EVALUATION AND SIMULATION OF WIRELESS COMMUNICATION AND TRACKING IN UNDERGROUND MINING APPLICATIONS

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Mining Engineering

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April 04, 2013

Blacksburg, VA

Keywords: mine design, wireless communication, wireless tracking, computer simulation, regulations

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ABSTRACT

In an underground coal mine, the measure of a communication system is the coverage area it can provide at a quality that ensures a miner can communicate with other miners in and out of the mine during normal and emergency operations. The coverage area of a wireless mesh communication system can be calculated using the tool, COMMs, developed and discussed in this document. This tool can also be used to explore emergency operations, or operations where the mesh infrastructure is degraded or destroyed. Most often, the communication system is also capable of transmitting data from sensors including a set of sensors, such as Radio Frequency Identification readers, described as the tracking system.

An underground tracking system is described as a system that calculates a location in a useful coordinate when a tracked device is underground. The tracked device is a representative of a miner, group of miners or equipment, depending on state law and the mine's deployment. The actual location of the miner or equipment being tracked is the Ground Truth Position (GTP) and the tracking system's representation in the same coordinate system at the same time is the Tracking System Position (TSP). In an excellent tracking system the actual location, GTP, and TSP will be very close to each other. This work also develops a set of calculated metrics that describe tracking system performance.

The Tracking Coverage Area metric refers to the area within the mine that the tracking system either actively measures a tracked device's location or infers it based on the spatial limitations of the mine and information other than active measurements. Average Accuracy is the arithmetic mean of a set of distances from the TSP to the GTP associated with a tracking system. The Average Cluster Radius metric is the average distance a set of TSPs are from their center point, which is determined by the average location of a TSP relative to the GTP. A 90% Confidence Distance is the distance from a

tracked device's actual location (i.e., GTP) that is greater than 90% of the collected distance from GTP to TSP magnitudes ("90th percentile").

Regulatory guidelines in the United States currently define different tracking qualities at locations in the mine. These can be classified in location categories of Working Face, Strategic Areas, and Escapeways and Travel-ways.

All direct paths via escapeway or travel-way from the mine portal to the working face should be simplified into a one-dimensional path that is subdivided by the three regulatory categories. Each of these subdivisions should be described using the metrics defined above.

These metrics can be predicted using COMMs for a tracking system that is utilizing an underground wireless mesh system that uses Received Signal Strength Indicators (RSSI) to calculate the TSP. Because the tracking system's algorithm to convert RSSI into a TSP is proprietary to the manufacturer, in order to develop predictions the engineer must collaborate with the manufacturer. In this document, the predictions and calculations were obtained in conjunction with the manufacturer and proved to be accurate describing the tracking system that was designed and tested.

DEDICATION

This dissertation is dedicated to my father Robert E. Schafrik, Ph.D P.E., who taught me that a life of learning and achieving is a life well spent.

ACKNOWLEDGMENTS

I think that it is impossible to thank enough people enough times for their contributions to so many years of work. I sincerely thank Kray Luxbacher for her guidance through the process and excellent manner of advising a part-time student like me. Her contributions to my work have been invaluable. I look forward to our future years of collaboration.

For almost 15 years Michael Karmis has been directing my work and collaborating on projects, papers, and just about anything that comes down the pike. Without his support, not least of which was funding my graduate studies, this work could not have been done. I have thoroughly enjoyed my time working for him.

Zacharias Agioutantis has been a longtime collaborator on many different projects that span the breadth and depth of my knowledge, but not his.

The entire faculty of the Mining and Mineral Engineering Department at Virginia Tech has contributed to my work. Erik Westman and Gerry Luttrell have been excellent guides along the path and extremely helpful.

My good friend Steven Richards has been a great resource through the course of this work. He has also been very encouraging and excited to see this work finished. In many ways, he is the audience for this work.

Our work in the underground coal communication and tracking field has involved several different companies in several different industries. Many of which would prefer to remain anonymous, for those of you who know who you are I thank you for your help and lending of knowledge and experience.

My family, especially Tammie Frazier, have been the largest supporters of this work on a daily basis. I could not have completed it without their love and support.

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LIST OF ACRONYMS

Acronym	Description
90%CD	90% Confidence Distance
AA	Average Accuracy
ACR	Average Cluster Radius
AEV	Average Error Vector
A-GPS	Assisted-Global Positioning System
AOA	Angle of Arrival
BCN	Beacon
CDMA	Code Division Multiple Access
COMMs	Software developed at Virginia Tech for Signal Strength calculations
CSV	Comma Separated Value
E-OTD	Enhanced-Observed Time Difference
ERP	Emergency Response Plan
EV	Error Vector
EW	Escapeway
FCC	Federal Communications Commission
FM	Frequency Modulation
FMN	Fixed Mesh Node
GB	Gigabyte
GDOP	Geometrical Dilution of Precision
GHz	Gigahertz
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite Systems
GPPS	Gaussian Process Positioning System
GPS	Global Positioning System
GSM	Global Systems for Mobile Communications
GTP	Ground Truth Position
GTPE	Ground Truth Position Estimate
GWN	Gateway Node
HPC	High Performance Computing
IA	Instantaneous Accuracy
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IWT	Innovative Wireless Technologies
KHz	Kilohertz
LASER	Light Amplification by Stimulated Emission of Radiation

MB	Megabyte
MF	Medium Frequency
MINER Act	Mine Improvement and New Emergency Response Act
MS	Mobile Station
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
OTD	Observed Time Difference
OTDOA	Observed Time Difference of Arrival
PPL	Program Policy Letter
RADAR	Radio Detection and Ranging
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SDA	Standard Deviation of Accuracy
SONAR	Sound Navigation and Ranging
SSDOA	Signal Strength Difference on Arrival
TCA	Tracking Coverage Area
TDOA	Time Difference of Arrival
TNEA	Thermal Noise Equivalent Acceleration
TOA	Time of Arrival
TSP	Tracking System Position
TSPE	Tracking System Position Estimate
TTE	Through-the-Earth
VCCER	Virginia Center for Coal and Energy Research
VT	Virginia Tech
VTIP	Virginia Tech Intellectual Properties
WLAN	Wireless Local Area Networks
X% CD	X% Confidence Distance

PREFACE

This research effort comprises five major tasks as summarized below. These tasks are addressed in a set of scholarly works which are either published or are being sought for publication. This document is organized in a fashion to first give background in communication and tracking systems used in underground coal mining and the challenges that confront assessment of these systems. The compendium addresses the five tasks stated. Simulation tools developed by the author of a particular and popular technology deployed for communication and tracking systems is discussed, along withhow they can be used by the mine designer.

Task 1. Development of a Tracking System Evaluation Methodology and Performance Baseline

The main objectives for Task 1 are:

a) To develop an engineering description of methods and procedures that support a general framework for evaluating the performance of personnel tracking systems in underground mines.

b) To define a "baseline tracking system" as a test subject for exercising and applying the metrics proposed.

Task 2. Simulation of Underground Communication and Tracking Systems

The main objectives for Task 2 are:

a) To develop simulation software capable of predicting and optimizing wireless mesh networks.

b) To apply simulation software for evaluating tracking systems and performance predictions.

Task 3. Development of Test Plan

The main objective for Task 3 is:

a) To develop of testing layouts for performing data measurements that include static (where mining has been completed) and dynamic (active mining section) tracking system tests.

Task 4. Analysis of Test Data and Comparison with Analytical Results

The main objectives for Task 4 are:

a) To analyze measured data to test the validity of simulation methods and refine the simulation procedures.

b) To confirm applicability and utility of the developed performance metrics.

Task 5. Conclusions and Recommendations

The main objective for Task 5 is:

a) To recommend a protocol for the uniform evaluation and compliance of communication and tracking systems.

GEOLOCATION FOR UNDERGROUND COAL MINING APPLICATIONS: CLASSIFICATION OF SYSTEMS AND LIMITATIONS[1]

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Introduction

The ability to track miners and communicate with them while they work in underground coal mines is important during normal daily operations, and critical in emergency conditions. As was evident during recent incidents at underground coal mines worldwide, communication with miners and the knowledge of their location is of great importance for rescue efforts and the preservation of life.

Numerous technologies have been developed, adapted, and deployed to meet tracking requirements of the Mine Improvement and New Emergency Response (MINER) Act. Evaluating the performance of these systems has proven to be difficult for mine operators, system manufacturers, and regulatory agencies. The MINER Act of 2006 requires operators to improve accident preparedness by developing an emergency response plan specific to each mine. With the recent implementation of the provisions of the MINER Act of 2006, all underground coal mines in the United States are subject to the mandates of legislation concerning communication and tracking system installation.

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[1] This paper is intended to be submitted for publication. Portions of this work are modified from the Analytical Methodology Report For NIOSH BAA 2010-N-12081 "Development of a Uniform Methodology for Evaluating Coal Mine Tracking Systems"
This manuscript was organized, directed, and researched by Steven Schafrik. Several sections, including (Published Classifications of Tracking Systems) were authored by Carl Dietrich. Cary Harwood provided limited editorial input.

As of June 2011, 203 new or revised tracking and/or communication systems had been approved by the Mine Safety and Health Administration (MSHA), with nearly 50 other systems or revisions in the approval process (MSHA, 2011). At that time, the available approved systems for underground coal mine use included these types:

- Leaky Feeder Communication Systems
- Fixed Node-Based Communications and/or Tracking Systems
- Wireless Node-Based Communications and/or Tracking Systems
- Medium Frequency (MF) Communication Systems
- Communication System Peripherals

Other types of tracking systems have since been developed and some manufacturers are seeking approval for use in this application. Some of the new products include Through-the-Earth (TTE) systems and various radio frequency (RF) adaptations. New technologies that are currently being developed and deployed in other industrial applications should also be considered, including acoustical, optical, inertial, and hybrid technologies.

To date, no uniform method has been employed in the industry to effectively compare and evaluate the performance of installed systems. Neither industry operators nor regulatory agencies can accurately assess the capabilities of installed systems in the continuously changing mine environment. There is need for a uniform evaluation method that provides the ability to assess how different systems and technologies perform in various mining applications, and whether they can satisfy the regulatory requirements.

Background

Systems that track the locations of people and equipment use a variety of geolocation methods. Underground coal mine tracking systems can only use a subset of the common methods, given the physical constraints. These constraints include inaccessibility to GPS satellites, signal blockage by coal and rock, rugged environment, explosive potential, and equipment permissibility.

In this section, the literature related to communication and tracking methods is reviewed to provide a basic background for the evaluation of underground coal mine tracking systems. Geolocation systems are categorized by application and location techniques. This section also

discusses the physical phenomena and parameters that affect reliability of communications and location.

Communication Systems

The following sections describe the communication and tracking technologies that meet MINER Act requirements. These classifications are consistent with the classification system that is used by MSHA.

Through-the-Earth Technologies

Through-the-Earth communications are achieved by using Extremely Low Frequency radio waves. A simple diagram of an example TTE system is shown in Figure 2. The first TTE communications were established at 100 and 350 kHz using a horizontal antenna for broadcast and loop antennas to receive. The first successful system was developed in South Africa (Pittman et. al., 1985).

Many studies were carried out, funded by the U.S. Bureau of Mines, after several mining disasters. These studies assumed that miners would be trapped underground and their rescuers would be above ground. The TTE system could then be used to locate the miners underground. Unfortunately, none of these studies produced satisfactory results. Westinghouse Georesearch Laboratory created a prototype locating system (Pittman et. al., 1985). It included six transmitters and one receiver. The system was designed to work in a deep coal mine with relatively high conductivity. The system was able to work at 900-2,900 Hz (Durkin, 1984).
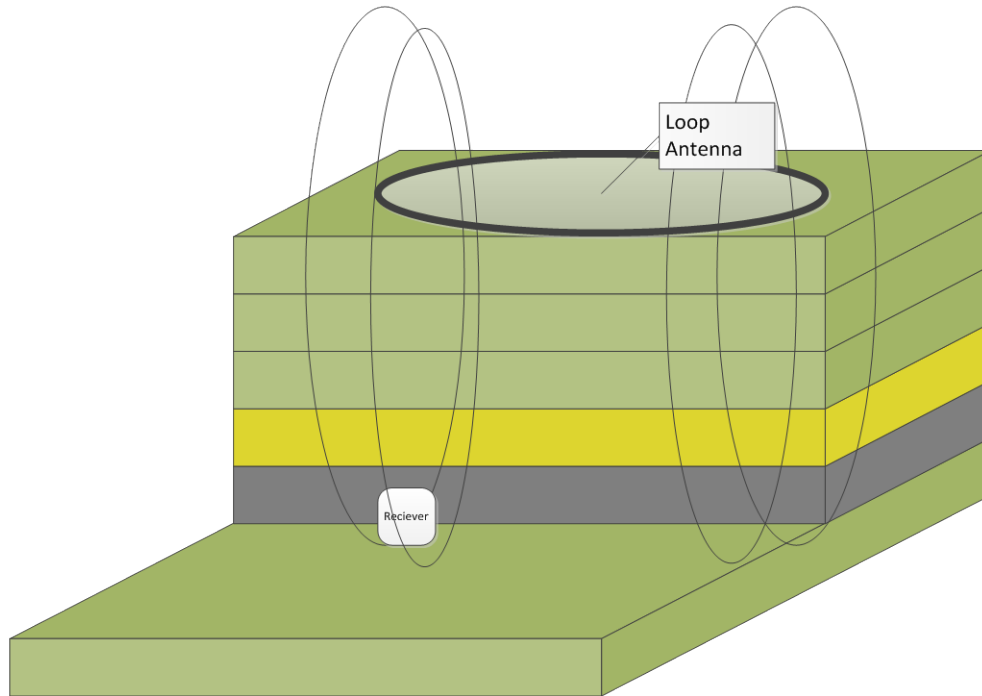
Figure 1 - Example Through-The-Earth System Diagram

One-way wireless communication had been available in the form of the PED system for over a decade at the time of the promulgation of the MINER Act, and this system is widely regarded as saving lives in the Willow Creek explosion, July 2000 (MSHA, 2003). However, the system is not MINER Act Compliant, because it is one way text communication only.

A two-way TTE system is the only system type that MSHA considers the closest to meeting the requirement for "wireless" communications under the MINER Act. This is because MSHA defines "wireless" as "no vulnerable wires in the mine" and TTE systems almost meet this requirement by using minimal infrastructure underground to complete the two-way communication (MSHA, 2009b). However, the MINER Act also requires the wireless communications to be available to all miners, and no such system exists that meet both requirements. There are systems such as the Lockheed Martin Magna-Link that approximate the fully wireless requirement. However, this system is a large antenna on the surface with a large pallet transported underground and provides the communications at that specific location, not coverage of all the escapeways and critical areas as required by current regulations. This system provides real time text, but voice communications is limited to one voice channel on a delayed delivery basis. As such, it does not have sufficient voice channels or data throughput to support

day to day operations in a modern day coal mine and is intended for emergency communications only, not for daily operations.

Leaky Feeder Communications

Leaky feeder systems are coaxial cables that are able to emit (i.e. leak) and receive (i.e. feed) radio signals. The cable is specially designed for the particular application. Because the signal travelling along the cable is lost to radiation, amplifiers are required at regular intervals to maintain the signal strength. The systems used in underground mines typically work on or about 150 MHz and 450MHz but operate as high as 900MHz or 1.8GHz for other applications.

The communication signal strength that is available in these systems will be highest at the amplifier or signal source and will steadily drop off along the length of the cable. This is due to the signal leaking out and attenuation in the cable. This system is diagrammed in Figure 2.
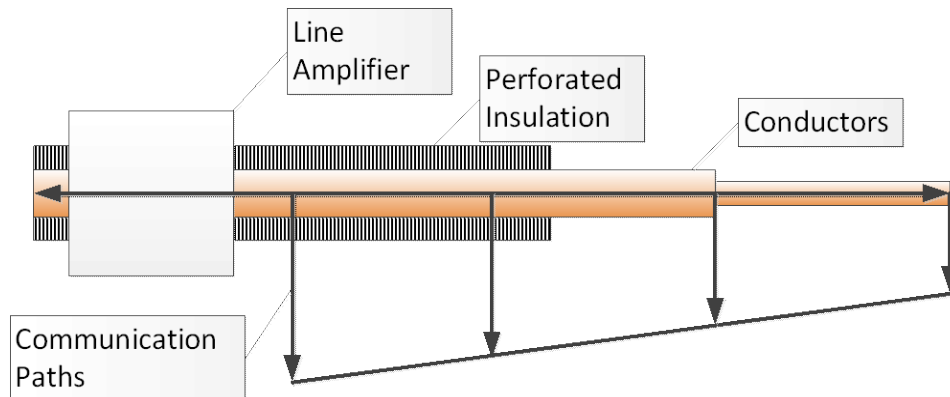
Figure 2 - Leaky Feeder System Diagram

As a system, Leaky Feeders are simple to design, however installation may be challenging. The most notable challenge is cumulative noise and system balance. Also, several systems are available which are not permissible but may be used away from the working face. For a place in a coal mine where communications are desired, a leaky cable must be in the room or within sight. The rule of thumb is the signal will be acceptable for communications within 150-250 ft. from the cable. A simple example layout of this system type is shown in Figure 3.
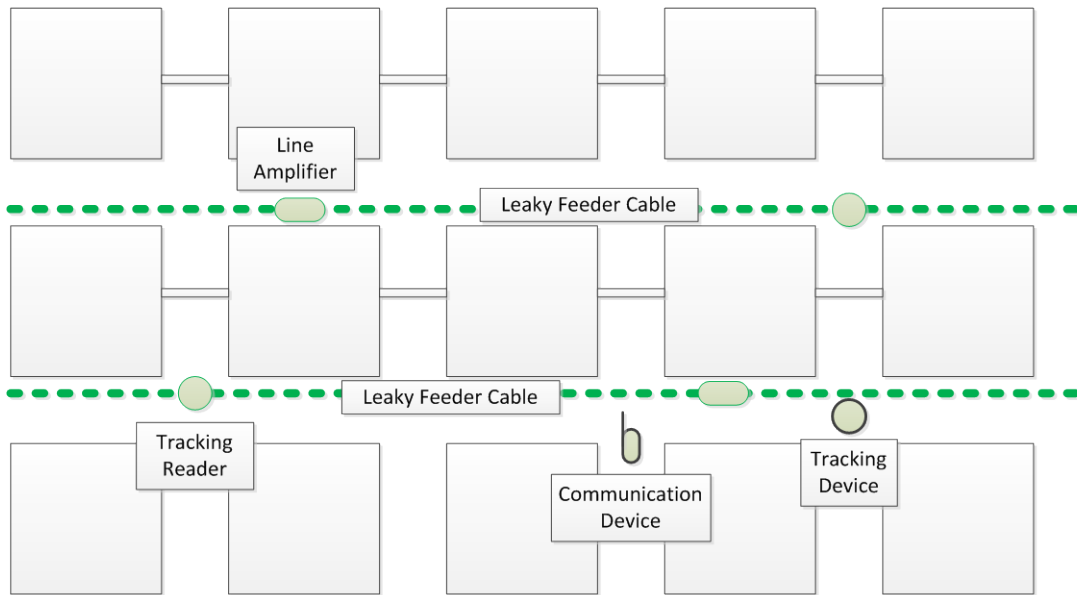
Figure 3 - Example Leaky Feeder Layout

Mesh Communications

Mesh systems are considerably more complicated than leaky feeder systems. These systems consist of nodes, or access points. The nodes interconnect by wireless signal, illustrated in Figure 4, or by wired connection, illustrated in Figure 5. Devices used to communicate will connect to the nearest node, or multiple nodes, to access the network services. Interconnection between nodes is referred to as backhaul communications. In a node system redundant communication is necessary; this provides both reliability and a need for backhaul capacity. Many of the mesh voice and text devices are able to extend the mesh network as well as provide service to the user. Mesh systems classified as "wireless nodes" by MSHA, most closely satisfy the intention of installing wireless communication systems in underground coal mines. This is because they require the least amount of wired infrastructure to be installed underground while still meeting the two-way voice, text, and location requirements. Mesh technologies are widely used in other communication applications and many of the mine communication systems are adaptations from other industries. Mesh communication systems are installed and used in approximately 1/3 of the underground mines across the country.
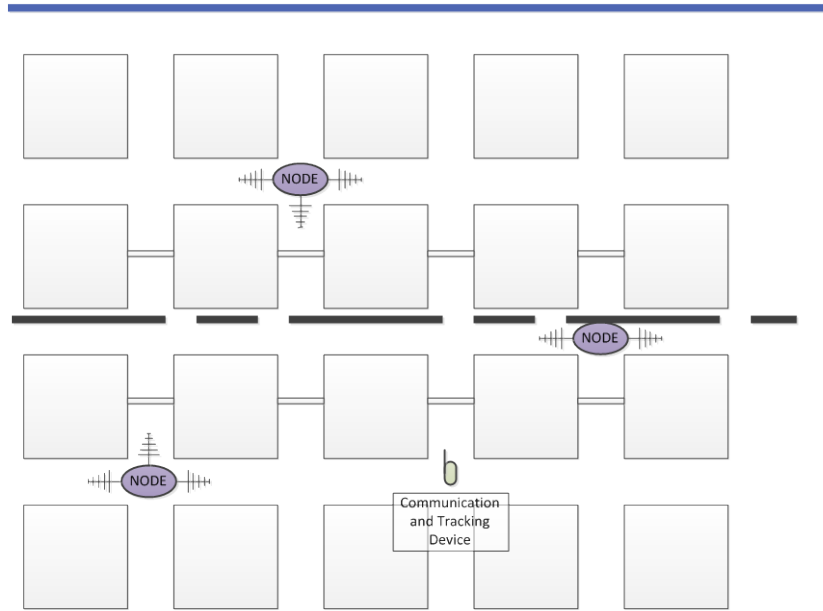
Figure 4 - Example Wireless Node System
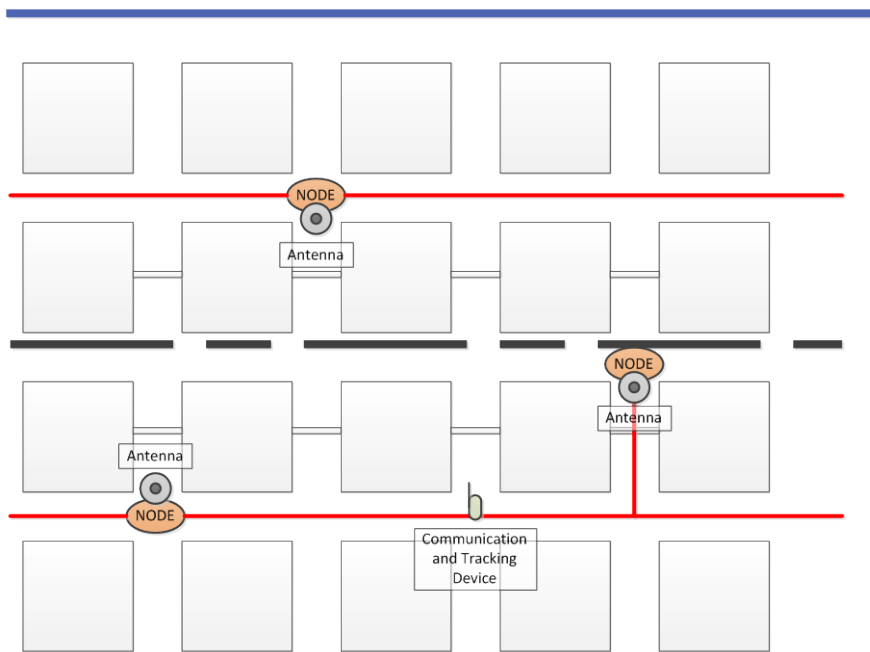
Figure 5 - Example Wired Node System

<u>**Categories of Geolocation and Tracking Systems**</u>

Geolocation systems, systems that locate a device relative to a geodetic landmark, can be classified by application, underlying technology, location technique or algorithm, or other

characteristics. Although terminology is not standardized in the relevant literature, an effort has been made in this report to use industry-accepted definitions, while taking into consideration the specific application to underground coal mines. Tracking systems are use synonymously but are relative to an arbitrary landmark, not necessarily a geodetic landmark.

Generally, the two main characteristics of immediate interest to users are the application or physical environment and the underlying technology that enables the system to operate.

Physical Operating Environment

The physical operating environment refers to the type of location in which a system will operate. The environment narrows the range of technology options (e.g., signals from satellites are restricted in indoor or underwater environments), setting the stage for selection of the tracking system. For purposes of classifying location systems, physical environments can be described in terms of contrasting categories such as the following:

- Outdoor/indoor
- Subsurface (underground or underwater)/surface/airborne/orbital
- Land/water
- Urban/suburban/rural
- Flat/rolling/mountainous terrain
- Sparse to thick vegetation

This study is concerned with underground mines, which fall into the land and subsurface category, while the ground above and around the mine could be described in terms of other categories listed above.

Underlying Measurement Technology

The underlying measurement technology must be appropriate to the environment (e.g., acoustic signals are not well suited to airborne applications, but are well suited to underwater applications and can also be used underground). For example, in the United States radio frequency technologies are subject to Federal Communications Commission (FCC) regulations, while other regulations apply to the other technologies. A list of underlying technologies that could potentially be used in a positioning or tracking application is presented below:

- Mechanical
- Radio Frequency

- Acoustic

- Optical

- Inertial

- Hybrid

Mechanical systems involve direct measurement of distance traveled or location. Radio frequency, acoustic, and optical systems all involve transmission and reception of energy through some medium or channel, and can be used to provide timing or directional information. Inertial systems use dead reckoning techniques, in which accurate velocity and bearing information are obtained by using inertial measurement units (IMUs) that typically contain accelerometers, magnetometers, and gyroscopes. Hybrid systems integrate two or more technologies to achieve improved reliability or accuracy for the specific application.

Example Technologies

Many types of positioning systems can be implemented using the technologies listed above. Mechanical measurement could be achieved through use of calibrated tethers, periodic markers or marked rails, or cables. RF systems, including Radio Detection and Ranging (RADAR) and Global Navigation Satellite Systems (GNSS), use the same techniques for measurement. They augment or replace GNSS satellites with fixed terrestrial pseudo-satellites ("pseudolites") that measure angle, range, and/or proximity. Acoustic systems include Sound Navigation and Ranging (SONAR) as well as range measurement systems and use a pattern recognition method (Yan and Turgut, 2009). In the optical realm, Light Amplification by Stimulated Emission of Radiation (LASER) measurement of distance is possible. Dead reckoning techniques combined with inertial measurement devices have been investigated for use in tracking emergency response personnel in environments that include Global Positioning System (GPS)-denied environments (Faulkner et al., 2009). Hybrid inertial/GNSS systems have been investigated for tracking pedestrians (Radzevicius et al., 2010) as well as for airborne applications (Tsujii, et al., 2008).

