DESIGN CRITERIA FOR WIRELESS MESH COMMUNICATIONS IN UNDERGROUND COAL MINES

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ABSTRACT

The Mine Improvement and New Emergency Response (MINER) Act of 2006 was enacted in response to several coal mining accidents that occurred in the beginning of 2006. The MINER Act does not just require underground mines to integrate wireless communication and tracking systems, but aims to overall enhance health and safety in mining at both surface and underground operations. In 2006, the underground communication technologies available to the mining industry had inherent problems that limited communication capabilities. Since the passage of the MINER Act, there have been several developing applications for underground wireless communications. Underground wireless communications allow signals to propagate and take multiple paths to destinations providing a survivable, redundant, and adaptable means of communication and tracking. An underground wireless communications allow underground and surface personnel to directly correspond to one another without being as restricted as hardwired systems. Communication systems also allow miners to be tracked underground to provide a real-time or last known post-accident position, and ensure a more efficient rescue operation.

In order to increase the overall efficiency of developing communication systems there is a need for modeling of wireless signal propagation in underground mines. Research, modeling, and analysis of wireless signal propagation in underground mines ongoing and developing with underground communications systems as the systems progress. The work on this project is based upon the Accolade system from L-3 Communications Global Security and Engineering Solutions but applies to all underground wireless mesh systems currently available. A general approach is taken to solving underground wireless communications networks to allow the design criteria to be adaptable to other communication systems belong the Accolade system.

The data is based upon measurements and field work that took place July 2007 through December 2008 in International Coal Group's Sentinel Mine in Philippi, West Virginia. Comms, a computer method developed at the Virginia Center for Coal and Energy Research at Virginia

Tech, allows underground mine communication networks to be solved and analyzed. Comms was developed to solve and analyze underground wireless communication networks. The method which Comms solves communication networks is not mine specific and may be adapted to predict the performance of a system(s) in another mine.

The developed model discussed in Chapters 3 and 4 highlights the general signal loss parameters that are encountered by wireless signals in a mine. The model predicted the signal strength observed when encountering those categorized signal losses within 16 percent of the data measured during a mine survey. The model has been developed in a general manner to allow future investigation and pinpointing of additional interferences that occur within the underground environment.

Wireless communications have proven to be the way of the future and will continue to be integrated into underground coal mines as mandated by the MINER Act. Wireless communications systems are a redundant and survivable means of communication that will be utilized in not only emergency and rescue efforts but daily operational communication as well.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ELF – Extremely Low Frequency

ERP – Emergency Response Plan

FMN – Fixed Mesh Node

GIS – Geographic Information Systems

ICG – International Coal Group, Inc

IEEE – Institute of Electrical and Electronics Engineers, Inc.

IP – Internet Protocol

IS – Intrinsically Safe

IWT – Innovative Wireless Technologies

L-3 – L-3 Communications Global Security & Engineering Solutions

LAN – Local Area Network

LF - Low Frequency

MF – Medium Frequency

MINER Act – Mine Improvement and New Emergency Response Act of 2006

MMR – Miner Mesh Radio

MSHA – Mine Safety and Health Administration

NIOSH – National Institute for Occupational Safety and Health

PDA – Personal Digital Assistant

RF – Radio Frequency

RFID – Radio Frequency Identification

RSSI – Received Signal Strength Indication

TTE – Through-the-Earth

UHF - Ultra High Frequency

VCCER/VT – Virginia Center for Coal and Energy Research at Virginia Tech

VHF– Very High Frequency

VLF – Very Low Frequency

VoIP – Voice over Internet Protocol

WiFi – Wireless Fidelity

WMN – Wireless Mesh Network

XP – Explosion Proof

Chapter 1 : INTRODUCTION

In 2006, Congress amended the Federal Mine Safety and Health Act of 1977 by its implementation of the Mine Improvement and New Emergency Response (MINER) Act of 2006. On June 15, 2006 President George W. Bush signed the MINER Act which is considered one of the most significant health and safety improvements to the mining industry in the past 30 years (MSHA, 2006a). The MINER Act required a plan to be developed and submitted within 60 days of the enactment of the MINER Act that included the actions that will be taken to improve the standards for Post-Accident Communications, Post-Accident Tracking, Post-Accident Breathable Air, Post-Accident Lifelines, Training, and Local Coordination. The MINER Act mandated the installation of Post-Accident Communication systems that provided two way communication, survivability, and surface to underground communication.

The MINER Act required that no later than 3 years after the enactment of the Act that a plan shall be approved that provides for post-accident communication between underground and surface personnel via a wireless two-way medium and also requires that an electronic tracking system will allow persons underground to be located (MINER Act). The State of West Virginia has taken the initiative to be one of the leaders of the implementation of the MINER Act and require that wireless communications are installed by January 1, 2009 in every underground coal mine in West Virginia. These wireless communication systems will enable miners to be able to communicate back and forth with one another as well as with miners on the surface. Federal and West Virginia state laws require that the communication system coverage in at least two different entries (MSHA, 2006a). In the event of an accident, these systems will be utilized in order to communicate with the miners involved as well as to pin point their last known location and to coordinate rescue operations.

The National Institute of Occupational Safety and Health (NIOSH) is administering the funding of several research projects through the Emergency Supplemental Appropriate Bill which includes $10 million dollars to develop technologies such as communications and tracking, oxygen supplies, and refuge chambers (Coal News, 2008). Funding through NIOSH has allowed wireless mesh communication systems that were already available to the military to be adapted into the harsh underground mine environment. As part of this project, L-3

Communications Global Security and Engineering Solutions (L-3) has created a gateway to transform wireless mesh technologies into a full mine communication system. Wireless mesh technology requires optimal node placement for the wireless mesh system to ensure communication.

The objective of this project is to develop the design criteria for optimal wireless node placement in an underground coal mine. In particular, this project focuses on the design of an underground coal mine wireless mesh communication system. The design criteria provides a pre-installation plan for the person(s) investigating into putting in a communications system. The design criteria allows mine planning to take into consideration where power and broadcast node placement is required in the future. Proper planning ensures that existing and planned mining activities will not interfere with the communication system. The efficiency of the communication systems is increased when broadcast nodes are placed in optimal areas to provide the largest coverage areas while ensuring that required places receive coverage as well. The criteria provides a systematic approach to develop the initial network topology for communication systems.

Chapter 2 : LITERATURE REVIEW

Communication systems in the underground mine environment are crucial to ensure the efficient production, maintenance, and execution of other various everyday tasks that occur in the mine. Communication systems can help to eliminate many types of injuries that would occur if there was no means to communicate between different areas. Communication must occur between areas such as the top and bottom of the hoist to ensure that no one is injured during its operation. Unexpected changes can present hazardous circumstances if the proper warning is not relayed to affected miners. Communication systems that operate in underground mines have been improving throughout the history of mining but are still limited in range and capabilities when compared to communication systems that operate in surface mines.

2.1 Available Communications Technologies

2.1.1 HARDWIRED MINE COMMUNICATIONS

Hardwired communication systems have been in daily operation in underground mines for decades. Hardwired communications consist of devices that are connected to both ends of the medium over which communication will take place. There are many different media that communication can occur in, such as twisted pair, coaxial cable, CAT5 (typical Ethernet cabling), fiber-optic cables, and trolley wire, which are normally used to power mine locomotives but can also act as the conveyor of medium frequency signals (NIOSH, 2008). Hardware (or transmitting devices) that work on hardwired communications includes telephones, handheld portable radios or walkie-talkies, and pager phones and other paging devices.

Bell signaling systems were used in the past to communicate with the hoistman when a hoist was used. A bell signaling system consisted of the signaling of a bell, which had different meanings based upon the set code. Bell signaling systems are inefficient and outdated given increasing automation and sophisticated hoist equipment. Pager phone systems are among the types of communication that have replaced bell signaling systems. According to Updyke, Muhler, & Turnage (1980), pager phone systems have basically two wiring configurations. Updyke, Muhler, & Turnage (1980) state that, "the first is the party line which consists of a

single No. 14 or No. 16 gauge twisted pair wire strung throughout the mine and extended to the surface. A second, but less common place wiring configuration is a multi-line scheme in which several twisted pairs, normally six to eight, are strung throughout the mine." A multiple line scheme creates different channels for communicating. Other options such as dial telephone systems have been explored but are limited because telephone companies do not always provide underground service.

Hardwired communication devices provide many advantages and disadvantages because the communication devices must be physically connected to the communication medium. An advantage of a hardwired device is that as long as the cable is intact, communication between endpoints should always be successful. Hardwired devices can also provide higher bandwidth speeds, allowing for clearer and more efficient communication. The communication locations of hardwired devices are limited by the locations where devices can be wired to the communication medium. If a miner is injured or trapped, they may not be able to get to a location where hardwired communications are located and hardwired communication devices are also susceptible to damage and interferences such as roof falls, fires, explosions, and power failures, from the areas surrounding the communication medium.

Recent developments in underground communications have led to the implementation of fiber-optics in mine communication systems. Fiber-optic cables do not transmit data using electrical pulses but instead uses pulses of light to transmit data. There are two different parts of a networking fiber-optic cable that are responsible for guiding the light transmissions. The inner layer, or core, is pure glass with a high index of refraction and the outer layer, or cladding, is a glass or plastic layer with a low index of refraction that surrounds the core (Cisco Systems Inc., 2002, p. 167). The low index of refraction acts much like a light guide and allows light transmissions to be trapped in the core's glass medium. Using pulses of light to transmit data, makes fiber-optic cables are not susceptible to electromagnetic or radio frequency interferences (Cisco Systems Inc., 2002, p. 166). Fiber-optic communication can operate at much higher speeds because light pulses travel faster than electromagnetic waves. Applications of fiber-optics are limited because of the high cost cabling. Fiber-optics are utilized in underground mining typically to provide high speed alternate gateways, which tend to alleviate some communication

on the network. Several vendors are investigating using fiber-optics to quantify health and safety concerns such as gas concentrations and pressures at different points in the mine.

Hardwired systems provide many distinct advantages over wireless systems, such as low cost, high data transmission speeds, and less susceptibility to interferences. In order to efficiently and accurately track and communicate with miners underground, a combination of systems is ideal. Hardwired systems can be used as high speed backbones with multiple gateways or paths out of the mine. Wireless systems were viewed as unnecessary and too expensive until the MINER Act of 2006 mandated their installation to track and communicate with miners.

2.1.2 WIRELESS MINE COMMUNICATIONS

Wireless is a term that applies to radiated, or unguided, electromagnetic waves (Cisco Systems Inc., 2002, p. 166). Wireless systems have gained popularity in mines since the MINER Act was introduced. Communication systems that are "completely wireless" or untethered still must send and receive data along an internal infrastructure, or backbone. Communication systems of all types require a backbone in the mine. The backbone is typically a hardwired connection and is generally where a communication system is most vulnerable and susceptible to physical damage. Hardwired and wireless communication technologies can to complement each other. Combinations of technologies will ultimately provide optimal service because the different technologies will complement each other and make up for weaknesses of the individual technologies by themselves. Certain parts of the mine will be nearly impossible to cover due to cost, permissibility and other health and safety hazards.

Wireless communication was invented in 1896 by Marchese Gugielmo Marconi, who was granted the first patent for wireless communication in the United Kingdom (Stavroulakis, 2003). This was the first form of communication that took place without a physical wired connection. Since Marconi's invention, regular forms of daily communication began to integrate wireless communication into the process of relaying communication data, because wireless is easy to install and flexible in not requiring a wire to be physically attached. Research on wireless communication in mines has been ongoing since 1922, when the United States Bureau of Mines performed experiments in its experimental mine in Bruceton, Pennsylvania (Schiffbauer &

Brune, 2006a). The only commercially available wireless communication systems in 2006 were limited by line of sight because the wireless signal degrades much faster underground than it does above ground and does not provide enough flexibility to be utilized efficiently in the underground mine environment. Wireless communication systems that were developed for the military have been adapted and modified to allow them to function safely and efficiently in the harsh underground mine environment.
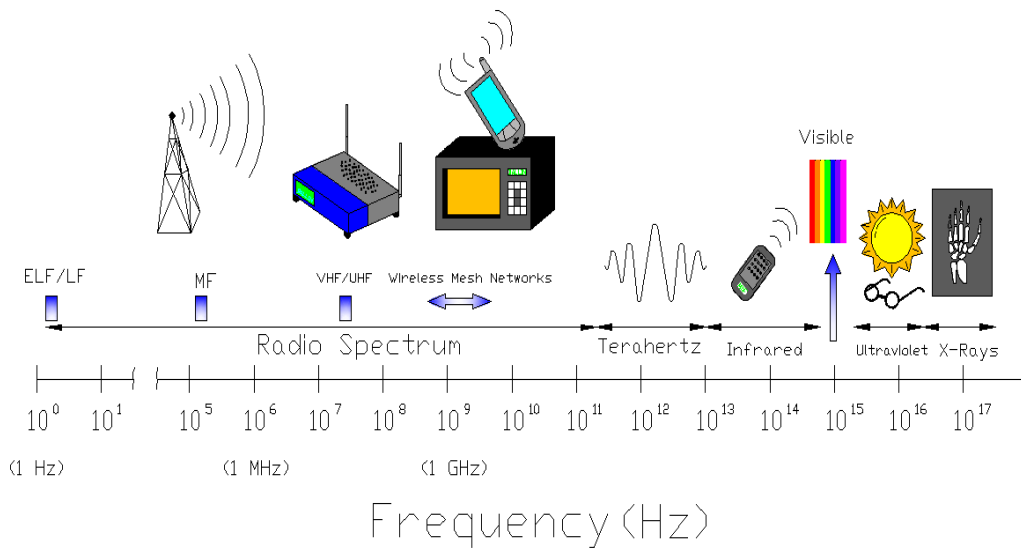
Figure 2.1: Frequency Spectrum (Adapted from University of Cambridge, 2005)

Figure 2.1 shows an illustration of the frequency spectrum adapted from the University of Cambridge (2005). The left side of the frequency spectrum is where most communications systems typically operate. The approximate operating frequency of Extremely Low Frequency/Low Frequency (ELF/LF), Medium Frequency (MF), Very High Frequency/Ultra High Frequency (VHF/UHF), and Wireless Mesh Networks (WMN) can also been seen in Figure 2.2.

6

ELF/LF   MF   VHF/UHF   Wireless Mesh Networks

Radio Spectrum   Te

10^0 10^1 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}

(1 Hz)   (1 MHz)   (1 GHz)
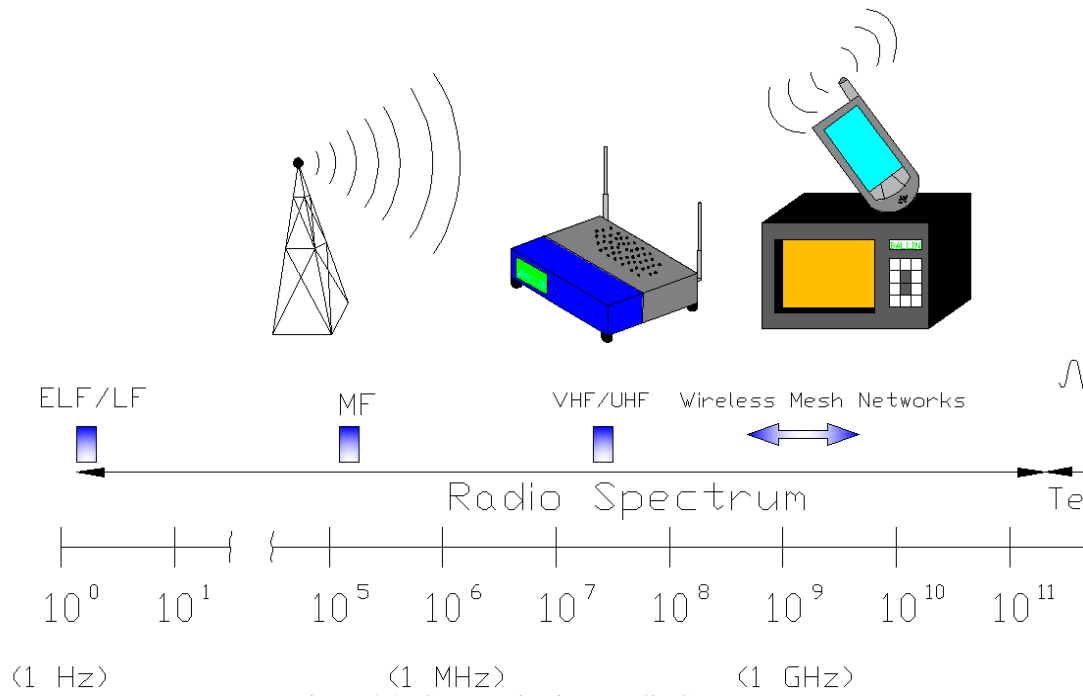
Figure 2.2: Communications Radio Spectrum

The harsh nature of underground coal mine tunnels drastically effects the propagation of radio waves. According to Dobroski and Stolarczyk (1982), "as early as 1922, Bureau of Mines experiments showed that radio propagation in mines was possible but not practical."As stated by NIOSH (2007), "the propagation of radio waves is affected by limited open space for the wave to propagate, natural and man-made interferences, the electrical properties of the coal and surrounding strata, water and humidity, and many other factors." There are also issues with equipment that produce a lot of noise or electromagnetic interferences, which can cause the wireless signal to degrade faster than anticipated. When the wireless signal propagates through the mine tunnels, the signal can take multiple paths, which can be beneficial when a path becomes blocked or the resistance is too high. This can cause problems such as multipath. Cisco Systems Inc. (2007) states that, "multipath propagation occurs when RF signals take different paths from a source to a destination. A part of the signal goes to the destination while another part bounces off an obstruction, then goes to the destination." When multipath occurs, errors are created in the communication due to the delay in arrival times of some parts of the wireless data transmission. The errors created in multipath propagation can cause the data from the source to be unreadable by its destination. A sign of multipath is when there is good quality signal strength but there is a high bit error rating of the communication packets over the network. Directional

antennas allow "the energy being transmitted from the antenna to be focused in a direction and significantly reduce the signal's scatter and far-out echoes," according to Stavroulakis (2003). Problems such as multipath, unanticipated interferences, and anticipated interferences can be planned for and resolved by the optimal placement of the wireless broadcast devices.

Wireless systems can provide a larger coverage area than hardwired systems since wires do not have to be run to every possible communication point. Wireless systems are overall less restrictive to miners than hardwired systems. Wireless systems also provide the ability for miners and equipment to be tracked. Figure 2.3 shows the concept of data transmission through a wireless system.
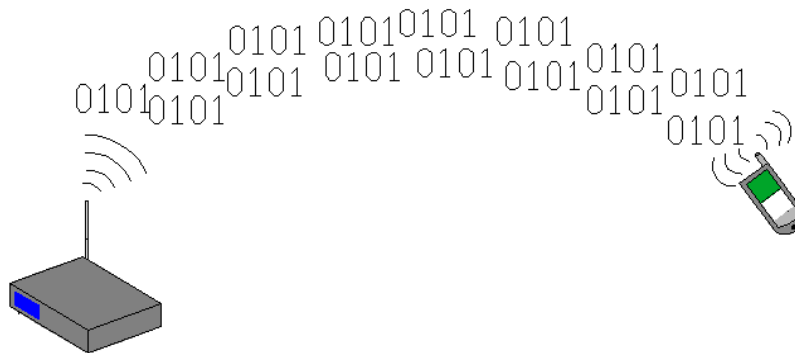
Figure 2.3: Concept of Wireless Data Transmission

Underground coal mines tend to encounter gases, thus leading to intrinsically safe permissibility issues. Ventilation controls are constructed in order to keep different air courses separate. In the event of an emergency one of the first things that is typically done is to turn off power to the mine, leaving natural ventilation as the only ventilation that will continue in the mine. Natural ventilation will not be sufficient to ensure that the atmosphere does not become toxic or explosive. Since communication systems are used in emergencies, these wireless broadcast devices must operate even in a potentially explosive atmosphere.

Wireless communication systems in underground coal mines may be broken down into four groups: ELF/LF, MF, leaky feeder, and WMN. Most recent communication breakthroughs have occurred for use in underground coal mines in those 4 types. ELF/LF systems are also known as through-the-earth (TTE) communication technologies. MF system developments typically utilize wave guides but can be used without wave guides. Leaky feeder systems utilize a technology where the signal leaks out of a leaky feeder cable. WMN systems operate at UHF,

900 MHz, 2.4+ GHz. No single system for communication is optimal in every set of circumstances; optimal communication solutions may be mine specific. The application of wireless communication systems in underground coal mines can be a combination of different systems depending upon the different systems compatibilities.

