing cables with slack (with or without service loops) is another installation consideration. This is a multipurpose practice in which the slack promotes better communications coverage, and the service loops allow equipment placement to be adjusted without rewiring. These practices also help the cable to be more compliant in the case of small rock falls and other incidental physical contact.

Cables can be inserted in a protective conduit. Mechanically reinforcing cables and the associated components (e.g., thicker cables, 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 also increase the chances that it will survive adverse conditions.

When installing a CT system, one should also consider hanging communications, data, and power cables on the roof or rib, laying the cables on the floor, or burying the cables 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 4-3. Examples of trenching conductors.

Replacing a trench with the material used to construct it is the simplest design. However, using concrete, foam, or other types of material may allow for better propagation of radio signals. Figure 4-3 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 mine floor material.

Burying the conductor at certain depths still allows for communications at both UHF and medium frequencies (MF). Figures 4-4 and 4-5 show examples of how 450 MHz and 472 kHz signals propagate in a 300-600 m (1,000-2,000 ft) mine entry when conductors are buried versus conductors being hung in the center of the entry. Burying conductors in a trench with a 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.

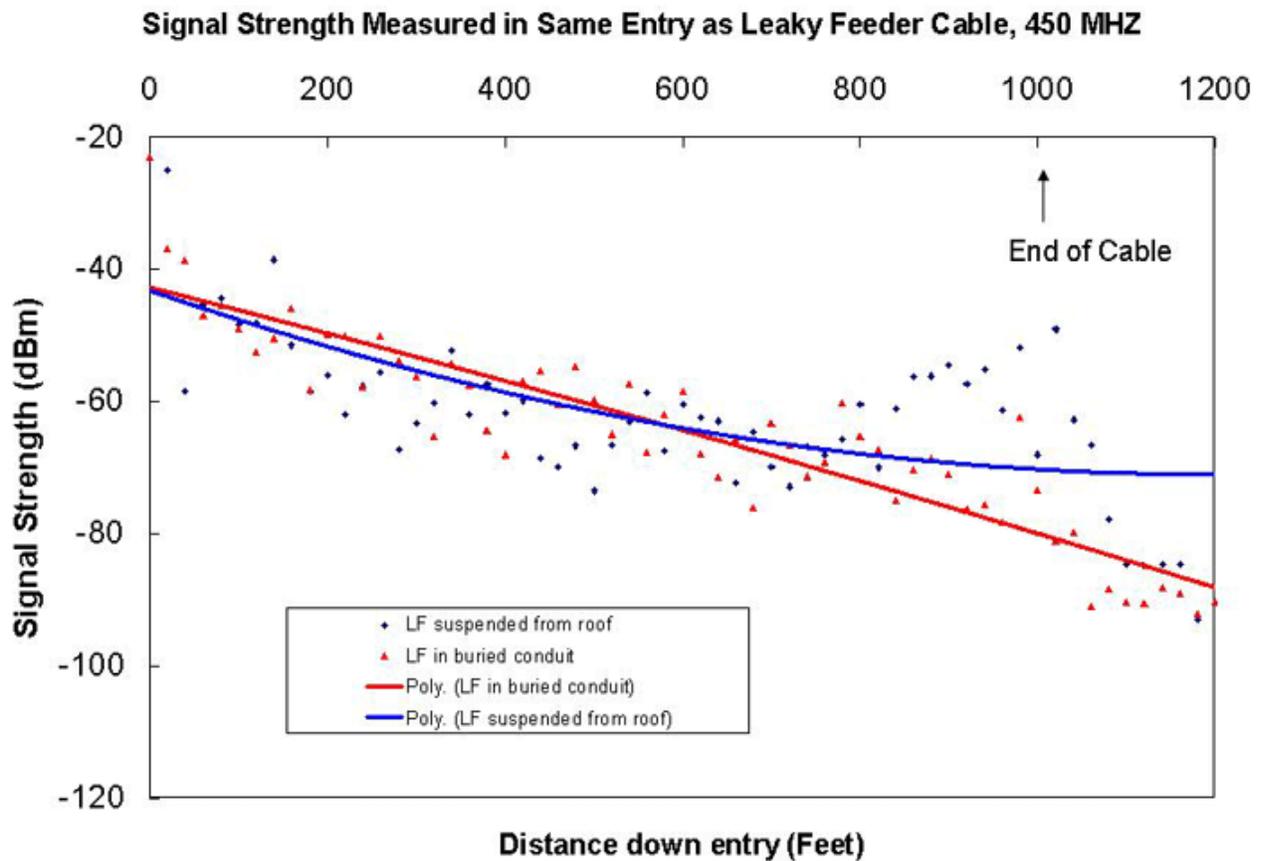


Figure 4-4. A 450 MHz signal propagating down a 300-m (1,000-ft) leaky feeder.

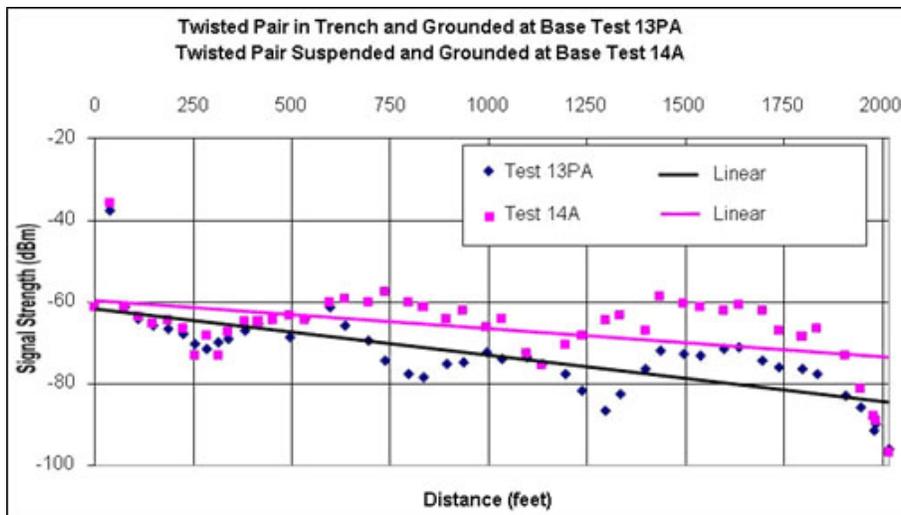


Figure 4-5. A 472 kHz signal propagating down a 600-m (2,000-ft) twisted-pair cable.

The results of these simulations (Figures 4-4 and 4-5) are only examples of possible trenching depth that may be used to provide for extra protection for certain conductors. Note that 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 mining 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.

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 4-6 shows an example of leaky feeder cables subjected to a more than 8-bar (120-psi) pressure wave and shows the effects on conductors that were parallel compared to perpendicular to the pressure wave.

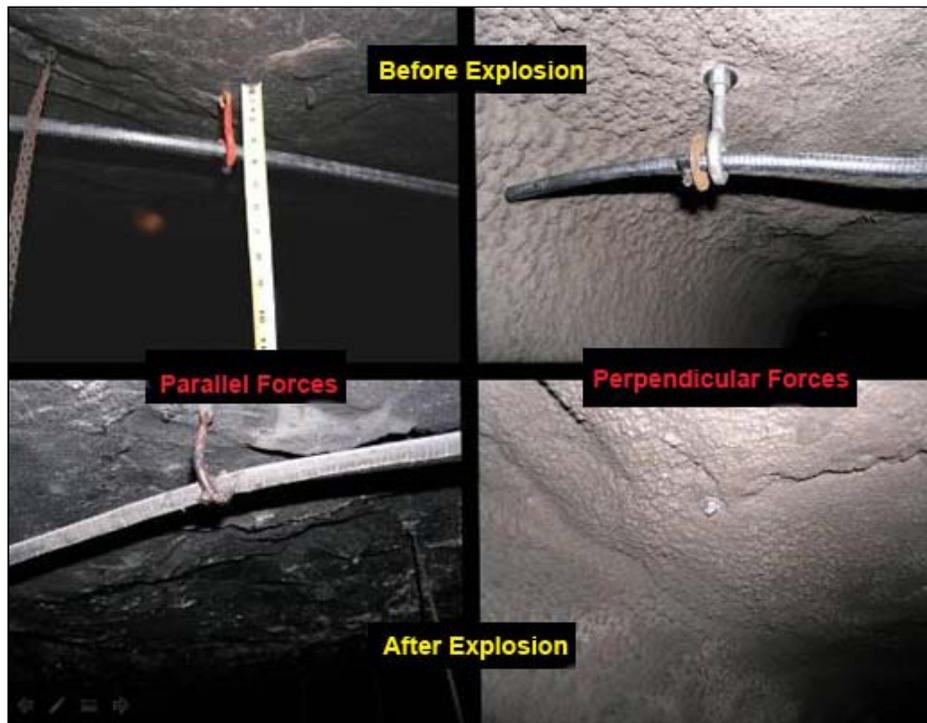


Figure 4-6. Examples of parallel versus perpendicular explosion forces on a conductor.