Influence of Communications Technologies on Choice of Tracking System

The choice of tracking technology or technique is also influenced by the specific communications technology that is used or planned for use in the same setting. For example, different tracking technologies are compatible with each of the three types of RF communication technologies used in underground mines. In the case of mesh networks, tracking capability is a

straightforward addition to the system, while other technologies such as leaky feeder systems and analog MF systems require use of separate tracking infrastructure such as Radio-Frequency Identification (RFID) systems (Novak et al., 2010).

Published Classifications of Tracking Systems

Location systems can be categorized based on a variety of characteristics. Table 1 summarizes the approaches used by various authors to classify location systems. While no single approach is comprehensive, together they provide several useful perspectives for understanding the array of possible and existing systems.

Table 1 - Summary of Approaches Used to Classify Tracking Systems

Reference		Zeikempis, et al., 2003	Hightower and Borriello, 2001	Sun, et al., 2005	Pahlavan, et al., 2000	Liu, et al., 2007
Types of Categories	General properties/ Application	X				
	Technology	X				X
	Sensing technique/metric		X	X	X	X
	Signal processing technique			X		
	Accuracy	X				X
Classification of existing systems						X
Recommended approaches		X				

One sample classification system is based on application environment (indoor/outdoor) and accuracy requirements (Zeikempis et al., 2003). It includes location method, location of position calculation (at the device or network), and positioning technology (e.g., triangulation or cell proximity). Other ways to classify location systems are by the sensing technique used and other characteristics (Hightower and Borriello, 2001). It is also possible to classify location systems in terms of the signal processing techniques used (Sun, et al., 2005), or in terms of general approaches and metrics such as Angle of Arrival (AOA), Time of Arrival (TOA), Time Difference of Arrival (TDOA), and Received Signal Strength (RSS) (Pahlavan, et al., 2000). Sun et al., (2005) describe two examples of indoor geolocation systems. One study characterizes 20 commercial location systems in terms of broad categories of location techniques such as triangulation, scene analysis, and proximity, as well as in terms of technologies used and performance (Liu, et al., 2007). The studies mentioned above do not offer specific information

on underground applications, but Zeikempis et al (2003) propose GPS using pseudolites for indoor applications.

Location System Properties and Techniques

Table 2 summarizes location system properties identified in Zeikempis et al., (2003).

Table 2 - Location System Properties (Zeikempis et al., 2003)

Property	Example/Explanation
Physical vs. Symbolic	Coordinates vs. "next to doorway"
Absolute vs. Relative	Position relative to a fixed reference or not
Localized location computation	Computation at mobile or within infrastructure
Accuracy and Precision	Location determined within x meters y% of time.
Scale	Worldwide, local, or within mine
Recognition	Identification of object to be located
Cost	Cost of system
Limitations	E.g., satellite systems are restricted indoors

Location Techniques Surveyed

Location techniques identified in the literature are summarized below in Table 3.

Table 3 - Location Techniques (Sun, et al., 2005)

Application	Techniques
Cellular Networks	Enhanced-Observed Time Difference (E-OTD) using Observed Time Difference (OTD) in Global Systems for Mobile Communications (GSM)
	Mobile Station (MS)-assisted and MS-based Assisted-Global Positioning System (A-GPS) for narrowband Code Division Multiple Access (CDMA)
	Observed Time Difference of Arrival (OTDOA) for wideband CDMA
	Use of Cell Identification
	AOA based location using smart antennas at the base stations
	Hybrid positioning that merges different types of data for improved accuracy
	Pattern matching or "fingerprinting," considering multipath characteristics
Wireless Local Area Networks (WLAN)	Client-based
	Client-assisted
Ad-hoc Sensor Networks	Localization with beacons
	Localization with moving beacons
	Beacon-free localization in which node positions are determined by local communication among nodes

Types of Systems Most Applicable to Underground Mines

Some types of systems are more applicable to underground mines than others. Systems that require continuous access to satellites are not suitable for underground applications, although personnel and some equipment will be above ground periodically. This allows calibration of other systems, e.g., Inertial Navigation System (INS), using GNSS information. RF, acoustic, and optical systems are applicable to an underground setting. The topology of an underground mine is complex and affects various tracking systems in different ways. Triangulation will likely not work well in a tunnel system. A tunnel system's geometry can result in a lack of multiple direct paths and in geometrical dilution of precision where direct paths do exist. The known layout of tunnels, however, be used to improve tracking accuracy (Li et al, 2009). Liu et al. (2007), presents indoor positioning location systems. These systems may have applicability in underground mine environments, but are not directly germane. The systems that rely on GPS, AOA measurements, or cellular systems, such as SnapTrack, Ubisense, Gaussian Process Positioning System (GPPS), and GSM Fingerprinting, have been omitted from consideration because reported error values are large and cannot be considered representative of the accuracy that can be achieved in an underground coal mine.

Additional Techniques

A new technique not included in previous surveys is Signal Strength Difference on Arrival (SSDOA) (Papadakis and Traganitis, 2010). This approach uses RSS from multiple receivers and an exponential path loss model to calculate an estimated location, and could potentially be applied to underground mines. Scene analysis or pattern recognition/fingerprinting techniques can be used in indoor RF systems and have been proposed for use in acoustic systems within underground mines (Yang and Turgut, 2009). Pattern recognition/fingerprinting is reliant on radio maps, which must be updated with all changes to the system environment. Therefore, this tracking technique loses its practicality in dynamic environments (Wannasai, 2010), such as active mines. In the case of geolocation systems that operate in underground mines, by locations of interest that are constrained to tunnels, it is possible to use knowledge of the mine's layout to refine position estimates. In Li et al (2009), two methods for improving tracking system accuracy are presented that are based on a coplanar node-path network mine model.

Physical Phenomena that Affect Location System Performance

Location and tracking system performance are limited by physical effects. Phenomena that affect RF, acoustic, and inertial systems are described in this section. The first five phenomena affect acoustic and, in particular, RF systems and have some applicability to optical systems, while the final subsection describes limitations on inertial measurement units and inertial navigation systems.

Propagation

Transmitted radio and acoustic signals travel or propagate through space. If no obstacles are present, this propagation is easy to model, as described below. Obstructions introduce effects that can impair operation of systems that use radio or acoustic signals.

Unobstructed Environments

Propagation of electromagnetic energy is straightforward only in free space (a vacuum with no obstacles), where the received power is inversely proportional to the square of the transmit–receive distance. In such environments, received signal strength itself could be used to measure distance from an RF or acoustic signal source. However, local variations in signal strength are small if the distance from the source is large. This limits accuracy of systems based solely on RSSI, but reception of signals for use in other positioning techniques is straightforward in an unobstructed environment.

Acoustic propagation follows a similar relationship in an unobstructed air-filled space. Unlike RF signals, however, acoustic signals propagate at higher velocities through denser mediums such as liquids and solids. For this reason, acoustic signal propagation through the mine tunnel walls could be used for communication and tracking (Yang and Turgut, 2009). However, the commercial application of this approach is still highly speculative due to the heterogeneous nature of coal, the surrounding geology, and the configuration of room and pillar mining as well as the intense power requirements needed for signal generation.

Obstructed Environments

In environments where position location is desired near, at, or below the earth's surface, there are obstructions that affect signal propagation in several ways. Outdoor RF systems are affected by "the presence of the earth, the atmosphere, the ionosphere, and atmospheric hydrometeors (precipitation) such as raindrops, snow, and hail" (Collin, 1985). Indoor and

underground propagation are similarly affected by the atmosphere and objects in the environment. Propagation characteristics have a significant effect on performance of acoustic and RF based positioning systems. In addition to effects such as path loss or attenuation, shadowing, fading, and time dispersion, the physical environment can affect the polarization of electromagnetic waves. As a result, the effectiveness of a tracking system that operates in these environments is affected by the location of fixed units in relation to these obstacles, as well as the location of fixed and body-worn devices in relation to surfaces such as tunnel walls and roof or the body. Further, in the case of RF devices, performance depends on the antenna's orientation, which determines the polarization of the antenna, the signals it transmits, and the signals it is able to receive effectively. Orientation of fixed and body-worn devices is also likely to affect performance when directional antennas or other transducers such as directional microphones are used.

The inverse square law for signal power does not apply in obstructed environments for either acoustic or RF signals. Path loss is often modeled empirically using a power law with an exponent that is typically greater than two, indicating a more rapid decrease in signal strength as a function of distance. Typical exponent values range from three to six, with higher values indicating greater signal loss, such as in an urban environment where many obstructions are present. Values lower than two are also possible in corridors that act as waveguides, consistent with the modeling of coal mine tunnels as waveguides by Emslie et al (1975).

Obstructions resulting from shadowing, diffraction, reflection, and scattering also effect RF signal propagation. Shadowing occurs when an obstacle blocks the line of sight to the transmitter. Even if the signal can penetrate the obstacle, the result is attenuation or weakening of the signal after it has traveled through the obstacle. Knife edge diffraction, described in the literature (Jakes, 1974), is used to model electric field strength in the shadow region due to propagation over or around obstructing objects. Specular or mirror-like reflection occurs when an object in the propagation environment is large relative to the wavelength of the signal and has surface variations that are small relative to the wavelength, and is dependent on material properties of the object. Scattering occurs when the surface variations are large in proportion to the wavelength.

These effects result in multipath propagation, in which a signal travels in the form of multiple direct, reflected, diffracted, or scattered components that add together differently at

varying locations. Because the signals are time-varying (e.g., sinusoidal), they can reinforce or cancel each other at a particular location, depending on the phase as well as the amplitude of each signal at that location. Since phase changes by 360 degrees over one wavelength and UHF RF signals have wavelengths from ten centimeters to one meter, this can result in extreme signal level variations over short distances. In urban outdoor environments, "Fades of 40 dB or more below the mean level are common, with successive minima occurring about every half wavelength (every few inches) of the carrier transmission frequency" (Jakes, 1974). Multipath propagation causes rapid fading in narrowband cell phone and frequency modulation (FM) radio signals, which can be particularly noticeable as a vehicle slows to a stop. Similar effects are seen indoors. In wideband systems, the phase relationship among multipath signal components varies across the signal bandwidth. If these variations are large, frequency selective fading occurs, resulting in notches and peaks in the signal spectrum that vary with time and location. However, if the phase variations across the signal bandwidth are small, flat fading occurs and affects the entire signal.

Radio wave propagation in underground mines is a special case of indoor propagation. A 1993 review of indoor radio propagation literature (Hashemi, 1993) identified 50 references on propagation in mines and tunnels. Emslie et al (1975) modeled mine tunnels as waveguides in order to develop a theory for UHF propagation in coal mines.

Polarization Effects

Polarization is a property of electromagnetic waves that is relevant to RF and optical systems. Stutzman (1993) describes polarization as "the motion the electric field vector goes through at a point in space as an electromagnetic wave travels by," and provides a detailed mathematical treatment. The initial polarization of a wave depends on the orientation of the transmitting antenna, and in free space (a vacuum with no obstructions) the polarization does not change. However, in multipath channels, the polarization of an electromagnetic wave is altered when the wave is reflected or scattered. These propagation effects depend on the angle at which the electromagnetic wave meets a surface or object and the wave's initial polarization relative to the surface or object with which it interacts. The result is that signals become depolarized or differently polarized as they propagate in multipath environments, and the polarization, like the signal power, varies as a function of position. These effects are difficult to predict unless the geometry of the environment can be modeled in detail. Polarization-dependent propagation can

be used to increase channel capacity for communications (Andrews et al, 2001) by using multiple antennas with different orientations relative to the position of the transmitter and/or receiver. Multi-Input, Multi-Output (MIMO) techniques, such as those used in WLAN systems based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11n standards, can exploit these effects for communication. For geolocation, polarization information could be included in a fingerprinting approach.

Geometrical Dilution of Precision (GDOP)

The relative locations of transmitters and receivers in a location system affect the system's accuracy; accuracy is degraded for some combinations of locations. This effect, called geometrical dilution of precision or GDOP, affects both GNSS and terrestrial systems. For example, this occurs if RF nodes and the mobile to be located are nearly collinear. The results of GDOP errors in the measured angle or distance can lead to larger errors in estimated location than with other geometries (Tekinay et al, 1998).

Phenomena that Limit Inertial Navigation Systems

For inertial navigation systems, there are several limiting effects, as described by Hoenk (1994), related to the design of accelerometers used to measure distance in these systems. Hoenk concentrates on effects that limit performance of small accelerometers, but indicates that similar effects exist that limit performance of gyroscopes in measuring orientation. An accelerometer consists of a proof mass, a spring, and a transducer for measuring displacement of the mass. Measured acceleration is integrated twice to find position. This results in accumulated measurement error due to thermal noise. The error increases with noise density and with integration time. Thermal Noise Equivalent Acceleration (TNEA) is one measurement of accelerometer performance. Tradeoffs are identified among proof mass, quality factor Q, and TNEA.

Hoenk identifies other effects that are potential sources of error in accelerometers that need to be taken into account. These include, in order of decreasing magnitude, gravitational effects of the earth, variation in spring restoring forces, buoyancy of the proof mass in air, the earth's rotation, magnetic forces, and gravitational effects of nearby objects.

Current improvements in reducing the drift of INSs over fixed time periods have greatly reduced the average error in position estimates. Micro-machined electromechanical systems

(MEMS) inertial sensors are lightweight, compact, and capable of human motion capture. This technology generates an average error, over a 60 second interval, of approximately five meters. While this is a great improvement over previous INS technology, a position accuracy of one meter for a stationary device over a period of 60 seconds has not yet been achieved (Woodman, 2007).

Acknowledgements

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DESIGNING AND MODELING WIRELESS MESH COMMUNICATIONS IN UNDERGROUND COAL MINES[2]

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Abstract

New and developing communication systems enable underground miners to not only connect to the surface from an increased communication coverage area but also to be discovered in the event of an emergency. Communication and tracking systems are required by MSHA regulations, aiming to enhance health and safety and routine production in underground operations. Modeling a mine's potential communication coverage area will assist in increasing overall coverage and efficiency of the communication network. Modeling the propagation of wireless communications enables ideal broadcast locations to be found when designing a communications network. Strategic placement of broadcast devices results in a reliable communication network that can better withstand disruption in both daily operation and emergencies. This paper will discuss recent regulatory developments in underground coal communication systems, the implementation of these new technologies, and how communication system's networks can be modeled and analyzed using computer simulations.

Introduction

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 and Brune 2006a). 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." In 2006, the underground communication technologies available to the mining industry had inherent problems that limited communication capabilities. Because harsh underground mine environments significantly reduce line of sight and propagation range and introduce power and safety concerns, the overall effectiveness of underground communication technologies were limited. After several coal mining accidents in early 2006, the United States Congress responded with the Mine Improvement and New Emergency Response (MINER) Act, enacted on June 15, 2006. Congress stipulated that an established link of quality two-way communication among the underground miners, mine rescue teams, and coordinators on the surface is vital for the safety of the miners. The Act required the development of communication and tracking systems that allow emergency planning and rescue operations to proceed in a more efficient manner, ultimately saving lives. Adaptations of technologies widely used in other industries have been tested in harsh mining environments and approved for use by The Mine Safety and Health Administration (MSHA). These systems have wide reaching implications for the mining industry, with potential benefits that are not limited to health and safety concerns.

The MINER Act calls for post-accident communications to "provide for a redundant means of communication with the surface for persons underground, such as a secondary telephone or equivalent two-way communication." The MINER Act also calls for a post-accident tracking plan that "shall provide for above ground personnel to determine the current, or immediately pre-accident, location of all underground personnel" (U.S. Congress, 2006). Overall, the MINER Act requires that some sort of survivable communication and tracking system be integrated into underground mines or be in the process of being integrated. Since it is not practical to assume that an entire mine will receive coverage, MSHA, which enforces mine regulations in the United States, requires communication and tracking areas to provide for, 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. Strategic areas are defined as belt drives and transfer points, power centers, loading points, SCSR caches, and other areas identified by the MSHA district manager (MSHA 2009).

Mining companies are interested in maximizing the functionality of communication and tracking systems not only to satisfy MINER Act requirements, but also for increasing mine efficiency, simplifying production, enhancing mine monitoring, and maintenance coordination. Newly developed communication systems not only significantly increase the communication coverage area but will also provide gateways for miners and mine operators to use the systems to increase efficiency throughout the mine. Daily operational use of the communication and tracking systems will benefit miners and mine operators because they will learn how to effectively communicate and coordinate production and maintenance tasks using the system. Communication systems can be customized to particular mine circumstances to increase a mine's efficiency in reporting daily production numbers and health and safety hazards, and in dealing with other safety and production issues that may be encountered during daily operation. In turn, detailed historical information during routine production will greatly benefit post-accident coordination efforts. Communication system sensors are being developed for real-time monitoring of carbon monoxide, methane, and oxygen levels. Gas sensors can be placed throughout the mine to help monitor and detect areas that are experiencing high gas concentrations.

Applications of Communication Systems

Immediately upon ratification of the MINER Act, a major effort was undertaken to adapt existing technologies to the harsh conditions of the underground coal environment. A wide variety of communication technologies using different system operating frequencies have been investigated and pursued by researchers and vendors. These technologies include leaky feeders, extremely/very-low frequency, medium frequency, Radio Frequency Identification (RFID), and wireless mesh technologies. According to Cisco Systems Inc. (2002), wireless mesh networks create a redundant connection by "multiple nodes being connected and if any link fails, information can still flow through other links in the network to the destination." Figure 6 shows an example of a wireless mesh network topology.
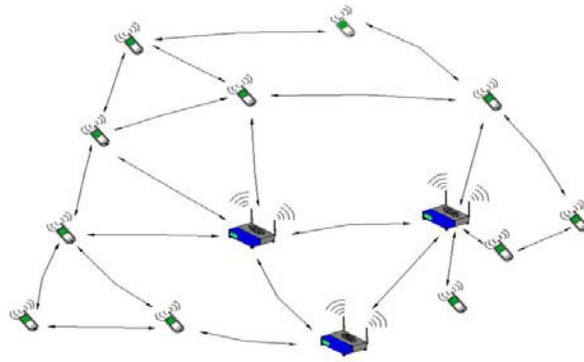
Figure 6 - Wireless Mesh Network Topology Example

Gürtunca (2008) presents an overview of communication system technologies. Developments in these technologies have enabled different technologies to operate more efficiently underground. Each specific system provides different benefits depending on its operating frequency, available bandwidth, and power requirements.

Operating frequency, available bandwidth, and power requirements are directly related. Typically the higher the operating frequency, the higher the bandwidth rating and power requirements will be. Since voice communication requires a higher bandwidth rating than text-based communication, voice communication systems have greater power requirements. Communication system power requirements can become an issue in underground coal mines because they are exposed to a wide variety of dangerous gases, potentially increasing the chance for an explosion. NIOSH has conducted extensive research on the safe threshold of power through communication systems. MSHA defines permissibility requirements for communication systems in 30 Code of Federal Regulations Part 23 (MSHA 2010).

Companies have been required to design systems to be able to operate in emergency circumstances even when the mine fills with harmful gases. Companies can utilize wireless technologies that operate at different frequencies to overcome different obstacles. According to Schiffbaurer and Brune (2006b), some operating frequencies will propagate further because of "electrical properties of the coal attenuate some frequencies more than others." Sacks and Chufo (1978) observed, "large variations in signal attenuation rate have been found between three coal seams investigated which are widely separated geographically." This indicates that each mine will yield a unique solution even while utilizing the same communication system.

Ultimately there are tradeoffs with operating at different frequencies because the power required and the bandwidth the system is provided with is proportional to the operating

frequency (Radunovic et. al. 2009). No one specific operating frequency will provide optimal performance in every set of circumstances, nor is there any way to capture the event of a disaster into a single root cause. Typically, disasters are comprised of several small events that are linked together and create a set of unforeseen circumstances. Communication systems are crucial to ensure communication between miners and mine rescue teams. Without certain crucial information being relayed from the surface to underground, both the miners and mine rescue teams ultimately are put at a higher risk of encountering danger. Communication systems will also open the door for endless possibilities of applications and intelligent solutions that can be used during daily operation and in the event of an emergency.

Method for Modeling Underground Wireless Mine Communications

A major goal of the research presented in this study is the modeling of the propagation of wireless communications in underground coal mines. The location of broadcast devices or nodes is important to ensure that handsets receive the best service throughout the areas miners will likely be in. Creating a model for the propagation of wireless signals allows the optimal communications node locations to be calculated. The locations that will provide the communications network with the best service can be calculated by creating a model to simplify the mine and solving the mine's communication network. Solving a mine's communication network 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 can be used to increase the efficiency of the system and ensure that all the desired areas have communication coverage. Several methods were investigated and a Geographic Information Systems (GIS), or network based, approach was chosen. This method was chosen because of its ability to model the spatial relationships encountered in a mine, given that the wireless signal encounters sources of interference from ventilation regulators, belts, and other losses, 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 a pressure loss in a ventilation network. The nature of underground mining lends itself to intersections and connections to those intersections. It is assumed that a broadcast source will be located at an intersection and not in an entry. The approach used in this study 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 selected. 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.

Comms is a computer modeling method developed at the Virginia Center for Coal and Energy Research at Virginia Tech (VCCER/VT) that can be used to model communications networks in mines. Comms utilizes IntelliCAD software and programmed routines to calculate necessary values to both quantitatively and qualitatively solve for and analyze predicted coverage areas. Comms solves a mine's communication network by building the communication, solving the network, predicting ideal coverage, and optimizing the communications network. Signal strength thresholds are defined by the user and determine if an area receives acceptable signal strength. Comms builds the mine's communication network using the pillar/perimeter method and/or the centerline method (Schafrik et. al. 2011). The pillar/perimeter method uses existing line work 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, such as a pillar, and determines where the search line encounters the pillar or perimeter line from the drawing, placing a point half way between the edges of the area of interest and the next pillar or perimeter that is encountered. Figure 7 depicts a small portion of a mine's communication network when using the pillar/perimeter method.
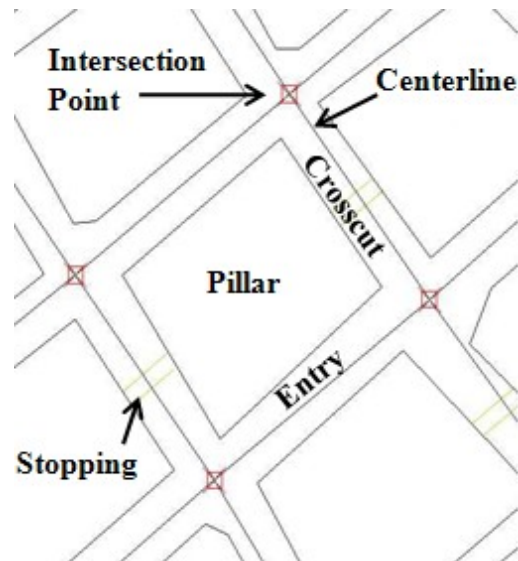
Figure 7 - Communication Network Pillar/Perimeter Method

With the centerline method, a user defines a start point and direction, which COMMs follows. COMMs 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 points.

In either method the user is required to edit the mine communication network to ensure all links and intersection points are connected. Both the pillar/perimeter method and the centerline method will ultimately create a series of conceptual points (intersections) and links (tunnels) that connect 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 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 signal strength range at that point. This can be calculated by 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 at 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 determining the links available and whether 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 stored to text files of comma separated values that also register 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.

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. 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. 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 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 1 (McCaffrey, 2004).

Equation 1 - The number of possible solutions or combinations (C)

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

Where,

N, is the total number of points in the communication network

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

Field Work

The authors have been studying the modeling of wireless communication wave propagation in underground mining environments in cooperation with NIOSH, 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 team has tested the methods discussed above in several different underground coal mining operations. Extensive research and testing took place in both room and pillar and longwall underground coal mines in West Virginia. Interferences and design parameters for modeling underground wireless wave propagation have been developed through field testing and experience. Using the anticipated interferences and design parameters, pre-installation network plans as well as coverage maps can be created. Once the communication system has been integrated into the mine, additional interferences and design parameters are revealed by comparing theoretical signal strengths versus measured signal strengths. Results predicted from modeling matched field results. The L-3 Accolade underground mine communication and tracking system well has exceeded initial expectations.

Conclusion

Wireless communications have proven to be the way of the future. Wireless communication systems can be used not only to track and communicate with miners but also to simplify coordination of production and maintenance tasks. Wireless communication systems are developing continually, are less restrictive than hardwired systems, provide communication coverage areas significantly larger than hardwired systems, and provide multiple redundant paths

for communication to travel through if one is blocked. It is not feasible to attempt to provide communication coverage to every part of the mine due to cost efficiency, health and safety issues, and other natural and manmade interferences the signal will likely encounter. Communication systems will continue to develop as time and scenarios test the systems.

Future work is necessary to address issues of optimization of wireless mesh location network. Issues such as driving factor should be resolved. Additional work in mine changing scenarios or installed mine mesh network systems should be ongoing. Research, modeling, and analysis of underground communications are ongoing at the VCCER/VT.

Acknowledgements

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WIRELESS MESH COMMUNICATION SYSTEMS OPTIMIZATION IN UNDERGROUND COAL[3]

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Abstract

The Virginia Center for Coal and Energy Research has been developing models of wireless signal propagation in underground coal mines since 2007. The current mine propagation modeling software, named COMMS, is able to locate potential broadcast points for underground wireless mesh systems and estimate their coverage. COMMS utilizes programmed routines to calculate necessary values to both quantitatively and qualitatively solve and analyze predicted coverage areas. The program approximates the spatial relationships that are encountered, such as ventilation regulators, belts and other obstructions. Using this model for propagation allows the optimal communications node locations to be calculated, by using lessons learned from current installations and experience with the new technology. In addition, the optimization can be calculated by checking all possible combinations of broadcast locations. This paper compares these optimization calculation methods. The ability to solve a mine's communication network

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Wireless Mesh Communication Systems Optimization in Underground Coal

S.J. Schafrik, M.K. Luxbacher, M. Karmis 2011 SME Annual Meeting, SME Preprint 11-106.

Steven Schafrik researched and prepared this manuscript, with Kray Luxbacher and Michael Karmis providing technical and editorial input.

provides a pre-installation mine network design map, creates coverage maps of the mine and allows planning for future communication activities

Introduction

Wireless communications and tracking systems in underground coal mines are required to be installed and must meet certain requirements. The MINER act states: "POST ACCIDENT COMMUNICATIONS.--… a plan shall, to be approved, provide for post accident communication 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". MSHA's Program Policy Letter NO. P09-V-01 (PPL) defines the minimum requirements of the communication systems (MSHA 2009). The PPL defines coverage in working sections of the mine, escapeways, belt drives, power centers, SCSR caches and other areas as identified by the MSHA District Manager. The MINER Act was written before wireless systems were available to the mine operators and the PPL was written as they are being developed. While working on the development of a wireless node system, the authors identified a need for the mine designers and the regulatory communities to predict the coverage of various wireless technologies.

