Designing Robust Wireless Sensor Networks for Urban Development

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Presentation Outline

- Motivation for Wireless Sensor Networks in an Urban Environment
- Application of OR techniques in WSN design
- Reality of wireless communications – case study of a wireless sensor network deployment
- Concluding remarks – Bridging Theory and Reality

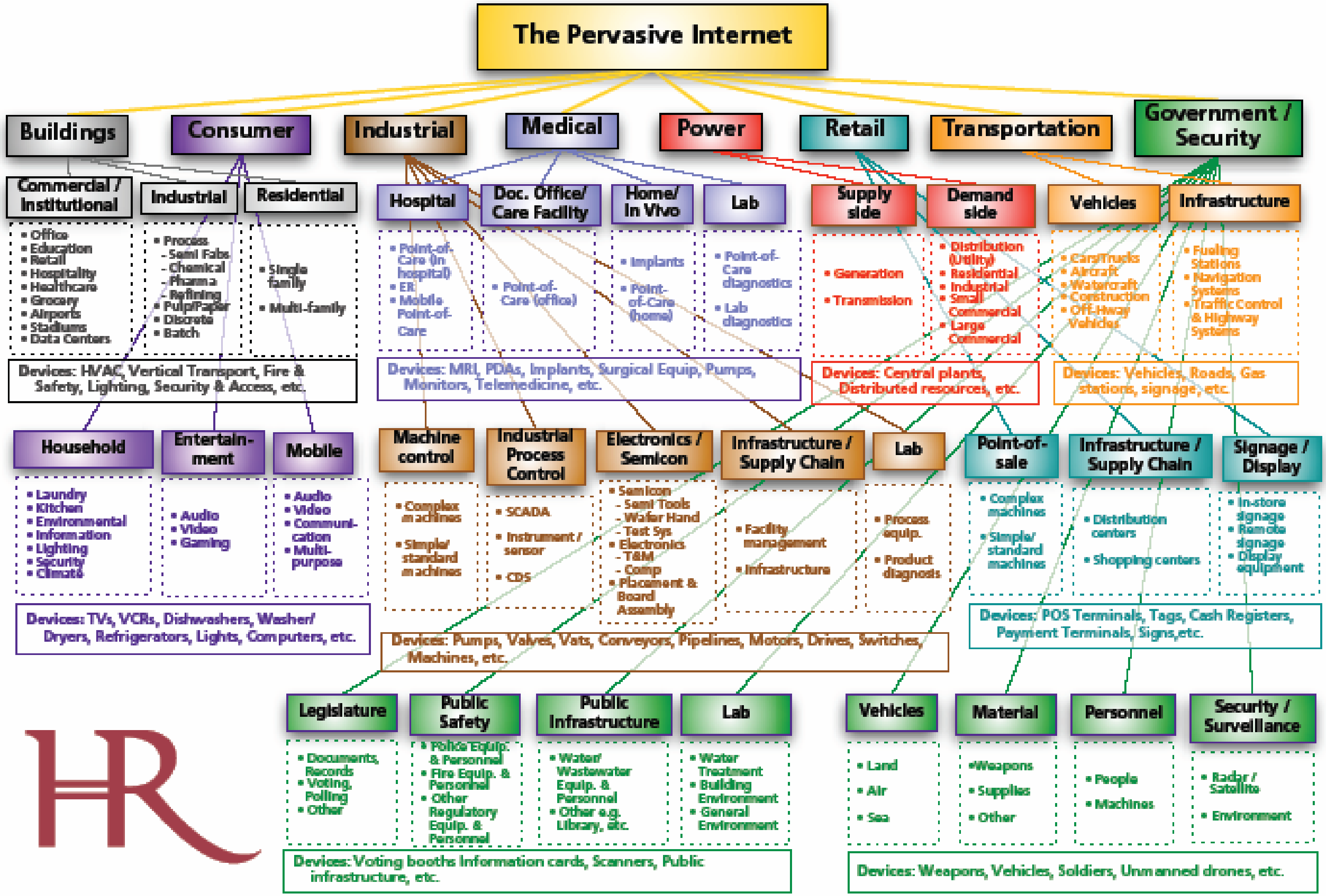
Visions and Trends

- Internet will become increasingly ubiquitous and pervasive

  machine-to-machine communications ⟩⟩⟩ human-oriented communications

- Numerous intelligent embedded devices perform relatively simple tasks of monitoring the status of structures and equipment, or the well-being of humans, and communicating this information

Venue Segmentation Map for Intelligent Device Networking & Management



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Motivation

Demand for Smart Environmental Sensing

1) Smart Sensors to address the "Global Warming" issues
2) Sensing and Measurement is the basis of data collection and analysis in Intelligent Systems
3) Energy auditing and real-time data for operational control requirement is demanded by customers
4) Market size for smart sensor network will grow but still at its infancy stage now, main driver is the low cost of public wireless infrastructure and seamless connectivity between local and wide area network
5) Good potential for smart sensor networks to be deployed in the instrumentation and monitoring of various structural systems for greater automation in safety and security.

Sensor Technology

1) Sensor are getting smaller and smarter due the advancement of MEMS micro miniature sensor technology
2) Sensor are moving away from providing analogue signals to digital data to facilitate accurate data processing and transmission
3) Smart Sensors are becoming prevalent due to lower cost and demand for distributed sensing and control across all industries

Benefits of wireless

- Ease of deployment
  - Without extensive cabling between sensors and data acquisition systems
- Low costs of deployment
  - Savings on cabling costs; wireless sensors also possess computation capability
- Fine grain of monitoring
  - Ease and low costs → larger numbers and denser placement that increases spatial resolution of data collection, and better quality of assessment.

Application areas and issues

- Structural monitoring
  – May need lifetime of sensors to be in the order of decades, especially the deeply embedded ones
- In-door environmental monitoring
  – Multi-modal, coupled with actuation
- Extreme event alerts & response
  – Need realtime and dependability guarantees, e.g. escape path finding through hazardous regions

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Why do we need robust WSNs

- Nodes may fail (due to wear and tear, power depletion, etc.)
- Nodes may drop packets because of buffer overflow, congestion, channel contention
- Poor channel conditions can lead to retransmission timeouts → packets are discarded
- Nodes may be malicious

Our Goal

- To minimize the maximum load transmitted by any node
- This ensures gradual degradation of performance when nodes do not forward data packets.

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Analytical Modeling

- To derive the relationship between transmission power and robustness
- To derive relationship between energy consumption and robustness
- To find the optimal robust routing algorithm using linear programming

Network Model

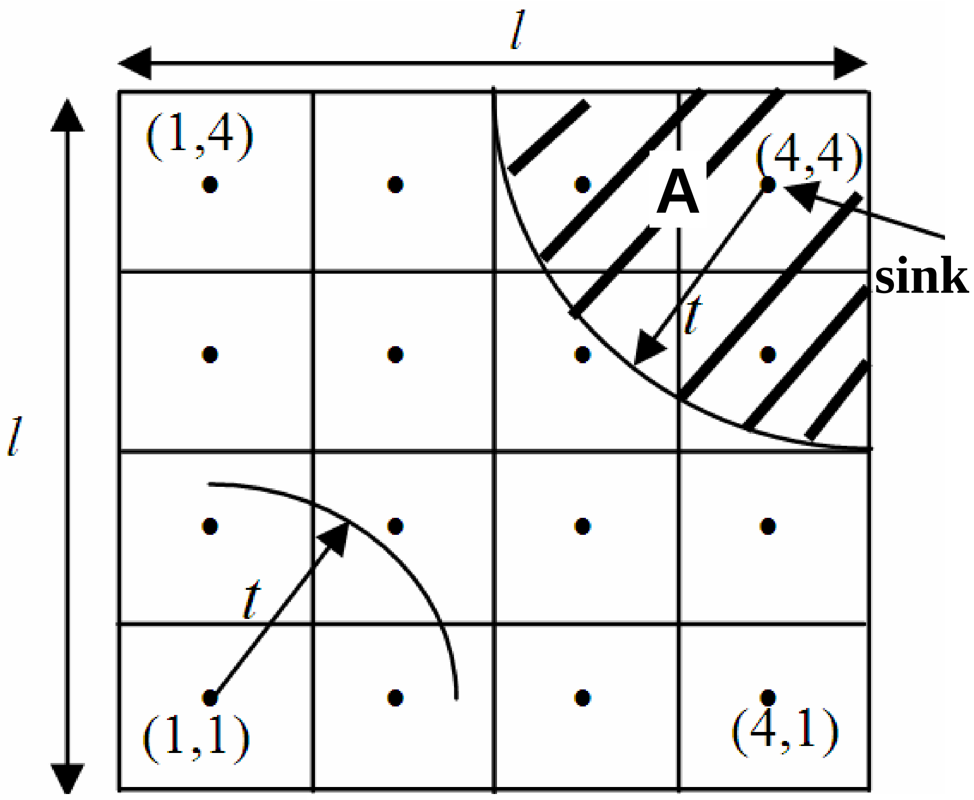
edge $(u,v) \in E$ iff

$$\sqrt{(x_u - x_v)^2 + (y_u - y_v)^2} \le t$$

f(u,v) – total amt of data transmitted from sensor node *u* to sensor node *v*

w(u,v) – weight of edge $(u,v) \in E$ is the transmission cost from node *u* to node *v*