System Components

The primary communications system for most mines consists of hardwired mine paging phones. These systems still dominate the industry, and hardening of them will be important until other communications systems are more widely adopted. 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 therefore would be vulnerable to the impact of 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 rib line 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 rib lines rather than in the center of the entries due to loading from the retreating face.

System 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 cutouts and crosscuts to avoid damaging perpendicular forces. For example, amplifiers and power couplers can be located in blind crosscuts 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 crosscuts can reduce the level of blast pressure the equipment experiences during an explosive event.

Some wireless nodes may be installed in crosscuts; 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 dust tight enclosures, protected against jets of water, and resistant to corrosion.

Small antennas used for frequencies greater than 900 MHz, could be enclosed in an RF-transparent dome of Lexan or some other type of polycarbonate material.

4.2.3.2 Redundancy Techniques

Redundancy is another 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, as discussed in more detail below.

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

- An alternate communications 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 using 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 is severed or the component is 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 both wired and wireless systems coexist in separate entries. Any weaknesses in one system may be compensated for by the other system.

Power Supplies

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

The first step of the methodology is to define the emergency power supply system. The system engineer will identify the parameters, specifications, and requirements against which the performance of the system will be analyzed. Although some of these parameters may be the same as in routine use of CT systems, other parameters may be different. As the entire mine may be potentially explosive, the entire emergency power system must be designed to be intrinsically safe.

Alternate Communications Paths (ACP)

Alternate communications 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 borehole, 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 use an ACP must be capable of reversing the direction of message flow, at least over a portion of the backhaul system.

Figure 4-7 shows an example of an ACP layout with the bidirectional 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 surface location.

BiDirectional Communications Challenge

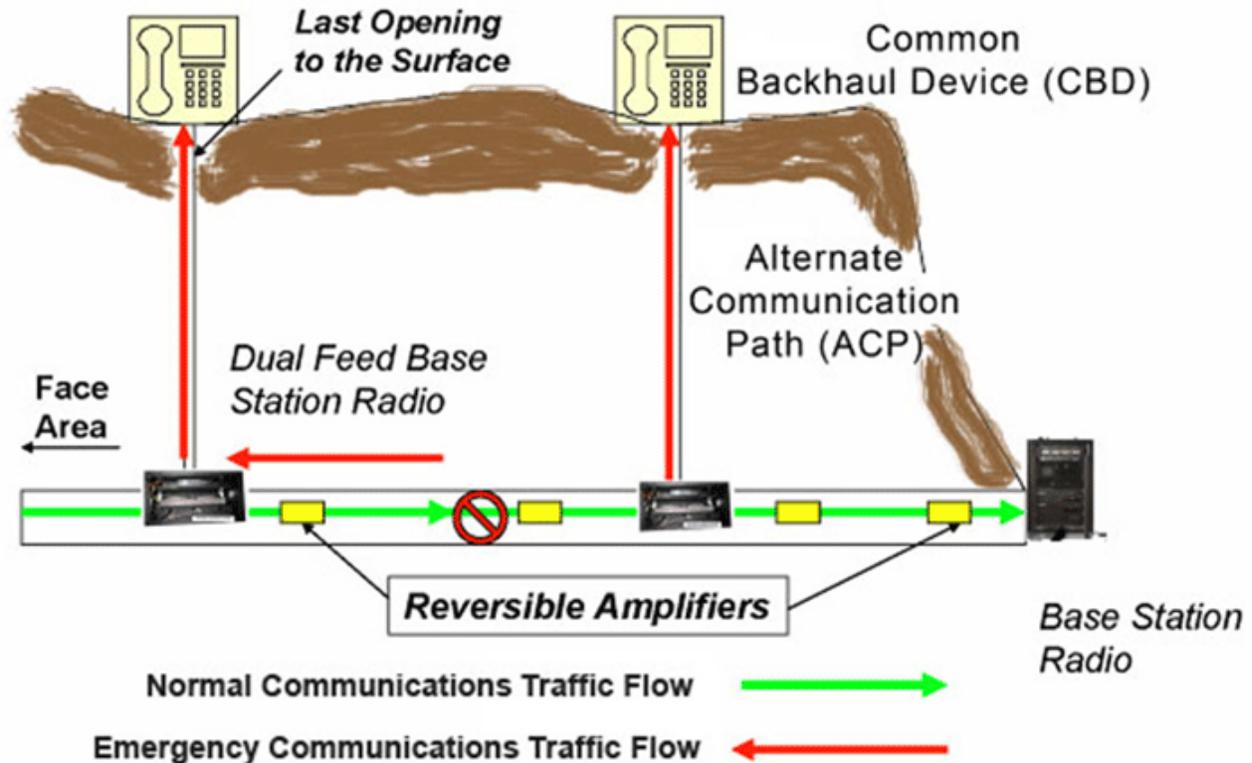


Figure 4-7. Bidirectional communications challenge.

4.2.3.3 Hardening and Redundancy Considerations for Electronic Tracking Systems

Most tracking systems share the backhaul with the communications system, so redundancy and hardening improvements made to the communications system also directly benefit the tracking system.

A tracking system's redundancy can be further improved by adding more location tracking reference points. Depending on the type of tracking system, the reference point may be an RFID reader, an RFID tag, or a wireless access point (WAP). The more tracking reference points installed in a mine, the more accurate the system, plus it allows the system to provide tracking information even if one or more of the reference points are lost.

4.2.3.4 Hardening and Redundancy Considerations for Atmospheric Monitoring System (AMS)

Manufacturers of [atmospheric monitoring systems \(AMSs\)](#) (i.e., systems that measure one or more types of mine gases such as methane, carbon monoxide, etc.) have indicated that there are no industry requirements for a redundant AMS system. Therefore, mine operators generally do not request system redundancy. However, some leaky feeder and wireless systems do offer add-on AMS equipment which would then benefit from the redundancy of those systems.

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

True mine-wide AMS systems do not yet exist in most 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.

4.2.3.5 Reconfiguration Techniques

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 hand-held radio after a leaky feeder becomes inoperable. The new channel would link the hand-held 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.

4.2.4 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. It is highly recommended that these methods and tools be tailored for use in the mining industry and for CT systems in particular.

All the tools for calculating survivability and reliability require developing a model to describe the CT system. For example, for each communications system discussed in Chapter 2, a block diagram of the main components 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 4-8 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.

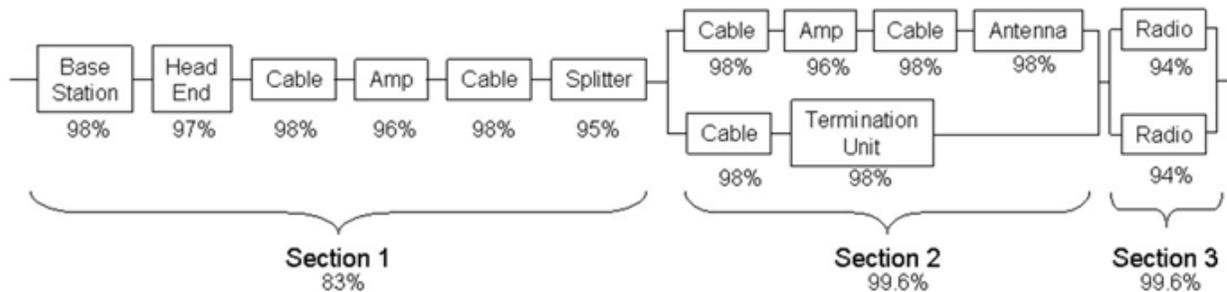


Figure 4-8. Block diagram of portion of leaky feeder showing percentage reliability of each component [QinetiQ 2008].