2.1.2.1 LEAKY FEEDER

Leaky feeder communication technology consists of a "coaxial cable that is designed to create external leakage fields large enough to allow reception by mobile or portable radios" according to Updyke, Muhler, & Turnage (1980). The leaky feeder system gets its name from the external leakage field it creates, allowing wireless communication to take place near the coaxial cable. Leaky feeder systems require regularly spaced repeaters or amplifiers along the cable in order to boost the communications signal as it degrades along the cable. Leaky feeder systems that are found in operation in underground mines today typically operate at Very High Frequency (VHF) or Ultra High Frequency (UHF). VHF systems typically operate around 150-170 MHz and UHF around 400-500 MHz. Recent developments in leaky feeder technologies have enabled new leaky feeder systems to operate at higher frequencies, from 800 MHz and 2.4 GHz. Figure 2.4 illustrates how a leaky feeder system operates.
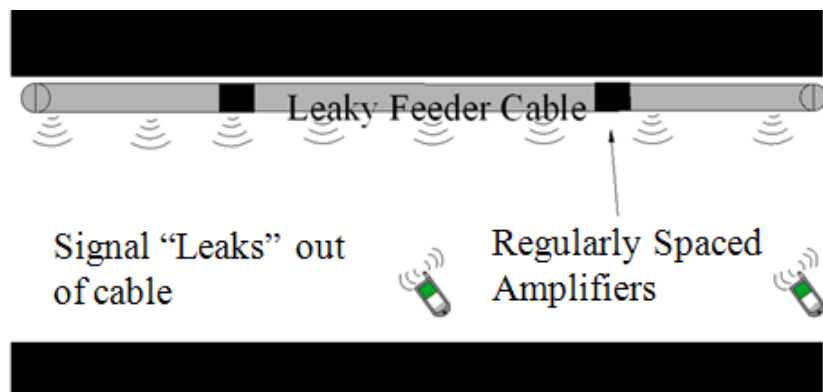
Figure 2.4: Concept of Leaky Feeder Communication

The headend and amplifiers of the leaky feeder system require wired power for regular operation and back-up batteries to supply power in case there is a power failure. Leaky feeder systems can be utilized nearly anywhere in the mine given that they meet intrinsically safe MSHA ratings. The leaky feeder cable itself is susceptible to roof falls and other physical damage to the cable. Updyke, Muhler, & Turnage (1980) noted that, "serious interest in the use

of leaky feeder systems in mines did not occur until the late 1960s, primarily in Europe. Leaky feeder systems have been historically utilized primarily to coordinate traffic along railway systems. Leaky feeder systems have eliminated the need for rail operators to stop to visually check for traffic at every intersection. Leaky feeder systems have enabled production and maintenance workers to work more efficiently. Travel time to and from hardwired devices is eliminated when workers are given the flexibility of carrying wireless handsets.

Leaky feeder systems are found in most underground coal mines in the United States today, having been quickly adopted after the 1960s because of their ease of installation, ability to communicate on an everyday basis, and cost effectiveness. Older leaky feeder systems have several limitations. They are often limited by line of sight, by the limited distance from the leaky feeder cable, and overall coverage concerns. Leaky feeder system developments are focused on expanding coverage throughout the mine, physically protecting the system from explosive forces, and burying the leaky feeder cable (Kohler, 2008). Newer leaky feeder systems address some of these limitations. Tracking, sensors, higher rated data communications, equipment production statistics, and video cameras are a few of the many developing leaky feeder technologies.

2.1.2.2 *EXTREMELY LOW FREQUENCY/ VERY LOW FREQUENCY/ LOW FREQUENCY*

ELF, VLF, and LF technologies operate at frequencies between 200 Hz and 4000 Hz in order to allow communication to take place TTE. Low frequency radio waves can propagate through the earth more efficiently than higher frequencies. This is because wave lengths (frequency and wave length being proportional) of lower frequency waves are longer and less susceptible to natural interferences than higher frequencies. ELF is characterized by low attenuation and high atmospheric noise, whereas VLF is similar to ELF except that VLF is slightly less reliable (Sorooshyari, 2004). Lower frequencies require significantly less power than higher frequencies. TTE communication systems require large loop antennas that may have to span large distances based upon the size of the communications area. Generally, the larger the loop (up to a maximum of 12 km), the better the coverage will be (Mine Site Technologies, 2006). Figure 2.5 shows how TTE communication works. The loop antennas in Figure 2.5 are not drawn to scale. Loop antennas may be large enough to enclose the entire mine in a loop.
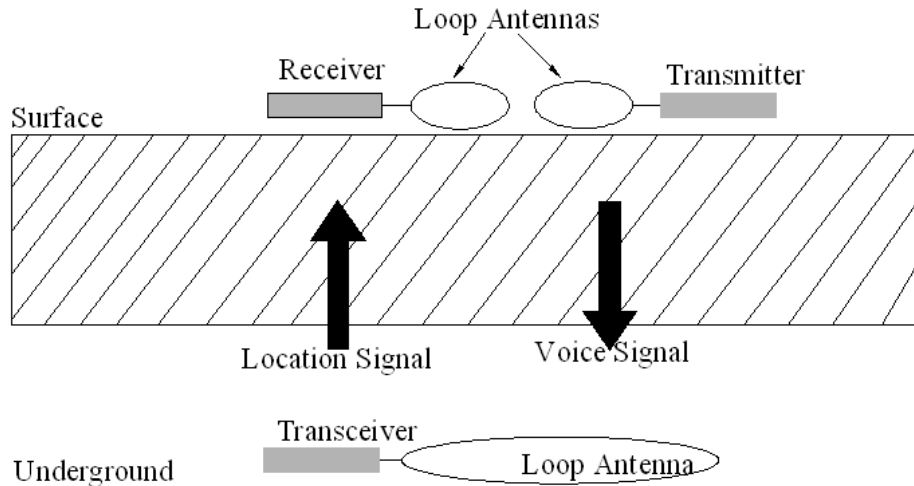
Figure 2.5: Concept of Through-the-Earth Communication

Loop antennas may be located on the surface or underground. Surface antennas are larger and more desirable but underground loops are smaller. The propagation of radio waves through rock strata can vary greatly based upon interferences it encounters. TTE communications are affected by natural and man-made noise sources (such as motors, power lines, thunderstorms, and equipment), which need to be filtered out or eliminated in order to communicate efficiently. TTE communications have low bandwidth, limited communication distance, and require larger antennas than wireless communication devices operating at higher frequencies. TTE communications low bandwidth limits communication to a text message 32 characters long. According to Pittman, Church, & McLendon (1985), "as early as 1899, Nicola Tesla suggested the use of what are today described as extremely low frequencies for worldwide communication using an earth medium." Arnold Sommerfeld and Hermann Weyl helped to build some of the theoretical basis of TTE communications. Sommerfeld and Weyl derived mathematical descriptions of the propagation of radio waves through the earth. Mallett, Einicke, & Glynn, 2001 state that, "the PED system which was developed in Australia is a system that allows communication to take place from the surface to units underground." A PED system that allows communication from units underground to the surface is currently under development. Recent TTE communications developments have been overshadowed due to their low bandwidth and because they have only text communication capabilities. TTE communication systems have been looked into as a possible means of communication with refuge chambers in some circumstances.

2.1.2.3 MEDIUM FREQUENCY

Medium frequency technologies operate between 300 kHz and 3 MHz. Medium frequency communication technologies can make use of existing conductors such as rails, metal pipes, trolleylines, or power cables by allowing the signal to use the conductor as a wave guide to extend coverage. According to Sacks & Chufo (1978), "medium frequency systems have a range of 150 to 500 meters in a conductor free area to over 1,000 meters in the presence of mine conductors." Medium frequency communication systems were researched as early as 1975, when the Bureau of Mines bought and performed underground tests on some prototype 355-kHz portable transceivers that were manufactured in South Africa (Sacks & Chufo, 1978). This showed potential greater than anticipated but the system left uncertainty whether or not it was efficient enough to be used in place of systems already available in the United States. As Sacks & Chufo (1978) observed, "large variations in signal attenuation rate have been found between three coal seams investigated which are widely separated geographically." NIOSH, 2008a states that "medium frequency communications typically have less severe attenuation characteristics than VHF and UHF and do not require a leaky feeder cable." Medium frequency communications do not encounter the noise limitations that ELF/VLF systems encounter. Figure 2.6 contains the ideal medium frequency communication system operation.
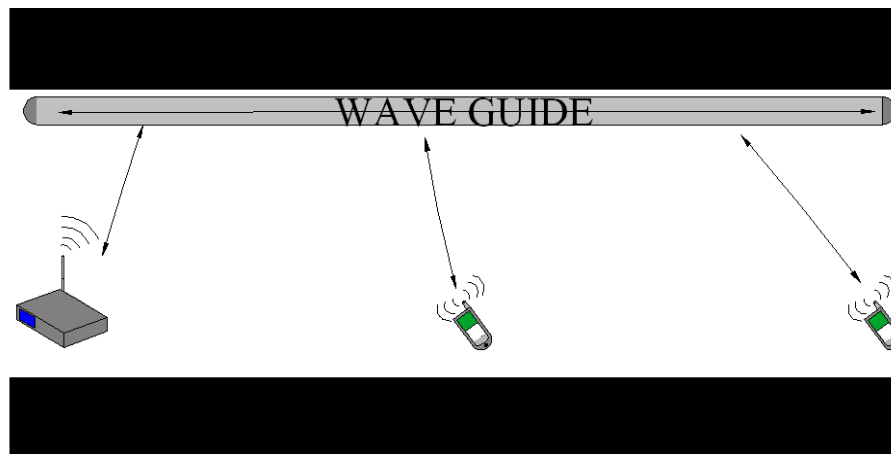
Figure 2.6: Concept of Medium Frequency Communication

Stolarczyk L. G. (1983) found that, "theoretical research and actual measurements in coal and metal/non-metal mines indicated that the communication range was maximum in the MF band (300 kHz – 3 MHz) and peaks around 500 kHz." Medium frequency's abilities to use existing structures as a wave guide can utilize structure within the mine. Medium frequency's

parasitic signal wave guide ability can be utilized in areas near the working face where mining is constantly advancing; it is not practical to constantly extend hardwired or wireless communication systems that are limited due to the distance from the broadcast point. Medium frequency communication systems must rely on wave guides in order to extend the range of the system to a desirable distance. Medium frequency systems will be limited to voice communication unless other frequencies are used to increase the bandwidth capabilities. Power requirements for medium frequency systems are lower than systems that operate at higher frequencies. Cory (1979) found that, "in certain system's power configurations the intrinsic safety of the system resides solely in the intrinsic safety of the individual radio units due to the power requirements to specific devices being detached from one another." Medium frequency systems still require repeaters and other parts of the system to be powered for daily operation as well as a backup battery. Recent medium frequency communication system developments have been to utilize leaky feeder systems that operate on VHF and UHF frequency bands. Other developments include gas sensors and using medium frequency systems in a mesh network system configuration to increase redundancy, coverage, and data capabilities of the system.

2.1.2.4 WIRELESS MESH

The implementation of wireless mesh systems in underground coal mines is a development that has gained popularity since the MINER Act was passed, because of the advantages of mesh network topology. Advantages of a mesh network topology are multiple communication routes are made in order to create a redundant communication links, communication links are self-healing in case of a point of failure, and are more flexible and expandable than older systems. A mesh network topology utilizes nodes connected directly to multiple other nodes in the network. Cisco Systems Inc., 2002 states that "a redundant connection is created by multiple nodes being connected and if any link fails, information can still flow through other links in the network to the destination." WMNs have been configured to be "self-healing" and "learning" so that wireless mesh broadcast nodes can discover and terminate connection links as neighboring nodes' availability changes (Schiffbauer & Brune, 2006b). Mesh networks operate at a wide variety of frequencies but most frequently at 868 MHz, 900 MHz, 2.4 GHz, and 5.8 GHz. WMNs typically utilize the 802.11 and 802.15 IEEE

protocols. WMNs operate underground in the same fashion as they operate on the surface for a local area network (LAN), wireless fidelity (WiFi), and other applications that are used for daily surface communication. Figure 2.7 shows an example of a mesh network topology. In Figure 2.7, the smaller green and gray devices are handsets and the larger blue and gray devices are broadcast devices (used to route the handset's communication between one and another).
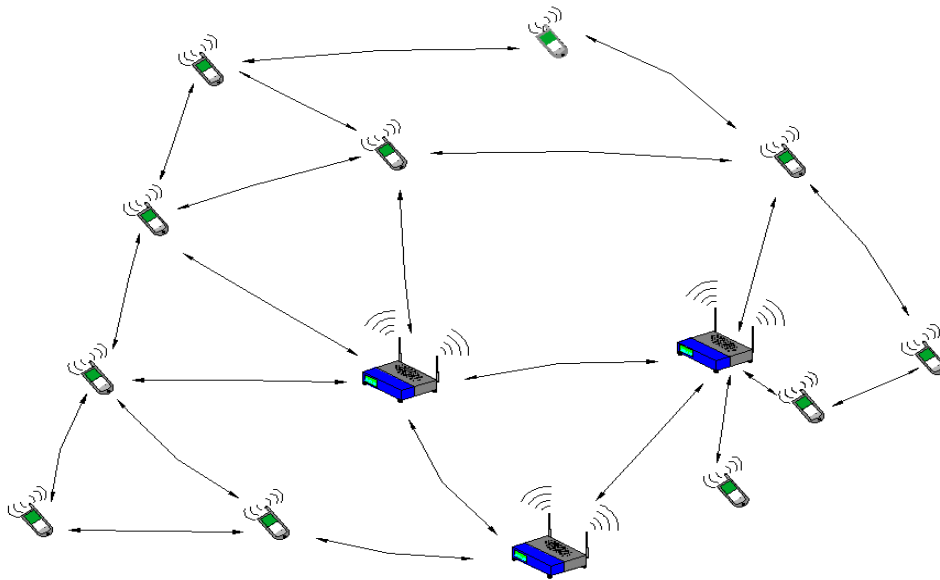
Figure 2.7: Concept of Wireless Mesh Communication

A mesh network topology is not limited to the scheme shown in Figure 2.7 but allows for multiple separate networks to be created and customized to each specific application. Underground mesh networks operate much like cell phones, typically utilizing voice over the telecommunications protocol internet protocol (VoIP) to establish a voice communications link over the network (Schiffbauer & Brune, 2006b). Each device on the network has an internet protocol (IP) address that allows individual communication with each device. Text messages and calls may be placed to an individual device.

2.1.3 THEORETICAL FREQUENCY TRADES

The harsh nature and environment of underground coal mining significantly decreases the propagation range of wireless signals. Underground coal mines are exposed to a wide variety of interferences and harmful gases. The development of communication systems in underground

14

coal mines must take into account that given the wrong mixture of gases in the mine, the underground mine could potentially spark an explosion at any moment. The selection of a wireless communication system's operating frequency will directly dictate the communication range of the system. According to Schiffbauer & Brune (2006b), some operating frequencies will propagate further because the "electrical properties of coal attenuate some frequencies more than others." The wireless signal will also encounter other interferences that different operating frequencies will handle differently based upon the specific interference (i.e. stoppings and belts).

Operating frequency does not only dictate the wave's propagation range but also directly dictates the available bandwidth and power requirements. Typically the higher the operating frequency, the higher the bandwidth rating, but the result is greater power requirements. Mesh networks communication systems require greater power requirements than medium frequency systems. Voice and text communication require different bandwidth ratings. Voice communication requires a higher bandwidth rating than what is required for text communication. Thus, there is a significant difference in power requirements for voice communication and text communication. Ultimately there are tradeoffs with using different operating frequencies because power requirements and the bandwidth provided by different frequencies are proportional to the operating frequency. There is not a specific optimal operating frequency but instead different operating frequencies contain different specifications that are beneficial in certain circumstances. Extensive research on the propagation of radio waves in underground mines has been ongoing since 1922 (Schiffbauer & Brune, 2006a). A combination of systems which operate at different frequencies will prove to be more effective than a system that operates at a single frequency.

2.2 Health and Safety

2.2.1 EFFECTS OF COMMUNICATION DEVICES

The effect of enhanced communication and tracking systems is a widely debated issue between legislators, mine operators, and miners. Some believe that these systems will provide a safeguard and ultimately improve the safety of miners in underground mining operations. Other groups believe that these systems are often costly but that these systems may be utilized to

simplify the coordination of daily operation, routine maintenance, and emergency situations. Some miners are worried that these systems will exploit their privacy and that they may be used as a watchdog by the mine operator. Other miners believe that these systems will benefit them from both a task oriented and safety standpoint. Before the MINER Act was passed, communication and tracking devices were viewed by some organizations as negative and unnecessary pieces of equipment. Those organizations believed that mine operators could potentially watch the tracking information and ultimately try to distinguish between a miner working and taking a routine break, which in practice is necessary due to the exhausting work.

2.2.2 EMERGENCY AND RESCUE PLANNING

Planning, organization, and communication are crucial to safe and efficient mine production. Coal mining's unpredictable and dangerous nature sometimes creates unforeseen events that link together to create a disaster that could not be planned for. According to Sauer, 1998, "safety engineers can prepare a general plan, but individual workers must decide when and how to adapt to these plans in highly unpredictable and uncertain local conditions," which means that communication is critical to ensure general plans can be applied to the circumstances encountered by miners at any given time. Sauer, 1994 states that, "attempting to examine and break down accidents into a root cause eliminates many human factors that have led to the accident. All too frequently, agencies publish unwieldy, disorganized, unreadable reports when writers attempt to reduce the complex elements of the debate to a single, linear narrative—a single "snapshot" of the disaster at a single moment of crisis." It is nearly impossible to summarize and depict what exactly went on in those few short moments in the darkness in a single snapshot. Recent developments in communication techniques and technologies since the MINER Act was passed have completely changed the communicating capabilities readily available to miners. The development of communication systems will radically change many aspects of coordination and organization both underground and on the surface of how coal mines operate day to day.

Communication and tracking systems will help to make the communications gap smaller by allowing miners to communicate with the people on the surface who are coordinating rescue

efforts. There may be things that the miners know that the people on the surface do not know that could completely change the rescue plan. Tracking systems will also give the last known location of miners (or real-time location) which enables mine rescuers to act as quickly as possible and try to be as direct as possible. Miners may also then communicate with mine rescuers and possibly help each other in the rescue process. Enabling direct communication between surface personnel and miners underground will reduce the uncertainty in the rescue process.

Wireless communication will be the way of communication underground in the future. Wireless technologies give the last known location (if not real-time) of the miner and allow two-way communication between hundreds of feet of solid rock through openings. Multiple pathways give the miner the best chance for the communication link to work. If one pathway is blocked off then the wireless signal will be routed another way. The only thing that can be done is to implement systems that can be utilized by miners in case of an emergency that will allow communication to be as smooth and clear as possible. Communication between everyone involved in the disaster has been mixed up in past disasters, so any possible scenarios that could cause confusion or require extra time to be spend on a process that could be eliminated by technology must be eliminated. During emergencies every second counts and could be the defining time when the worst scenario can occur. In the event of an emergency, there is little time to do a root cause analysis but instead rescuers must act safely and quickly.

The technology readily available to miners has come in leaps and bounds in response to disasters. One of the distinct advantages of modern developing underground communication and tracking systems is that they are able to operate if the mine's power is shut down, which frequently happens in case of an emergency. This causes the ventilation fans to stop pushing clean air into the mine which can cause buildups of toxic gases. High concentrations of toxic gases can make the mine's air hazardous or even deadly. Developing underground communication and tracking systems are required to have a backup power source in case of power failure. This will allow communication and tracking systems to operate during an emergency in the mine. In the event of a disaster, many miners must maneuver their way out of the mine to safety through smoke, dust, fires, and falling rock. Other miners will not be as fortunate and may either be killed or trapped in the event. The only thing a miner can do when they are trapped is barricade themselves into accessible parts of the mine using line curtains, rock

dust, and any other materials that the miner may be able to find. While miners barricade themselves in parts of the mine or seek shelter in newly implemented refuge chambers, they will be able to help coordinate and relay information that may be critical to their rescue. Miners are directly impacted by the disaster and experience the disaster first hand. Underground coal mining has been notorious for its harsh environment and dangerous workplace. Every day that a miner steps onto the mine property their life is at risk in some way or another. Communication and tracking systems will decrease many unknown factors of the emergency such as the last known location of miners, possible radio communication with trapped miners, and the relaying of information that will make rescue efforts more efficient.

The implementation of underground communication and tracking systems in underground coal mines is a process that has taken decades to accomplish and is still ongoing. Underground communication and tracking systems provide distinct advantages over older technologies that have been used in mines for decades. These distinct advantages are found in both emergency and rescue planning and for daily operations.

Equipment being used in daily operation allows operators and miners to get to know their equipment. The more familiar the operator is with their equipment, the greater the chance that the operator will use the equipment to the best of its capabilities. Equipment that requires less maintenance and is used every day is better suited than high maintenance equipment. High maintenance equipment is less likely to work in the event of an emergency because its many limitations may have an impact at the worst possible time. High maintenance equipment is overall more complex and more likely to break down at the worst possible time. High maintenance equipment is typically not very user friendly and will require a substantial more amount of time for miners to get to know the system (Coal Age, 2008).

2.2.3 CABLE PROTECTION SCHEMES

The cabling of communication systems is the most susceptible component of the system. Cabling may be damaged or broken by roof falls, machinery, and other various cabling hazards. Damaged or broken cables can often expose miners to unwanted health and safety issues. Health and safety issues can range from explosions, electrical shock, and loss of communication and tracking. According to Schiffbauer & Brune (2006b), "efforts to protect cables include, armor or conduit, burying cables, enclosing cabling in boreholes, and having loop-around or redundant cabling." Cable protection schemes are necessary in order to prevent (if preventable) unwanted damaged to cabling that ensures communication and tracking.

2.3 MINER Act Communication and Tracking Requirements

The MINER Act post-accident communication and tracking requirement states:

> Not later than 3 years after the date of the enactment of the Mine Improvement and New Emergency Response Act of 2006, a plan shall, to be approved, provide for post-accident communications between underground and surface personnel via a wireless two-way medium, and provide for an electronic tracking system permitting surface personnel to determine the location of any persons trapped underground (Congress, 2006).

The MINER Act states that a plan for post-accident communications must "provide for a redundant means of communication with the surface for persons underground, such as a secondary telephone or equivalent two-way communication" (Congress, 2006). The MINER Act also requires that a plan for post-accident tracking "shall provide for above ground personnel to determine the current, or immediately pre-accident, location of all underground personnel" (Congress, 2006). Communication and tracking requirements apply to all mines except anthracite mines with one intake and one return aircourse (MSHA, 2009b). In the case of a mine with one intake and one return aircourse redundant hardwired systems may be placed in the same aircourse. Overall the MINER Act requires that within three years of the enactment of the Act (June 15, 2009), some form of survivable communication and tracking system must be integrated

or in the process of being integrated (given developmental time constraints) into underground mines. Due to health, safety, and cost constraints, the entire mine will not receive coverage. MSHA, which enforces mine regulations in the United States, requires communication and tracking areas to contain but not be limited to coverage throughout each working section, continuous coverage along escapeways, and a coverage zone both inby (towards the working face) and outby (away from the working face) of strategic areas (MSHA, 2009). Strategic areas are described by MSHA in the Program Policy Letter from January 16, 2009.

