Communications & Tracking in Underground Coal Mines

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NIOSH OMSHR
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Department of Health & Human Services

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Centers for Disease Control

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National Institute for Occupational Safety & Health
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Office of Mine Safety and Health
OMSHR

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

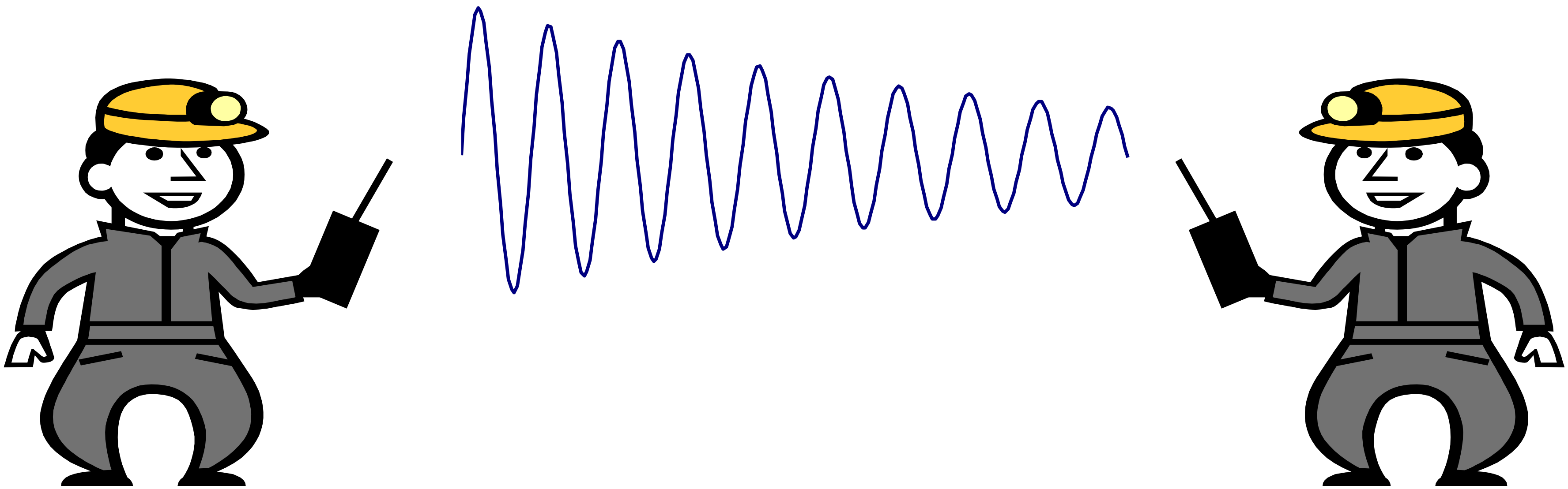
CT Tutorial, Part 2

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

Tutorial Outline

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

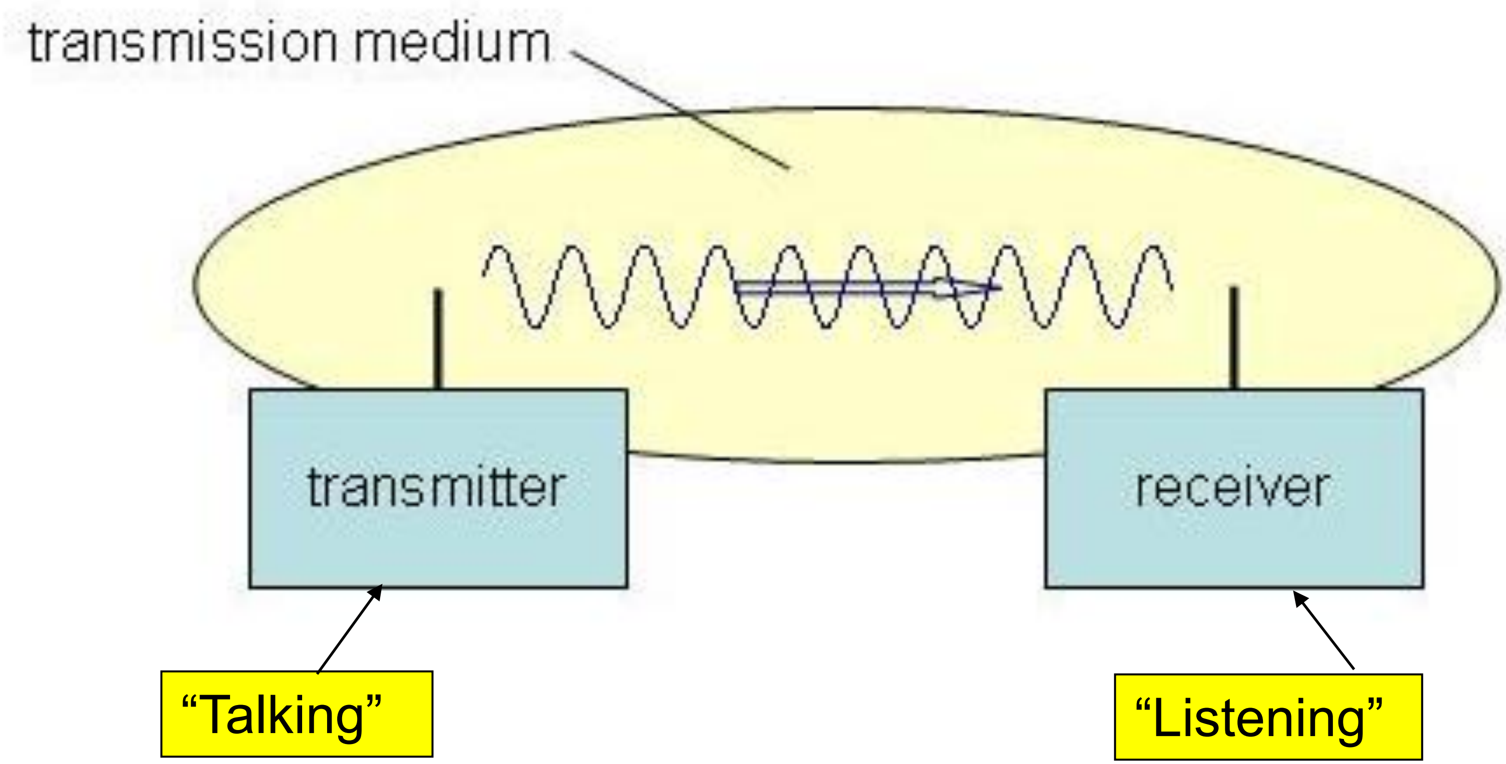
Wireless Communication



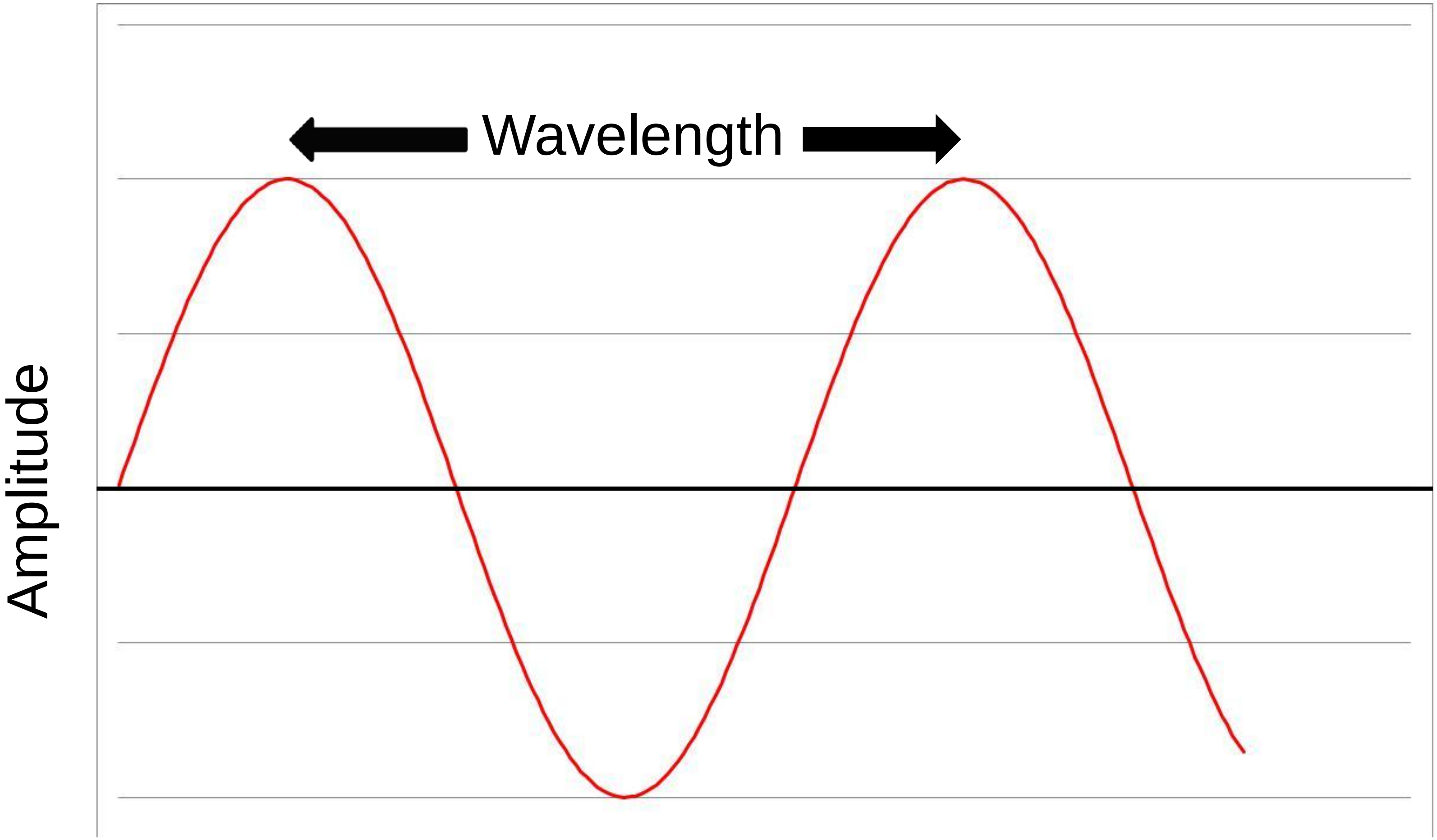
Transmitter (Tx)
sender / talker

Receiver (Rx)
listener

A Communications Link



Characteristics of Wave



Frequency = number of peaks (cycles) per second = Hz

Speed of Radio Wave

Frequency X Wavelength = Speed

or

$$\text{Wavelength} = \frac{Speed}{Frequency}$$

Speed of light = 3×10^8 m/s = 186,400 miles/sec
(in air)

Some Examples (wavelengths)

UHF radios:

900 MHz

$$\frac{3\ X\ 10^{8} m/s}{900\ X\ 10^{6} Hz} = 0.33 \text{ m} \cong 1 \text{ foot}$$

2400 MHz = 2.4 GHz

$$\frac{3\ X\ 10^{8} m/s}{2.4\ X\ 10^{9} Hz} = 0.125 \text{ m} \cong 5 \text{ inches}$$

Couple more examples
(wavelengths)

MF radios:

500 kHz

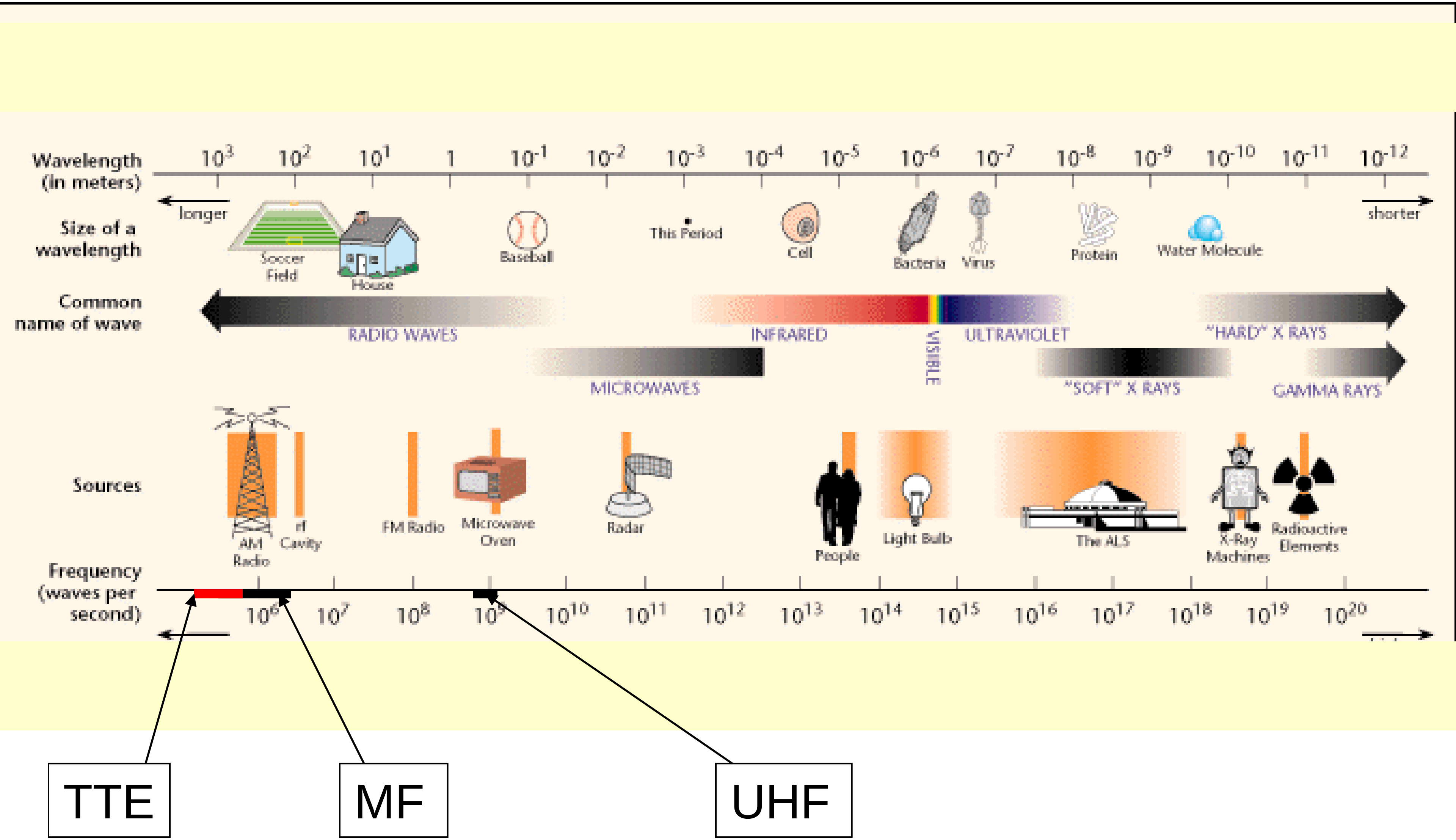
$$\frac{3\ X\ 10^{8} m/s}{500\ X\ 10^{3} Hz} = 600\text{ m} \cong 1970\text{ feet}$$

TTE radios:

2000 Hz

$$\frac{3\ X\ 10^{8} m/s}{2000\ Hz} = 150\text{ km} \cong 93\text{ miles}$$

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

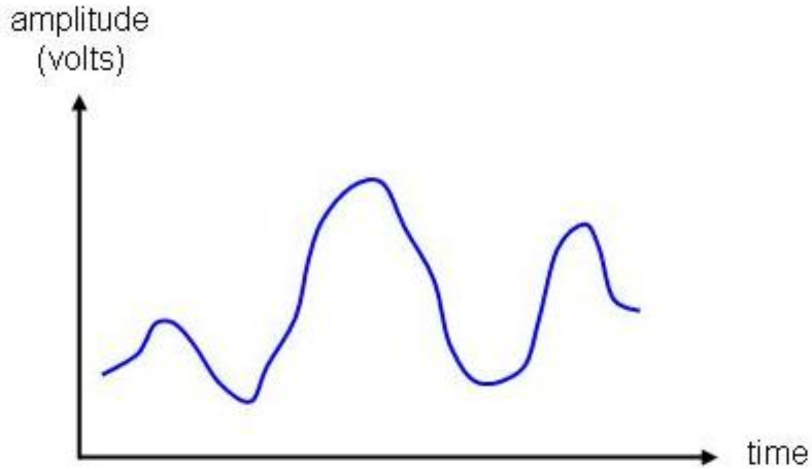
What is required to send a wireless RF message between two radios?

OR

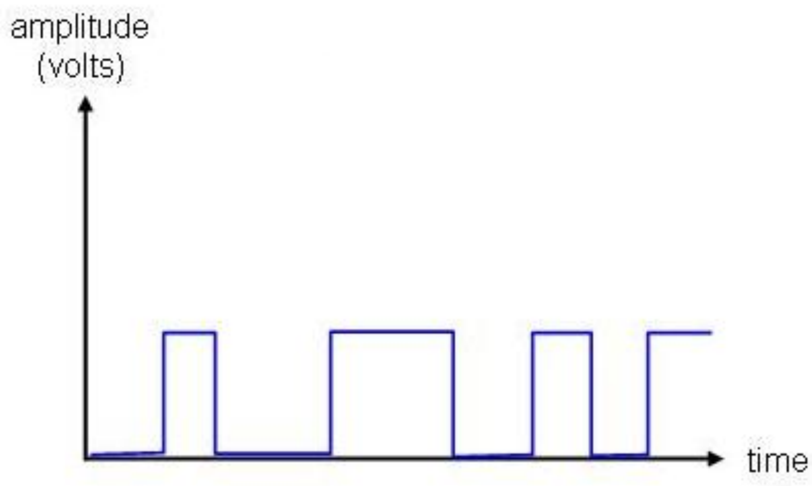
What is the process of sending an RF message between two radios?