All the components in Section 1 of Figure 4-8 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:

$$\text{Section 1 reliability} = 0.98 \times 0.97 \times 0.98 \times 0.96 \times 0.98 \times 0.95 = 0.83 \text{ or } 83\%.$$

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

Section 2, in by 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.

$$\begin{aligned} \text{Reliability of upper cable} &= 0.98 \times 0.96 \times 0.98 \times 0.98 = 0.90 \\ \text{Reliability of lower cable} &= 0.98 \times 0.98 = 0.96 \\ \text{Section 2 reliability} &= 0.90 + 0.96 - [0.90 \times 0.96] = 0.996 \text{ or } 99.6\%. \end{aligned}$$

Notice that the operational reliability of systems in parallel (upper cable is in parallel with lower cable of Figure 4-8) 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 4-8 is the product of the reliabilities of each section:

$$\text{Total system reliability} = 0.83 \times 0.996 \times 0.996 = 0.82 \text{ or } 82\%.$$

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:

$$\text{The total system reliability without the lower cable} = 0.83 \times 0.90 \times 0.996 = 0.74 \text{ or } 74\%.$$

The reliability with the redundant or parallel system has a higher operational reliability of 82% compared to the system without the redundant path, 74%. This quantitatively illustrates the benefit of having a redundant communications system.

Similar modeling and calculations can be established for determining survivability.

4.3 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:

$$availability = \frac{uptime}{(uptime + downtime)} \tag{12}$$

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 used to repair a failed system or component. With these definitions, the availability can be expressed as:

$$availability = \frac{MTBF}{(MTBF + MTTR)} \tag{13}$$

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 4-1 shows the relationship between availability and downtime.

Table 4-1. 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 4-9a 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 4-9b 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 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.

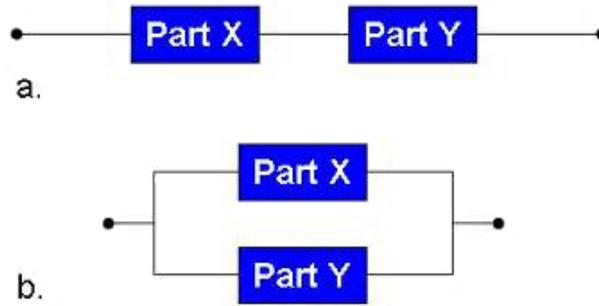


Figure 4-9. Components connected in (a) series and in (b) parallel.

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.

5.0 CT System Safety

One of the main goals of the MINER Act is to increase mine safety by providing two-way communications between miners and surface personnel, especially following a significant accident. In addition, electronic tracking is required to allow surface personnel to determine the current, or at least immediately pre-accident, locations 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; [electromagnetic radiation \(EMR\)](#) hazards to personnel, fuels, and blasting caps; and electromagnetic compatibility between RF-emitting systems. These concerns are individually addressed in the sections below.

5.1 Permissibility

Ventilation is required in coal mines to prevent the buildup 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 airflow resulting in a buildup of methane or other flammable gases, creating a potentially explosive or flammable atmosphere. The electrical power to the mine is then 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 \(XP\) 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](#) (IS). These two permissibility designations are discussed in detail below.

Methane or coal 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 blasting explosives can disperse coal dust layers into the atmosphere that subsequently ignite and propagate as powerful coal dust 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 in the last open crosscut [30 CFR 75.500], or within 50 m (150 ft) of pillar workings or longwall faces [30 CFR 75.1002], or in return entries [30 CFR 75.507], must be permissible. The requirements of 30 CFR 75.313 for electrical equipment apply when main mine fan stoppage occurs with persons underground. The 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 webpage [Title 30 CFR](#) .

As mentioned above, 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.

5.1.1 Explosion-Proof Enclosures

Sparks, electrical arcs, and hot surfaces have the thermal 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 5-1 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 mine electrical power is shut off.



Figure 5-1. Example of an XP enclosure.

5.1.2 Intrinsic Safety Certification

An alternative or additional approach to obtaining MSHA-permissible equipment approval is through the intrinsic safety (IS) certification. 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 methane-air 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.

The MSHA IS test requirements are specified in 30 CFR Part 18.68. There is further clarification of IS requirements in MSHA documents ACRI2001, "Criteria for the Evaluation and Test of Intrinsically Safe Apparatus and Associated Apparatus," and ACRI2011, "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 Approval and Certification Center](#)  webpage.

5.2 Battery Requirements

Batteries are 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 a 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 and/or coal dust environment). Miners 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-compliant enclosures (see Section 5.1.1 and also 30 CFR Part 7). One concern is that the XP enclosure may not survive a roof collapse, and therefore a hazardous situation could occur. Damage is also a concern for IS devices with lithium-type batteries which, for example, may be susceptible to *thermal runaway*. Lithium battery safety is a subject of ongoing research, but these batteries appear to present potentially greater risks to safe operation than other battery chemistries.

Stationary CT 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. Both the state of charge and health of batteries should be visible on the batteries or stationary equipment and/or displayed in the MOC.

Some areas of further investigation for batteries are listed below:

- What operational 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 hand-held radios, include the following: capacity (operating time), size, weight, limitations on safe locations for recharging or battery change-out, potential failure modes and consequences, use of battery types (such as various lithium chemistries) that may present an increased hazard in explosive atmospheres or near flammable material, 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.

5.3 Hazards of Electromagnetic Radiation

Electromagnetic radiation is pervasive in our environment. It allows us to receive satellite TV stations, listen to 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 5.4. Another required task is to identify and address any safety issues and hazards that might arise with the introduction of the CT system. In the mine environment, the following three areas may be adversely impacted by EM radiation or what is commonly called radiation hazards (RADHAZ): personnel, explosive atmospheres, and electrically initiated devices (e.g., blasting caps).

5.3.1 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 nonionizing radiation. This means that the RF radiation has insufficient energy to ionize atoms (strip off electrons), unlike x-rays, for example. However, the nonionizing radiation can cause electrostimulation (electrical shock) or thermal heating effects in humans. A HERP analysis on representative CT systems has been completed in a Joint Spectrum Center report [JSC 2008c]. 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).

5.3.2 Explosive Atmosphere

Coal mine operations generate coal dust and methane gas which 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 (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 2008c]. 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).

5.3.3 Electro-explosive Devices

[Electro-explosive device \(EED\)](#) is a general term for devices 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 CFR 77 Subpart N; by the Occupational Safety and Health Administration (OSHA) in 29 CFR Subparts H and U; and by the Department of Transportation (DOT) in 49 CFR 173. 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 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 reradiated from conductors within an entry. Quantitative analysis of this RF hazard in the mine environment is an area of ongoing research. In the near future, the safest recourse may be to use highly efficient RF shielding, such as shown in Figure 5-2. These enclosures or shielding blankets provide 50 to 60 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 detonate.



Figure 5-2. Examples of RF-shielding enclosures [TE3MI 2009].

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 5-3. 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 maintaining a minimum distance of separation between RF emitters and the blasting cap leads.

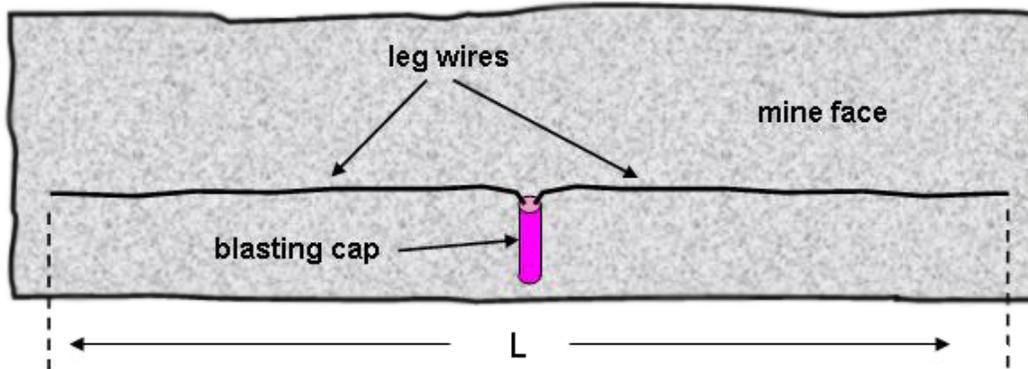


Figure 5-3. Blasting cap being deployed.