A portion of the overall prediction tools is the COMMS project, developed for underground wireless mesh systems. The COMMS program began by answering the question, if you broadcast a signal underground at point A, as shown in Figure 8, what would the signal be at the other alphabetical points? A goal was also to make tools that can be utilized by the average engineer while evaluating, installing or maintaining a wireless system. The model was designed to allow for prediction using standard parameters. The parameters chosen are measurable in the specific mines and the system can adjust all calculation based on the designer's or evaluator's experience and test results. The resulting approach and software is discussed in this paper. This program is being licensed to users by Virginia Tech Intellectual Properties (VTIP:10-079).
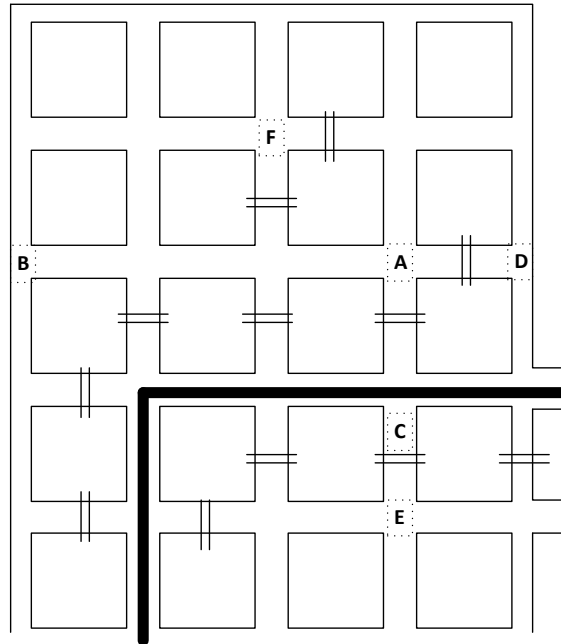
Figure 8 - Simplified Mine Section

Background

Development of the program, COMMS, began in 2007 to assist the engineer in locating wireless communication components in underground coal mines. COMMS is a network creation and solving program that uses rules and heuristics to solve a network. The network is a collection of nodes (points) and links (two point lines). Nodes are intended to be the center of intersections. Links are intended to provide a connection between only two nodes; links should not overlap each other. Each node is capable of being labeled, as discussed below, and nodes that are potential broadcast locations will be source points for a broadcast and part of the solve routine. The calculated properties are then considered in the optimization routine.

The program is broken up into several sub programs, one of which, DrawEntities, is useful for many other applications. The most important step for the COMMS program accuracy is creation of the network. DrawEntities has the most sophisticated routines for creation of the network. These routines were broken out into a separate program because the network created is useful for more than just the wireless solve routine; there are several other applications that are not discussed in this paper. The programs are written to work with IntelliCAD or AutoCAD to reference mine maps. The programs are written in Microsoft Visual Basic due to its

straightforward source code and its ease of connection to the CAD program engine. The program has the following capabilities and functions:

- Locate Centerline by Point and Direction
- Automatic Center Point Location by various methods
- Automatic Link Creation
- Node and Link Clean Up
- Read Nodes and Links from Drawing
- Read Nodes and Links from CSV Files
- Draw Labels
- Find or Pick Node or Link
- Define Node Type
- Create Pre-Calculated Links
- Find Path from Node to Node
- Pre-Calculate Paths
- Calculate Node(s) Communication Area
- Draw Node(s) Communication Area
- Solve Network
- Optimize Network

To create a model, the user must first design and then calculate the paths of a network. Next, the path parameters of the communication system can be inputted and used to solve the network. After the full network has been solved it can be optimized. The functions above have been developed to give the user flexibility in creating and solving the network. At all points the software allows the user to override the defaults. Each function is described below.

Centerlines are typically drawn when creating coal mine projections. These centerlines are sometimes available to the modeler and sometimes are not. The simplest means of locating the intersections in the mine is locating the intersections of centerlines. If all the centerlines are available to the modeler, there is an automatic node and link creation routine that is capable of using them. If the centerlines are not available to the modeler, which has been the typical case, other means of creating them can be employed.

The simplest and most user interactive centerline location technique is by point and direction. Given a point inside a mine void and a direction, the program will attempt to follow the bearing until it encounters an obstacle. There are several parameters needed for this function: distance step, angle step, search attempts, maximum turn angle, search offset, forward looking multiplier and maximum line distance. The program starts at the first point and then uses the second as the next point of the center line. The next point is taken along the same bearing at the distance step, while the forward looking multiplier is used to create an imaginary point further along the bearing. If the new line segment plus the forward looking line intersect an obstacle, the new segment is invalid. Additionally, a forward looking cone is created using the search offset and the step segment length multiplied by the search multiplier. If there is an obstacle inside of the search cone, the new line segment is deemedinvalid. If the line is invalid it is rotated by the angle step and the search for an obstacle is repeated. This process will be repeated until the maximum angle is met or a valid line segment is found. If no segment is found then the line stops at the last valid segment. If a valid line segment is found, the line will continue on the new bearing.

Various methods to find intersection points have been explored and refined to use as-built pillar and perimeter lines. The first method was to overlay a grid and determine if the grid point is mostly void or mostly coal. The centers of adjacent void grid points are end points of centerlines and intersections of these centerlines are considered intersections of the entries. This method, however, proved inefficient when working with a coal mine that is not aligned orthogonally and was quickly abandoned.

All other methods are refinements of a centroid method, in which each pillar is identified and enumerated. For each pillar the centroid is calculated. These are done in a batch for calculation speed. Each pillar and then all pillars and perimeters within a 35 foot offset are selected. For the adjacent pillar a temporary line is made from centroid to centroid. Where this line intersects, the pillar lines are noted. The midpoint of the intersection points is used as a center point. A check is performed to ensure another center point is not in the vicinity; if not, then the point is considered a node. If a perimeter line is adjacent to the pillar, then additional considerations are made. A line parallel to the perimeter line passing through the centroid is used to mirror the found nodes. These mirrored nodes are refined by the offset distance of the perimeter line. Some cannot be refined and are discarded. If a Carlson Software Grid file is

available for the bottom or top of seam, then the grid can be read to determine a node's elevation. Elevations of nodes can be defined or refined by hand later in the process.

While these node points are being drawn for each pillar they are also being tracked. After nodes have been located, the program begins finding valid links. A valid link is a two-point line that connects two nodes without overlapping another link. Found nodes are connected in a clockwise manner. The links are checked to ensure they do not overlap or intersect an obstacle. If the user has asked the program to remove extra nodes, then nodes that have only two links, where the points on the other end of the links can connect each other without intersecting obstacles, are removed. There are reasons for keeping these intermediate points for other applications. However, in the case of underground communications these points can increase the amount of calculation time, especially for optimization, and should therefore be discarded.

Nodes and links are drawn in the CAD program by DrawEntities or COMMS. The node and link creation process is acceptable but requires the modeler to refine intersections (nodes) and links (entries). The refinement of the network must be done manually in the CAD environment. There are several cleanup routines that aid the user in the hand correction, most notably the node and link cleanup routines, which perform several checks, but more importantly, ensure that nodes are not within pillars, elevations of nodes are reasonable, links are exactly connected to nodes, links are not intersecting obstacles, and link types are defined. At this point, the user is finished using DrawEntities and can begin working exclusively in COMMS. Many of these routines are available in both program interfaces.

Nodes and links for a finished network are saved in the drawing file and can be saved as Comma Separated Value (CSV) files. Saving as a CSV file is preferred as it allows the user to edit the network parameters. COMMS can read the information about the network from either source and can synchronize the data. Nodes represent potential locations for broadcast of a wireless signal; they also represent potential places to receive the signal. Links represent the path the signal can take. All identified nodes are automatically classified as being broadcast or receive locations. In order to reduce the number of nodes that need to be solved, the user can specify nodes as being undefined (broadcast and or receive), broadcast only, receive only, or no signal required. These classifications are used in the solve routines as well as the optimization routines to trim the search space. For instance, receive-only nodes are never calculated as broadcast locations.

Links are also automatically classified based on encountering items in the mine map. There are classifications for links that intersect ventilation controls and belt structure. These items are used to define the properties of the link and are not considered obstacles. Items such as pillar and perimeters lines are obstacles. Link classifications and properties can be modified by hand, and the parameters of the classification can be modified in the CSV files. This allows for whole mine parameter changes or changes to particular links. These parameters can also be measured in the field and can greatly affect the solve accuracy. Modifying link classifications and properties speeds up the solve routine to create pre-calculated links. This makes a file that is used by the path finding routine. For both of these edits, the draw labels, find link, find node, pick link and pick node functions are all ways to cross reference the node and link lists with the coal mine drawing.

The user can troubleshoot the network or double check it by using routines such as find path from node to node. This will tell the user which path the solve routine, as it is currently set, will take. The path solution will either minimize distance and turns or minimize resistance encountered. To see the difference in the specific mine, this routine can be used to highlight the path that the path finding routine will take.

The path finding routine used is not based on a standard path finding process. Instead, it is based on a recursive network search function. The routine works by examining the node it is at and determining if it is the final node. If it is the final node, the routine is finished. If it is not the final node, the routine moves to the adjacent nodes and calculates cumulative counter items, such as path taken, distance and resistance. There are several cutoffs to the search , such as maximum hops, maximum distance, and maximum resistance, any of which terminate fruitless searches. All paths taken that are successful are then evaluated to find the best path based on the resistance and minimum number of turns. This path finding routine has been found to be very effective in this scenario and is able to output the path and paths to CSV files that are pre-calculated paths. These can be useful for other applications, such as cabling calculations. COMMS treats these paths as the last of the pre-calculation variables.

With a completed network it is possible to draw a node's communication area. This is done by the solve routine. The solve routine takes the node's paths and given the starting signal strength, signal strength multiplier and properties of the paths to every other node (these can be pre-calculated or not) and calculates a perceived signal strength at each node that can hear the

signal. Signal is depreciated by signal resistance characteristics of the path taken; this is the reason for the two path solutions. Resistance parameters are both on the links that are followed and in the overall parameters of the solve routine. The details of the calculations are not discussed in this paper but are summarized in "Designing and Modeling Wireless Mesh Communications In Underground Coal Mines" (Griffin, Schafrik and Karmis 2009). To solve the mine network, this same routine is run for broadcast only nodes or broadcast and receive locations. Each node's broadcast area details are outputted into a CSV file. These CSV files are made to contain both summary and detail for each node's relationship to each other node. The CSV files can also be used as inputs to the optimization routine. This allows the user to change the parameters in each solve file to make it match observations underground.

A summary matrix is created in the whole mine solve that is used in the optimization routines. The optimizations are discussed in the next section which includesan overview of the COMMS systems and explains how the program creates the network used to solve the expected signal strength values.

Optimization Techniques

Determining an optimization of a burgeoning technology is a difficult task. It is made more complex in the case of underground communications systems since these systems also provide tracking, or communication of tracking systems, and are expected to survive an incident. Presented in this paper is a means of optimization that takes into account only coverage of an area that must receive passable communications. Redundancy and/or protection from incidents will be covered in a later publication, as this work is ongoing. At this point a modeler has used COMMS to create a network for a mine, classified the network, and solved it. The modeler can then go into the network and define nodes as being broadcast nodes, draw the broadcast area and continue the process until the coverage required is achieved. This process is automated in the Heuristic Optimization. Brute-force optimization is also available to the modeler, which looks at all possibilities of communication source locations. It is not possible at this time to discuss a specific as built example project; this discussion will be kept theoretical.

Coverage at the working face is not considered. The communication system at the face is assumed to be a static system that is determined independently of this optimization. This

optimization is the communication network for the mine as a whole system, not just specific to the working face.

Brute-force Optimization

As described above, Brute-force optimization examines every single possible combination of the solved network to determine if it achieves the desired coverage percentage. Since every possible combination is checked, the optimum must be found. This process can involve several billion calculations for a small number of potential broadcast points. The choose function, see Equation 2, is the total number of possible combinations given n number of choices and k subset of the choices. For illustration purposes, a simple 6 choice example will be discussed. If there are a total of 6 possible node broadcast locations then the optimum would be the minimum number of actual broadcasts that still give full coverage. The breakdown of the number of possible combinations is in Table 4. For this case there are a total of 63 possibilities which will be investigated trying to minimize k.

Equation 2 - Number of possible combinations

$$Choose(n,k) = n! \Big/ k! \cdot (n-k)!$$

Equation 3 - Total number of combinations possible

$$AllChoices = \sum_{k=1}^{n} n! \Big/ k! \cdot (n-k)!$$

Table 4 - Number of Combinations

N	k	Number of Combinations
6	1	6
6	2	15
6	3	20
6	4	15
6	5	6
6	6	1
Total:		63

The process of checking the combinations starts with the matrix that is produced by the solution. An example of a matrix is shown in Table 5. This example is a square matrix, but symmetry is not required to solve using this technique. The broadcast nodes are listed in the columns and the nodes that can receive a signal are listed at the rows, the data is a binary one or

zero indicating that a signal can be heard. The quality of the signal is not considered in this step, that is covered by the solve routine.

Table 5 - Solution Matrix

		Broadcast Nodes					
		0	**1**	**2**	**3**	**4**	**5**
Receiving Nodes	**0**	1	0	1	0	0	0
	1	1	1	0	0	0	0
	2	0	1	1	0	1	0
	3	0	0	1	1	0	0
	4	0	1	0	1	1	1
	5	0	0	0	0	1	1

The solve routine uses the total number of broadcast nodes as the n value and calculates all possible. First, a single broadcast point is selected. If a broadcast node is capable of broadcasting to all other nodes then it is the optimum broadcast location. After each single node is investigated, combinations of nodes are investigated. This is done through a process of selecting nodes that are broadcasting and then calculating several items. These calculations and an example of two nodes being selected is shown in Table 6. The status line is used as a multiplier for the matrix that was shown in Table 4. The number of nodes being serviced is the total number of nodes that receive a signal from the broadcast location. In the solve routine, preference is given to nodes that service more nodes, or have a greater number of nodes being serviced. The current number of nodes being serviced is the total number of nodes that can hear from the broadcast locations currently selected. The sum of the current nodes being serviced is the number of servicing nodes. In this example, Node 1 is able to get a signal from two locations, Node 0 and Node 1. The column being serviced is a one if the number of servicing nodes is one or greater. If the sum of the being serviced column is equal to the number of receiving nodes then a solution has been found. A solution with the minimum of the sum of the number of servicing nodes is the optimum. This means that all nodes that must receive a signal are getting a signal, but the amount of overlap is minimized. A case where the sum of being serviced is equal to the sum of the number of servicing nodes is an ideal case.

The process can be stopped when repeated checks produce the same or worse results. For these systems there is a point where turning on an additional node will only add repetitive

service. This is the case when the node is added between nodes that already service the area, since quality of service is taken care of by the solve routine.

This process will find the optimum broadcast locations given that the solve routine solution is correct because each and every potential scenario will be calculated. This strength is also the solution's weakness. There are far too many possibilities to consider, even for a small mine. Given a potential two fresh air entry mine that is 2,000 feet deep with cross cuts every 80 feet, there are potentially forty node points that can be used for broadcast. Using n=40 in equation 2, there is a possibility of over 1 trillion combinations. Even if checking each case takes a computer 0.1 seconds, to check all trillion combinations will take over 100 million years. The practical limit of this type of solution is around 30 broadcast locations, which is 1,073,741,823 possibilities.

Table 6 - Solution Matrix and Example Calculations

	Status (1=on 0=off)	1	1	0	0	0	0	2	
		Broadcast Nodes							
		0	1	2	3	4	5	**Number of Servicing Nodes**	**Being Serviced**
Receiving Nodes	**0**	1	0	0	0	0	0	1	1
	1	1	1	0	0	0	0	2	1
	2	0	1	0	0	0	0	1	1
	3	0	0	0	0	0	0	0	0
	4	0	1	0	0	0	0	1	1
	5	0	0	0	0	0	0	0	0
Current Number of Nodes Being Serviced		2	3	0	0	0	0	5	4
Number of Nodes Being Serviced		2	3	3	2	3	2		

Virginia Tech has several High Performance Computing (HPC) resources available. One such resource is available in the Mining and Minerals Engineering Department. The Mining Department's HPC head node is a Dell PowerEdge R710 with 48 GB memory (12x4 GB) for 2 E5540 Xeon processors, 2.53 GHz, 8M Cache, Turbo, HT, 1066 MHz with 4 1 TB SATA Hard Drives. There are 4 Compute Nodes that are Dell PowerEdge R410 with 48 GB memory (6x8 GB) for 2 E5540 Xeon processors, 2.53 GHz, 8M Cache, Turbo, HT, 1066 MHz with 750 GB SATA Hard Drive. There is also a set of alternate computers that can bring the total number of

processors available to the cluster to 70. The operating system is Fedora 12 (Linux) with modifications for the HPC.

An additional sub-program to COMMS was developed specifically to solve the brute-force optimization on HPC clusters. The program accepts the solution matrix and then begins the solve process. The process can be started at the beginning or in a subset. The program is written in Standard C++ with connections to OpenMPI and compiled to run on Linux based clusters. The multiprocessor architecture used is a head and child thread model. In this model one instance of the program is created and run per processor available to the program. In the case where the full 70 processors are utilized, one processor acts as a director. It distributes memory and loops to the children threads. The solution of the sum of number servicing nodes and sum of being serviced are distributed to the cluster. At the end of the process it was determined that speeding up the brute-force optimization requires more than just increasing processing power. The brute-force solve inside of COMMS can be modified so that only portions of the solve will be completed. For instance, if the user has an idea that the minimum number of nodes needed is higher than 1, they can specify a search start. In the example above, Table 5, the total number of solutions can be trimmed down by starting at 4 broadcast nodes. This leaves only 22 potential solutions, which is a savings from the total 63. This can be a saving in the number of potential solutions to check, but the majority of the possible solutions are when k is half of n. The distribution is normal and shown in Figure 9. This is also the point that replication of signal should be expected. The main search space for the routine is in the peak of the curve.
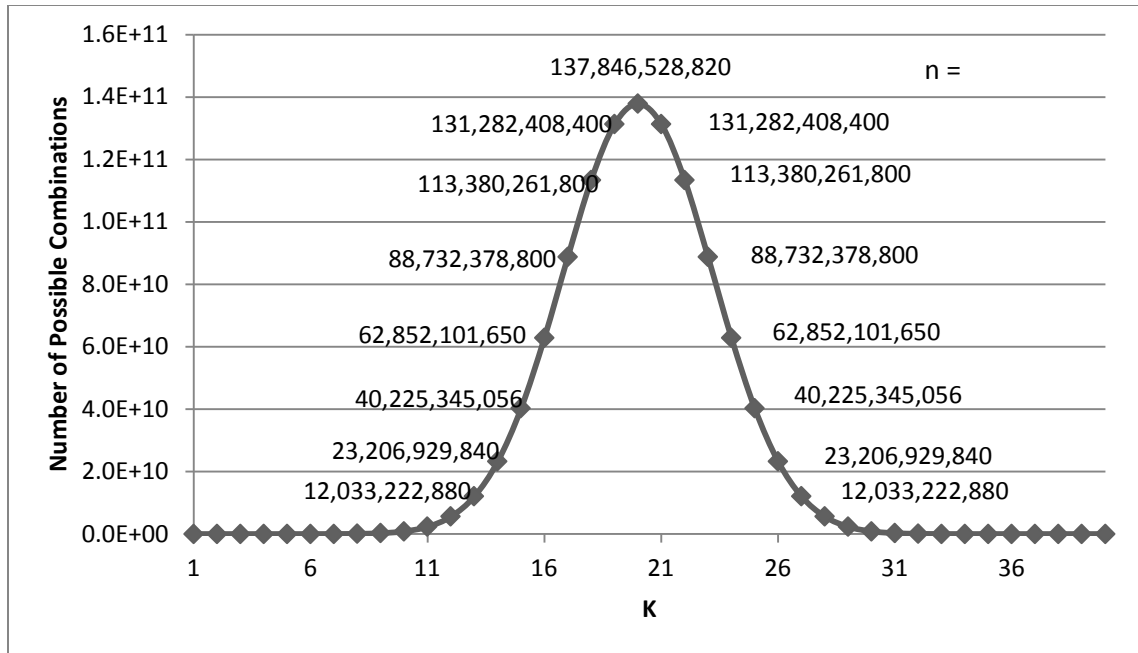
Figure 9 - N=40 Number of Combinations at K

Various efforts at making the simple calculations faster have been attempted and are ongoing. It is inescapable that a simple calculation done billions or trillions of times is impractical. The main reason for the various node types is to pare down the search area. The brute-force method may offer the best solution but not the best process.

Heuristic Optimization

COMMS has a heuristic optimization routine available to the modeler. The heuristic approach to optimization takes into account many different parameters of underground wireless systems. The heuristic optimize method can be run after the solve routine; however, it does not take into account the solution matrix, as does the brute-force algorithm. The heuristic engine also requires the user to select a starting point. The starting point can easily be selected where the primary escape way exits the mine.

From the first selected point the communication area is evaluated. The end points of the area are evaluated for a second point to be selected. The second point is selected from one of a few points. The search area is selected from the straightest and furthest points. The next point selected will have the most surrounding nodes without a signal that are required to get a signal.

The third and successive optimization points are selected in a similar manner. The successive nodes are considered by the engine to be more complicated. The network is a blind

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network and cannot determine the direction to follow. Instead up to 4 directions that are most promising are followed. If a direction does not have more than 50% increase in new nodes covered then it is not followed. The direction bearings are taken from the 4 longest and straightest paths. The routine selects the four next points that have the most number of new nodes in the communication area and the least number of repeated or already covered nodes. This process continues until the desired coverage level for the mine is achieved.

This process is fast and closely replicates the process used by manufacturers. The design process has been observed by the authors. The design process is assisted with software developed by the authors that uses COMMS as a component. However, amongst other irregularities the heuristic optimization tends to put two nodes next to each other in turns off the mains. These are areas that do necessarily require service, yet the locations of the broadcast sources are not ideal. While this produces the coverage desired, it requires additional consideration for factors such as multipath interference.

Ideally, a mine wireless system would be presented that had a system designed using the heuristic method. This would be compared directly to the output from the brute-force method. This would give an independent comparison of the solutions found. However, this is impractical even for a very simple network that does represent a real coal mine.

Conclusions

Further work is being pursued in modeling of underground wireless communication systems using COMMS. The COMMS system is able to create a nodal network, solve it and then analyze it in such a way to allow the engineer to design a communications system's broadcast locations. Location redundancy and/or protection from incidents will be covered in a later publication, as this work is also ongoing. The techniques used in the COMMS system were developed with the underground wireless mesh systems but are also being investigated with other wireless underground communication systems. Work is ongoing to combine the speed of the heuristic optimization techniques with the accuracy of the brute-force method. The brute-force method is preferred, but the time consuming nature of it makes it impractical. The heuristic based method discussed closely replicates the methods used by professional wireless system designers. More development is needed on this topic, and this development is currently

ongoing. Active research is in areas of optimization and evaluation of systems under emergency conditions.

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EVALUATION OF UNDERGROUND COAL MINE COMMUNICATION AND TRACKING SYSTEMS[4]

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Abstract

Underground coal mines in the United States are in the process of completing installations for tracking and communication systems, mandated by congress after a number of recent coal mine disasters. Yet, evaluation, modelling and testing of such systems has lagged due to the abrupt introduction into the coal mining industry forced by legislation. System installation in a wide array of mine types, configurations, layouts, and characteristics has provided a wealth of

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Steven Schafrik prepared and wrote the majority of this manuscript. Cary Harwood provided limited technical input. Kray Luxbacher and Michael Karmis and Stephen David provided editorial and technical input.

information regarding their potential in underground environments. Data collected from numerous installations for a variety of systems can be used to further define true capability and accuracy of communication and tracking packages. This paper describes a uniform means of evaluating the performance of a communication and tracking system. Several performance measures are proposed and described. These measures can also be predicted using an interactive software program. This program predicts the signal propagation given the input mine characteristics and layout with numerical and visual feedback. New or alternative system installations can also be more accurately designed to potentially minimize initial system cost and time required for trial and error installs. The focus of this research is to develop tools and protocols that can evaluate and measure the effectiveness of installed underground communication and tracking systems.

Introduction

The ability to track miners and communicate with them while they work in underground coal mines is important during normal daily operations, and critical in emergency conditions. As was evident during recent incidents at underground coal mines worldwide, communication with miners and the knowledge of their location is of great importance for rescue efforts and the preservation of life. In the USA, the Mine Improvement and New Emergency Response (MINER) Act of 2006 requires operators to improve accident preparedness by developing an Emergency Response Plan (ERP) specific for each mine. The MINER act also states that the mine must be able to "*determine the current, or immediately pre-accident, location of all underground personnel.*" Mine Safety and Health Administration (MSHA), the agency responsible for regulating and inspecting mines in the USA, will approve ERPs on a mine by mine basis. The ERP must contain how the mine communication system works, survives, and tracks miners, amongst other requirements. MSHA reviews determine the survivability of a system, which is established only by the redundancy (i.e., number of pathways to the surface) in the system (El-Bassioni, 2009). MSHA specifies that the tracking system must be able to determine the location of miners within 61 meters (200 ft.) at the working face and near strategic locations or key junctions and within 610 meters (2,000 ft.) in an escapeway (MSHA, 2009). These requirements are stated, but the terms are not clearly defined, and are to be evaluated on a mine by mine basis by the local MSHA District Manager.

In addition to approvals needed for the ERP, the communication and tracking system must be approved for underground coal installation and use. As of May 2011, 192 approvals for tracking and/or communication products were processed by MSHA, with 48 additional products still undergoing the approval process (MSHA, 2011). MSHA has categorized these systems into four major technology groups: Leaky Feeder, Fixed Node Based, Wireless Node Based, and Medium Frequency (MF). Other types of tracking systems have since been developed and are also seeking approval. These include Through-The-Earth (TTE) systems and various other radio frequency (RF) adaptations. Technologies that are currently being developed and adopted from other industrial applications, such as acoustical, optical, inertial, and hybrid systems, are also relevant technologies.

Leaky Feeder systems are based on a cable, or set of cables, that radiate and transmit RF signals. Fixed node and wireless node systems use RF source and destination nodes that create a communication network; they are distinguished from each other by the node interconnectivity medium. MF systems work on a wide frequency band that is used in common communication technologies. TTE systems work on a low band frequency that is capable of passing through solid rock (Snyder, 2007).

Some types of systems are more applicable to underground mines than others. For instance, systems that require continuous access to satellites are not suitable for underground applications, although personnel and some equipment will be above ground periodically. Access to satellite signals allows for calibration of these systems, e.g., Inertial Navigation System (INS), using Global Navigation Satellite Systems information. On the other hand, RF, acoustic, and optical systems are applicable to underground settings. The topology of an underground mine is complex and affects various tracking systems in different ways. Triangulation may be limited in a tunnel system since the geometry can result in both a lack of multiple direct paths and in geometrical dilution of precision where direct paths do exist. The known layout of tunnels can be used to improve tracking accuracy (Li, Snyder, and Damiano, 2009).