Strategic areas are those locations where miners are normally required to work or likely congregate in an emergency and can include belt drives and transfer points, power centers, loading points, SCSR caches and other areas identified by the District Manager. MSHA (2009b) states, "while a coverage zone of 200 feet inby and 200 feet outby strategic areas normally should be adequate, the District Manager may require longer or shorter distances given circumstances specific to the mine." A procedure must be established to log when miners are entering and leaving communication areas. The MSHA District Manager of the area is responsible for overseeing the integration of each mine's communication system. The communication requirements for refuge alternatives are provided under 30 C.F.R. § 75.1600-3.

2.3.1 SURVIVABILITY

Communication and tracking systems are exposed to many hazards that can damage both the hardwired and wireless components of the system. A communication and tracking system can achieve survivability by hardening system components and creating redundancy throughout the system. Snyder (2007) states that, "the redundancy of a system may be increased by creating multiple power sources, more than one signal pathway, self-healing network, and provide the maximum efficient coverage." Optimal communications node placement will ensure that the communications network achieves the highest level of redundancy and maximum coverage.

2.3.1.2 IMPACTS SPECIFIC TO UNDERGROUND MINING METHOD

Radio waves tend to propagate farthest down straight clear tunnels. There are advantages and disadvantages that are circumstantial to the mining methods at the mine. The two most common mining methods in underground coal mines are the room and pillar and longwall methods. Room and pillar mining tends to create a grid of intersections connected by tunnels. An advantage of the room and pillar mining method is there are often long straight spanning distances where RF waves can propagate freely without having to turn corners. A significant signal loss occurs when the waves must propagate around 90 degree turns into perpendicular tunnels. The longwall mining method provides straight and extensive distances for wireless waves to travel along. In theory this can be advantageous because the entire longwall section is able to receive radio coverage using a minimal amount of broadcast devices. Longwall methods utilize large metallic machinery that may significantly impact signal propagation due to metal reflecting and dissipating some of the wireless signal. Longwall mining introduces permissibility issues for which solutions are currently being addressed.

2.3.2 POWER REQUIREMENTS AND ISSUES

All devices that are a part of the communication and tracking system must be line powered and have a back-up battery in case of a power failure. There are significant issues with the power requirements of wireless systems in underground coal mines. An underground coal mine is potentially explosive given the wrong mixture of gases in the mine at any given point in time. In order for devices to continue to operate during emergencies, a battery is required. The first thing that is done in an emergency is for the mine's power to be shut down. This will stop the ventilation in the mine, causing the mine to become filled with the gases that are naturally being emitted from the rock exposed underground. System battery life is a widely debated issue due to environmental concerns, permissibility, and other safety issues. According to MSHA (2009b), specific standby power requirements for underground components and devices include:

1. Stationary components (infrastructure) generally should be equipped with a standby power source capable of providing sufficient power to facilitate evacuation and rescue in the event the line power fails or is cut off. In

many mining situations, 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) should be adequate, but mine-specific conditions may warrant more or less standby power capability.

2. Untethered devices, such as hand-held radios, generally should provide sufficient power to facilitate evacuation and rescue following an accident. In many mining situations, at least 4 hours of operation in addition to the normal shift duration (12-hour minimum total duration) based on a 5/5/90 duty cycle should be adequate, but mine-specific conditions may warrant more or less capability. This total operation time may be achieved via spare portable devices or cached batteries if the device is approved for battery replacement in the hazardous area.

Each mine is treated as a separate case when determining the power requirements for communications and tracking systems.

2.3.3 MSHA APPROVAL PROCESS

MSHA is directly responsible for approving all equipment used in a mine. MSHA wants to make absolutely sure that negative impacts are not felt by the implementation of developing communication systems. If systems are designed incorrectly, a disaster could occur from something as simple as a small spark being created between two exposed contacts on any part of the communication system. The evaluation of communication systems is found under the existing guidelines for Telephones and Signaling Devices. This may be found under Title 30 Code of Federal Regulations Part 23. These regulations are intended for audible and visual communication devices. Communication system devices must be intrinsically safe (IS) or in an enclosure that is MSHA certified to be explosion-proof (XP) and flame-resistant, or is in a hose conduit (interconnecting cables) that is flame-resistant and MSHA-approved (MSHA, 2006a). System devices are required to either be IS or XP in case there is a loss of ventilation in the mine. All devices (including tracking tags, which are considered portable apparatuses) are subjected to regulatory drop tests. Devices must have a back-up power supply in order to

continue to operate if there is a power outage in the mine. MSHA will accept communication systems for evaluation that meet the criteria described in the Code of Federal Regulations. According to MSHA, 2006b, evaluation determines "how well system's signals propagate, how much overburden systems can penetrate (if TTE), coverage areas, interference issues, and accuracy of tracking features." Further information regarding approved communication systems and devices may be found in the Code of Federal Regulations or obtained directly from MSHA.

2.3.4 AVAILABLE PERMISSIBLE COMMUNICATION TECHNOLOGIES

As stated by MSHA, "The communication system must be approved by MSHA to comply with 30 C.F.R. part 23 and applicable policies." The available permissible communication and tracking technologies list is growing every month. MSHA continues to certify systems that have met the requirements and are permissible or intrinsically safe. Further testing of and experience with communication and tracking systems in operation will continue to allow MSHA to monitor and increase requirements in order to ensure the safety of miners and operators.

2.3.5 TRACKING TECHNIQUES

There are multiple ways of tracking miners, depending on the operating frequency of the tracking system. Tracking techniques are classified by MSHA into zone or proximity based systems, radio location "node" based technologies, and infrastructure "autonomous" systems. The accuracy of tracking depends on the type of technique used for tracking. Within the different techniques, the accuracy of tracking will also vary based upon the system. Different systems use different tracking algorithms, and some tracking algorithms are more accurate than others. Zone or proximity tracking techniques utilize zones, proximities, and Radio Frequency Identification (RFID).

2.3.5.1 ZONE OR PROXIMITY TRACKING

Zone or proximity tracking was commonly used in mines before the MINER Act pushed for new communication and tracking developments. Using the zone or proximity technique, a mine is split up into zones. When a miner travels from one zone into another, miners will notify the dispatcher or surface coordinator that they have gone into a different zone. The dispatcher is responsible for keeping an up to date log of the last zone of the miner. The routine of miners notifying the dispatcher with their movements is often inaccurate because miners forget to call when they pass from one zone to another. This would lead rescue teams to a completely different area of the mine if the miner fails to notify the dispatcher. RFID has helped to increase the accuracy and ease of using a zone or proximity tracking technique. An RFID tracking system consists of tags and tag readers (Sweeney II, 2005, p. 78). Each RFID tag can be uniquely identified to enable dispatchers to track individual miners without notification by miners. RFID tags are placed somewhere on the miner (inside their hard hat or another designated area) and RFID tag readers can be placed on pillars or other parts of the mine infrastructure. When a tag comes into the range of a tag reader (the tag reader's range is dependent on the specific tag reader), the tag reader will relay the information along the infrastructure of the system and that location is recorded as their last known location. The placement of tags and tag readers is not limited to a specific location or spacing but can be adjusted based upon in mine specifics. The accuracy of using RFID tags and tag readers depends on the frequency of tag readers. For example, if tag readers are placed every 50 feet, then the accuracy of the system will be approximately 50 feet.

2.3.5.2 RADIO LOCATION "NODE" BASED TRACKING

Radio location "node" based tracking techniques use the power present in a received radio signal or received signal strength indication (RSSI) on the handsets carried by miners to calculate their current position. According to Srinivasan & Levis (2006), the signal strength, or RSSI, "is the strength of a received radio frequency signal present between the handsets and the fixed broadcast nodes of the communication and tracking system." This tracking technique has been improving with the development of communication and tracking systems since the MINER Act. The accuracy of this tracking technique depends on the algorithm that the specific system

uses. Algorithms for tracking miners are refined and change constantly as communication and tracking systems develop.

2.3.5.3 INFRASTRUCTURE "AUTONOMOUS" TRACKING

The last common form of tracking is the infrastructure or autonomous tracking technique. This tracking technique is used with both TTE and reverse RFID systems. TTE tracking systems are very primitive and the reporting of location is not as frequent as with a reverse RFID system. Reserve RFID uses the same concept of a tag and tag reader as RFID systems do except that the location of tags and tag readers are switched. RFID tags are placed on pillars or other mine infrastructure and tag readers are placed inside of handsets. The advantage of this system is the battery life span on RFID tags is significantly longer than tag readers. This will reduce the amount of maintenance that is required or allow maintenance to typically consist of recharging the handset batteries above ground rather than having to go to each location underground where a tag reader has been placed (as with non-reverse RFID systems).

Chapter 3 : U*NDERGROUND* C*OAL* M*INE* W*IRELESS* M*ESH* S*YSTEM* C*ASE* S*TUDY*

3.1 System Case Study Overview

Underground wireless mesh communication systems typically are comprised of gateway broadcast devices, fixed broadcast devices located within the mine, and handsets. Gateway broadcast devices are directly linked to the surface. Fixed broadcast devices located within the mine allow the wireless signal to propagate and take multiple paths to its destination. An underground wireless mesh communications system made up of gateway (GW) broadcast devices, fixed broadcast devices or fixed mesh nodes (FMN), and handsets or Miner Mesh Radios (MMR) has been developing in the International Coal Group's Sentinel underground coal mine located in Philippi, West Virginia. The Sentinel mine uses the room and pillar mining method. The roof in the Sentinel mine averages approximately seven feet but varies as low as five and a half feet. Entries and mains are typically 18 feet wide. Pillars are on 72 feet by 90 feet centers. The modeling of wireless communication wave propagation, field work and research in underground mining environments has been studied in cooperation with NIOSH under contract number 200-2007-20388, L-3 Communications Global Security and Engineering Solutions, Innovative Wireless Technologies, Pyott-Boone Electronics, Alion Science and Technology, Marshall Miller and Associates, and International Coal Group.

This work is based on the Accolade system from L-3 but applies to all underground wireless mesh systems currently available. The Accolade system is comprised of fixed broadcast nodes and handsets. Broadcast nodes are capable of communicating to each other, handsets, and other communication technologies (e.g. leaky feeder, fiber-optic network). Additionally wireless handsets are capable of communication directly with each other and through fixed broadcast nodes. The purpose of my research is optimizing the location of broadcast nodes such that handsets will receive the best service throughout the areas miners will likely be in. Creating a model for the propagation of wireless signals will allow the optimal communications node placement to be calculated. Optimal communications node placement is achieved by simplifying the mine and solving the mine's communication network. Solving a mine's communication

networks will provide a pre-installation mine network design map, create coverage maps of the mine, and allow planning for future communication and mining activities. Modeling a mine's communication system will overall increase the efficiency of the system and ensure that all the desired areas have communication coverage. Several methods have been investigated and a Geographic Information Systems (GIS) or network based approach was chosen. This method was chosen due to the spatial relationship of the mine communication encountering interferences such as ventilation regulators, belts, and other losses being much like navigating through roads where travel is regulated by speed limits, stop signs, and other traffic regulations. Wireless signal degradation is treated in a similar method as ventilation network. The nature of underground mining lends itself to intersections and connections to those intersections. It is assumed that a broadcast source would be located at an intersection and not in an entry. This approach examines every intersection of the mine and finds both the shortest distance and the path of least resistance to every other intersection in the mine. Resistances are applied per unit length and obstacle encountered giving a signal loss for a distance from one intersection to another intersection. Categorizing tunnels based upon measured signal loss values allows communication areas to be calculated and the locations of necessary communication points to be pin-pointed. This method is not mine specific and was created to allow signal loss parameters to be adjusted based upon the performance of the system being investigated.

Initial testing and prototype developments of the system have been ongoing since the summer of 2007. Initial testing has been conducted and a coverage map for the mine has been developed which has placed the fixed wireless nodes. The integration of the Accolade underground wireless mesh system in Sentinel mine has provided a case study to develop a model to describe and predict the propagation and behavior of the Accolade system. When new sections are being developed in the mine additional fixed nodes will need to be placed in order to ensure a link for communication with miners at the new sections. Resistances can be estimated in order to predict optimal node placement and highlight problematic areas. The wireless mesh network can be analyzed and areas where equipment movement may cause interferences are located. Tools to analyze and predict signal loss had to be developed in order to validate the model. Small amounts of data are used to predict initial signal losses that occur in openings classified as clear non-obstructed openings, beltways, stoppings, turning corners, and elevation.

3.2 Initial Signal Loss Parameters

Initial signal loss parameters are used in the data analysis chapter in Sections 4.2 and 4.3. Initial signal losses were estimated (FMN to FMN) using test data from the L-3 Communications GS&ES Above and Below Ground Phase II reports that were prepared for NIOSH. Figure 3.1 shows the underground test area contained in Below Ground L-3 Communications GS&ES, (April, 2008) report.
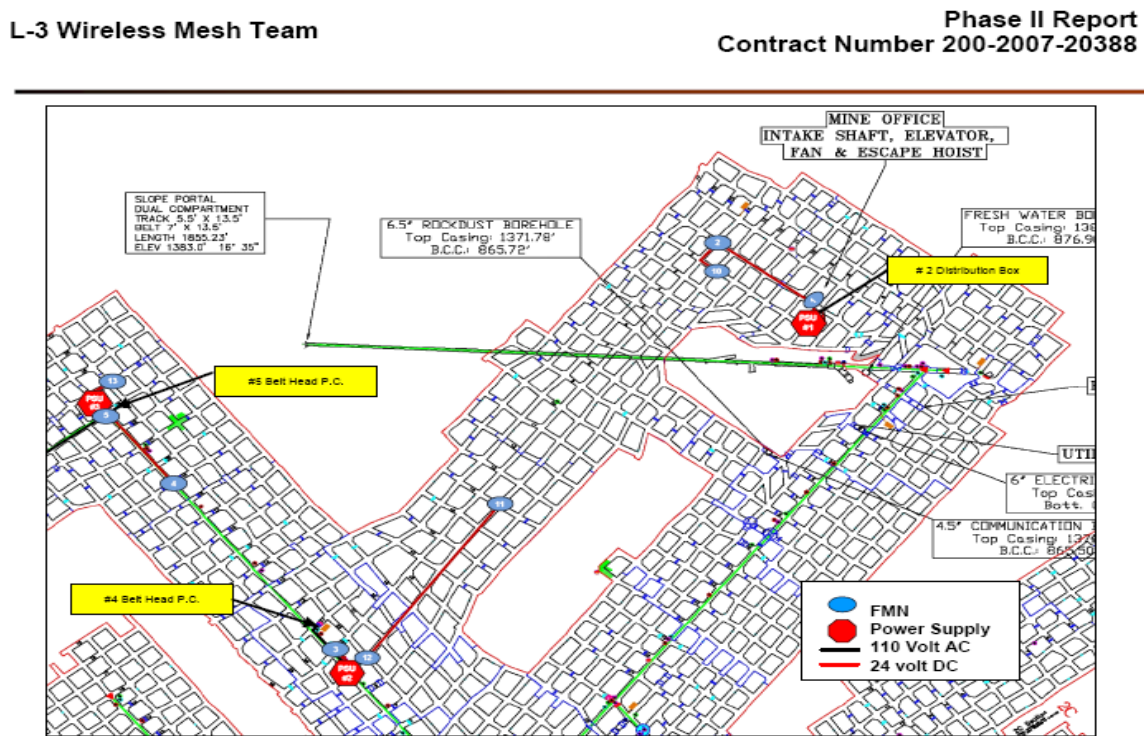

Figure 3.3: Demonstration Node Section Close-up

Figure 3.1: L-3 Phase II Test Area (L-3 Communications GS&ES, April 2008)

The data available to make initial signal loss estimations was extremely limited. The available data consisted of a table of RSSI values for FMN to FMN connectivity and the distances between these FMNs. Figure 3.2 contains the table of Phase II mesh installation RSSI values found in the Below Ground L-3 Communications GS&ES, (April, 2008) report.

TX Node	RX Node	RSSI
GWN	FMN 1	-43
FMN 1	FMN 2	*Saturated
FMN 1	FMN 10	-68
FMN 2	FMN 10	-43
FMN 2	FMN 3	-69
FMN 3	FMN 4	-76
FMN 4	FMN 5	-25
FMN 5	FMN 6	-64
FMN 5	FMN 13	-60
FMN 6	FMN 7	-77
FMN 10	FMN 11	-69
** FMN 10	FMN 12	-99
FMN 11	FMN 12	-45
FMN 12	FMN 13	-53
FMN 13	FMN 14	-69
FMN 14	FMN 15	-76

Table 3.4: Mesh Installation RSSI Values

Figure 3.2: L-3 Phase II Mesh RSSI Values (L-3 Communications GS&ES, April 2008)

The FMN broadcast signal is approximately 29 dB. The sensitivity of the receiver is estimated to be 111 dB. The sensitivity is a measurement of how sensitive of signal the receiver can interpret properly. Signal loss can be impacted and increased by many unknown interferences in the harsh underground coal mine environment. It is necessary to create general categories of signal losses that account for the majority of signal loss in order to pinpoint unanticipated interferences. General categories of anticipated major signal losses can be used to estimate coverage while designing systems for new mines as well. After several trips to work underground with the communication system, the typical FMN signal losses observed were categorized into five different general parameters.

1. Non-Obstructed Clear

2. Beltways

3. Stoppings

4. Corners

5. Elevation

3.2.1 INITIAL SIGNAL LOSS PARAMETER ESTIMATIONS

Initial signal loss parameters have been separated and estimated based on different scenarios observed in the Sentinel mine. It is necessary to separate each parameter into an isolated ideal case because many unknown signal loss parameters still exist that the model does not take into account. Initial signal loss theoretical equations can be found in Section 4.2.Computer analysis using initial signal loss estimations can be found in Section 4.3. The following categories examine the path loss that occurs over the distance the signal travels. The path loss that is encountered is equal to the power out or broadcast signal minus the Received Signal Strength Indicator (RSSI). RSSI is discussed in the Radio Location "Node" Based Tracking, Section 2.3.5.2.

3.2.1.1 NON-OBSTRUCTED CLEAR LOSS

A Non-Obstructed Clear tunnel is used to categorize a mine opening that is straight (does not contain a bend greater than 15 degrees), fairly flat, and is clear (does not contain any major obstructions). Standard continuous signal losses were assumed to be linear due to the nature of radio frequency signal degradation. The initial estimate for a Clear Non-Obstructed tunnel is 5.9 dB/100 ft loss. This was estimated using the connectivity from FMN 12 to 13. The path loss between FMN 12 to 13 was calculated by the following calculation.

Path Loss FMN 12 to FMN 13
(RSSI = -53)(Pout = 29) Path Loss = 29 –(-53) = 82 dB
Distance = 1403 ft
(82 dB/1403 ft)*1/100ft = ~5.9 dB/100 ft loss

This FMN pair was chosen because of the area in the mine is flat and straight natured (minor negligible bend). Figure 3.3 contains a profile of the tunnel between FMN 12 to 13.
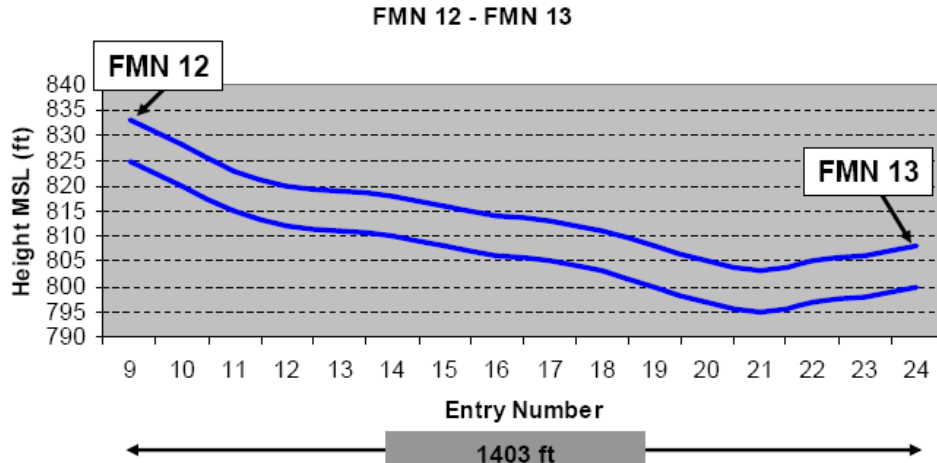
Figure 3.3: Tunnel Profile Between FMN 12 to 13 (L-3 Communications GS&ES, April 2008)

3.2.1.2 BELTWAY LOSS

A Beltway Loss is used for a tunnel that contains a belt structure. The initial estimate for a Beltway Loss is 14 dB/100 ft loss. This was estimated using the connectivity between FMN 3 to 4 and FMN 4 to 5. The path loss between FMN 3 to 4 and FMN 4 to 5 was calculated by the following calculations.