There is an IEEE standard C95.4 [IEEE 2002b] 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 et al. 1985]; these effects are not accounted for in the standards. This is an active area of research for NIOSH.

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 2002a], 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 either by direct 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 60 m (200 ft) from electric blasting caps during deployment, and all MF transmitters should be turned off.

5.4 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 of 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 emissions 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 aspect or susceptibility aspect). These topics are discussed in greater detail in the following subsections.

5.4.1 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 emissions and proper operation of equipment, or it may be from unintentionally generated RF emissions. A hand-held 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 occurs. 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 Section B.6.1. Additional EMI concerns are discussed in a Joint Spectrum Center report [JSC 2008b].

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.

5.4.2 Standards and Regulations

Usage of the electromagnetic 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 tunnels and underground mines).

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 U.S. standards that address EMC. The military, on the other hand, has very detailed standards on EMC.

Military equipment often contains 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 underground coal mine CT systems. For example, military equipment is often required to meet military standard MIL-STD-461F [DoD 2007], which could be tailored for underground coal mine CT systems.

MIL-STD-461F establishes emissions 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, 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 emissions 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 2008b]. The intent is to achieve electromagnetic compatibility between systems at a reasonable cost.

5.4.3 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; 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 (CO) sensor that is mounted in a plastic enclosure. The sensor may give erroneous readings if a hand-held radio is too close. The sensor could be hardened by using a metal enclosure instead of plastic.

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.

6.0 Mine Operations Center (MOC)

Wireless communications must be established between miners and surface personnel as required by the MINER Act of 2006. Similarly, for tracking systems, the electronic location information must also be available at the surface. An obvious central location on the surface to meet both these requirements is the *mine operations center (MOC)*. At least one dispatcher should always be in the MOC, monitoring operations, directing needed resources, and checking the status of sensor readings. The MOC must have computers 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 MOC should function to ensure effective communications and worker safety.

6.1 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 each 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 as specified by MSHA.

An example of a mine worker tracking display is shown in Figure 6-1.

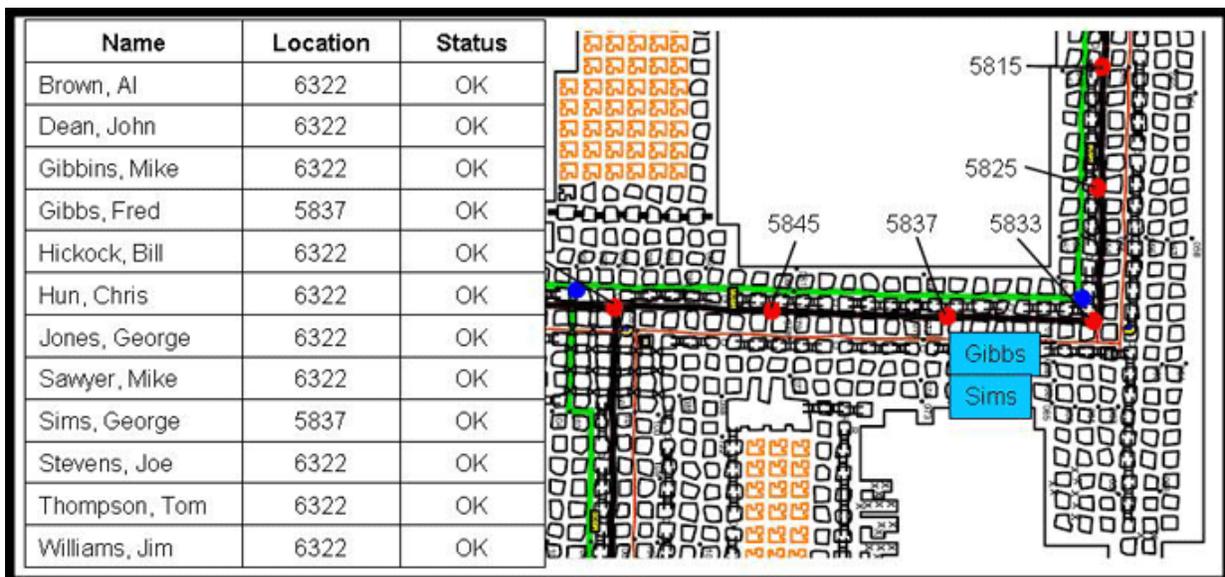


Figure 6-1. Example of tracking location display.

6.2 Surface Communications

As mentioned at the beginning of this chapter, communications from underground will likely be centralized at the MOC. During normal operations, the CT communications backhaul system will go directly to the MOC. Under emergency conditions, the CT system may be damaged and communications 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 be 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 a high-power transmitter or a 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 vicinity of the ACP access point and MOC.

Figure 6-2 presents three of the methods discussed for connecting the ACP access point to the MOC on the surface. Figure 6-2a 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 6-2b shows a wireless transmission through the air used to link the ACP with the MOC. Figure 6-2c 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 6-2), 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. Although only a few mine communications systems currently 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, tracking, AMS, and other data links. 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.

