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DESIGNING AND MODELING WIRELESS MESH COMMUNICATIONS IN UNDERGROUND COAL MINES

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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 increase overall coverage and efficiency of the communication network itself. 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 on going since 1922, when the United States Bureau of Mines performed experiments in its experimental mine in Bruceton, Pennsylvania (Schiffbauer & 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 1 shows an example of a wireless mesh network topology.

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.
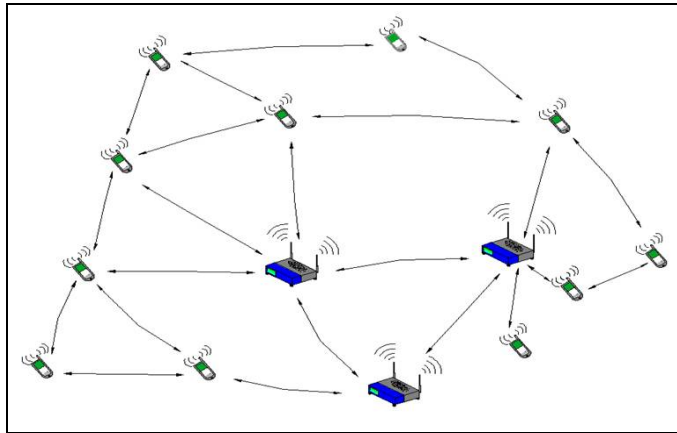

Figure 1. Wireless Mesh Network Topology Example.

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 & Brune (2006b), some operating frequencies will propagate further because of "electrical properties of the coal attenuate some frequencies more than others." Sacks & 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. 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, allowing for more efficient escape and rescue operations. 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 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 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. Comms builds the mine's communication network using the pillar/perimeter method and/or the centerline method. 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 2 depicts a small portion of a mine's communication network when using the pillar/perimeter method.
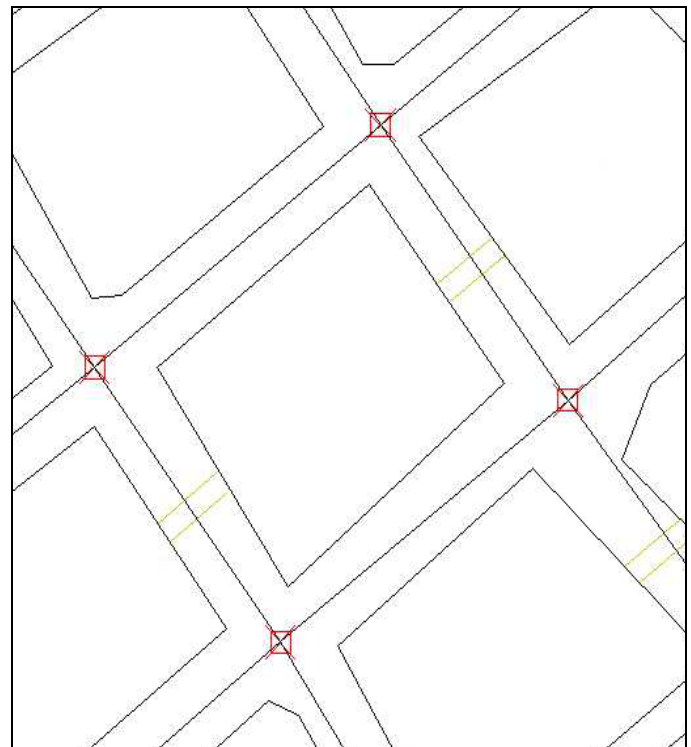

Figure 2. Communication Network Pillar/Perimeter Method.

With the centerline method, a user defines an ideal centerline, 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.

Thus, the expected coverage areas can be drawn, measured signal strengths that do not match predicted values can be searched for, and other problematic areas pinpointed. Signal strength values that are calculated when solving the mine's communication network may then be used to draw in the coverage area that would be provided at each individual point, if that point was a broadcast point. The solve routine can be time-consuming depending on the number of points in the network; if the network does not change then the network only needs to be solved once. 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 will reveal optimal locations for broadcast nodes.

FIELD WORK

The authors were participants in a major research effort funded by NIOSH, with multiple partners including L-3 Communications Global Security and Engineering Solutions, Innovative Wireless Technologies, Pyott-Boone Electronics, Alion Science and Technology, Marshall Miller and Associates, and the 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 and fiber optic network). Additionally, wireless handsets are capable of communication directly with each other and through fixed broadcast nodes. The team tested the methods discussed above in several different underground coal mining operations, 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 and coverage maps can be created. Generalized anticipated signal loss parameters can be categorized into clear non-obstructed, beltway, stopping, and corner losses. The signal loss due to a clear non-obstructed opening is the

natural signal degradation. A beltway signal loss is used to categorize the signal loss encountered in a belt entry. Stopping signal loss is the loss encountered when passing through a stopping, which is used in the ventilation of underground mines to separate different aircourses. Corner signal loss is the loss experienced when the signal must turn to propagate down a crosscut. Signal loss across a distance is known as path loss. Path loss is described by Equation 1.

$$Path\ Loss = \left[\sum Non\ Obstructed\ Clear\ Losses\right] + \left[\sum Beltway\ Losses\right]$$
$$+ \left[\sum Cinderblock\ Stopping\ Losses\right] + \left[\sum Metal\ Stopping\ Losses\right]$$
$$+ \left[\sum Corner\ Losses\right] + \left[\sum Power\ Center\ Losses\right]$$
$$+ \left[\sum Unknown\ Losses\right]$$

Equation 1. Description of Path Loss.