At present, there is not a uniform and accepted methodology to compare and evaluate the performance of installed systems for such widely varying technologies. Neither industry operators nor regulatory agencies are able to accurately assess the capabilities of installed systems in the continuously changing mining environment. Mines currently install partial or temporary systems to examine if they "work". Based on performance in temporary or

demonstration installations and system costs, a selection will be made and incorporated in the mine's ERP. Once MSHA has approved the ERP, the systems must be fully installed and maintained in accordance with the manufacturer's recommendations and the ERP.

The choice of tracking technology or technique is influenced by the specific communications technology that is used or planned for use in a setting. For example, different tracking technologies are compatible with each of three types of RF communication technologies used in underground mines. In the case of mesh networks, tracking capability is a straightforward addition to the system, while other technologies, such as leaky feeder systems and analogue MF systems, require use of separate tracking infrastructure such as Radio-Frequency Identification (RFID) systems (Novak, Snyder, and Kohler, 2010).

Research has been performed into tracking system performance measures, or metrics. Some of this work is centred on the method utilized (e.g., Time of Arrival, Time Difference of Arrival, and Received Signal Strength Indication) by the tracking system (Zeikempis, Giaglis, and Lekakos, 2003 and Hightower and Borriello, 2001). Some of these studies are targeted at indoor positioning systems (Sun et al., 2005) and are not applicable to underground mining applications. Published suggestions for assessment measures include:

- accuracy, blocking rate, coverage, and capacity (Tekinay, Chao, and Richton, 1998)
- accuracy, reliability, latency, availability, and applicability (Adusei, Kyamakya, and Jobmann, 2002)
- accuracy, precision, complexity, robustness, scalability, and cost (Liu et al., 2007)
- accuracy, integrity, availability, compatibility, interoperability, continuity, and communication (Progri, 2003)

A critical part of the adaptation of new and regulated technologies is the development of a standard means of discussion and definition of terms. Such a development of a methodology for assessment and means of discussion is being undertaken by the authors under a project funded by the National Institute of Occupational Safety and Health (NIOSH) in the USA. An objective of the project is to produce an analytical framework that is demonstrated through in-mine testing and refined using installed CT systems. The ongoing work incorporates many different technologies and technology providers.

Methodology

A methodology is being developed that characterizes the performance of an underground tracking system in industry accepted terminology such as coverage, accuracy, confidence radius, availability, reliability, robustness, susceptibility, and latency. By using the evaluation method in underground mines, testing against a baseline CT system arrangement, and refining through an iterative process, a standard performance characterization model can be established. That model can then be used to assess performance estimates for systems installed in specific mines. This, coupled with a planned portable test system, will allow operators and regulators to predict the performance of proposed installations and assess the metrics of each system as-installed. The methodology will ultimately have the capability of assessing not only the tracking systems currently employed in the field but new types of systems as technology develops.

The methodology will apply to any mine geometry using any tracking system and will be of benefit to both industry operators and regulatory agencies. For industry operators, a uniform methodology for evaluating tracking systems can be a useful tool for system selection given a particular mine layout. By knowing the limitations and expectations of a given system or systems, mine planners can effectively design mine works to accommodate the physical operating features of their selected system and plan accordingly. Regulatory agencies such as MSHA and state mining regulators can use the evaluation technique to ensure that the installed system and future extensions can meet the legislative requirements. All parties can benefit by using this tool for planning future mine expansion and adequate preparation for emergency response.

Two underground coal mines in the United States have been selected to perform testing of the evaluation methodology. Both mines are currently equipped with a unique arrangement and type of CT system. The two mines have differing physical features, underground equipment, and mining arrangements which are expected to aid in CT system testing in different underground environments. As work progresses, refinements to the evaluation methodology will be made from the in-mine test results from multiple visits and data generated from CT system logs.

Measures of Tracking System Performance

A tracking system should be capable of measuring its location accurately and also reporting that measurement. Using this definition, there are several terms that must be dimensioned to describe the performance of a tracking system. These terms describe the actual location, tracked location, and ability to communicate. A known location, such as a proper landmark that is assumed to have no error in location description, is to be used as a reference location. The Ground Truth Position Estimate (GTPE) is the position estimate relative to reference locations made using a measurement tool that produces errors that are a small percentage of the maximum error requirements of the tracking system under test. The Tracking System Position Estimate (TSPE) is the position estimate relative to reference locations made by the tracking system under test. The GTPE of a tracking device is relative to the reference location, the TSPE reported by the tracking system is relative to the GTPE. The difference in these three values, over time and in different conditions from different technologies, defines the measures of tracking system performance.

Under this project, the research team has proposed a set of performance metrics, based on widely accepted engineering terms, which can be used to describe the ability of a tracking system to function. These have been chosen to be consistent with tracking industry terms as well as the nature of underground coal mines. All tracking systems must measure some physical phenomena in order to generate a TSPE. Because not all conditions can be controlled in a complex environment like a coal mine, the characteristics of the measured phenomena will vary over time. In addition, tracking system equipment may introduce variability into measurements of the phenomena, e.g., from noise or variations in equipment configurations. Variations in measurements of physical phenomena produce variations in repeated measurements at a single location. In addition, the position, route, speed, and nature of travel may affect the measurement and processing of physical phenomena and cause variability in tracking system position estimates. The metrics listed below are equally applicable to all types of tracking systems in use in underground coal mines. The proposed metrics and their brief definitions are as follows:

- **Predictable Accuracy** is the difference between the location (GTPE) and the mean of repeated independent tracking system reported locations (TSPE). It is a measure of the

systematic error, or bias, of a tracking system. It may be reported as a magnitude or as an error vector. Each location tested may have a unique accuracy value.

- **Repeatable Accuracy** is the root mean squared deviation of repeated independent tracking system reported locations (TSPE) measurement results at a constant location (GTPE).

- **Confidence Radius** describes an area in which a level of location (GTPE) certainty, by precedent of measurements taken, may be reached by tracking system reported locations (TSPEs). Confidence Radius incorporates both the TSPE deviations of the Repeatable Accuracy metric and the TSPE deviations of Predictable Accuracy metric.

- **Relative Accuracy** is a measure of the error in the difference in position between two simultaneously tracked devices (e.g., the difference between simultaneously measured TSPE values at two different GTPE locations).

- **Coverage** is the area within the evaluation area in which a tracking system is able to function within metric values that are acceptable.

- **Latency** is the time difference between the occurrence of a change in location (GTPE) and when the tracking system generates and reports a corresponding TSPE.

- **Availability/Reliability** is the percentage of time that a tracking system meets its specified performance metrics requirements.

- **Susceptibility** isolates and characterizes the deviation of a system's metric values due to an individual event that occurs during the course of normal tracking system and mining operation from the variations that occur due to all variation during normal operation.

- **Robustness** refers to the effect on a system's metrics when an event outside normal operating conditions occurs, including failures of internal components to the system.

The tracking system performance measures described above do not consider the means by which the tracking system arrives at a location estimate. In this approach, the tracking system itself is independent of the measures and speed by which it performs, allowing for comparison of systems that use different technologies. As explained above, other work has suggested similar approaches, treating the tracking system as a calculator, not just as a technology. These approaches were useful in providing guidance; however, no single approach given was directly applicable to the underground mining case.

Underground Tracking System Simulation Method

Underground communications can be modelled by means of signal attenuation by distance and obstruction from signal source. COMMs is a computer method developed at the Virginia Center for Coal and Energy Research at Virginia Tech (VCCER/VT) which utilizes this method. COMM interacts with IntelliCAD and many sub-programs to calculate values, both quantitatively and qualitatively, for prediction of RF strength from sources. COMMs solves a mine's coverage values by building the communication network of the mine, solving the network, predicting ideal coverage, and optimizing the communications network (Griffin, Schafrik, and Karmis, 2010).

COMMs is a suite of software that provide mine network building, radio signal propagation, tracking prediction from signal strength, and mapping of position estimates. Nominal levels of radio signals transmitted and received by components of a tracking system at each tunnel location in a grid covering a specified area, are used in the tracking predictions. Tracking system position estimates of a stationary tracked device are at each tunnel location in a grid. Tracking system position estimates of a tracked device moving through a sequence of tunnel locations at specified velocities using nominal signal levels at each tracked location can also be calculated. These values can also be used for relative position estimates between two tracked devices moving through a sequence of tunnel locations at specified velocities using nominal signal levels at each tracked location. A component of the system provides statistical deviations from nominal levels of radio signals transmitted and received by components of a tracking system.

The tracking system simulator will allow the user to simulate signal levels in mines at frequencies from 450 Kilohertz (KHz) to 6 Gigahertz (GHz). Simulation of L-3 ACCOLADE® system performance provides the source data for the development of the simulation. The simulation is done by signal attenuations, which make it independent of the frequency.

Simulations estimate the level of attenuation of radio signals propagating through mine tunnels and structures. The propagation model parameters come from a literature survey and mine measurement results. The system being developed will provide the capability to incorporate new propagation models with minimal modification of other simulator functions (Schafrik, Luxbacher, and Karmis, 2011).

Mine Features

Mine tunnels act as waveguides (Emslie, Lagace, and Strong, 1975) and, therefore, mine features affect attenuation from one point in a mine to another. As feasible, the simulation software imports physical information about mine features from the mine map. This information is used to create an estimate of signal strength based on details of the mine environment. Not all mine features influencing signal attenuation are available from mine maps. The features not included in mine maps may contribute to uncertainty in simulation results. RF systems are sensitive to atmosphere and atmospheric effects (Collin, 1985). These may be manually entered into the simulation by attaching attenuation values to the communication paths taken by the simulation.

The following mine features are assumed to be constant over simulation time and affect signal attenuation. Where possible, information about these features is imported from the mine map and included in simulation calculations.

- Tunnel network structure
- Intersection shapes and number of connections
- Propagation path direction change at intersections
- Tunnel cross section
- Stoppings, overcasts/undercasts
- Conveyor belts, mechanics, and structures
- Elevation changes (vertical tunnel bends)
- Roof mesh
- Gob/roof falls/cribbing

The two underground coal mines selected for testing exhibit all of the above features in different arrangements and quantities. Many of the features appear on mine maps produced by the operator. Those features not available from the mine maps can be visually observed and subsequently placed into the model manually.

Estimate Of System Performance

Performance measures that can be used for evaluation of mine communications and tracking systems are defined above. It is important to describe how the values of these metrics may be

predicted, so that predictions, or hypotheses, can be tested. Test results can and will be used iteratively to improve the prediction model, to the point where the predicted results are a reasonable approximation of results achieved underground. Because of the time and space dependence of the tracking metrics; the prediction process must be grounded in a good understanding of the states of the particular underground environment, considered in the following section. It is expected that metric values interrelate.

Coal Mine Circumstances/States

Numerous events can occur in an underground mine environment that can alter the baseline performance of tracking systems. Any change in an underground coal mine setting that affects the tracking system performance metrics will, for the purposes of this project, be classified as a variation-causing event. There are three types of such events: Intentional events, unplanned events and background events.

Intentional events are planned events or cycles that are routine or expected in a mine setting. A list of routine or "common cause" variations from intentional occurrences are identified.

- Outby mobile equipment movement
- Face mobile equipment movement
- Foot traffic of underground miners
- Construction of stoppings, roof and rib supports
- Tracking system maintenance/extension
- Communication system signals
- Stationary underground equipment operation
- Electrical current fluctuations
- Ventilation changes
- Movement of tracking system components

Unplanned events are significant, typically localized, and usually fairly sudden events that can affect the performance of a tracking system in underground coal mines. These events can sever tracking system redundancy paths and possibly separate portions of tracking system networks. A partial list of unplanned or unexpected disturbance events likely to cause special variations listed below.

- Outby mobile equipment failure/immobility

- Face mobile equipment failure/immobility

- Emergency foot traffic of underground miners

- Power interruptions or loss

- Interruption of tracking network

- Tracking system component damage

- Tracking system component failure

- Pooled water accumulations

- Flood or inundation

- Changes in entry cross-sections

- Total blockage of signal path (e.g., collapse)

- Partial blockage of signal path (i.e., change in cross sectional area)

- Fires/Explosions

Background events that may also affect tracking system performance can be attributed to measurable changes in the mine environment that do not necessarily provide an individually distinguishable impairment. Humidity, pressure, and suspended solids in the mine atmosphere are examples of parameters that can affect the tracking system but are difficult to repeat experimentally in the mine environment for specific degradation of performance. Measurable changes in the underground coal mine environment possibly affecting tracking system performance are listed below.

- Changes in humidity
- Changes in air pressure
- Suspended solids level in the mine air
- Electrical power supply variations
- Changes in temperature
- Solids/moisture adhering to system components
- Ventilation air velocity changes
- Electromagnetic radiation from other sources
- Various density mine gases in ventilation air

Performance Measures and Mine States

The Robustness of a tracking system has been defined as its operational change or reaction to an interruption or repeated interruptions. This metric is confined to nonstandard operating events such as those listed as unplanned events or background changes. Tracking capabilities may be lost in some areas while others may only experience reduced capabilities temporarily. Planned events are not expected to affect the Robustness of the tracking system installed. System components should be capable of withstanding general maintenance and frequent relocation as required by the manufacturer or as necessary according to constantly changing underground mine conditions.

The Susceptibility of a tracking system to be affected by a disturbance event is measured by its reaction to intentional events. The result can be a reduced tracking capability or a complete loss of any tracking capabilities for a local area or entire network. This can be a function of the event geometry (extent of affected area) and the event duration. When the event affects a greater area, the expected area of tracking system network capability variation is expected to rise. Events that have a very short duration may not have a measurable effect on the performance of a tracking system if latency is high. Conversely, Latency can be affected by all of the planned and unplanned events listed above. If any event causing an interruption has a duration longer than the update frequency for the network then the signal can be assumed to be interrupted, therefore increasing the system Latency.

The Confidence Radius, Repeatable Accuracy, Predictable Accuracy, and Relative Accuracy of a tracking system can all be affected by the events described as planned disturbances, unplanned disturbances, and measurable changes above. Since these performance metrics require measurements of TSPEs and GTPEs, any events occurring during or for the duration of the TSPE collection period can affect the distribution of the data. This could either increase or decrease deviation distribution, providing false information in reference to the GTPEs.

Coverage will be affected differently for each type of event described above. Intentional events can be taken into consideration when designing and installing a tracking system in an underground coal mine. Redundancy in coverage capability of network components can compensate for expected operational events that create blockages or interference. System coverage can remain unchanged in ability during these events while still providing the prescribed

performance. These events and conditions may be replicated in the underground test areas with the exception of the catastrophic events that void all underground equipment, such as a flood inundation or exceptional explosion.

Summary

The ability to track and communicate with miners while in underground coal mines is required during both normal daily operations and emergency situations. A method of evaluating the numerous technologies that have been developed, adapted, and deployed to meet tracking requirements of the 2006 MINER Act is being developed. The results of this study will provide a uniform methodology for evaluating underground coal mine communication and tracking systems. The evaluation method will have not only the ability to assess the performance of current systems available for underground use but also those technologies that are adapted for this purpose. A comprehensive methodology for reproducing specific mine characteristics and modelling the performance of various communication and tracking systems will be provided with this evaluation method. The end product will aid underground coal mine operators, system manufacturers, and regulatory agencies in ensuring that communication and tracking systems are effective and meet regulatory requirements. Information developed from this methodology will assist mine operators in mine designs that are more efficient from a communication and tracking standpoint, resulting in safer and more efficient work places.

Acknowledgements

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BASELINE ANALYSIS OF PREDICTED TRACKING SYSTEM PERFORMANCE[5]

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Introduction

A few years ago, most mines had limited or no electronic tracking or wireless communications system in place. Mine operators were only aware of the names of the individuals that were in a mine at a given time, but had little knowledge of each individual's location. As a result of coal mine disasters and fatalities, the United States Congress passed the Mine Improvement and New Emergency Response Act (MINER Act) in 2006. Among other changes, the MINER Act amended existing laws and mandated that the current location of all underground personnel should be determined by the above ground personnel. US coal mines had three years to comply and should have a wireless tracking system plan in place for their miners as of 2009.

A number of systems were developed and installed that allowed for both tracking of underground personnel as well as two-way communication between the surface and miners underground. Although tracking and communications may seem unrelated, current systems combine both, since the underground location of personnel needs to be communicated to the surface in real time. For tracking systems the main design constraints are the accuracy

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[5] This paper is intended for publication. Portions of this text are modified from the Analytical Methodology Report For NIOSH BAA 2010-N-12081 "Development of a Uniform Methodology for Evaluating Coal Mine Tracking Systems"
Steven Schafrik collected the data, researched, and wrote this manuscript with significant technical input from Michael Karmis and David Snyder.

constraints. According to guidelines, the location of an individual should be known with an accuracy of +/- 2000 ft. (~660m) when not in an active mining section or near strategic areas, whereas in active mining sections or strategic areas, the miners' locations should be known within 200ft. (66m).

Measures of Tracking System Performance

Tracking systems can be measured by a set of metric values that are described in this section. The metrics are based on the accuracy of position calculations across a special area over time. The purpose of the metrics is to provide a basic set of values that can be calculated simply and are independent of the technology used in the tracking system. The metrics treat the tracking system as a black-box calculator and are only concerned with the actual location of a tracked device and the tracking system's calculation of the location of the tracked device. The tracked device's actual location is expected to have very little error in the location relative to the tracking system and is referred to as the Ground Truth Position (GTP) or the Ground Truth Position Estimate (GTPE), used interchangeably. The tracking system calculates a location for the tracked device. This location is referred to as the Tracking System Position (TSP) or Tracking System Position Estimate (TSPE), used interchangeably. These two positions can be thought of as where the device really is located (GTP), and where the device is considered to be located by the tracking system (TSP) at a point in time. The technology used by the tracking system and its reporting capabilities will have the major impact on the details of how one collects data form the tracking system. These details are not covered in this report. It is assumed that all tracking systems installed in underground coal mines will be capable of reporting a tracked device's history over the last 14 days in sub-minute time frames. Only metric values used in this report are discussed. Other important metrics such as Reliability, Availability and Relative Accuracy are discussed elsewhere.

The most basic metric is the **Tracking Coverage Area** (TCA). Tracking Coverage Area (TCA) refers to the area within the mine that the tracking system either actively measures a tracked device's location or infers it based on the spatial limitations of the mine and information other than active measurements. This is the area of the mine in which the tracking system is working. Because mines are confined spaces the TCA can be broken into Active TCA areas, where the tracking system is actively producing TSPs or Inferred TCA, where the TSP is not

being actively calculated, but the general position can be ascertained. It is worth noting that in some mines there will be areas that miners rarely go, and where the electronic tracking system makes no attempt to determine the location of a tracked device, these areas are referred to as untracked or manually tracked areas.

The next fundamental metric is the Instantaneous Accuracy (IA) of the TSP. Instantaneous Accuracy (IA) is the difference between an actual location (GTP) and the tracking system position estimate (TSP) actively made at that GTP at an instant in time. This is a simple straight line distance from any single TSP to the GTP at the same point in time.

Instantaneous Accuracy:

$$IA_0 = \sqrt{(TSP_{x0} - GTP_{x0})^2 + (TSPE_{y0} - GTPE_{y0})^2}$$

The GTP of a miner's location at time T_0 is $(100, 100)$. The TSP for the miner's location at time T_0 is $(96, 103)$. The Instantaneous Accuracy at time T_0 is

$$IA_0 = \sqrt{(96 - 100)^2 + (103 - 100)^2} = \sqrt{-4^2 + 3^2} = 5.$$

At any location in the mine, over time there will be several TSP values that are calculated. For these TSP values there will be an associated IA, but the general accuracy of the tracking system for that area is described by the Average Accuracy and the Standard Deviation of Accuracy.

The Average Accuracy (AA) is the arithmetic mean of a set of IAs and the Standard Deviation of Accuracy (SDA) is calculated by taking the standard deviation of a set of IA measurements.

Average Accuracy:

$$AA = \frac{\sum_{i=1}^{N} IA_i}{N}$$

Standard Deviation of Accuracy:

$$SDA = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (IA_i - AA)^2}$$

X% Confidence Distance (X% CD) is the distance from a tracked device's actual location (i.e., GTP) that is greater than X% of the collected Instantaneous Accuracy measurement magnitudes ("X percentile"). Confidence Distance can be specified as a metric based on a

standardized, fixed percentile of measurements, as this section is entitled, but a variant of the concept can also be specified with a percent of TSPs occurring within a standardized distance. This metric is only descriptive within the Active TCA, because it derives from a set of IAs.

The 90% Confidence Distance (90%CD) describes the 90th percentile of IA values from a GTP. This is an IA measurement in which there is a very high confidence, 90%, that a subsequent IA calculation will be within the 90%CD. The calculation is done by ranking IA measurements and the IA that is at the 90th percentile rank is the value. This metric value is the closest match to the regulatory guidelines of accuracy required in various parts of the mine. The important difference is that this is a confidence that a value will be within the limit, it is not a set measurement. For instance, an IA value at 105 ft., in an area where the 90%CD is 100 ft. is not an indication that the 90%CD of that area is in fact larger than 100 ft. A set of measurements that show a 90%CD greater than 100 ft. is an indication that the 90%CD should be increased for that area.

The values of for AA, SDA and 90%CD as calculated for a particular system/section are one dimensional representations of the accuracy of the tracking system. It is also important to describe the relative skew in the TSP in two dimensions to physically locate a tracked device on a map. The Analogy of the IA in two dimensional space is the Error Vector (EV), which is the simple difference vector between the Cartesian X and Y components of the GTP and TSP. The Average Error Vector (AEV) is the average displacement of a set of TSPs from their corresponding GTP. The Average Cluster Radius (ACR) is the average of distances a set of TSPs are from their center point, which is the Average Error Vector end point. These values are determined by normalizing each GTP and the average TSPs to their corresponding relative location. The resulting graphs show the bias and spread in the tracking system, which is described by the AEV and ACR.

Error Vector:

$$\langle EV_{x0}, EV_{y0} \rangle = \langle TSPE_{x0} - GTPE_{x0}, TSPE_{y0} - GTPE_{y0} \rangle$$

For a set of **N** TSP measurements in the Active TCA and corresponding GTPs, the Average Error Vector (AEV) is expressed as the vector representing the average EV associated with the set.

Average Error Vector:

$$\langle AEV_x, AEV_y \rangle = \left\langle \frac{\sum_{i=1}^{N} EV_{xi}}{N}, \frac{\sum_{i=1}^{N} EV_{yi}}{N} \right\rangle$$

In order to describe the variation of the set of TSP around the AEV, the Average Cluster Radius (ACR) is described. This is the average of the distance of a TSP from the AEV end point. It describes a circular area around the AEV end point within which the average TSP value would be located.

Average Cluster Radius:

$$ACR = \left(\sum_{i=1}^{N} \sqrt{(TSPE_{xi} - AEV_x)^2 + (TSPE_{yi} - AEV_y)^2} \right)/N$$

This report covers the method of taking a mine map with locations for a mesh based tracking and communication system and predicting system performance in terms of metrics. A test site is discussed in detail which was used as a demonstration of the techniques developed.

Simulation of Tracking System Performance

Prior to the installation and testing of the communication and tracking system, computer simulations were used to generate anticipated results. These predictions are then used as the baseline for the system under test. In this project there is one system under test; it is a partial mesh system that has several different components that provide network resources. The system uses fixed nodes that are powered by mine power with battery backups. This backbone has tracking beacons that are used to supplement the tracking calculations. Tracked devices are the same radios or handsets that are used to communicate.

Testing was performed in a mine in central West Virginia that is typical of central Appalachian coal mines in dimension and mine design. This mine has been in place and actively working for several decades. The area studied is at the mine's portal, an area that has 10 entries in total, 4 of which are return air and were excluded from the data in this report. The intake and neutral air splits, where passable, were considered in the data included in this report.

The communication and tracking system hardware was installed, with the assistance of the authors, using guidelines to be obtained from the manufacturer. Placement of infrastructure will be based on designs provided by the manufacturer and estimates that are generated by the

authors as presented here. The system installed will be referred to as the Test System, and not by the manufacturer's name.

Example Mine Layout

The analysis flow begins with the mine map (in this report it was an established mine) but mine projections will work with this technique as well. Because the analysis is intended to demonstrate the technique for the typical mine with a typical installation, the design of the tracking system was determined by the manufacturer. This prevented the desired software results from dictating the system design. Software simulation flow that is followed in this report is shown graphically in Figure 10.
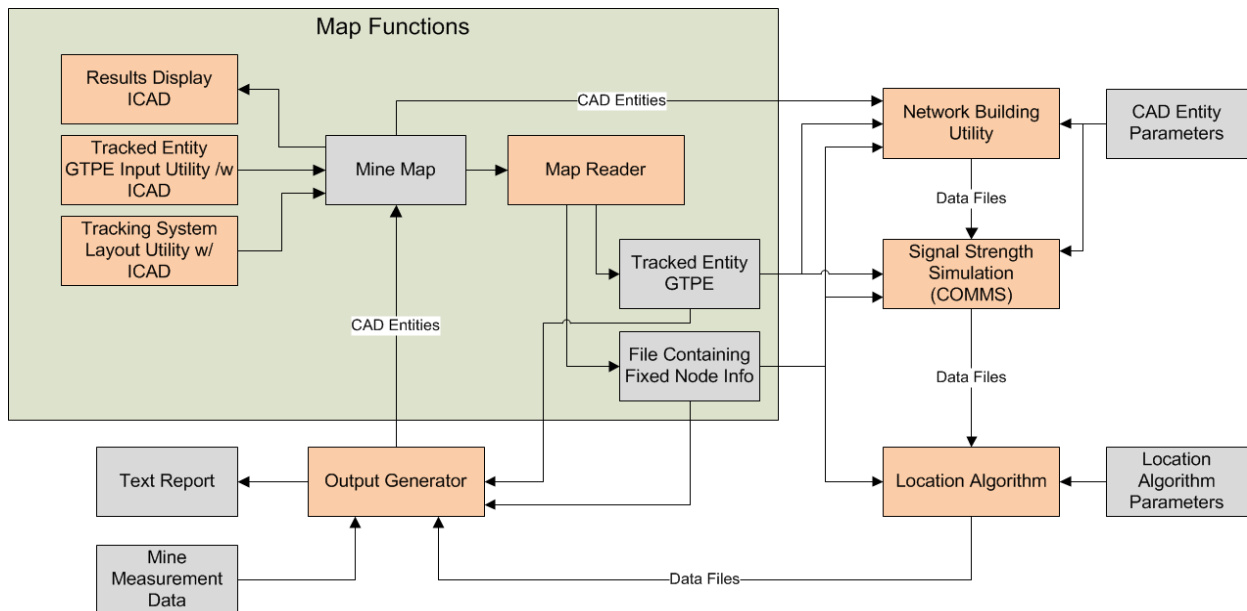

Figure 10 - Function blocks and data flow for simulation results

The function blocks start with the Mine map. In this study only the Mains section of the mine is under consideration. This area of the mine is shown in Figure 11. The portal is indicated on the map as well as key infrastructure, such as power transformers (red dots), ventilation controls (blue lines), ventilation air splits (red arrows for return air), conveyor belts (green line), track haulage (orange line) and existing tracking units (yellow dots).
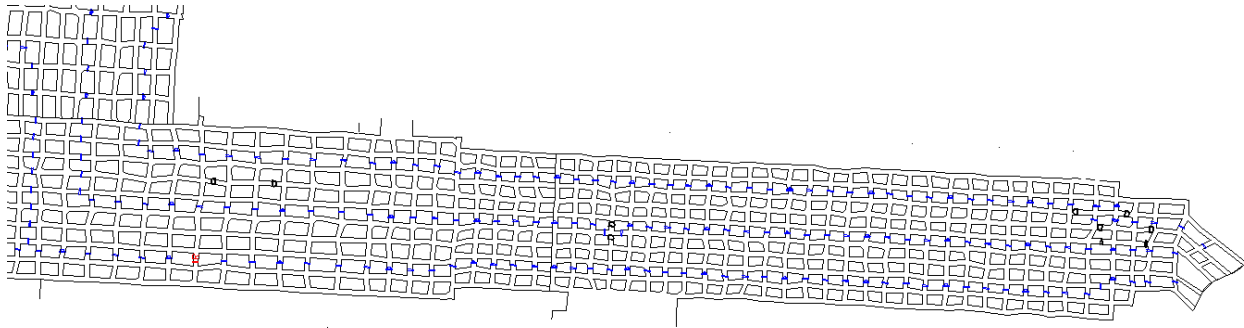
Figure 11 - Map of Mains Area

Current regulations require that the mine track the location of miners in the primary and secondary escapeways and in special areas to which miners are trained to go in emergencies. Areas of the mine not normally occupied by workers, which are not places a worker would go to in an emergency are not required to be actively tracked. In the case of the Mine, the area in which coverage will be tested is enclosed in the gray regions in Figure 12.