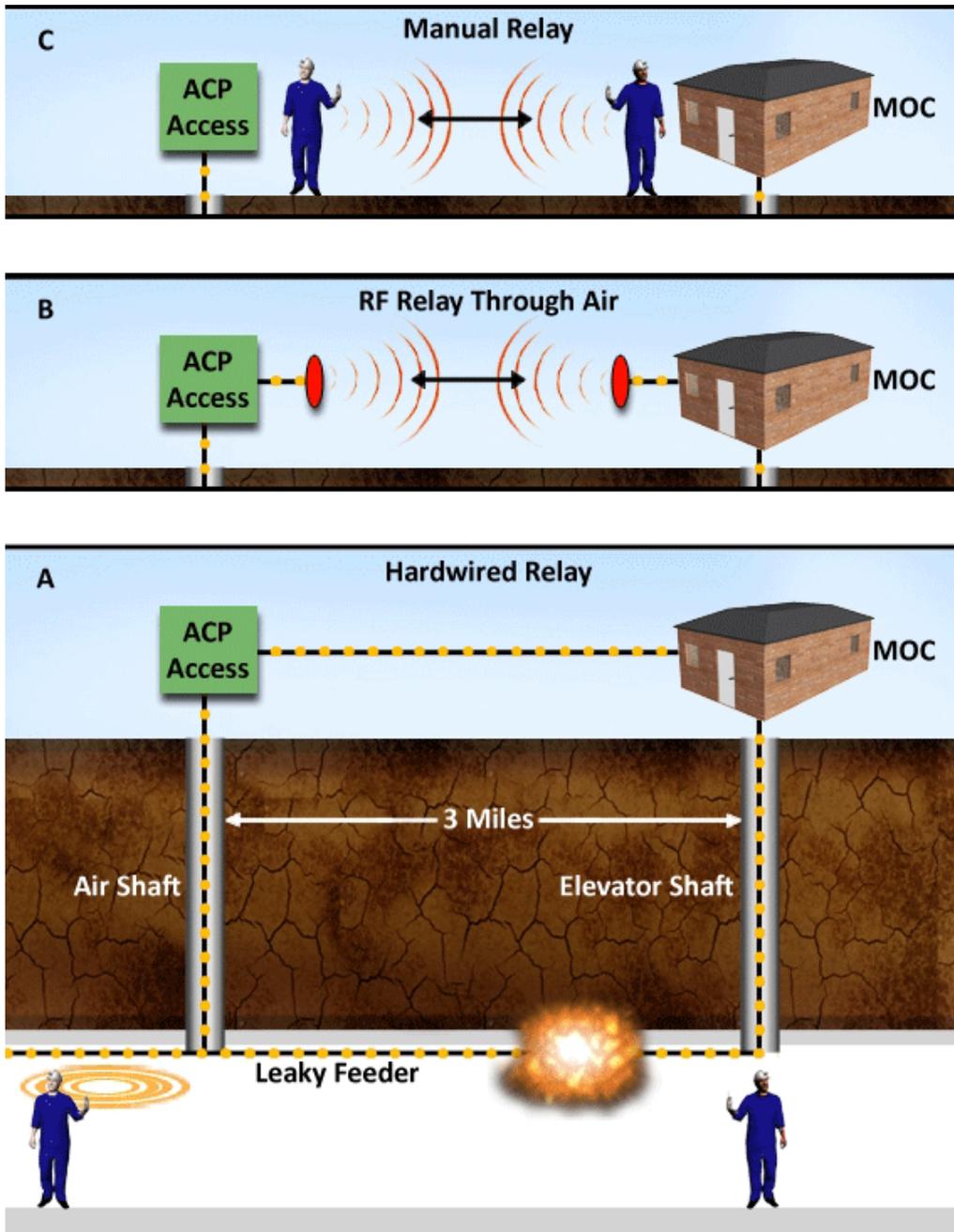


Figure 6-2. Several approaches for connecting ACP access to the MOC.

7.0 References

Balanis CA [2005]. Antenna theory, analysis and design. 3rd ed. Hoboken, NJ: John Wiley, 1117 p..

CFR. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

DoD [2007]. Requirements for the control of electromagnetic interference characteristics of subsystems and equipment. MIL-STD-461F. Department of Defense, Washington, DC: Dec.10.

Emslie AG, Lagace RL, Strong PF [1975]. Theory of the propagation of UHF radio waves in coal mine tunnels. Arthur D. Little, IEEE Transactions on Antennas and Propagation, Vol. AP-23(2), March: pp. 192-205.
[\[http://www.cdc.gov/niosh/mining/pubs/pdfs/totpo.pdf\]](http://www.cdc.gov/niosh/mining/pubs/pdfs/totpo.pdf). 

Freeman RL [2005]. Fundamentals of telecommunications. 2nd ed. New York, NY: Wiley-IEEE Press, 704 p.

Iannacchione A, Prosser L, Esterhuizen G, Bajpayee T [2007]. Methods for determining roof fall risk in underground mines. Mining Engineering 59(11), pp. 47-53. [\[http://www.cdc.gov/niosh/mining/pubs/pdfs/mrdrf.pdf\]](http://www.cdc.gov/niosh/mining/pubs/pdfs/mrdrf.pdf). 

IEC (International Electrotechnical Commission) [2007]. IEC 60079-0: Assessment of inadvertent ignition of flammable atmospheres by radio frequency radiation - guide. 5.0 ed. Geneva, Switzerland: July 20.

IEEE (Institute of Electrical and Electronics Engineers) [2006]. IEEE Std C95.1-2005, IEEE Standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. New York, NY: IEEE International Committee on Electromagnetic Safety (SCC39), April 19.

IEEE (Institute of Electrical and Electronics Engineers) [2002a]. IEEE Std C95.4-2002, IEEE Recommended practice for determining safe distances from radio frequency transmitting when using electric blasting caps during explosive operations. New York, NY.

IEEE (Institute of Electrical and Electronics Engineers) [2002b]. IEEE Std C95.6-2002, IEEE Standard for safety levels with respect to human exposure to electromagnetic fields, 0-3 kHz. New York, NY: IEEE International Committee on Electromagnetic Safety (SCC28), Sept. 12.

JSC (Joint Spectrum Center) [1997]. JSC-CR-97-010, EMC analysis handbook. Annapolis, MD: March.

JSC (Joint Spectrum Center) [2006]. JSC-CR-06-072, Communications receiver performance degradation handbook. Annapolis, MD: November.

JSC (Joint Spectrum Center) [2008a]. JSC-TR-08-119, Electromagnetic wave propagation modeling. Annapolis, MD.

JSC (Joint Spectrum Center) [2008b]. JSC-TR-08-120, Underground mine wireless communications compatibility standards. Annapolis, MD.

JSC (Joint Spectrum Center) [2008c]. JSC-WP-08-217, Minimum separation distances due to possible radiation hazards in an underground coal mine. Annapolis, MD.

Kraus J [1992]. Electromagnetics. 4th ed. New York, NY: McGraw-Hill.

Kutta Radios [2011] DRUM® Communication System (medium frequency radios) www.kuttarradios.com.

NTIA (National Telecommunications and Information Administration) www.ntia.doc.gov.

QinetiQ [2008]. Foster-Miller Report NSH-090164-1866. System reliability and environmental survivability, McLean, VA: QinetiQ North America [\[http://www.qinetiq-na.com/\]](http://www.qinetiq-na.com/). 

Stallings W, ed. [2007]. Data and computer communications. Upper Saddle River, NJ: Prentice Hall.

TE3MI [2009]. Products - RF shielding figure. Lake Ridge, VA: TE3MI Support Services.

Thompson RH, Stuart JG, Cipkins AW [1985]. A study of RF hazards at low and medium frequencies to blasting in underground coal mines. U.S. Bureau of Mines, Contract J0318023, Franklin Research Center, 314 p.
[\[http://www.cdc.gov/niosh/mining/pubs/pdfs/j0318023.pdf\]](http://www.cdc.gov/niosh/mining/pubs/pdfs/j0318023.pdf). 

White RF [1975]. Engineering considerations for microwave communications systems. 2nd ed. San Carlos, CA: GTE Lenkurt Inc.

7.1 Additional Resources

ARRL (American Radio Relay League) [2009]. The ARRL handbook for radio communications, 2009 ed., Newington, CT.

ARRL (American Radio Relay League) [2008]. The ARRL antenna book, 21st ed.. Newington, CT.

ARRL (American Radio Relay League) [2007]. The ARRL RFI book, practical cures for radio frequency interference. , 2nd ed. Newington, CT.

Loftness, M [2007]. AC power interference handbook, 3rd ed. Newington CT.

Page-Jones R [1998]. The RSGB guide to EMC, 2nd ed. Bedford, UK: Radio Society of Great Britain.

Rappaport TS [2002]. Wireless communications: principles and practice, Prentice Hall Communications Engineering and Emerging Technology Series, 2nd ed., Upper Saddle River, NJ: Prentice Hall, 707 p.

Appendix A - CT Systems Engineering Specifications

A.1 Definitions of Equipment Parameters

The equipment parameters that are typically required for coverage and electromagnetic compatibility (EMC) analysis of communications and tracking systems, and often specified in technical literature, are described in the following sections.

A.1.1 System

The equipment parameters that are generally applicable to a radio frequency (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:

- Frequency modulation (FM) - analog
- Single sideband (SSB) amplitude modulation (AM) - analog
- Binary phase shift key (BPSK) - digital
- Quadrature phase shift key (QPSK) - digital

The data rate is the number of bits per second (BPS) in a digital waveform. The units of kilobits per second (kbps) are also commonly used. This parameter is applicable only for digital modulation types and is normally 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

The equipment parameters that are 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 Appendix Section B.1.1 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 1,350 to 1,410 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	Ms
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 (μ s) 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. The signal level of the carrier is dBc. The unit dBc/Hz refers to the noise density with respect to the signal level of the carrier.

Table A-4. Transmitter emission spectrum

Parameter	Units
Emission bandwidth	MHz
At attenuation level	dB
Rolloff	dB/decade
Broadband transmitter noise (BBTN)	dBc/Hz

The transmitter 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 electromagnetic interference (EMI) analysis are the -3 dB BW and the rolloff in dB/decade.

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.

A.1.3 Receiver

The equipment parameters that are 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. 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 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 because 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

The equipment parameters that are 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	Degees
Beamwidth, vertical	Degees

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 also 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	meters

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.