In general, $w(u,v) \propto d^k$ where *d* is the distance between 2 nodes and *k* = (1..6) is the path loss exponent



Robustness Metric

- We define a robustness metric for analytical modeling and comparison between different routing algorithms

$$\lambda = \frac{1}{\text{Maximum Load Transmitted by any sensor node}}$$

- Loss or malfunction of any sensor node would not have a high impact on the total amount of sensor information received by the sink.

See also: Q. Yin, *et al.*, "Quantitative Robustness Metric for QOS Performances of Communication Networks", *Proceedings of IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications* (PIMRC 2006), Sep 2006, Helsinki, Finland.

Impact of Transmission Power

- Once the sink is disconnected from the network, the sensor network fails → the number of sensors (within A) that are directly connected to the sink is a critical factor

$$A = \frac{\pi}{4}\left(t + \sqrt{\frac{l^2}{2n^2}}\right)^2$$

- For $t \leq \frac{n-1}{n} l$, # of sensors within txn range of the sink is

$$s \approx \rho A - 1 = \frac{\pi\left(t + \sqrt{\frac{l^2}{2n^2}}\right)^2 n^2}{4l^2} - 1$$

Observations

- If each sensor has α units of data to send, total data received by sink is

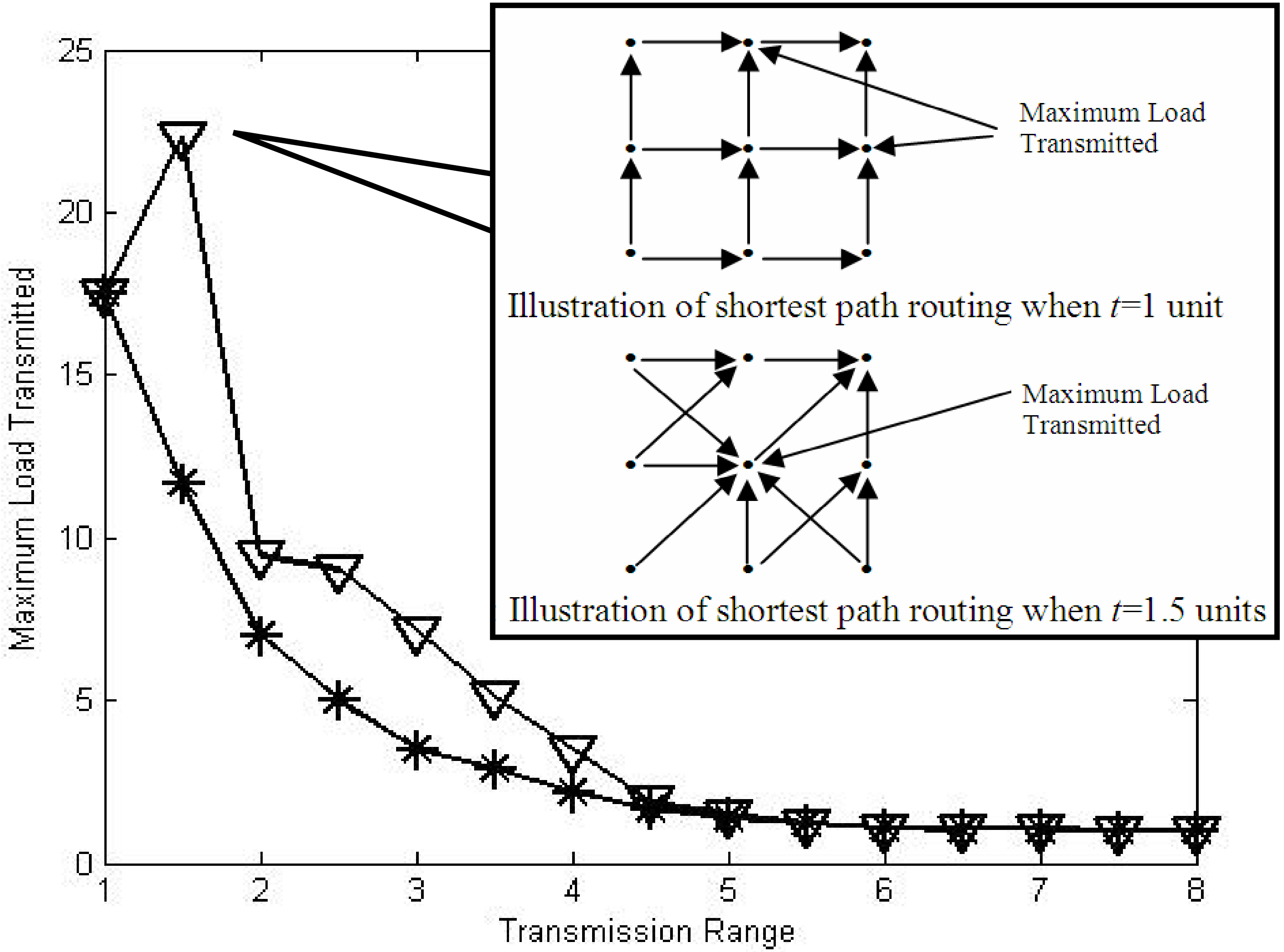
$$(n^2 - 1)\alpha$$

- Therefore, optimal maximum load per critical sensor is

$$(n^2 - 1)\alpha / s$$

- If we increase transmission power linearly, there is a quadratic increase in robustness.

Observations



Energy Consumption

- E_m – energy required to transmit 1 unit of sensor data over 1 unit distance
- hE_m – total energy required to send 1 unit of sensor data to the sink which is h hops away when t is 1 unit distance.
- For $t > 1$, the energy required per hop is $t^k E_m$ with number of hops reduced to $\lceil h/t \rceil$
- Total energy require is $ht^{k-1}E_m$ if $h/t \in$ integer
- When free space propagation model is used, the benefits of an increase in robustness outweighs the increase in energy utilized.

Impact of Routing Algorithms

- Study of 5 different routing algorithms
  - Shortest Path Routing
  - Greedy Geographic Routing
  - Energy-Efficient Routing
  - Optimal Robust Routing (ideal case)
  - Robust Geographic Routing

Ref:
- S. Wu and K.S. Candan, “GPER: Geographic Power Efficient Routing in Sensor Networks”, IEEE International Conference on Network Protocols, pp. 161-172, 2004.
- H. Dai and R. Han, “A Node-Centric Load Balancing Algorithm for Wireless Sensor Networks”, IEEE Global Telecommunications Conference 2003, pp. 548-552, 2003.
- I. Raicu, L. Schwiebert, S. Fowler, and Sandeep K.S. Gupta, “Local Load Balancing for Globally Efficient Routing in Wireless Sensor Networks”, International Journal of Distributed Sensor Networks, Vol. 1 No. 2, pp. 163-185, 2005.

