Underground Wireless Networking: A New Frontier of Communications

Oct. 29, 2008

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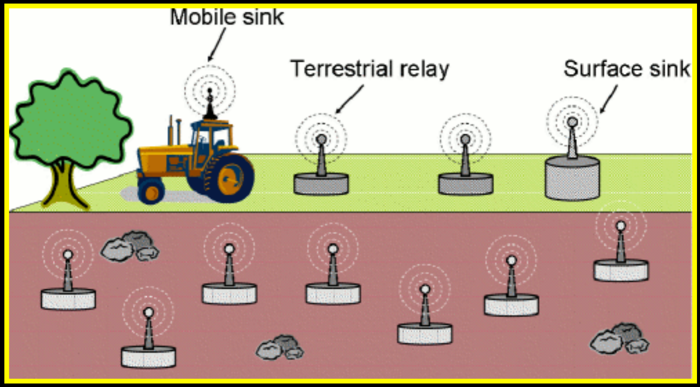
Underground Wireless Networking

Mines & Tunnels

Soil Medium



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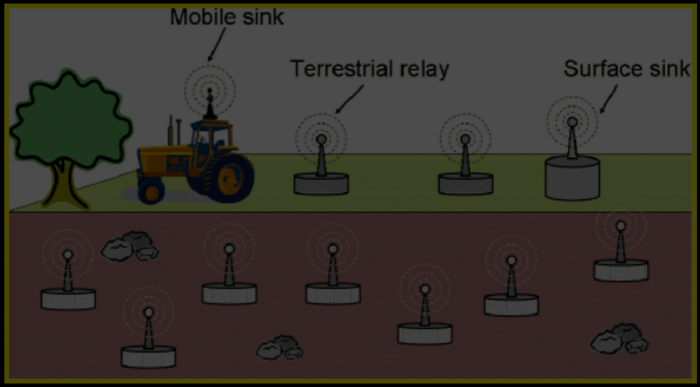
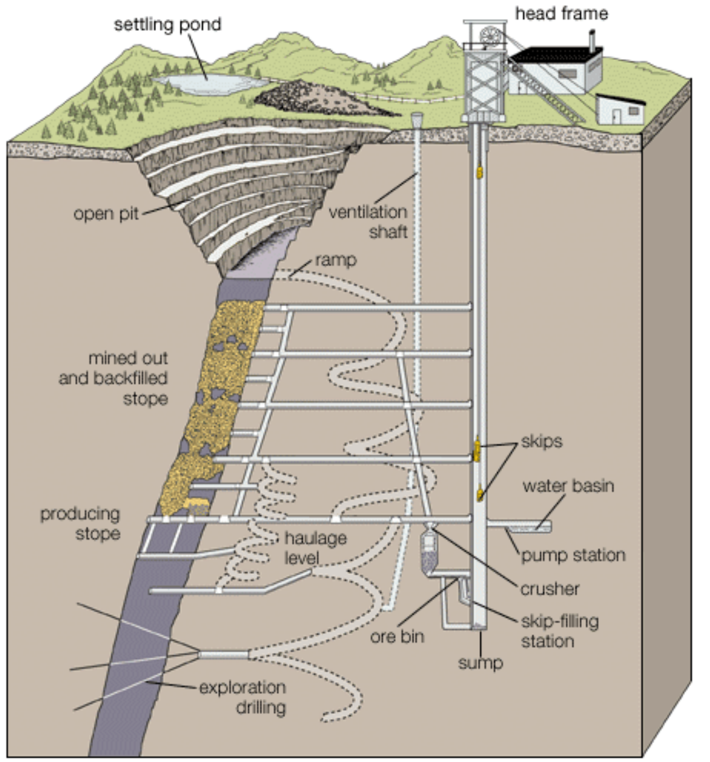


Applications

- **Communications:**
  - Improve mining productivity
  - Enhance communication in road tunnels
- **Security:**
  - Mine disaster
    - Gas explosion
    - Water leakage
  - Anti-terrorism
    - London subway explosion

Underground Mine Structure

- Multiple passageways are developed to connect the aboveground entrance and different mining areas.
- The structure of mining area is determined by mining methods, which is influenced by the shape and position of ore body



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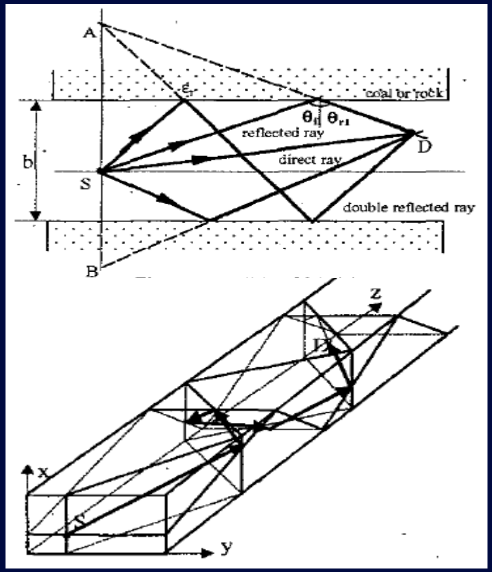
Source: H. Hamrin, *Guide to Underground Mining Methods and Applications* (Stockholm: Atlas Copco, 1997)

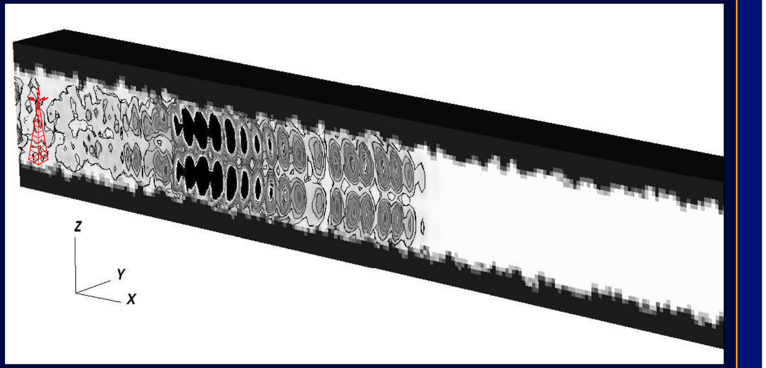
Channel Model for Tunnels



- Two Methods to characterize the EM waves' propagation

- Geometrical optical (GO) method
  - Sum of all reflected, refracted, diffracted and direct rays.
  - Numerical solution / high computation burden

- Waveguide method
  - Propagation modes derived from Maxwell's equations
  - Analytical solution / limited applicability



Our Solution: Multimode Model

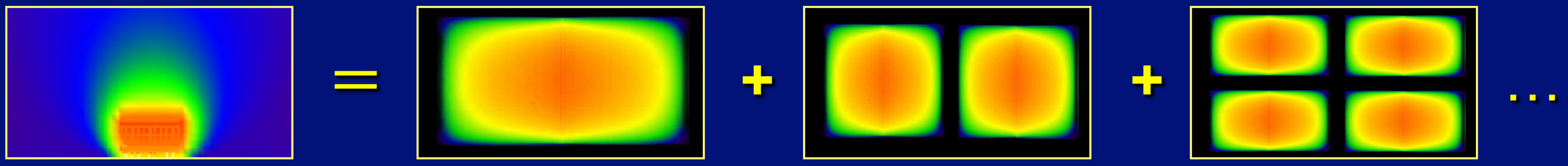
– Combining GO and Waveguide Model

Z. Sun and I.F. Akyildiz, “Channel Modeling of Wireless Networks in Tunnels", IEEE Globecom 2008

Z. Sun and I.F. Akyildiz, “Channel Modeling and Analysis for Wireless Networks in Underground Mines and Road Tunnels", submitted to IEEE Trans. Communications, revised in Oct. 2009

- On the excitation plane, the field distribution obtained by GO model can be considered as the weighted sum of the field of all modes.

i.e.