2 basic electrical signal formats

Analog



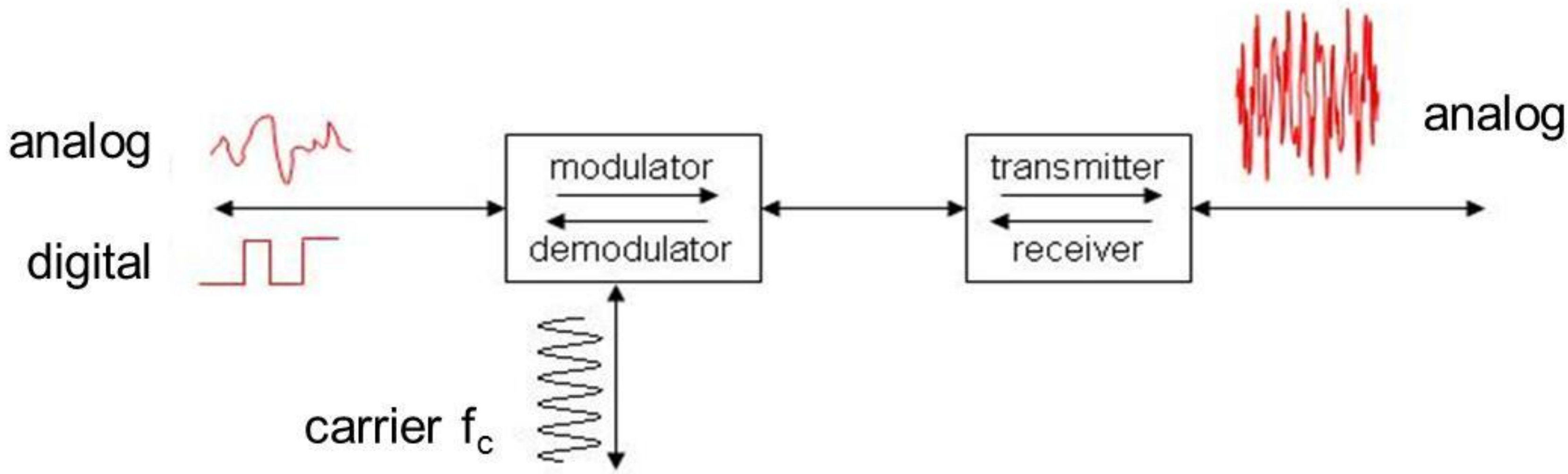
Digital



b) digital signal

analog or digital

Message **Transmission**

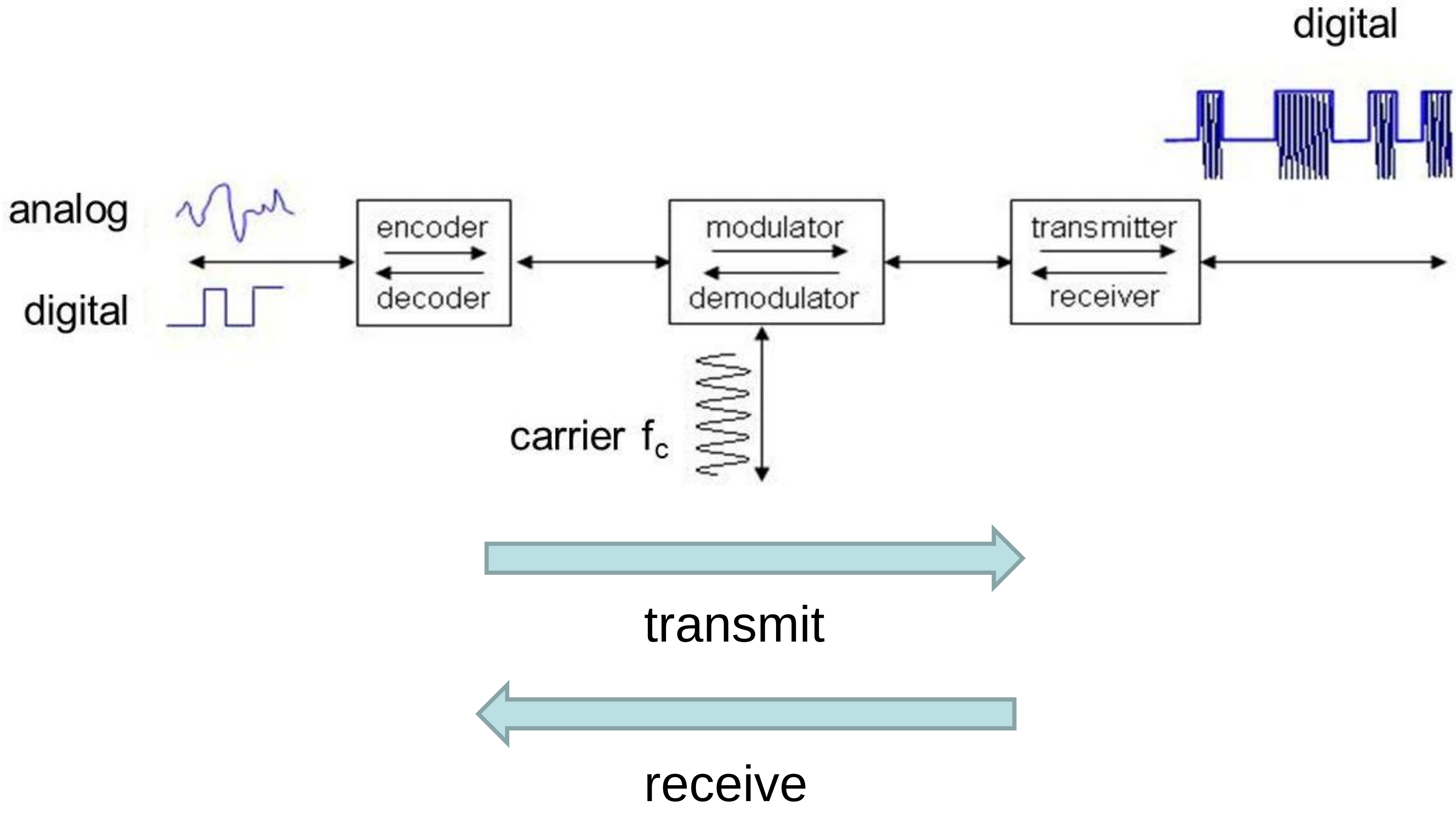


transmit

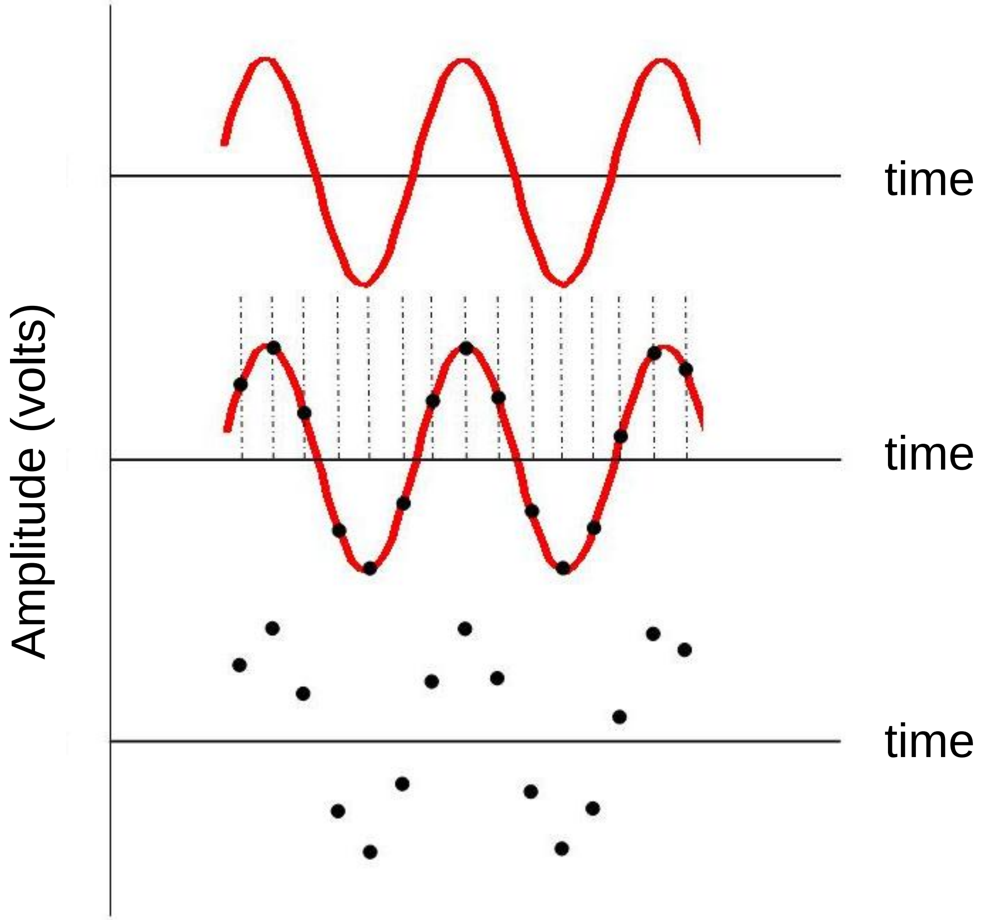
receive

analog or digital

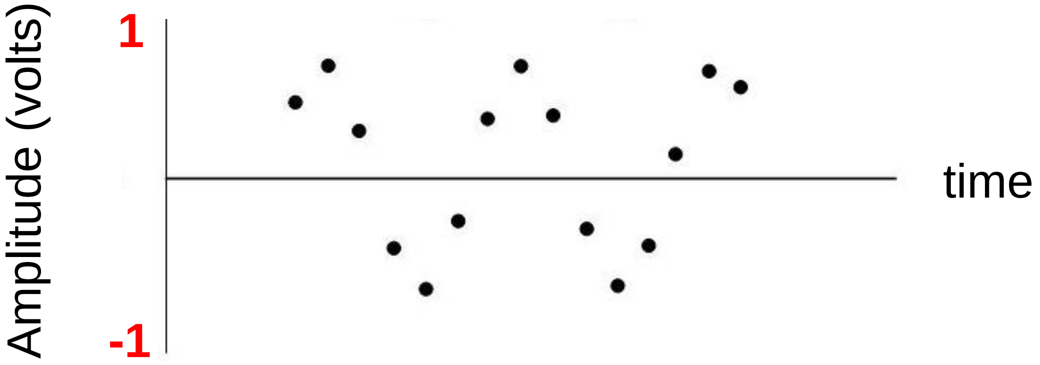
Message **Transmission**



Convert from analog to digital



Digital ‘bits’



The voltage value at each time interval
is chosen from nearest of 2^n values, where

n = 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

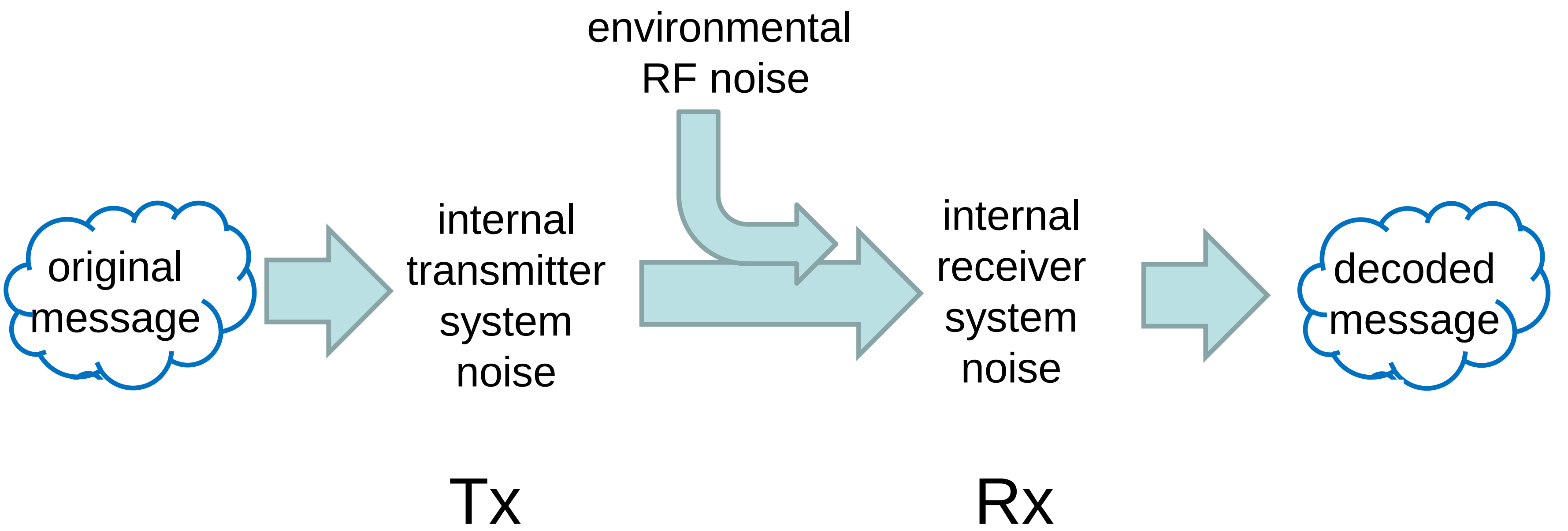
- Message transmitted at bits per second (bps)

- 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

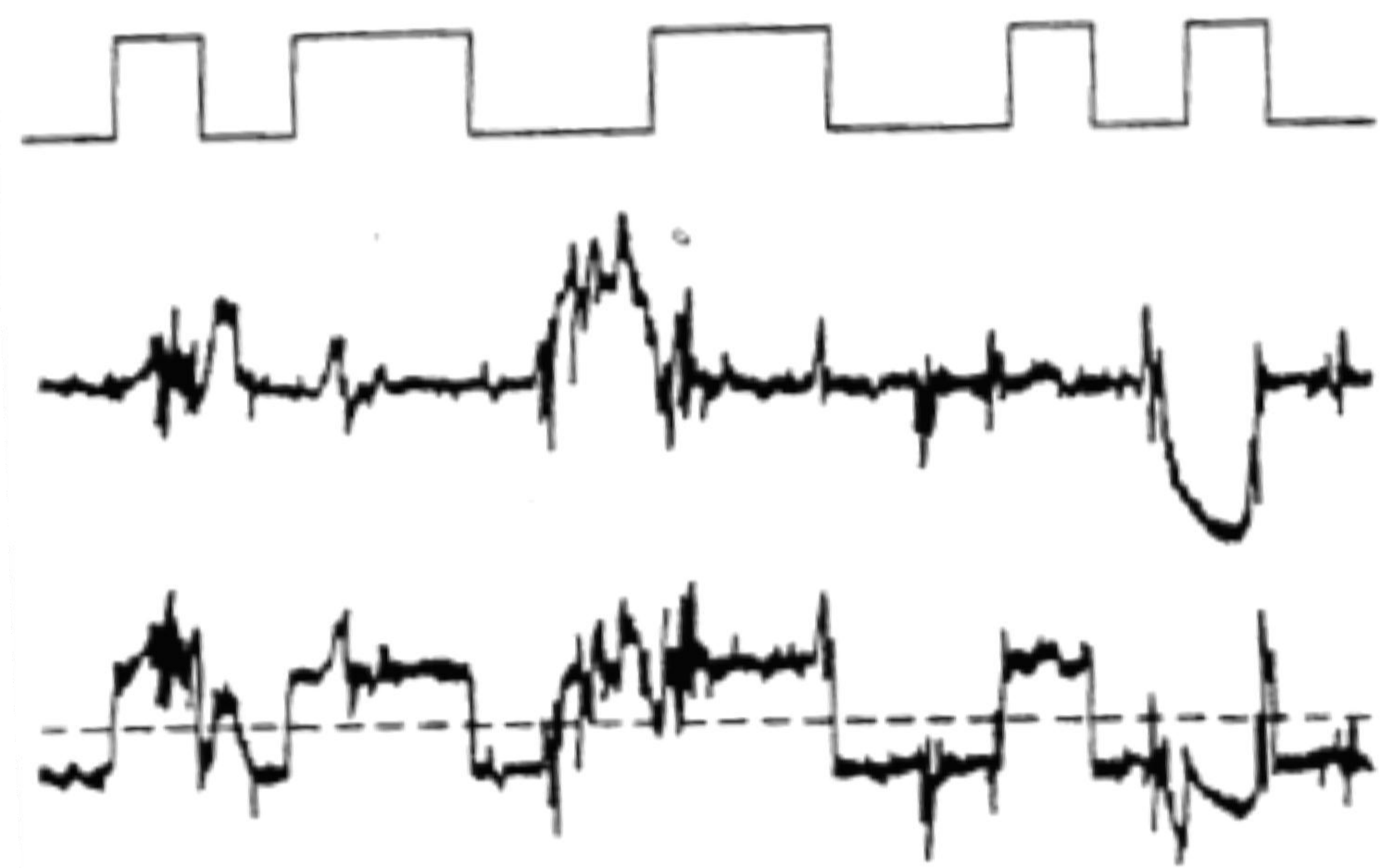


Example: signal + noise

signal

noise

signal +
noise



Sources of RF Noise

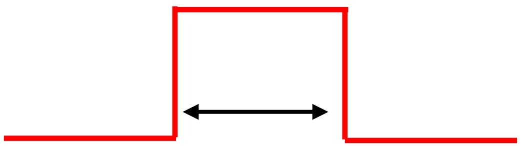
- Internal to electronics
  - Thermal noise, $k_B TB$ = -174 + 10 log(B) dBm
  - Inherent to electronics ~ 7 – 15 dB
- Environmental noise
  - TV, radio, cell phone/tower (intentional radiator)
  - Electrical mine equipment, power lines (unintentional radiator)
  - Interference: Radiated or Conducted

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 = duration (seconds) of a waveform associated with bit



- R = bit rate, or data rate (bits/second)