The currently installed tracking system is an RFID tag system with readers located at the portal and the turn. This provides small active TCA that indicates the transient presence of a tracked entity, but leaves a majority of the Mains structure to be left as an inferred TCA.
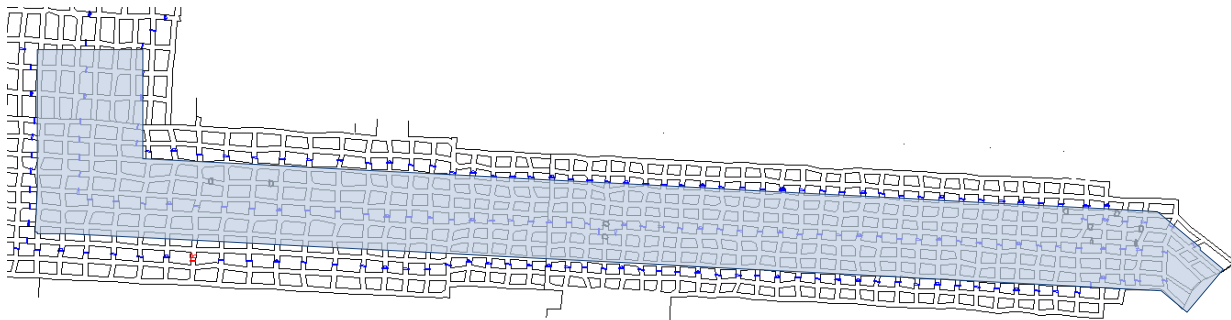

Figure 12 - Coverage Area

In the Test System, a tracked entity must be in radio contact in order to be actively tracked. During active tracking, a computer running software in the mine office receives frequent reports from mobile radios relaying signal strength the mobile radios measure from fixed radios in range (Fixed Mesh Nodes, or FMNs, and Beacons or BCNs). The locations of the fixed nodes are known to the computer, via the tracking database, which applies a proprietary algorithm to estimate the location of the mobile radio. The antenna and fixed node placement in the mesh network is determined by the system manufacturer based on the manufacturer's system design procedure. The signal level modeling tool developed for this project, generates estimates of

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tracking system metrics at a large number of locations throughout the mine area under evaluation. The same calculations of tracking system metrics can be produced manually, though much more efficiency is possible when using the simulation tool.

The calculation of metric values follows the flow presented in Figure 10. The mine geometry is extracted from the mine map and simulation locations emplaced at every intersection of entries and crosscuts, and also at locations halfway between the intersections. Mesh infrastructure device locations and configuration are likewise emplaced as CAD entities, being input parameters from which the signal paths to each simulation from each antenna are found. The CAD entity parameters determine signal loss of the path with the least nominal loss. The simulator then runs a number of statistical cases chosen by the analyst, for which the path loss is varied in a uniform distribution within the range of variation of loss along each path. The output from these predictions is used to calculate metrics for the tracking system. The estimated nominal and variation values used are listed in Table 7.

Table 7 - Nominal Values and Variation used in Simulation

Parameter	Nominal Value, dB	Max. Variation, dB
Transmitter Power, at antenna	BCN: -2 dBm	+/- 1 dB
	FMN: 16 dBm	+/-1 dB
Forward propagation loss in entries and crosscuts	6 dB/100 ft.	+/- 1 dB
Loss through ventilation control stoppings	14 dB	+/- 5 dB
Loss around 90 degree corner	36 dB	+/- 10 dB
Loss crossing conveyor belt	17 dB	+/- 10 dB

After calculation of the signal levels and variations at a location are completed, the manufacturer's tracking algorithm is applied to signal strengths appearing at half-pillar and intersection locations to generate calculated position estimates. These position estimates in turn are used to determine the estimated values of tracking system metrics. Two examples of plots of 250 TSP around the GTP for which they were simulated are shown in the four illustrations that follow. For the first example, a close-up of the mine map where the selected GTP is shown in Figure 13.
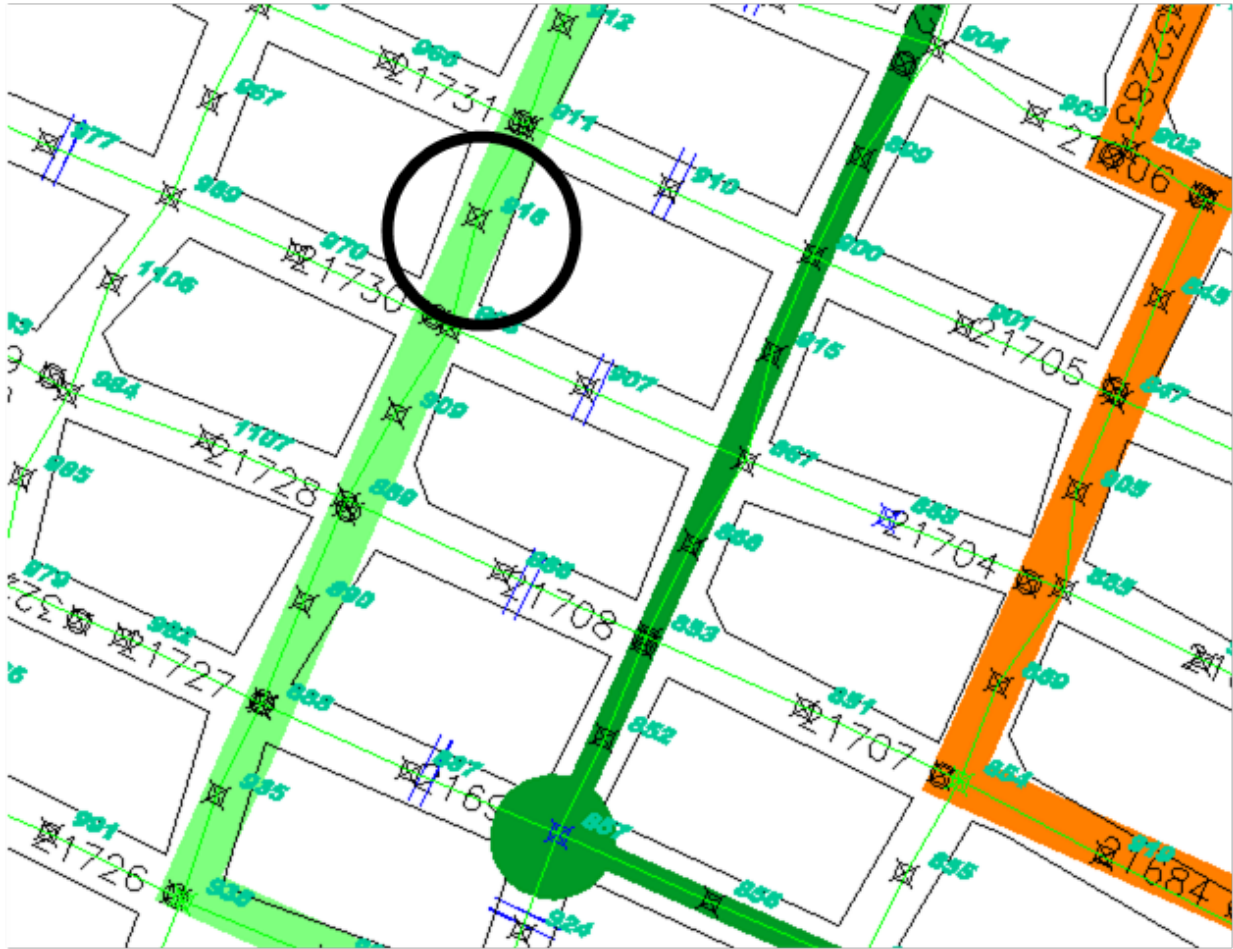
Figure 13 - Mine map view of GTP location 916, on primary escapeway about 4650 ft. inby portal

Next, is the scatter plot of tracking position data around location (GTP) 916 for randomized signal attenuation factors. The maximum tracking error for this example is less than 40 ft.
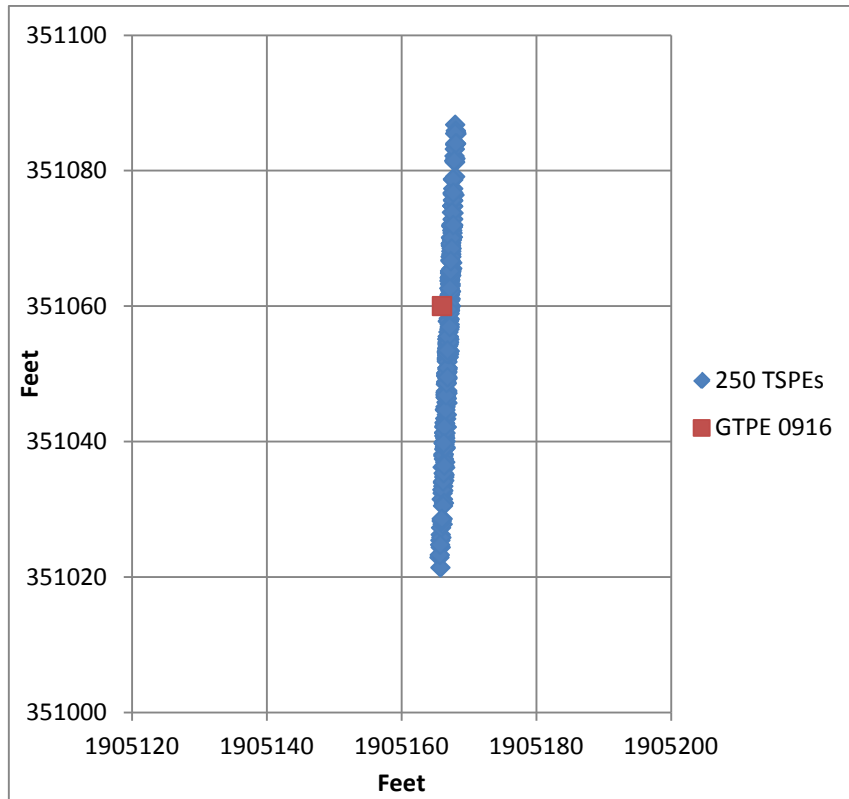
Figure 14 - Plot of 250 randomized TSPs around GTP location 916.

Plotting the scattered TSPs shown in Figure 14 and adding some of the nearby fixed radio nodes on the mine map, renders an option view like the one in Figure 15: Both show a straight line pattern because this location receives signal only from two nodes. As the RSSI input values are varied for the tracking algorithm, the location is varied along the Escapeway.
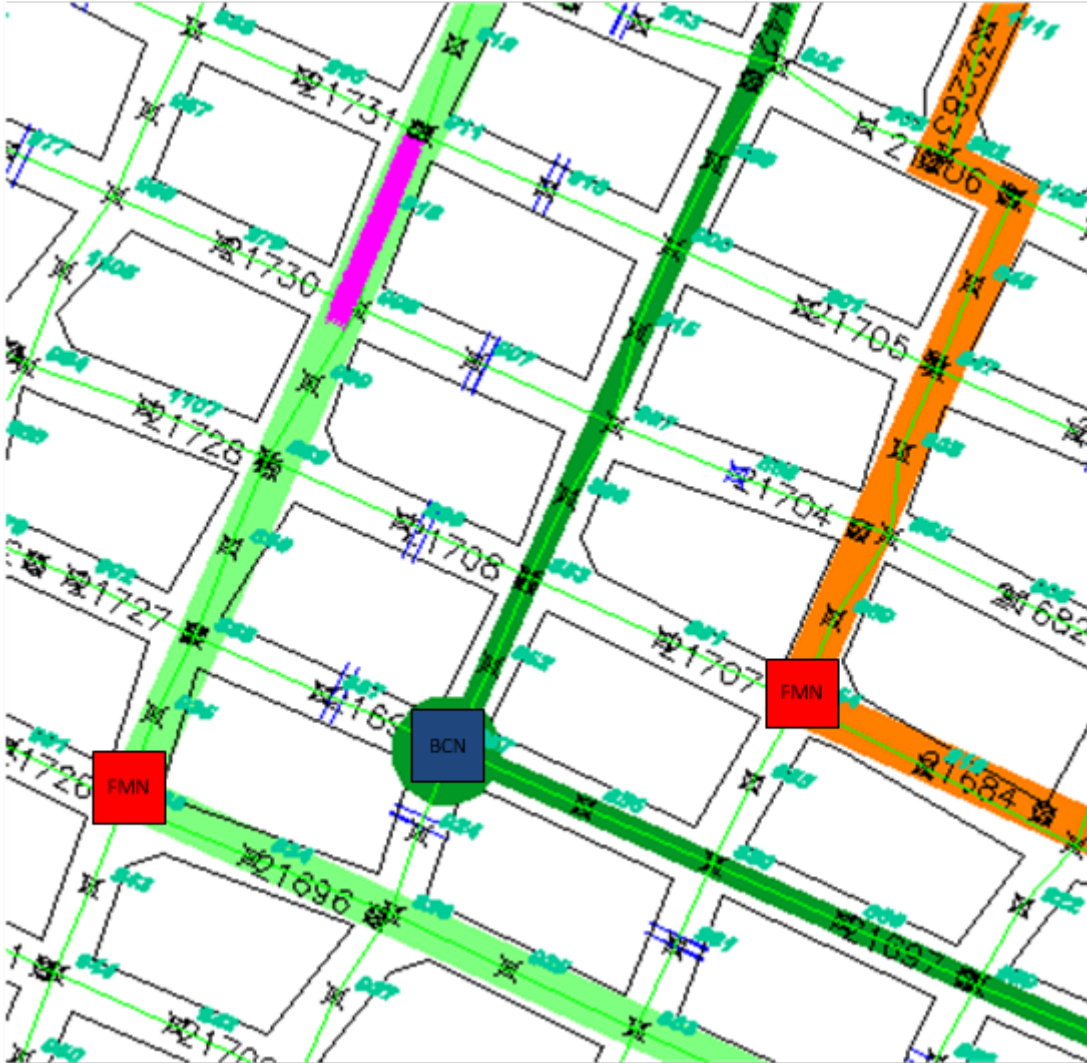
Figure 15 - Plot of simulated tracking TSPs around GTP 916 superimposed on the mine map.

Next is an example of tracking results at GTP 357 located about 800 ft. inby the portal on the secondary escapeway. Figure 16 shows the location enclosed in a ring on a portion of the mine map:
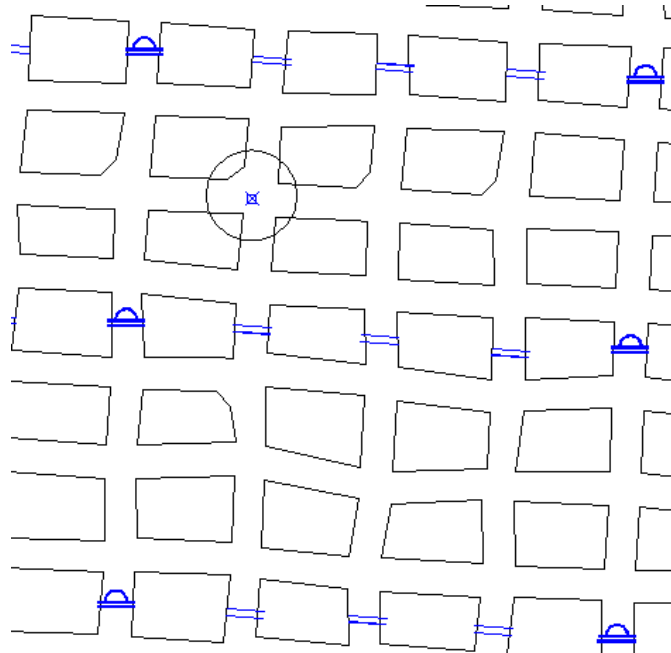
Figure 16 - Close-up of mine map showing the location of GTP 357 (encircled), an intersection on the secondary escapeway.

The next illustration, Figure 17, is a scatter plot with proportional mine map scale showing the 250 TSPs produced from tracking measurements made at GTP 357. The maximum tracking error for this location is a single outlying TSP at a distance of 971 ft. inby GTP 357.
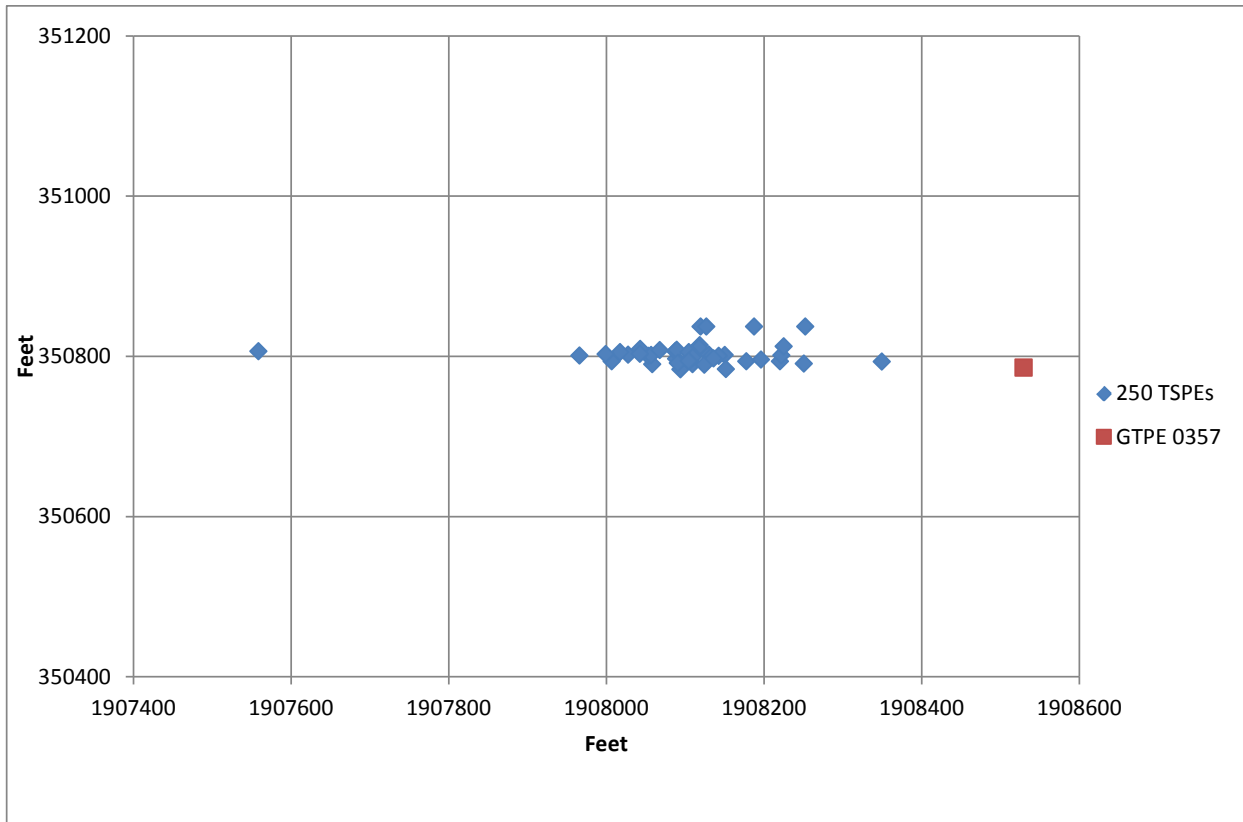
Figure 17 - Proportional plot of 250 simulated TSPs for GTP 357.

The simulations and calculations also can estimate how changing the tracking system component configurations affects the metric values. Node and antenna position shifts and addition or removal of nodes are examples of configuration changes that can be evaluated. When accurate values of the CAD entity parameters are determined, the simulation and calculations of metric values for different tracking system configurations may help optimize system design to meet tracking system requirements.

The goal of this project is to cover the primary and secondary escapeways and typical strategic areas in the study portion of the Test Mine, and generally to get signal into the belt entry, which is not an escapeway in this mine. The Test System layout for the Test Mine has been designed by the vendor to provide radio coverage to meet the communication and tracking standards set by MSHA.

In Figure 18 through Figure 25, the fixed mesh nodes (FMNs) themselves are shown as blue ellipses, however, the placement and direction of the antennas connected to the FMNs is the most important factor for modeling signal levels throughout the mine. Antenna positions and orientations for each FMN are shown by the blue arrows.   There are 15 FMNs underground, and

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two above-ground just outside the primary (entry 5) and secondary (entry 7) escapeway ("EW") portals. The belt entry (entry 6) has no FMNs and is expected to receive radio coverage through crosscuts from entries 5 and 7. The two FMNs above-ground provide links to the gateway node (GWN) at the control shack. The gateway nodes in this case are ignored in the simulation because they will have no underground signal. Beacons are shown as purple ellipses. There is one about 210 ft. inby from the portal on the belt entry. There are 2 at SCSR caches, about 2,500 ft. and 4,300 ft. inby the portals, and 1 at the belt head at the corner, also approximately 4,300 ft. inby. Figure 18 provides an overview of the test area and radio tracking node deployment used for baseline simulations. Pictures on following pages (Figure 19 through Figure 25) show more detailed views of the deployments.
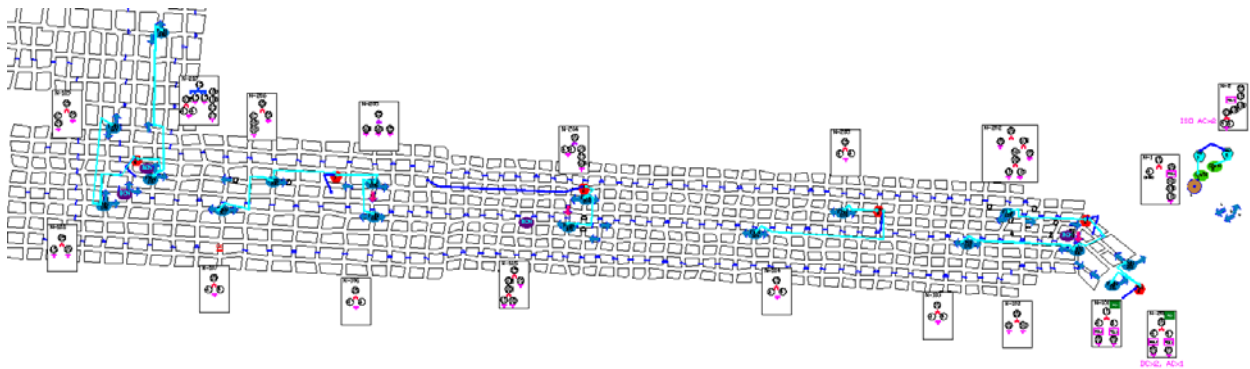

Figure 18 - Overview of Test System

Figure 19 depicts the outside nodes at the portals, linking to the first inby pair of fixed nodes on the escapeways. The outside FMNs have antennas pointing into the portals and also to the gateway at the control building about 300 ft. away. Figure 20 shows the short distance of underground coverage afforded by the FMNs outside the portals. However, the short distance assures robust links to the FMNs at the dog-leg bends in the entries in the middle of the picture. Also note the airlock door (large "D" symbol) which may attenuate radio signals, one cross-cut inby the secondary EW (orange color).
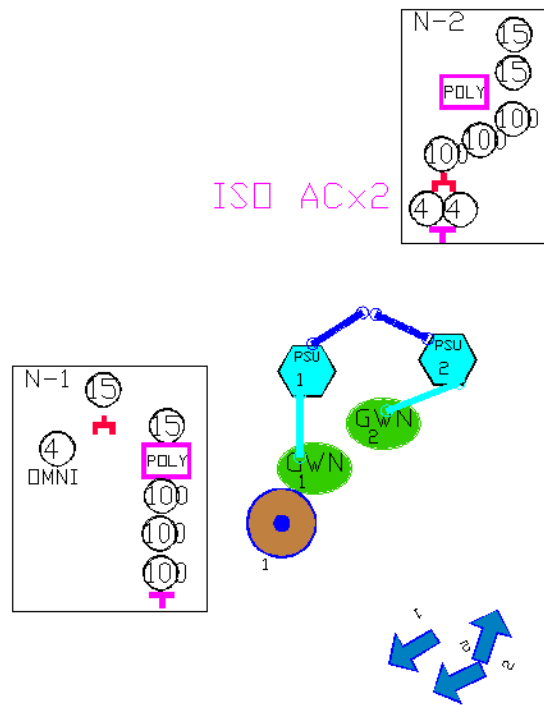
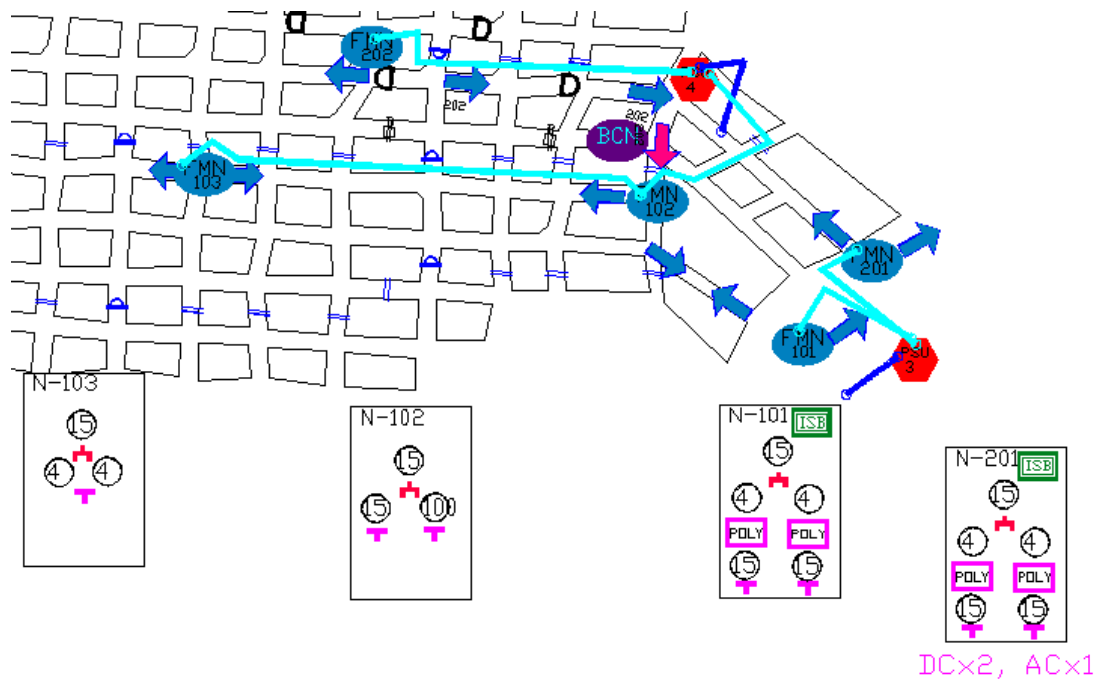**Figure 19 - Layout - Gateway Nodes and Antennas at the Mine Office Building**