Routing Algorithms

- Shortest Path Routing
  – minimize the number of hops to the sink
- Greedy Geographic Routing
  – maximize the distance gained towards the sink
- Energy Efficient Routing
  – minimize the energy consumption at each node

Optimal Robust Routing Algorithm

Step 1: Minimize the maximum load transmitted by any sensor node, *c*

$$f(u,v) = 0 \quad \text{for each} \quad (u,v) \notin E \qquad (1)$$

$$f(u,v) \geq 0 \quad \text{for each} \quad (u,v) \in E \qquad (2)$$

$$\sum_{v \in V} f(u,v) \leq c \quad \text{for each} \quad u \in V - \{\text{sink}\} \qquad (3)$$

$$\sum_{v \in V} f(u,v) - \sum_{v \in V} f(v,u) = L_i \quad \text{for each} \quad u \in V - \{\text{sink}\} \qquad (4)$$

$$\sum_{v \in V} f(u,v) = 0 \quad \text{for} \quad u \in \{\text{sink}\} \qquad (5)$$

$$\sum_{v \in V} f(v,u) = \sum_{i=1}^{n^2-1} L_i \quad \text{for} \quad u \in \{\text{sink}\} \qquad (6)$$

Optimal Robust Routing Algorithm

If there is no unique solution in step 1, we minimize the maximum energy consumed by any sensor node in step 2:

minimize p subject to the following constraints:
Constraints (1), (2), (4), (5) and (6)

$$\sum_{v \in V} f(u,v) \leq c_m \quad \text{for each} \quad u \in V - \{\text{sink}\} \qquad (7)$$

(c_m is the solution obtained in step 1)

$$\sum_{v \in V} f(u,v) w(u,v) \leq p \quad \text{for each} \quad u \in V - \{\text{sink}\} \qquad (8)$$

Optimal Robust Routing Algorithm

If there is no unique solution in step 2, we minimize the total energy consumed by all the sensor nodes in the network in step 3:

$$\text{minimize} \quad \sum_{u \in V} \sum_{v \in V} f(u,v) w(u,v)$$

subject to the following constraints:

Constraints (1), (2), (4), (5), (6) and (7)

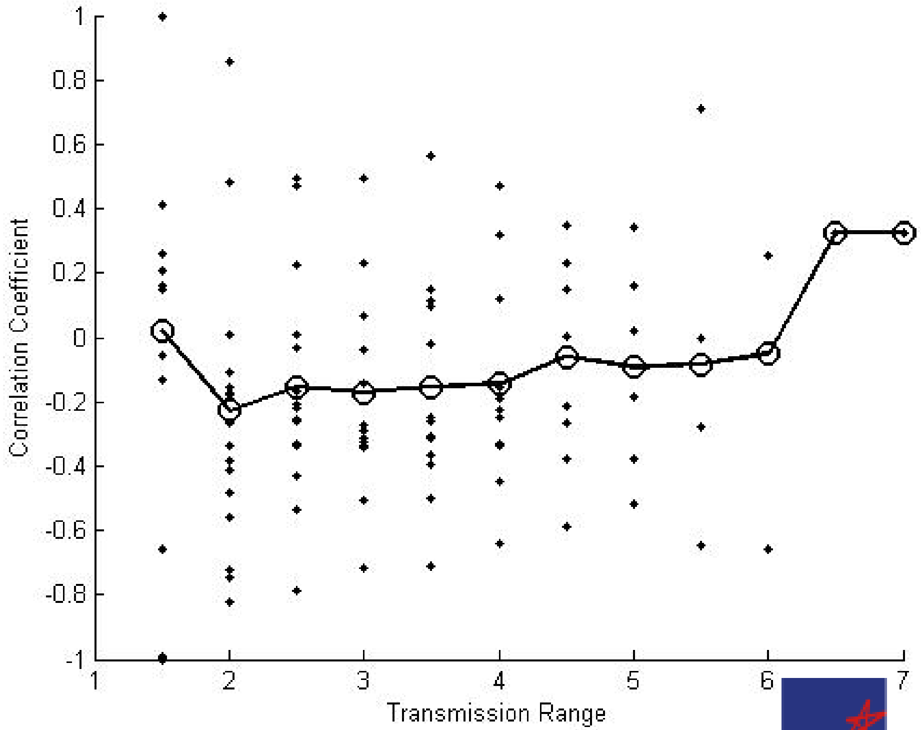
$$\sum_{v \in V} f(u,v) w(u,v) \le p_m \quad \text{for each} \quad u \in V - \{\text{sink}\} \qquad (9)$$

(p_m is the solution obtained in step 2)

Correlation Analysis

- Using a correlation test, we find that there is no linear relationship between the amount of load to forward to a particular neighbor and its distance away from the sink

→ *(distributed) robust geographic routing* algorithm that is near-optimal



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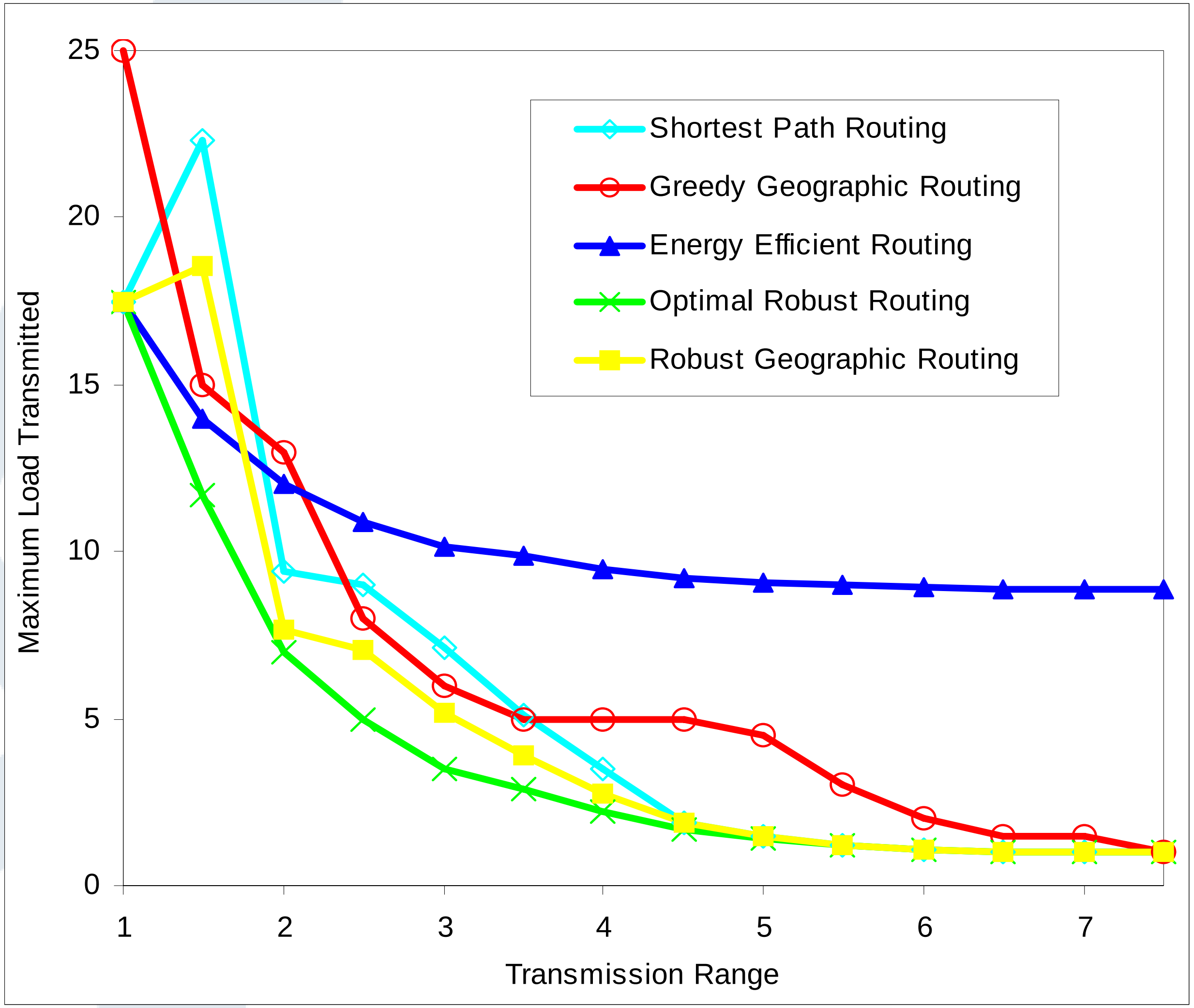
Network Topology