GO model EH_{11} EH_{21} EH_{22} …

- The intensity of each mode is worked out by a mode matching technique.

Analytical Solution for Mode Matching

- **The closed form of mode EH_{mn}'s intensity is:**

$$C_{mn} = \frac{E_0 \pi}{ab\sqrt{1 - (\frac{m\pi}{2ak})^2 - (\frac{n\pi}{2bk})^2 + \frac{3}{4}(\frac{m\pi}{2ak})^2(\frac{n\pi}{2bk})^2}} \sin\left(\frac{m\pi}{2a}x_0 + \varphi_x\right) \cdot \cos\left(\frac{n\pi}{2b}y_0 + \varphi_y\right)$$

- **The predicted received signal power is:**

$$P_r(x,y,z) = P_t G_t G_r \left(\frac{1}{E_0}\sum_{m,n} C_{mn} \cdot E^{eign}_{m,n}(x,y) \cdot e^{-(\alpha_{mn}+j\beta_{mn})\cdot z}\right)^2$$

Where,

P_t : Transmitting Power

G_t : Tx antenna gain

G_r : Rx antenna gain

α_{mn}: attenuation coefficient

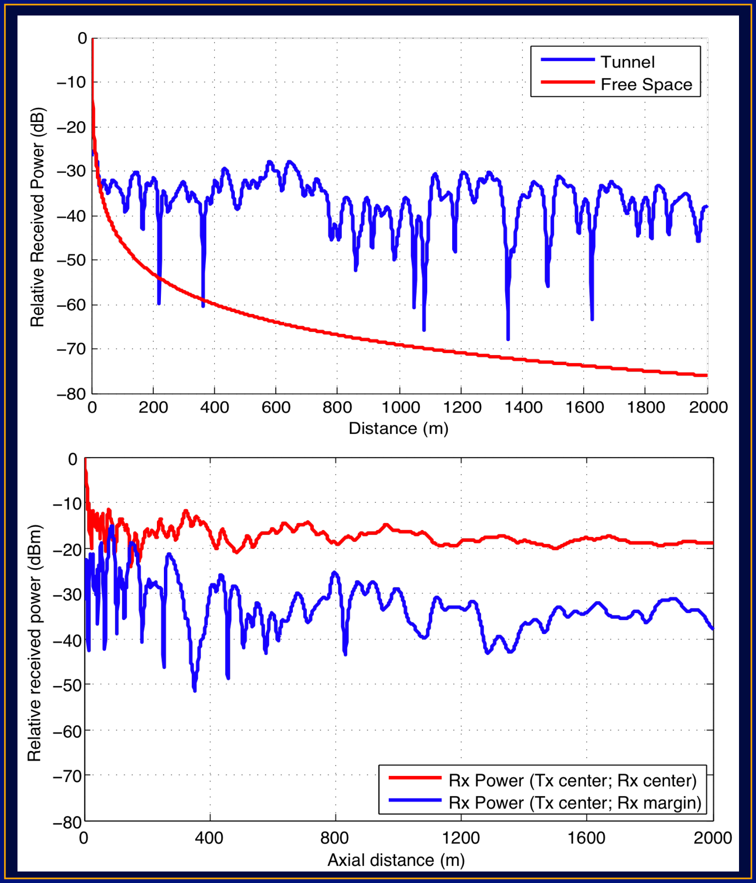
β_{mn} : phase shift coefficient

$$\alpha_{mn} = \frac{1}{a}\left(\frac{m\pi}{2ak}\right)^2 Re\frac{\overline{k_v}}{\sqrt{\overline{k_v} - 1}} + \frac{1}{b}\left(\frac{n\pi}{2bk}\right)^2 Re\frac{1}{\sqrt{\overline{k_h} - 1}}$$

$$\beta_{mn} = \sqrt{k^2 - \left(\frac{m\pi}{2a}\right)^2 - \left(\frac{n\pi}{2b}\right)^2}$$

Channel Characteristics in Empty Tunnels

- **Severe deep fading throughout the whole tunnel**
  - Causing high probability of disconnected network
- **Very slow attenuation of the signal envelope**
  - Causing high interference
- **Severe fading and interference happen in the same time.**
- **Need solutions to solve both the two problems**



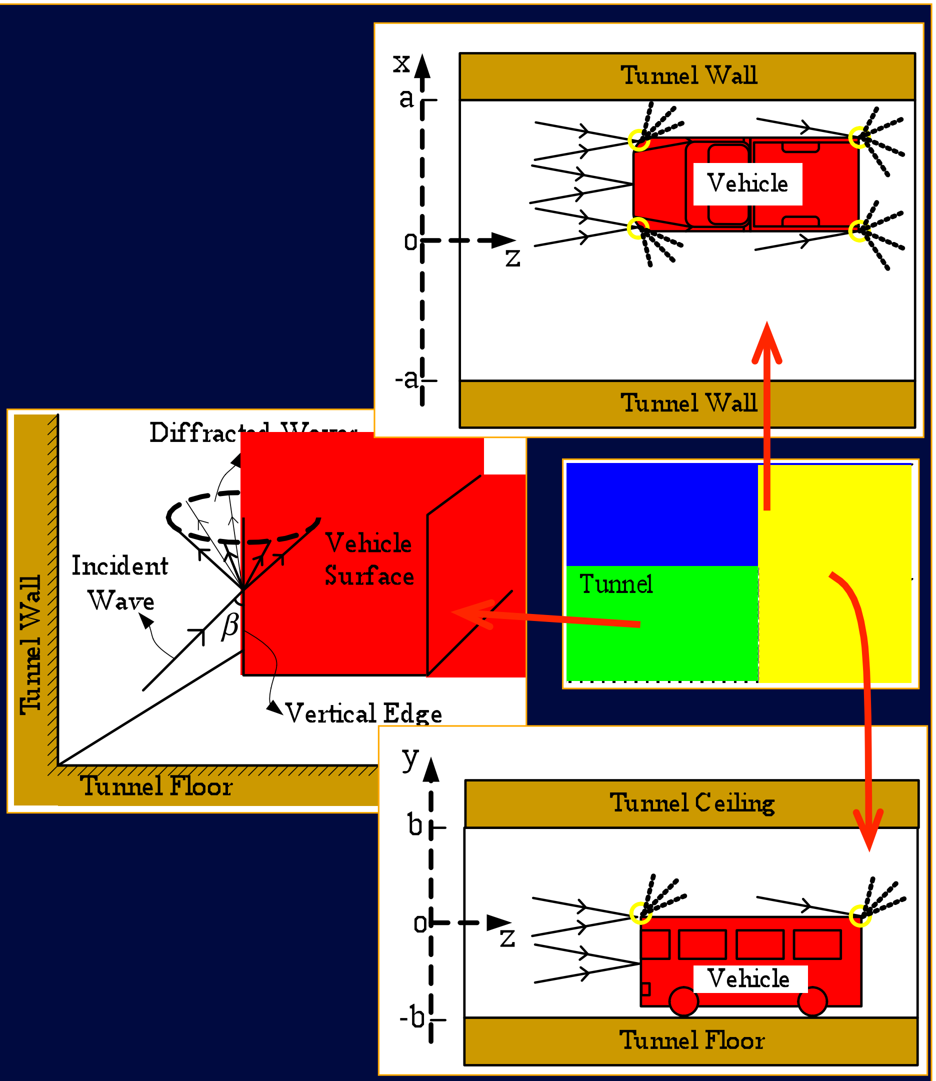
Tunnels with Obstructions

Z. Sun and I.F. Akyildiz, “Influences of Vehicles on Signal Propagation in Road Tunnels",
submitted to IEEE ICC 2010

- The propagation modes can travel along the tunnel without interference with each other if the tunnel is empty.
- Operating tunnels in real world are filled with obstructions.
- Obstructions in the tunnel may cause additional propagation loss of each mode.
- Moreover, part of the energy of each mode may be coupled to the other modes due to the existence of the obstructions.