Figure 20 - Layout- FMNs at the portal

Figure 21, next, shows in detail the location of FMNs and respective antenna directions about 700 ft. inby from the portal on the primary EW.   The nearest FMN on the secondary EW is also shown. The two airlock doors on the secondary EW, also shown, attenuate radio signals passing through them. Antennas on the secondary EW are placed on either side of the air lock doors. These antennas are connected to FMN 202 by coaxial cables avoiding attenuation due to the air lock doors, providing coverage.
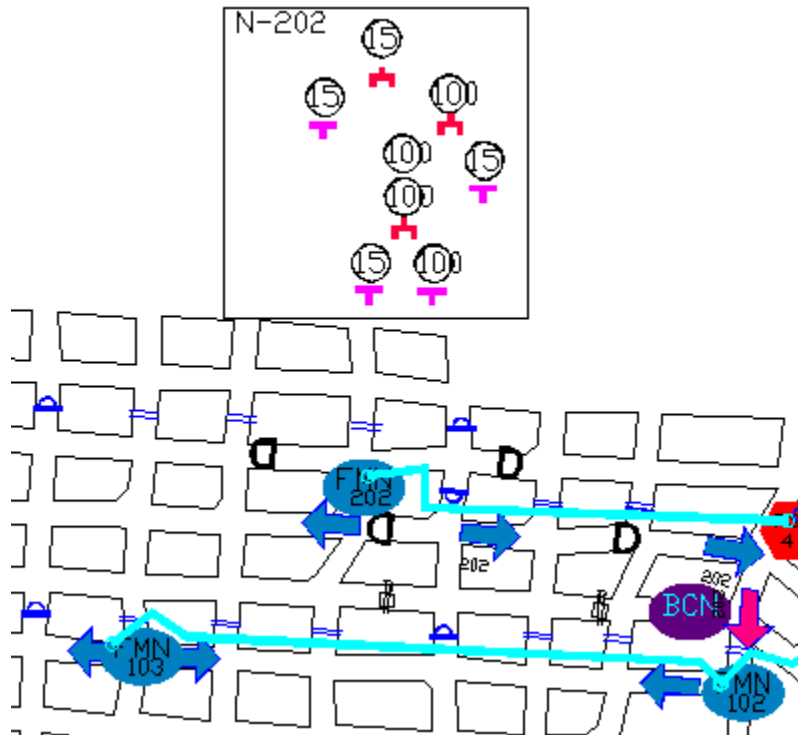

Figure 21 - Layout - Primary EW node about 700 ft. inby from the portal and nearest secondary EW node

The next picture, Figure 22, shows mine features in the area of the FMNs deployed about 1,600 ft. inby the portals on the primary escapeway. The FMN on the secondary EW several breaks outby is also shown. These nodes provide network links in long straight sections of these entries. FMN 104 on the primary EW is 900 ft. from the next FMN outby, FMN 103. FMN 203 is 700 ft. from the next FMN outby, FMN 202 on the secondary EW.
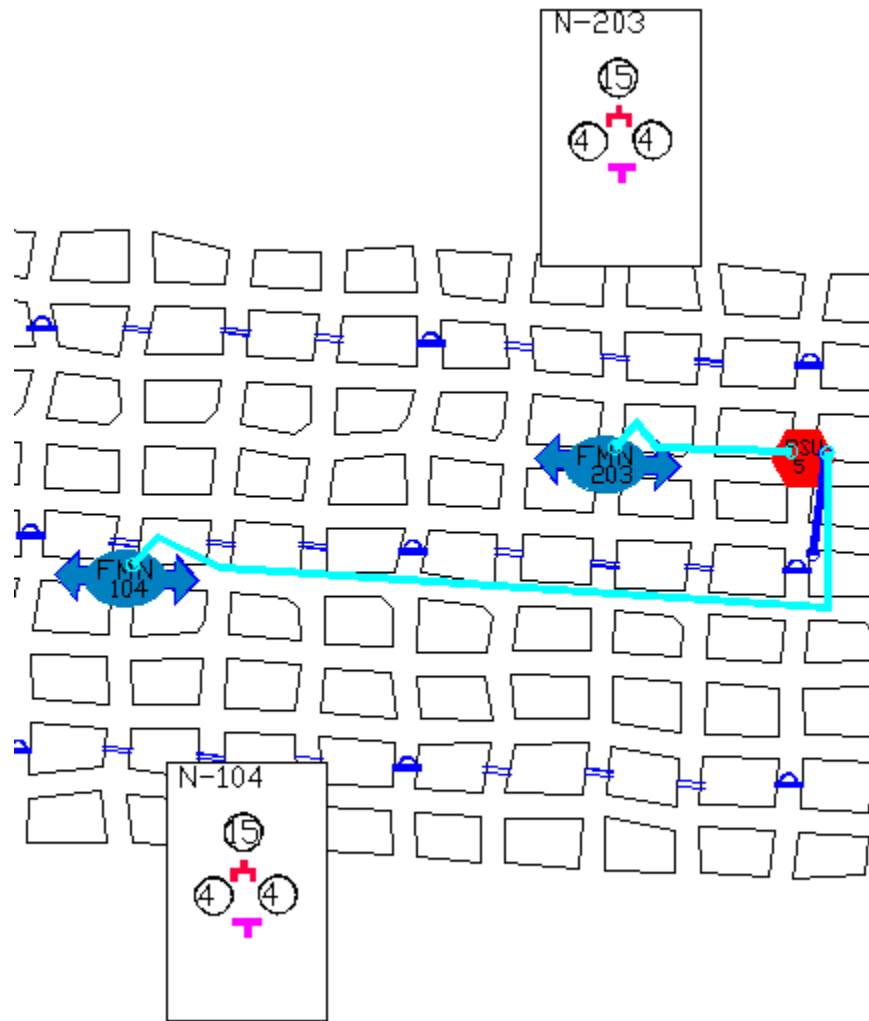
Figure 22 - Layout - Primary EW node about 1600 ft. inby from portal and nearest secondary EW node.

Figure 23, next, shows the FMN layout 2400 ft. inby the portals on the primary EW. Of interest in this picture is the primary EW detour to entry 4 for two breaks and then back to entry 5, around a pair of airlock doors providing vehicle access to the belt entry, and two related stoppings blocking entry 5. The SCSR cache is designated a "strategic area" by the operator, where more accurate tracking is warranted, and accordingly a beacon is placed at the cache. In the Test System, mobiles radios carried by mine personnel report receipt of signals from nearby tracking beacons via the communications links afforded by the FMNs.
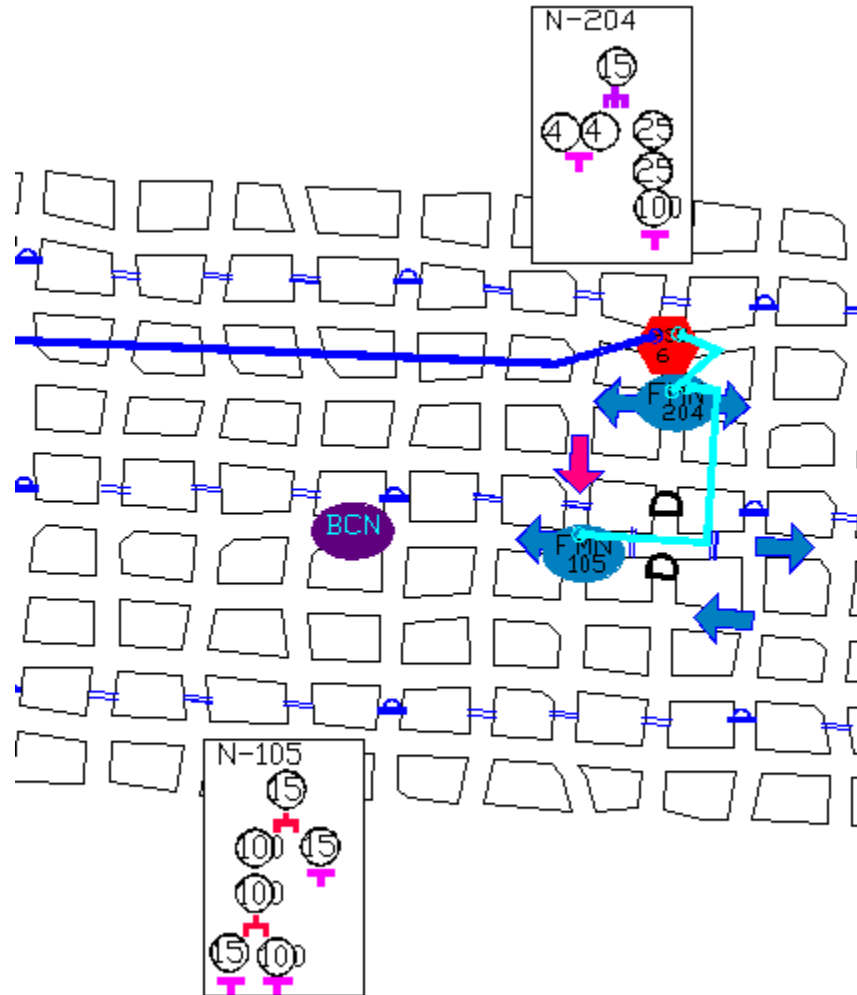
Figure 23 - Layout - Primary EW node about 2400 ft. inby from the portal and nearest secondary EW node.

Figure 25, shows location details a pair of FMNs in the area near 3200 ft. inby on the primary EW. These nodes provide links in long straight tunnel segments with no major obstructions.

Figure 24 –Layout- Primary EW node about 3200 ft. inby from portal and nearest secondary EW node

Figure 25 shows the FMN on the primary EW 3,850 ft. from the portal. The nearest FMN on the secondary EW, also shown, is located between a set of air lock doors. The inby pointing antenna associated with the node is positioned inby the airlock. .
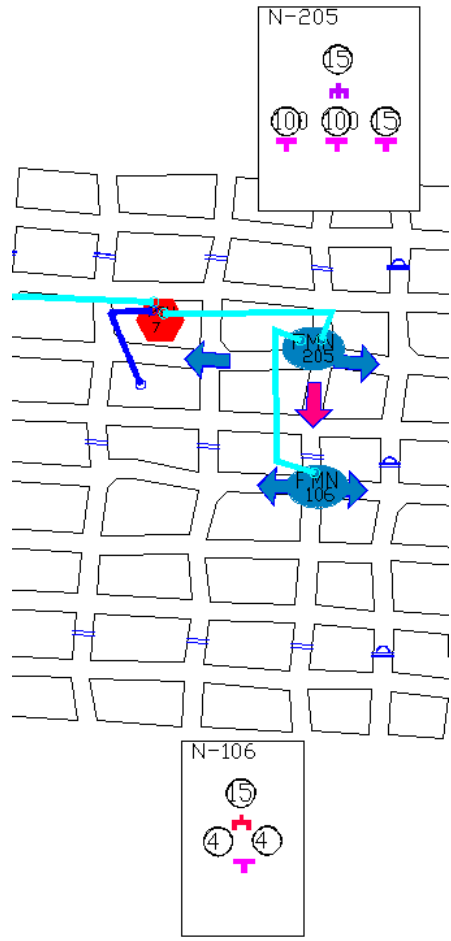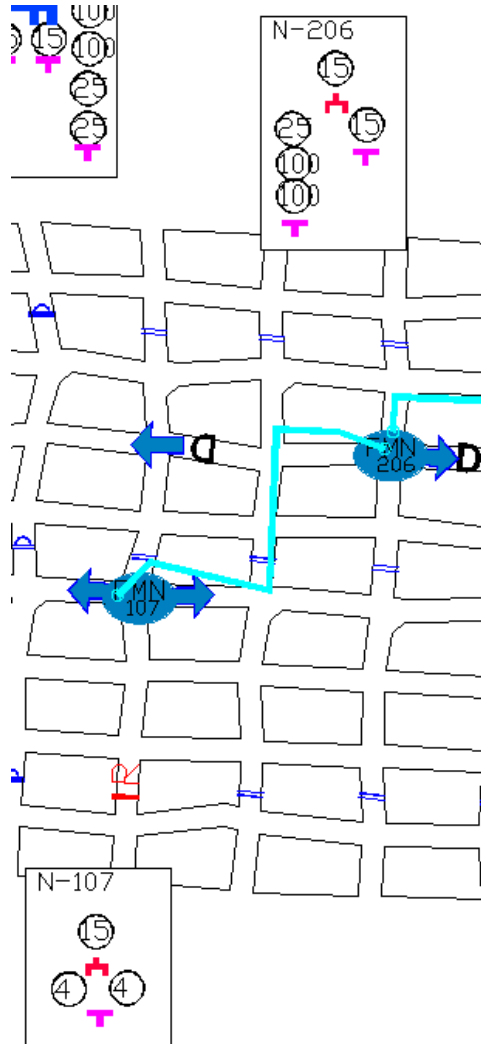
Figure 25 - Layout - Primary EW node about 3850 ft. inby from the portal and the nearest secondary EW node.

Figure 26, shows the terminal portion of the EW test area. The 90 degree corner of the primary EW is about 4400 ft. inby the portal. There are two beacon locations in the area of the corner. The primary EW FMN is at the corner with two antennas directed at right angles, inby and outby. The secondary EW FMN at the corner has three antennas configured for 25%/25%/50% power split. The 50% portion is directed outby toward the airlock (backward "D" symbol at the lower right of the picture). One of the two 25% portions is directed inby on the secondary EW, covering the approaches to the SCSR cache and associated beacon there; and the other 25% power portion antenna is placed in the belt entry enhancing coverage there, with the strategic area beacon located at the belt head.

The inby-most portion of tracking test area has two FMNs at offsets in entry alignment resulting from change in pillar dimensions. These locations allow antenna placement which should assure signal past these offset corners. The inby-pointed antennas of these FMNs are estimated to extend coverage to well over 5000 ft. inby the portals on both EWs.
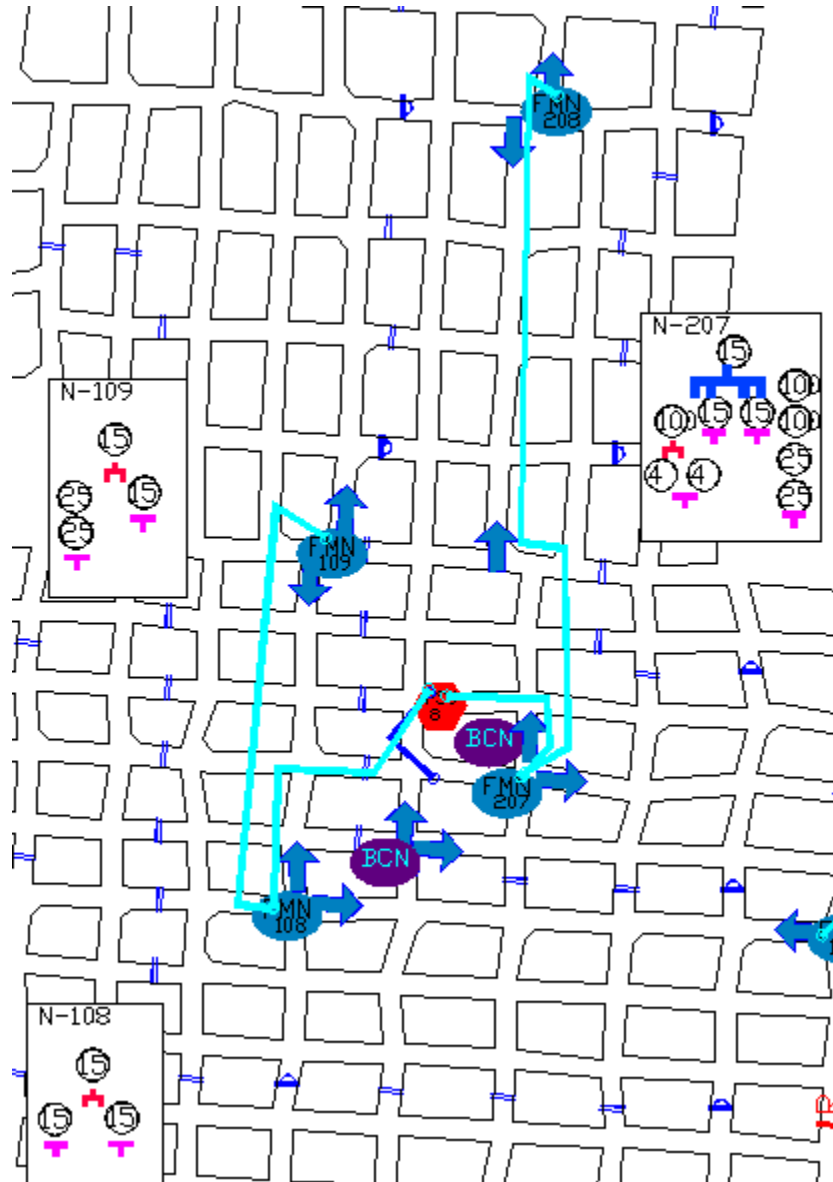
Figure 26 - EW node about 3850 ft. inby from portal and nearest secondary EW node.

Using the mine map, the Network Building Utility was run in order to create the network that can be used by COMMs, the signal strength tool, to create field strength values that may be used by the tracking calculator. The tracking calculator values can then be used to show the

metric values in various Zones. A majority of the network is automatically generated by the utility and a full version of the network is shown in Figure 27 with a detailed view in Figure 28.
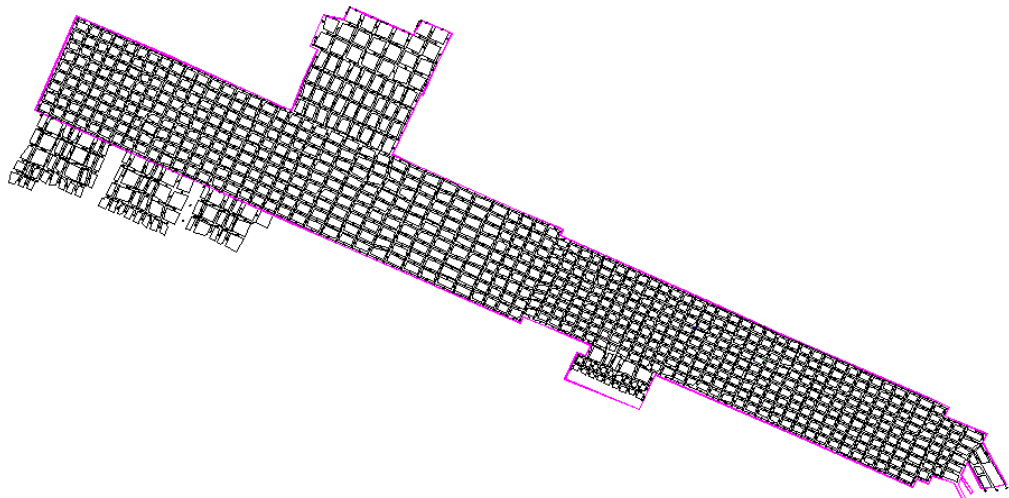
Figure 27 - Isolated mains area of Mine with COMMs Network
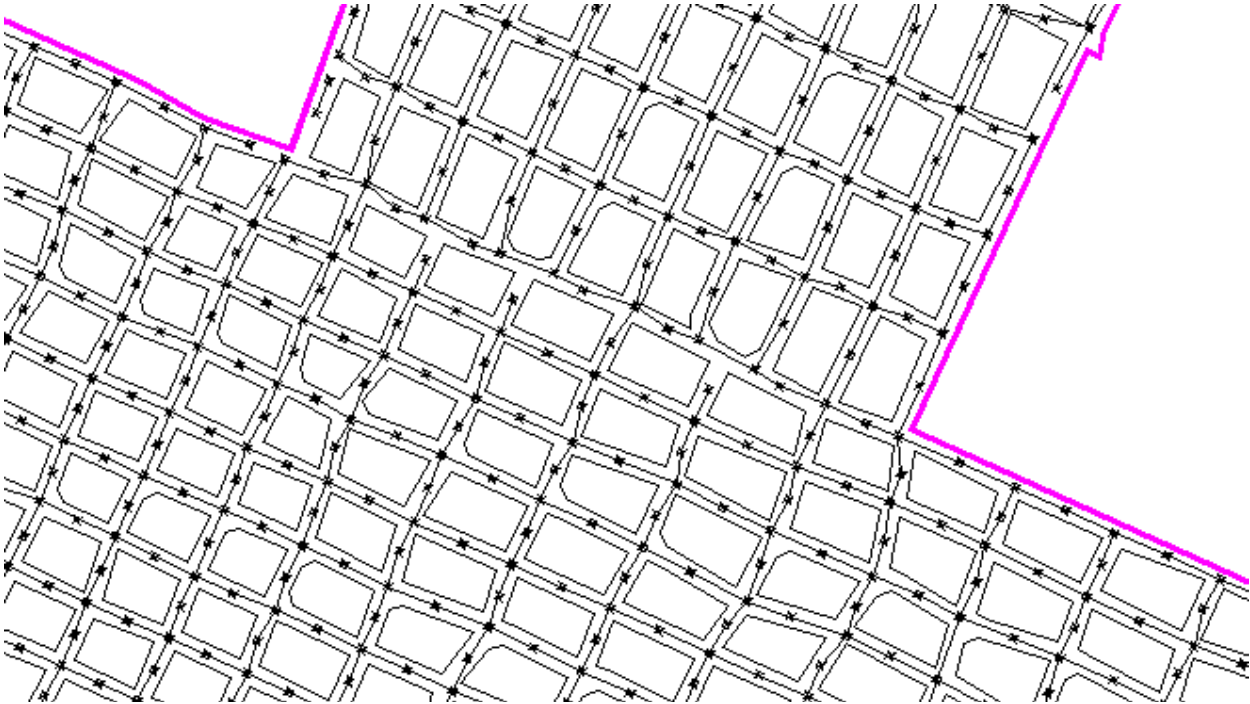
Figure 28 - Detailed Area of the COMMs Network

The area of the mine that is in the ventilation returns have been removed from the network, as shown in Figure 29.
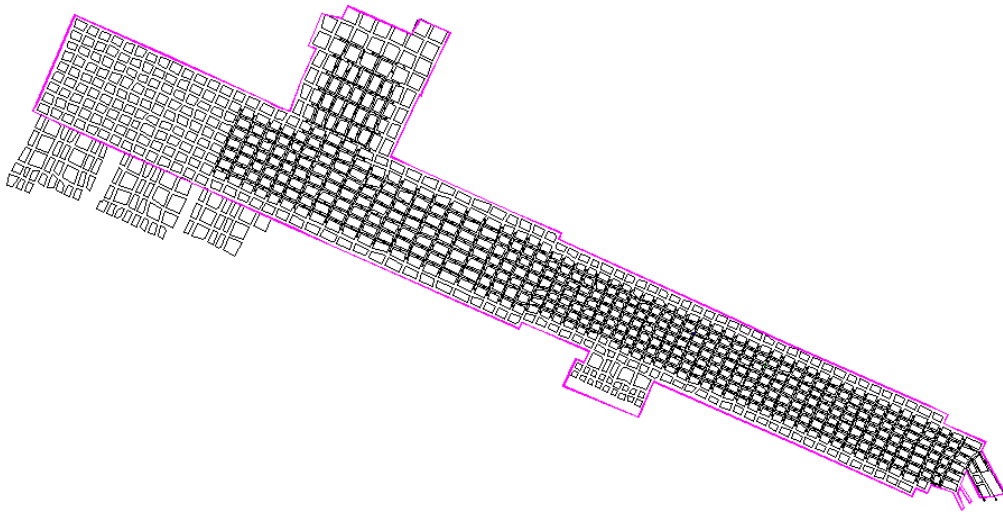
Figure 29 - Reduced Network

The reduced network is then used to place the FMNs and BCNs as described in the layout, Figure 19 through Figure 25. An example of this is shown in Figure 30. The connections between the intersections have been changed to grey for display purposes. The intersections containing FMNs are shown in light green, and the links from the intersections that contain the directional antennas is also depicted in light green.
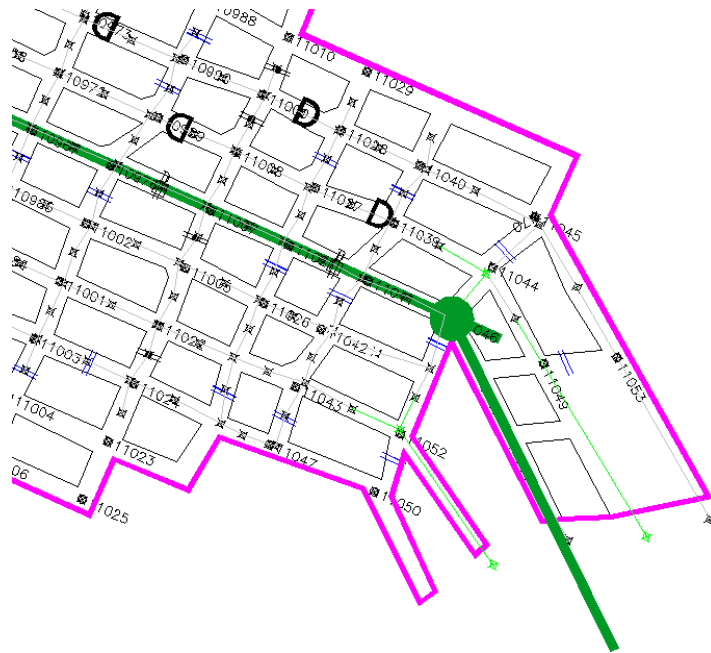
Figure 30 - Example Layout Including Antenna Directions

