Communications & Tracking in Underground Coal Mines

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Dec 6, 2011

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MINER Act of 2006

• The disaster at Sago Mine in West Virginia has highlighted the need for advanced communication and tracking systems that can function during an emergency.

• Mine Improvement and New Emergency Response Act of 2006.
  – Wireless two-way communications
  – Electronic tracking system to locate miners
NIOSH Communications & Tracking (CT) Support

- CT equipment development contracts
- CT studies: survivability, battery safety, modeling and simulation tools, ...
- CT workshops
- CT tutorial
- BAA process (limited funds) & specific competitive solicitations
  - Generally fund demonstration of new or enabling technology
- Internal research
Webinar Focus: Status of NIOSH Research

- CT Tutorial Part 2 (updated, to be posted on web)
  - http://www.cdc.gov/niosh/mining/

- Internal Research (NIOSH):
  - Three main frequency bands for coal mine radio systems
    - UHF, ultra-high frequency, (VHF/UHF/SHF) 150 MHz – 6 GHz
    - MF, medium frequency, 300 kHz – 3 MHz
    - TTE, through-the-earth, 10 Hz – 5 kHz

- Electronic tracking
  - RFID (active, passive), Reverse RFID, RSSI, inertial
CT Tutorial, Part 2

CT Tutorial Part 1
http://www.cdc.gov/niosh/mining/
Tutorial Outline

• Background on wireless communications
• UHF (leaky feeder, node-based)
• MF
• TTE
• Tracking
Wireless Communication

Transmitter (Tx)
sender / talker

Receiver (Rx)
listener
A Communications Link

transmission medium

transmitter
“Talking”

receiver
“Listening”
Characteristics of Wave

Frequency = number of peaks (cycles) per second = Hz
Speed of Radio Wave

Frequency X Wavelength = Speed

or

Wavelength = \( \frac{\text{Speed}}{\text{Frequency}} \)

Speed of light = \( 3 \times 10^8 \text{ m/s} = 186,400 \text{ miles/sec} \) (in air)
Some Examples (wavelengths)

UHF radios:

900 MHz

\[
\frac{3 \times 10^8 m/s}{900 \times 10^6 Hz} = 0.33 \text{ m} \approx 1 \text{ foot}
\]

2400 MHz = 2.4 GHz

\[
\frac{3 \times 10^8 m/s}{2.4 \times 10^9 Hz} = 0.125 \text{ m} \approx 5 \text{ inches}
\]
Couple more examples (wavelengths)

MF radios:
500 kHz

\[
\frac{3 \times 10^8 \text{m/s}}{500 \times 10^3 \text{Hz}} = 600 \text{ m} \approx 1970 \text{ feet}
\]

TTE radios:
2000 Hz

\[
\frac{3 \times 10^8 \text{m/s}}{2000 \text{ Hz}} = 150 \text{ km} \approx 93 \text{ miles}
\]
Electromagnetic Spectrum
Use of Electromagnetic Spectrum is Regulated

- National Telecommunications and Information Administration (NTIA)
  - Regulates Federal Government’s use of the spectrum

- Federal Communications Commission (FCC)
  - Regulates commercial use of spectrum in U.S.
  - Limits emissions from underground mines (Code of Federal Regulations - CFR)
  - Does not require *Frequency Planning*
  - Does not regulate *Electromagnetic Compatibility* (EMC)
Transferring an RF message

What is required to send a wireless RF message between two radios?

OR

What is the process of sending an RF message between two radios?
2 basic electrical signal formats

Analog

Digital

b) digital signal
Message

analog or digital

Transmission

transmit

receive

carrier $f_c$

modulator

demodulator

transmitter

receiver

analog

digital
analog or digital

Message

Transmission

carry \( f_c \)

transmit

receive
Convert from analog to digital
The voltage value at each time interval is chosen from nearest of $2^n$ values, where 

$$n = \text{number of bits}$$
Example: bits

- Suppose voltage range is -1 to +1 volts
- Suppose 8 bit digitizer is used (n=8)
- Implies $2^8 = 256$ voltage values
- Voltage resolution = 2 volts/256 = 7.8 mV ~ 0.008 V
- Actual voltage assigned to nearest value
- Each voltage level is represented by eight 0’s & 1’s e.g. 01001101
- Lowest voltage might be 00000000 and highest voltage 11111111
Message in form of bits

