The findings and conclusions in this presentation have not been formally disseminated by NIOSH and should not be construed to represent any agency determination or policy.
Path to wireless communications

• Communications & Tracking (CT) systems introduced were generally similar to or adapted from surface systems

• Coal mine environment is different from surface
  – No open spaces: restricted spaces, long entries, with cross-cuts
  – Operating environment: restrictions on location and size of antennas or other components
  – Sidewalls, roof, floor are somewhat conducting
  – Permissible system required
  – Different regulations apply in mine

• Radio waves propagate quite differently underground compared to surface systems – mechanisms not fully understood
What to expect in these presentations

- Underground radio technologies fall into 3 frequency bands
- Quick description of each (present projects; 4 year effort)
  - UHF
  - MF
  - TTE
- Electronic tracking: related but somewhat different area
- NIOSH/OMSHR research to assist in enhancing performance & reliability & survivability (MINER Act goals)
- Transfer knowledge
- Gap: How does signal vary with distance (path loss) specifically in the mine environment? (mine environment includes specific noise environment)

\[ P_r(dB) = P_t + G_t + G_r + \text{path loss} \]
Importance of Path Loss & Noise

- Degradation and loss of favorite radio station when drive out of coverage area
Importance of Path Loss & Noise

- Experienced degradation and loss favorite radio station when drive out of coverage area
- Implies quality reception
  - requires certain signal strength to work
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• Implies quality reception
  – requires certain signal strength to work
  – signal strength decreases with distance
• From tutorial presentation
  – signal quality depends on adequate signal to noise ratio (SNR)
• Successful radio system design
  – Relies on valid predictions and assumptions about signal propagation
  – Relies on characteristics of signal path
  – Relies on nature of anticipated noise and interference
Why modeling?

- Modeling: use of computer programs to simulate path loss (attenuation) between Tx and Rx

- Interaction of EM wave with environment can be complex
  - From tutorial, each frequency band propagation very different
  - Frequency of operation big effect on performance
  - Behavior likely to depend on characteristics of individual mine
  - Don’t want to perform RF experiments in every mine
  - Need physics to understand and formulas to predict

- Want to develop a tool for users to obtain mine-specific results
Other thoughts on modeling

- Easy to evaluate/understand ‘what if’ scenarios (sensitivity analyses)
- Can’t reasonably measure every mine – need model
- Incredible variety of powerful computational tools available
- Computational tools can be expensive
- Can require extensive computer resources
- Require experience to use
- Models must be validated with measurements
- Enhance understanding and develop modeling tools to make results available to all (webinar)

- Ultimately: a tool for users
UHF – mine entry propagation

• Research propagation from 450 MHz to 5.8 GHz
  – SHF 3 GHz – 30 GHz
  – Leaky feeder at 150 MHz (VHF)

• Path loss or propagation
  – Tunnel
  – Room and pillar
  – Obstructions – stoppings, equipment, people, wires/cables/pipes

• UHF radio wave propagation & attenuation down an entry
UHF measurement block diagram

- RF signal source
- Power Sensor
- Power meter (+3.17 dBm)
- Tx
- Rx
- Spectrum analyzer
Initial UHF measurements
2500 ft Abandoned train tunnel
UHF measurements in tunnel

Some measurements with patch antennas
Characterize antenna pattern
Antenna radiation pattern

2.4 GHz

EIRP (dBm)
UHF Measurements in NIOSH research mines
Mobile Rx antenna
Representative data sample

FREQ(0915) POL(horizontal) TX(center) RX(center) DIR(forward+reverse)
DATE(110503)
Fundamental wave property: wave front

Series of water waves

Seen from above (series of peaks)
Each plane is at the peak of the wave
Occurs after some distance (about a wavelength) from source

Generally not a consideration with MF or TTE because of such long wavelengths.
Tunnel acts as waveguide

Walls are somewhat conducting
EM (radio) waves confined to tunnel
Ray is perpendicular to wave front

Wave strikes wall (red):
Part reflects (green)
Part transmitted (blue) (removes some energy from the ongoing wave)
Ray optics model of UHF in tunnel

Remcom: Wireless InSite

TX antenna pattern
Model inputs

- Tunnel dimensions: height, width, length
- Electrical properties of each surface material
- Frequency of operation
- Tx and Rx antenna types: dipole, or other, or data
- Location of Tx and Rx antennas (can move)
Sample model results

915 MHz horizontal polarization, center of tunnel
1st year UHF research summary

• Determined/acquired appropriate RF equipment
• Characterized Tx and Rx antennas for 450 MHz – 5.8 GHz
• Made initial path loss measurements
  – Train tunnel
  – NIOSH research mines
  – Several working mines scheduled (next year)
• Developing models (& continue)
  – Ray optics
  – Several analytical models
  – NIST support
MF Research
MF Research

- MF radios alone – through air – 50 ft
- Near conductor – can propagate 1000’s feet
MF Parasitic Coupling

- MF propagates by parasitic coupling to conductors
- Want to start modeling and measurements with simplest configuration (build confidence)
- Relatively easy to model single isolated conductor
- Not so easy to measure/duplicate model geometry in practice
- RF currents can travel multiple paths (different from DC); environment plays big role
Separate coupling from transport

Coupling

1. How signal inductively couples from Tx/Rx loop to conductors

2 wire transmission line
Separate coupling from transport

Transport

2. How signal propagates down conductor(s)
   - Single conductor, coal return
   - Multiple conductors
   - How transition from one mode to other
   - How signal disperses at intersection/cross-cut
Start simple: measurements & modeling

• Difficult to find mine entry with no conductors or only one conductor

• Easier to do measurements on surface
  – Single conductor
    • earth for return path
    • earth electrical properties
  – 2 parallel conductors
    • reasonably far from surface
    • as determined by model
Transmission line model