Path Loss FMN 3 to FMN 4
(RSSI = -76)(Pout = 29) Path Loss = 29 –(-76) = 105 dB
Distance = 792 ft
(105 dBm/792 ft)*1/100ft = ~13.3 dB/100 ft loss

Path Loss FMN 4 to 5
(RSSI = -25)(Pout = 29) Path Loss = 29 –(-25) = 54 dB
Distance = 367 ft
(54 dBm/367 ft)*1/100ft = ~14.7 dB/100 ft loss

The average between these two FMN pairs was calculated to be 14 dB/100 ft loss. Figure 3.4 contains the tunnel profile between FMN 3 to 4 and FMN 4 to 5.
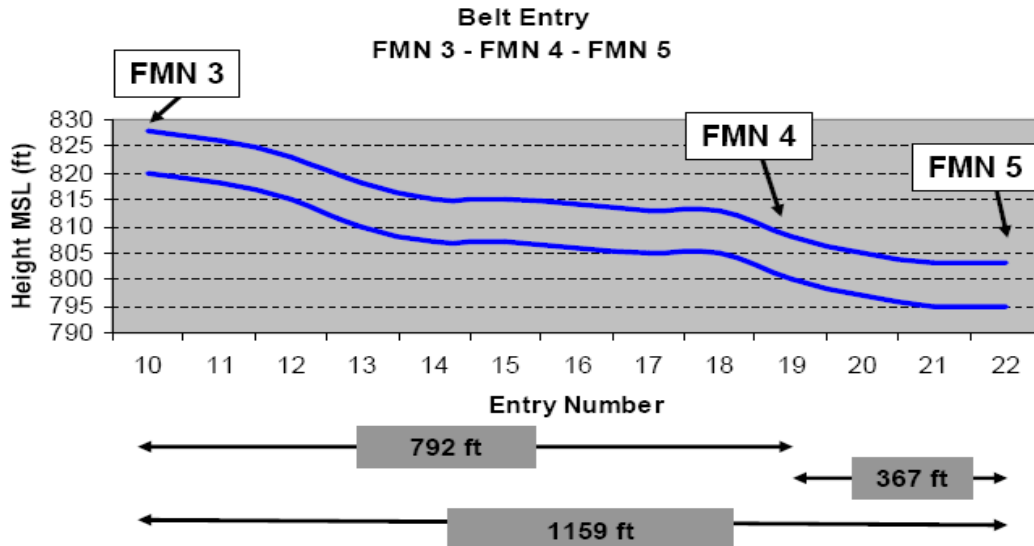
Figure 3.4: Tunnel Profile Between FMN 3 to 4 and FMN 4 to 5 (L-3 Communications GS&ES, April 2008)

3.2.1.3 STOPPING LOSS

A Stopping Loss is used for when the wireless signal encounters a stopping that is used for ventilation control. The initial estimate for a Stopping Loss is 15.5 dB/stopping. This was estimated using the connectivity between FMN 5 to 13 and FMN 2 to 10. The connectivity between these two pairs of FMNs was considered to be identical except FMN 5 to 13 contained a stopping. The difference between different types of stopping was not estimated because of the lack of data. Figure 3.5 contains the two FMN pairs on the mine map.
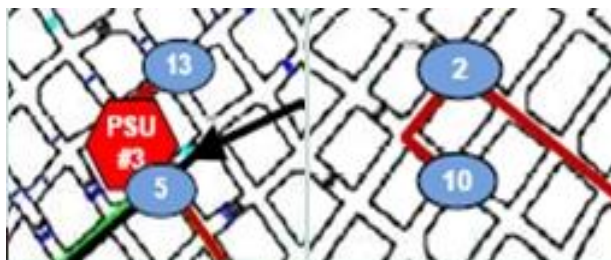

Figure 3.5: Initial Stopping Estimate FMN Connectivity Pairs (L-3 Communications GS&ES, April 2008)

The path loss between FMN 5 to 13 and FMN 2 to 10 was calculated by the following calculations.

Path Loss FMN 5 to FMN 13

(RSSI = -60)(Pout = 29) Path Loss = 29 −(-60) = 89 dB

Distance = 162 ft

Path Loss FMN 2 to 10

(RSSI = -43)(Pout = 29) Path Loss = 29 −(-43) = 72 dB

Distance = 162 ft

The difference between the two FMN pairs is calculated to be 17 dB. The estimate for a stopping was lowered to 15.5 dB per stopping due to a lot of mining supplies (rock dust, several barrels, etc) were stored along one of the ribs (side of the entry) which was believed to add a slight additional loss.

3.2.1.4 CORNER LOSS

Corner loss estimations are considered to be estimated with less accuracy than the previously discussed signal loss parameters. Corner loss is when the wireless signal must propagate from one entry around a 90 degree turn into a crosscut. Corner loss was not explicitly studied due to the high paced nature and goal to develop the communication system as fast as possible. Corner loss was estimated to be around 55 dB per 90 degree turn (turning the corner onto a perpendicular opening). A theoretical estimation for corner loss was required because corner loss had not been explicitly tested for. The following three parameters were used in order to theoretically estimate a corner loss.

1. Non-Obstructed Clear Opening - 5.9 dB/100 ft loss
2. One Entryway Over - 12.3 dB/100 ft loss
3. Two Entryways Over - 13.9 dB/100 ft loss

Figure 3.6 and Figure 3.7 contain the graphs of test data for One and Two Entries over obtained from the L-3 Above Ground Demonstration.
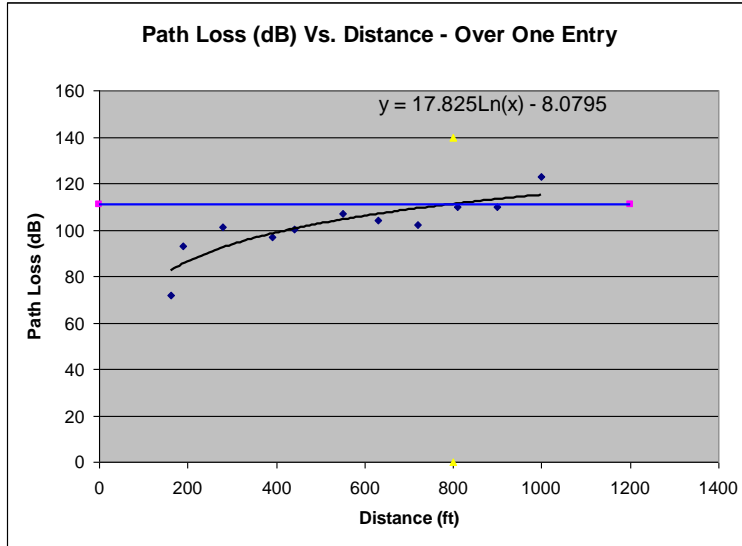
Figure 3.6: Path Loss One Entry Over (Adapted from L-3 Communications GS&ES, March 2008)
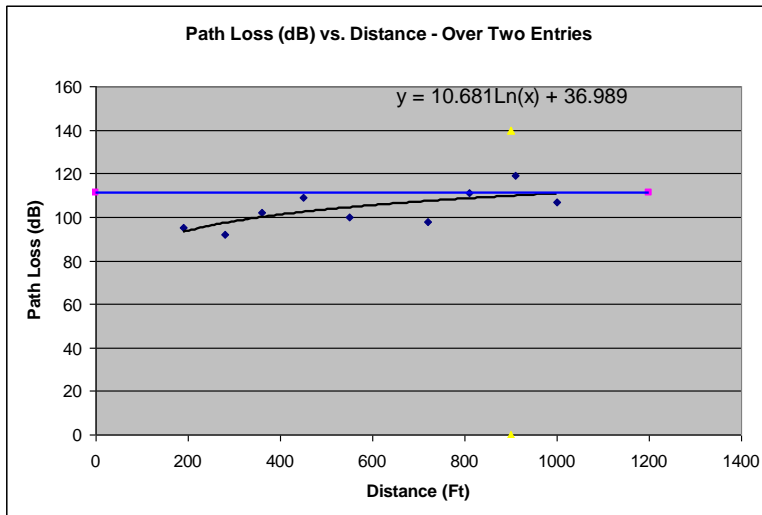

Figure 3.7: Path Loss Two Entries Over (Adapted from L-3 Communications GS&ES, March 2008)

The wireless signal losses for over one and two entries were 12.3 dB/100 ft loss and 13.9 dB/100 ft loss respectively. Non-Obstructed Clear opening, one entry over, and two entries over were used in order to classify a grid of partially known signal strengths at given points. Figure 3.8 shows the classification for the different tunnels in the area of interest.
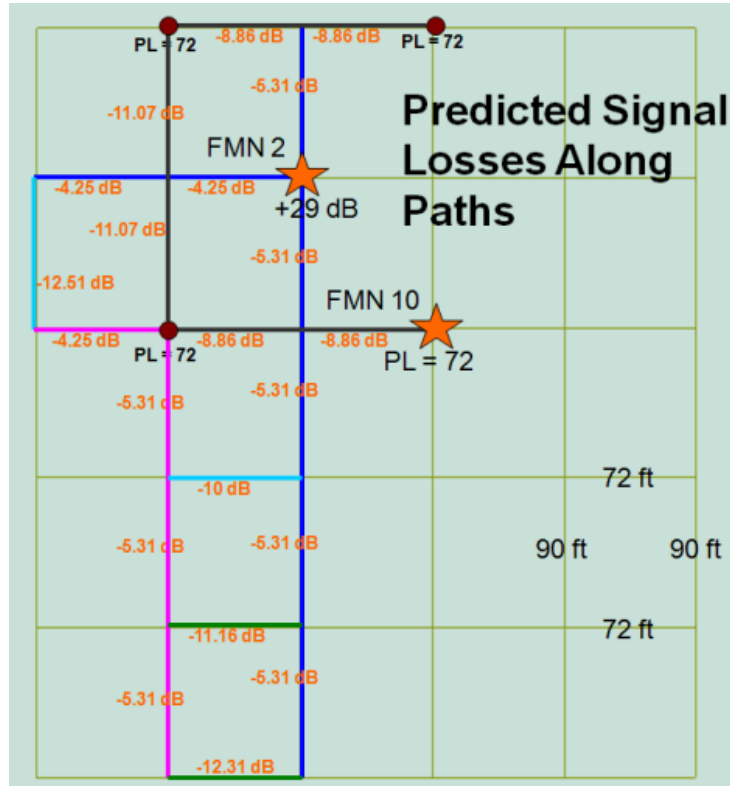
Figure 3.8: Theoretical Signal Losses along Classified Paths for Corner Loss

The given information consists of the path loss between FMN 2 to FMN 10 is 72 dB. It is assumed that the four locations (including the position of FMN 10) will all encounter a path loss from FMN 2 of 72 dB. This is assumed because these four locations are symmetrical and equal distance from the broadcast source of FMN 2. The mine tunnels to the right hand side of the area of interest are excluded due to the signal from FMN 1 providing these areas with saturated signal strength. The blue lines in Figure 3.8 are assumed to be Non-Obstructed Clear openings, black lines are one entry over, cyan lines are two entries over, pink lines are assumed to have standard signal losses similar to Non-Obstructed Clear openings after the corner is turned, and green lines are considered to be special areas where a three or four entries over estimation is required. The effects seen three and four crosscuts over were not tested, therefore a uniform increase in signal loss of 1.6 dB per additional crosscut was assumed. This was the given increase between one and two entries over. Three crosscuts over is assumed to have a loss of 15 dB/100 ft and a loss of 17.1 dB/100 ft for four crosscuts over. Given the distance of the tunnel and the assumed standard signal loss, a signal loss may be calculated over that specific distance. After theoretical losses have been estimated along paths, the signal strength at different intersections may then be calculated as shown in maroon in Figure 3.9.
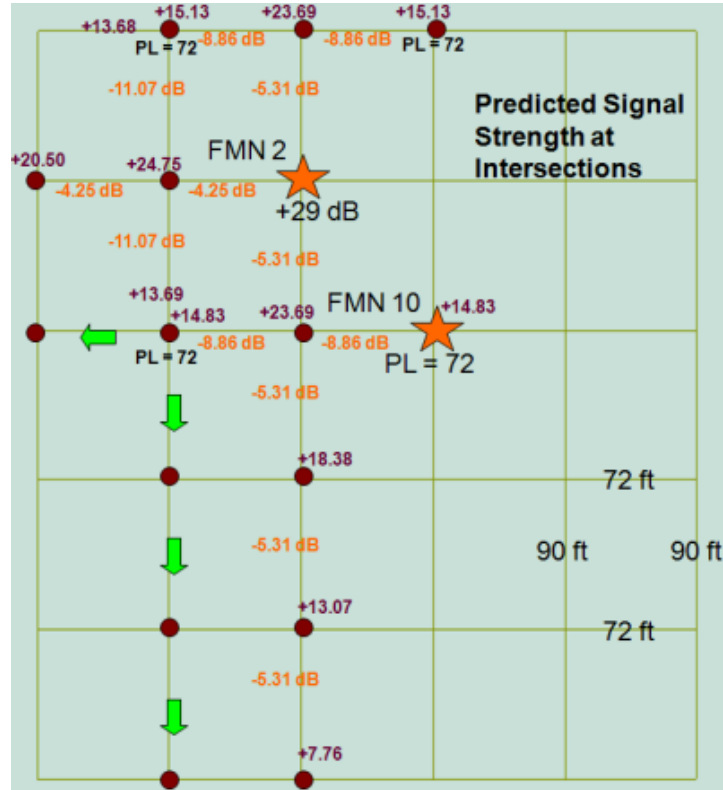
35

Figure 3.9: Theoretical Signal Strength at Intersections

Intersections may contain multiple calculated signal values based upon the direction that the wireless signal propagates to that intersection. If there are two calculated signal strength values then the calculated value with the highest signal strength is taken as the signal strength at that intersection. Using the highest signal strength at intersections with multiple calculated signal strengths, the signal strengths for the remaining area of interest are calculated as shown in Figure 3.10.
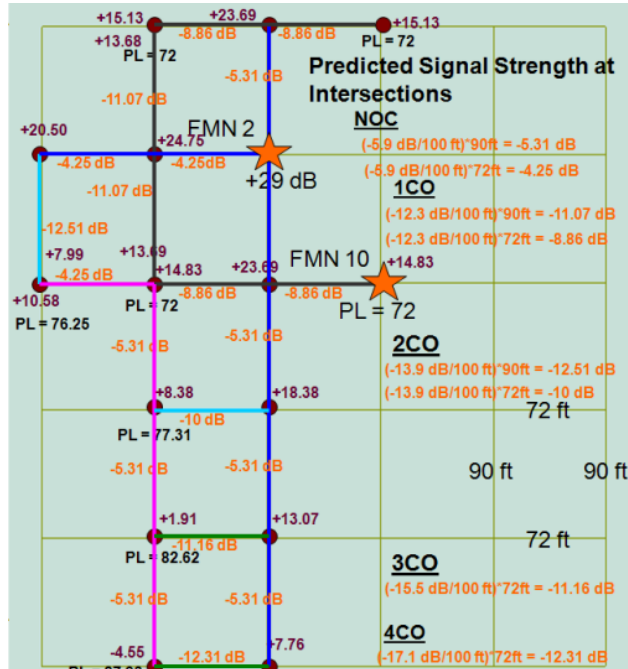
Figure 3.10: Calculated Theoretical Signal Strengths

Now that the signal strength values at intersections have been calculated, the theoretical signal loss when a 90 degree corner is turned into a crosscut may be calculated.

The signal loss (K) from turning a corner is calculated by:

$$K = PL - S$$

Where,

Pout = Initial Signal Power (dB)

PL = Path Loss (dB)

S = (Pout – Signal Strength) (dB)

Figure 3.11 shows the theoretical corner signal loss.
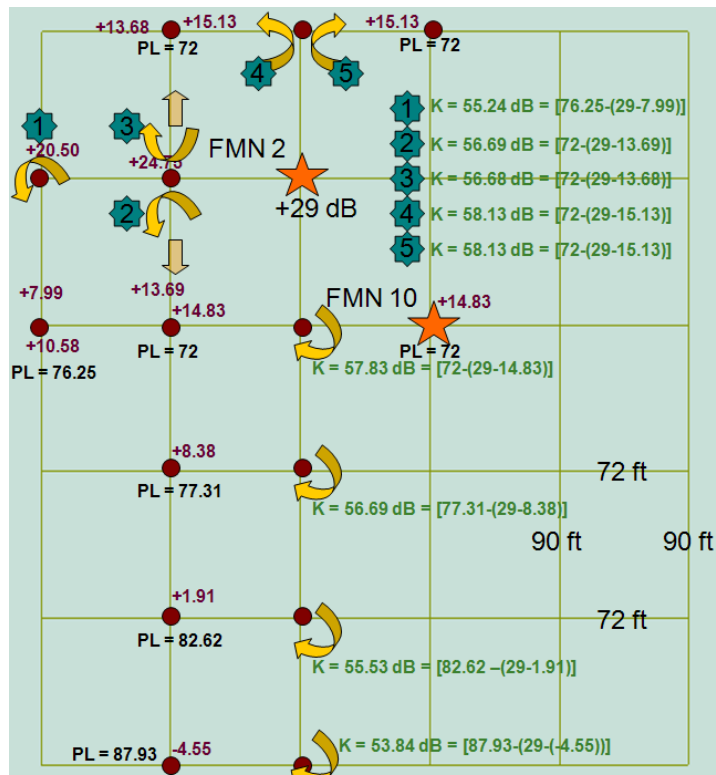
Figure 3.11: Theoretical Corner Signal Loss

Corner signal loss is estimated to have a loss of 55 dB per 90 degree turn.

3.2.1.5 ELEVATION LOSS

The impact of elevation is unknown and the connectivity between FMN 2 to 3 was chosen to highlight the impact elevation had on the wireless signal due to the significant dip between these FMNs. Figure 3.12 shows the profile contained in the L-3 Communications GS&ES (April, 2008) report of the area between FMN 2 and 3 where signal loss may occur due to the significant elevation change.
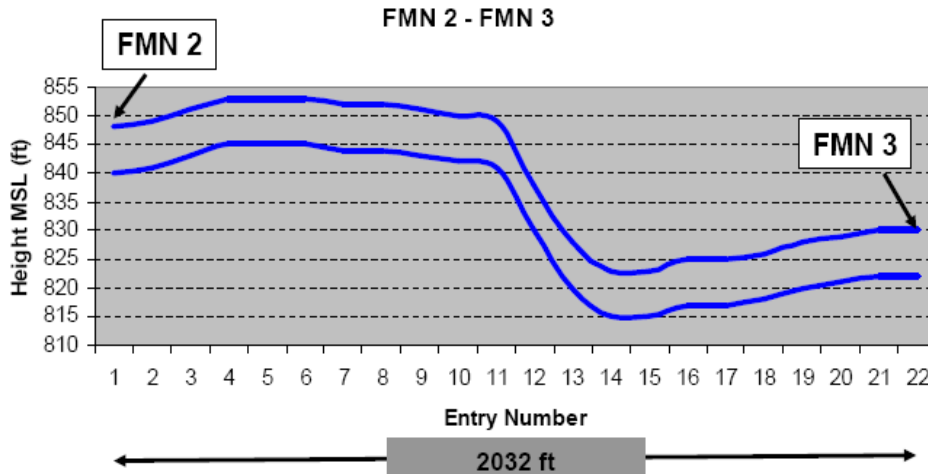
Figure 3.12: L-3 FMN 2 to 3 Tunnel Profile (L-3 Communications GS&ES, April 2008)

The path loss between FMN 2 to 3 was calculated by the following calculations.

FMN 2 to 3

Flat Distance = 2032 ft

Elevation Change = 42 ft

Path Loss = 29-(-69) = 98 dB

~4.8 dB/100 ft loss

In this area, elevation had a negligible effect. Due to the lack of abundance of data and inconclusive findings, the initial signal loss estimate due to change in elevation was considered to be negligible and therefore excluded until further evidence showing elevation having a significant impact was observed.

3.3 Field Work

The data reviewed in this section is used in the data analysis in Sections 4.4 and 4.5. The team which consisted of individuals from the companies in the project made trips to the Sentinel mine to test on a consistent basis. Field testing appeared to yield improving results as hardware and software changes were made in response to observations made in the mine. Initial signal loss parameters were established for Phase II and further testing and additional data is required in order to validate and adjust signal loss parameter estimations. Using the anticipated interferences and design parameters, pre-installation communications network coverage maps were created. Once the communication system has been fully integrated into the mine, additional interferences and design parameters are revealed by comparing theoretical signal strengths versus measured signal strengths

The opportunity to use test equipment was scarce due to testing underground was limited based upon the availability of ICG miners. ICG miners were needed in order to serve as escorts in the mine. This is important in order to ensure the team is aware of health and safety hazards that both testing and mining activities create. Wireless propagation testing is only allowed to take place in the intake and neutral aircourses because, the equipment used to conduct tests is not permissible and could potentially cause an explosion if the equipment was subjected to a toxic atmosphere. Measuring wireless signal strengths can be subjected to many conditions such as which way the source or broadcast point is in relation to how you are standing, equipment currently in that area, and many other various circumstances that may be introduced during normal mining operation. The RSSI or signal strength of a wireless signal can be measured with a spectrum analyzer or an Accolade handset attached to a PDA.

The data collection utility using an Accolade handset was written by IWT. Broadcast nodes are turned on underground and the communication system is made available. The Accolade handset is used by a person underground to measure the RSSI and the PDA is used to record data such as the node the handset is communicating with, RSSI measured at that point, and other communication properties at that specific time. Data is polled for 5 seconds and then the averages within that 5 second interval are recorded by the utility. A person on the surface works in cooperation with the person underground by creating a log of the RSSI and mine map

position description and time that, that position is reached by the person underground. The time and positions are cross-referenced between the PDA log and the log created on the surface. Cross-referencing the two logs enables the data to be compiled into one useable log with all the collecting data. Figure 3.13 shows the testing devices used in the IWT method for mine surveys that is contained in the Phase III JDA Mine Tracking System Rev A report in August 2008.
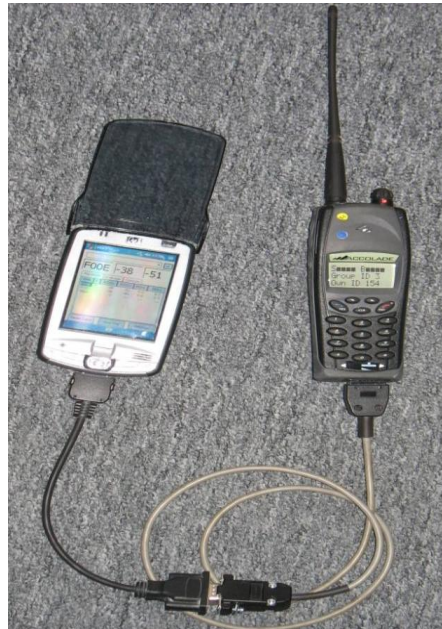

Figure 3.13: IWT Survey Method, PDA and Accolade Handset (IWT, August 2008)

The second method to collecting data is using a spectrum analyzer. While the broadcast nodes and communication system is turned on, a spectrum analyzer with an antenna attached can measure the RSSI of a radio frequency at a specific location. Specific points must be measured in order to compare those values to assume that the difference between the measured signal strength and the normal predicted path loss is the interference of interest. Measurements during the stopping and corner tests were taken at a static position.