- 6 by 6 grid of sensor nodes with the sink at the corner
- Each sensor node is 1 unit distance away from other sensor nodes in the *x* and *y* axes
- Each sensor node has 1 unit of data to send to the sink

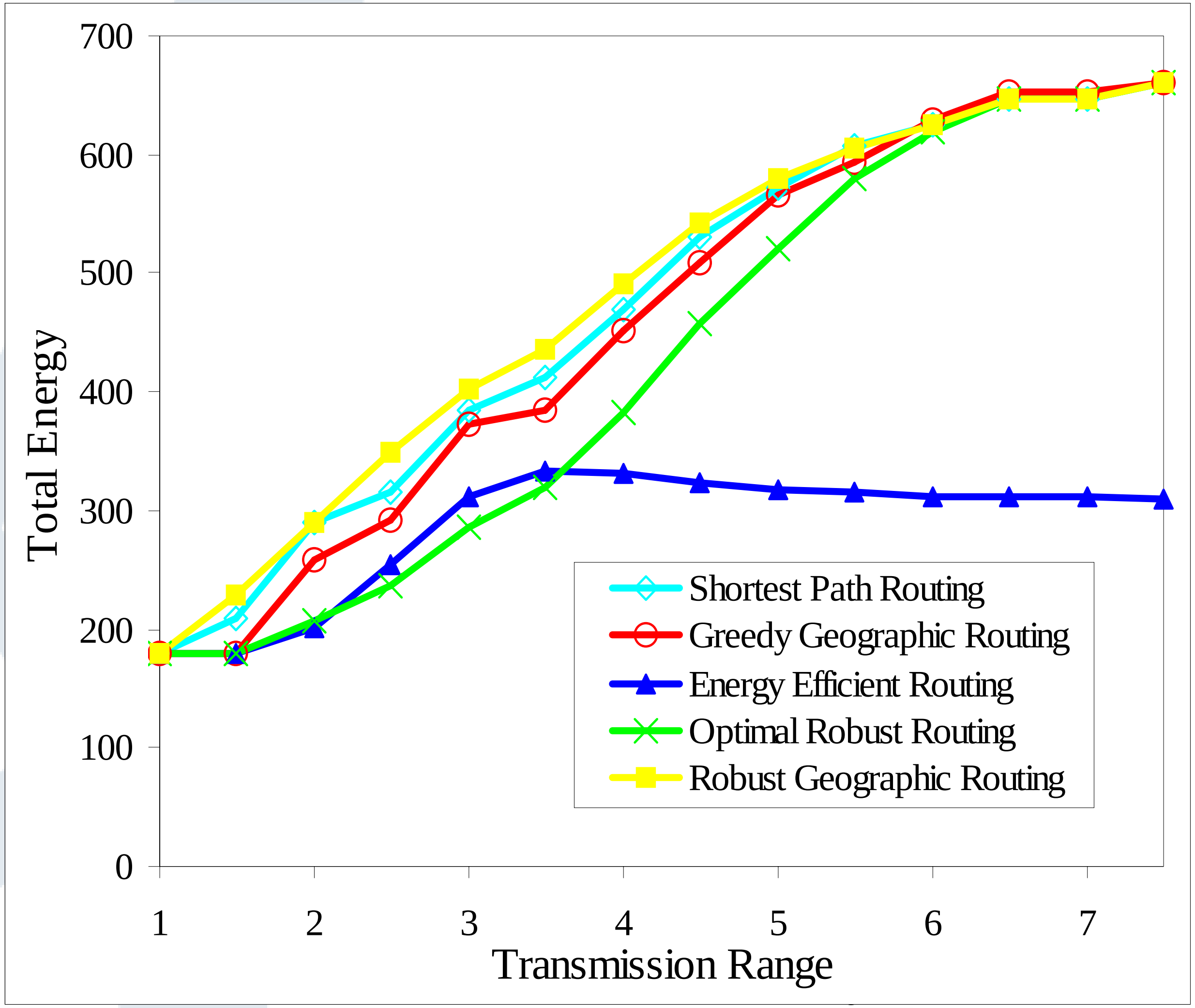
Robust Geographic Routing

- Distribute the load evenly among all the neighbors who are nearer the sink than itself
- Performance metrics used to compare different routing algorithms
  - Maximum load transmitted by any sensor
  - Total energy consumed by the network
  - Transmission cost per unit of robustness

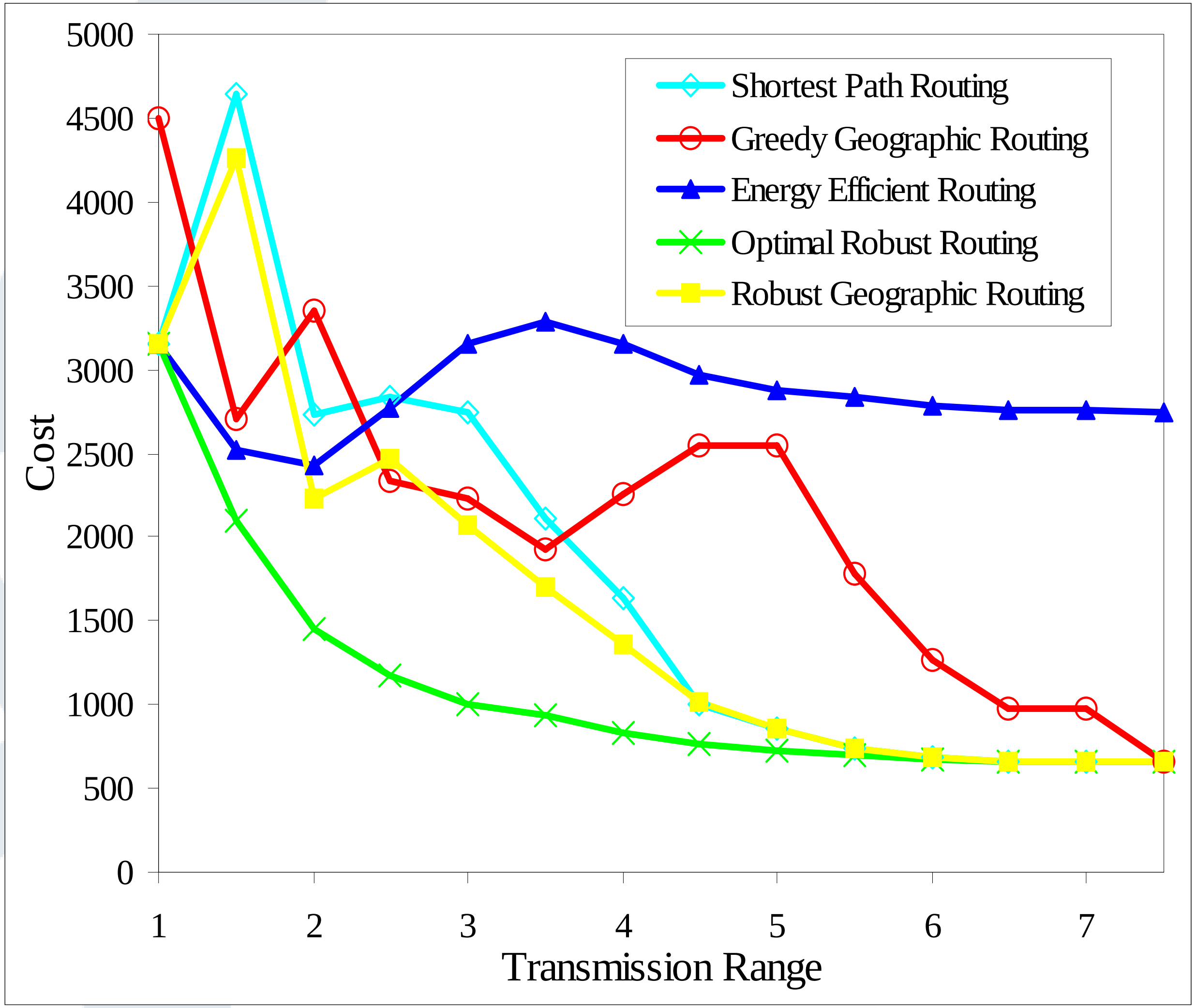
Maximum Load Transmitted by any sensor



Total energy consumed by the network



Transmission cost per unit of robustness



Summary

- Increasing transmission power can increase robustness at the expense of higher energy usage
- Different routing algorithms can affect the robustness of the network
- Future work
  - More network topologies
  - Different traffic patterns
  - More realistic environmental parameters, e.g. medium access contention

