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Wireless Sensor Networks for Infrastructure Monitoring: Radio Propagation

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EPSRC WINES II: Smart Infrastructure

Tube Lines THEHUMBERBRIDGE UNDERGROUND

Computer Laboratory & Department of Engineering

The Problem

- Aging infrastructure is a problem worldwide, e.g.,
  - Large part of London Underground built around 100 years ago
  - Bridges carrying much heavier vehicle loads than anticipated when they were built. Higher than expected rates of corrosion.
  - Corrosion in pipes leading to high leakage in local water distribution network
- Failure of critical infrastructure can give rise to
  - loss of life
  - high cost to the economy

The Solution

- Currently, continuous monitoring is very rare
  - Periodic visual inspections, e.g., for bridges tunnels
  - Faults reported by users, e.g., leaks
- Retrofitting wired sensors to existing infrastructure is very expensive
  - Can be considered for new structures
- Wireless sensor networks (WSNs) have the potential to lower deployment costs and so permit continuous monitoring
  - However, WSNs at a fairly embryonic stage and understanding of radio propagation in infrastructure environments is limited

The Project

- Collaboration between teams at Cambridge and Imperial
  - Computer Lab, and Civ. Eng. in Cambridge
  - Dept. of Elec. And Dept. of Civil in Imperial
- EPSRC Wines II funding – 3 years
- Cambridge team deployed WSNs in
  - Bridges – Humber bridge and an approach bridge (Ferriby Rd.). Hammersmith flyover
  - Tunnels – London Underground (near Bond St.), and Prague Underground

Computer Lab. Tasks

- Determination of Path Loss models for the infrastructure environments of interest – principally tunnels
  - Extensive measurement campaigns
  - Empirical modelling
  - Electromagnetic (EM) modelling
- Support deployments, e.g.,
  - Measurement of wireless node radio frequency (RF) performance
  - Input to wireless node and antenna selection
  - Installation advice and trouble shooting

Computer Lab. Tasks

- Investigate applicability of diversity techniques to improve link performance in WSNs
  - Frequency
  - Space
- Security issues
  - Authentication
  - Encryption
  - Denial of service and other attacks

WSN Hardware

- Wireless nodes from Crossbow Inc. – MICAz and IRIS
  - 2.4GHz ISM band
  - 802.15.4 Radios
- Gateways
  - Initially, Crossbow Stargate. Then ‘Balloon’ SBC.
  - ADSL or GPRS backhaul
- Crossbow Xmesh multihop routing
- Sensors
  - Crossbow boards and/or custom built, e.g., inclinometers

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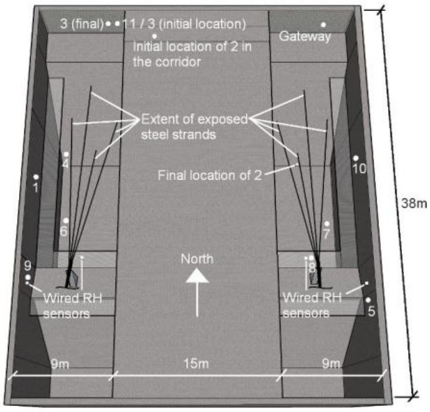
Humber Bridge Anchorage

Anchorage Deployment – RH and temperature monitoring



- 12 node network
- 10 nodes measure RH and temperature using off-the-shelf hardware
- 1 node acts as a relay
- 1 node measures inclination of the splay saddle
- Gateway is connected to the Internet via ADSL
- http://www.bridgeforum.com/humber/