3.3.1 ADDITIONAL STOPPING AND CORNER TESTING

In order to properly quantify the losses due to stoppings and corners, further testing was required. A spectrum analyzer was used to measure the signal strength at specific positions. To test the loss through a stopping, the broadcast node with a yagi or directional antenna was placed barely within the crosscut at position Y. The broadcast node's antenna was positioned

41

horizontally and pointed towards the stopping. The signal strength was measured approximately 5 feet on each side of the stopping in the center of the opening at both point A and behind the stopping at point B. A yagi antenna was used with the spectrum analyzer in order to keep the antenna configuration consistent with Accolade broadcast nodes. The spectrum analyzer antenna was oriented horizontally pointing in the direction of the broadcast node. Figure 3.14 shows the broadcast point Y, and positions A and B where the signal strength was measured.
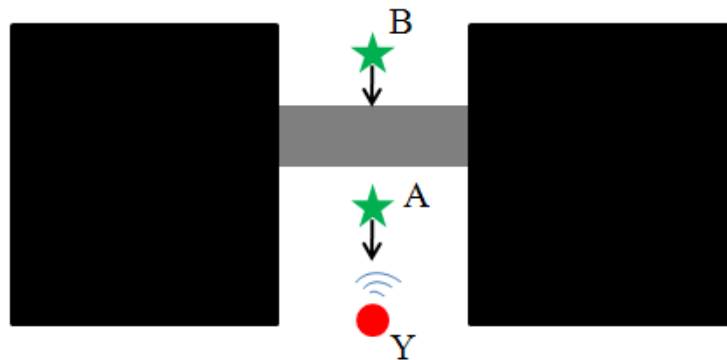

Figure 3.14: Stopping Test Diagram

The test was performed at both 900 and 450 MHz. Table 1 contains the results from the stopping tests.

Table 1: Stopping Test Measurements

Radio Frequency (MHz)	Transmit Antenna Type	Receive Antenna Type	Power Measured A (dBm)	Power Measured B (dBm)	Calculated Difference
921.58	Directional (Yagi)	Directional (Yagi)	-9.8	-20.74	10.9
470.97	Directional (Yagi)	Monopole (Whip)	-41.36	-51.49	10.1

The signal loss due to natural propagation degradation is considered negligible due to the clear straight nature of the test site. The next series of tests were performed in order to quantify the signal loss due to turning a corner. Figure 15 shows the locations of the points of interest in the corner test.
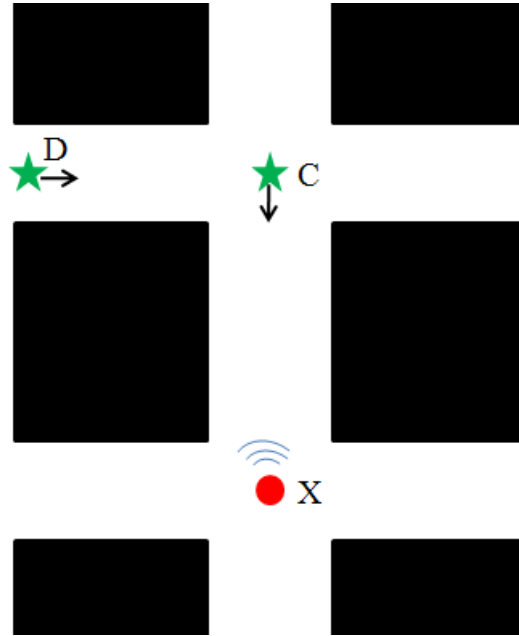
42

Figure 3.15: Corner Test Diagram

The broadcast node was placed at point X and measurements were taken at both points C and D. Table 2 contains the data from the corner test.

Table 2: Corner Test Measurements

Radio Frequency (MHz)	Transmit Antenna Type	Receive Antenna Type	Power Measured C (dBm)	Power Measured D (dBm)	Calculated Difference
921.58	Directional (Yagi)	Directional (Yagi)	-25.3	-61.6	36.3
470.989	Directional (Yagi)	Monopole (Whip)	-44.51	-76.46	32.0

Additional testing on the losses due to turning corners and stopping losses yielded results more accurate than estimated initially.

3.3.2 HEURISTIC/ACQUIRED KNOWLEDGE

During field testing and installation of the communication system, the design parameters were categorized into radio frequency performance in the area, radio frequency coverage provided by that broadcast node, the location of power sources, and the overall logistics of the installation. These categories take into consideration the ease of installation and the necessary requirements in order for FMNs to operate properly. Poor propagation performance is observed if the antenna is pointed into the roof. Target connectivity between FMNs is desired at approximately 75 dB.

During the West Virginia approval process of the communication system it is required that the system's performance is demonstrated. Communication was observed at a "good" quality at eight (8) crosscuts up and one entry over. Coverage in the main haulage was approximately 1500 to 2000 feet. Coverage in a belt entry was observed to be 800 to 1000 feet. Federal and state laws regulate that the cable length between the power supply and the last junction box may not exceed 1500 feet. Given this in mine heuristic or acquired knowledge, it is appropriate that signal loss estimations are adjusted to increase the range and coverage originally predicted.

3.4 Team Mine Survey

The results using initial signal loss estimations did not fully model the behavior of the Accolade system appeared to have underground. L-3/IWT released (given information was protected) additional data in October 2008 from a site survey that was done in June 2008. The data obtained from L-3 was recorded by IWT during testing in June 2008. The mine survey data was collected using a PDA and Accolade handset as shown above in Figure 3.13. Figure 3.16 shows the points in the Sentinel mine where data was collected in the mine survey. Figure 3.16 is the test area during the team mine survey as recorded in the Phase III JDA Mine Tracking System Rev A report in August 2008.
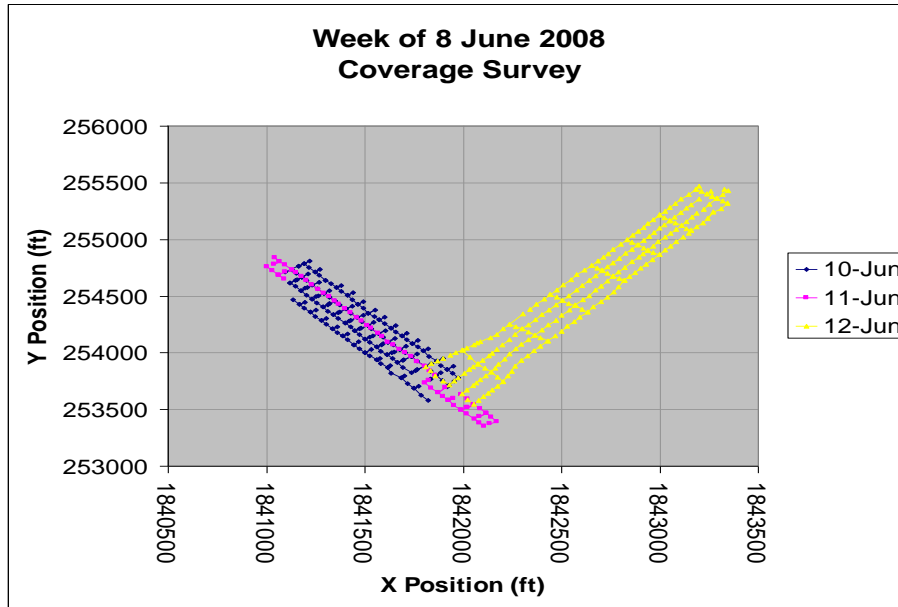
Figure 3.16: Mine Survey Data Points (IWT, August 2008)

The data collected during the mine survey includes date time (M/DD/YY HH:mm:SS), map location, location x (ft), location y (ft), location X change (ft), location Y change (ft), location distance change (ft), node number of packets received, node max RSSI during 5 second interval, node mean RSSI during 5 second interval, node standard deviation of RSSI during 5 second interval. The date time and location (X,Y) can be related between the information logged during the survey on the surface and underground in order to create useable data. The RSSI ranges for the bars of service shown on the Accolade handset were used to classify RSSI values into five different categories. The RSSI ranges can be found in the L-3 Communications GS&ES Phase II Above Ground report from March, 2008 which is shown in Figure 3.17.

RSSI Range (dB)	Bars Shown
>-40	4
-41 to -50	3
-51 to -64	2
-65 to -87	1
<-88	None

Table D-2: RSSI Bar Chart Values

Figure 3.17: RSSI Ranges with Accolade Handset Service Bars (L-3 Communications GS&ES, March 2008)

3.4.1 MINE SURVEY ANALYSIS

The survey data was recorded by the IWT FMN ID codes which were not available at the time the data was received. Coverage maps were created to narrow down exactly which position the FMN was broadcasting from under the specific IWT ID. The mine survey test data was sorted by the mean data values because the mean is assumed to be the signal that would be received majority of the time in that location. Table 3 contains cross reference values between L-3 Phase II Report FMN placement, Comms FMN placement, and IWT's mine coverage survey in June 2008.

Table 3: Mine Survey FMN Location and Cross Reference Table

L-3 FMN Position	X Coordinate	Y Coordinate	CommsID	IWT FMN ID		
				6/10/2008	6/11/2008	6/12/2008
FMN 1	1843506	255044	323	--	--	FBAE
FMN 10	1843159	255193	334	X	X	F007
FMN 2	1843166	255313	1759	--	--	FB03
FMN 11	1842434	254244	164	X	X	F00E
FMN 12	1841994	253631	77	F009	F009	F009
FMN 3	1841872	253646	70	FB01	FB01	FB01
FMN 4	1841338	254334	932	FB13	FB13	--
FMN 5	1841118	254616	916	F007	F007	X
FMN 13	1841132	254735	904	F00E	F00E	X

Table 4 contains the IWT ID FMN references to the FMNs that were used during testing.

Table 4: IWT ID FMN Reference Table

F000	Out Of Range	F000_18	F000_39
FB1F	No Data	FB15_15	--
F00E	Includes	F00E_14	F00E_35
F007	Includes	F007_7	F007_28
F009	Includes	F009_9	F009_30
FB01	Includes	FB01_13	FB01_34
FB03	Includes	FB03_4	FB03_25
FB13	Includes	FB13_3	FB13_24
FBAE	Includes	FBAE_10	FBAE_31

The Phase III JDA Mine Tracking System RevA 29Aug2008 word document written by IWT cites that on June 10th and 11th, L-3 FMNs 10 and 11 were not active and on June 12th FMNs 5 and 13 were moved to L-3 FMN 10 and 11's locations. In Table 4, these FMN locations are noted by an X. To show continuity and reference the different FMN location schemes, the following coverage maps have been created. It is necessary to sort RSSI measurements by the date and time they occurred to accurately analyze coverage maps because FMNs were moved and only active on certain days. Data points which no location was specifically noted and points which the RSSI value was equal to zero were omitted. Figure 3.18 contains the same RSSI range classification that is shown in Figure 3.17. The software Surfer by Golden Software was used to create coverage maps for the June data. A pink X denotes a known location of an L3 Phase II Report FMN (possible location of an FMN used in IWT's mine coverage survey).
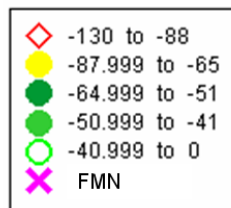

Figure 3.18: Surfer RSSI Range Classifications

Figure 3.19 shows all of the mine survey data conglomerated. It shows that the data must be split up to gain further understanding of the data.
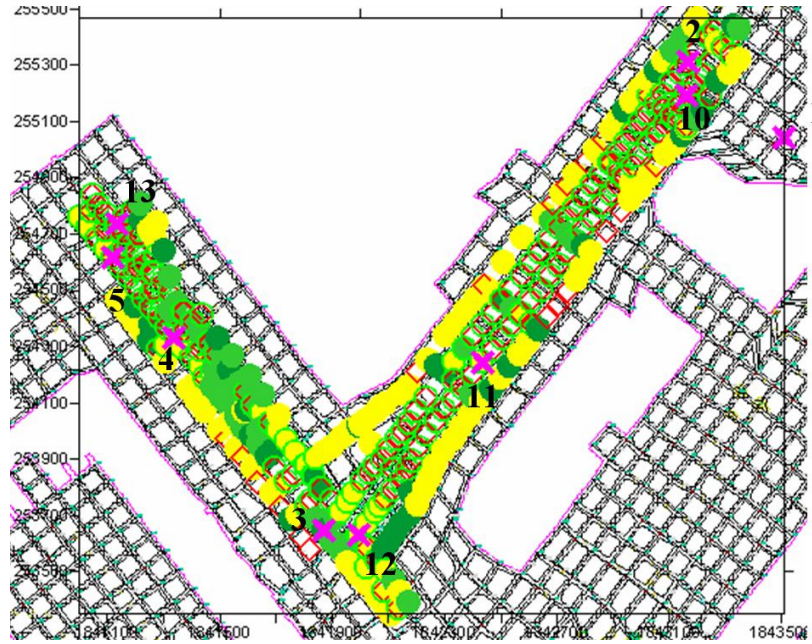

Figure 3.19: Conglomerated Mine Survey

IWT FMN ID F00E coverage maps contain RSSI measurements in different parts of the mine thus indicating that the FMN was one of the FMNs that was moved during the testing. In Figure 3.20 the signal strength is decreasing from L-3 FMN 13.
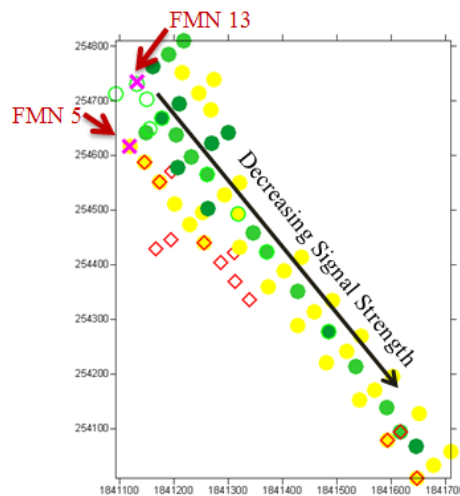

Figure 3.20: IWT FMN ID – F00E_14 June 10

Figure 3.21 also shows the signal decreasing from L-3 FMN 13. IWT FMN ID F00E is the L-3 FMN 13 position on June 10th, and 11th.
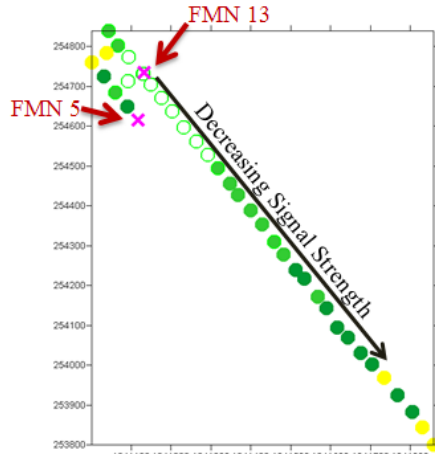
Figure 3.21: IWT FMN ID – F00E_35 June 11

Figure 3.22 shows the signal strength decreasing in both directions away from the L-3 FMN 11 position. F00E is in the L-3 FMN 11 position on June 12th.
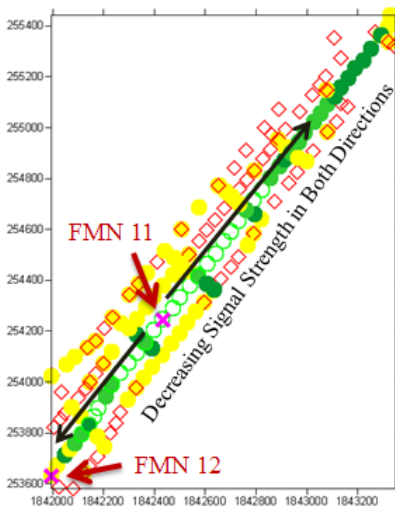

Figure 3.22: IWT FMN ID – F00E_14 June 12

Coverage maps (Figure 3.23 and 3.24) from the FMN IWT ID F007 occur in two different parts of the mine so it is assumed that this is one of the FMNs that was moved during testing.
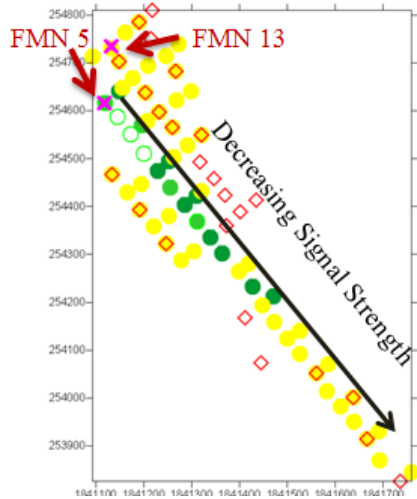
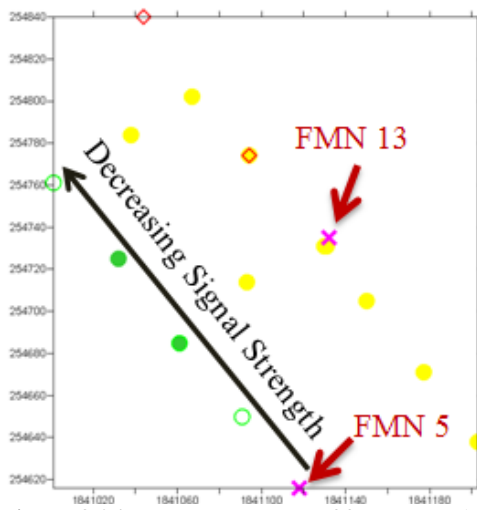Figure 3.23: IWT FMN ID – F007_7 June 10

Figure 3.24: IWT FMN ID – F007_7 June 11

Figures 3.23 and 3.24 both show decreasing signal from the L-3 FMN 5. IWT FMN ID F007 is located in the L-3 FMN 5 position on June 10th and 11th.

Figure 3.25 shows the signal strength decreasing from the L-3 FMN 10 location on June 12th. It is also noted that the signal strength is too low at FMN 11 to be the broadcast location.
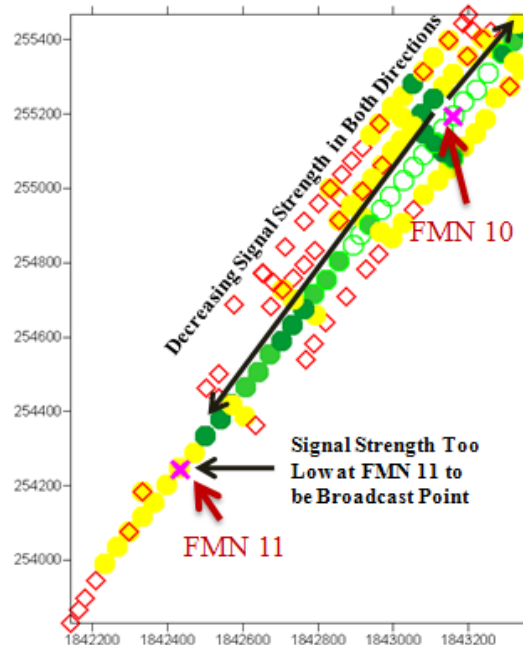
Figure 3.25: IWT FMN ID – F007_7 June 12

IWT FMN ID F007_7 is in the L-3 FMN 10 location on June 12th.

Figures 3.26, 3.27 and 3.28, show that IWT FMN ID F009 are all decreasing in signal strength from the L-3 FMN 12 location. IWT FMN ID F009 is the L-3 FMN 12 location on June 10th, 11th, and 12th. Figure 3.40 shows that the signal strength is too low at L-3 FMN 3 for that position to be the location of the broadcast node.

Figure 3.26: IWT FMN ID – F009_30 June 10
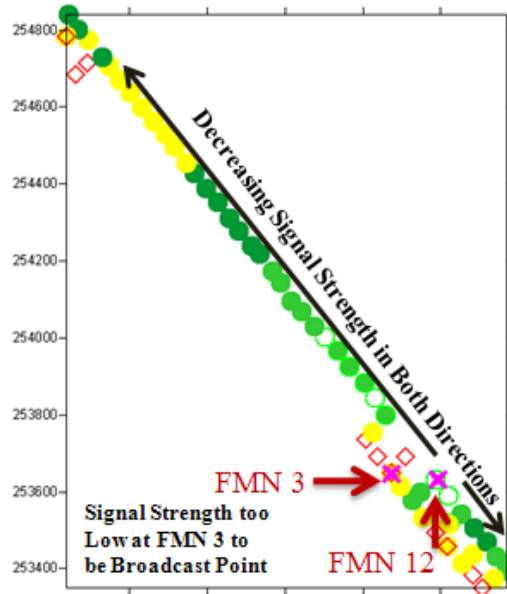
Figure 3.27: IWT FMN ID – F009_9 June 11
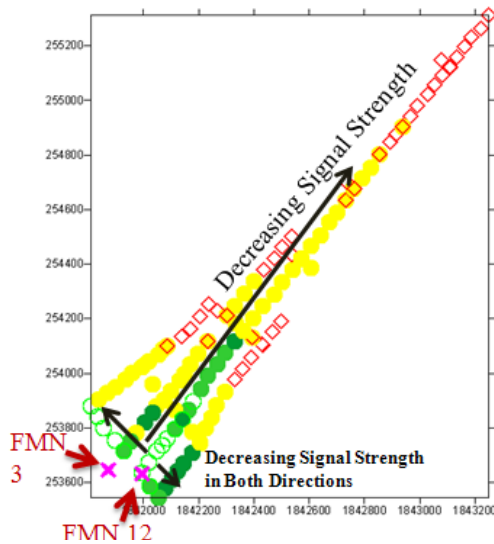
Figure 3.28: IWT FMN ID – F009_30 June 12

IWT FMN ID F009 contains service to both of the test areas in the mine but fits the L-3 FMN 12 placement due to FMN 12 sitting in the bend which will provide service to both of the test areas as shown in Figures 3.26, 3.27, and 3.28.