Influence of Obstructions

- The EM waves hitting the obstruction's front surface will be reflected back.
  - In-mode-loss
- The plane waves hitting the edge between two surfaces will be diffracted.
  - Mode-coupling



Analytical Results

- **In-mode-loss coefficient:**
  - Multimode model
- **Mode coupling coefficient:**
  - Uniform theory of diffraction
  - Poisson sum formula
  - Saddle point integration
- **The channel can be characterized by combing the multimode model and the above two coefficients.**

$$L_{mn} = \frac{\int_{x_v-\frac{w}{2}}^{x_v+\frac{w}{2}} \int_{-b}^{-b+h} [E^{eign}_{mn,(x,y)}]^2 dxdy}{\int_{-a}^{a}\int_{-b}^{b}[E^{eign}_{mn,(x,y)}]^2 dxdy}$$

$$= \frac{1}{4ab}\left[w - \frac{2a}{m\pi}(-1)^m \cos(\frac{m\pi}{a}x_v)\sin(\frac{m\pi}{a}w)\right] \cdot \left[h - \frac{b}{n\pi}\sin(\frac{n\pi}{b}h)\right]$$

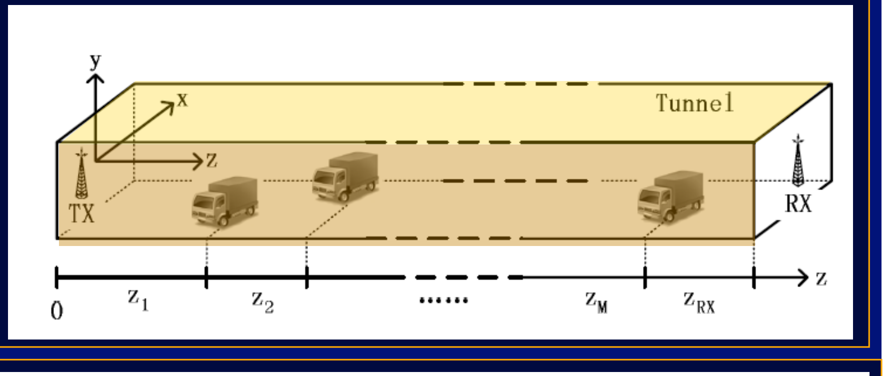
$$B^{total}_{mn\to ms} = \sin(\frac{m\pi x_v}{2a}+\varphi_x)\sin(\frac{m\pi w}{4a})\cdot\cos(\frac{s\pi}{2b}h+\varphi_y) \cdot\frac{a\sqrt{2\pi k}}{2m\pi kb\cos(\beta_s)}\cdot\Big\{\rho_2(n)\cdot e^{ik(h-b)\sin(\beta_n)}\cdot D(\alpha_m,\pi-\beta_s,-\beta_n) +\rho_1(n)\cdot e^{ik(h-b)\sin(-\beta_n)}\cdot\left[2D(\alpha_m,\pi-\beta_s,\beta_n)+D(\alpha_m,\pi+\beta_s,\beta_n)\right]\Big\}$$

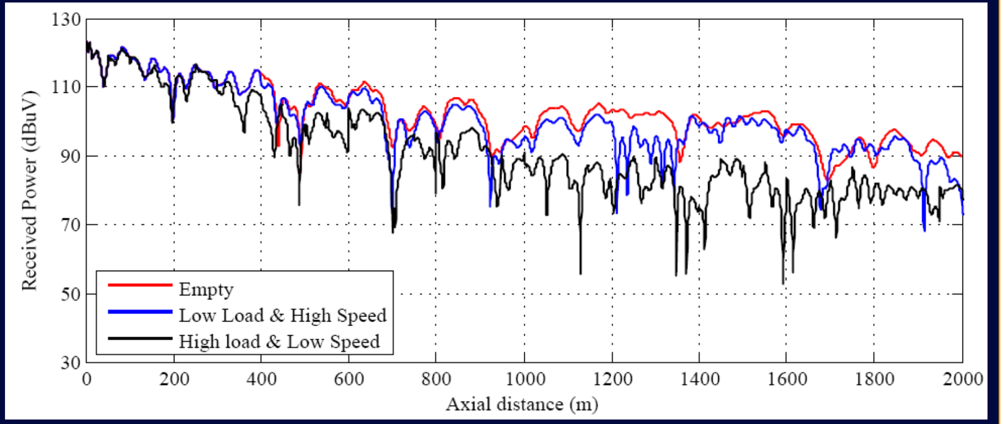
$$\begin{pmatrix} C'_1 \\ C'_2 \\ \vdots \\ C'_{\overline{N}} \end{pmatrix} = \begin{pmatrix} 1-L_1 & B^{total}_{2\to 1} & \cdots & B^{total}_{\overline{N}\to 1} \\ B^{total}_{1\to 2} & 1-L_2 & \cdots & B^{total}_{\overline{N}\to 2} \\ \vdots & \vdots & \ddots & \vdots \\ B^{total}_{1\to\overline{N}} & B^{total}_{2\to\overline{N}} & \cdots & 1-L_{\overline{N}} \end{pmatrix} \cdot \begin{pmatrix} C_1 \\ C_2 \\ \vdots \\ C_{\overline{N}} \end{pmatrix}$$

$$E^{RX}(x_r,y_r,z_r) = \mathbf{E}^{eign}_{(x_r,y_r)}\cdot\mathbf{A}(z_r-z_M)\cdot\prod_{i=1}^{M}\left[\mathbf{I}_i\cdot\mathbf{A}(z_i-z_{i-1})\right]\cdot\mathbf{C}^{TX}$$

Channel Characteristics in Tunnels with Obstructions

- The traffic flow in a two-lane road tunnel is modeled as a Poisson point process.
- Additional path loss and even more severe fading
  - In-mode-loss
  - Mode-coupling
- The vehicle’s size and the traffic load have significant influence

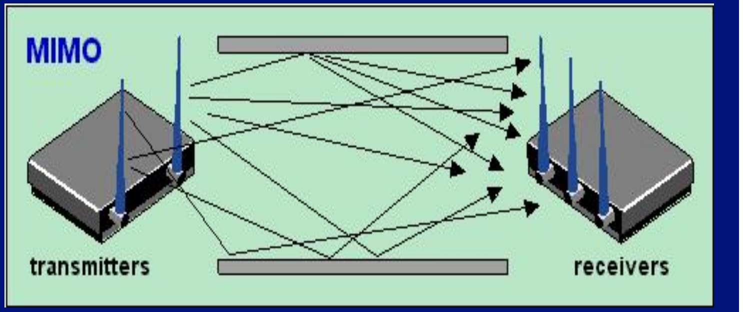




MIMO in Tunnels

Z. Sun and I.F. Akyildiz, “Optimal Antenna Geometry Analysis of MIMO Communication Systems in Underground Tunnels", IEEE Globecom 2009

- According to our channel analysis, fading is one of the most severe problems in tunnels.
  - Seek spatial diversity (MIMO & Cooperative Comm)
- The positions of TX and RX have significant influences.
- The EM waves have certain propagation patterns (modes) in tunnels.
- It is possible to find the optimal MIMO antenna geometry to maximize the channel capacity according to the EM field distribution of the modes.