After all the nodes and beacons were inputted into the model, the areas that receive adequate signal for communications are calculated Figure 31 through Figure 33 show these "radio

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coverage" areas as magenta lines. There are several links that are not covered, but the intersections on both sides are covered. Each map does show an area that is expected to have degraded radio coverage, but this is not in the primary escapeway or along the belt. For each broadcast location a database file is generated that shows all the other locations in the mine and the maximum signal that is available in each of those locations. The database files are used in the next step.
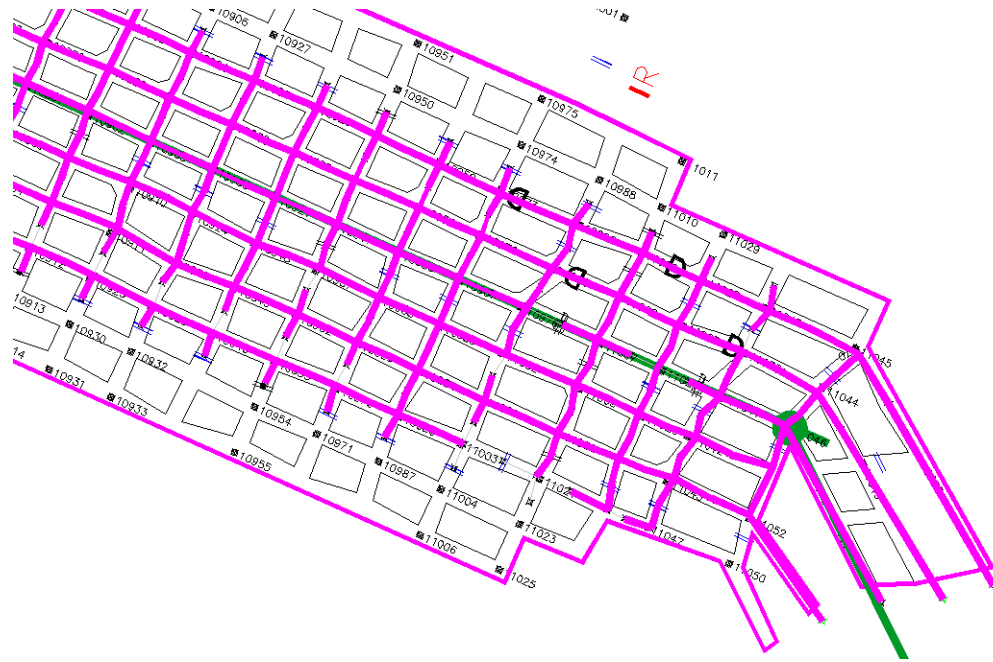
Figure 31 - Radio Coverage Map 1 of 3
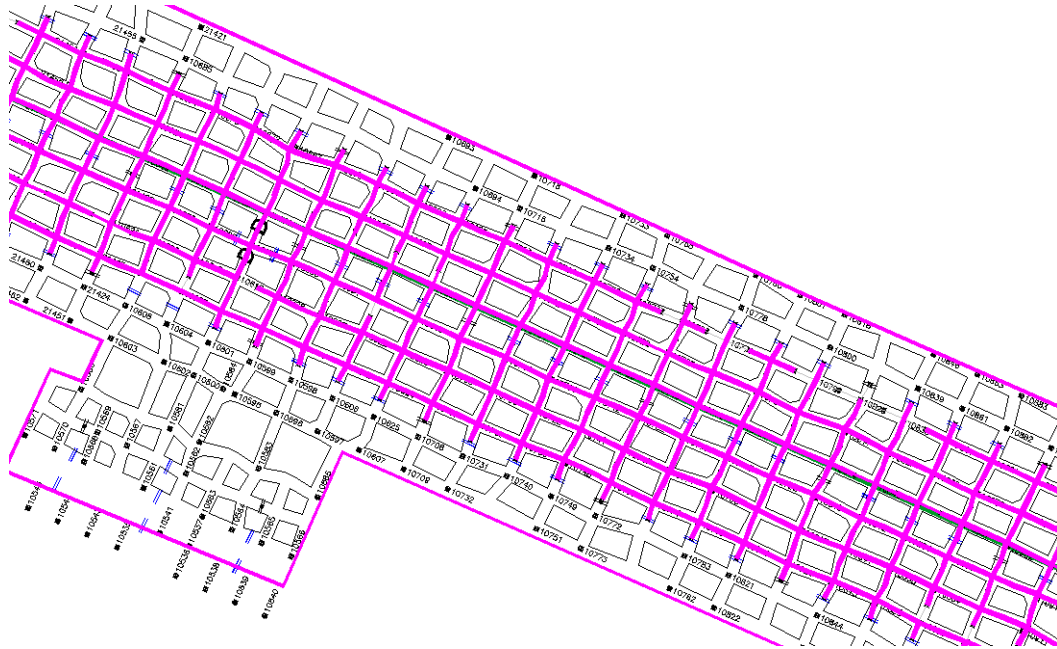
Figure 32 - Radio Coverage Map 2 of 3
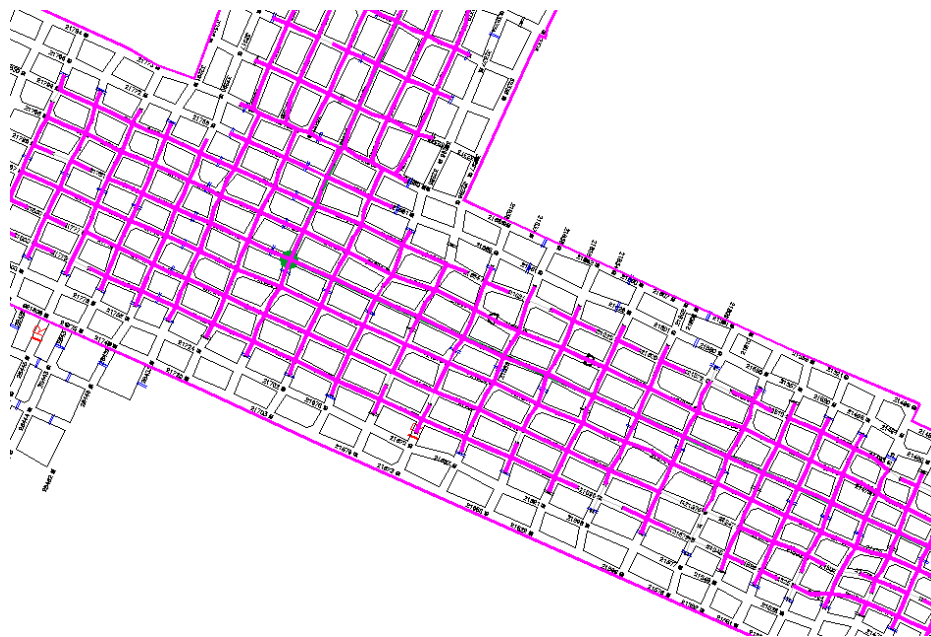
Figure 33 - Radio Coverage Map 3 of 3

The prediction point GTPs along the primary and secondary escapeways were selected as inputs into the tracking simulation. This simulation interrogates the signal strength that is available from all signal sources in the model. These values were calculated in the previous step as well as a variation value in the form of a confidence interval. This average value and confidence interval are used by a pseudo random number generator that is capable of outputting

numbers that meet a prescribed statistical model. In this case, a uniform distribution random model was picked and a sufficient number of random values were made to show the randomness of the system, 250. COMMs will also output the header and position files that are used by the tracking simulator. The tracking simulation will then output a coordinate in X,Y pairs that are in mine coordinates.   This means that for an intersection in the mine (GTP), 250 signal strength estimates generate 250 coordinates (TSPs). These values are used in the subsequent calculations. The estimates represent the answer from the model; they are not inputs to the design. If the values are unacceptable, areas of the mine must be examined to modify the tracking accuracy. This process is consistent with the current standard practice.

Metric Values in Example Layout

Following are examples of metric calculations to describe the tracking system as installed. Some metrics are not described because they are not predicted in this analysis. For instance, latency will not be described. The scenario based metrics - Susceptibility, and Robustness - are not described. For all of the following metrics, areas of the mine are modeled. For instance, all of the intersections along the primary escapeway are listed out as the GTPs of interest. For each of these GTPs, 250 TSPs are generated. These TSPs are used in the calculations. The following is a summary of the simulation results:

- For the static testing area in the test mine, the Active TCA is highlighted green in Figure 12. The Inferred TCA will sporadically occur in the entries adjacent to the escapeways as shown in Figure 31 through Figure 33. No escapeway inside the test area may have tracking error greater than 2,000 ft. and no strategic area will have tracking error greater than 200 ft. Therefore this FMN configuration will mean that the static testing area in test mine will be included in the Compliant TCA. The Compliant TCA is the area inside the TCA where tracking quality guidelines are met.

- For the primary escapeway in the Test Mine, it is expected that the Instantaneous Accuracy (IA) of measurements ranges from 1.14 ft. (nearly perfect IA) to 1,237 ft. For the secondary escapeway IA is calculated to range from 1.33 ft. to 985 ft. The belt line is covered, but in spite of its much higher attenuation, rendering lower signal strengths, the IA range from 1.25 ft. to 896 ft. remains comparable to that of the escapeways.

- Based on this estimated installation of Test System equipment, the simulation predicts the primary escapeway in Test Mine will have an AA of 267 ft. and AA will be 334 ft. in the secondary escapeway. The calculated AA in the beltway is 383 ft.

- The primary escapeway simulation IAs have an SDA of 248 ft. and the secondary escapeway is comparable with SDA of 217 ft. The beltway SDA is 221 ft.

- Figure 34 though Figure 36 graphically shows the Average Error Vector and the Average Cluster Radius for the three areas of interest in the mine. The primary escapeway has an ACR of 94 ft. with an AEV of <212,-26>. The secondary escapeway has an ACR of 73 ft. with an AEV of <152,-7>. The belt entry has an ACR of 89 ft. with and AEV of <95,-25>. These AEVs are consistent with the angle of the mine, meaning the tracking system is calculating the TSP in the correct entry, but the distance inby is variable. The linearity of the primary and secondary is therefore expected. The belt entry shows a greater spread, and this can also be anticipated because the entry does not contain any transmitter equipment. Therefore, some TSPs tend to be drawn to the primary and secondary escapeways where the signal is stronger, located in this mine respectively on either side of the belt entry.
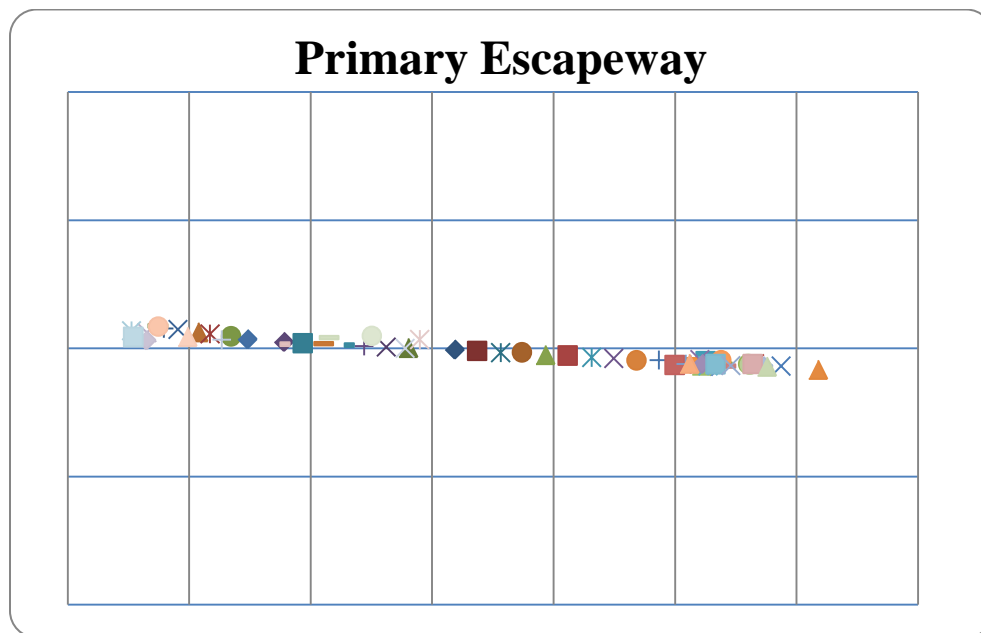

Figure 34 - Average TSP Plot along Primary Escapeway
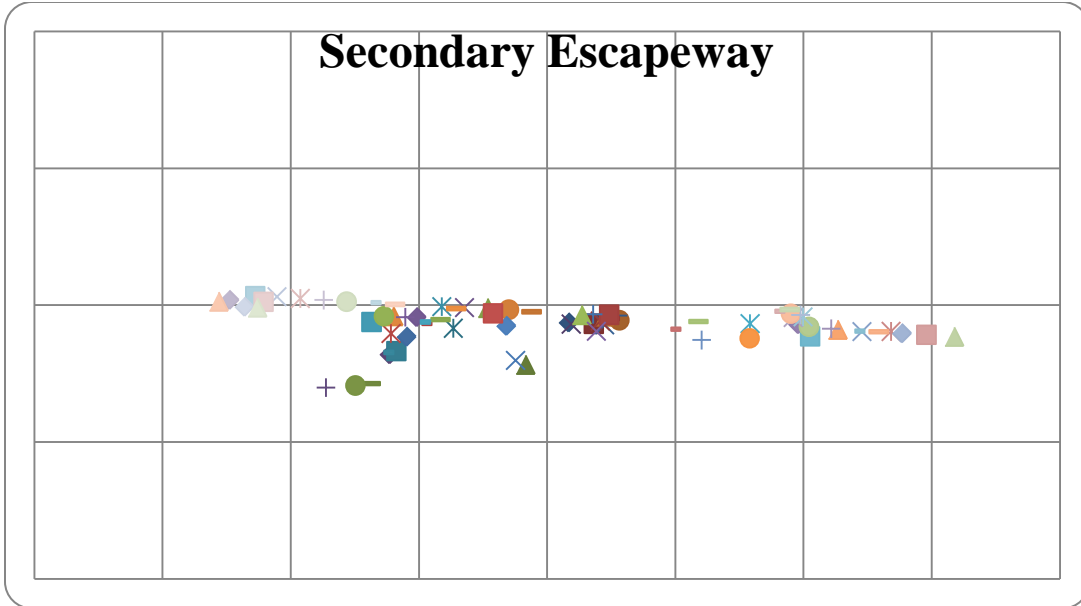
Figure 35 - Average TSP Plot along Secondary Escapeway
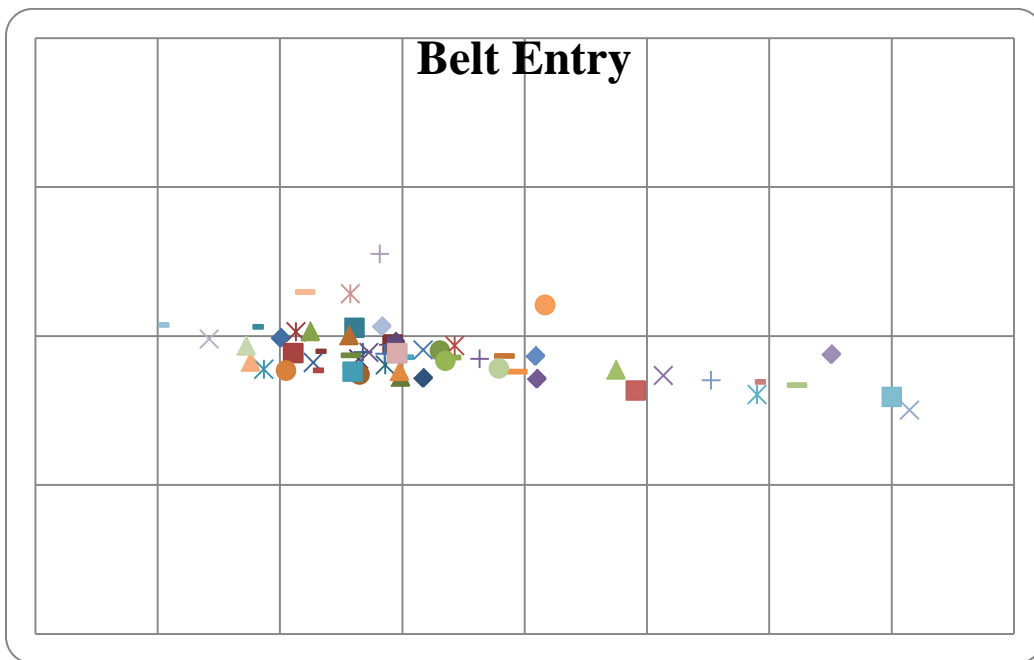
Figure 36 - Average TSP Plot along Belt Entry

The thousands of values calculated are filtered by area and then ordered by IA. These simulations predict a 90% CD of 185 ft. in the primary escapeway, 162 ft. in the secondary escapeway and 254 ft. within the belt entry.

Measurement of Tracking System Performance

The tracking system that has been discussed in this report has been installed. Care was taken to keep the infrastructure devices in the locations that are simulated. Data was collected over the course of several months and several surveys to compare to the simulation results. It also has several tests that are designed to isolate specific effects that may impact the tracking system. In addition, the Test System was installed in the Test Mine on is the secondary system, allowing the research team to modify the system. The system is not installed to the working face in this mine, the most inby node is located at a turn in the mains.

Measurement of Tracking System Variations when Stationary

In order to gain an understanding of the variation in the tracking system with the least number of perturbations, a device was hung from a roof bolt at 2012-10-25 11:44:00 until 12:47:57. The device was hung at the location 1907839,350827. This location yields measured results of an AA of 99.5 and SDA of 19.4 an AEV of <40,-4> and an ACR of 84. Selected records from the tracking database are in Table 8 with a map of the GTP and TSPs in Figure 37.

Figure 37 - Map of Stationary Handset Test

Table 8 - Stationary Handset Data Table

Time Inserted	Reported Time	TSP	IA	Time Inserted	Reported Time	TSP	IA
11:43:46	11:44:07	1908018,350816	179	12:23:27	12:25:17	1907943,350820	104
11:44:07	11:44:16	1908035,350813	196	12:25:17	12:25:37	1907930,350820	91
11:44:16	11:44:26	1907985,350816	146	12:25:37	12:25:47	1907943,350820	104
11:44:26	11:44:37	1907933,350820	94	12:25:47	12:25:57	1907920,350820	81

Time Inserted	Reported Time	TSP	IA	Time Inserted	Reported Time	TSP	IA
11:44:37	11:44:46	1907913,350820	74	12:25:57	12:26:37	1907939,350820	100
11:44:46	11:44:56	1907703,350833	136	12:26:37	12:26:47	1907752,350829	87
12:12:47	12:12:57	1907739,350829	100	12:26:47	12:27:17	1907943,350820	104
12:12:57	12:13:47	1907946,350820	107	12:27:17	12:27:27	1907733,350829	106
12:13:47	12:13:57	1907739,350829	100	12:27:27	12:27:57	1907939,350820	100
12:16:17	12:17:47	1907939,350820	100	12:27:57	12:28:47	1907953,350820	114
12:20:57	12:21:07	1907930,350820	91	12:28:47	12:29:07	1907939,350820	100
12:21:07	12:21:17	1907949,350820	110	12:35:17	12:35:27	1907907,350820	68
12:21:17	12:22:37	1907936,350820	97	12:35:27	12:35:47	1907933,350820	94
12:22:37	12:22:57	1907920,350820	81	12:35:47	12:37:17	1907946,350820	107
12:22:57	12:23:07	1907746,350829	93	12:37:17	12:37:27	1907959,350820	120
12:23:07	12:23:17	1907936,350820	97	12:37:27	12:37:57	1907933,350820	94
12:23:17	12:23:27	1907916,350820	77	12:46:47	12:48:17	1907943,350820	104

The device was hung from a roof bolt at 2012-10-26 10:15:54 until 11:57:00. The device was hung at the location 1905962,350799. This location yields an AA of 79.7 and SDA of 33.6 an AEV of <-46,3> and an ACR of 48.8. Selected records from the tracking database are in Table 9 with a map of the GTP and TSPs in Figure 38.
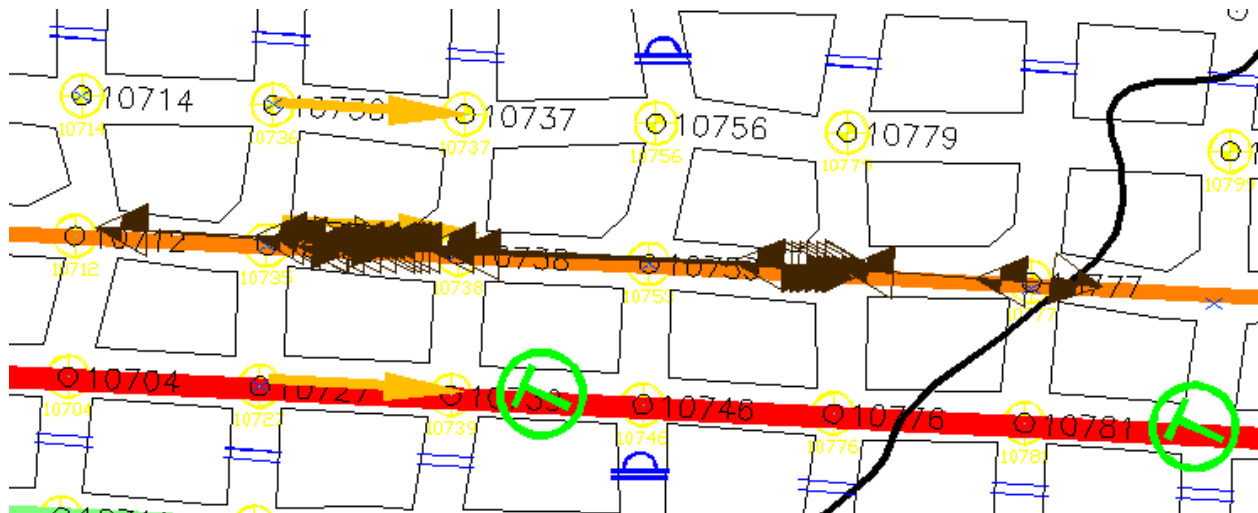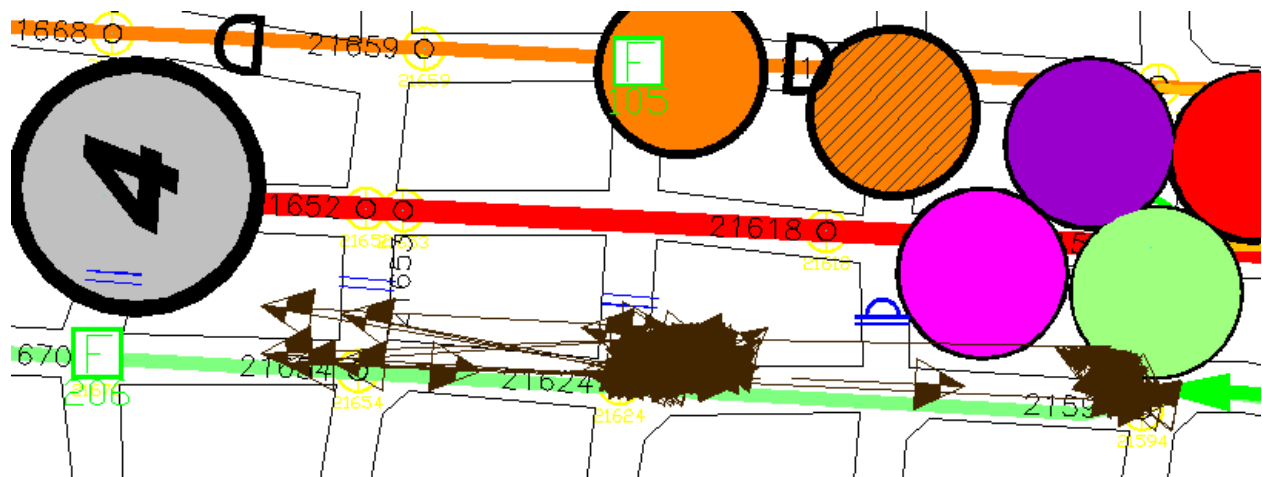

Figure 38 - Map of Stationary Handset Test

Table 9 - Stationary Handset Data Table

Time Inserted	Reported Time	TSP	IA	Time Inserted	Reported Time	TSP	IA
10:15:43	10:16:03	1905787,350806	175	11:52:04	11:52:14	1905869,350803	93
10:16:03	10:16:13	1905754,350806	208	11:52:14	11:53:04	1905886,350800	76
10:16:13	10:16:33	1905781,350806	181	11:53:04	11:53:14	1905869,350803	93
10:16:33	10:16:43	1905810,350803	152	11:53:14	11:53:34	1905892,350800	70
10:16:43	10:16:53	1905751,350806	211	11:53:34	11:54:14	1905873,350803	89

Time Inserted	Reported Time	TSP	IA	Time Inserted	Reported Time	TSP	IA
10:16:53	10:17:03	1905899,350800	63	11:54:14	11:54:24	1905918,350800	44
10:17:03	10:17:13	1905925,350820	42	11:54:24	11:55:04	1905905,350800	57
10:17:13	10:17:33	1905886,350800	76	11:55:04	11:55:24	1905889,350800	73
10:17:33	10:17:43	1905892,350816	72	11:55:24	11:55:34	1905895,350816	69
10:17:43	10:17:53	1905889,350800	73	11:55:34	11:55:54	1905909,350800	53
10:17:53	10:18:13	1905912,350800	50	11:55:54	11:56:04	1905892,350816	72
10:18:13	10:19:13	1905886,350800	76	11:56:04	11:56:14	1905895,350800	67
10:19:13	10:19:23	1905922,350800	40	11:56:14	11:56:24	1905882,350800	80
10:19:23	10:19:33	1905869,350803	93	11:56:24	11:56:34	1905863,350803	99
10:19:33	10:20:33	1905882,350800	80	11:56:34	11:56:44	1905846,350803	116
10:20:33	10:21:13	1905909,350800	53	11:56:44	11:56:54	1905918,350800	44
10:21:13	10:21:23	1905935,350800	27	11:56:54	11:57:04	1905935,350800	27

The handset hung in the secondary escapeway is compared to the prediction values for that same location. Figure 39 shows in red the locations that are calculated by the tracking system and in black the predicted values, the location of the handset are circled in red and the prediction location is a blue point, the prediction point is not necessarily the same as where the handset was physically located. The tracking system locations are taken from the surveys performed in the area, not including the values from the stationary handset test that is described above. The TSP values in the figures and tables below are taken from the surveys conducted with the survey buggy, described below. The figure indicates that the prediction values describe the same sort of distribution, but are trending more toward the other escapeway than the calculated values.
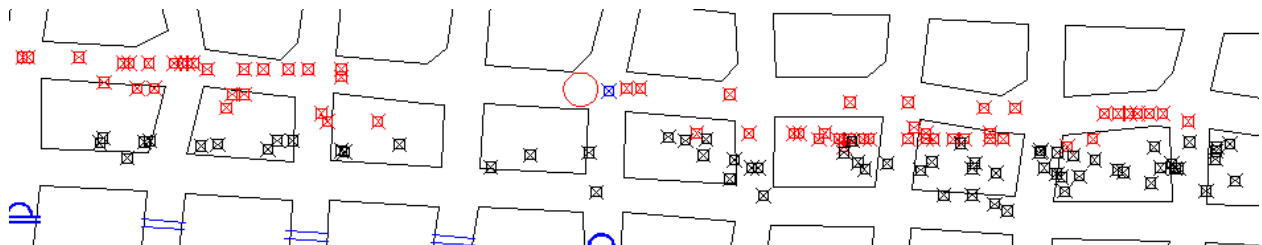

Figure 39 - TSP and Predicted TSP for Stationary Handset in Secondary Escapeway

Table 10 shows metric values for this single location. AA, SDA, 90%CD and ACR values from the prediction and the measured are within an acceptable range. AEV describes the predicted values to be further toward the primary escapeway.