Figures 3.29, 3.30, and 3.31 show the signal strengths decreasing from L-3 FMN 3 position on all three test days.

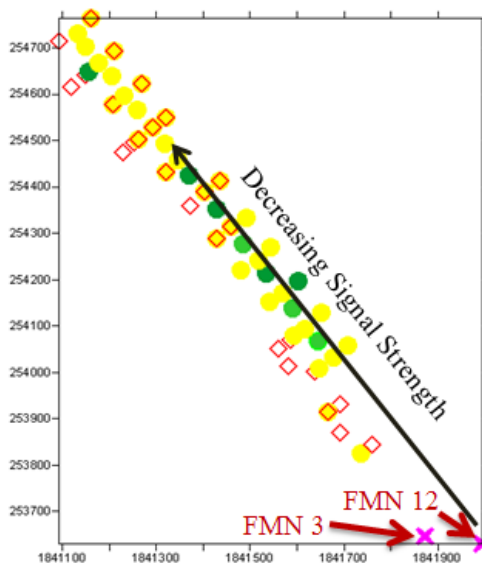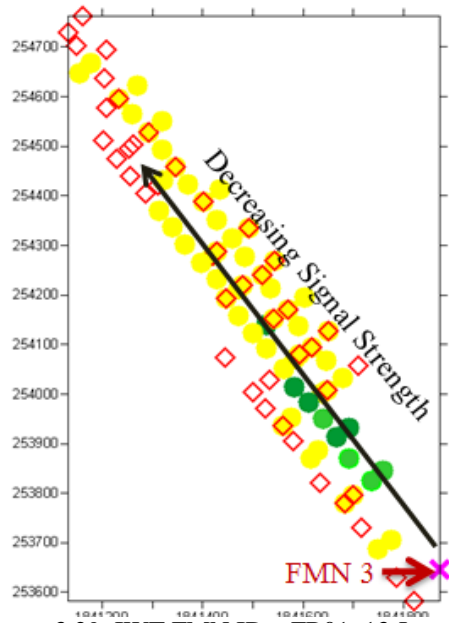Figure 3.29: IWT FMN ID – FB01_13 June 10
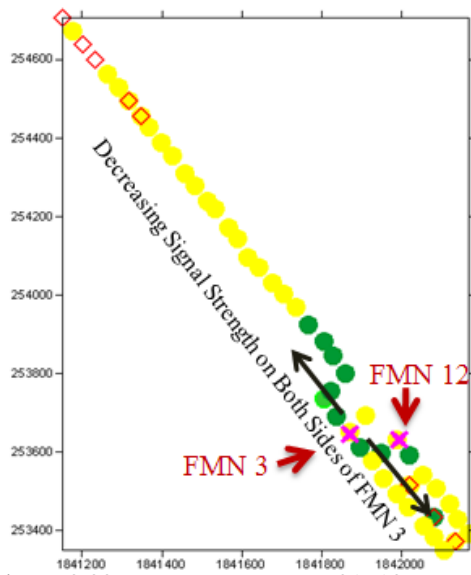
Figure 3.30: IWT FMN ID – FB01_13 June 11
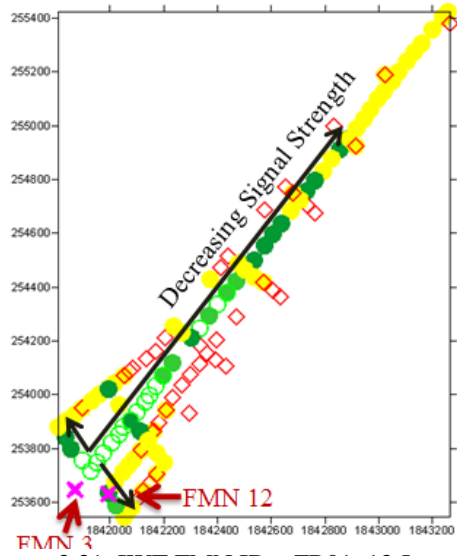
Figure 3.31: IWT FMN ID – FB01_13 June 12

IWT FMN ID FB03 was only was active on June 12th. Figures 3.32 and 3.33 both show decreasing signal from the L-3 FMN 2 position.
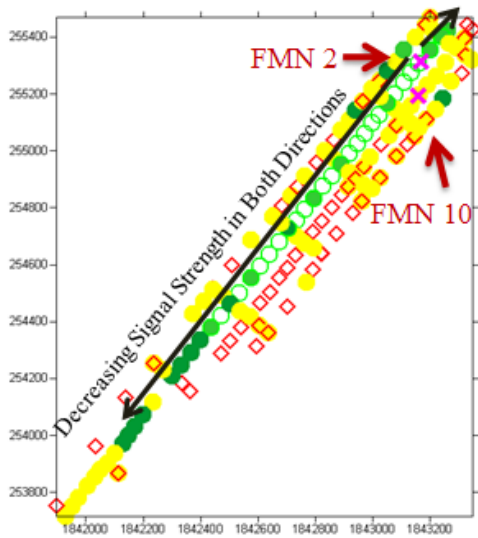
Figure 3.32: IWT FMN ID – FB03_4 June 12
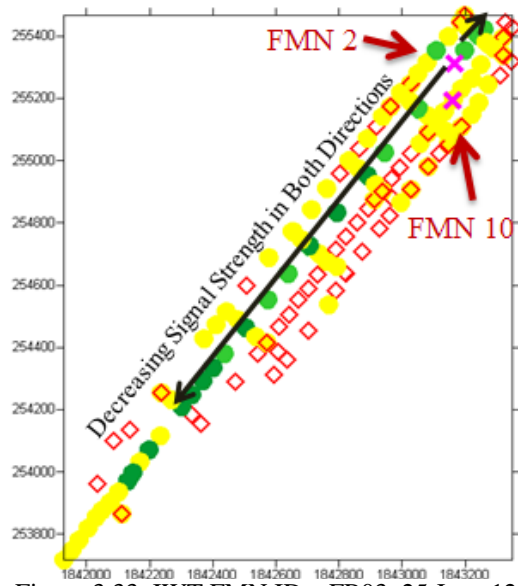
Figure 3.33: IWT FMN ID – FB03_25 June 12

IWT FMN ID FB13 was active on June 10th and 11th. Figure 3.34 shows decreasing signal strength in all four directions from the L-3 FMN 4 position.
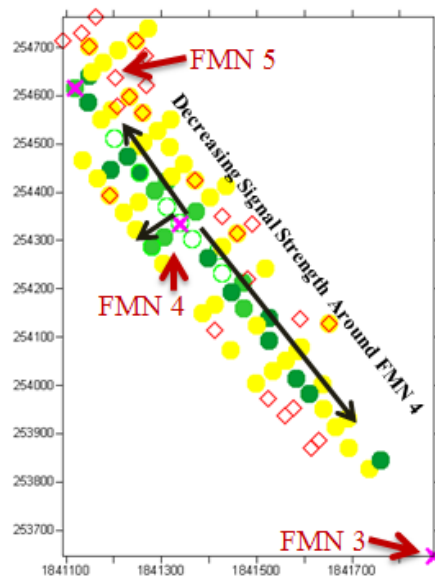
Figure 3.34: IWT FMN ID – FB13_24 June 10

Figure 3.35 shows that the signal strength at the L-3 FMN 5 and 3 is not strong enough to be the broadcast points.
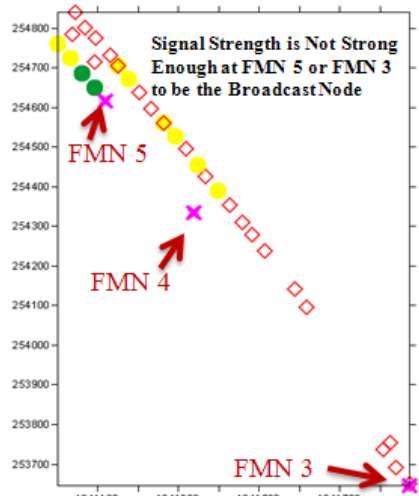
Figure 3.35: IWT FMN ID – FB13_24 June 11

Figures 3.34 and 3.35 show that on both test days the IWT FMN ID FB13 are in the L3 FMN 4 position.

Figures 3.36 and 3.37 do not show decreasing signal strength from the L-3 FMN 2 and 10 locations. It appears that IWT FMN ID FBAE is the L-3 FMN 1 position.
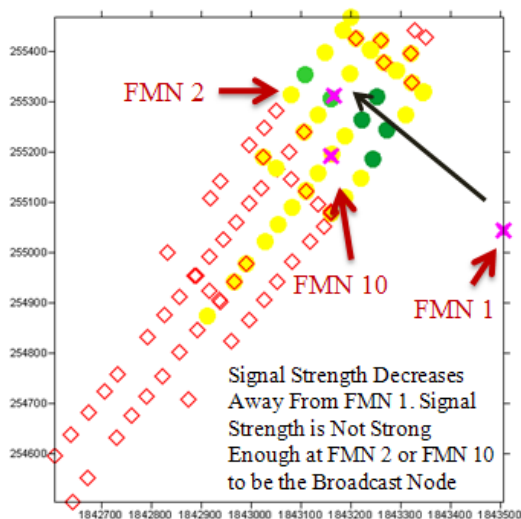
Figure 3.36: IWT FMN ID – FBAE_10 June 12
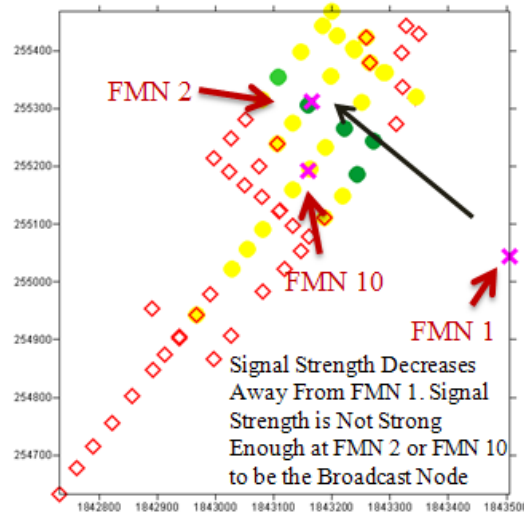
Figure 3.37: IWT FMN ID – FBAE_31 June 12

The mine survey data was used to compare measured data to calculated signal strength by Comms. The data is used in later sections to predict FMN connectivity and placement of FMNs that use directional antennas.

3.5 Issues and Problems

Data collection in the underground coal mine environment is not a simple task. The underground mine environment itself is damp, unlevel, and overall not ideal for the natural propagation of radio waves. The data measured in the mine can vary based upon the exact location within openings, the orientation of the antennas, vehicles moving in the area, poorly placed antennas, and other unanticipated interferences that are encountered in the mine. A miner can decrease the received signal strength alone by standing with their body in between the handset and the nearby FMN.

Survey data provides a unique challenge when attempting to predict the signal losses using a logical or computer program model method. A computer model operates in a radial or equal in every direction, while the FMNs for the Accolade system utilizes directional antennas. The computer model operates in the radial fashion like a monopole antenna. The mine survey test data was collected using an Accolade handset which uses a monopole antenna. A monopole antenna transmits/receives data radial or equal in all directions from the antenna (some antennas

may vary based on design). The discrepancy with modeling in a radial fashion is assumed to be negligible when using initial and adjusted signal loss parameters for Comms as discussed in Sections 4.2, 4.3, 4.5, 4.6, and later accounted for in 4.7. Section 3.3 uses a combination of directional and monopole antennas to measure the signal loss due to stoppings and corners. The differences in the antenna types are considered to be minor and may reflect issues seen in the operation of FMNs and MMRs.

Coverage maps from measured and predicted signal strengths can be used to adjust and finalize signal loss estimations to account for the performance of the signal in that specific part of the mine. Section 4.8 contains a comparison of the Comms predicted signal strength versus the measured signal strength in the mine survey.

Chapter 4 : DATA ANALYSIS

4.1 Comms

Comms is a computer method developed at the Virginia Center for Coal and Energy Research at Virginia Polytechnic Institute and State University which can be utilized to solve a mine's communication network. Comms was developed in cooperation with Steven Schafrik in order to analyze and solve a mine communications network. Existing software did not necessarily function as the observed signal losses that underground communication networks encounter. Comms utilizes the IntelliCAD software and programmed routines to calculate necessary values to both quantitatively and qualitatively solve and analyze predicted coverage areas. Comms was developed Comms was initially tested using a basic grid. Figure 4.1-basic grid contains the basic grid.
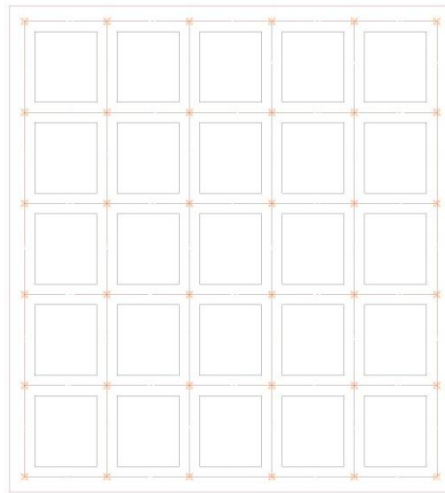
Figure 4.1: Basic Grid

Initial testing was done on a small scale to ensure Comms predicted signal losses from obstructions and normal signal degradation. Figure 4.2 contains the theoretical wireless node broadcast service area when the node does not encounter signal losses except the assumed normal signal degradation.
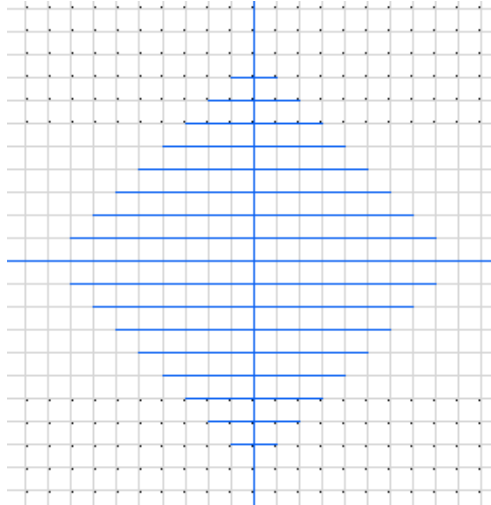
Figure 4.2: Theoretical Wireless Node Broadcast Service Area

Comms solves a mine's communication network by building the communication network of the mine, solving the network, prediction of ideal coverage, and optimization of the communications network. Figure 4.3 contains a screen shot of the mine communication network tool Comms.
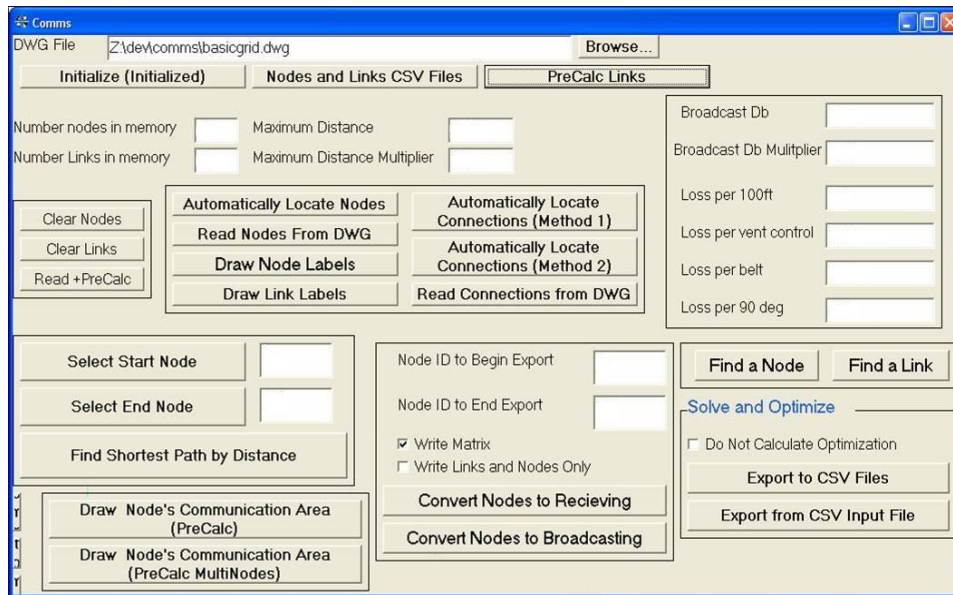
Figure 4.3: Comms, Mine Communication Network Tool

Comms builds the mine's communication network using the pillar/perimeter method and/or the centerline method. The pillar/perimeter method uses the drawn lines in the mining design (pillars, mine perimeters, etc.) to determine which areas have been mined out and attempts to locate the center of those mined out areas. The pillar/perimeter method draws a

search line from the center of the area of interest (ex: pillar) and determines where the search line encounters a pillar or perimeter line from the drawing and places a point half way between the edges of the area of interest and the next pillar or perimeter that is encountered. This will typically locate eight points around a typical room and pillar method pillar. Half of the located points will be reduced from a pillar because the removed points are the midpoints between the mine's intersections. Figure 4.4 contains a typical scenario of the pillar/perimeter method before the number of points is reduced. Figure 4.5 shows automatically reduced points. Points are reduced if the interior angle between their corrections is above a threshold value (170 degrees in the depicted case).
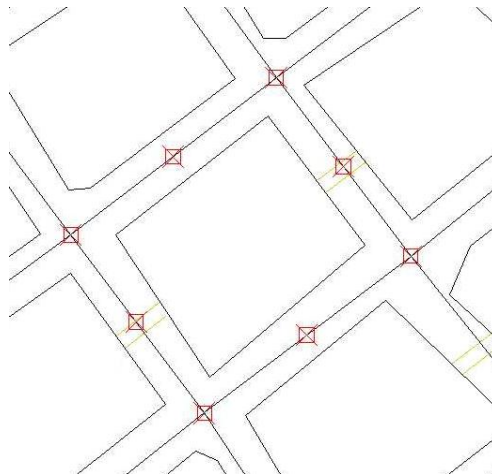
Figure 4.4: Comms Pillar/Perimeter Method
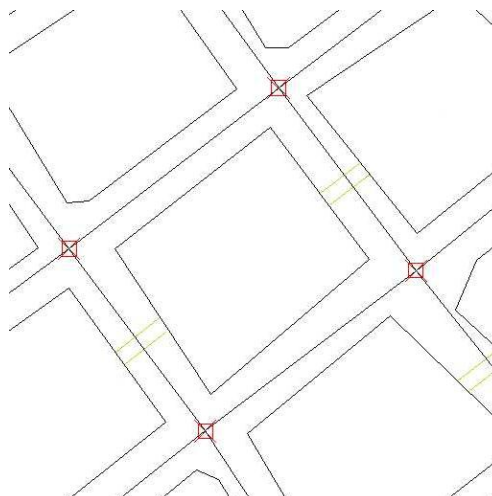
Figure 4.5: Comms Pillar/Perimeter Method Reduced

The second method available for building the communications network is the centerline method. The centerline method is when a user defines an ideal centerline for Comms to continue along. Comms will attempt to fit a line in the straightest possible fashion along the intersections of the actual mine design. Intersections of the centerlines are used as the points. Figure 4.6 contains a scenario of the centerline method.
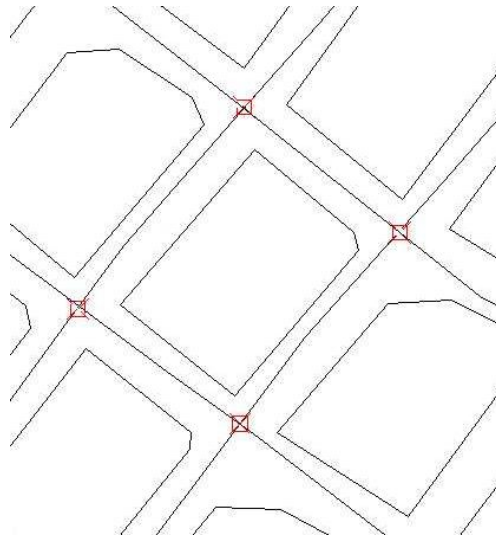
Figure 4.6: Comms Centerline Method

The pillar/perimeter method is time consuming because of the amount of calculations in each pillar area encountered. It is careful not to repeat calculations but is not yet optimized. The pillar/perimeter method is very accurate at determining intersections but does have trouble with non-rectangular mine layouts. The centerline method is not as automated, requiring a user to provide a start point and direction. It is computationally faster because it only needs to find intersections of centerlines. The pillar/perimeter and centerline methods both have issues in certain scenarios and a combination of both can be used.

In either method the user is required to edit the mine communication network to ensure all links and intersection points are connected. The pillar/perimeter method and centerline method will both ultimately create a series of conceptual points (intersections) and links (tunnels) that are connecting the intersections. This will form a grid where links can be categorized based upon the specific signal loss parameters the signal will encounter from that link or tunnel. The mine's communication network is crucial because it directly relates the

62

physical mine model to the mine communications model. Once the mine's communication network has been created, Comms will then solve the network.

Solving the network consists of defining every single point as a potential broadcast point and calculates the range given that point is a broadcast point. This is done in two methods, shortest distance and path of least resistance (which takes into account the cumulative resistance as each link or distance is walked). In both methods Comms determines the links that are available to any point and then determines if the point on the end of the search line is the end point of the path.

For every point in the network, Comms determines the path to every other point in the network. This process is done by starting at a point and determines the links available and if the point across the link is the end point. Comms then recursively follows every link available until a maximum search of the endpoint is encountered. Comms returns the path of least resistance or the shortest distance. These paths are outputted to text files of comma separated values that also put properties of the path such as resistance, obstacles encountered, and angles of turns made. These two methods give predicted coverage for every point in the network. Figure 4.7 contains an example of the solve excel output from Comms.