- $R = \frac{1}{T_b}$

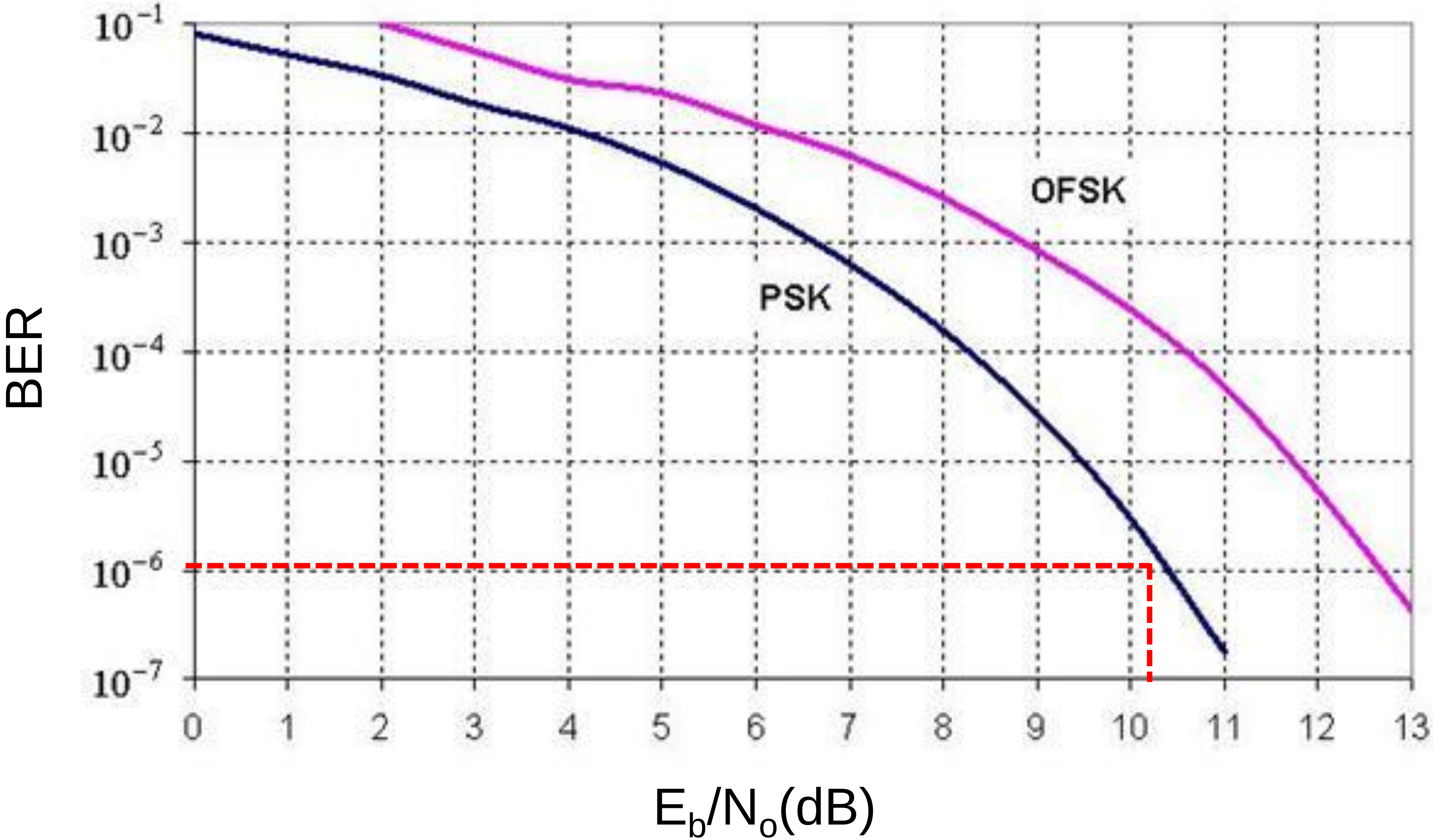
Errors related to energy in bit

- S = signal power (watts)
- E_b = RF energy in bit waveform (joules)
- $E_b = ST_b$ (watt second = joule)

Effect of Noise

- $N = N_oB$ = noise power (watts)
- N_o = thermal noise in 1 Hz of bandwidth (watts/Hz)
- B = bandwidth (Hz)
- SNR $= \frac{S}{N} = \left[\frac{E_b}{N_o}\right] \left[\frac{R}{B}\right]$

BER will depend on modulation type



SNR example

E_b/N_o = 10.2 dB => $10^{10.2/10} = 10.5$

R = 40 kbps

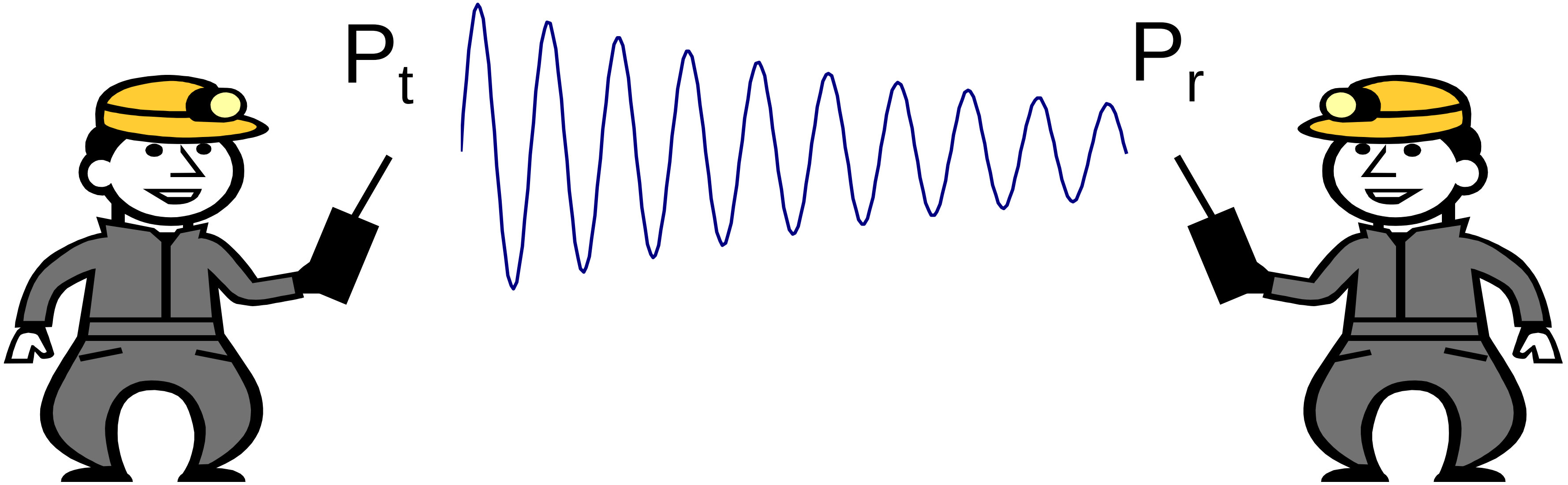
$$\text{SNR} = \frac{S}{N} = \left[\frac{E_b}{N_o}\right]\left[\frac{R}{B}\right]$$

B = 80 kHz

SNR = 10.5 * (40 kbps)/(80 kHz) = 5.25 => 7.2 dB

Signal must be 7.2 dB above noise to get BER=10^{-6}

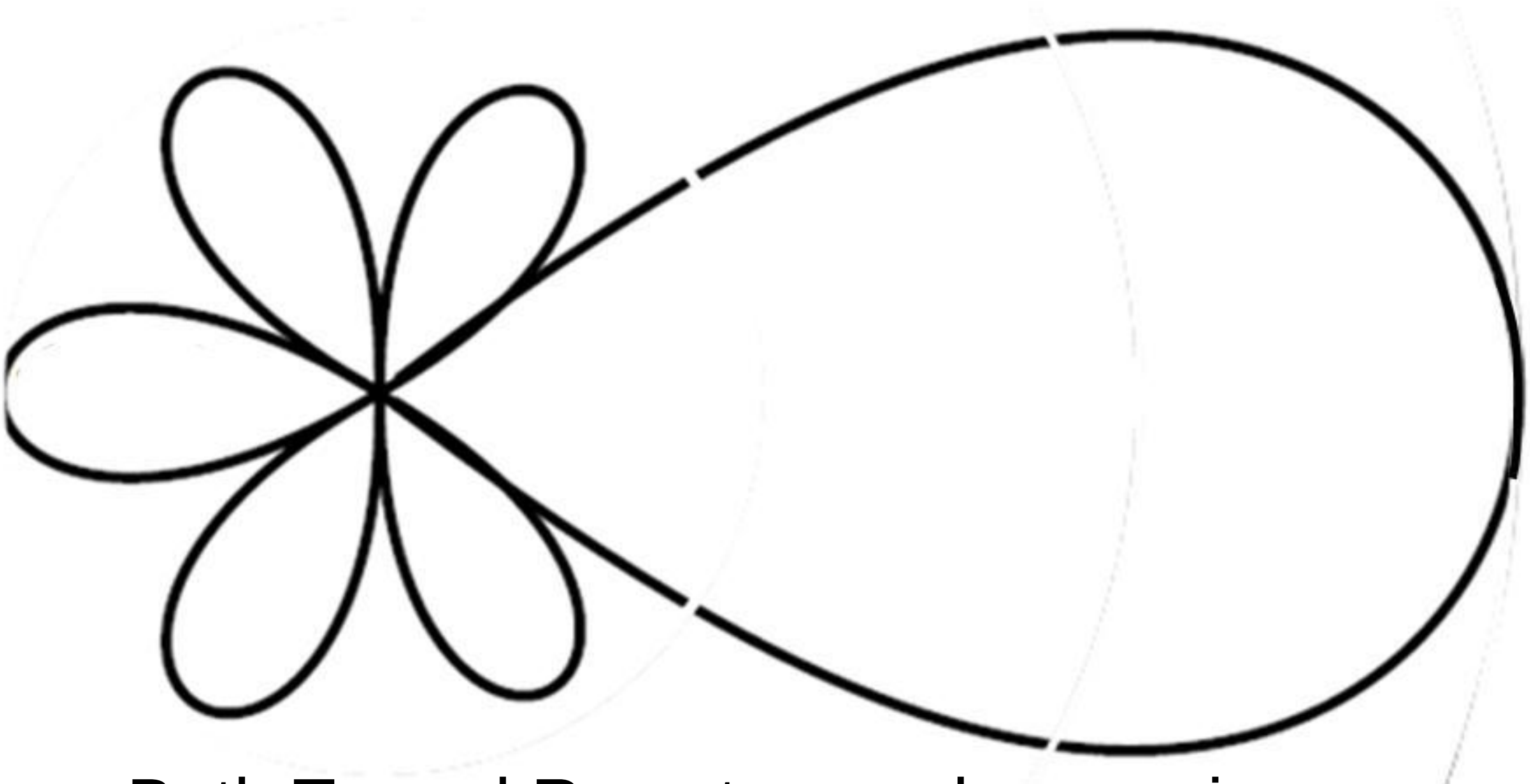
Find received power, Pr



P_r depend on P_t

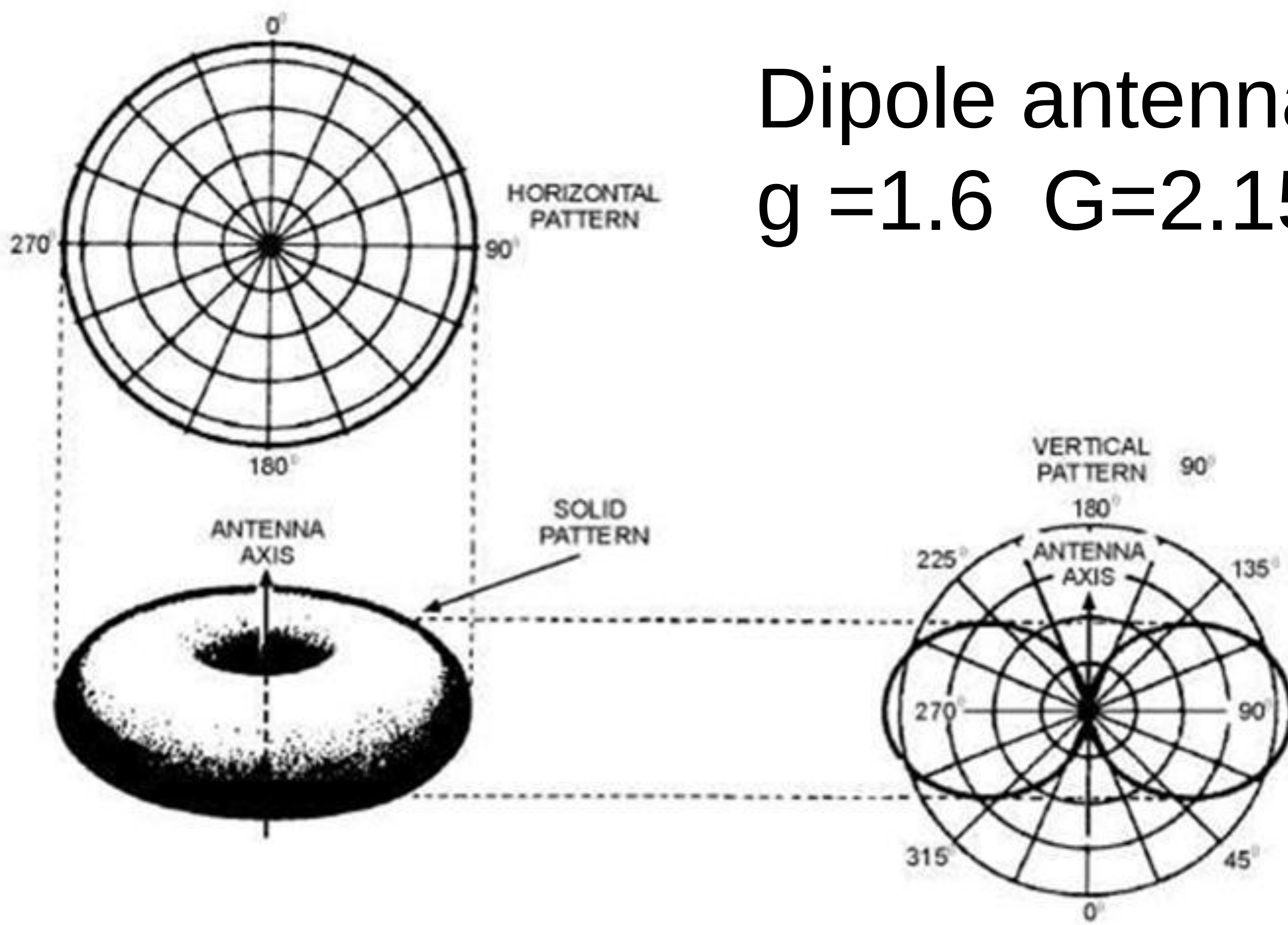
Pr depends on radiation pattern

High directivity = High gain (G) antenna pattern



Both Tx and Rx antennas have gain

Radiation pattern: gain



Dipole antenna

g =1.6 G=2.15 dBi

Tx power incident on Rx antenna

Effective isotropic radiated power from antenna

$$EIRP = p_t * g_t$$

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’

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

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

λ= wavelength of radiation

Power captured by Rx antenna

$$p_R = \overbrace{\left(\frac{p_T g_T}{4\pi R^2}\right)}^{\text{Tx}} \bullet \overbrace{\left(\frac{g_R \lambda^2}{4\pi}\right)}^{\text{Rx}}$$

Incident power density effective aperture of receiver

p_r = power dissipated in receiving antenna (W)
p_t = power transmitted by radio, (W)
g_t = transmit antenna gain
R = separation distance between Tx and Rx
g_r = receive antenna gain
λ = wavelength of transmitted frequency

Quick Example

$$p_R = \left(\frac{p_T g_T}{4\pi R^2} \right) \bullet \left(\frac{g_R \lambda^2}{4\pi} \right)$$

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

$$p_R = \left(\frac{1W\,1.65}{4\pi(100m)^2} \right) \bullet \left(\frac{1.65(0.33\,m)^2}{4\pi} \right) = 1.9 * 10^{-7}\ W$$

$$= 10\ log\left(\frac{1.9 \cdot 10^{-7}}{10^{-3}}\right) = \ -37.2\ dBm$$

Link Budget

Take log of both sides of previous equation

$$P_r(dB) = P_t + G_t + G_r + \underbrace{20*\log\left[\frac{4\pi R}{\lambda}\right]}_{\text{free space path loss}}$$

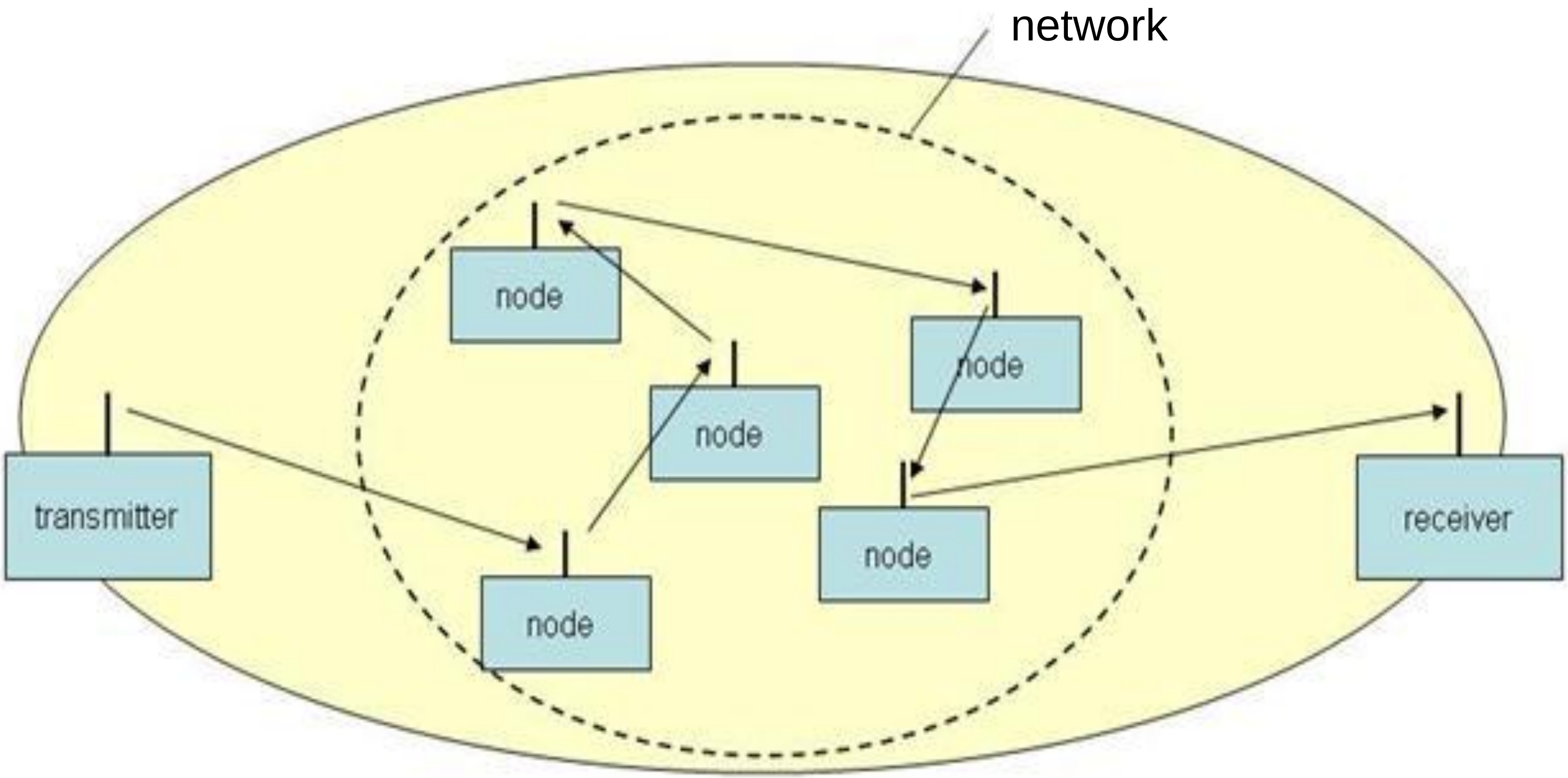
May have additional terms:

- 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

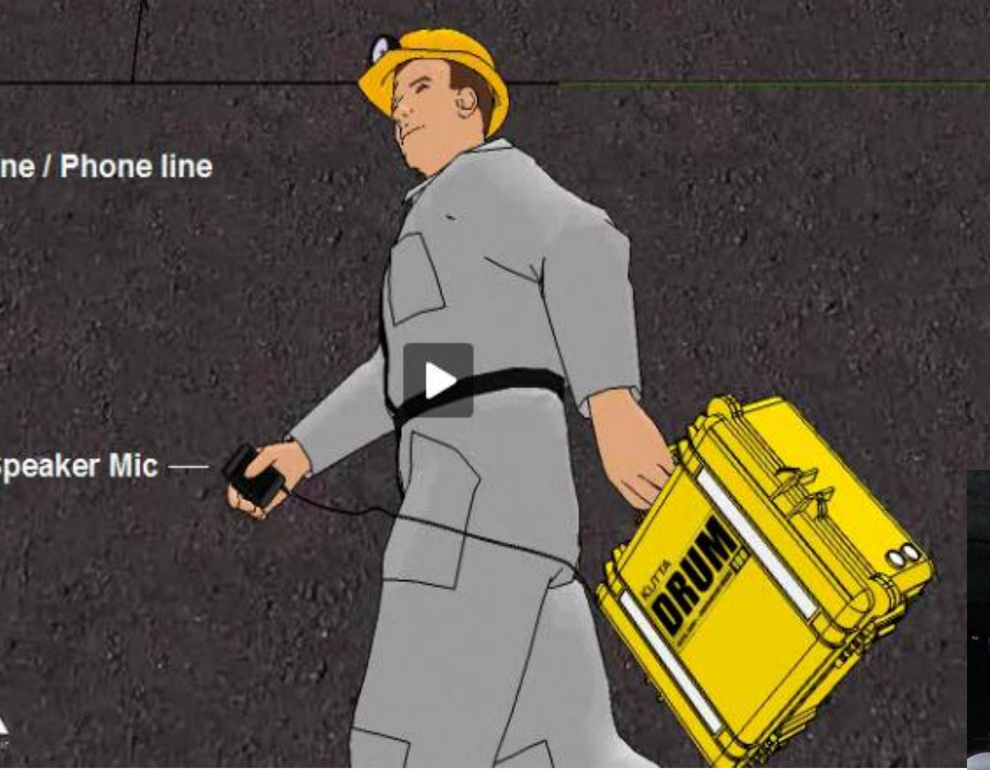
Primary Communications

- 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


MOTOROLA
MOTOROLA
ARCHER
SPACE PATROL
INTERNATIONAL MORSE CODE

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



Kutta – MF radio

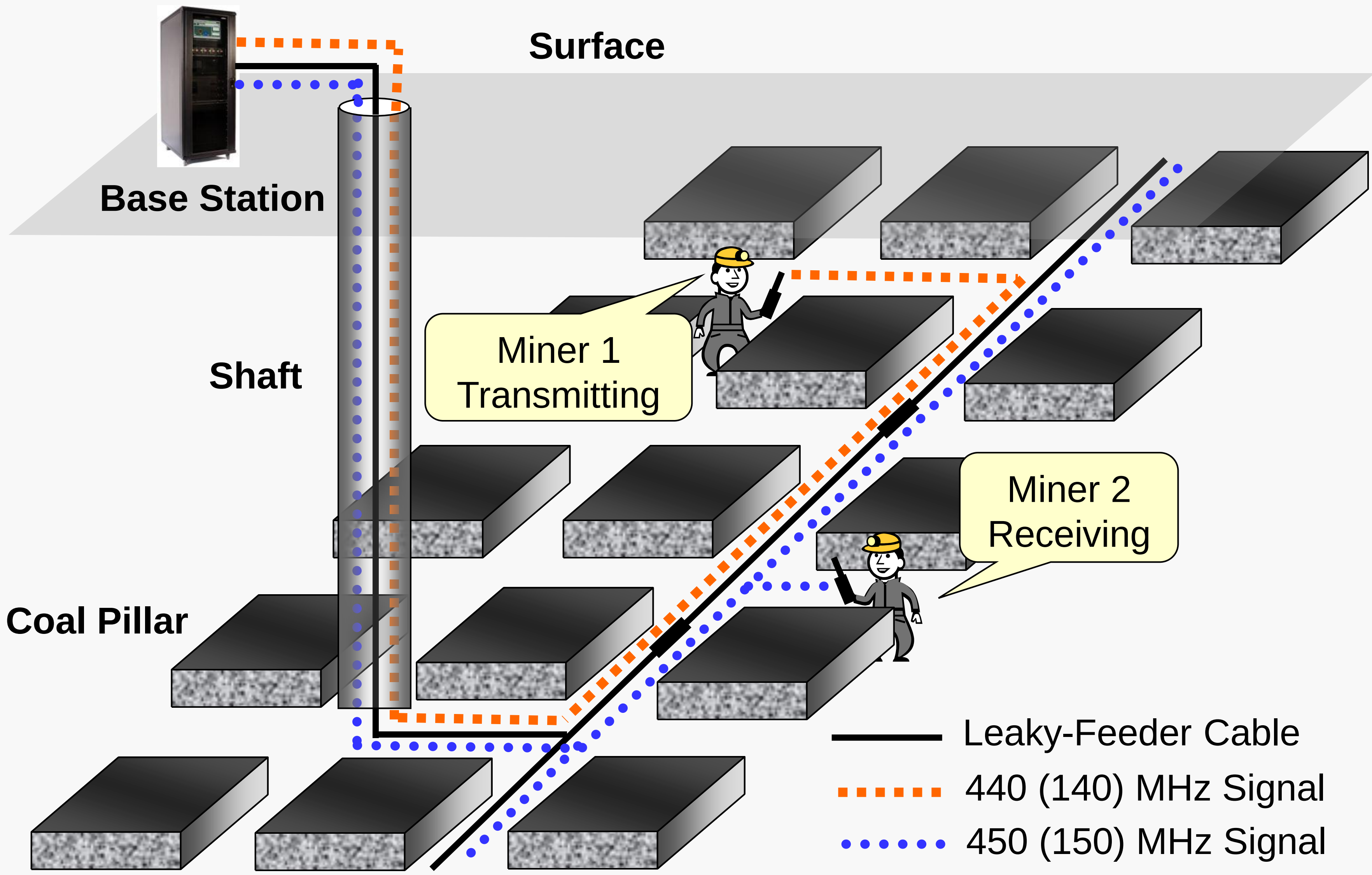
Lockheed – TTE

Mention of any company or product does not constitute endorsement by NIOSH.

Primary: Leaky Feeder

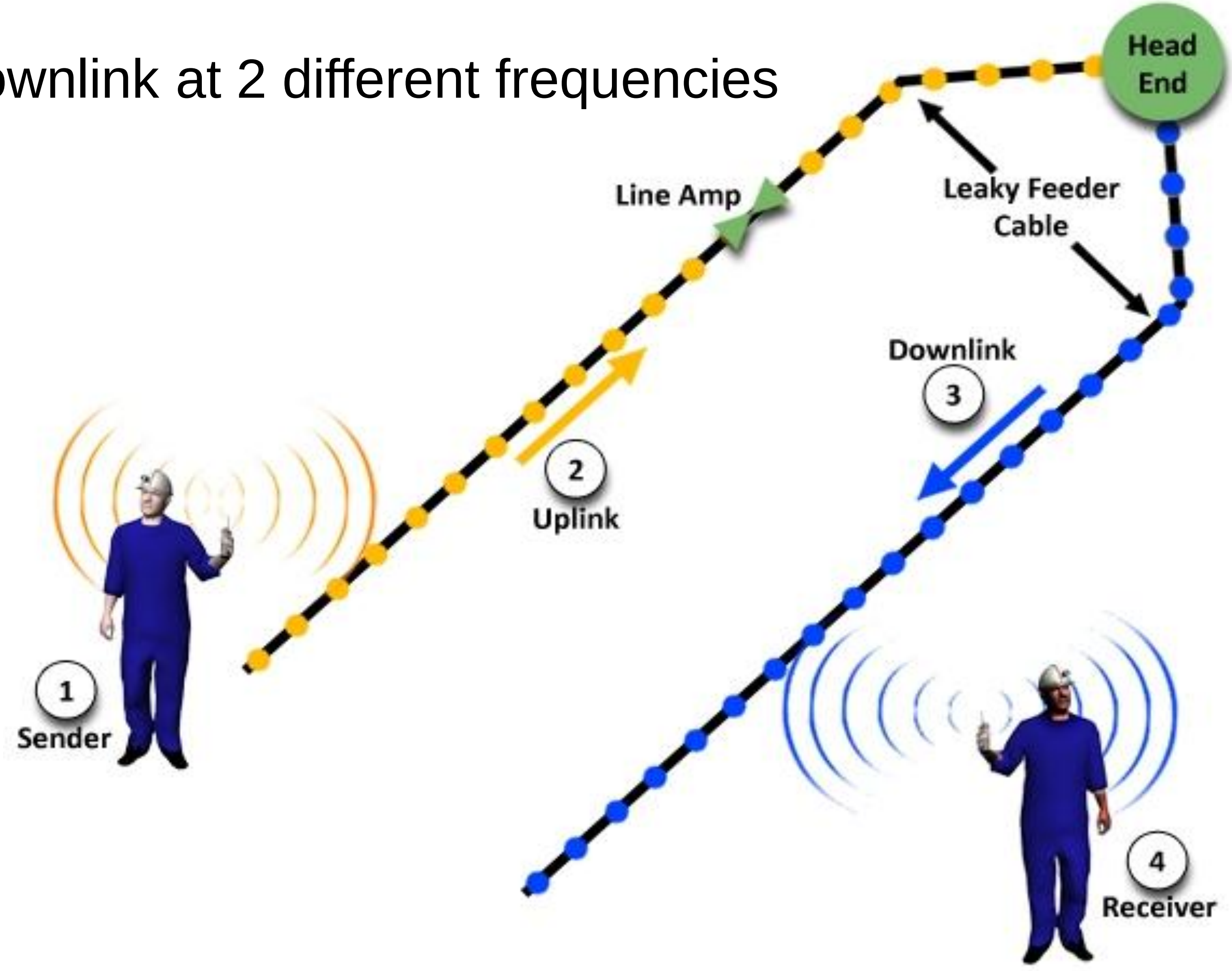
VHF ~ 150 MHz
UHF ~ 450 MHz

Leaky feeder cable – distributed antenna

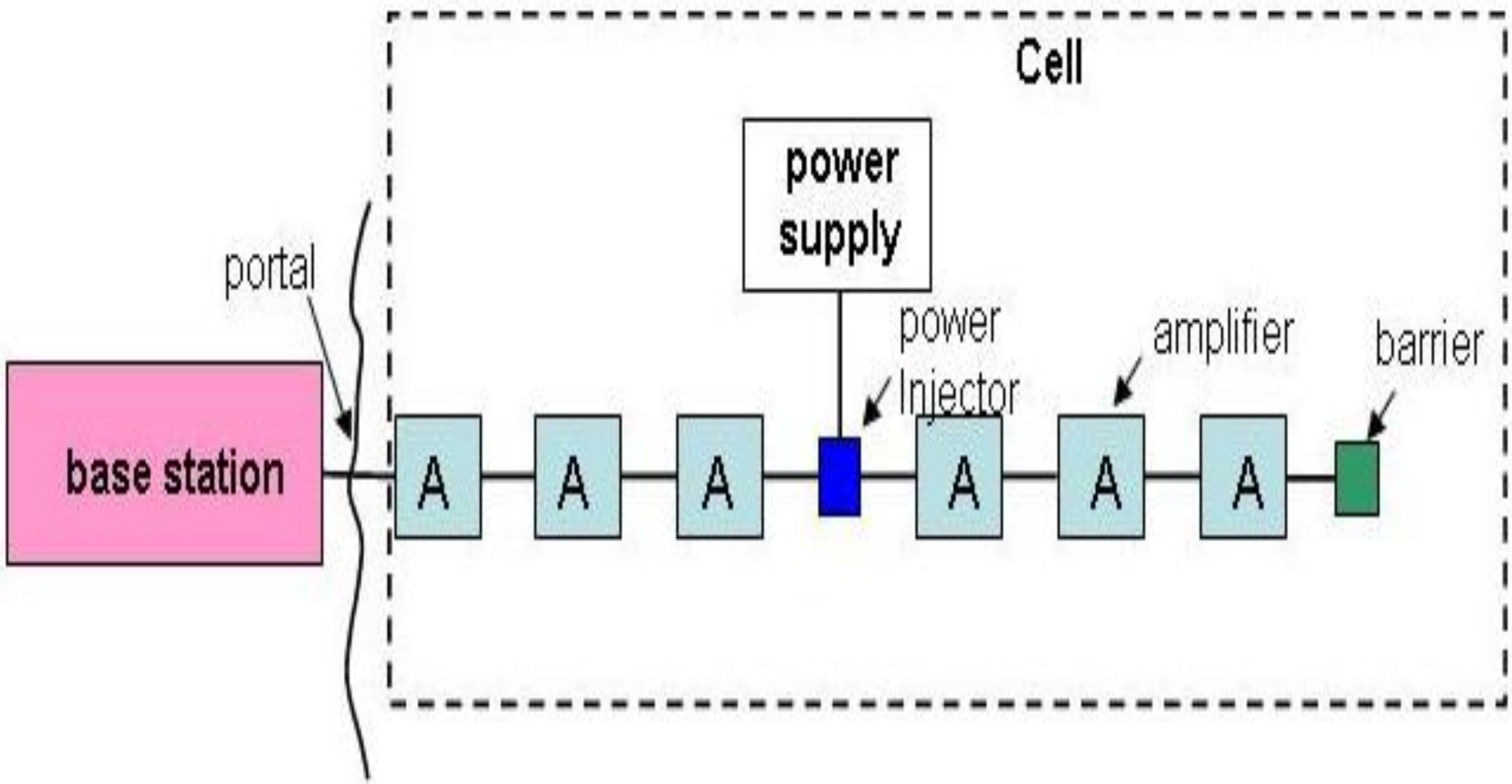

Surface
Base Station
Shaft
Coal Pillar
Miner 1 Transmitting
Miner 2 Receiving
Leaky-Feeder Cable
440 (140) MHz Signal
450 (150) MHz Signal

Push to Talk Radio: half duplex

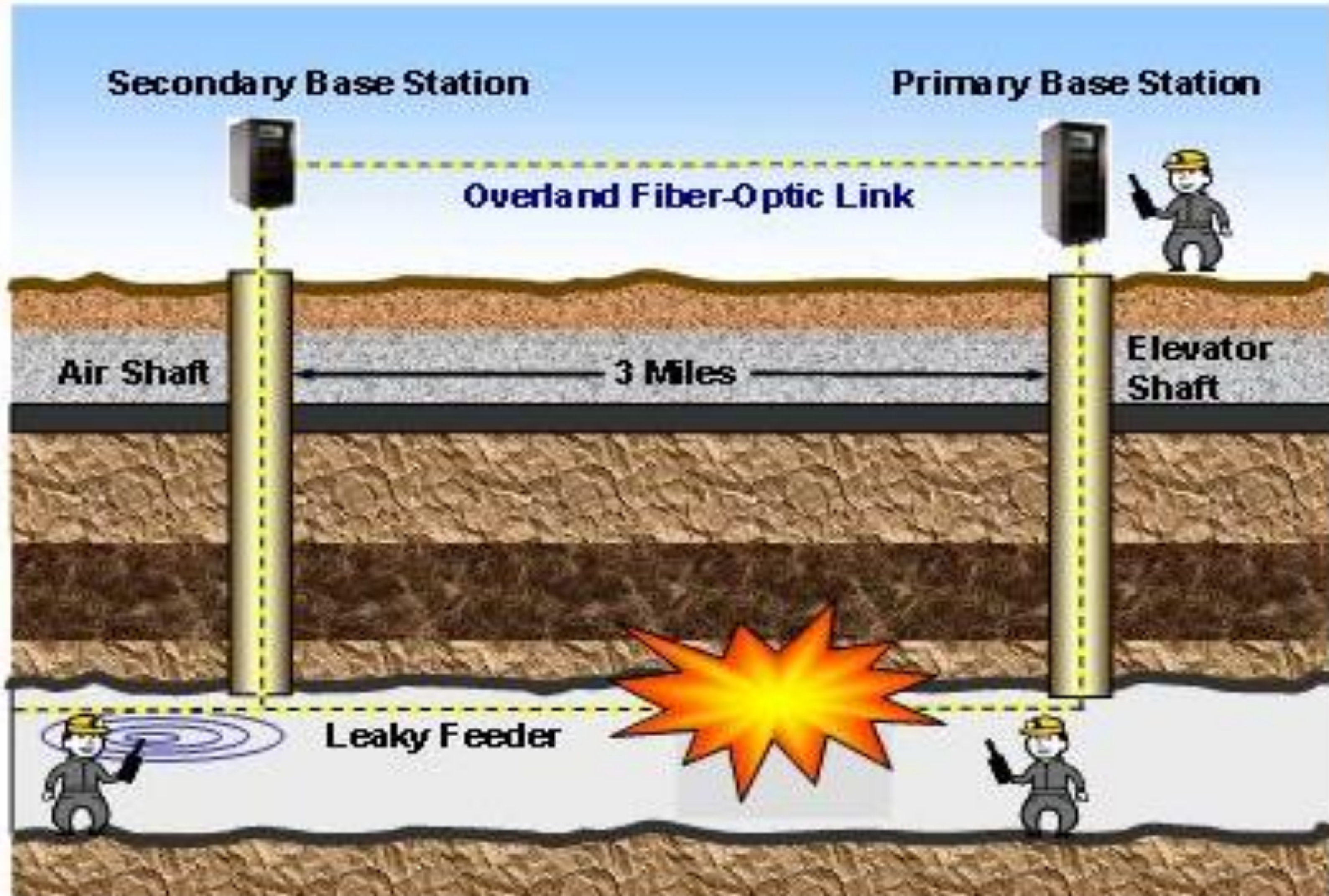
Uplink and downlink at 2 different frequencies