Appendix B - Theory of Wireless Communications

B.1 Basic Equations

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 equation:

$$p_{mW} = 1000 p_W$$

(B1)

where

$$\begin{aligned} p_{mW} &= \text{power (mW)}, \\ p_W &= \text{power (W)} \end{aligned}$$

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:

$$P_{dBm} = 30 + 10 \log p_W$$

(B2)

where

$$\begin{aligned} P_{dBm} &= \text{power (dBm)} \\ p_W &= \text{power (watts)} \end{aligned}$$

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:

$$p_W = 10^{\frac{P_{dBm} - 30}{10}}$$

(B3)

where all terms were identified previously.

B.1.2 Antenna Gain Conversions

Antenna gain is often given in dBi units (The "i" stands for isotropic, a perfect point source which radiates in a spherical manner). To convert dBi to a numeric value, use the following equation:

$$g = 10^{\frac{G}{10}}$$

(B4)

where

g = numeric antenna gain (dimensionless)
 G = antenna gain (dBi)

Given the numeric antenna gain, the gain in dBi may be computed as follows:

$$G = 10 \log g \tag{B5}$$

where all terms were identified previously.

B.1.3 Wavelength

An electromagnetic (EM) signal has a frequency and a wavelength. Given the frequency, the wavelength may be computed using the following approximate equation:

$$\lambda = \frac{300}{f} \tag{B6}$$

where

λ = wavelength (meters)
 f = frequency (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 (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. Conversely, when the antennas are in the near-field of each other, 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 minimum value for the distance to the far-field region is four wavelengths. For directive types of antennas (e.g., Yagi-Uda), the distance to the far-field region may be calculated using the following equation:

$$D_{FF} = \frac{2D_{ant}^2}{\lambda} \tag{B7}$$

where

D_{FF} = distance to the far-field region (meters)
 D_{ant} = largest dimension of the antenna (meters)
 λ = wavelength at the system's frequency (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 amperes (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 (W/m²).

B.3.1 Effective Isotropic Radiated Power

The effective isotropic radiated power (EIRP) is 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:

$$EIRP = P_T - LL_T + G_T$$

(B8)

where

$EIRP$ = effective isotropic radiated power (dBm)

P_T = transmitter power (dBm)

LL_T = line loss (dB)

G_T = transmit antenna gain (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 s , in mW per square meter (mW/m²) incident on a point may be computed using the following equation:

$$s = \frac{P_T g_T}{4\pi R^2}$$

(B9)

where

s = power density (mW/m²)

P_T = transmitter power (mW)

g_T = transmit antenna gain (near-field or far-field) (dBi)

R = distance from the antenna to the point of interest (m)

The power density in dBm per square meter (dBm/m²) may be evaluated using the following equation:

$$S = 10 \log \left[\frac{P_T g_T}{4\pi R^2} \right]$$

(B10)

where

S = power density (dBm/m²)

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; consequently 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:

$$E = \sqrt{120 \pi s}$$

(B11)

where

E = root-mean-square (rms) E-field strength (V/m)
 s = power density (W/m^2)
 120π (~377) = 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:

$$H = \sqrt{\frac{s}{120 \pi}}$$

(B12)

where

H = root-mean-square (rms) H-field strength (A/m)

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:

$$L_{FS} = 20 \log \frac{\lambda}{4 \pi D}$$

(B13)

where

L_{FS} = free-space propagation loss (dB)
Free-space propagation losses do not include any additional diffraction and reflection losses (e.g., reflection, multipath, refraction) along the ray path.
 λ = wavelength at the receive frequency (m)
 D = distance between antennas (m)

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 dielectric 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 Figure B.4-1.

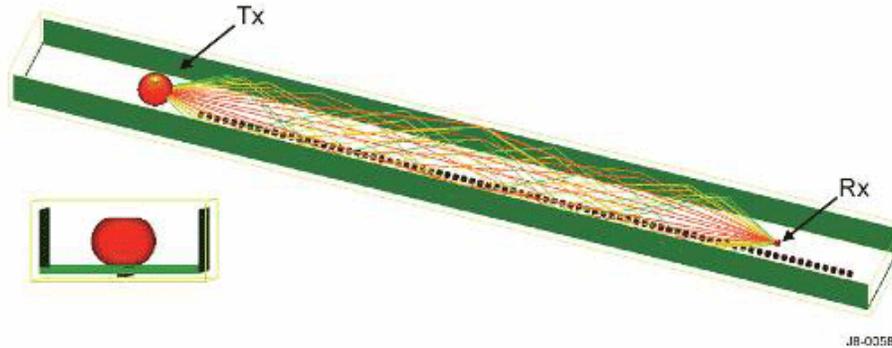


Figure B.4 1. Straight rectangular tunnel.

The propagation loss can be modeled [JSC 2008a] as following free-space loss up to a breakpoint distance, and then following a linear decay rate for distances beyond the breakpoint. The propagation loss depends on the polarization of the wave. Only the EM wave polarization that experiences the least amount of attenuation as it propagates through the tunnel is of interest, 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 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:

- Find the breakpoint distance, d_{FSL} , in meters using the following equation:

$$d_{FSL} = 2 \left[\frac{b^2}{\lambda} \right]$$

(B14)

where b and λ are in meters.

- Find the free space loss, FSL_{bp} , in dB at the breakpoint distance d_{FSL} using the following equation:

$$FSL_{bp} = 32.4 + 20 \log \left[\frac{d_{FSL}}{1000} \right] + 20 \log f_{MHz}$$

(B15)

where

d_{FSL} = breakpoint distance, (m)
 f_{MHz} = the frequency (MHz).

- Determine the far-zone linear decay rate, α_{spe} , in dB/m from the following equation:

$$\alpha_{spe} = 8.686 \alpha_{mn}$$

(B16)

where α_{mn} is given by:

$$\alpha_{mn} = \frac{2}{a} \left[\frac{m\lambda}{2a} \right]^2 \frac{1}{\sqrt{\epsilon_r - 1}} + \frac{2}{b} \left[\frac{n\lambda}{2b} \right]^2 \frac{\epsilon_r}{\sqrt{\epsilon_r - 1}}$$

(B17)

where

ϵ_r = relative dielectric constant of the wall (typical value is 6)

λ = wavelength (m)

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:

$$L = 32.4 + 20 \log \left[\frac{d}{1000} \right] + 20 \log f_{MHz} ; d \leq d_{FSL}$$

$$L = FSL_{bp} + \alpha_{spe} (d - d_{FSL}) ; d > d_{FSL}$$

- 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}):

$$d_{max} = \frac{L_{max} - FSL_{bp}}{\alpha_{spe}} + d_{FSL}$$

(B19)

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 (dB) 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 communications 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 miners 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:

$$P_R = P_T + G_T - L_P + G_R - L_{Misc}$$

(B20)

where

P_R = received desired signal power (dBm)

P_T = transmitter power (dBm)

G_T = transmit antenna gain (dBi). G_T is the gain in the direction of the *propagation ray path*.

L_P = 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 = receive antenna gain (dBi). G_R is the gain in the direction of the propagation ray path.

L_{misc} = total of any additional miscellaneous losses (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 of 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:

$$P_R = P_T + C$$

(B21)

where

P_R = received signal power (dBm)

P_T = transmitter power (dBm)

C = coupling evaluated at the receive frequency (dB)

The coupling term, C , must be evaluated using numerical EM software (e.g., Numerical Electromagnetics Code (NEC)), 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 intermediate frequency (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:

$$N_T = 10 \log(kTBf_n) + 30$$

(B22)

where

N_T = receiver's effective input thermal noise power, ignoring any external noise (dBm)

k = Boltzmann's constant (1.38×10^{-23} J/°K)

T = absolute temperature, in degrees Kelvin. The standard value is 290°K (62.3°F).

B = bandwidth of the IF stage (Hz)
 f_n = 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 underground 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:

$$N = 10 \log(kTBf_n + n_e) + 30$$

(B23)

where

N = receiver's effective input noise power including any external noise (dBm)
 n_e = environmental noise power in the mine (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 (SNR)

The SNR is useful in desired-signal analysis and may be found as follows:

$$SNR = S - N$$

(B24)

where

SNR = available signal-to-noise power ratio (dB)
 S = signal power (dBm)
 N = receiver effective noise power level including any external noise (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 Receiver Sensitivity

The method for determining receiver 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:

$$S = N + SNR_{req}$$

(B25)

where

S = receiver sensitivity (dBm)
 N = receiver effective noise power level (dBm)
 SNR_{req} = required signal-to-noise power ratio (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. The AS is usually evaluated by a listener panel [JSC 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, because 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.