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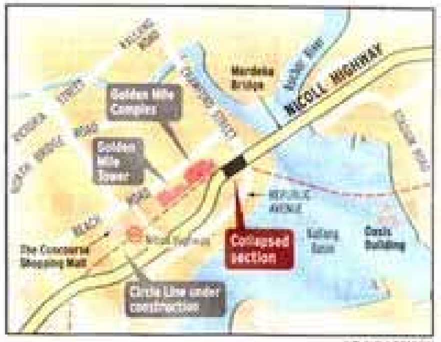
Source: The Straits Times, Apr 2004

MRT worksite collapse wrecks Nicoll Highway

- One dead, three hurt, three missing
- Thousands of commuters hit
- Highway will stay closed for months



ST GRAPHICS

By SHARON LOH

A MASSIVE collapse of a Mass Rapid Transit (MRT) construction site yesterday afternoon wrecked a stretch of Nicoll Highway, which will now be closed for many months.

The mid-afternoon accident near the Merdeka Bridge killed one construction worker and injured three others. Three men were missing and feared dead.

By last night it appeared that the accident occurred after a temporary supporting wall for a tunnel of the MRT's Circle Line collapsed.

There might have been more casualties, except that most of the site workers were having their tea break when the tragedy happened.

While completion of the Circle Line now looks likely to be delayed, thousands of commuters must now use alternative routes into and out of the city, and put up with congestion for several months while the highway is repaired.

The volume of traffic disrupted is unprecedented, the Land Transport Authority (LTA) said.

Everything happened very quickly yesterday afternoon.

Thai construction worker Vehakul Somchia, 28, was bringing tools down to the site at about 3.30pm when he saw a crane and wall collapse.

He dumped his tools and ran.

"I just knew that I must get off this bridge or I would fall in and die," he said. "When the crane sank into the ground there was a man inside."

Within minutes, the surrounding area caved in, leaving a gaping ravine 30m deep strewn with twisted steel beams, rubble, cranes and excavators.

Motorists ground to a halt in time, as a 100m stretch of the highway collapsed.

Home Affairs Minister Wong Kan Seng arrived at the scene and assured the public: "There is no indication that this is foul play."

Transport Minister Yeo Cheow Tong, who came in the late afternoon, said the surrounding buildings were safe, and the top priority now was the search and rescue operations, involving some 75 firefighters and rescue dogs.

'THERE IS NO INDICATION THAT THIS IS FOUL PLAY.'
— Home Affairs Minister Wong Kan Seng

'JUDGING FROM THE SCALE OF THE IMPACT, IT WILL BE MANY MONTHS BEFORE WE CAN OPEN THE HIGHWAY.'
— Transport Minister Yeo Cheow Tong

The body of a Malaysian crane operator in his 40s, Mr Vadivil Nadason, was brought out at 6.15pm, while search teams worked on to find three others believed to have been driving machinery at the bottom of the site when the wall came down.

Three others were injured and taken to hospital. Two were later discharged from Tan Tock Seng Hospital — an Indian national, 25, and a Singaporean, 47, both with leg injuries.

A Thai worker, 21, with head injuries is still at the Singapore General Hospital.

Even as curious onlookers crowded the area, police cordoned off Merdeka Bridge and sealed all roads leading to Nicoll Highway.

The impact of the accident was felt far and wide.

As Nicoll Highway sank, gas, water and electricity cables snapped, causing power to go out for about 15,000 people and 700 businesses in the Marina and Suntec area.

Tenants and residents in the Golden Mile Complex, near the collapsed stretch, were also evacuated.

Several callers to The Straits Times said they heard an explosion, while others reported blackouts.

Though some eyewitnesses said they saw flames flash across Nicoll Highway, the LTA said it had no evidence of an explosion.

When leaking gas was detected, Power Gas shut off the supply to the severed pipe, said Mr Rajan Krishnan, LTA's director of projects, at a news conference last night.

The loud sound of the collapsing wall "might have sounded like an explosion", he said.

Electricity was restored at 3.50pm.

The huge boom which sounded at 3.30pm sent many office workers scurrying to their windows, to be stunned by what they saw.

From his 19th-floor office at Golden Mile Tower, Mr Vincent Chan, 28, said he heard a loud sound "like a huge aircraft approaching the building".

Rushing to the window, he saw a ball of fire on the far side of Nicoll Highway.

"Then the steel reinforcements lying horizontally across the road started to fall into the hole one by one, like dominoes," he said.

Others ran out of their buildings for safety.

Ms Sirirat, 48, a permanent resident from Thailand, was sewing in her shop on the first floor of the Golden Mile Complex when she heard a loud bang.

"I saw many women running out of their shops," she said. "They said: 'Gas explosion! Run for your life'. So I followed them. I thought it was a bomb."

Speaking to reporters yesterday, the Transport Minister said the LTA would now stabilise the ground and ensure the buildings in the area remained secure.

"Tunnelling has been going on for many years but this has never happened before," he said.

"LTA will do its utmost to repair the damage and the rest of the Circle Line project will continue."

The LTA said it could be six to nine months before Nicoll Highway might be opened again.

[More reports and pictures HOME: H1-H3]

A 30m-deep ravine opened up within minutes of the first collapse, which has initially been blamed on a temporary supporting wall.

Findings as reported in the press

TheStraitsTimes INTERACTIVE

AUG 13, 2004

Readings 'normal 1/2 hour before cave-in'

By Woon Wui Tek

THE day the Circle Line MRT worksite near Nicoll Highway caved in, an automatic system that monitored pressure on its network of support beams was still showing readings at normal ranges, the inquiry panel was told.

According to the man who checked the system, the 3pm readings - the last taken before the 3.30pm collapse - were still below 'trigger values', a point at which there would be cause for concern.

The system was installed onsite and checked regularly by Monosys, a monitoring sub-contractor.

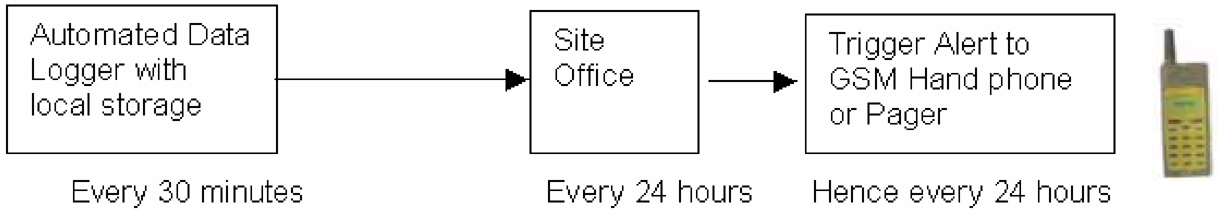
If one of the strain gauges failed to work, no reading would be shown for that beam, only a series of '999'. However, no one would be automatically alerted, he said.