MIMO Capacity in Tunnels

- **MIMO capacity:**

$$Capacity = E\left[\log\det\left(\mathbf{I}_{q\times q} + \frac{\rho}{p}\mathbf{H}\mathbf{H}^*\right)\right]$$

- **The channel gain matrix:**
  - Multimode model
  - Obstruction influence

$$\mathbf{H} = \frac{\sqrt{G_t G_r}}{2k}\ \mathbf{E}^{RX}\cdot\mathbf{D}\cdot\mathbf{C}^{TX}$$

$$\mathbf{D} = \mathbf{A}(z_r - z_M)\cdot\prod_{i=1}^{M}\left[\mathbf{I}_i\cdot\mathbf{A}(z_i - z_{i-1})\right]$$

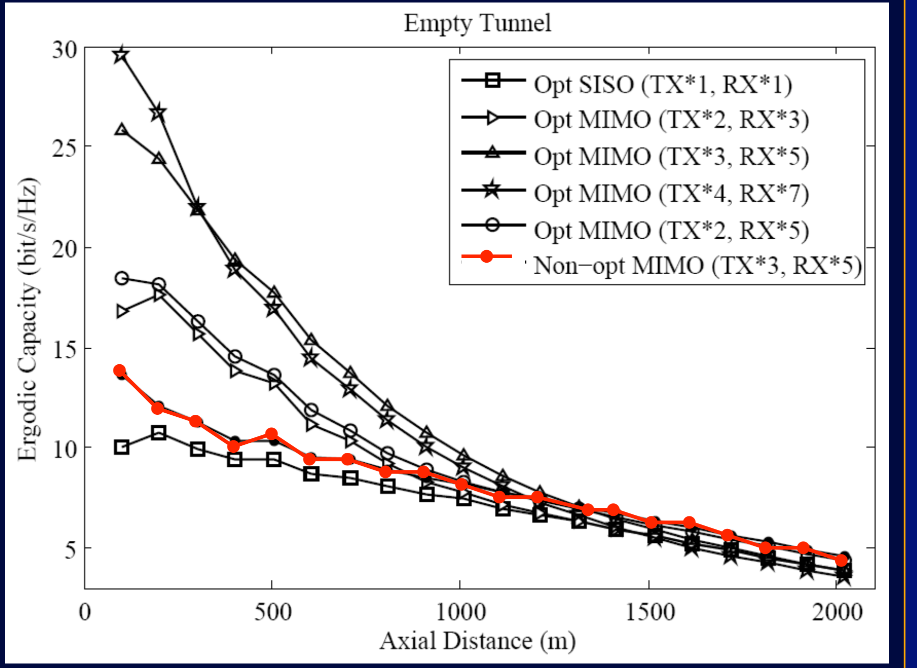
- **MIMO capacity in tunnels:**

$$Capacity \approx E\left\{\log\det\left[\frac{G_t G_r \rho}{2k}(\mathbf{D}\mathbf{D}^*)\right]\right\} + \log\det\left(\mathbf{E}^{RX*}\mathbf{E}^{RX}\right) + \log\det\left(\frac{1}{p}\mathbf{C}^{TX}\mathbf{C}^{TX*}\right)$$

- **The design of TX and RX antenna geometry can be conducted separately.**

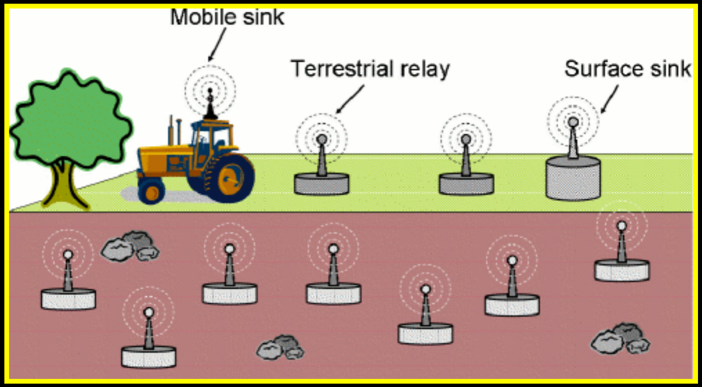
MIMO Performance in Tunnels

- The antenna elements are placed at the positions:
  - The eigenfunctions of the significant modes reach their extrema values.
- Optimal antenna geometry performs much higher than the undesigned geometry.
- In the near region, the MIMO with more antenna elements has higher capacity.
- As the distance between TX/RX increases, the advantages of more antenna elements become trivial.