The sensitivity criterion depends on the modulation type of the receiver. The curves of the required SNR for various analog modulation types as a function of the AI are available [JSC 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 bit error rate (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. The curves of the required E_b/N_o as a function of the required BER for various digital modulation types are available [JSC 2006]. To convert from E_b/N_o to SNR , use the following equation:

$$SNR_{req} = 10 \log \left(\frac{E_b}{N_o} \frac{R_b}{B_R} \right)$$

(B26)

where

SNR_{req} = required SNR (dB)
 E_b = energy required per bit of information (joules or watt-second (W-s))
 N_o = thermal noise density in 1 Hz of bandwidth (W/Hz)
 R_b = system bit rate (data rate), in bits/s (or Hz)
 B_R = receiver IF-stage bandwidth (Hz)

The parameter N_o may be found by using the following:

$$N_o = N / B_R$$

(B27)

where

N = receiver effective noise level (dBm)

B_R = receiver IF bandwidth (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 [JSC 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

The term fading applies to unexpectedly large variations in the desired signal power at the receiver [JSC 2006]. 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.

Because fading over time and with miners moving around in the mine 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:

$$S_{\min} = S + M_F$$

(B28)

where

S_{min} = minimum signal level required to minimize fading (dBm)
 S = receiver sensitivity (dBm)
 M_F = fade margin (dB)

B.5.5.2 Digital Receivers

Because the path loss between a node and a mobile hand-held radio has a random component, and the path loss predicts the median path loss, the fade margin allows consideration of random fading. The fade margin is related to the "edge reliability" percentage, 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:

$$P(RSL > RSL_{Th}) = P(x > x_0) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x_0} e^{-1/2\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

(B29)

where

P = probability of rim coverage
 x = receiver signal level (RSL)
 x_0 = receiver signal threshold (RSL_{Th})
 μ = mean value representing the average received signal level
 σ = standard deviation.

The standard deviation (μ) 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 is 0.65.

Table B.5-4. Fade margin analysis

Terms	Mine
Coverage objective	Mine coverage
Area coverage probability	90% (n=4)
Rim coverage probability	74%
Standard deviation (dB)	8 dB
Fade margin (dB)	0.65 x 8 = 5.2 dB

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:

$$D_C = \frac{\lambda}{4\pi} \sqrt{\frac{p_T g_T g_R}{S_{min}}}$$

(B30)

where

D_C = maximum coverage distance (m)
 p_T = transmitter power (mW or W)
 g_T = transmitting antenna gain (numeric)
 g_R = receiving antenna gain (numeric)
 λ = wavelength at the frequency of interest (m)
 S_{min} = 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 crosscut. The reflector is arranged so that radiation from a transmitter reflects incident radiation into the crosscut. This configuration may have a lower path loss than a nonreflector 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:

$$G_{reflector} = 20 \log_{10} \left[\frac{4\pi A \cos \alpha}{\lambda^2} \right]$$

(B31)

where

$G_{reflector}$ = passive reflector gain (dB)
 A = reflector area (m²)
 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 rewritten in convenient units as:

$$G_{reflector} = 22.2 + 40 \log_{10} F_{GHz} + 20 \log_{10} A_{sq.ft.} + 20 \log_{10} \cos \alpha$$

(B32)

where all terms were previously defined.

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 redirect 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 90° (α is 45°) 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 radio or phone 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. A higher overlapping area ensures reliable coverage but increases the cost. See Section 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 that enables 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 (W)	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 (E_b/N_0) (dB)		k	Section B.5.4.2
Node Rx Sensitivity (dBm)	-90	$RSL=k+j+i+h$ or given	Section B.5.4.2 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/ $\Delta^\circ K$) x room temperature (290°K) = -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 unit 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	Manufacturer
Mobile Tx power (W)	0.0316	b	Manufacturer
Mobile antenna gain (dBi)	0.0	c	Manufacturer
Mobile EIRP (dBm)	15	a+c	Section B.3.1
Body loss (dB)	2.0	d	Manufacturer
Fade margin (FM) (dB)	5.2	e	Section B.5.5.2
Node receiver 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
Mixed mobility average (E_b/N_0) (dB)		k	2
Node Rx sensitivity (dBm)	-90	$RSL=k+j+i+h$ or given	Section B.5.4.2 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		Manufacturer
Maximum distance (m)	302	Section B.4.2	Calculated

$$*kT = \text{Boltzmann's constant } (1.38 \times 10^{-23} \text{ joules}/\Delta^{\circ}\text{K}) \times \text{room temperature } (290^{\circ}\text{K}) = -174 \text{ dBm/Hz}$$

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 unit 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 (W)	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 (E_b/N_0) (dB)		k	Section B.5.4.2
Mobile Rx sensitivity (dBm)	-90	$RSL=k+j+i+h$ or given	Section B.5.4 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

$$*kT = \text{Boltzmann's constant } (1.38 \times 10^{-23} \text{ joules}/\Delta^{\circ}\text{K}) \times \text{room temperature } (290^{\circ}\text{K}) = -174 \text{ dBm/Hz}$$

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 communications link with mobile users. Designing the coverage of adjacent nodes to overlap increases the reliability of mobile connections in the edge region because 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. A 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 $(2 \times 302) \times 0.75 = 453$ m to ensure 75% rim coverage probability with a coverage overlap of 25%.

B.6 Electromagnetic Interference (EMI) 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 analysis, but all the losses and gains from a potential source system to the victim are cataloged.

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 transmitter 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 out-of-band (OOB) effects, but are still a concern.

The 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:

$$I = P_T - L_{OOB} + G_T - L_P + G_R - FDR - L_{Misc}$$

(B33)

where

I = received undesired signal power (dBm)

P_T = transmitter power at the fundamental frequency (dBm)

L_{OOB} = 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 = transmit antenna gain (dBi). G_T is the gain in the direction of the propagation ray path.

L_P = 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 = receive antenna gain (dBi). G_R is the gain in the direction of the propagation ray path.

FDR = frequency-dependent rejection (FDR) (dB). See Section B.6.3 for a description of this parameter.

L_{misc} = 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. Because 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)

FDR consists of two components. The on-tune rejection (OTR) component is due to the difference in bandwidths (BW) 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:

$$FDR = OTR + OFR$$

(B34)

where FDR, OTR, and OFR are all in dB.

When the BW of the receiver 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. The 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 [17], 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 emissions 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 emissions spectrum data. In the absence of data, typical rolloffs are -40 dB per decade for the transmitter and -80 dB per decade for the receiver.

B.6.4 Interference-to-Noise Ratio

The interference-to-noise power ratio (INR) is useful in undesired-signal analysis and may be found as follows:

$$INR = I - N$$

(B35)

where

INR = available interference-to-noise power ratio (dB)
 I = undesired signal power (dBm)
 N = 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:

$$I_T = N + INR_T$$

(B36)

where

I_T = undesired signal power threshold (dBm)
 N = receiver effective noise power level, including any external noise (dBm)
 INR_T = 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 B.6.4. 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:

$$M = I - I_T$$

(B37)

where

M = EMI margin (dB)
 I = received undesired power (dBm)
 I_T = 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 (RFS)

The required frequency separation (*RFS*) may be computed using a loss, L_{RFS} , that is similar to the EMI margin, but with frequency dependent rejection (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. The L_{RFS} may be computed using the following equation:

$$L_{RFS} = P_T - L_{OOB} + G_T - L_P + G_R - L_{Misc} - N - INR_T \quad (B38)$$

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 miners. Higher levels of EM radiation can have the potential of detonating blasting caps and can even cause a methane or coal dust explosion under certain optimal conditions.