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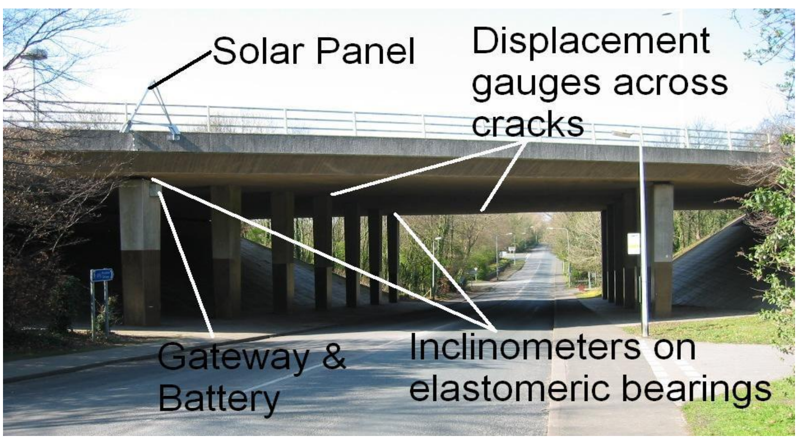
Ferriby Road Bridge



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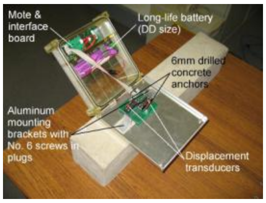
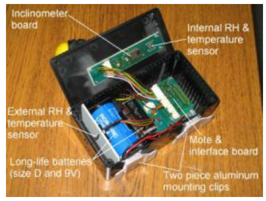
Ferriby Road Bridge network





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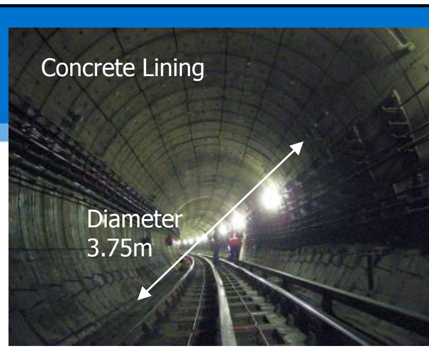
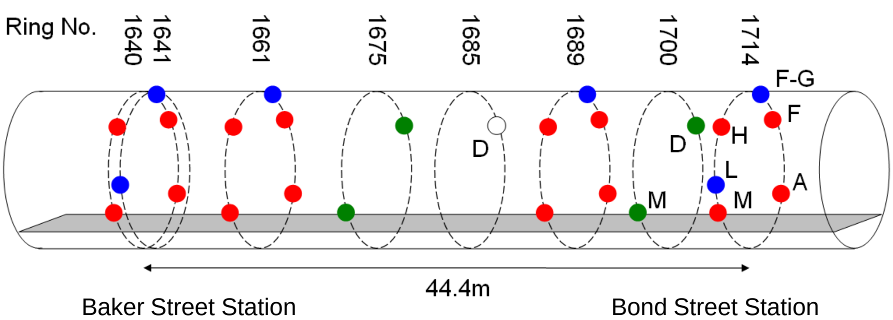
London Underground

- Sensor Nodes
  - Inclinometers: 16
  - Crackmeters: 6



Inclinometer LPDT Relay Gateway



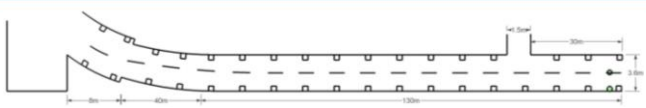
Radio Propagation in Tunnels

- No simple analytical models
- Previous measurements only address near central antennas
- For WSN, antennas mounted close to tunnel wall
- Possible approaches
  - Modelling as an oversize waveguide
  - Ray tracing
  - Empirical modelling
  - EM modelling, e.g. Finite Difference Time Domain (FDTD)

Radio Propagation in Tunnels

Aldwych Tunnel:

Cast Iron Lining



Jubilee Line:

Concrete and Cast Iron Lining

Measurements

- Tests at 868MHz and 2.45GHz (licence free bands)
  - Battery powered signal generators and power amps
- Close to wall as well as centre antennas
- Portable spectrum analyser to measure received signal power
  - Data logged on a laptop
  - Samples taken once per wavelength in high resolution (HR) mode
  - 100 samples taken in area 1m^2 in low resolution (LR) mode