- Message transmitted at bits per second (bps)

- Bit rate is limited:

\[ C = B \log_2 \left( 1 + \frac{S}{N} \right) \]

\( C = \) channel capacity (bits/s),
\( B = \) channel bandwidth (Hz),
\( S = \) signal strength (watts),
\( N = \) noise power (watts).
Noise Added to Signal

original message → internal transmitter system noise → environmental RF noise → internal receiver system noise → decoded message

Tx

Rx
Example: signal + noise

signal

noise

signal + noise
Sources of RF Noise

• Internal to electronics
  – Thermal noise, $k_B T B = -174 + 10 \log(B) \text{ dBm}$
  – Inherent to electronics $\sim 7 – 15 \text{ dB}$

• Environmental noise
  – TV, radio, cell phone/tower (intentional radiator)
  – Electrical mine equipment, power lines (unintentional radiator)
  – Interference: Radiated or Conducted
Performance with noise

• Message is sequence of bits

• Reliability of reading a bit correctly with noise present depends on SNR

• Bit error rate (BER) is probability of incorrectly reading a bit

• BER = (number of errors/number of bits sent)
Errors related to bit rate

• $T_b = \text{duration (seconds) of a waveform associated with bit}$

• $R = \text{bit rate, or data rate (bits/second)}$

• $R = \frac{1}{T_b}$
Errors related to energy in bit

- \( S = \) signal power (watts)

- \( E_b = \) RF energy in bit waveform (joules)

- \( E_b = ST_b \) (watt second = joule)
Effect of Noise

- $N = N_0 B = \text{noise power (watts)}$

- $N_0 = \text{thermal noise in 1 Hz of bandwidth (watts/Hz)}$

- $B = \text{bandwidth (Hz)}$

- $\text{SNR} = \frac{S}{N} = \left[ \frac{E_b}{N_0} \right] \left[ \frac{R}{B} \right]$
BER will depend on modulation type

![Graph showing BER vs. Eb/N0 (dB) for different modulation types, including PSK and OFSK.]
SNR example

\[ \frac{E_b}{N_o} = 10.2 \text{ dB} \implies 10^{10.2/10} = 10.5 \]

R = 40 kbps

B = 80 kHz

SNR = \frac{S}{N} = \left[ \frac{E_b}{N_o} \right] \left[ \frac{R}{B} \right]

SNR = 10.5 \times \frac{40 \text{ kbps}}{80 \text{ kHz}} = 5.25 \implies 7.2 \text{ dB}

Signal must be 7.2 dB above noise to get BER=10^{-6}
Find received power, $P_r$

$P_r$ depend on $P_t$
$Pr$ depends on radiation pattern

High directivity = High gain ($G$) antenna pattern

Both Tx and Rx antennas have gain
Radiation pattern: gain

Dipole antenna

$g = 1.6 \quad G = 2.15 \text{ dBi}$
**Tx power incident on Rx antenna**

Effective isotropic radiated power from antenna

$$\text{EIRP} = p_t \cdot g_t$$

Power density (watts/m$^2$) at distance $R$ from Tx

$$pdensity = \left( \frac{P_T g_T}{4\pi R^2} \right)$$
Rx antenna aperture

Rx antenna has ‘effective area’ or ‘aperture’

\[ A_e = \left( \frac{p_R}{pdensity} \right) = \frac{power\ absorbed}{incident\ power\ density} \]

\[ A_{e\ max} = \left( \frac{g_r \lambda^2}{4\pi} \right) \]

\( \lambda = \) wavelength of radiation
Power captured by Rx antenna

\[ p_R = \left( \frac{p_T g_T}{4\pi R^2} \right) \cdot \left( \frac{g_R \lambda^2}{4\pi} \right) \]

Incident power density \hspace{1cm} \text{effective aperture of receiver}

\[ p_r = \text{power dissipated in receiving antenna} \ (W) \]
\[ p_t = \text{power transmitted by radio} \ (W) \]
\[ g_t = \text{transmit antenna gain} \]
\[ R = \text{separation distance between Tx and Rx} \]
\[ g_r = \text{receive antenna gain} \]
\[ \lambda = \text{wavelength of transmitted frequency} \]
Quick Example

\[ p_R = \left( \frac{p_T g_T}{4\pi R^2} \right) \cdot \left( \frac{g_R \lambda^2}{4\pi} \right) \]