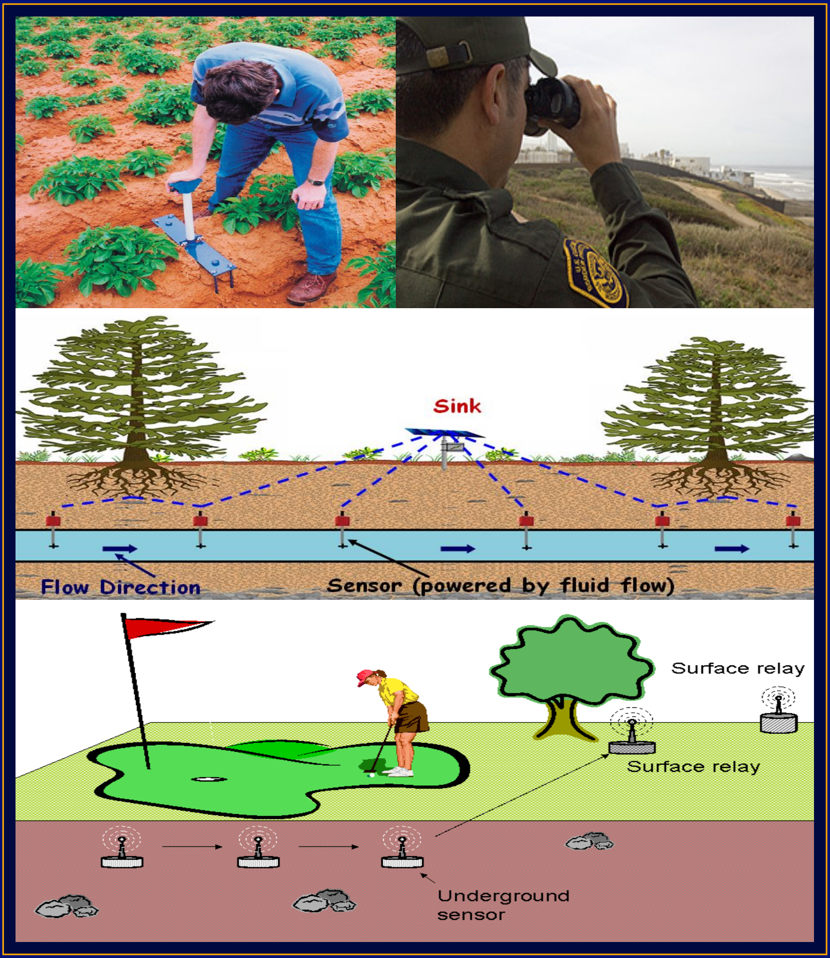
Underground Wireless Networking

- Mines & Tunnels
- Soil Medium



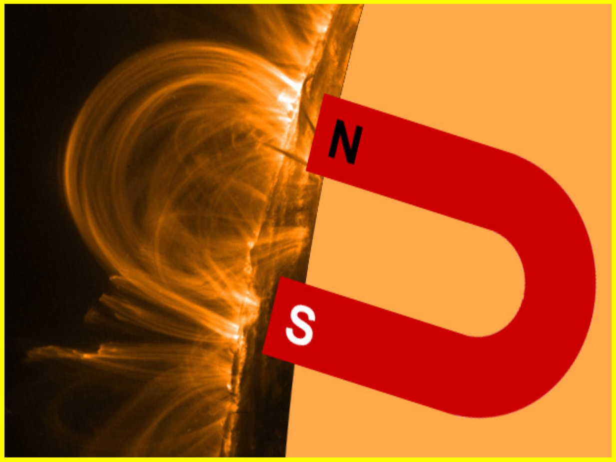
Applications

- **Intelligent Agriculture:**
  - Irrigation
  - Pest / disease control
- **Border patrol**
- **Pipe leakage detection**
- **Sports field monitoring:**
  - Soccer / football / Baseball fields
  - Golf courses



Possible Solutions

Electromagnetic Waves



Magnetic Induction

Possible Solutions

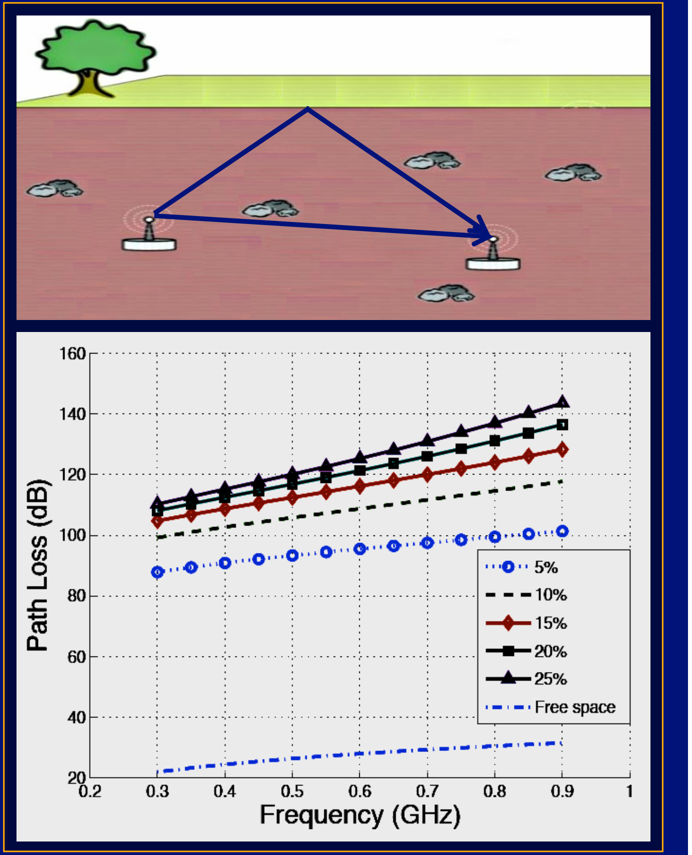
Electromagnetic Waves

Magnetic Induction

Channel Model for EM Waves

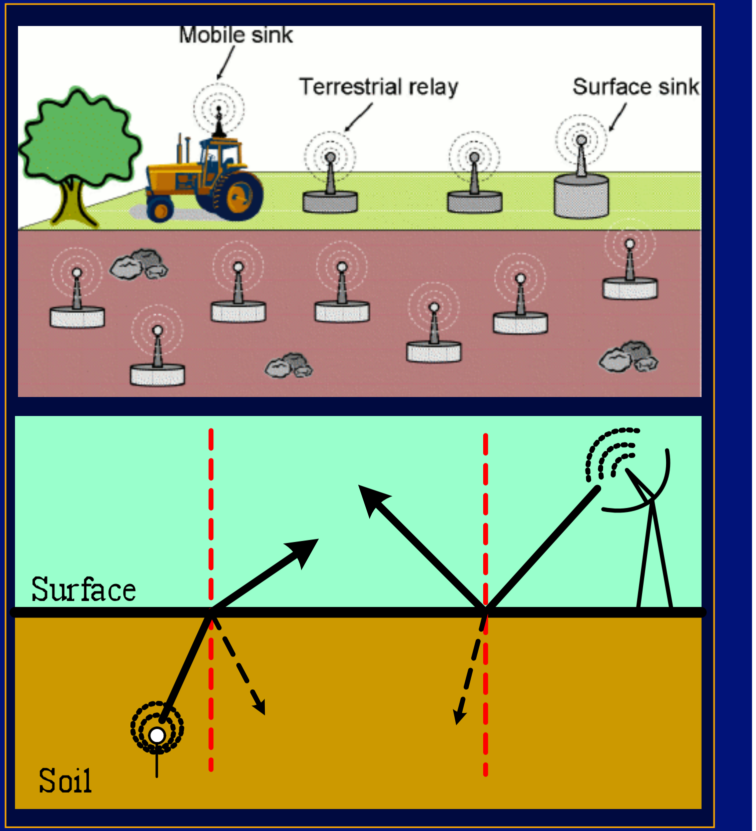
L. Li, M. C. Vuran and I.F. Akyildiz, “Characteristics of Underground Channel for Wireless Underground Sensor Networks", MED HOC NET, 2007

- **Path loss due to material absorption is a major concern.**
- **Losses are determined by both**
  - **Properties of the soil**
    - ***Water content***
    - **Soil composition**
  - **System parameters**
    - **Operating frequency**
    - **Deployed depth**
- **Two main propagation route plus multi-path fading**



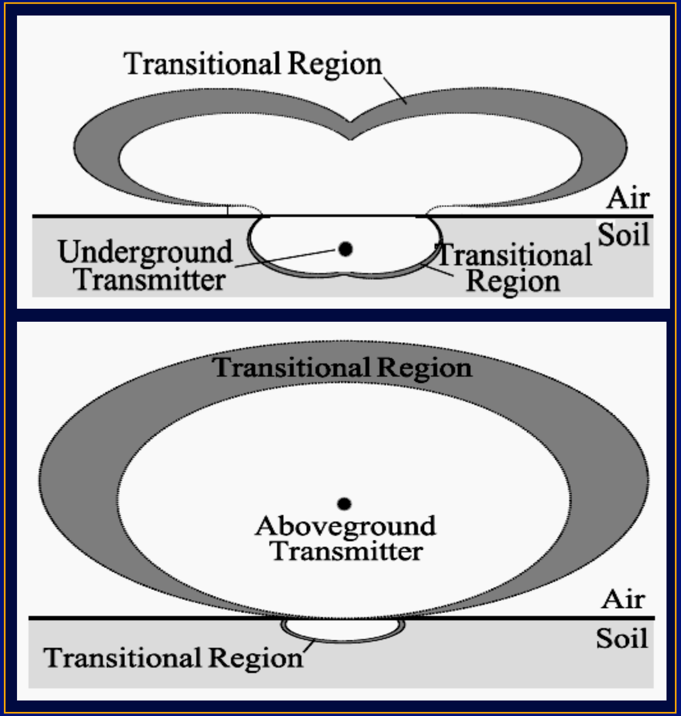
Connectivity & Delay of Underground Sensor Networks (On Going Work)

