Evaluation of Mine Communication and Tracking Systems Performance

Steven Schafrik
Research Associate Professor
Virginia Center for Coal and Energy Research
Virginia Tech
Acknowledgements

- A major portion of this presentation is based on research funded by the National Institute for Occupational Safety and Health (NIOSH), under contract no. BAA-2010-N-12081. In addition to Virginia Tech, the research partners include Innovative Wireless Technologies and SkyMark. The presenter would like to acknowledge the discussions and suggestions by many of the staff at NIOSH. Appreciation is also given to the coal companies that have joined the project and have agreed to provide facilities and support during the mine testing phase.

- Equipment discussed in this presentation was created for NIOSH and has been gifted by NIOSH to Virginia Tech.
Introduction

- Every coal mine has a communication and tracking system
  - Is it working everywhere?
  - Is it in compliance?
  - Is it over built?
- Vendors provide network diagnostic tools to assist with parts of these questions

- There is a lack of uniform evaluation methodology to assess how different systems and technologies perform in various mining applications, and whether they can satisfy the regulatory requirements
A “Black Box” Approach

- All data regarding the tracking system must be regarded as pairs of coordinate at the same point in time.
- Investigators have no knowledge of a tracked device’s velocity, orientation, or the values it supplies to the tracking calculation.
- We do not know the internal workings of the tracking algorithm, therefore we do not know all parameters that impact the values.
Tracking Terms

- Measured Location (ML)
- Actual Location (ACTL)
- Known Location
- Landmark (Named Known Location)
Every Tracking System has a Probability Distribution.

- Actual Location
- Measured Location

Small probability of exceeding target accuracy requirement. Some IA values may be larger.

Many small IA values. Full distribution must be considered when evaluating a tracking system.
Discussion, Statistical Deviations and Samples

- MLs will be more accurate in some areas than in other areas within the same mine.
- Measure this variability, tests at different locations throughout the mine should be performed, this is covered later.
- Collecting large amounts of independent data within a mine affords greater confidence in the distribution of position estimates.
- An unknown statistical distribution of accuracy varies with location, it will also vary over time, as mine conditions that may affect tracking system performance vary in time scales of minutes, hours, shifts, or days.
- Sample as much as you can, approximating the situation you are describing.
Coordinate Systems

- Each mine has its own coordinate system for their mapping.
- Each tracking system has its own coordinate system.
- Only a few tracking systems use the mine’s coordinate system.
- All comparisons of ACTL and ML must be done in the same coordinate systems.
- The coordinate system must translate to real units (e.g., feet).
Measurements of System Performance: Metrics

- **Tracking Coverage Area**: The tracking system’s coverage of the required spatial area.

- **Tracking Accuracy**: The tracking system’s accuracy of measured positions - the magnitude of the difference between the tracking system’s measured locations and the actual locations of tracked entities.

- **Tracking Coverage Time**: The tracking system’s coverage on the basis of time - throughout the duration of operations.
Metrics: Tracking Coverage Area

- Tracking Coverage Area: The area within the mine where 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.

![Diagram of tracking coverage areas]
Tracking Coverage Area

- **Active TCA** is the area within the mine that the tracking system actively measures a tracked device’s location. An active measurement occurs when the tracking device reports or is capable of reporting the phenomenon it measures.

- **Inferred TCA** is the area within the mine that the tracking system infers a tracked device’s location based on the spatial limitations of the mine and information other than active measurements.
TCA Example - Tag Reader Tracking System
TCA Example - Wireless Mesh Network Tracking System

Wireless Mesh Network Tracking System Fixed Mesh Node Transceiver
Wireless Mesh Network Tracking System Active Tracking Coverage Area (Active TCA)
Wireless Mesh Network Tracking System Inferred Tracking Coverage Area (Inferred TCA)
Fresh air ventilation direction
Return air ventilation direction
Coal pillar (e.g., 40' x 50')
Stopping
Stopping with man door
Conveyor belt
There are several measurements of accuracy that might be used for evaluating mine tracking systems:

- **Average Accuracy (AA)**
- **Standard Deviation of Accuracy (SDA)**
- **90% Confidence Distance (90%CD)**
- **Relative Accuracy (RA)**

All are based on Instantaneous Accuracy (IA)
Instantaneous Accuracy (IA)

- Instantaneous Accuracy is the difference in distance between an actual location (ACTL) and the tracking system’s position estimate (ML) actively made at that ACTL at an instant in time.
- Instantaneous Accuracy is the most basic of measurements that a mine operator or inspector will be able to make.