Tx: 1 W radio at 900 MHz with dipole antenna
Rx: dipole antenna; 100 m from Tx

\[ p_R = \left( \frac{1W \cdot 1.65}{4\pi (100m)^2} \right) \cdot \left( \frac{1.65(0.33m)^2}{4\pi} \right) = 1.9 \times 10^{-7} \text{ W} \]

\[ = 10 \log \left( \frac{1.9 \times 10^{-7}}{10^{-3}} \right) = -37.2 \text{ dBm} \]
Link Budget

Take log of both sides of previous equation

\[ P_r (dB) = P_t + G_t + G_r + 20 \times \log \left( \frac{4\pi R}{\lambda} \right) \]

free space path loss

May have additional terms:
- Losses in lines connecting amplifier to antenna
- Losses through media other than free space

Given SNR discussion, there exists minimum Rx power
Frequently use equation to determine allowable path loss
Network: extends sender/listener separation
CT Tutorial, Part 2

Finished background

Now communications technologies
Primary Communications

- Primary communications systems are those that:
  - Operate in the conventional radio bands
  - Use small antennas that allow the miner to have wearable devices with long battery life
  - Have sufficient throughput for general operations

- Leaky feeder and node based systems are examples of primary systems
Secondary Systems

• A secondary system is one which:
  – Operates in non-conventional frequency bands
  – Uses a large antenna that is best suited for fixed locations or portable applications
  – Does not have sufficient throughput for general operations

• Medium Frequency Systems and TTE Systems are viable secondary systems that can provide alternate communications paths out of the mine
Mention of any company or product does not constitute endorsement by NIOSH.
Primary: Leaky Feeder

VHF ~ 150 MHz
UHF ~ 450 MHz

Leaky feeder cable – distributed antenna
Push to Talk Radio: half duplex

Uplink and downlink at 2 different frequencies
LF system composed of cells

Diagram showing a LF system composed of cells connected sequentially. The system includes a base station, portal, cell units, power supply, injector, amplifier, and barrier.
LF Alternate Communication Path

- Secondary Base Station
- Primary Base Station
- Overland Fiber-Optic Link
- Air Shaft
- Elevator Shaft
- 3 Miles
- Leaky Feeder
Primary: Node based

Nodes communicate each other wired or wireless
Example of Access Point
Fiber optic backhaul
Wireless backhaul
Node based configuration
Node based
Alternate Communications Path
Secondary: MF
Portable MF radio
Interoperable with UHF (option)
Extend LF coverage (option)
Secondary: TTE

- loop antenna
- surface
- radio signal
- loop antenna in mine entry
Deployable loop antenna
TTE within mine

Communicate horizontally – not need access to surface
Separate Tx and Rx antennas
Electronic Tracking

- RFID & Reader
- Reverse RFID
- Received Signal Strength Indicator (RSSI)
Tracking System
Radio Frequency ID (RFID)
RFID tag and reader
Reader ‘interrogates’ tag
Zone based location

Miner A

Miner B

reader
Reader notifies MOC
Reverse RFID

Miner wears reader;
Tags in entries at known locations
Reader on miner

MOC

RFID reader

RFID reader

RFID reader

RFID reader

Tag

Tag

Tag

RF link

RF link

leaky feeder cable
Another technique: RSSI

RSSI: received signal strength indicator
Summary

- Frequency, wavelength, speed of radio waves
- Analog, digital signals
- Message vs transmission (digital/analog)
- Bits
- Channel capacity, bps
- Noise
- SNR, BER
- Link Budget
- Antenna patterns
- Primary Communications: leaky feeder, node based
- Secondary Communications: MF, TTE
- Tracking systems: RFID, Reverse RFID, RSSI
Additional Tutorial Topics

• Survivability, reliability, availability
• Alternate communications paths
• CT system safety
  – Permissibility
  – Explosion proof enclosures
  – Intrinsic Safety certification
  – Battery requirements
  – Hazards of Electromagnetic Radiation
    • Personnel, explosive atmosphere, electroexplosive devices
    – Electromagnetic Compatibility
• Mine Operations Center
• Appendices: more detailed formulas and calculations
Talks to follow

Internal Research

• Understanding RF signal path loss
  – UHF
  – MF
  – TTE

• Tracking
  – Inertial
  – 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.
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