- UG-UG channel (sensing & control)
  - High path loss
  - Dynamic channel determined by:
    - Soil water content
    - sensor depth
- UG-AG channel (sensing)
  - Able to penetrate the ground surface
- AG-UG channel (control)
  - Lose most energy while penetrating the ground surface



Communication Ranges

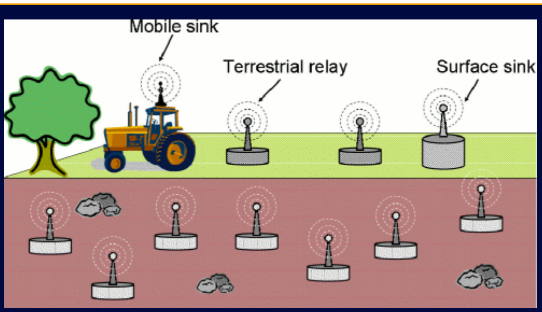
- UG-AG > UG-UG > AG-UG
- Asymmetrical communication between UG and AG nodes
- Much more difficult for AG node to communicate with UG node than the opposite direction
- Two layered/phased graph



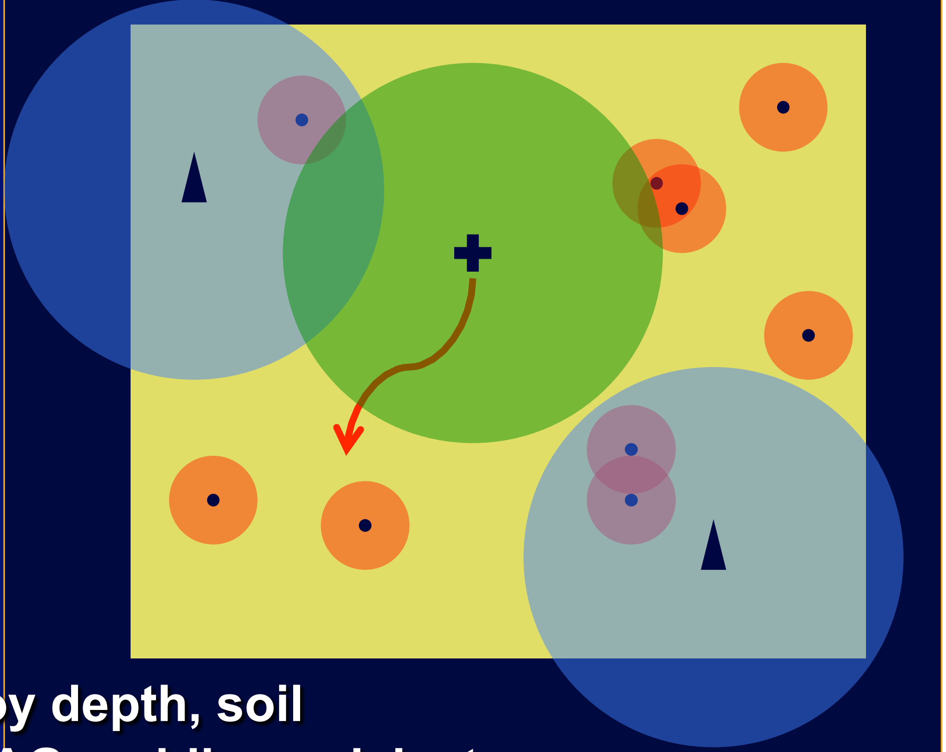
J. Tiusanen, “Wireless Soil Scout prototype radio signal reception compared to the attenuation model,” Precision Agriculture, 2008.

M.C. Vuran, “CAREER: Bringing Wireless Sensor Networks Underground,” Proposal, 2009.

Sensing Phase

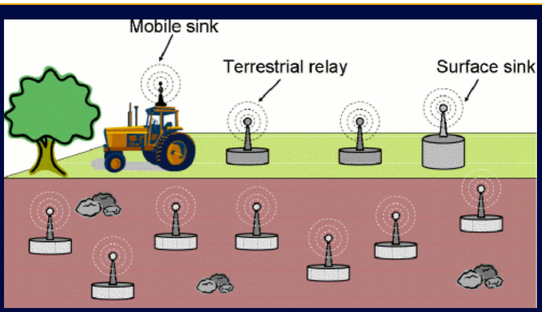


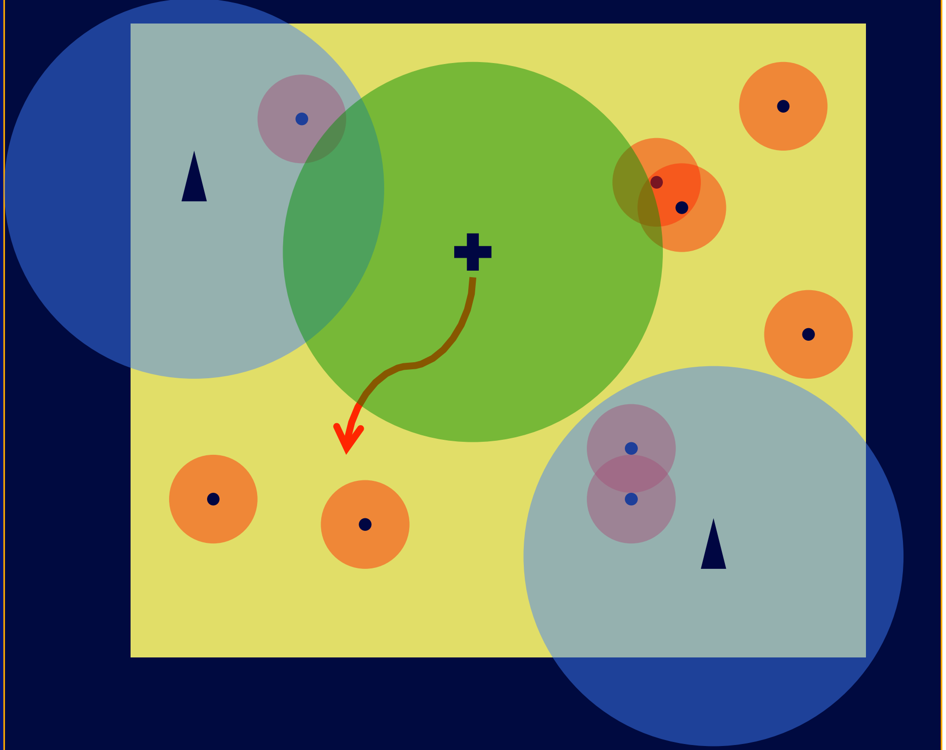
- Project the UG nodes to the AG plane
- Find critical density of each kind of nodes to achieve connectivity
- Find average delay of forming a path from a UG sensor to AG sink
- Challenges
  - 3 independent point process
  - Node mobility
  - Parameters: water contents, deploy depth, soil composition, AG antenna height, AG mobile model, etc



Control Phase

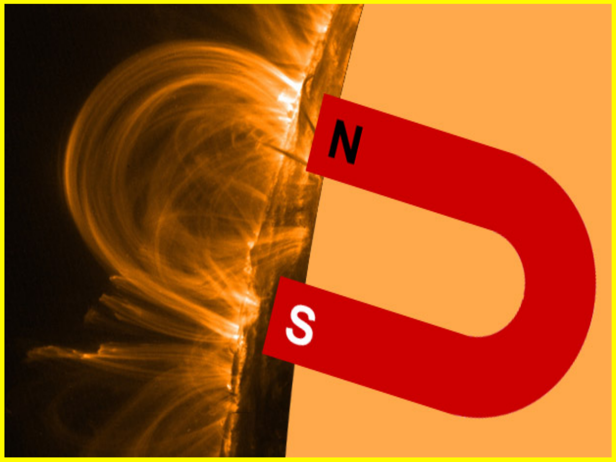
- Project the AG nodes to the UG plane
- The range of AG-UG link decreases dramatically
- The cost for full connectivity would be very huge
- Rely on the mobile sink to send control info (delay-tolerant network)
- Joint design with the sensing phase