\[ IA_0 = \sqrt{(ML_x - ACTL_x)^2 + (ML_y - ACTL_y)^2} \]
The ACTL of a miner’s location at time $T_0$ is $(100, 100)$. The ML for the miner’s location at time $T_0$ is $(96, 103)$. The Instantaneous Accuracy at time $T_0$ is

\[ IA_0 = \sqrt{(96 - 100)^2 + (103 - 100)^2} = \sqrt{-4^2 + 3^2} = 5. \]
Sets of IA

- No matter the size of the mine, or the number of active face areas, there are two paths from a portal to the working face
  - For a mine with 2 working sections there will be at least 4 escapeway paths
  - Areas must be surveyed completely travelling in both directions

- Distance will be divided into segments that are equal to two times the average pillar length, alternatively, 200 feet

- All IA values collected in these areas in any single examination will be aggregated for the following metrics

- These aggregated values, can then be further aggregated to describe the entire path
Average Accuracy

- Average Accuracy is the arithmetic mean of a set of Instantaneous Accuracy measurements.
- At locations within the Active TCA, Average Accuracy represents the average distance, or error, between ACTLs and corresponding MLs, which could be taken at one or more ACTLs.
- Different locations within the Active TCA may have different Average Accuracy values.
Average Accuracy

- Simple arithmetic average
- For a set of N Instantaneous Accuracy measurements:

\[
\text{Average Accuracy} = \frac{\sum_{i=1}^{N} IA_i}{N}
\]
A tracking system estimates the location of a miner eight times, producing Measured Locations (MLs) M1, M2, M3, M4, M5, M6, M7, and M8 for the Actual Locations (ACTLs) of A1, A2, A3, A4, A5, A6, A7, and A8, respectively.
The x and y values of the MLs and ACTLs for each updated time of this example are compiled in a table:

<table>
<thead>
<tr>
<th>Time</th>
<th>Actual Location</th>
<th>Estimated Location</th>
<th>Instantaneous Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
</tr>
<tr>
<td>1</td>
<td>160</td>
<td>60</td>
<td>116</td>
</tr>
<tr>
<td>2</td>
<td>163</td>
<td>105</td>
<td>176</td>
</tr>
<tr>
<td>3</td>
<td>165</td>
<td>145</td>
<td>198</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>180</td>
<td>189</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>185</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>200</td>
<td>111</td>
</tr>
<tr>
<td>7</td>
<td>110</td>
<td>230</td>
<td>146</td>
</tr>
<tr>
<td>8</td>
<td>106</td>
<td>275</td>
<td>76</td>
</tr>
</tbody>
</table>

Average Accuracy = 36.7
The Standard Deviation of Accuracy is the standard deviation of a set of Instantaneous Accuracy measurements at locations in the Active TCA. SDA may be expressed as a value for an individual location, or a zone.

The Standard Deviation of Accuracy is calculated by taking the standard deviation of a set of IA measurements:

\[
\text{Standard Deviation of Accuracy} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (IA_i - AA)^2}
\]
## Standard Deviation of Accuracy

<table>
<thead>
<tr>
<th>Time</th>
<th>ACTL</th>
<th>ML</th>
<th>IA</th>
<th>IA - AA</th>
<th>(IA - AA)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>160</td>
<td>60</td>
<td>116</td>
<td>54</td>
<td>44.2</td>
</tr>
<tr>
<td>2</td>
<td>163</td>
<td>105</td>
<td>176</td>
<td>121</td>
<td>20.4</td>
</tr>
<tr>
<td>3</td>
<td>165</td>
<td>145</td>
<td>198</td>
<td>110</td>
<td>48.0</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>180</td>
<td>189</td>
<td>153</td>
<td>47.6</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>185</td>
<td>79</td>
<td>184</td>
<td>41.1</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>200</td>
<td>111</td>
<td>190</td>
<td>15.0</td>
</tr>
<tr>
<td>7</td>
<td>110</td>
<td>230</td>
<td>146</td>
<td>239</td>
<td>36.9</td>
</tr>
<tr>
<td>8</td>
<td>106</td>
<td>275</td>
<td>76</td>
<td>248</td>
<td>40.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Average Accuracy (AA)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Standard Deviation of Accuracy</strong></td>
</tr>
</tbody>
</table>
The 90% Confidence Distance is the distance from a tracked device’s actual location (i.e., ACTL) that is greater than 90% of the collected Instantaneous Accuracy measurement magnitudes (“90th percentile”).