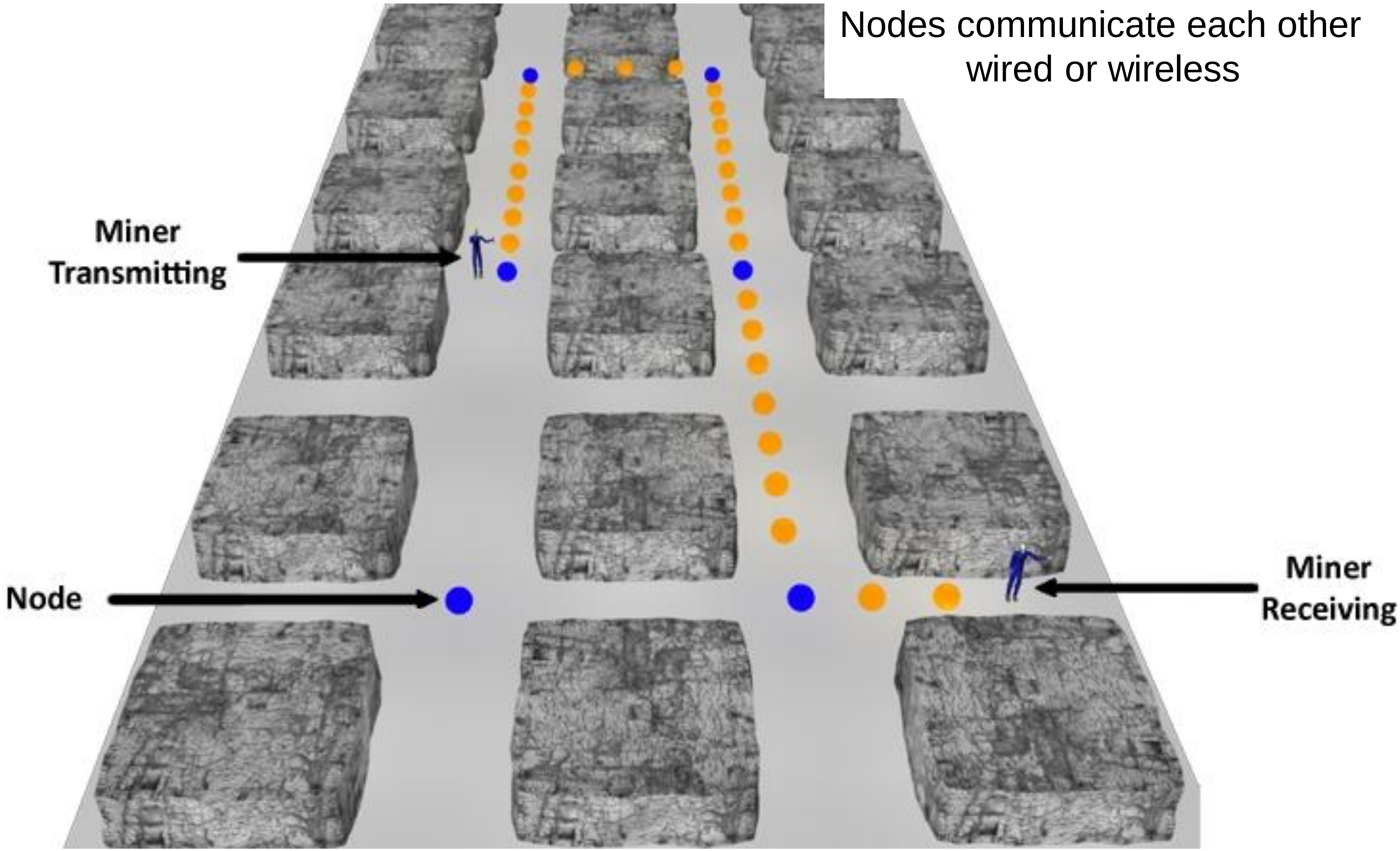
LF system composed of cells



LF Alternate Communication Path

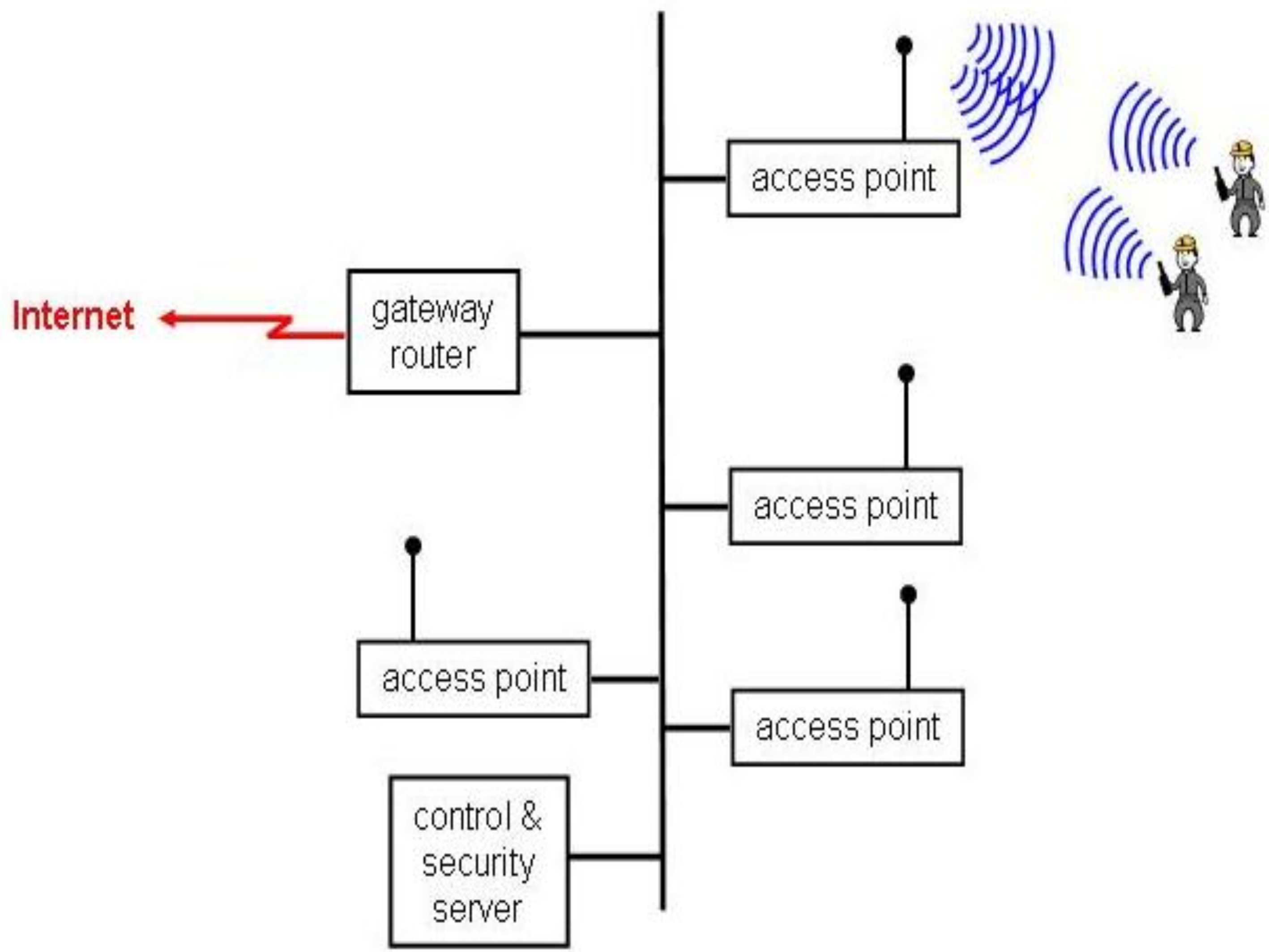


Primary: Node based



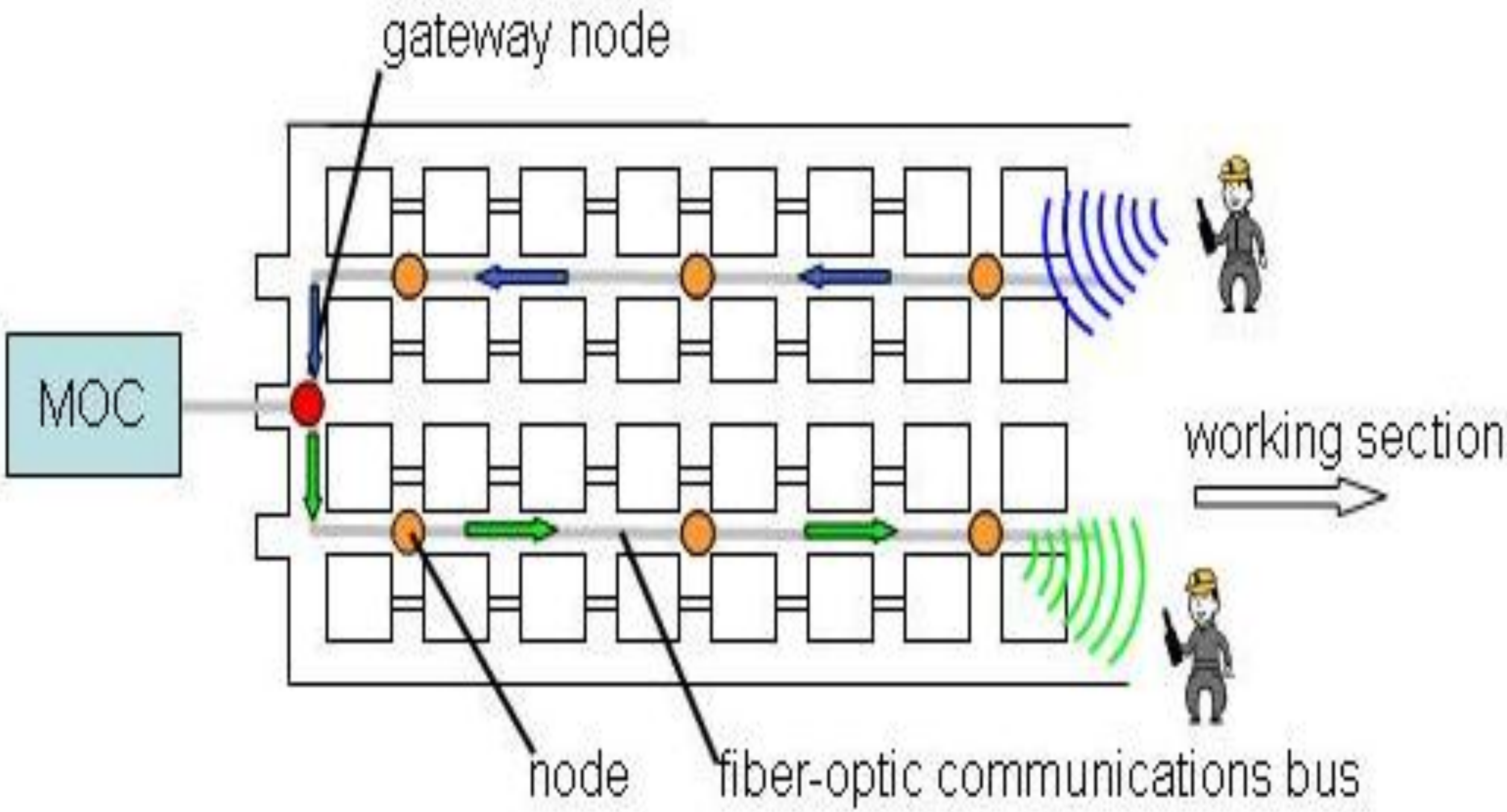
Nodes communicate each other wired or wireless

WLAN mesh

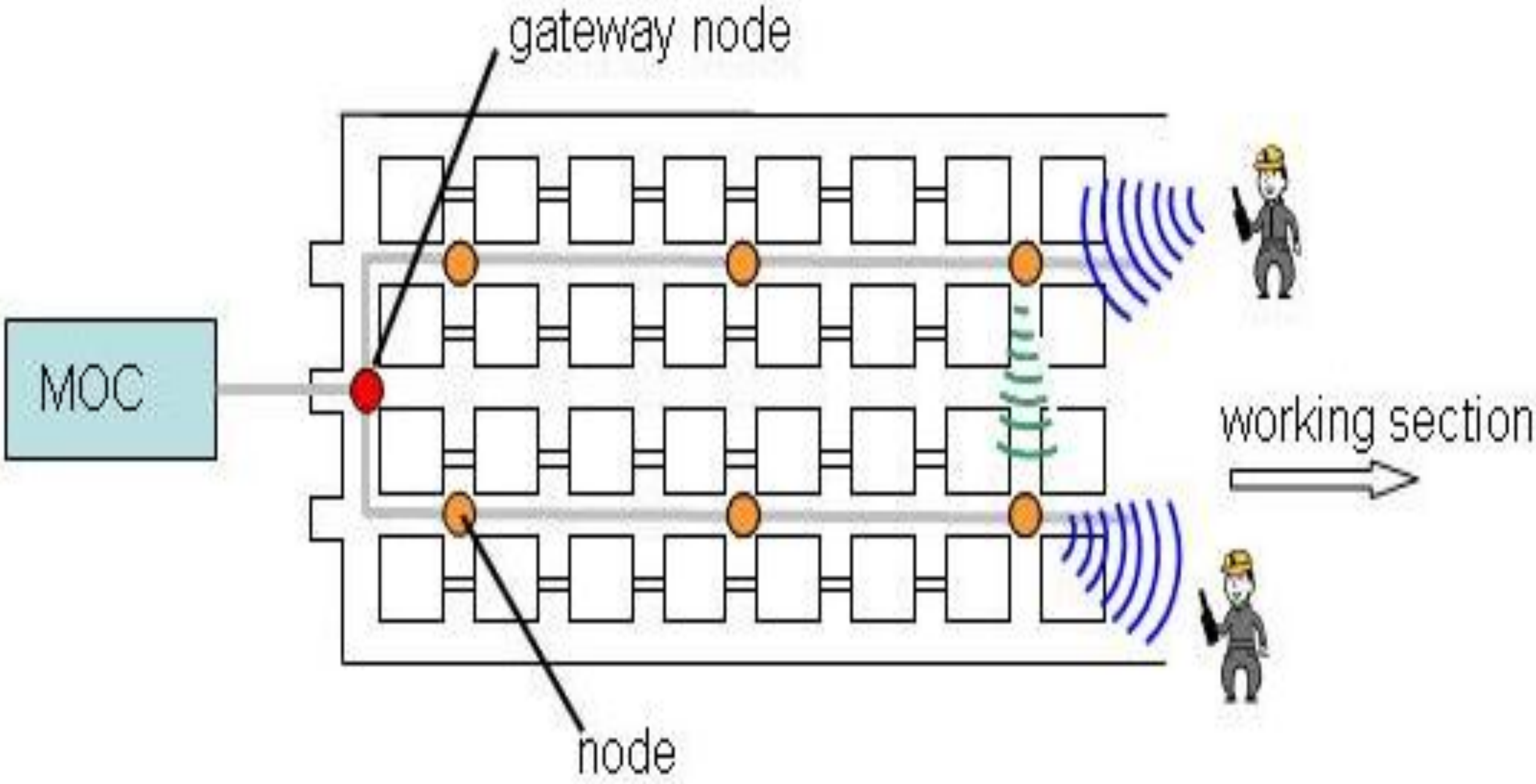

Internet
gateway router
access point
access point
access point
access point
control & security server