Possible Solutions

Electromagnetic Waves



Magnetic Induction

Limitations of EM Waves in UG

- Dynamic channel conditions
  - Water content changes in different time and positions
- Limited UG transmission range
  - Around 1 m
- Rely on AG nodes to achieve reasonable connectivity & delay
  - AG nodes are not permitted in many applications
  - E.g. battle field monitoring, border patrol, etc

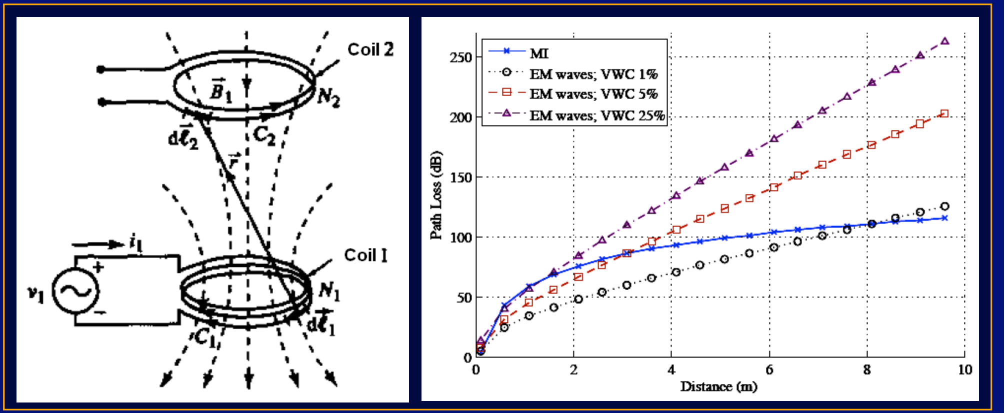
Alternative Solution: Magnetic Induction

Z. Sun and I.F. Akyildiz, “Underground Wireless Communication using Magnetic Induction,” IEEE ICC 2009

Z. Sun and I.F. Akyildiz, “Magnetic Induction Communications for Wireless Underground Sensor Networks,” submitted to IEEE Trans. Antenna & Propagation, revised in Nov. 2009

- **MI: only field spread**
  - **Distance factor:** $60 \log r$
  - **Dielectric factor: only** u

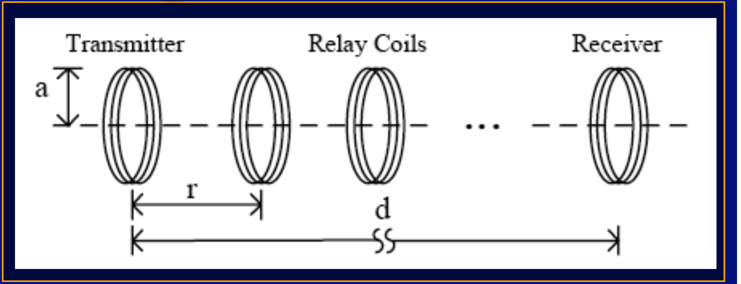
- **EM wave: material absorption + field spread**
  - **Distance factor:** $20 \log r + 8.69 \alpha r$
  - **Dielectric factor:** ε, u



- **It solves the problem of various channel condition.**

- **However, the transmission ranges of both systems are still too short for a practical applications in underground medium.**

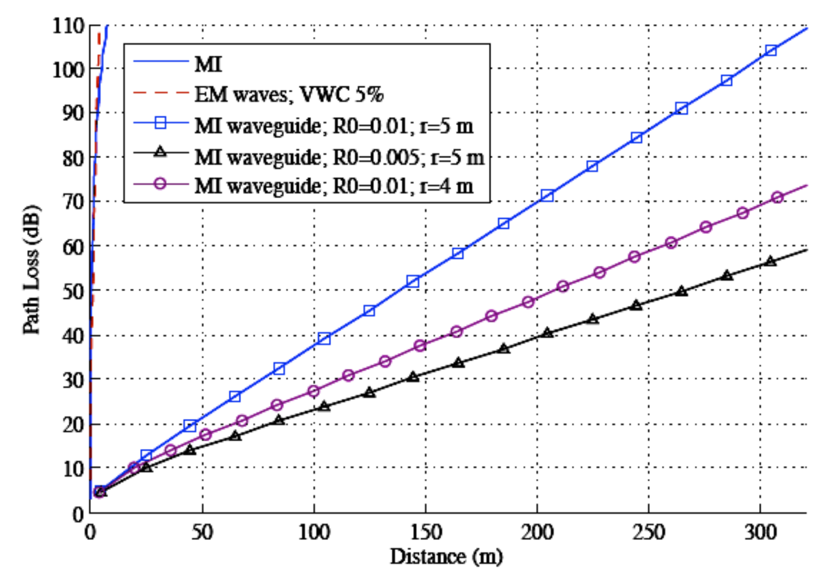
Enlarge Transmission Range - MI Waveguide

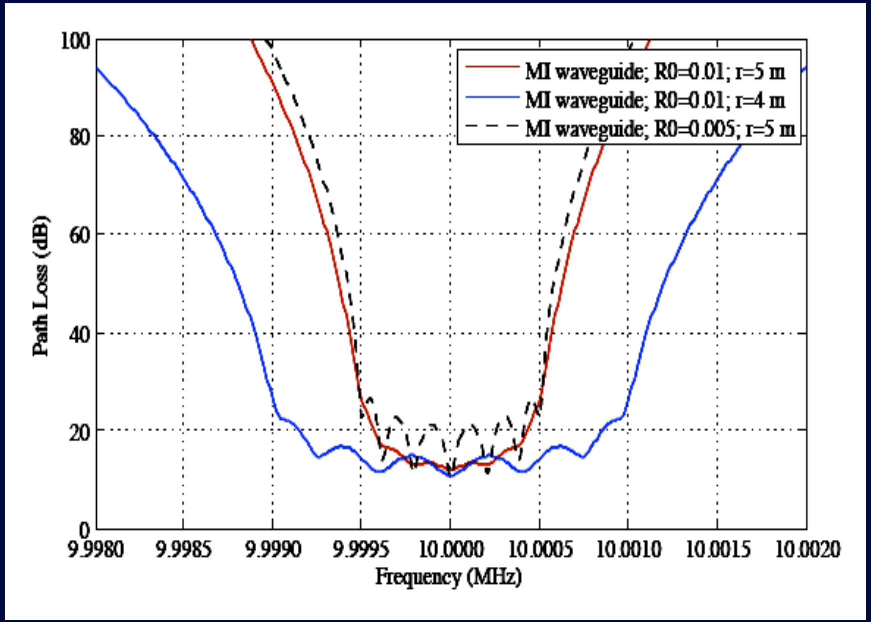


- **Deploy some relay coils between the transceivers - Forming an MI waveguide**
- **MI waveguide has 3 advantages in UG communications:**
  - **Communication range achieves *several hundreds meters*.**
  - **It is only required to deploy one relay coil every 5 meters (or even longer) between the transceivers.**
  - **The relay coils do not consume any energy and the cost is very small.**
- **Each coil is loaded with a capacitor, so that the coils are resonant**
- **The path loss is calculated using the equivalent transformer circuit:**

$$L_{MIG}(d) = 10\lg 4\left[1+\frac{1}{(\frac{R}{\omega M})^2+\frac{1}{1+\frac{1}{(\frac{R}{\omega M})^2+\frac{1}{1+\cdots}}}}\right] + 20\lg\left[b_{n-1}(\frac{R}{\omega M})^{n-1}+\cdots+b_1(\frac{R}{\omega M})+b_0\right]$$