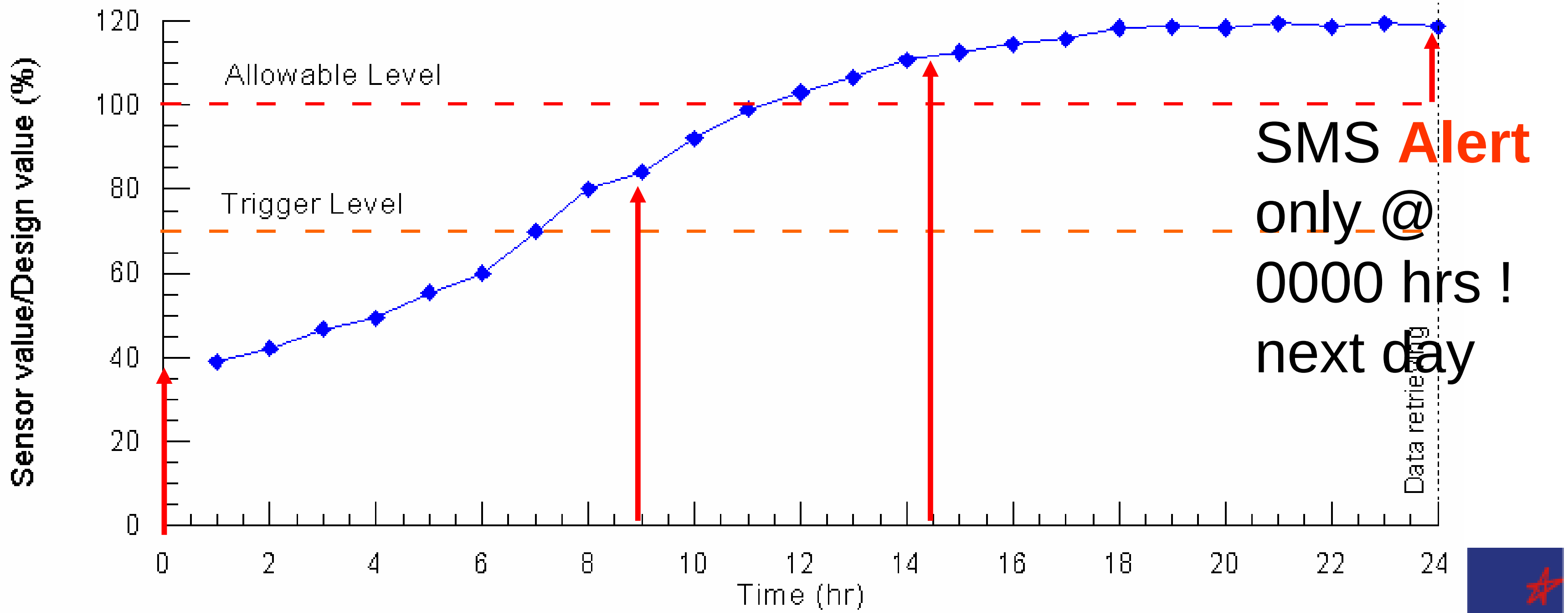
Inquiry panel head Richard Magnus quipped that the 'real time' system operated all day, but 'it can be incorrect real time'.

If, however, the gauges were working and trigger values were exceeded, several people at the LTA and main contractor Nishimatsu-Lum Chang Joint Venture (NLC) would be alerted - but only by an e-mail sent daily.

System installed is NOT a REAL Time Monitoring but rather Real Time Data Logging with once a day email alert !

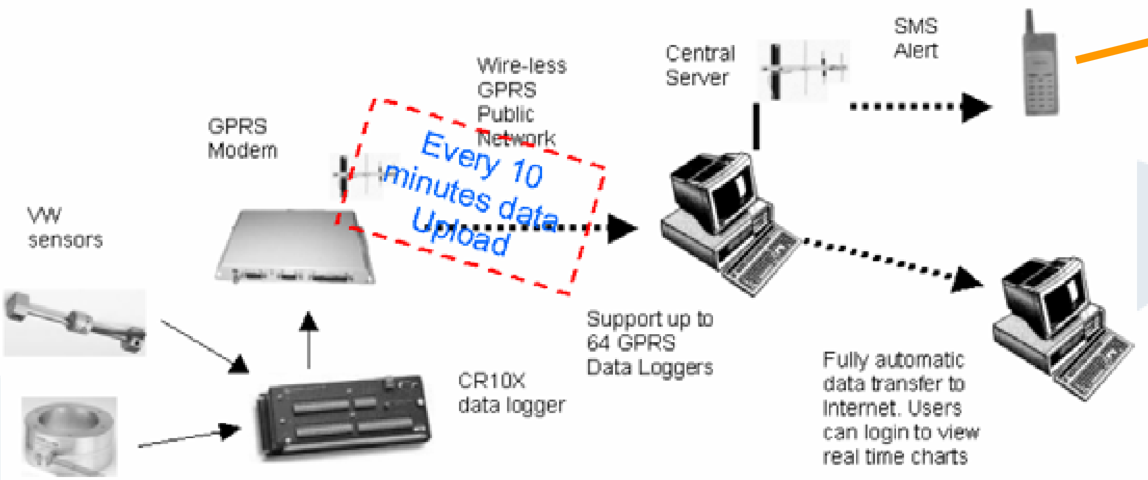
Typically a “Real Time Monitoring System” is **Actually Only Real Time Data Logging !**