For example, the 90% Confidence Distance of a hypothetical tracking system was measured to be 743 feet. That means that 90% of the Instantaneous Accuracy ML results were less than or equal to 743 feet from their corresponding ACTLs. A test may require that 90% of ML measurements be within 1,000 feet of the true location, in which the hypothetical tracking system installation would be found to pass the requirement.
90% Confidence Distance Example

<table>
<thead>
<tr>
<th>Time</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>63</td>
<td>67</td>
<td>68</td>
<td>63</td>
<td>51</td>
<td>59</td>
<td>31</td>
<td>34</td>
<td>40</td>
<td>35</td>
<td>33</td>
<td>35</td>
<td>34</td>
<td>38</td>
<td>45</td>
<td>63</td>
<td>61</td>
<td>54</td>
<td>64</td>
<td>73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>6</th>
<th>10</th>
<th>7</th>
<th>12</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>8</th>
<th>14</th>
<th>4</th>
<th>17</th>
<th>5</th>
<th>16</th>
<th>0</th>
<th>3</th>
<th>15</th>
<th>18</th>
<th>1</th>
<th>2</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>31</td>
<td>33</td>
<td>34</td>
<td>34</td>
<td>35</td>
<td>35</td>
<td>38</td>
<td>40</td>
<td>45</td>
<td>51</td>
<td>54</td>
<td>59</td>
<td>61</td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>64</td>
<td>67</td>
<td>68</td>
<td>73</td>
</tr>
</tbody>
</table>

| Sort Order | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |

90% Percentile is 67.1 in Excel or 67 if done by hand
Availability (AVAIL)

- Availability refers to the percentage of time that a tracking system is operational and meets regulations. Conversely, Availability can be thought of as 100 percent minus the percentage of time a tracking system is not operational or fails to meet regulations.

- The Availability of a tracking system indicates what percentage of time it meets regulations. If this percentage is not high (i.e., the tracking system is down often or requires excessive time to repair), the tracking system is not suitable for continuously tracking miners.


Susceptibility (SUS)

- Susceptibility is the change in a tracking system's 90% Confidence Distance when an event, expected or likely to occur, happens during the tracking system's normal operation.

\[
SUS = \frac{90\% \text{ Confidence Distance for Event} - 90\% \text{ Confidence Distance Normal}}{90\% \text{ Confidence Distance Normal}}
\]
Susceptibility (SUS)

- Under normal conditions, a set of MLs is taken at a single ACTL.
- Based on the Instantaneous Accuracy for each ML, the 90% Confidence Distance for that ACTL is calculated to be 48.1 feet.
- During an expected event, a scoop is moved into the vicinity of the same ACTL, and a new set of MLs is taken at the ACTL. Based on the new MLs, the 90% Confidence Distance for that ACTL during the scoop event is calculated to be 66.3 feet.
- Using the calculation formula, the Susceptibility of the tracking system during the scoop event is 37.8%. This means the system is approximately 38% susceptible to blockages of the entry from a scoop.

\[
\text{Susceptibility} = \frac{66.3 - 48.1}{48.1} = 0.378 = 37.8\%
\]
Mine Face Testing
Records collected by a Mine Survey Crew

- **Record Locations**
  - Records will be taken directly underneath spads, entries
  - Offsets at 25 ft. and 50 ft. offsets in four directions (Inby, Outby, Left and Right) where possible (optional)

- **Record Information**
  - Spad ID number
  - Position relative to spad (distance in feet, direction)
  - Tracked Device ID
  - Date and Time (hh:mm:ss)
  - Time is synchronized to tracking system

- **Tracking System Location Estimation Acquisition Time**
  - The handset is stationary for ML recording interval. The system makes a position estimate update once every ML recording interval.
Survey Crew Data
Time Study Logs

- Time Study Crew Data Collection Tasks
  - Time studies will be executed in the normal manner.
  - Additional information required in the time study logs is the tracker ID’s of the miners in the area.
  - Time stamps in the time study records must be synchronized to the tracking system computer.
- Data will then be analyzed in the same manner as the Survey Crew Data
Outby Testing
Mine Communication and Tracking Test Bed

- Sensor and Location Data
- Location and Sensor Hub
- Additional Sensor Bays
- Tracking Devices
- Operates by manpower or tow
Baselining a Tracking System

- These are tests of the “noise” and speed inside of the tracking system, results of which should be used as a filter for all other testing

- Mine Condition Survey
  - Get to know the radio environment in your mine

- Tracking System Variation when Stationary Testing

- Multiple Tracked Devices Effects Testing

- Travel Speed Testing

- Susceptibility Testing
Tracking System Variation when Stationary Testing

- Tracked handset is left at ACTL for extended interval
- Suggested location is in the Active Tracking Area and in constant contact to two or more infrastructure devices
- Record Information
  - Tracked Device location
  - Descriptive estimation of location of equipment
  - Date and Time (hh:mm:ss)
  - Tracking system configuration in area
- Records will be collected for several minutes up to several hours and shall not interfere with mining operations
Stationary Testing
Implications