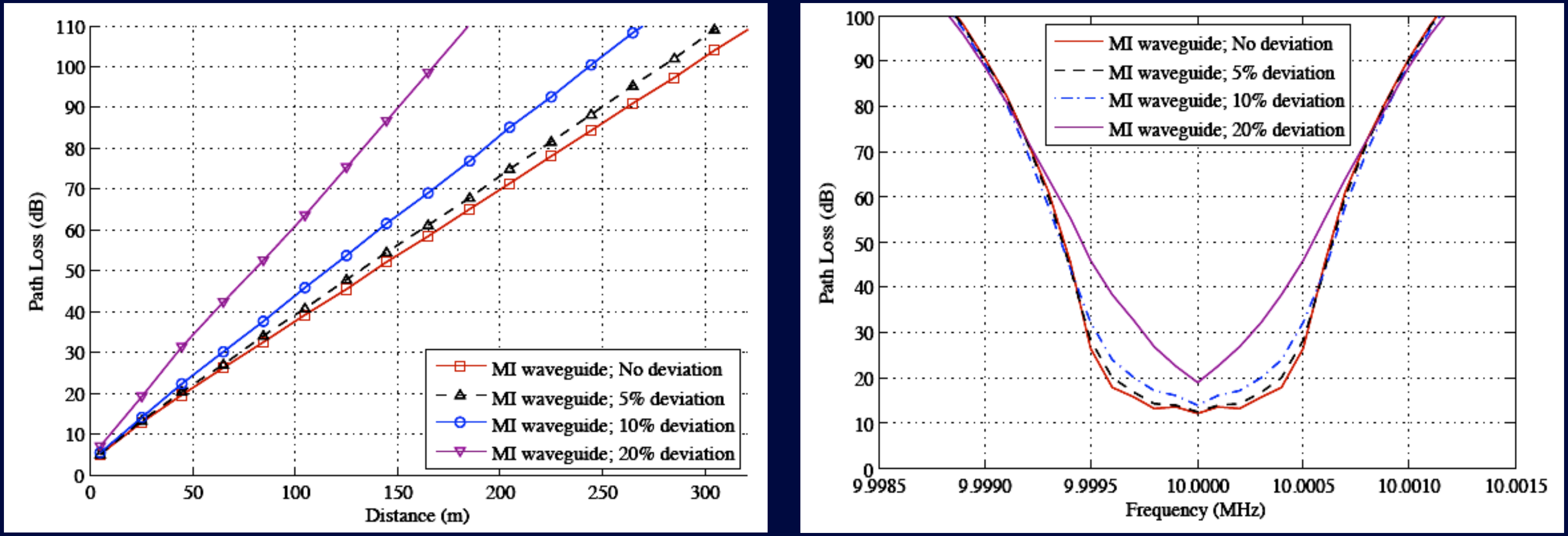
MI Waveguide Channel Characteristics





- The communication range of MI waveguide achieves more than 250 m
- The 3-dB bandwidth of the MI system is around 2 KHz.

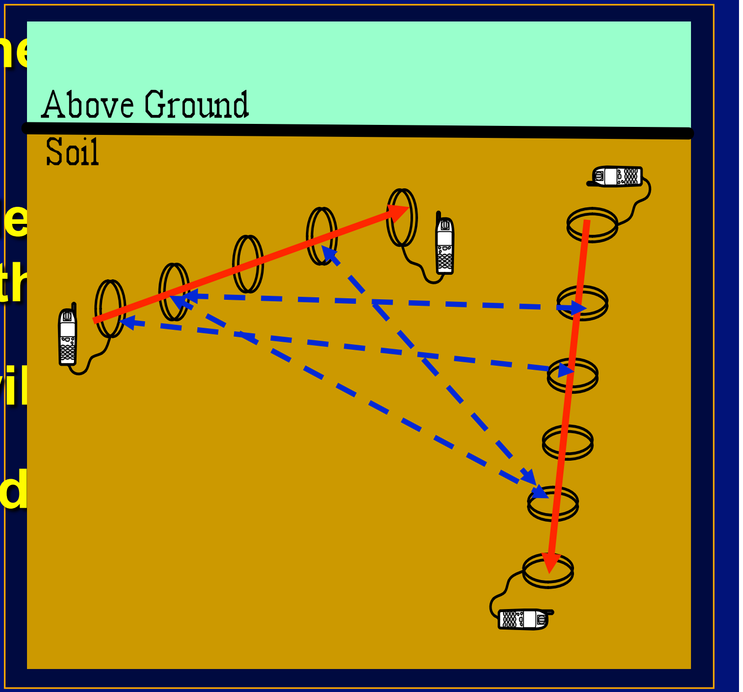
Influence of Non-ideal Deployment



- Deployment constraints, such as rocks or pipes in the soil.
- Position changes, due to the above ground pressure or the movement of the soil.

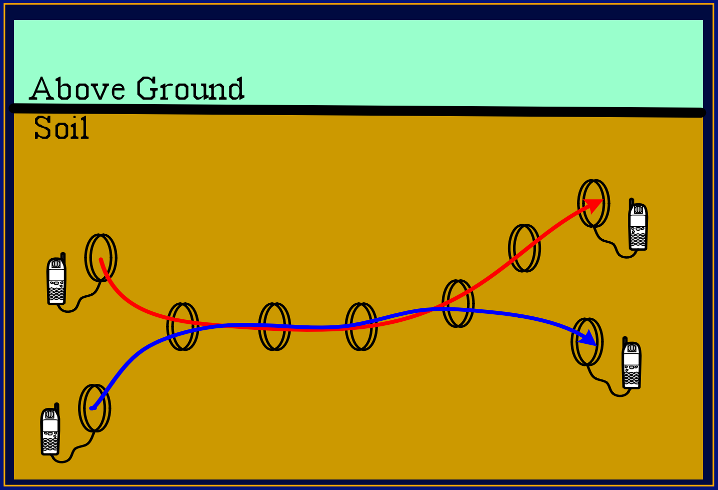
Interference Model (Next Step Work)

- We have already develop the p2p channe
  waveguide in soil
- When there are multiple pairs of MI node
  model is much more complicated than th
- All the relay coils of one MI node pair wil
- Other parameters include position and d
  waveguide set



MI Waveguide Network in Soil

- Multi-hop channel model for the MI waveguide tech in 3D topology
- Topology Control
  - The number of relay coils
  - Can two sets of transceivers share one set of relay coils?



- Network Robustness
  - The performance of the MI waveguide relay on the deployment
  - Find solutions to mitigate the influence if the positions changes

Conclusion

- Underground Communications in Mines & Tunnels
  - Empty Tunnel
    - Multimode Model
  - Tunnel with obstructions
    - Influence of the obstructions
  - MIMO in Tunnels
    - Optimal MIMO antenna geometry

- Underground Sensor Networks in Soil Medium
  - EM Waves in Soil
    - Channel Model
    - Connectivity & Delay of the UG Sensor Network
  - MI Waveguide in Soil
    - Channel Model
    - Interference Model & Topology Control

Thank You!!!

Questions?