Example of Access Point

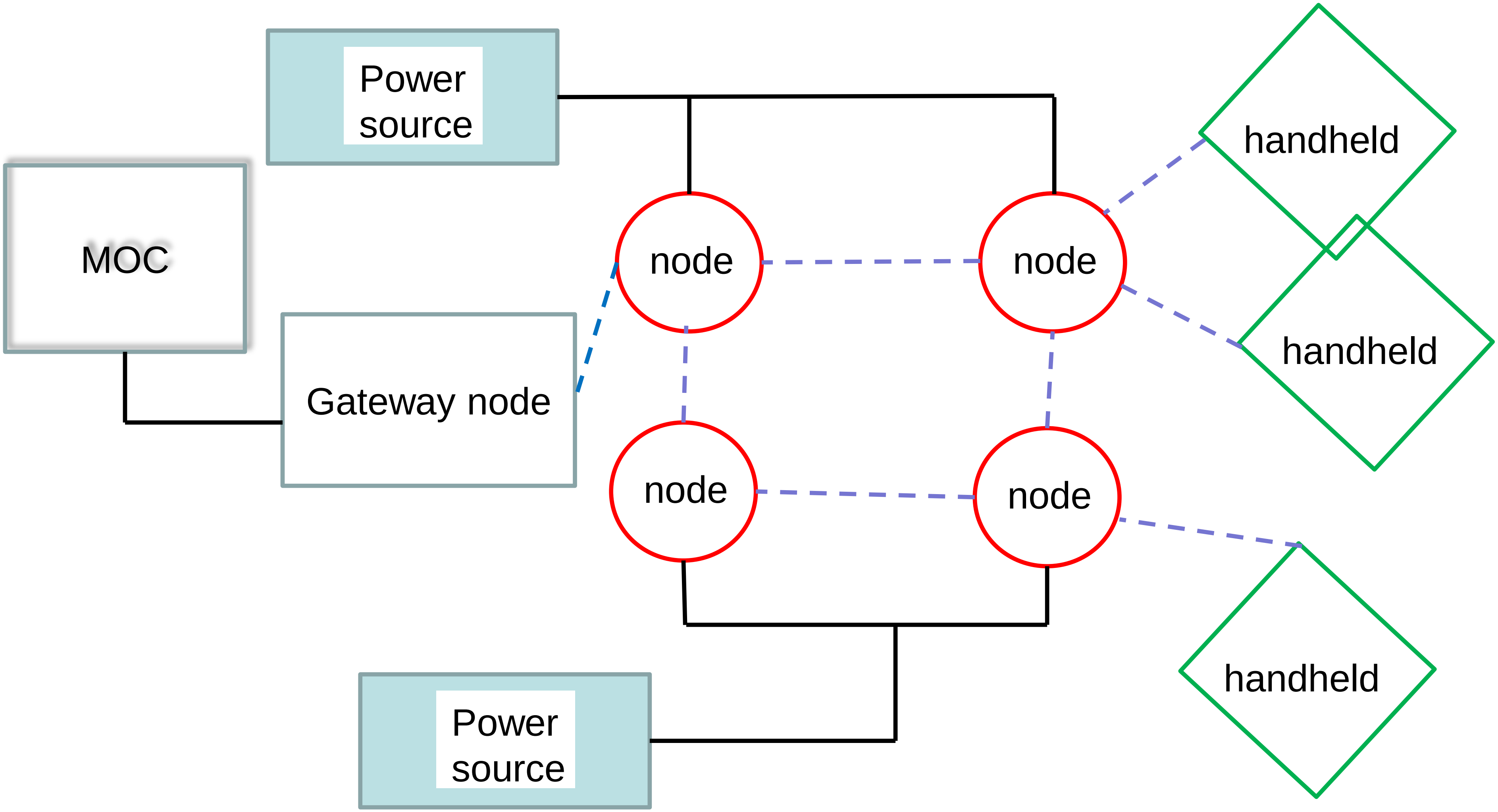
Fiber optic backhaul



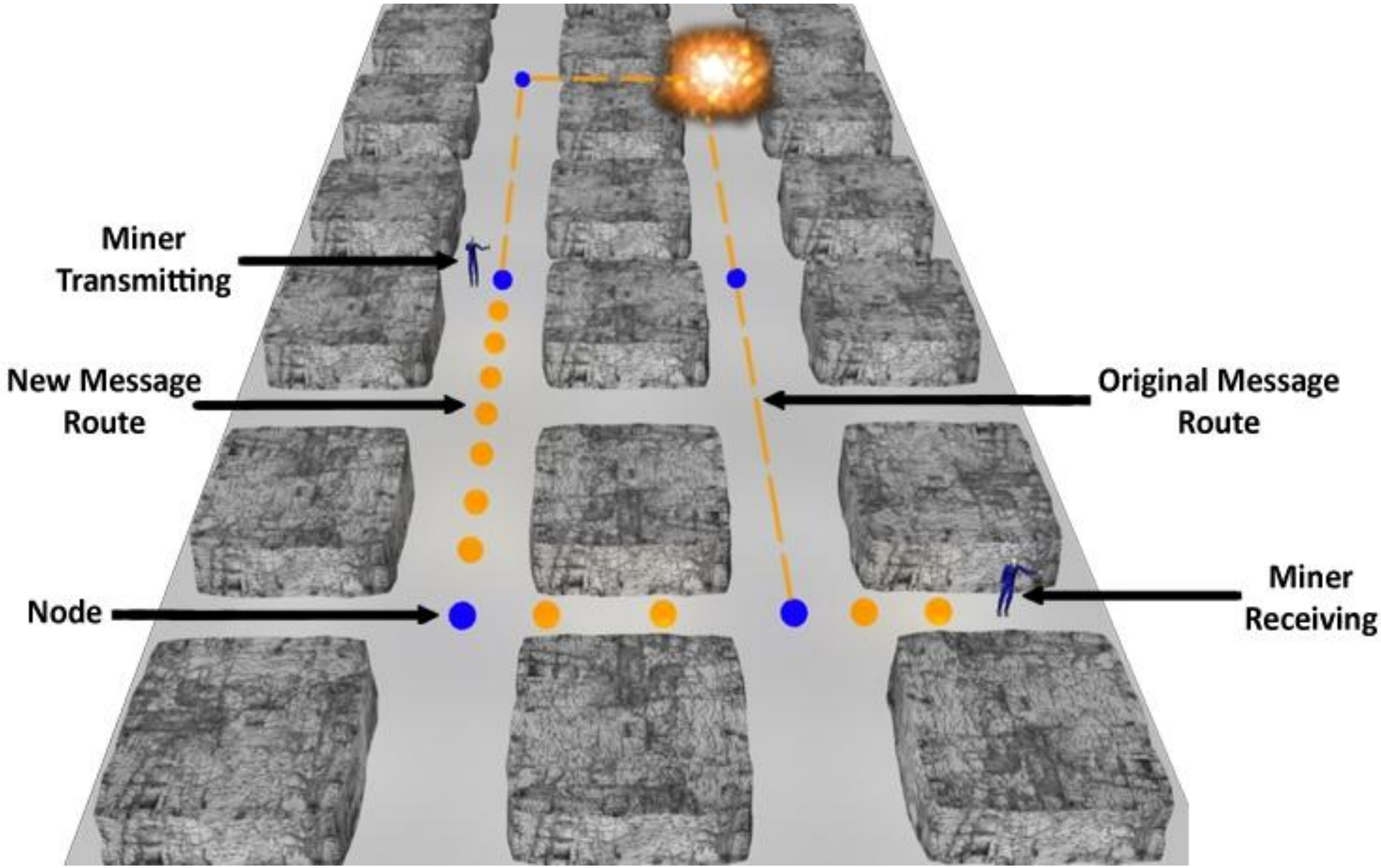
Wireless backhaul



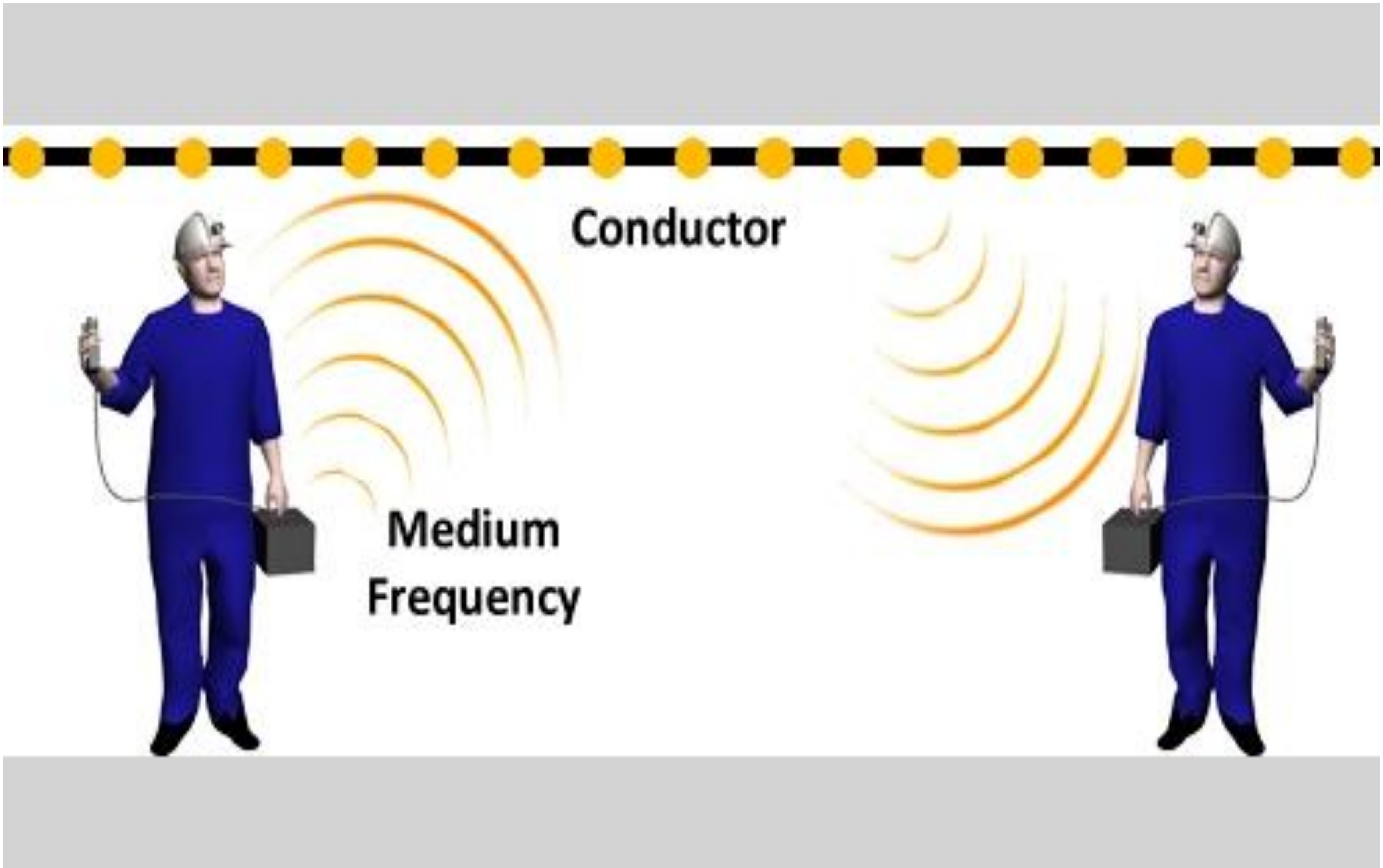
Node based configuration



Node based
Alternate Communications Path

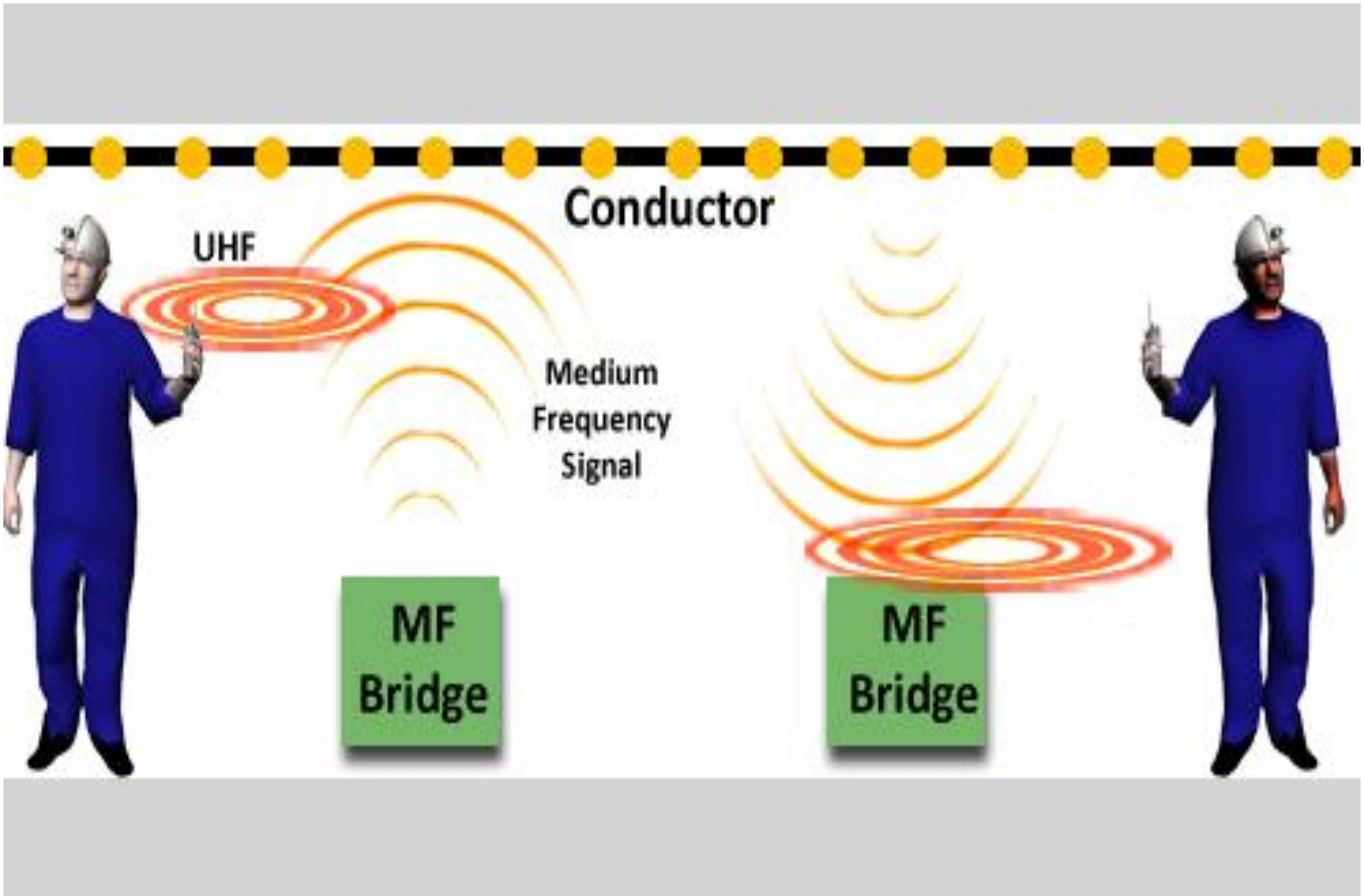


Secondary: MF

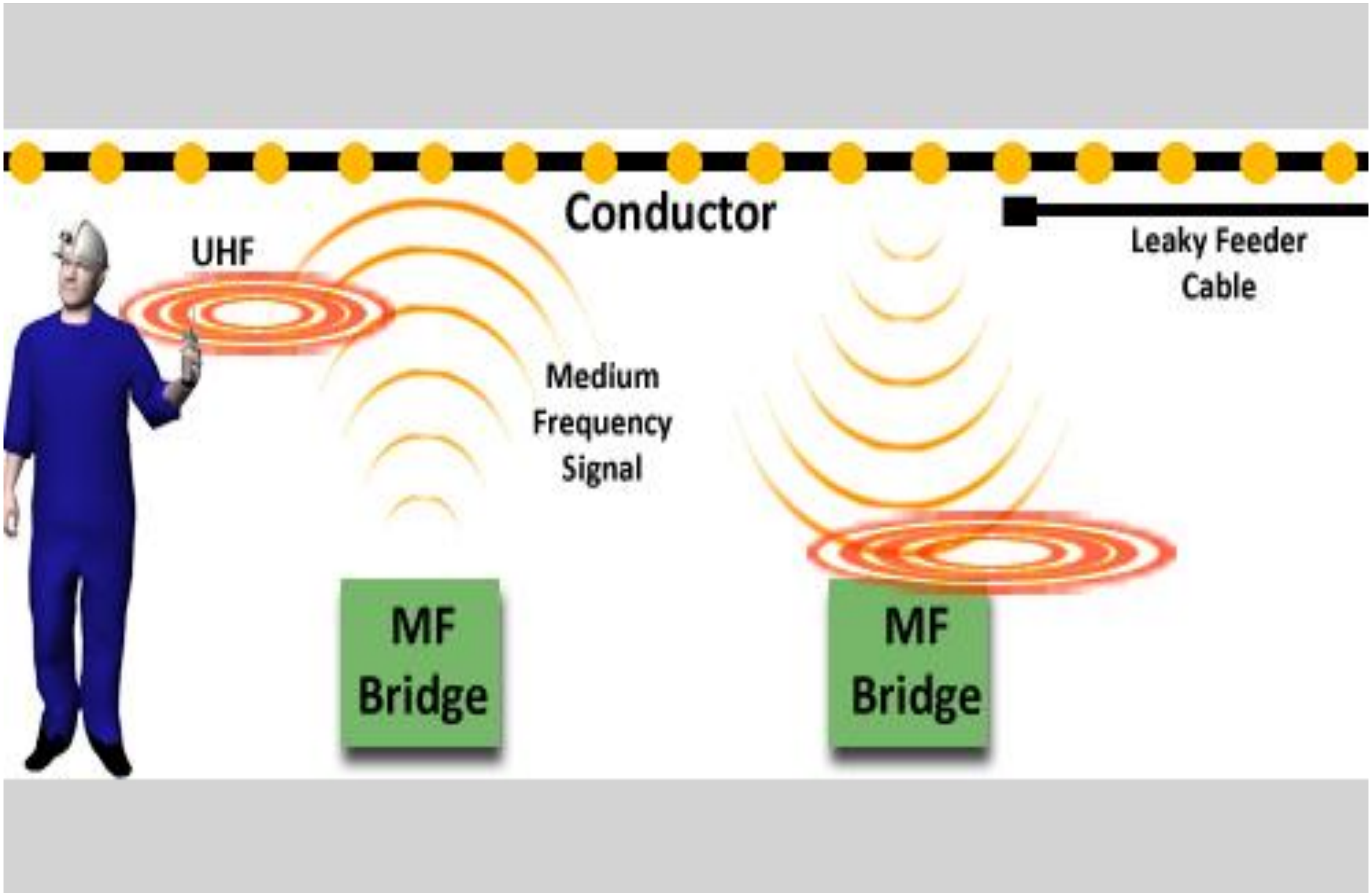


Portable MF radio

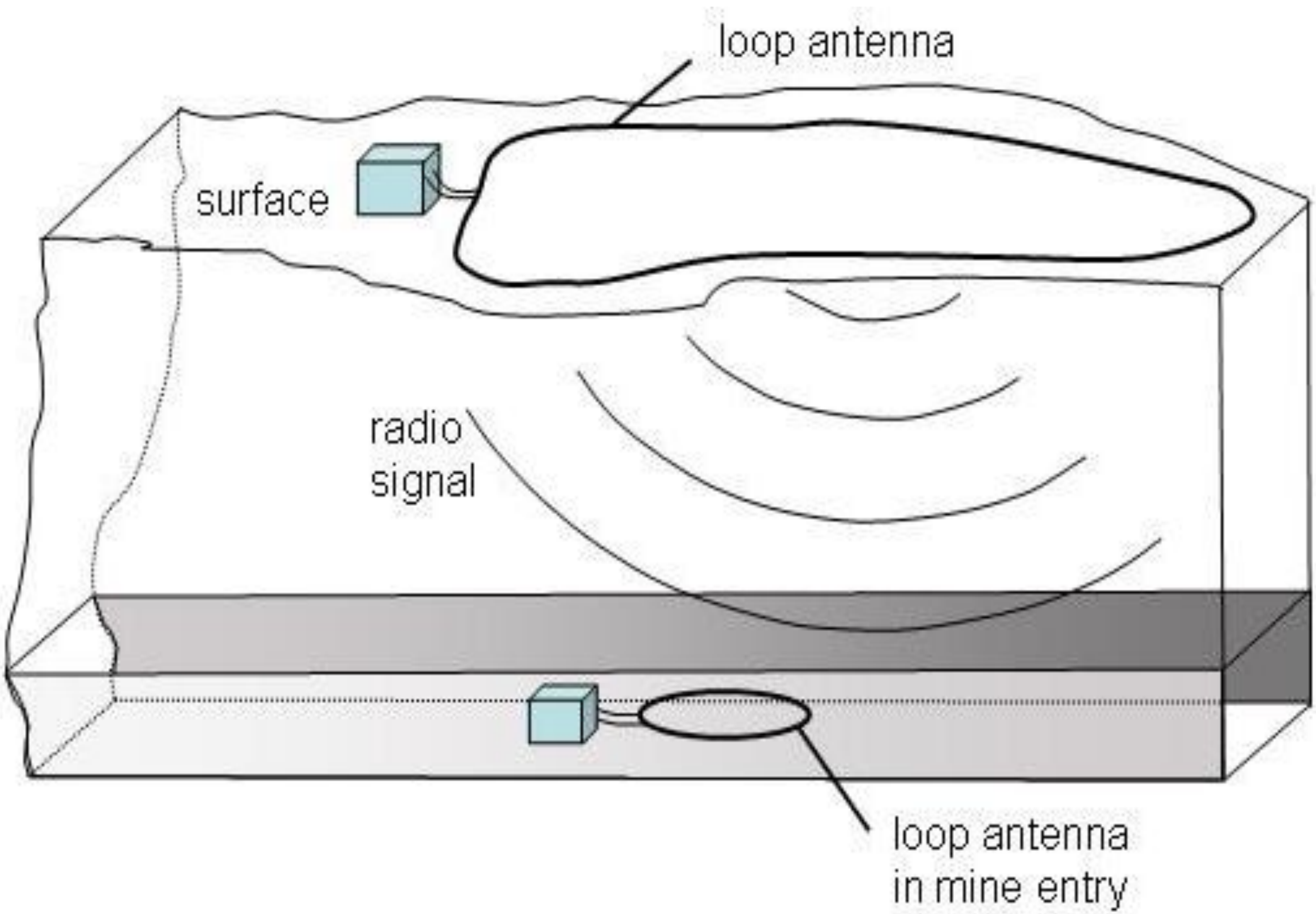
Interoperable with UHF (option)