FROM	ID 0								
To ID	Distance	Resistance	Link ID	Distance	Rho	Single Rho	Distance Resistance	Angle Between	A
0	0	0							
1	80	4.72							
			0	80	5.9	0	4.72		
2	160	24.34							
			0	80	5.9	0	4.72		
			2	80	5.9	14.9	4.72	180	
3	240	43.96							
			0	80	5.9	0	4.72		
			2	80	5.9	14.9	4.72	180	
			4	80	5.9	14.9	4.72	180	
4	320	48.68							
			0	80	5.9	0	4.72		
			2	80	5.9	14.9	4.72	180	
			4	80	5.9	14.9	4.72	180	
			6	80	5.9	0	4.72	180	

Figure 4.7: Comms Solve Excel Output Example

This enables the expected coverage areas to be drawn, search for predictions that do not match predicted values (heuristic knowledge that tells us otherwise), and find other problematic areas. Signal strength values that are calculated when solving the mine's communication network may then be used to draw in the coverage area each individual point would provide given that the point is a broadcast point. The user can input the points that need to be solved to avoid having to

solve every point in the network. This is especially useful if communication network infrastructure is already in place. Solve routine can be time consuming depending on the number of points in the network but if the network does not change then the network only needs to be solved one time. This is because the paths found are saved in comma separated variable text files that can be loaded into the program for additional analysis. Output from the solve routine also includes a file that is useful in optimization of the network.

The optimization routine uses the predicted values from shortest distance and cumulative resistance to calculate the percent coverage. Output from the solve routine includes a service array that indicates which points will receive service when a particular point is broadcasting. The total number of points in the network a subset of points is chosen which are assumed to be broadcasting, the broadcast area from this subset of points is calculated if it meets the percent coverage criteria of all points then it is considered a valid solution. The valid solution with the least number of broadcast points is the optimal solution. Optimization begins searching from the least number of broadcast points to the most number of broadcast points. The first iteration calculates the percent coverage if there is only one broadcast point. This broadcast point is not a set point but instead the method examines every point in the network as if it was the only point broadcasting. Iterations continue to incrementally, increasing the number of broadcast points until a valid solution is found. The percent coverage area will be calculated increasing the number of broadcast points until the number of broadcast points is equal to a user inputted percent coverage of points receiving coverage in the mine communication network. The least number of broadcast points that satisfies the desired percent coverage is chosen as a possible solution. Figure 4.8 contains an example of the excel optimization data that can be outputted by Comms.

Num Being Serviced	Total Num Recieving	Num Broadcasting Nodes	Broadcast Nodes Locations		
36	54	2	8	25	
36	54	2	8	26	
36	54	2	8	28	
36	81	3	8	14	28
36	81	3	8	15	25
36	81	3	8	15	26
36	81	3	8	15	28
36	81	3	8	20	25
36	81	3	8	20	26
36	81	3	8	20	28
36	81	3	8	21	25

Figure 4.8: Comms Optimization Excel Output Example

The optimization routine is slow and a simple case requires millions of iterations. For instance, a small network with 30 points given 10 possible broadcast points will yield 30,045,015 possible solutions. The number of possible solutions is calculated using equation (4.1) (McCaffrey, 2004).

The number of possible solutions or combinations (C) is equal to:

$$C = \frac{N!}{K! * (N - K)!}$$

(4.1)

Where,

N, is the total number of points in the communications network.

K, is the number of points being examined in the iteration scenario.

4.2 Initial Signal Loss Theoretical Equations

Initial signal loss theoretical equations have been created to describe the current path loss model discussed in Section 3.2. The predicted path loss is equal to the sum of the resistances caused by the signal loss parameters due to Non-Obstructed Clear (NOC), Beltway (Belt), Stopping (Stopping), and Corner (Corner) losses. A non-obstructed clear loss and beltway loss are standardized to have consistent losses normalized over a range of 100 feet. Stopping and corner losses occur in a constant loss per stopping or corner the signal encountered. The follow equation is the simplified form of the initial theoretical path loss.

$$Path\ Loss = \left[\sum Non\ Obstructed\ Clear\ Losses\right] + \left[\sum Beltway\ Losses\right] + \left[\sum Stopping\ Losses\right] + \left[\sum Corner\ Losses\right]$$

The following equations are the expanded forms of the initial theoretical path loss equation shown above. Initial signal loss parameter values are substituted into the second equation.

65

$$Path\ Loss = \left[\sum\left[NOC\ Loss\left(\frac{dB}{100ft}\right) \times (\#\ NOC\ ft)\right]\right]$$

$$+ \left[\sum\left[Belt\ Loss\left(\frac{dB}{100ft}\right) \times (\#\ Belt\ ft)\right]\right]$$

$$+ \left[\sum\left[Stopping\ Loss\left(\frac{dB}{stopping}\right) \times (\#\ Stoppings)\right]\right]$$

$$+ \left[\sum\left[Corner\ Loss\left(\frac{dB}{90°}\right) \times (\#\ Corners)\right]\right]$$

$$Path\ Loss = \left[\sum\left[5.9\left(\frac{dB}{100ft}\right) \times (\#\ NOC\ ft)\right]\right] + \left[\sum\left[14\left(\frac{dB}{100ft}\right) \times (\#\ Belt\ ft)\right]\right]$$

$$+ \left[\sum\left[15.5\left(\frac{dB}{stopping}\right) \times (\#\ Stoppings)\right]\right]$$

$$+ \left[\sum\left[55\left(\frac{dB}{90°}\right) \times (\#\ Corners)\right]\right]$$

4.3 Comms Coverage Analysis Using Initial Signal Loss Estimations

Using initial signal loss estimations Comms was used in order to create coverage maps of the Sentinel Mine. This section covers the data discussed in Section 3.2. Coverage maps were created obtain a qualitatively understanding of how the model predicts coverage. Table 5 contains a summary of the initial signal loss estimations that were used for the following initial coverage maps.

Table 5: Initial Signal Loss Estimations

Loss	Initial Estimation
Broadcast (dB)	89
Multiplier	1.25
Non-Obstructed Clear (dB/100 ft)	5.9
Ventilation (dB/vent)	*Cinderblock/Metal*
	15
Beltway (dB/100 ft)	14
Corner (dB/90deg)	55

A broadcast signal was assumed to be 89 dB with a multiplier of 1.25 thus resulting in a total signal of 111 dB. Along non-obstructed clear entries it was assumed to have a standard loss of 5.9 dB per 100 feet traveled. A loss of 15 dB was estimated to occur through a stopping. Cinderblock and metal stoppings were categorized as having the same signal loss. A standard loss of 14 dB/100 feet traveled along the belt and a loss of 55 dB per 90 degree turn was assumed. The Figure 4.9 shows the communications network that was built using Comms.
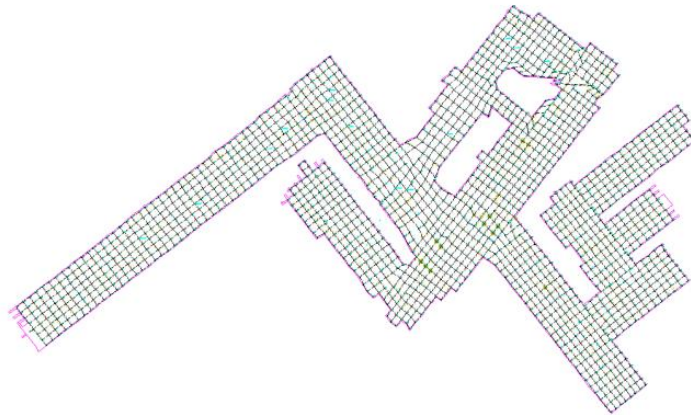
Figure 4.9: Sentinel Mine Communications Network

It is necessary to hand correct the communications network that Comms builds to correct areas that were not correctly interpolated by Comms. Figure 4.10 shows the hand corrected Sentinel communications network zoomed in. The pillars layer is turned off in Figure 4.10 to show the network more clearly.
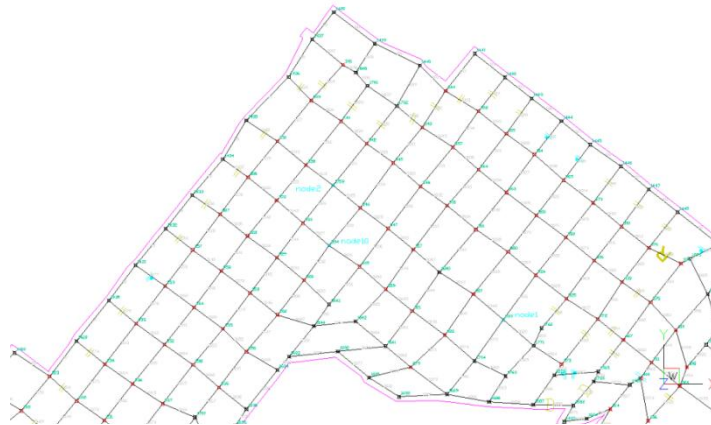
Figure 4.10: Hand Corrected Sentinel Communications Network

The initial communications network model contained 1,855 nodes and 3,392 links. The Draw Node's Communication Area option in Comms was used to create coverage maps after the communications network was solved using the initial signal loss estimations. Figure 4.11 and Figure 4.12 show the initial coverage prediction of L-3 FMN 1 and 13 in green.
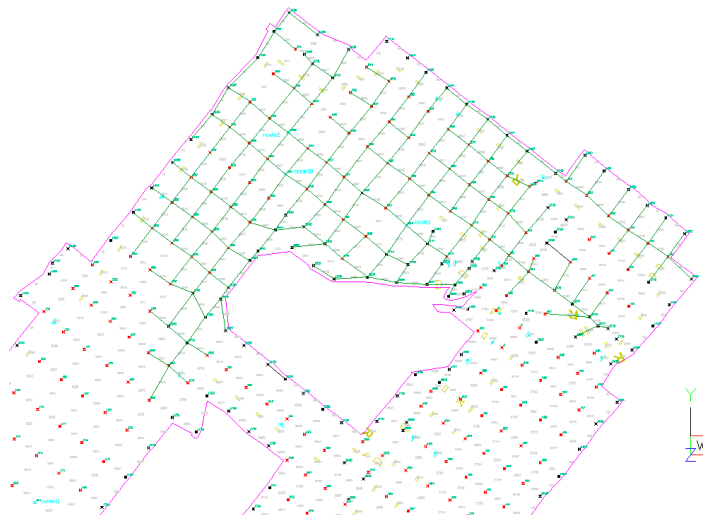
Figure 4.11: Comms Initial Coverage Prediction of L-3 FMN 1
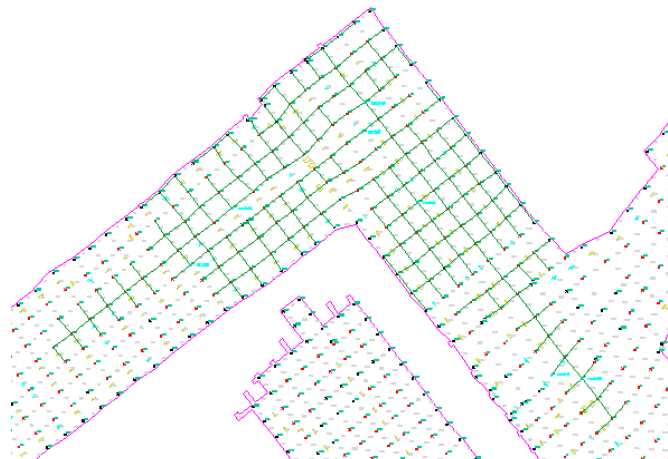
Figure 4.12: Comms Initial Coverage Prediction of L-3 FMN 13

Phase II consisted of rapid developments and improvements to the functionality of the communications and tracking system in terms of both hardware and software, which is believed to of increased the actual coverage performance of the system. There was limited data and signal loss parameters had not been accurately established quantitatively during Phase II. Due to lack of information available when initial FMN coverage maps were created, there is not a way that coverage maps can be validated. The optimistic initial mine coverage is shown in Figure 4.13.
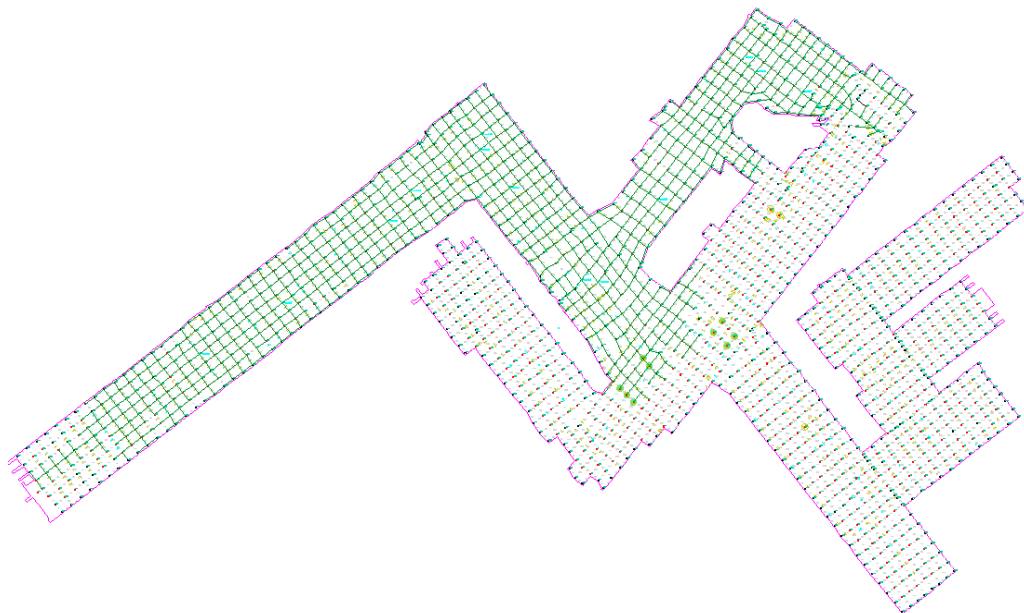
Figure 4.13: Optimistic Initial Sentinel Mine Coverage

4.4 Comms Initial Comparison to Mine Survey

Parts of the team field mine survey had been completed which allowed an initial comparison of the Comms predicted values. The following coverage maps were made in IntelliCAD using Comms to estimate the accuracy of initial signal loss parameters. Figure 4.14 shows the coverage predicted by Comms of L-3 FMN 10. The green lines indicate the links that would receive coverage with varying strength.
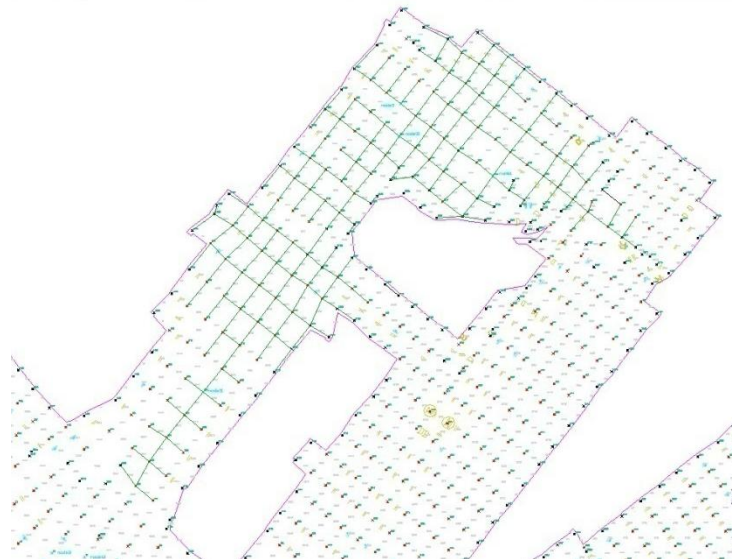
Figure 4.14: Comms Intellicad L-3 FMN 10 Coverage Map

Figure 4.15 shows the mean coverage map of IWT FMN ID FB03_4 which is located in the L-3 FMN 2 position. Figure 4.15's scale was adjusted so the coverage predicted by Comms could be directly compared.
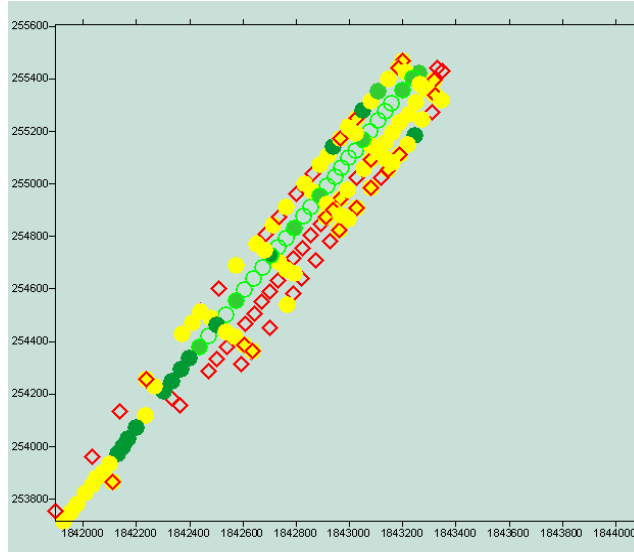
Figure 4.15: Scaled Mine Survey IWT FMN ID FB03_4 Mean Coverage Map

Figure 4.16 contains the Comms predicted coverage map of L-3 FMN 2.
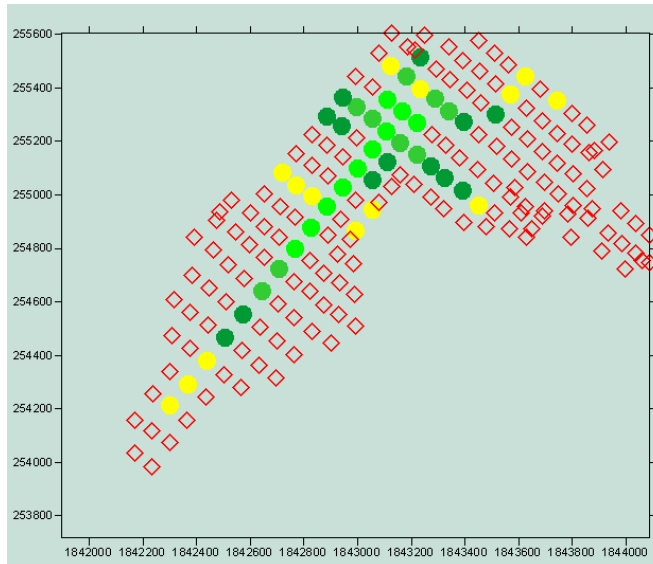
Figure 4.16: Scaled Comms Predicted Coverage Map – L-3 FMN 2

Figure 4.17 shows an active comparison of the mine survey and the Comms predicted coverage map. The Comms predicted coverage map legend is on the left and the mine survey data legend is on the right.
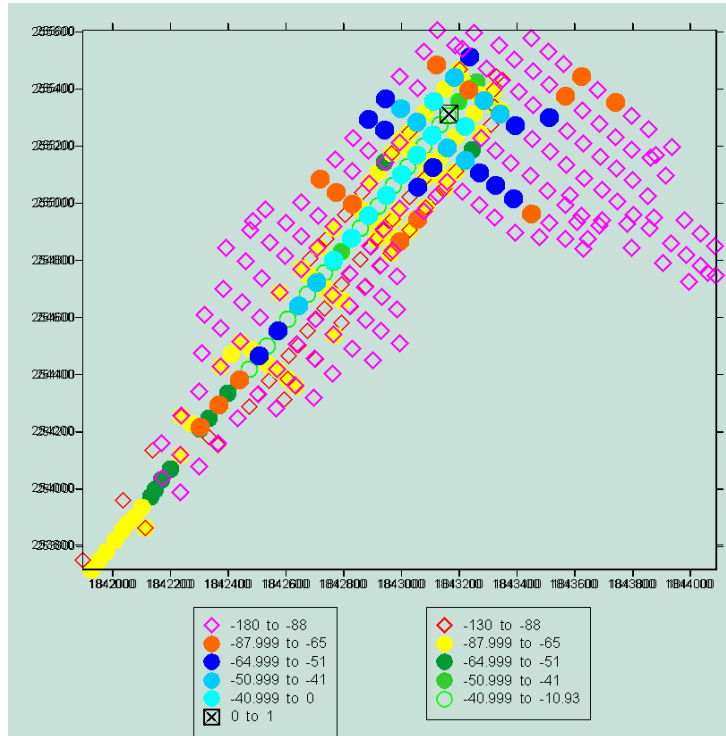
Figure 4.17: Active Comparison of Comms Predicted and Measured Data

Figure 4.17 shows that there are many similarities of the way the Comms predicted and the measured data signal strength behaves. Although, the active comparison concludes that the measured coverage area of the system is larger than the predicted Comms coverage area. It is also necessary to add extra resistances to links around FMN locations that do not have antennas pointing in those directions. This will account for directional antennas because Comms' solves for signal strength equally in every direction from the selected FMN position.

4.5 Adjusted Signal Loss Parameters Estimations

Signal loss estimations were then adjusted to extend the range of the predicted Comms coverage as discussed in Section 4.4. Table 6 contains the adjusted FMN signal loss estimations.

Table 6: Adjusted Fixed Mesh Node Signal Loss Estimations

Loss	Adjusted Estimation
Broadcast (dB)	89
Multiplier	1.25
Non-Obstructed Clear (dB/100 ft)	5
Ventilation (dB/vent)	*Cinderblock/Metal*
	11
Beltway (dB/belt link)	5
Corner (dB/90deg)	36

The broadcast signal was still assumed to be 89 dB with a multiplier of 1.25 thus resulting in a total signal of 111 dB. Along non-obstructed clear entries it was assumed to have a standard loss of 5 dB per 100 feet traveled. A loss of 11 dB was measured to occur through a stopping cinderblock stopping. A metal stopping was not classified but it is theorized that a metal stopping should reflect more signal than a cinderblock stopping. Each belt link in the Comms model was predicted to have a loss of 5 dB/per belt link traveled and a loss of 36 dB per 90 degree turn was measured for a corner. Elevation was still considered to be negligible due to no direct evidence of elevation caused signal loss. The Phase III Mine Tracking System document that was included with the June mine survey data from IWT indicates if antenna is not paired with another in the same entry default loss values of 0.03 dB/ft for clear tunnels and 0.05 dB/ft for belt tunnels are assumed. The signal assumed to leak from non-antenna direction(s) is considered to be approximately 10 dB or slightly less than the gain of the antenna.