Table 10 - Predicted and Measured Metrics for Secondary Escapeway Location

Location	Type	AA	SDA	90%CD	AEV	ACR
193	Predicted	241	105	376	<178,-36>	154
193	Measured	275	162	421	<28,-9>	180

The stationary handset in the primary escapeway, see Figure 40, was located at the location circled in red. The red points are the points calculated by the tracking system and the black points are the predicted points. The clustering of locations in this escapeway is the opposite of the predicted values. Although the prediction does show the same sort of distribution, it is trending in the opposite direction.
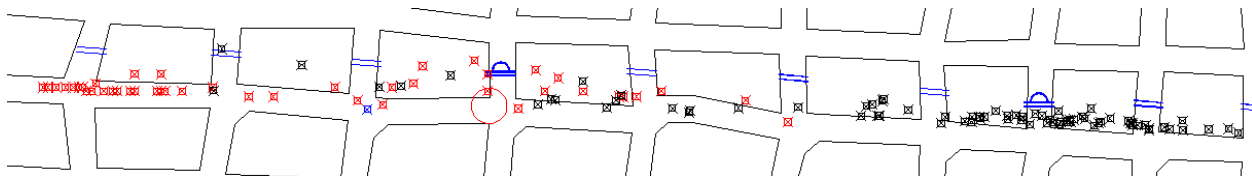
Figure 40 - TSP and Predicted TSP for Stationary Handset in Primary Escapeway

Calculating the metrics for this point shows the errors that are apparent in Figure 40. Table 11 shows the values calculated. AEV clearly shows the major difference in the cluster locations. Also, the Predicted values have much more variation and are an average distance further away. Most important, the 90%CD is much better than the predicted value. The prediction value is much worse than the measured value, but it well within the 2,000 ft. guidelines established by MSHA.

Table 11 - Predicted and Measured Metrics for Primary Escapeway Location

Location	Type	AA	SDA	90%CD	AEV	ACR
729	Predicted	412	165	547	<400,-2>	149
729	Measured	157	69	233	<-25,16>	154

In order to determine the cause of the difference between the predicted values and the measured values a two other specific points were investigated in the primary escapeway. Location 844, shown in red in Figure 41, was drawn with the red points for the tracking system's locations and black for the predicted points.
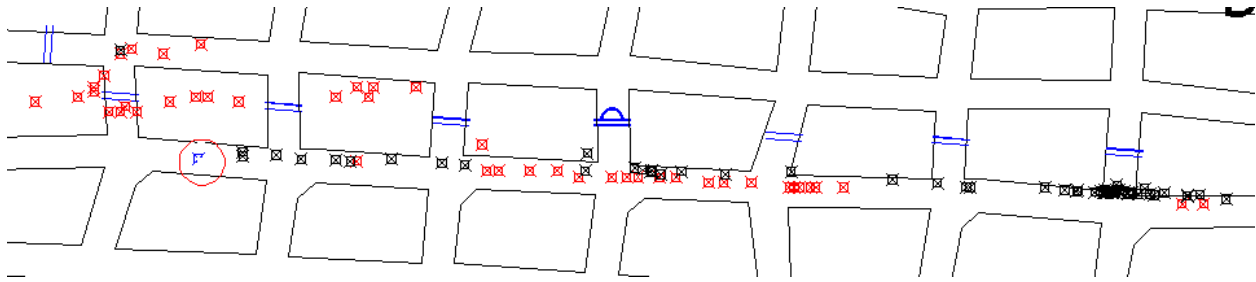
Figure 41 - TSP and Predicted TSP for a Location in Primary Escapeway

The metric values for this location are in Table 12 and show the same variation between the predicted and measured values. Again the predicted cluster is much further outby from the measured cluster. This location is also showing a greater pull toward the other escapeway.

Table 12 - Predicted and Measured Metrics for Primary Escapeway Location

Location	Type	AA	SDA	90%CD	AEV	ACR
844	Predicted	402	215	550	<220,19>	251
844	Measured	193	125	370	<146,13>	140

In this location and the last there are two factors not adequately accounted for in the simulation and predictions. Near the location of the man door to the right of the circled location in Figure 41 is a significant topographical change in the coal seam, within the two breaks outby that location is a reversal of elevation from floor and roof. This roll is completed to the right of the red circle in Figure 40, but in the opposite direction. Accurate elevation and thickness data was not available at the time of the simulation and predictions and were not inputted into the model.

Figure 42, shows location 199 circled in red with black points for the prediction values and red points for the tracking system calculations.

Figure 42 - TSP and Predicted TSP for a Location in Primary Escapeway

Table 13 is the metric calculations for the location shown in Figure 42. The metric calculations and the figure are in acceptable agreement. As seen in the secondary escapeway, the

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AEV and ACR are not in complete agreement, but the other metric values are suitably close. This location is parallel to the static handset location in the secondary. At this place in the mine, there is consistent height and the topography is consistent.

Table 13 - Predicted and Measured Metrics for Primary Escapeway Location

Location	Type	AA	SDA	90%CD	AEV	ACR
199	Predicted	119	99	336	<-6,2>	119
199	Measured	103	66	220	<59,1>	64

The stationary handset tests were performed in order to understand the variation in the tracking system's location calculations under static conditions. The data show that there is a general variation of roughly 200 ft. in a direction following the escapeway, or 400 ft. in either direction. The 400 ft. of variation is still 1/5 of the 2,000 foot guideline set by MSHA. For both the primary and secondary escapeway a tracked device can be located in the general area of its actual location. A description from the tracking system could be relayed to a miner underground and at walking speed they would have encountered the tracked device within minutes, assuming a search along the escapeway.

Measurement of Tracking System Variations when in Motion

Measurements were taken using a SkyMark Survey Buggy. The device is a dead reckoning tool, which, when taken to a location underground it is capable of tracking its location and recording various sensor data with accurate time stamps. The tracking system does not communicate a device's location with the tracked device, but the tracked device locations are logged at the main tracking system computer with a time stamp that is synchronized with the Survey Buggy clock. The Survey buggy is used to calculate the GTP of a set of handsets. Figure 43 shows the general configuration of the cart while being towed. The radios are rotated around to be as far away from the tow vehicle and as height in the mine as possible without hitting the roof. Handsets are arranged in two orientations, 4 are held vertical and 2 are horizontal.

Figure 43 - General Test Configuration While Towing

The survey buggy records a single time and a location, while the tracking system records a calculated location and two times. The tracking system times are the time that a tracked device entered into a state or location and the last time the tracking system received a reported of the device being at that location. The handsets report the communication infrastructure RSSI at a pre-determined interval. This report is used to calculate the position by the tracking system computer. The survey buggy records the GTP by a survey number. Surveys are numbered by the operator; each survey was conducted to either measure values in an area or to conduct a specific test.

In this report, only surveys that are measuring areas are used. Several surveys were conducted in areas of the mine and then the buggy was taken outside. When the area of interest was exited, the record continued. The recorded values that did not have the operator actively working the survey buggy are excluded from the data used in this report. Data collected from these surveys is the data that is used in the stationary handset discussions.

The predicted values are created at specific locations in the mine. In order to compare these values to the continuous measurements done by the survey buggy, the continuous measurements were filtered. . For each time and handset, the TSP values are queried from the tracking database. This method of comparing may cause inconsistency with the metric values report for the simulation-only data earlier in this report. For the purposes of comparison, the data

presented comparing measured and predicted results will only include data points that meet the criteria described here.

An example of the surveys is survey 148, which was a survey of the secondary escapeway. Figure 44 is a map of this survey. The red line is the path traveled as reported by the survey buggy. Spads are drawn as yellow blocks and are included as reference. The green arrows are drawn every one minute of survey time from the GTP to the TSP for each device.
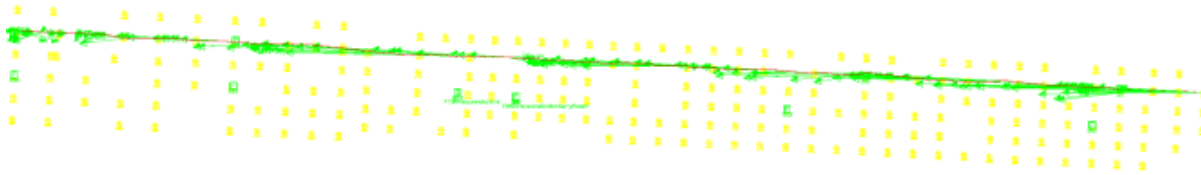

Figure 44 - Survey 148

Metric values for this particular survey are shown in Table 14. The device is the identification number for the individual radio. GTPs are recorded at a very high density since they are recorded every time the buggy changes location, which can be several records per foot; the total number recorded is shown in the count column. GTP is calculated as part of the survey buggy software. AA is calculated by taking the arithmetic average of all IAs as calculated from each GTP recorded. SDA is calculated in the same manner, except is the standard deviation by population. 90%CD is calculated by sorting the distinct IA values into percentile ranks, the 90th percentile rank is the cutoff value that is reported. Averaging the difference in the X and Y coordinates between the GTP and TSP yields the AEV. The GTP plus the AEV yields the end point of the AEV. The average of the distance of a TSP from the center of the TSP spread is the ACR. ACR is only calculated from a TSP that is not at the center of the TSP spread and distinct values to avoid weighting. The count of the TSPs used in the ACR is shown in parenthesis, this is generally the number of times the tracking system calculated a location during the survey. Delta GTP is the straight line distance from the minimum GTP to the maximum GTP, it is not the distance the survey buggy traveled, it is the diagonal distance of the bounding box area. The Cart could be used to cover a 5 foot area 1,000 times, for a distance traveled of 5,000 ft. but a Delta GTP of 5.

Table 14- Metrics for Survey 148

Device	AA	SDA	90%CD	Count	AEV	ACR (Count)	ΔGTP

9537	189	27	226	1978	<160,5>	55 (168)	93
9548	207	26	243	1983	<193,-2>	48 (173)	93
9593	282	29	322	1976	<278,-9>	46 (157)	99
9647	321	29	361	2256	<316,-12>	44 (158)	100
9775	249	26	285	2198	<244,-6>	42 (179)	88

The prediction points are at discreet locations, as described earlier. In order to compare the measured results to the predicted points GTPs from the surveys where queried that were within 15 ft. from the prediction point. This is shown in Figure 45, the green points are the GTPs collected by the cart for the surveys included in the data set that are within 15 ft. of location 680. The red points are the TSPs and the black points are the predicted TSPs. The distance from the location of 15 ft. was chosen because the average intersection interval is 100 ft. and there are locations at the near halfway point, such as 680, or roughly every 50 ft.. A radius of 15 ft. yields a total travel distance of 30 ft. along the escapeways, with a sufficient buffer to prevent double counting of a GTP.
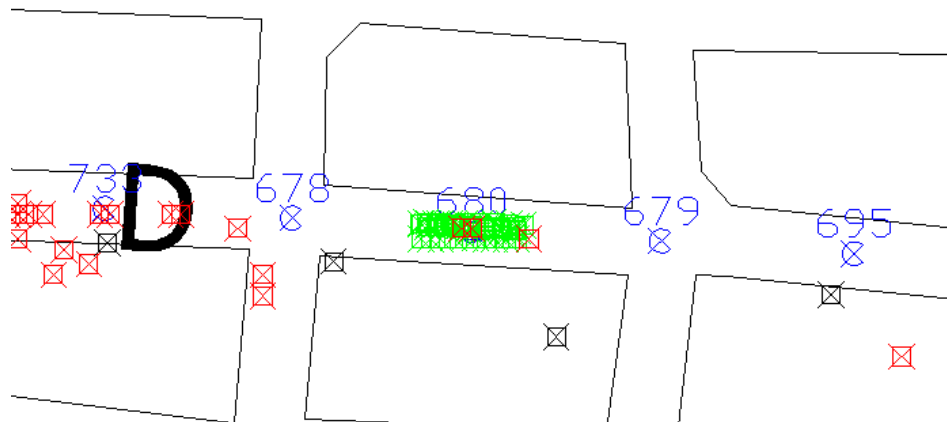
Figure 45 - GTP, TSP and Predicted TSP for Location 680

The surveys conducted that include the belt line and the entries away from the escapeways are excluded from the data used in this report. These areas of the mine are areas that do not need to be covered by the tracking system and that increase the variability. Survey 1127 and Survey 1130 were conducted in the secondary escapeway of the mine. Survey 1127 is included in the data set that is used in this report and the map is shown below in Figure 46. Survey 1130 was conducted perpendicular to survey 1127 and is shown in Figure 47. For the purpose of this report, the added variability is unnecessary.
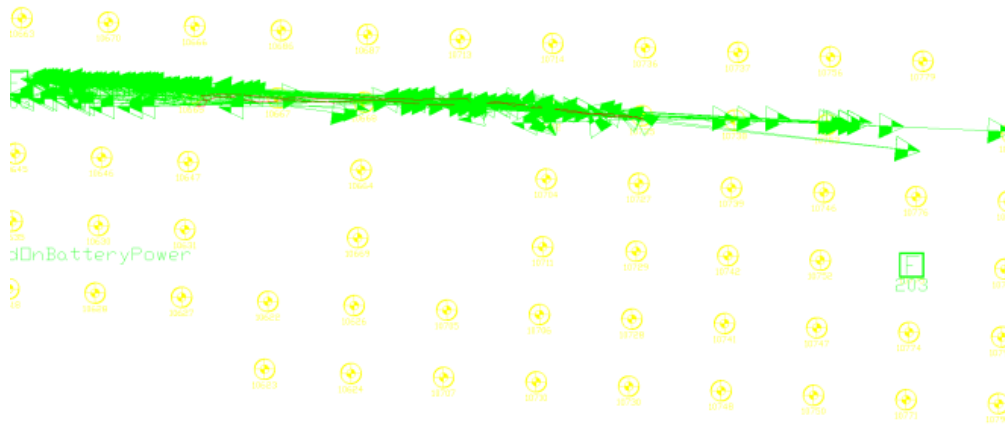
Figure 46 - Survey 1127
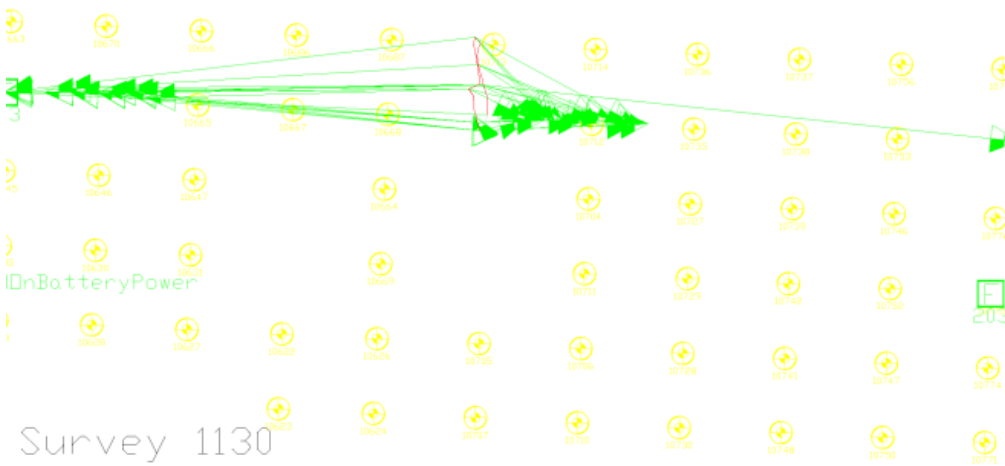
Figure 47 - Survey 1130

Included in the set are 21 surveys that were collected from September of 2012 to February of 2013. These surveys have over 800,000 data points after the filtering by node point. Randomly selected locations, with their predicted values and the measured values are presented below in Table 15 and Table 16. The values are calculated as described above in the description of Table 14, but count values have been excluded for formatting. There are 2-4 times more measured values at any particular location than predicted values.

Table 15 - Selected GTP and TSP with Prediction Values for the Primary Escapeway

Location	Predicted					Measured				
	AA	SDA	90%CD	AEV	ACR	AA	SDA	90%CD	AEV	ACR

13	149	128	609	<14,-1>	152	180	94	292	<143,-7>	136
17	151	101	539	<44,5>	147	207	114	341	<159,-6>	165
24	150	132	643	<30,0>	150	157	85	268	<133,-6>	97
26	231	131	672	<-133,17>	170	130	77	231	<129,-5>	88
121	116	98	508	<29,0>	116	219	138	378	<180,-6>	181
199	119	99	336	<-6,2>	119	103	66	220	<59,1>	64
293	212	114	395	<-161,11>	146	152	45	206	<-37,14>	146
316	208	135	470	<12,0>	205	222	118	412	<-53,7>	239
362	143	99	334	<23,5>	139	244	98	420	<-72,5>	231
427	90	65	224	<44,9>	83	123	114	291	<-128,12>	99
601	154	71	371	<-153,19>	55	215	109	295	<108,10>	281
702	115	88	287	<53,5>	112	116	55	181	<-35,12>	109
734	407	132	475	<373,-11>	141	223	74	326	<27,12>	202
844	402	215	550	<220,19>	251	193	125	370	<146,13>	140
1002	59	11	77	<50,-18>	25	146	32	179	<-16,-139>	28

Table 16 - Selected GTP and TSP with Prediction Values for the Secondary Escapeway

Location	Predicted					Measured				
	AA	SDA	90%CD	AEV	ACR	AA	SDA	90%CD	AEV	ACR
4	221	116	397	<-55,-5>	209	263	159	392	<-71,4>	172
62	264	163	525	<-180,-19>	193	336	187	666	<-183,11>	280
75	129	57	263	<-106,-6>	70	284	212	585	<198,-15>	278
129	218	141	480	<-37,-36>	205	329	205	573	<207,-16>	257
213	180	72	334	<126,-57>	106	311	149	547	<131,-13>	80
266	116	93	326	<56,-9>	96	306	360	453	<-43,5>	200
325	115	66	241	<82,-34>	74	382	262	386	<97,-17>	237
365	123	74	248	<68,-20>	102	302	283	438	<-57,-10>	208
406	80	52	325	<21,-19>	70	317	325	459	<-155,0>	131
517	206	114	381	<123,-36>	163	376	139	563	<-140,4>	320
579	203	122	362	<9,-17>	200	319	141	405	<-108,9>	295
620	89	60	218	<20,-20>	85	136	109	297	<-18,-4>	153
679	284	139	493	<236,-47>	152	133	64	204	<-31,-6>	129
733	65	46	199	<29,-13>	56	98	107	261	<47,-13>	132
770	517	156	550	<-4,-63>	176	218	96	473	<26,31>	52
839	462	57	466	<451,-53>	34	230	142	466	<133,5>	223

Table 17 is a summary of the predicted and measured results by only the one dimensional values, AA, SDA and 90%CD. This table shows that the predicted values are higher than the measured values but they are descriptive of the same system because both the predicted values and the measured values are significantly lower than the target values for the tracking system. Along the entirety of the escapeways the 90%CD should be less than 2,000 ft. and the average of both escapeways is one quarter of this target. The AA both predicted and measured describes a tracked device's location within two breaks with two breaks of potential error (SDA). A break along the travel way (100 ft.) can be crawled (3 feet/second) in less than a minute (34 seconds). Meaning a potential search area of 400 ft. can be slowly traversed by a rescue team in 2-3 minutes. These prediction results are only for the prediction locations that were visited by the survey buggy during one of the surveys in the data set. This may lead to some inconsistencies with the previous reported results. The values are of a consistent order of magnitude and indicate the importance of the data set that is used to calculate the metric values.

Table 17 - Summary of Predicted and Measured Results

		Predicted	Measured
Primary	AA	221	170
	SDA	193	112
	90%CD	605	420
Secondary	AA	209	158
	SDA	205	126
	90%CD	504	601

Conclusions

This report describes a realistic simulated baseline deployment of the Test System and Tracking system in the first mile of mains in Test Mine. There are 13 FMNs underground, two above-ground and three BCNs located at strategic areas. Using anticipated loss parameters for the Test System radio signals, the fresh and belt air entries of the mine are simulated in order to calculate anticipated performance metrics. Several dozen physical tests of the designed and described test system are compared to the predicted results.

The measured values predicted results proved to be higher better than the predicted results in most metric values that are measured. However, the measured results are collected by a device that is continually measuring locations, but the predictions are from single point values. A

comparison technique was used to collect all the data that was collected in both the prediction and measurement cases. Variations in this comparison technique have a large impact on the measurements. This is especially true when a survey was conducted for a long period of time in a small area. The values collected during that time will have a greater impact on the overall average because there are more of them, than in an area that was visited less or for a shorter period of time. This is further complicated by the internal reporting intervals of the tracking system. Many systems report the current calculated location of a tracked device and the duration at that location. They do not report the number of times the device was reported to be at that location. A smoothing algorithm that is easy to understand needs to be developed to solve the time and location weighting problems that can be caused during measurements.

This report does describe a method of predicting the performance of a tracking system that is in line with the observed performance. More importantly it demonstrates that the predicted measures and observed values using standardized metrics do describe the same tracking system because the general values and trends are correct. The magnitude of the changes can be adjusted with the input parameters of the simulation, changing the values to be more specific to that location.

Acknowledgements

SUMMARY AND CONCLUSIONS

In an underground coal mine, the measure of a communication system is the coverage area it can provide at a quality that ensures a miner can communicate with other miners in and out of the mine during normal and emergency operations. The coverage area of a wireless mesh communication system can be calculated using the tool COMMs developed and discussed in this document. This tool can also be used to explore emergency operations, or operations where the mesh infrastructure is degraded or destroyed. Most often, the communication system is also capable of transmitting data from sensors including a set of sensors described as the tracking system.

An underground tracking system is described as a system that calculates a location in a useful coordinate when a tracked device is underground. The tracked device is a representative of a miner, group of miners or equipment, depending on state law and the mine's deployment. The actual location of the miner or equipment being tracked is the Ground Truth Position (GTP) and the tracking system's representation in the same coordinate system at the same time is the Tracking System Position (TSP).

Regulatory guidelines in the United States currently define different tracking qualities at locations in the mine. These can be classified in three location categories:

1. Working Face, required to know a miner's location within 200 ft. (61 meters)
2. Strategic Areas, required to know a miner's location within 200 ft. (61 meters)
3. Escapeways and travel-ways, , required to know a miner's location within 2,000 ft. (610 meters)

To address the shortcomings of the current systems, much work was done. Specifically, work during this project accomplished the following:

1. A number of metrics were defined such as Average Accuracy, Standard Deviation of Accuracy, Repeatable Accuracy and a base line tracking system study was conducted where the metrics are shown to describe the tracking system
2. A simulation algorithm capable of predicting and optimizing wireless mesh networks was developed (COMMs) and applied for evaluating the performance of tracking systems

3. The coverage area of a wireless mesh communication system can be calculated using the tool COMMs

4. COMMS can accurately predict and validate metrics that describe a tracking system

In an excellent tracking system the actual location, GTP and TSP will be very close to each other. The approach employed in this work was multifaceted. Initially the methods and procedures that support a general framework for evaluating the performance of personnel tracking systems in underground mines were developed. A number of metrics were defined such as Average Accuracy, Standard Deviation of Accuracy, Repeatable Accuracy, etc. and a base line tracking system study was conducted where the proposed metrics where applied. All direct paths via escapeway or travel-way from the mine portal to the working face should be simplified into a one-dimensional path that is subdivided by the three regulatory categories. Each of these subdivisions should be described using the metrics defined above.

Subsequently a simulation algorithm capable of predicting and optimizing wireless mesh networks was developed (COMMs) and applied for evaluating the performance of tracking systems. Using the same software the layout of a tracking system can be accurately designed.

These aforementioned metrics can be predicted using COMMs for a tracking system that is using an underground wireless mesh system that uses Received Signal Strength Indicators (RSSI) to calculate the TSP. Because the tracking system's algorithm to convert RSSI into a TSP is proprietary to the manufacturer, in order to do predictions the engineer must collaborate with the manufacturer. In this document, the predictions and calculations were done in conjunction with the manufacturer and proved to be very good at describing the tracking system that was designed and tested.

These predictions were validated by developing two separate methodologies. The first methodology involved the development of testing layouts for performing data measurements that include static (where mining has been completed) and dynamic (active mining section) tracking system tests. The second involved the development of an actual dead reckoning device for use in underground coal mines. The development of this device complete with the software that enabled the recording of positioning data, enabled actual measurements of underground locations for which tracked locations were available, under different operating conditions. The simulated models were then validated which a) confirms the applicability and utility of the developed performance metrics and b) compares well with simulated results for similar conditions. The

tools that are now available to public greatly increase the understanding of communication and tracking systems as well as how they can be designed and deployed as efficiently as possible to increase the safety of the underground coal worker.

Detailed results are given in each of the publications listed in the main body of this work.

Further work

There remains a problem when measuring the accuracy of a tracking system in data collection and analysis. The tracking system has its own internal location reporting times and any device or method used to measure the tracking system will have its internal location reporting times. Because the internal working of the tracking system will not be known to the prediction and measuring engineer, there will be error introduced into the calculation from the asynchronous nature of the locations. This is further complicated by the reality of moving underground. Even with the best of intentions, to maintain a constant speed to get uniform measurements is difficult to impossible over a large area. A filter that can smooth the measurements taken is needed. This will make the Averaging in the calculated metrics more accurate and easy the process of comparing to the predicted results.

A set of programs that are specific to manufacturer's tracking system should be developed that will take output form a program such as COMMs and create predicted TSPs. This will help to assess and monitor the installed system as well as aid the mine designer.

Mine designers need a set of rules and guidelines to help them determine the costs of the communication and tracking system and how that system's costs are impacted by their specific mine design. Discussion of this is presented in this work, but the guidelines are not complete and need to be tested against many different mine designs that are typical of current practices.