Extend LF coverage (option)



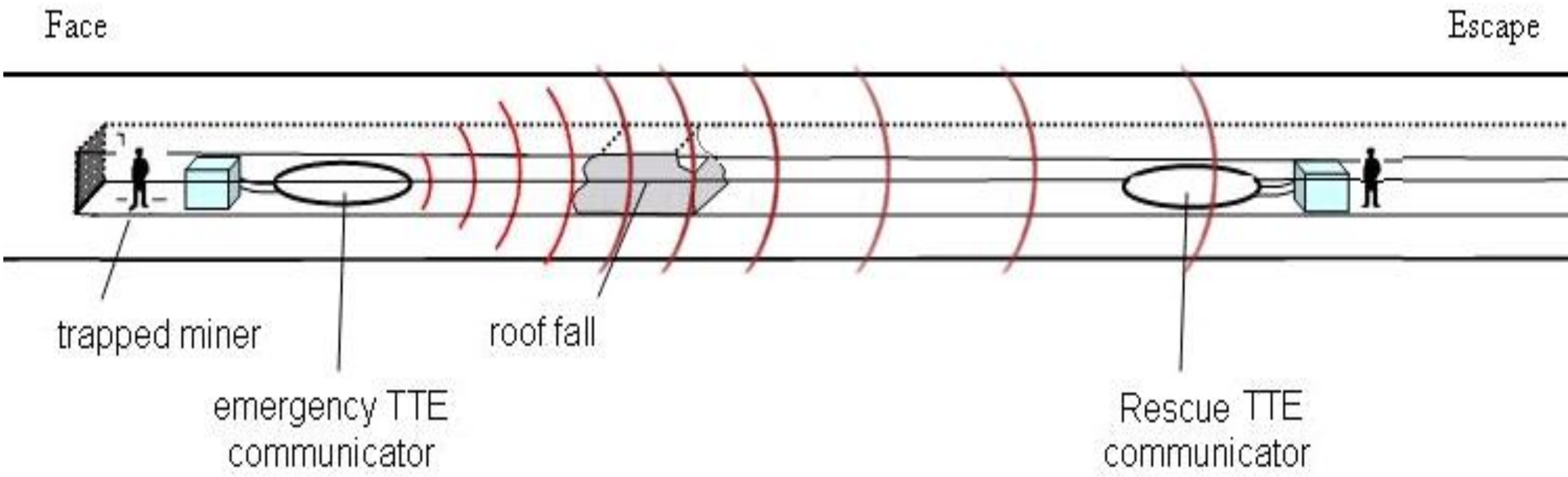
Secondary: TTE



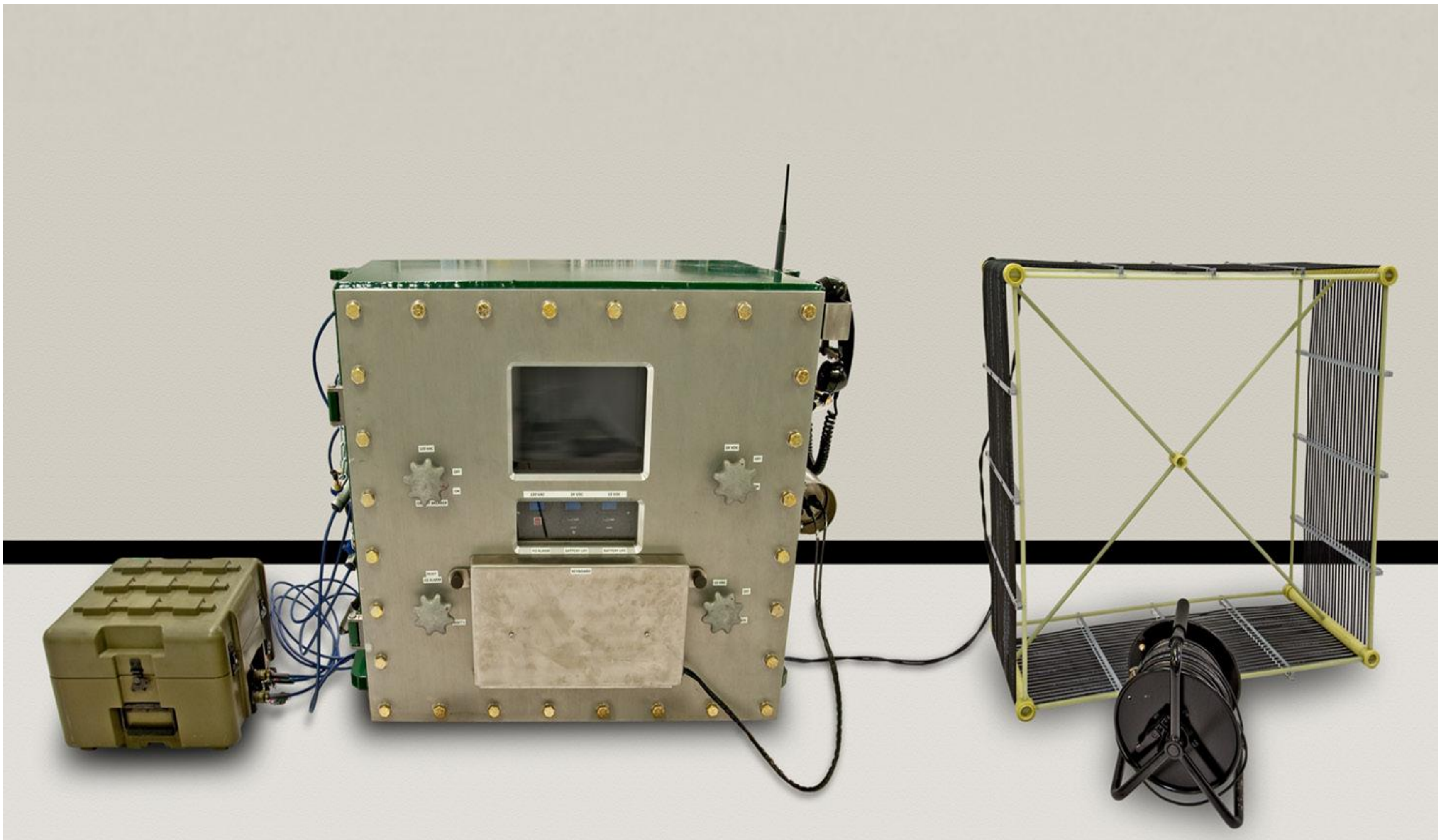
Deployable loop antenna

TTE within mine

Communicate horizontally – not need access to surface



Separate Tx and Rx antennas

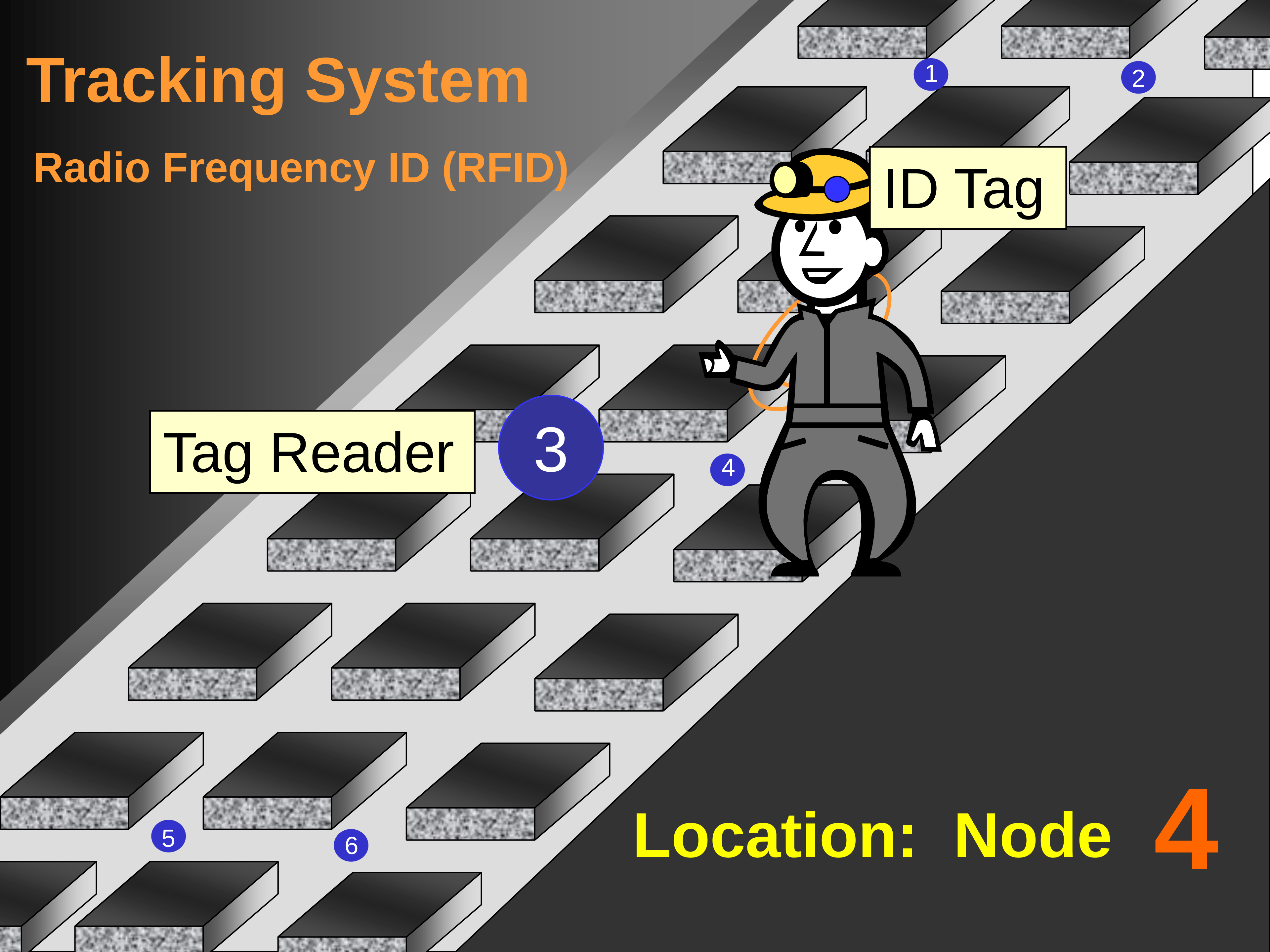


Electronic Tracking

- RFID & Reader
- Reverse RFID
- Received Signal Strength Indicator (RSSI)

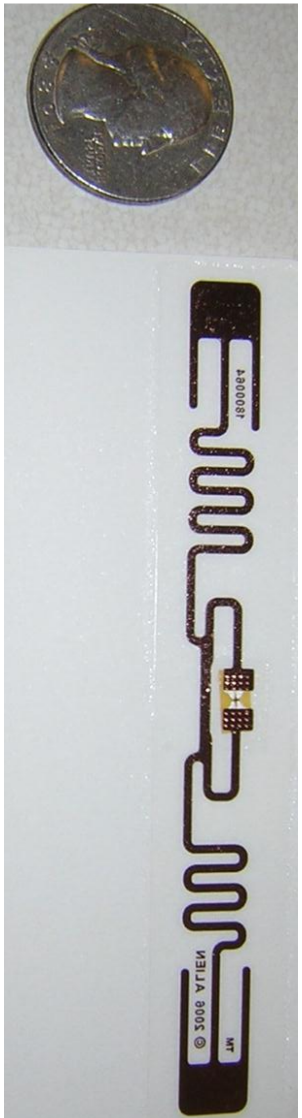
Tracking System

Radio Frequency ID (RFID)