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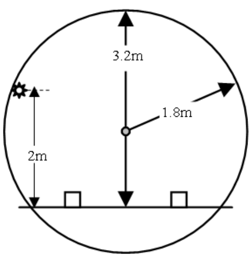
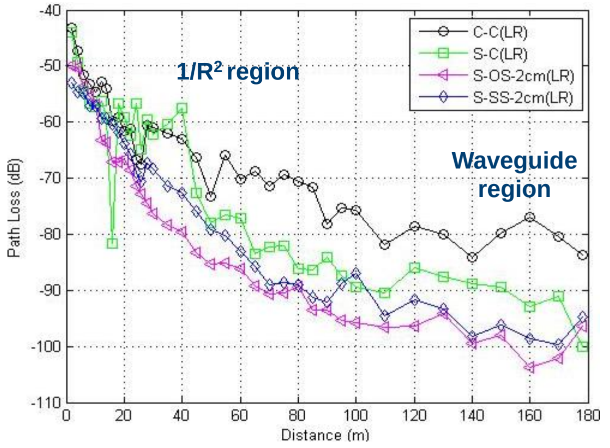
Measurements





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Comparisons

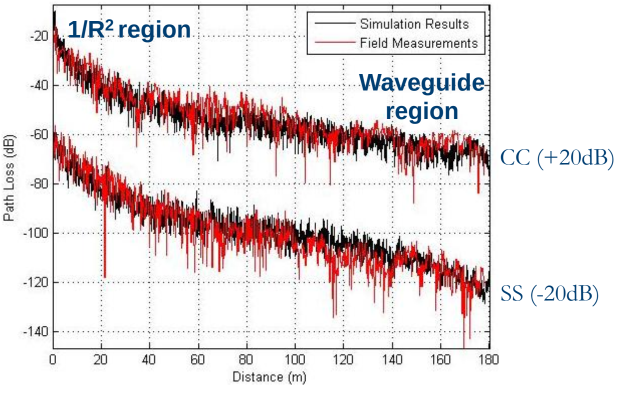
Factor	Comparative Path Loss Performance
Antenna Position	Centre to Centre (CC) > All other Side cases (SS)
Operating Frequency	CC case: 868MHz > 2.45 GHz SS case: 868MHz ≈ 2.45GHz
Material	Cast Iron > Concrete
Course	Straight ≈ Curved

FDTD Modelling

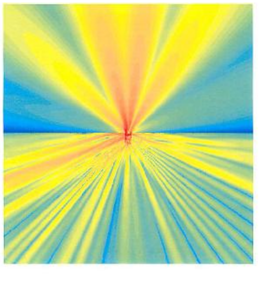
- Finite Difference Time Domain (FDTD) is a time domain iterative solution to Maxwell's equations
- Full 3D FDTD model takes too long to run and uses too much memory
  - Problem reduced to 2D
  - Results need to be corrected to yield results corresponding with a 3D model – so called 'modified 2D FDTD'
  - Correction factors (CFs) determined for well known free space and flat earth models
    - Concept extended to tunnels
    - CF determined by comparison with measurements

FDTD Modelling - Tunnel

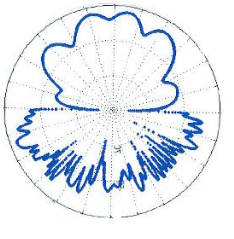
- Comparison of modified 2D FDTD with measurements



