

WIRELESS MESH COMMUNICATION SYSTEMS OPTIMIZATION IN UNDERGROUND COAL

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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 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 1, 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).

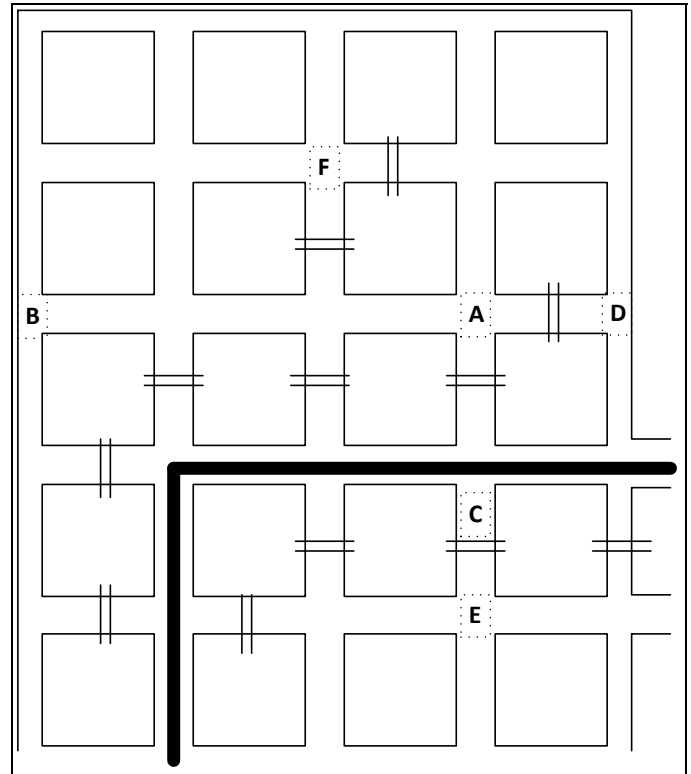


Figure 1. Simplified Mine Section.

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 deemed invalid. 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 perimeter 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 includes an 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 1, 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 1. For this case there are a total of 63 possibilities which will be investigated trying to minimize k.

$$Choose(n, k) = \frac{n!}{k!(n-k)!}$$

Equation 1. Number of possible combinations.

$$AllChoices = \sum_{k=1}^n \frac{n!}{k!(n-k)!}$$

Equation 2. Total number of combinations possible.

Table 1. 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 2. 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 2. Solution Matrix.

Receiving Nodes	Broadcast Nodes					
	0	1	2	3	4	5
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 3. The status line is used as a multiplier for the matrix that was shown in table 2. 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.

Table 3. Solution Matrix and Example Calculations.

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

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.

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 2, 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 2. 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.

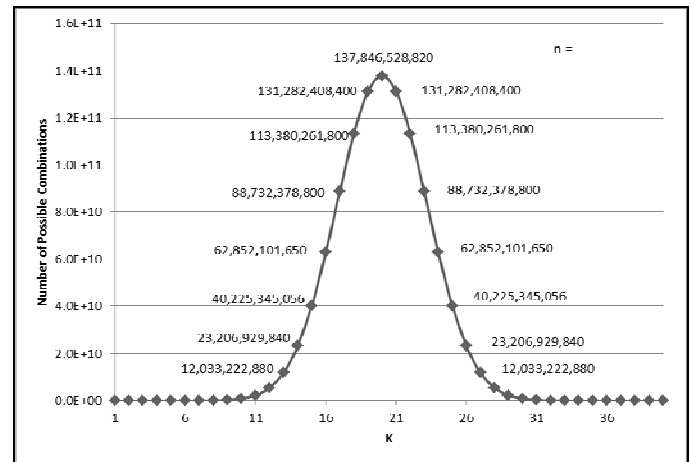


Figure 2. $N=40$ Number of Combinations at K .

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 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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