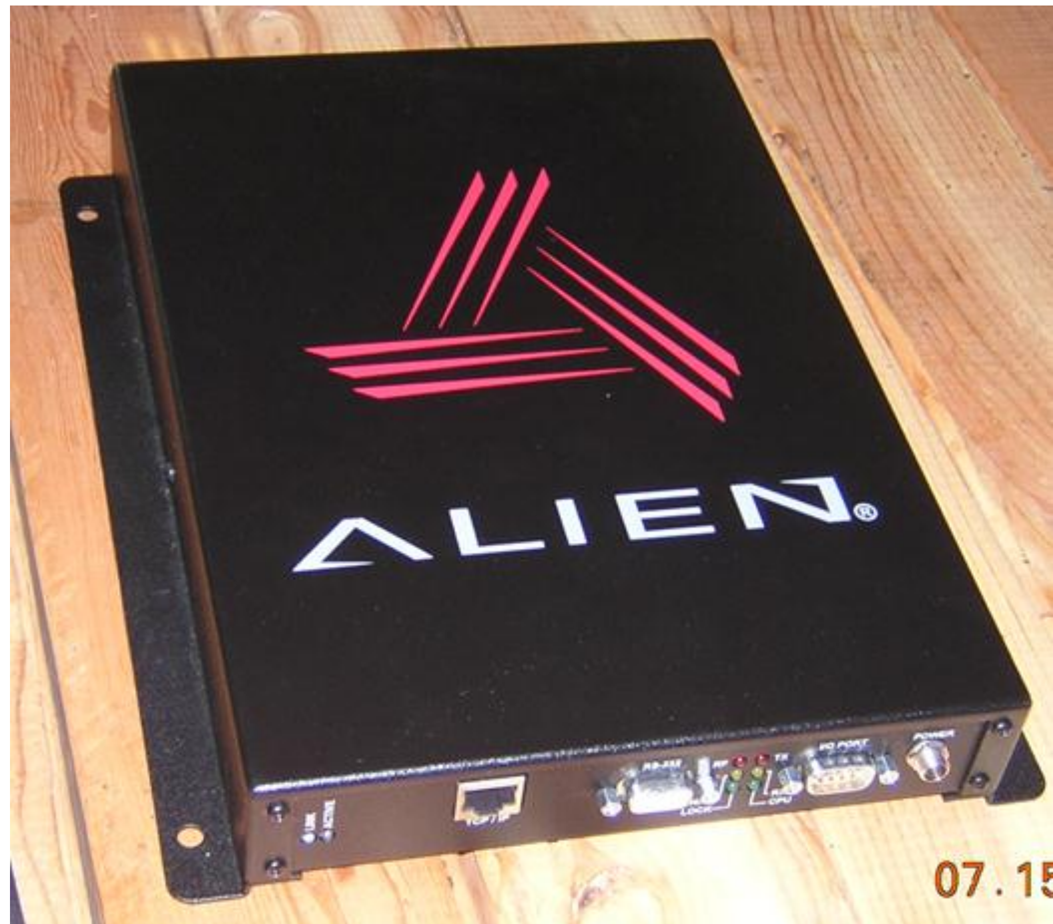
Location: Node 4

RFID tag and reader

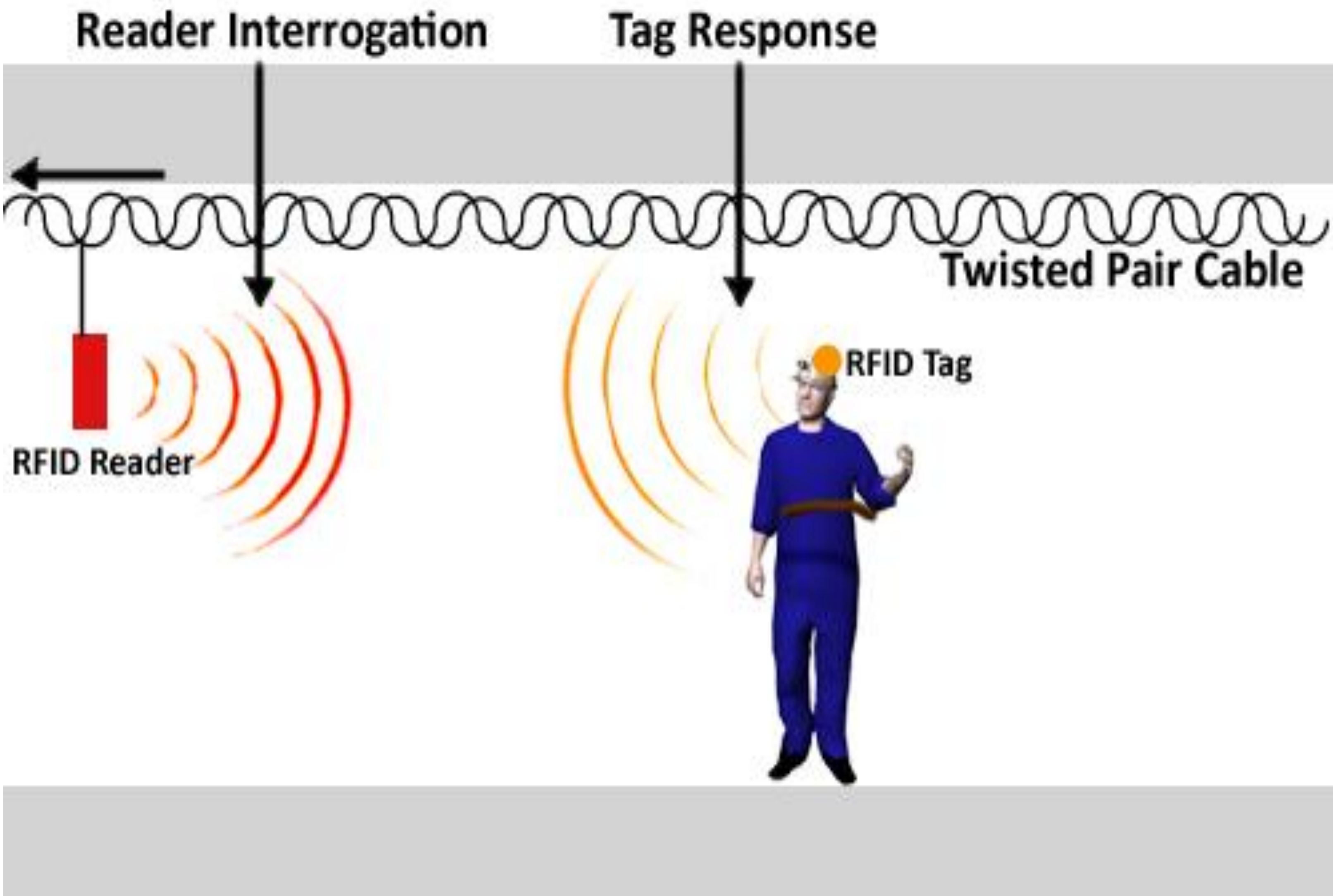


tag

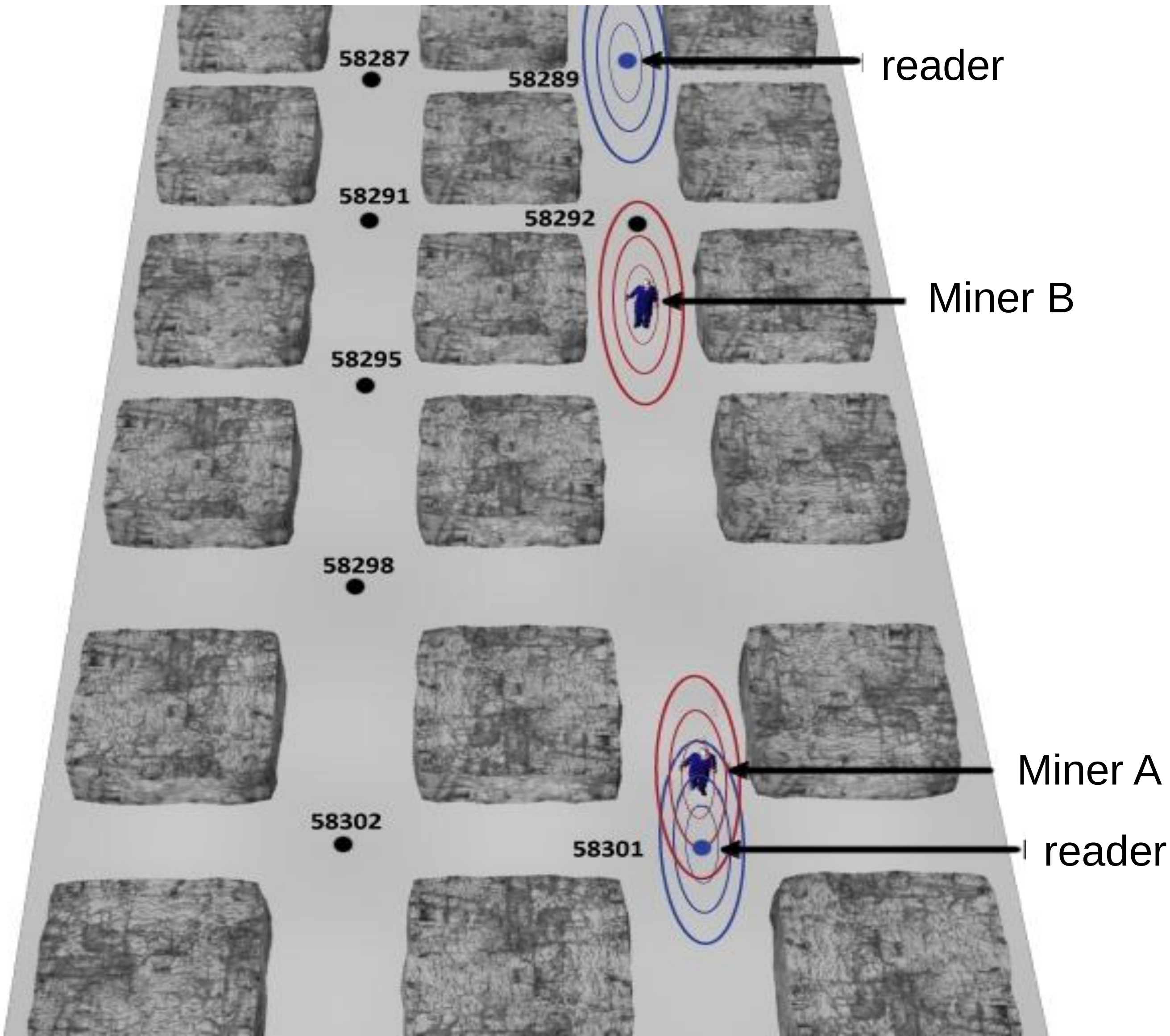
reader



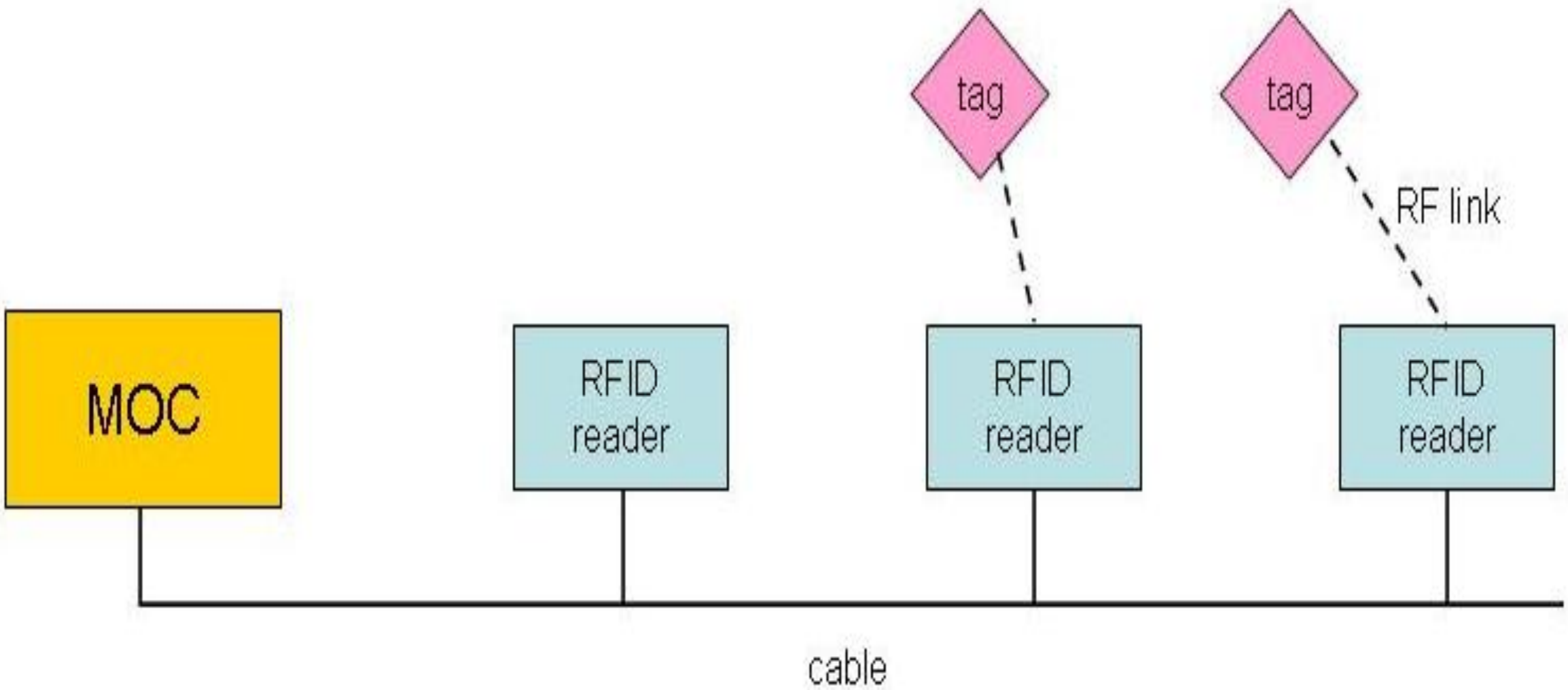
Reader ‘interrogates’ tag



Zone based location



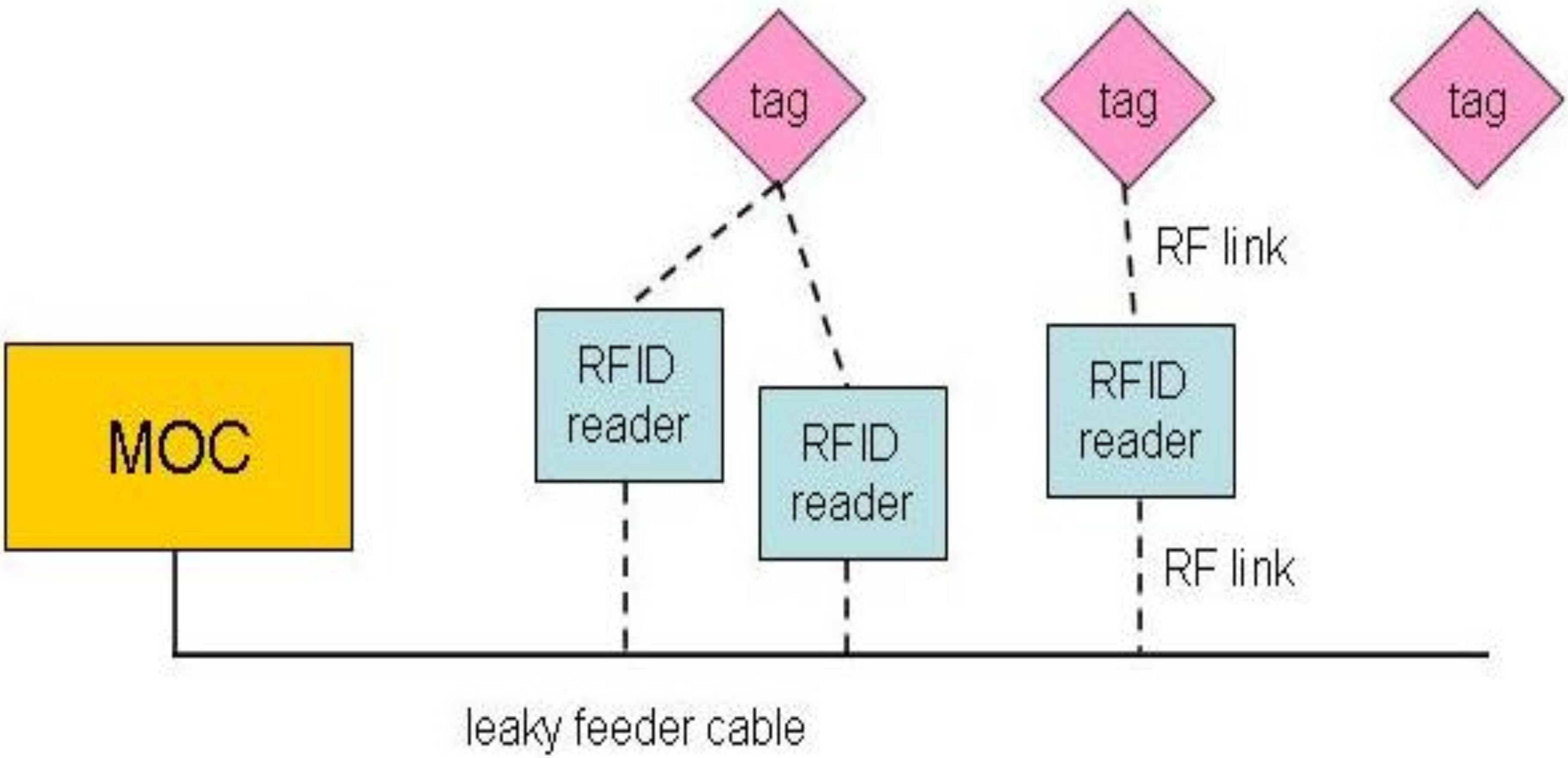
Reader notifies MOC



Reverse RFID

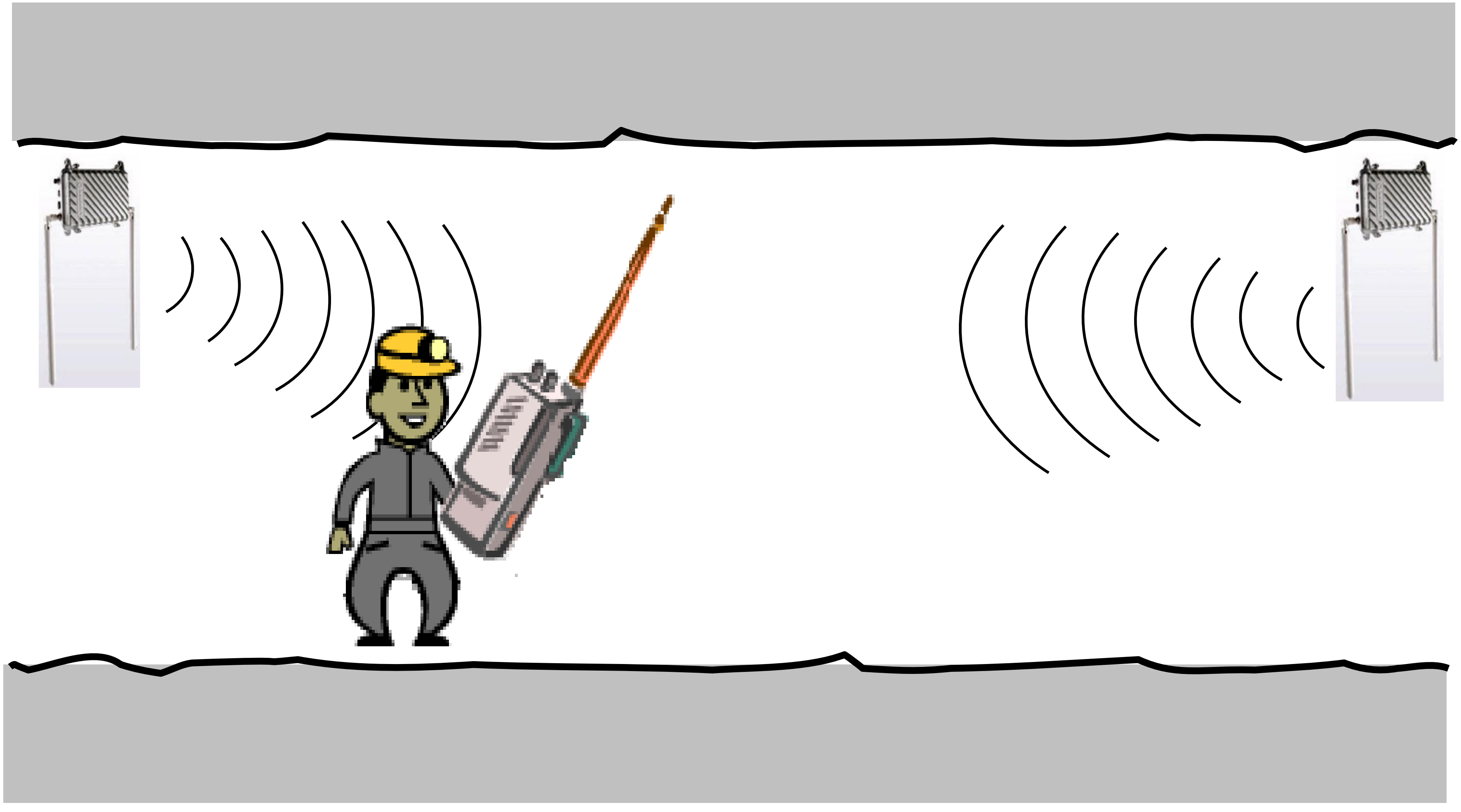
Miner wears reader;
Tags in entries at known locations

Reader on miner



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

Contact Information

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NIOSH is a division of the Centers for Disease Control and Prevention within the Department of Health and Human Services www.hhs.gov