R = resistance per length
L = inductance per length
G = shunt conductance per length
C = shunt capacitance per length

\( \alpha \) = attenuation per length (dB/100 ft)
VF = velocity factor (fraction of speed of light)
\( Z_0 \) = characteristic impedance (ohm)
MF measuring equipment
Surface MF Experiments

- Two wire transmission line
- Single wire – earth return transmission
Rare nice day
MF impedance measurements

- Black: short circuit
- Red: open circuit
MF impedance modeling

FEKO: method of moments

black: short circuit
red: open circuit
MF current distribution modeling

1000 kHz OPEN
sigma earth = 0.05
eps earth = 5
Red: measured data
Blue: Model

dB (I/I₀)

0 100 200 300 400 500 600 700 800 900

distance from source (feet)
MF in NIOSH mine
Attenuation determination

Twisted-pair pager phone wire with return through coal
1st year MF research summary

• Determined/acquired appropriate RF equipment
• Made initial path loss measurements
  – Surface
  – NIOSH safety research coal mine
  – Several working mines scheduled (next year)
• Developing models (& continue)
  – Method of moments
  – Several analytical models
  – Working with Penn State University
• Initial comparison of models and measurements is encouraging
TTE Research
Coupling between loops

Generate RF current in one loop
Induces RF current in other loop
Free Space loop coupling

Important parameters:
- \( I_{tx} \) = Current (total is N turns X current per turn) in Tx loop
- \( R_{Tx} \) = Radius of Tx loop
- \( R_{Rx} \) = Radius of Rx loop
- \( d \) = Separation distance
- \( f \) = Frequency

Voltage induced in \( R_{x} \) loop

\[
V_{Rx} = 1.1 \cdot 10^{-5} \frac{I_{Tx} R_{Tx}^2 R_{Rx}^2 f}{d^3}
\]

\( M = \text{magnetic moment} \quad M = NI_{Tx}(\pi R_{Tx}^2) \)
Loop coupling through earth

\[ V_{Rx \text{ with earth}} = V_{Rx \text{ free}} \frac{0.022}{d^{1.22} f^{0.58} \sigma^{0.363}} \quad \text{One approximation} \]

\[ \sigma = \text{conductivity of earth} \]
Use coupling to determine apparent/effective $\sigma$

$$H_z = \frac{M}{2\pi d^3} Q$$

NIOSH RI 8869
“Apparent Earth Conductivity…”
John Durkin

$\sigma$ overburden (S/m)
TTE Measurements

7.5 ft radius
10 turns

Transmit:
10 amps
100 Hz to 10 kHz

Built two: Tx and Rx
Use spectrum analyzer to measure Rx antenna signal
Field Strength in air

\[ H_z = \frac{NI(R^2)}{2\pi(R^2 + d^2)^{\frac{3}{2}}} \]
1st year TTE Research Summary

- Initial investigation of loop coupling models
- Evaluation of Bureau of Mines TTE data & comparison to models
- Determined/acquired appropriate TTE RF equipment
- Built two TTE loop antennas
- Optimized coupling to antennas
- Measured field from loop in air & compared to prediction
- Preparing for TTE measurements in mines
- Developing more sophisticated models (& continue)
Electronic Tracking Research

Reduced powered infrastructure more survivable

- Two main areas
  - Inertial tracking
    - Potentially reduced system infrastructure
    - Potentially high accuracy
  - Passive RFID
    - Potentially high accuracy
    - Potentially easy installation
Inertial tracking

- Inertial navigation unit (INU)
- Inertial measurement unit (IMU)
- Sensors
  - Detect linear, and angular acceleration
  - Integrate to get displacement
  - No external reference required (in theory, only need starting location)
- MicroElectroMechanical Systems – MEMS
  - Used in game consoles, automobile air bag systems, guided missiles, aircraft
IMU prototype testing

Carnegie Mellon University

- MEMS on boot
- MEMS drift offset
- Multiple sensor data to re-zero IMU
  - Ultrasonic range measurement between boots
  - RFID and readers throughout mine
IMU testing in NIOSH mine
IMU results

- Drift still an issue
- Too much data fusion required
- IMU research expensive & specialized
- Significant commercial (non-mining) interest in improving IMU; especially for GPS denied environments
- NIOSH will continue to monitor progress
- In future, may resolve drift
Passive RFID investigations

• Presently RFID underground uses ‘active’ tags
  – Whether tags are on miner or on mine walls – battery operated
  – To achieve significant read range need active tag
  – Passive has limited read range

• Passive tags
  – Inexpensive
  – Short read range
  – If closely spaced could increase accuracy at low cost
  – Working with Univ of Pittsburgh RFID Research Center
  – Attempt to achieve adequate read range
Presently establishing requirements

RFID reader

passive tag
1st year Tracking Summary

- Investigated several inertial tracking systems
  - Drift still an issue
  - Will monitor commercial progress

- Passive RFID
  - Working with Univ of Pittsburgh RFID Research Center
  - Establishing performance requirements
  - Will procure several systems and evaluate in near future
UHF, MF, TTE, Tracking
Research Summary

• Communications research focus is on path loss
• Major initial effort in evaluating equipment for specific frequency range of operation and for required measurements
• Obtained initial measurement data of path loss for each band
• Completed initial modeling efforts in each frequency band
• Near term efforts:
  – Acquire RF data in several mines
  – Enhance models
  – Validate models with measurement data
• Tracking mainly focused on passive RFID
The findings and conclusions in this presentation are those of the authors and do not necessarily represent the views of NIOSH. Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention.
Questions?

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