- This is the most basic measurement of “noise”, where the most variables have been removed.
- Information learned from this testing will inform all other test interpretation.
- Information from this testing can only be applied to the site and the escapeway, it is not a measure of the system from the manufacturer.
- It won’t hurt to do this test often and in a variety of areas.
General Data Collection Procedure

- Perform clock synchronization at start of day before data collection.
- Position tracking devices and protocol analyzer on Survey Buggy, and on personnel who will walk with buggy. Make a record of the tracking device identification number, and its orientation on the buggy, or position on personnel.
- Make sure all tracking devices and protocol analyzer are turned on.
- Start at a known location in the test area – for example, under a spad.
- Set Survey Buggy’s absolute reference position to the known location.
- Initiate buggy’s ACTL logging function.
- Push, or tow the buggy along the center of the break, or entry, being measured at a speed of less than 10 mph.
- Keep a speed consistent with the miners that would travel through the area.
Multiple Tracked Devices

- Metrics are measured in an area using multiple tracked devices located in the same distribution relative to one another that is used in the general testing.
- Compare tracking system metric for single handset with values with multiple handsets.
- Mark stops at the same locations with each run.
Multiple Tracked Device Implications

- Stationary Testing should be used as a noise filter for the data collected here, the single device should closely resemble the stationary device.

- In this testing the data analysis should start to show the latency of the system, but because the velocity profile is not set, latency cannot be measured.

- We are not aware of a tracking system currently on the market that will have interference, but it is probable and easy to test.
Travel Speed Testing

- Velocity dependent effects are determined by measuring metric values while traveling at maximum safe speed possible.
- Test course of at least 8 breaks in distance which require no turns.
- Tracking system metric values measured at high speed, walking speed (2-4 mph), and crawling speed (0-1 mph).
- Compared to determine whether the values are affected by speed of travel during measurements.
Travel Speed Implications

- This will be used to determine the latency of the system and the potential maximum speed in the Escapeway Testing.
- In the event of an emergency, information learned from this testing can be used to determine the motion of escaping miners.
Susceptibility Testing

- Susceptibility of tracking accuracy to common and unavoidable obstructions of radio signals
  - These are vehicles traveling and parking, other equipment or people that fill the entryway
- Tracked devices will be hung every other break and allowed to “settle” (information learned from Stationary Tracked Device)
- Equipment is moved through the area, as it would normally, with detailed notation of the times and locations
Susceptibility Testing

Implications

- Potentially, this testing will rule out the towing of the survey buggy
- Useful for mine operations, can explain temporary outages and other daily issues
- This may inform data that is collected from the working face
Escapeway Area Testing

- This area of the mine is where miners that are escaping the mine after a disaster are most likely to be located.
- No matter the size of the mine, or the number of active face areas, there are two paths from a portal to the working face.
  - For a mine with 2 working sections there will be at least 4 escapeway paths.
  - Escapeways must be surveyed completely, overlap must be repeated.
- Each path should be surveyed separately.
- Distance will be divided into segments that are equal to two times the average pillar length, if that’s too hard, 200 feet.
Escapeway Area Testing

- Follow general procedure
- Start Survey Buggy at the portal and travel to the face
  - As close to the face as possible
- Following the escapeway path at a consistent speed similar to the speed a miner would regularly travel
- Number of tracked devices should be consistent with the number of miners that would travel together
- Do not exceed 10 mph
  - At 10 mph (14 ft./sec) and a 30 second report rate, there is 440 feet between data points
- At the face, return over the exact same path with the same velocity profile
Escape Area Testing

Implications

- Most mines are only requiring tracking along the escapeways
- Values from the escapeway testing, when summarized across the bins describes the tracking in the mine
- This testing should be performed regularly, especially prior to escapeway training
- Baselining testing will inform all questions a tester or examiner would have about this testing, such as number of devices/samples and speed
Presented are the most useful testing that was performed by the research team and in the order in which they should be performed.

All tests collect quite a lot of data, not just single points.

Survey Buggy makes testing a lot easier, but this can be done without.

Tracking on the working face is very important because of guidance requirements.

Areas in Perspective:
- A 8 entry section with 100 ft. x 100 ft. pillars and 6 cross cuts from the feeder describes an area that is almost 700,000 ft² with 200,000 ft² of open area.
- 2 miles of a single escapeway describes 212,000 ft² of open area.
Conclusions 2 of 2

- Two mine test beds were donated by NIOSH to Virginia Tech
- We will help you perform the tests described in this presentation and develop the baseline and performance metrics for your mine