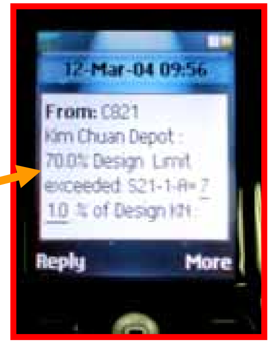




Upload 0000 hrs **Walers buckle** **More Walers buckle**

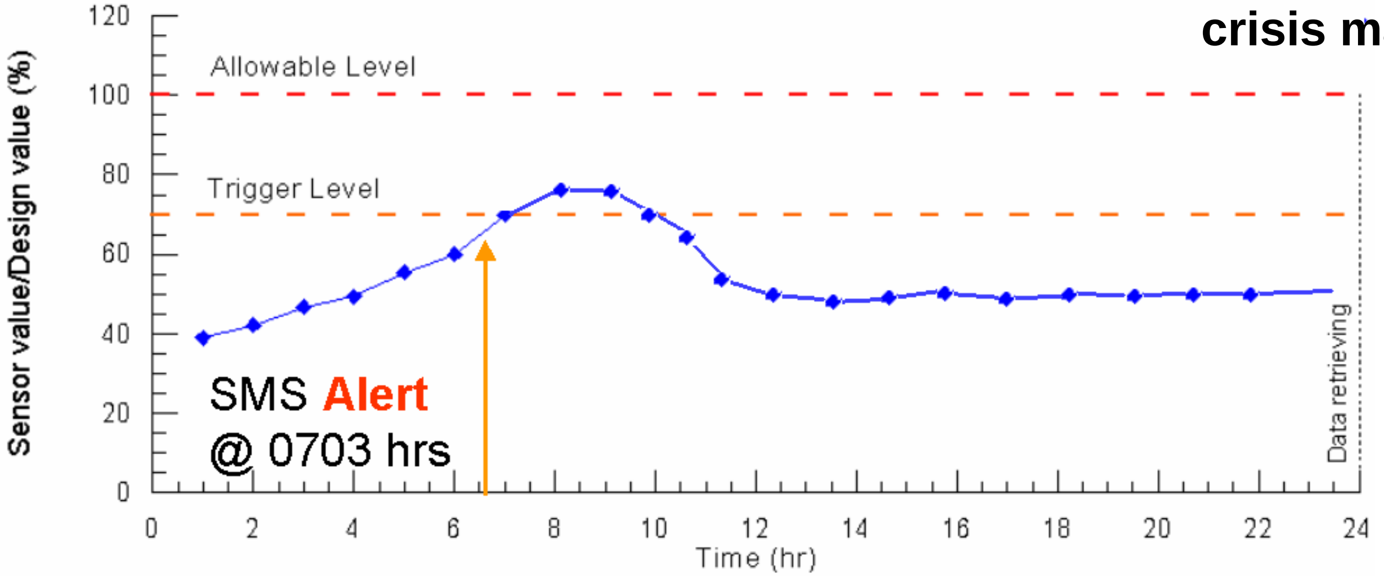
System in Use





SMS Alert

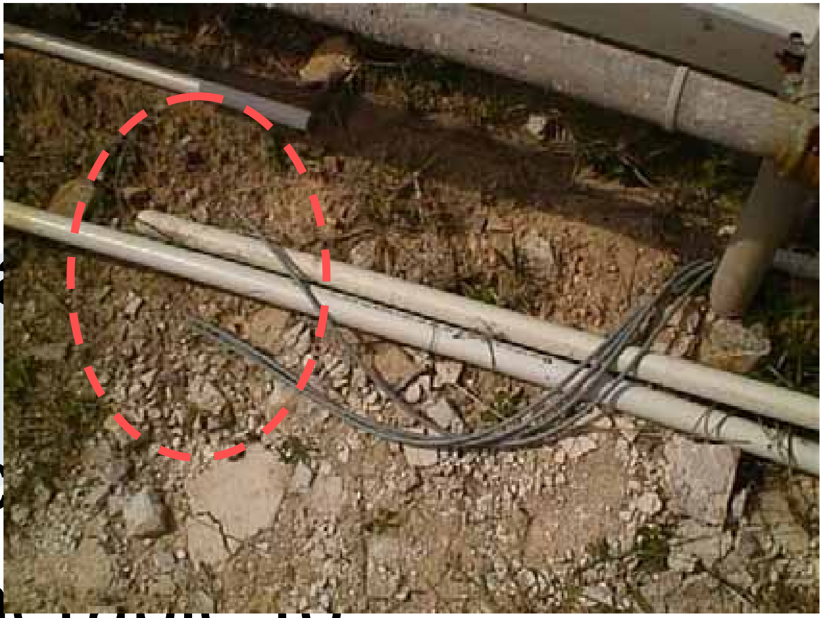
Real Time Monitoring System gives SMS Alerts within 10 minutes,hence earlier reaction time for crisis management



Typical Deployment Scenario

Performance Issues

- Strain gauges are ser
which are wired to or
linked via GPRS to rea
systems that process
send alerts automatic



- Wires/cables are vulnerable to:
  – Damage by construction workers
  – Interferences from electrical sources, welding, etc.
  – Lightning problems

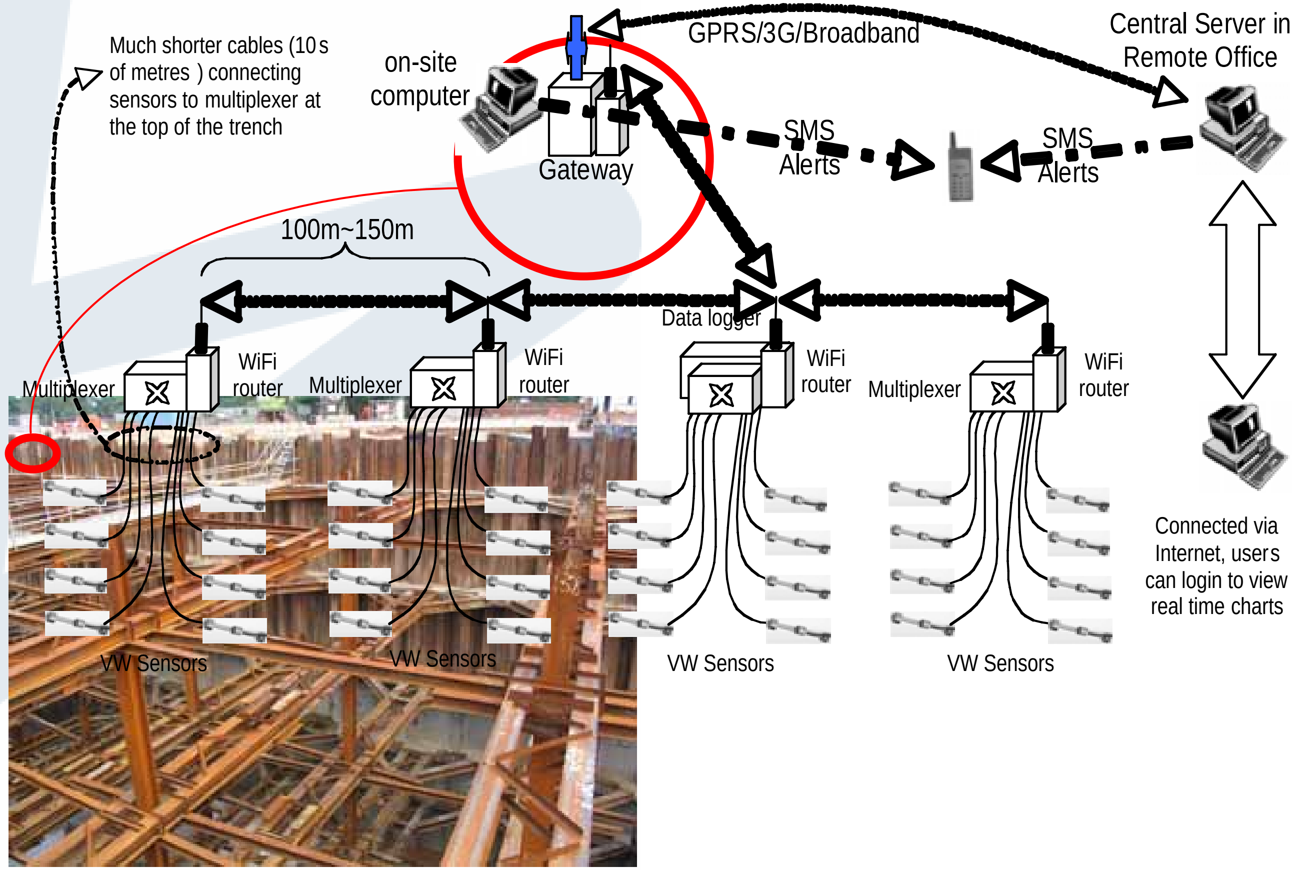
Costs and Deployment Issues

- High (material and labour) costs in laying wires
- Due to physical constraints, e.g. water, deep trough, muddy terrain, etc., laying of wires is extremely difficult → manual monitoring
- Manual monitoring is susceptible to human errors

Wireless Multihop Solution

Objectives:

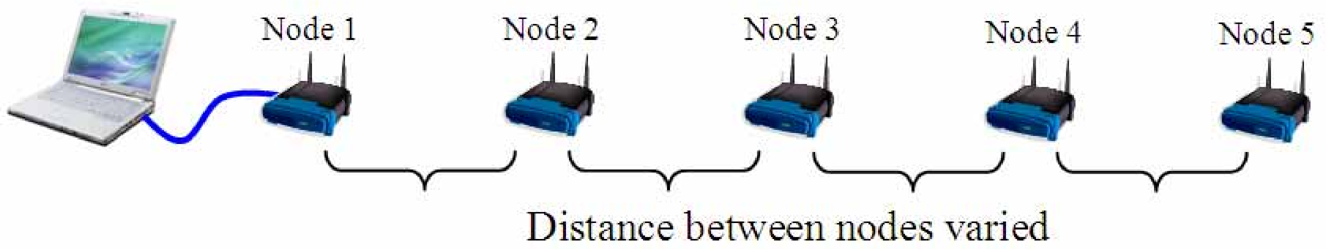
- Design algorithms for WiFi-based multihop routing used in Construction Site Monitoring and Alerts
- Implement prototype and deploy on site for field testing and performance evaluation purposes



Proposed deployment scenario

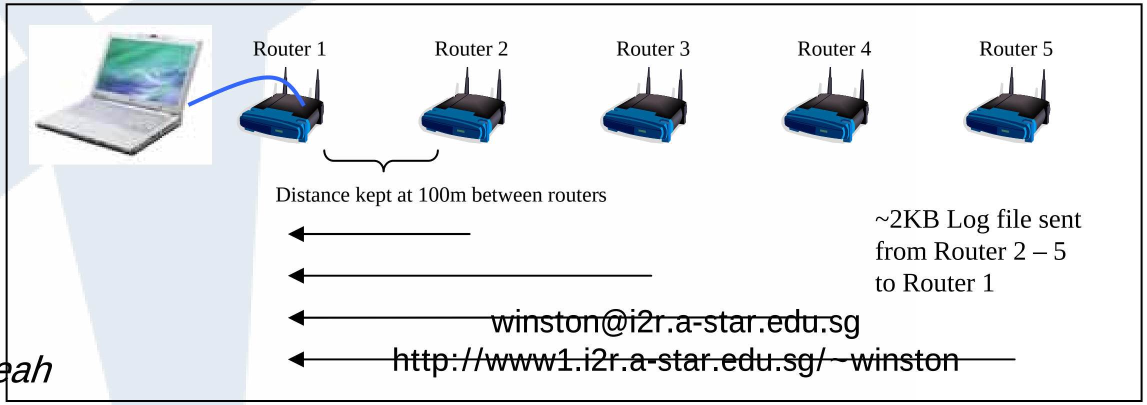
System Setup and Tuning

- COTS WiFi hardware – LinkSys WRT54G
- Vary transmission power (84mW, 79mW, 42mW and 1mW) and data rates (54Mbps, 11Mbps and 2Mbps)
- WiFi has been shown to be most optimal indoors at 76 feet using 79mW
- Goal: determine the optimal transmission range