4.6 Adjusted Signal Loss Theoretical Equations

The initial signal loss theoretical equations discussed in Section 3.4 have been modified to fit the adjusted model. The predicted path loss is equal to the sum of the resistances caused by the signal loss parameters due to Non-Obstructed Clear (NOC), Beltway (Belt), Stopping (Stopping), and Corner (Corner) losses. A beltway link is considered to be approximately 1 entry or crosscut. The following signal loss equations have been adjusted to fit the model discussed in Section 4.5.

$$Path\ Loss = \left[\sum Non\ Obstructed\ Clear\ Losses\right] + \left[\sum Beltway\ Losses\right]$$
$$+ \left[\sum Stopping\ Losses\right] + \left[\sum Corner\ Losses\right]$$

$$Path\ Loss = \left[\sum \left[NOC\ Loss\left(\frac{dB}{100ft}\right) \times (\#\ NOC\ ft)\right]\right]$$
$$+ \left[\sum \left[Belt\ Loss\left(\frac{dB}{Belt}\right) \times (\#\ Belt\ links)\right]\right]$$
$$+ \left[\sum \left[Stopping\ Loss\left(\frac{dB}{stopping}\right) \times (\#\ Stoppings)\right]\right]$$
$$+ \left[\sum \left[Corner\ Loss\left(\frac{dB}{90°}\right) \times (\#\ Corners)\right]\right]$$

The adjusted signal loss estimations are found in the follow equation and in Table 6 above. The equation below is the expanded equation from above with constant signal loss parameter values inputted.

$$Path\ Loss = \left[\sum \left[5\left(\frac{dB}{100ft}\right) \times (\#\ NOC\ ft)\right]\right] + \left[\sum \left[5\left(\frac{dB}{Belt}\right) \times (\#\ Belt\ links)\right]\right]$$
$$+ \left[\sum \left[11\left(\frac{dB}{stopping}\right) \times (\#\ Stoppings)\right]\right] + \left[\sum \left[36\left(\frac{dB}{90°}\right) \times (\#\ Corners)\right]\right]$$

4.7 Comms Predicted Survey of Sentinel Mine Survey Area

Further analysis of Comms was completed after signal loss parameter estimations had been adjusted. The mine survey data contains data that has a wide range of values based upon where the signal strength reading was specifically taken from. Figure 4.18 shows that data was measured multiple times within several feet of each other. Having multiple data points within a couple feet of each other could potentially cause problems when using Comms to predict the signal strength.
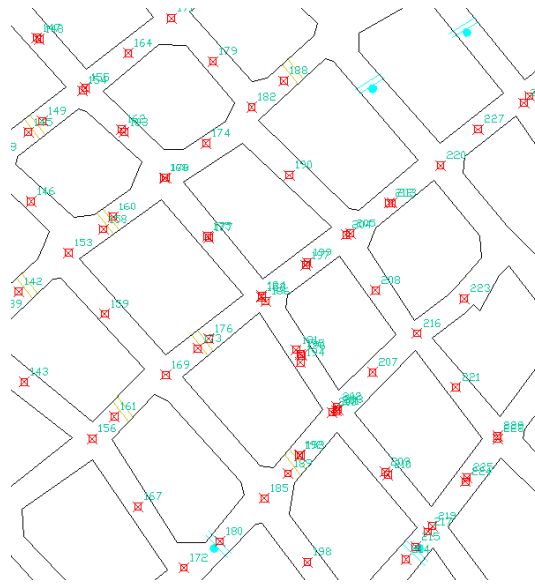
Figure 4.18: Original IWT Mine Survey Data Points

The mine survey test data was reduced in order to make this process or comparing the test data to predictions made by Comms. The original data contained 467 data points and contained 397 points after the 1st reduction of points. The reduced number of data points is shown in Figure 4.19. Figure 4.19 contains the same area as shown in Figure 4.18.
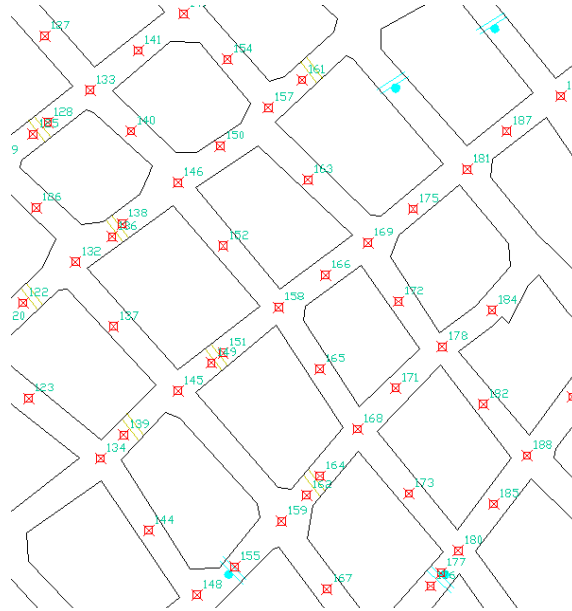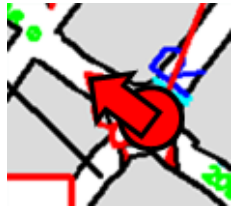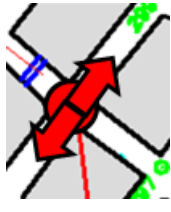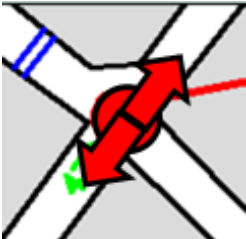
Figure 4.19: 1st Reduction - IWT Mine Survey

Further reductions of the nodes and links in the Comms model of the mine survey area were made in order to eliminate Comms from choosing paths other than the best route. Midpoints between intersections are removed as well to make the paths zigzag less due to the locations which data was sampled by the person walking in the mine. The second reduction of data points had 162 nodes and 253 links. The third reduction of data points has 161 nodes and 253 links. The communications network used to solve the 4th, 5th, and 6th tests contained 171 nodes and 274 links.

Table 7 shows an illustration of the FMN antenna configuration of the L-3 FMNs used in the team mine survey adapted from IWT, 2008. The arrows represent the directions which antennas are oriented in. A red arrow that is outlined in white and is labeled with an E indicates that the antenna's location has been extended by a coaxial cable and is not located directly next to the FMN. The antenna configuration is used to set resistances to non-antenna links that are connected to FMN broadcast points in the Comms model.

Table 7: L-3 FMN Antenna Configuration (adapted IWT, 2008)

FMN #1	FMN #2	FMN #10
FMN #11	FMN #3	FMN #12
FMN #13	FMN #5	FMN # 4

In Table 7, the coaxial cables running to the antennas on L-3 FMNs 3 and 5 were extended to the next entry. Phase III JDA Mine Tracking System RevA 29Aug2008 reports that the coaxial cable has "3.9 dB/100 ft loss at 900 MHz." The extended cable loss is considered to be nearly equal to if the antenna was located where the FMN was. Splitters were considered to be negligible due to the accuracy of the data and wide variety of data values. A resistance of 101 dB is set to links that are connected to the FMN on a non-antenna side. This is because approximately 10 dB of signal is leaked in non-antenna sides of the FMN due to the 11 dB gain of the antenna itself.

4.8 Comms Comparison with Mine Survey

Table 8 shows the connectivity between FMNs 12 to 3 and FMNs 13 to 5 reported in the mine survey. The average signal strength measured between FMN pairs do not reciprocate and the standard deviations of the pairs are reasonably close. The columns containing the connectivity between FMN 12 to 3 are indicated by an X and the columns containing the connectivity between FMN 13 to 5 are indicated by an O.

Table 8: June Mine Survey Comparable FMN Pairs

FMN to FMN	FMN 12 to FMN 3	FMN 3 to FMN 12	FMN 13 to FMN 5	FMN 5 to FMN 13
Average 1	-87.70	-64.73	-59.55	-80.37
Average 2	-	-63.37	-	-78.08
Std Dev 1	6.02	5.65	5.94	10.41
Std Dev 2	-	1.87	-	6.85
Maximum 1	-79.70	-58.80	-48.55	-70.77
Maximum 2	-	-61.24	-	-70.48
Minimum 1	-95.26	-72.51	-66.80	-90.31
Minimum 2	-	-64.77	-	-88.62
Comparable	X	X	O	O

The rest of the FMN connectivity data that was measured by during the mine survey is shown in Table 9.

Table 9: Mine Survey FMN Connectivity Values

FMN to FMN	FMN 10 to FMN 11	FMN 11 to FMN 12	FMN 4 to FMN 5	FMN 1 to FMN 2	FMN 1 to FMN 10	FMN 2 to FMN 10
Average 1	-69.15	-65.04	-49.81	-61.70	-83.79	-81.18
Average 2	-	-	-	-67.06	-83.89	-80.68
Std Dev 1	5.61	0.46	15.81	22.81	2.89	4.79
Std Dev 2	-	-	-	23.96	2.13	2.73
Maximum 1	-62.70	-64.52	-33.86	-30.09	-80.98	-75.72
Maximum 2	-	-	-	-37.39	-81.57	-76.81
Minimum 1	-75.76	-65.40	-70.33	-85.26	-88.94	-85.31
Minimum 2	-	-	-	-90.78	-86.62	-82.67
Comparable	-	-	-	-	-	-

Table 10 contains the signal loss estimations used during the 4th, 5th and 6th model and estimations validation tests.

Table 10: Signal Loss Estimations (4th, 5th, and 6th Tests)

Loss	4th Test		5th Test		6th Test	
Broadcast (dB)	89		89		89	
Multiplier	1.25		1.25		1.25	
Non-Obstructed Clear (dB/100 ft)	5		6		5	
Ventilation (dB/vent)	*Cinder*	*Metal*	*Cinder*	*Metal*	*Cinder*	*Metal*
	11	22	11	16	11	16
Beltway (dB/belt)	5		6		7	
Corner (dB/90deg)	36		36		36	
Power Center (dB/center)	?		6		6	

The final data table which is found in Appendix A shows many interesting results. The signal loss estimations used in the 6th test most accurately predicts the signal losses encountered given our parameters. The reason the values between the L-3 FMN 12 to 3 and FMN 13 to 5 pairs is unknown. Different signal strengths of the broadcast were not noted in any of the documentation. It was taken that the lower values seemed more accurate given the conditions observed and predicted by Comms. Comms predicts a 8.44 dB (15.16%) difference and -2.33 dB (3.84%) (negative differences describe when the Comms predicted signal strength is the higher of the pair) between L-3 FMN 3 to 12 and FMN 13 to 5 respectively.

The distance between L-3 FMN 10 to 11 is a long straight dip that is very similar to Figure 3.20 in the Initial Signal Loss Parameters Estimations, Elevation Loss section. Comms predicted a -1.61 dB between L-3 FMN 10 to 11. Between L-3 FMN 11 to 12, Comms predicted a signal difference of 37.90. It appears that in that area a bend or dog-leg in the mine causes a signal loss greater than anticipated.

Along the belt between L-3 FMN 4 to 5, Comms predicted a signal strength difference of 4 dB (0.25%). Signal losses calculated by Comms do not match the measured values around L-3 FMN 1. The elevation is less than an entry over from the elevator shaft which may cause it to behave in a non-standard means. The area surrounding L-3 FMN 1 is also a high traffic area where supplies and vehicles could cause unexpected losses. L-3 FMN 2 to 10 are on opposite corners of a pillar from each other and the Comms predicted signal value is significantly lower than the measured value.

4.9 Final Signal Loss Theoretical Equations and Estimations

The adjusted signal loss theoretical equations discussed in Section 4.6 have been modified to fit the adjusted model. The predicted path loss is equal to the sum of the resistances caused by the signal loss parameters due to Non-Obstructed Clear (NOC), Beltway (Belt), Stopping - Cinderblock (SC), Stopping – Metal (SM), Corner (Corner), power center (PC), and unknown losses. A beltway link is considered to be approximately 1 entry or crosscut. The stopping piece of the equation has been modified to take into consideration estimated losses due to metal stoppings and power centers. The values used in the final signal loss theoretical equation are listed under the 6th test in Table 10. Unknown losses are the losses that make up the difference between the measured and predicted Comms values.

$$
\begin{aligned}
Path\ Loss = {} & \left[\sum Non\ Obstructed\ Clear\ Losses\right] + \left[\sum Beltway\ Losses\right] \\
& + \left[\sum Cinderblock\ Stopping\ Losses\right] + \left[\sum Metal\ Stopping\ Losses\right] \\
& + \left[\sum Corner\ Losses\right] + \left[\sum Power\ Center\ Losses\right] \\
& + \left[\sum Unknown\ Losses\right]
\end{aligned}
$$

The following equation is the expanded form of the equation above.

$$Path\ Loss = \left[\sum\left[NOC\ Loss\left(\frac{dB}{100ft}\right)\times(\#\ NOC\ ft)\right]\right]$$

$$+\left[\sum\left[Belt\ Loss\left(\frac{dB}{Belt}\right)\times(\#\ Belt\ links)\right]\right]$$

$$+\left[\sum\left[Cinderblock\ Stopping\ Loss\left(\frac{dB}{stopping}\right)\times(\#\ Stoppings)\right]\right]$$

$$+\left[\sum\left[Metal\ Stopping\ Loss\left(\frac{dB}{stopping}\right)\times(\#\ Stoppings)\right]\right]$$

$$+\left[\sum\left[Corner\ Loss\left(\frac{dB}{90°}\right)\times(\#\ Corners)\right]\right]$$

$$+\left[\sum\left[Power\ Center\ Loss\left(\frac{dB}{Power\ Center}\right)\times(\#\ Power\ Centers)\right]\right]$$

$$+\left[\sum[Unknown\ Losses\ (dB)]\right]$$

Table 11 below shows the final signal loss parameter estimations. Table 11 describes the values used in the 6th test which are the final signal loss parameter estimations.

Table 11: Final Signal Loss Parameter Estimations

Loss	6th Test	
Broadcast (dB)	89	
Multiplier	1.25	
Non-Obstructed Clear (dB/100 ft)	5	
Ventilation (dB/vent)	Cinder	Metal
	11	16
Beltway (dB/belt)	7	
Corner (dB/90deg)	36	
Power Center (dB/center)	6	

The equation below is an expanded form of the equation above with the final constant numerical signal loss estimation values found in Table 11.

$$Path\ Loss = \left[\sum\left[5\left(\frac{dB}{100ft}\right)\times(\#\ NOC\ ft)\right]\right] + \left[\sum\left[7\left(\frac{dB}{Belt}\right)\times(\#\ Belt\ links)\right]\right]$$
$$+ \left[\sum\left[11\left(\frac{dB}{stopping}\right)\times(\#\ SC)\right]\right] + \left[\sum\left[16\left(\frac{dB}{stopping}\right)\times(\#\ MS)\right]\right]$$
$$+ \left[\sum\left[36\left(\frac{dB}{90°}\right)\times(\#\ Corners)\right]\right] + \left[\sum\left[6\left(\frac{dB}{Power\ Center}\right)\times(\#\ PC)\right]\right]$$
$$+ \left[\sum[Unknown\ Losses\ (dB)]\right]$$

There are unexpected interferences in areas of the mine such as around the elevator shaft, dog-leg or bends in entries, and reciprocating signal strengths between FMN pairs. The connectivity between L-3 FMN pairs show the different design parameters of Non-Obstructed Clear (FMN 10 to 11), Beltway (FMN 4 to 5), Stopping (FMN 13 to 5), and corner loss is shown in (FMN 3 to 12 and FMN 13 to 5). A percent difference of 15 or less proves that each of the design parameters has been validated as discussed above in Section 4.8. The signal loss estimates caused by metal stoppings and power centers have been roughly estimated and have not been measured.

Chapter 5 : CONCLUSIONS AND RECOMMENDATIONS

Since the enactment of the MINER Act in 2006, there has been a need for the research and modeling of the propagation of wireless communications in underground coal mines. A mine is a dynamic operation greatly determined by geology, mining conditions, and unforeseen circumstances that yield a unique working environment in every mine. It is important to evaluate and develop a generalized solution applicable to a broad spectrum of cases. For this reason, general categories of tunnel profiles are created to establish a model that will account for major signal losses that occur. General signal loss parameters may be applied to other mines in order to create pre-installation network communications plans as well as pinpoint unexpected interferences. Comparing predicted theoretical losses and measured signal strengths will allow future signal loss parameters to be developed and quantified.

Research and field work on this project was based on the L-3 Accolade underground wireless mesh communications and tracking system. Wireless mesh communications and tracking systems allow a radio signal to propagate through multiple openings providing a redundant and survivable means of communication. Research and field work provided challenges in quantifying signal loss parameters accurately. The signal strength at any point in the mine is subject to various circumstances that may not always be accounted for.

The design criteria utilizes Comms to predict the signal strength of broadcast fixed mesh nodes at given intersections. The modeling of directional antennas can be accomplished by setting resistances equal to the signal that would leak out of the non-directional side of the antenna. This method requires hand correction and adjustment of calculations made by Comms. The model that has been established in Section 4.8 is valid within the given design parameters. The design parameters Non-Obstructed Clear, Beltway, Stopping, and Corner estimates appear to be accurate and predict signal strength with a percent difference of 16 or less from actual measured data in the mine. It is unclear which interferences cause the additional signal losses seen in several of the FMN to FMN connectivity pairs.

Further investigation of several areas of the mine is needed to establish what additional signal losses are occurring between FMN pairs. Testing to calculate the signal loss caused by a bend or a dog-leg and how the angle of the bend affects the signal loss encountered. The losses

due to metal stoppings and power centers need to be quantified to more accurately predict signal strength in areas with these obstacles. Additional design parameters such as the sizes of openings, the differences between different types of stoppings, elevation effects, roof fall areas, and many other various parameters need to be created in order to more effectively model a mine. It is anticipated that signal strength may fluctuate during the changes in mining activities in the mine. A communications and tracking system must be dynamic and changing to account for current impacts and signal interferences due to a mine is a dynamic operation that changes day to day.

The research presented has provided insight to increase the understanding of the propagation of wireless communications in underground coal mines. Generalized signal loss parameters enable generalized solutions to be applied to a broad spectrum of dynamic operations. The research and modeling of wireless communications in underground coal mines improves the efficiency of the communications and tracking system during daily operational use and for emergency and rescue coordination. The integration of wireless communications and tracking systems will overall increase the health, safety, and production standards in underground coal mines.

This research developed a new methodology capable of building and solving mine communications networks in underground coal mines. The team mine survey provided a learning experience in several areas including the testing of survey equipment, organizing and conducting the survey, and the method in which the survey was conducted. The final signal loss equations, although developed from the limited data retrieved during the team mine survey, provide a powerful tool for evaluating signal losses. Signal loss estimations and equations can be further developed as more data becomes available. At this stage, final signal loss equations and parameters should be used as estimations of ideal signal loss parameters and a benchmark for future work.

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APPENDIX A

Final Data Table

Comms Predicted vs. Measured Data

A 1: Final Data Table

FMN to FMN	FMN 12 To FMN 3	FMN 3 to FMN 12	FMN 13 To FMN 5	FMN 5 to FMN 13	FMN 10 to FMN 11	FMN 11 to FMN 12	FMN 4 to FMN 5	FMN 1 to FMN 2	FMN 1 to FMN 10	FMN 2 to FMN 10
Average 1	-87.7	-64.73	-59.55	-80.37	-69.15	-65.04	-49.81	-61.7	-83.79	-81.18
Average 2	-	-63.37	-	-78.08	-	-	-	-67.06	-83.89	-80.68
Standard Dev 1	6.02	5.65	5.94	10.41	5.61	0.46	15.81	22.81	2.89	4.79
Standard Dev 2	-	1.87	-	6.85	-	-	-	23.96	2.13	2.73
Maximum 1	-79.7	-58.8	-48.55	-70.77	-62.7	-64.52	-33.86	-30.09	-80.98	-75.72
Maximum 2	-	-61.24	-	-70.48	-	-	-	-37.39	-81.57	-76.81
Minimum 1	-95.26	-72.51	-66.8	-90.31	-75.76	-65.4	-70.33	-85.26	-88.94	-85.31
Minimum 2	-	-64.77	-	-88.62	-	-	-	-90.78	-86.62	-82.67
Comparable	X	X	O	O	-	-	-	-	-	-
4th Verification	50.61	50.61	67.89	64.11	70.76	-	37.81	-	59.82	43.76
Difference (dB)	37.08	13.44	-8.33	15.12	-1.61	65.04	12	64.38	24.02	37.17
Num of Standard Devs	6.16	3.57	-1.4	1.45	-0.29	-	0.76	-	8.3	7.76
5th Verification	52.52	52.52	55.5	59.94	84.91	145.67	45.37	-	-	-
Difference (dB)	35.17	11.53	4.06	19.39	-15.76	-80.62	4.44	-	-	-
Num of Standard Devs	5.84	3.06	0.68	1.86	2.81	174.1	0.28			
6th Verification	55.61	55.61	61.89	58.11	70.76	27.14	45.81	21.78	59.82	43.76
Difference (dB)	32.08	8.44	-2.33	21.12	-1.61	37.9	4	42.6	24.02	37.17
Num of Standard Devs	5.33	2.24	-0.39	2.03	-0.29	81.84	0.25	1.87	8.3	7.76
Percent Difference (%)	44.78	15.16	3.84	32.15	2.3	82.22	8.37	95.64	33.38	59.9