B.7.1 Threshold Levels

B.7.1.1 Personnel

For hazards of electromagnetic radiation to personnel (HERP), levels of maximum permissible exposure (MPE) were obtained [IEEE 2006 and CFR 47]. Certain of the MPE levels of CFR 47 were determined to be lower than those of IEEE C95.1 [IEEE 2006), and were used in the analyses. IEEE C95.1 notes that the exposure limits in the frequency range from 100 MHz to 1500 MHz are generally based on guidelines from CFR 47§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 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." [IEC 2007]

The following are from Table 1, Limits for Occupational/Controlled Exposures [CFR 47 Part 1 Paragraph 1.1310 2007a]:

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 Std C95.1-2005 mandates that both the E and the H fields be computed. The reason for this is not indicated, 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

The root-mean-square (rms) electric field strength should not exceed $1842/f_{MHz}$ V/m averaged over 6 minutes, where f_{MHz} is the frequency in MHz.

The rms magnetic field strength should not exceed $4.89/f_{MHz}$ A/m averaged over 6 minutes.

Note: For frequencies below 30 MHz, Stallings [2007] 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/cm²) averaged over 6 minutes.

1.5-100 GHz

Average power density should not exceed 5 mW/cm² 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 [IEEE 2002a].

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 [IEC 2007]. IEC 60079-0 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. Underground coal mines fall under Group 1.

The thresholds are defined with respect to a “thermal initiation time.” 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 [IEC 2007] defines the transmitter threshold power level to be 6 watts, and the thermal initiation time to be 200 μs.

Threshold power is defined to be the effective output power of the transmitter multiplied by the antenna gain. In equation form, this is expressed in the follow equation:

$$P_{thr} = P_T g_T$$

(B39)

where

P_{thr} = transmitter’s threshold power (W)
 P_T = transmitter power at the input to the antenna (W)
 g_T = 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 μ s), the standard is defined in terms of the maximum threshold energy of the pulsed transmission in μ J. Table 5 of IEC 60079-0[IEC 2007] defines the maximum threshold energy level to be 1500 μ J for Group 1.

The threshold energy may be computed using the following:

$$W_{thr} = p_T g_T \tau \tag{B40}$$

where

w_{thr} = transmitter's threshold energy (μ J)
 τ = transmitter's pulse width (μ s)

and other terms were defined previously.

B.7.2 Required Separation Distances (RSD), VHF and Higher Frequency Bands

For systems having tuned frequencies in the VHF band and above, required separation distances (RSDs) were computed using transmitter power, far-field antenna gain, and free-space equations. Equations for computing the RSDs are given in the following subsections B.7.2.1 through B.7.2.4. Although 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 medium frequency (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 data from a manufacturer.

B.7.2.1 Power Density Threshold

The average power density (s) incident on a point may be computed using the following equation [Balanis 2005]:

$$s = \frac{c^2 p_T g_T}{4\pi R^2} \tag{B41}$$

where

s = average power density (W/m^2)
 c = constant multiplier to account for reflections
 p_T = transmitter power (W)
 g_T = far-field transmit antenna gain (numeric)
 R = 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 a value of 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 a value of 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 :

$$R = \sqrt{\frac{c^2 p_T g_T}{4\pi s}}$$

(B42)

where

$$\begin{aligned} R &= \text{RSD (m)} \\ s &= \text{threshold power density (W/m}^2\text{)} \end{aligned}$$

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 as follows [Kraus 1992]:

$$s = \frac{E^2}{120 \pi}$$

(B43)

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:

$$R = \sqrt{\frac{30 c^2 p_T g_T}{E^2}}$$

(B44)

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 as follows [Kraus 1992]:

$$s = 120 \pi H^2$$

(B45)

where H is the rms magnetic field strength in amperes/m and s was defined previously.

The RSD may be computed by substituting Equation B-45 into Equation B-41 and simplifying:

$$R = \sqrt{\frac{c^2 p_T g_T}{480 \pi^2 H^2}}$$

(B46)

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]:

$$P_R = P_T g_T g_R \left(\frac{\lambda}{4 \pi R} \right)^2$$

(B47)

where

- p_R = received power at the output of the receiving antenna (W)
- p_T = transmitter power (W)
- g_T = transmitting antenna gain (dBm)
- g_R = receiving antenna gain (dBm)
- λ = wavelength at the frequency of interest (m)
- R = 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 would be 1.64 [Balanis 2005].

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 :

$$R = \frac{\lambda}{4 \pi} \sqrt{\frac{c^2 p_T g_T g_R}{P_{thr}}}$$

(B48)

where R is the RSD in m.

Acronyms and Abbreviations

ACP

alternate communications path

AGC

automatic gain control

AM

amplitude modulation

AMS

atmospheric monitoring system

AP

access point

BBTN

broadband transmitter noise

BER

bit error rate

BPS

bits per second

BPSK

binary phase shift key

BW

bandwidth

CBD

common backhaul device

CBS

communications backhaul (or backbone) system

CFR

Code of Federal Regulations

CO

carbon monoxide

CT

communications and electronic tracking

DC

duty cycle

DOT

Department of Transportation

DSL

digital subscriber line

E

electric field strength – rms (V/m)

E-field

electric field

EED

electro-explosive device

EIRP

effective isotropic radiated power

EM

electromagnetic

EMC

electromagnetic compatibility

EMI

electromagnetic interference

EMR

electromagnetic radiation

FCC

Federal Communications Commission

FDR

frequency-dependent rejection

FM

frequency modulation

FSK

frequency shift keying

GNSS

global navigation satellite system

GPS

Global Positioning System

HERF

hazards of electromagnetic radiation to fuels

HERP

hazards of electromagnetic radiation to personnel

H

magnetic field strength – rms (A/m)

H-field

magnetic field

ID

identification

IEC

International Electrotechnical Commission

IEEE

Institute of Electrical and Electronics Engineers

INR

interference-to-noise power ratio

INU

inertial navigation unit

IP

Internet Protocol

IS

Intrinsically safe

IT

undesired signal power threshold

JSC

Joint Spectrum Center

LAN

local area network

LED

light-emitting diode

LOS

line-of-sight

M

interference or EMI margin

MEMS

micro-electromechanical system

MF

medium frequency

MINER

Mine Improvement and New Emergency Response

MOC

mine operations center

MP

mesh point

MPE

maximum permissible exposure

MSHA

Mine Safety and Health Administration

MTBF

mean time between failures

MTTR

mean time to repair

NASA

National Aeronautics and Space Administration

NAVSTAR

Navigation Signal Timing and Ranging

NF

noise figure

NIOSH

National Institute for Occupational Safety and Health

NTIA

National Telecommunications and Information Administration

NTSC

National Television System Committee

OFR

off-frequency rejection

OFSK

orthogonal frequency shift keying

OMSHR

Office of Mining Safety and Health Research

OOB

out-of-band

OSHA

Occupational Safety and Health Administration

OTR

on-tune rejection

Pr

received power

Pt

transmitted power

P2P

point-to-point

PPL

Program policy letters (released by MSHA)

PRF

pulse repetition frequency

PSK

phase shift key

PVC

polyvinyl chloride

PW

pulse width

QPSK

quadrature phase shift key

RADHAZ

radiation hazards

RF

radio frequency

RFID

radio frequency identification

RFRI

roof-fall rating index

rms

root-mean-square

RSD

required separation distance

RSL

received signal level

RSSI

received signal strength indication

Rx

receiver

S

power density (dBm/m²)

S

siemens (unit of electrical conductance)

S/m

siemens per meter

SCSR

self-contained self-rescuer

SNR

signal-to-noise ratio

SOC

state-of-charge

SOH

state-of-health

SSB

single side band

TDOA

time difference of arrival

TOF

time of flight

TTE

through-the-earth

Tx

transmitter or transmitter power

UHF

ultra high frequency

ULF

ultra low frequency

USBM

U.S. Bureau of Mines

UWB

ultrawide band

VHF

very high frequency

VoIP

voice over Internet Protocol

WAP

wireless access point

Wi-Fi

wireless fidelity

WLAN

wireless local area network

XP

explosion-proof

[1] Code of Federal Regulations. See CFR in references

December 5, 2011 December 5, 2011 [National Institute for Occupational Safety and Health \(NIOSH\)](#) Mining Division