The predicted and measured path loss will vary because there are still additional unknown signal losses observed underground that have not been quantified. The value of each signal loss parameter will vary based on mine conditions, operating frequency, and the strength of the broadcast signal. Comms enables users to adjust signal loss parameter values based upon conditions specific to particular mines. Once a communication system has been integrated into a mine, additional interferences and design parameters are revealed by comparing theoretical signal strengths versus measured signal strengths. Comms can draw expected coverage area maps, as required by MSHA and specified by NIOSH (2008). NIOSH also requires that a similar map be created for the tracking system. Figure 3 shows the communications and tracking map provided by NIOSH in the Communications and Tracking Instruction booklet.
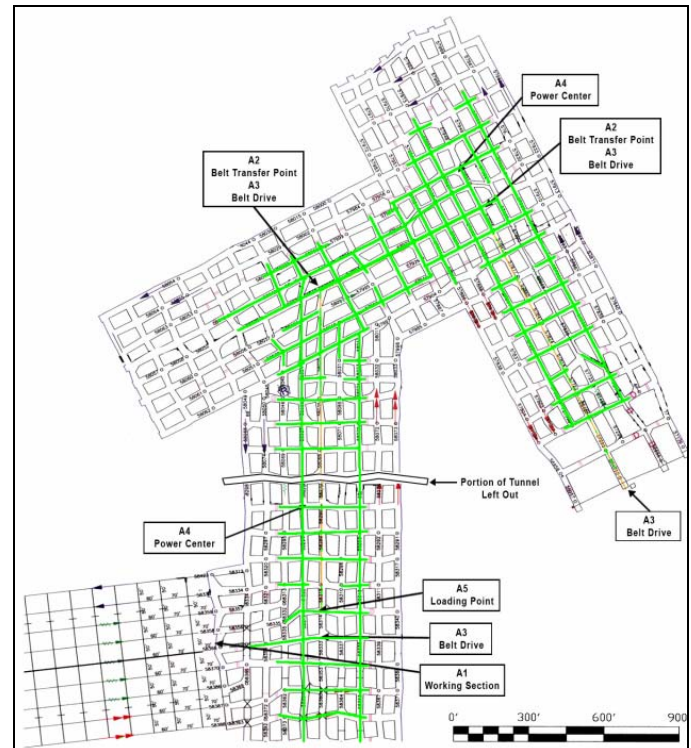

Figure 3. NIOSH Communications and Tracking Map Example (NIOSH 2008).

DISCUSSION OF RESULTS

The underground mine environment is damp, unlevel, and, overall, not ideal for the natural propagation of radio waves. Data collection in the underground environment is not a simple task, causing data measured in the mine to be extremely volatile. Data measured in a mine can vary based upon the particular location within openings, the orientation and placement of antennas, moving vehicles, nearby hoists,

and other unanticipated interferences. A miner can decrease the received signal strength just by standing between the handset and nearby broadcast device. Every mine's local geology, mining conditions, and other circumstances yield a unique working environment. Mine equipment and structures are constantly changing as mining progresses, forcing mine communication systems to constantly adapt to the current conditions. For this reason when modeling a mine's communication network, general categories of tunnel profiles are created to establish a model that will account for major signal losses that occur. Modeling the mine's communication network using general signal loss parameters allows the model to be applied to other mines. Results predicted from modeling of signal loss parameters from this study showed a percent difference of less than 16 percent from field results. Table 1 contains the comparison of calculated versus measured broadcast node connectivity.

Table 1. Calculated Versus Measured Node Connectivity.

	Node A to Node B	Node C to Node D	Node E to Node F	Node G to Node H
Percent Difference (%)	15.2	3.8	2.3	8.4
Categorized Path	2 Clear Breaks, 1 Corner, 1 Stopping	2 Clear Breaks, 1 Corner, 1 Stopping	11 Clear Breaks	5 Beltway Breaks

The connectivity between nodes A and B and nodes C and D should receive approximately the same signal strength because their categorized path (distance between the pair) is identical. It appears that node A to B experiences signal loss due to an unknown source that the model does not take into account. The other three predicted and measured node connectivity pairs shown in the table show a difference of less than ten percent. Signal loss parameters must be generalized because signal strength data underground are extremely volatile. A difference overall of less than 16 percent suggests that the signal loss model is valid within the given modeling parameters.

The study examines other parts of the mine but concludes that in those areas there were additional signal interferences that were causing the measured signal to vary significantly from the predicted signal strength. Comparing the predicted and measured signal strengths allows unanticipated signal loss interferences to be pinpointed and quantified. Additional signal loss parameters need to be identified to more accurately model the propagation of the wireless signal in problematic areas of the mine. This research develops a new methodology capable of building, solving, and modeling mine communication networks in underground coal mines. The signal loss equations and parameters developed provide a powerful tool for evaluating signal losses. Signal loss equations should be used as estimations of ideal signal loss parameters and a benchmark for future work. The L-3 Accolade underground mine communication and tracking system has well exceeded initial expectations.

CONCLUSION AND RECOMMENDATIONS

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 if one path 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.

Communication requirements in underground coal mines have changed in terms of regulation and not technology. There is no specific operating frequency that will be optimal in all scenarios. Communications and tracking systems must be dynamic and changing to account for current impacts and signal interferences because mines are dynamic operations. Generalized signal loss parameters enable generalized solutions to be applied to a broad spectrum of dynamic operations. There is a need for the simulation and design of wireless systems in underground coal mining applications. Future work is necessary to address issues of optimization, unknown signal loss parameters, longwall mining equipment interferences, and the function of communication systems in emergencies. Additional testing in mines is necessary to investigate and quantify unknown signal loss parameters. The integration of wireless communications and tracking systems will result in improved health, safety, and productivity standards in underground coal mines.

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