FDTD Modelling – Fire Hydrant Chamber



Power density distribution

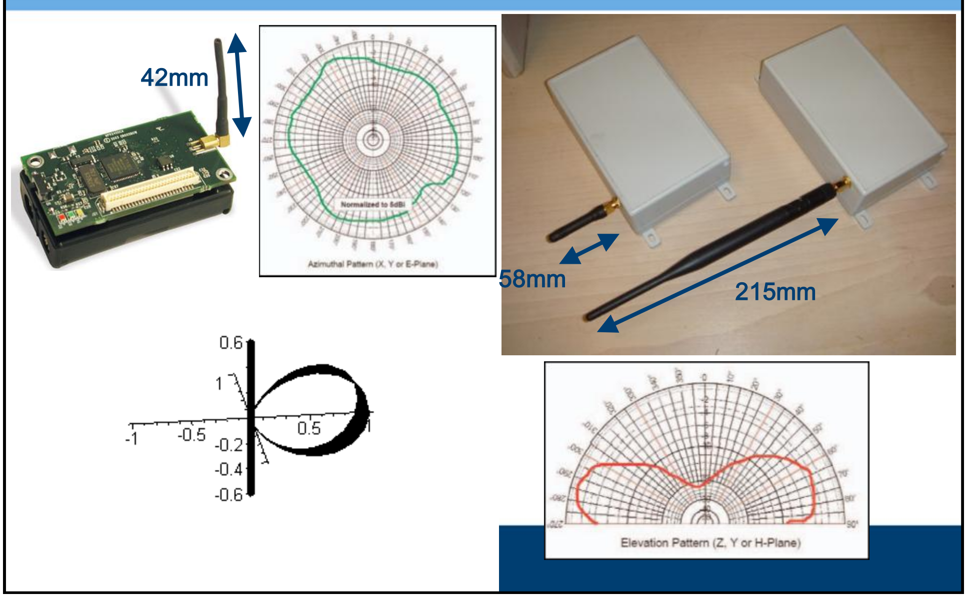


Effective radiation pattern

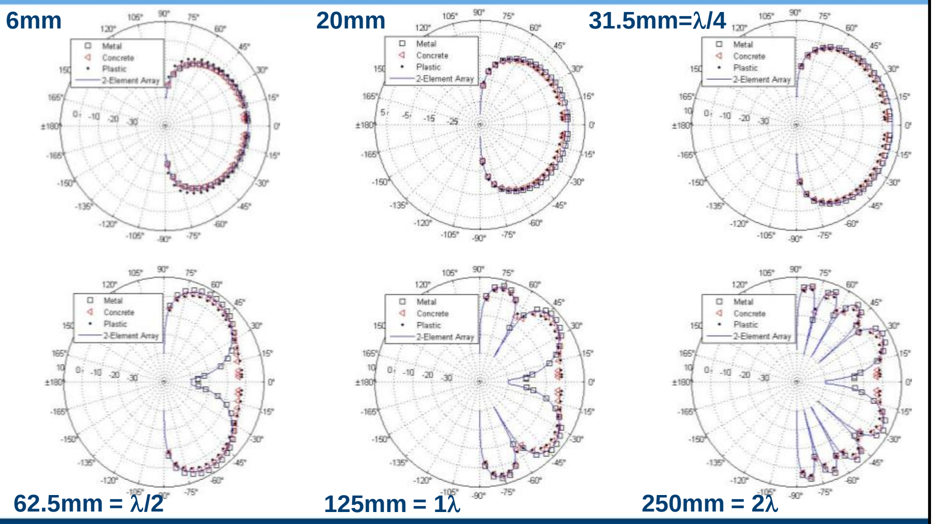
Current ways to Overcome Path Loss

- Increase transmit power
  - Battery life penalty
- Improve receiver sensitivity
  - Cost implications
- Relay/multihop networks
  - Cost, installation time
- Increase antenna gain
  - Size, cost, robustness issues

