Wireless Sensor Networks for Infrastructure Monitoring: Radio Propagation

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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

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/

Ferriby Road Bridge

- Solar Panel
- Displacement gauges across cracks
- Gateway & Battery
- Inclinometers on elastomeric bearings
Ferriby Road Bridge network

Node 2 - Crack measurement
Node 3 - Crack measurement
Node 1 - Crack measurement
Gateway & Node 7
Node 4 - Inclinometer
Nodes 5 & 6 - Inclinometers

Ferriby Road Bridge network

London Underground

- Sensor Nodes
  - Inclinometers: 16
  - Crackmeters: 6

Concrete Lining
Diameter 3.75m

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 1m² in low resolution (LR) mode

[Diagram showing path loss in different regions]
Comparisons

<table>
<thead>
<tr>
<th>Factor</th>
<th>Comparative Path Loss Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Position</td>
<td>Centre to Centre (CC) &gt; All other Side cases (SS)</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>CC case: 868MHz &gt; 2.45 GHz</td>
</tr>
<tr>
<td></td>
<td>SS case: 868MHz ≈ 2.45GHz</td>
</tr>
<tr>
<td>Material</td>
<td>Cast Iron &gt; Concrete</td>
</tr>
<tr>
<td>Course</td>
<td>Straight ≈ Curved</td>
</tr>
</tbody>
</table>

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

![Graph showing comparison of 1/R² region, Waveguide region, CC (+20dB), SS (-20dB) with distance (m)]

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

42mm

Elevation Pattern (Z, Y or H-Plane)

58mm

215mm
Effect of Close to Wall Antennas

6mm

20mm

31.5mm = \lambda/4

62.5mm = \lambda/2

125mm = 1\lambda

250mm = 2\lambda

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 – some locations no signal, inc. probability with distance

Power required to successfully receive

Measured
Simulation

No reception

OK

Distance / m

Path Loss / dB

-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160

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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

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
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)

Frequency Diversity (FD)

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

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

### 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