Antennas

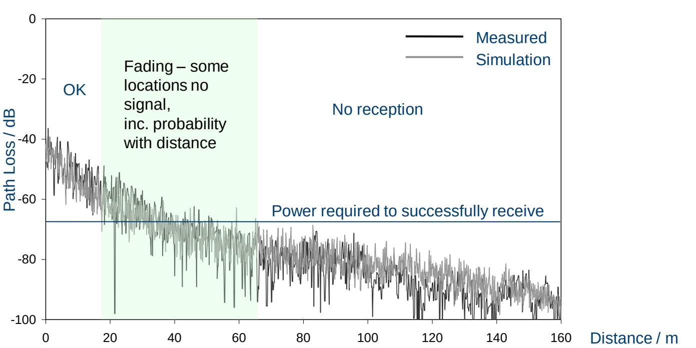


Effect of Close to Wall Antennas



Fading

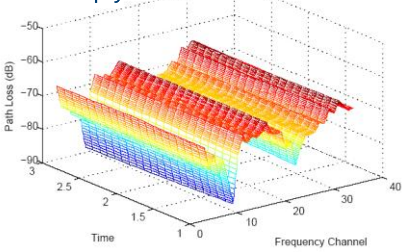
- Multipath fading
  - Destructive or constructive interference between multiple arriving signals at the receive antenna e.g., owing to multiple reflections in the environment



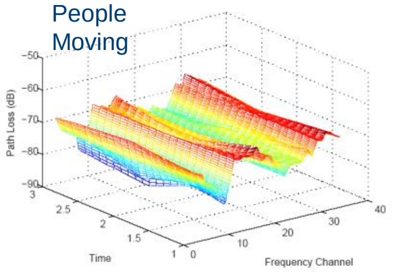
Fading

- Dependent on the environment – geometry, materials
  - Can be modelled stochastically – difficult to predict exact location
  - Fade positions static in a static environment
  - Possibly solutions include frequency or space diversity

Empty



People Moving



Frequency Diversity

- Measurements conducted every 10m in 90m cast iron lined tunnel
  - Measurements of received signal measured on 32 freq. channels, 5MHz spacing in 2.4GHz ISM band

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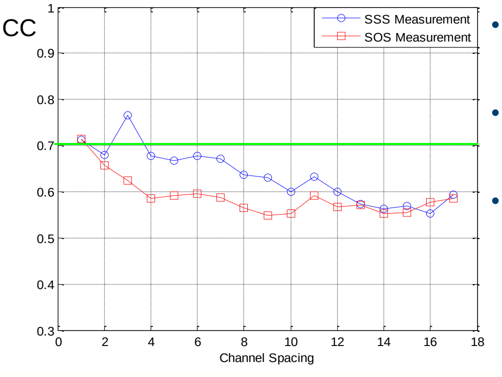
Frequency Diversity (FD)

- Potential diversity gain quantified using correlation coefficient (CC)
  - Values <0.7 indicate worthwhile gain



- Hopping by 1 channel gives reasonable FD gain
- FD gain increases with channel separation
- Antennas on Same side (SSS) of tunnel wall experience less FD gain than antennas on opposite side (SOS)

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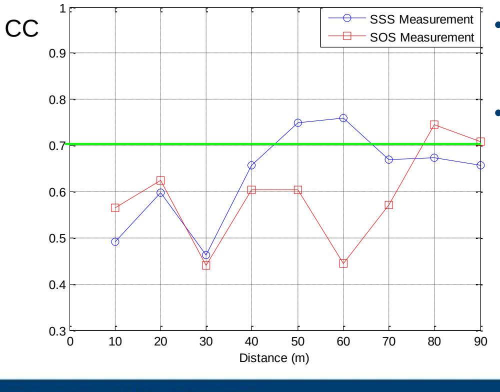

- FH gain decreases with distance
- SOS in general experience greater FD gain than SSS

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Frequency Diversity (FD)

- FD has the potential to achieve diversity gain in the tunnel environment
- Use of FD will improve link reliability and so ease deployment problems
- No additional hardware required, but will make media access control (MAC) layer more complicated
- Will give some immunity to radio frequency (RF) interference
- We will also be investigating the use of space diversity (SD)

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Conclusions

- Use of WSN speeds up deployment but raises question of reliability
- Propagation knowledge important when planning deployment
  - Lack of models for infrastructure deployments
- Antenna gain, radiation pattern and location important
- Fading a problem
  - Difficult to accurately predict
  - Frequency Diversity may be applicable in some environments
- Need for planning tools to assist in the deployment procedure, e.g.,
  - To optimise placement of relay nodes

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