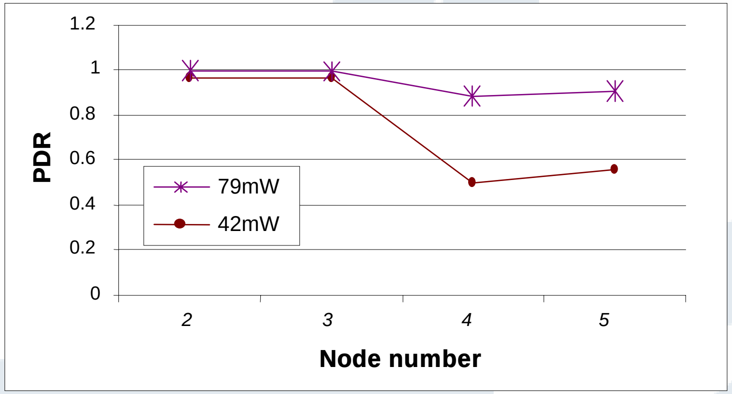


System Setup and Tuning

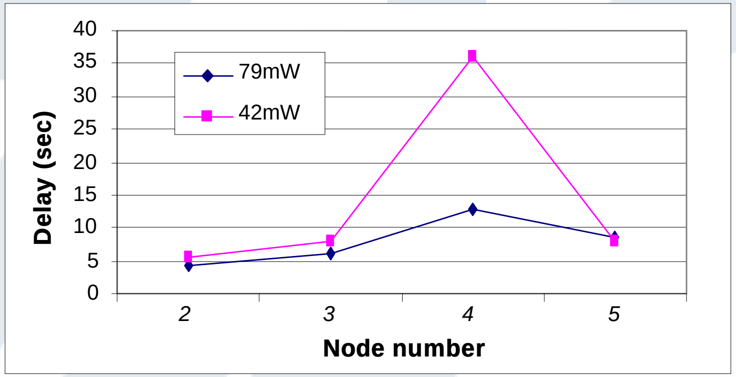
- Open Source Wireless Ad Hoc Routing software (AODV by Uppsala Univ) and Secure Copy Protocol
- 2Kbyte blocks of data are transmitted every 10 minutes from nodes 2, 3, 4 and 5, to node 1 which emulates the gateway node
- Nodes placed 100m apart (similar to the actual deployment scenario), operating at 11Mbps rate
- Two transmission power levels – 79mW (default setting) and 42mW (ensure multihop relaying at 100m internode distance)



Observations (1)



Performance Tuning - PDR

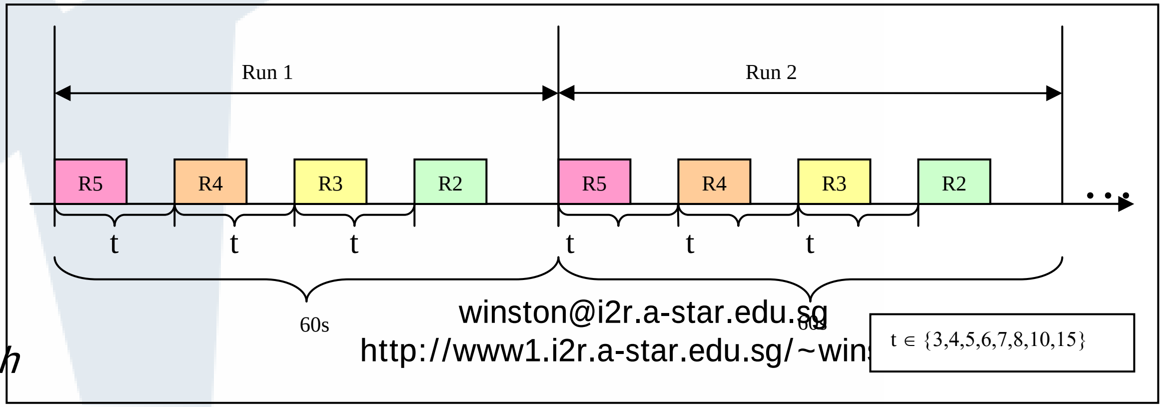


Performance Tuning - Delay

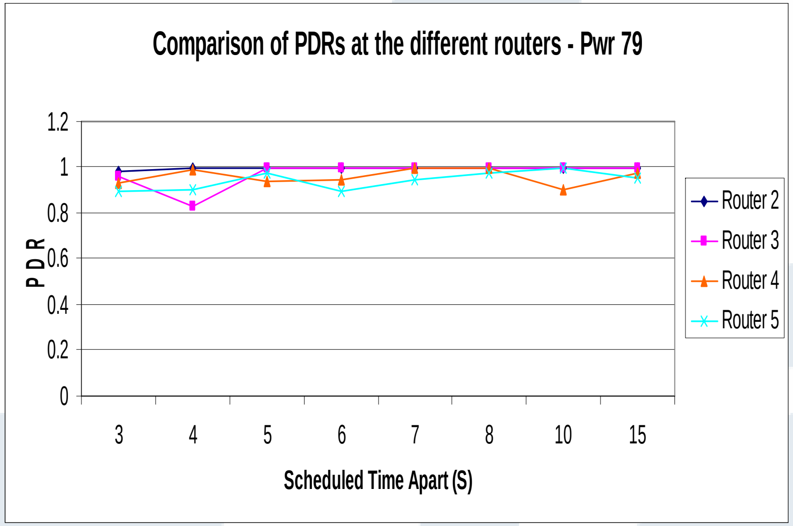
- Nodes *2* and *3* – send all packets directly to the gateway
- Nodes *4* and *5* – AODV route discovery & setup for multihop path may fail due to contention and collisions
- Node *4* needs to compete with nodes *3* and *5* → poorest performance
- Increasing transmission power
  - → higher power consumption
  - → undesirable as on-site devices are solar-powered
  - → Max allowed – 100mW

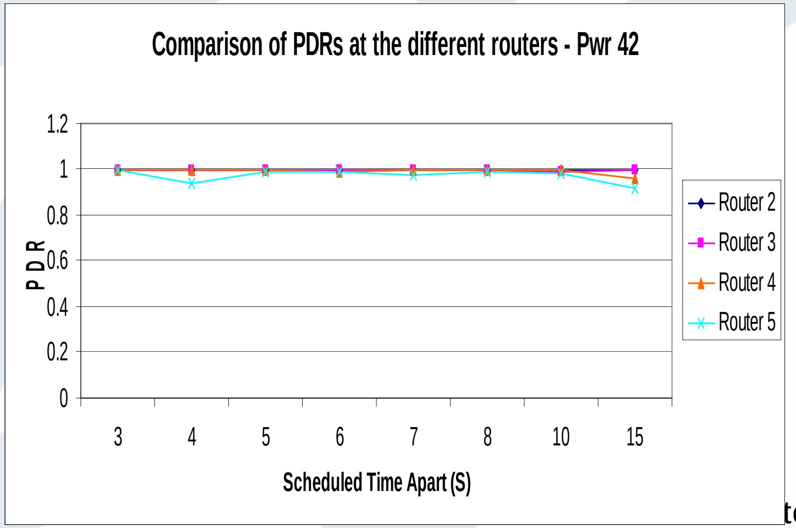
Application Traffic Scheduling

- 2K data every 10min should not cause contention at 11Mbps unless all transmit at the same time
- Channel congestion and inability to establish routes to the gateway → poor performance
- Schedule each node's transmission such that no other nodes within the two-hop topology will transmit at the same time



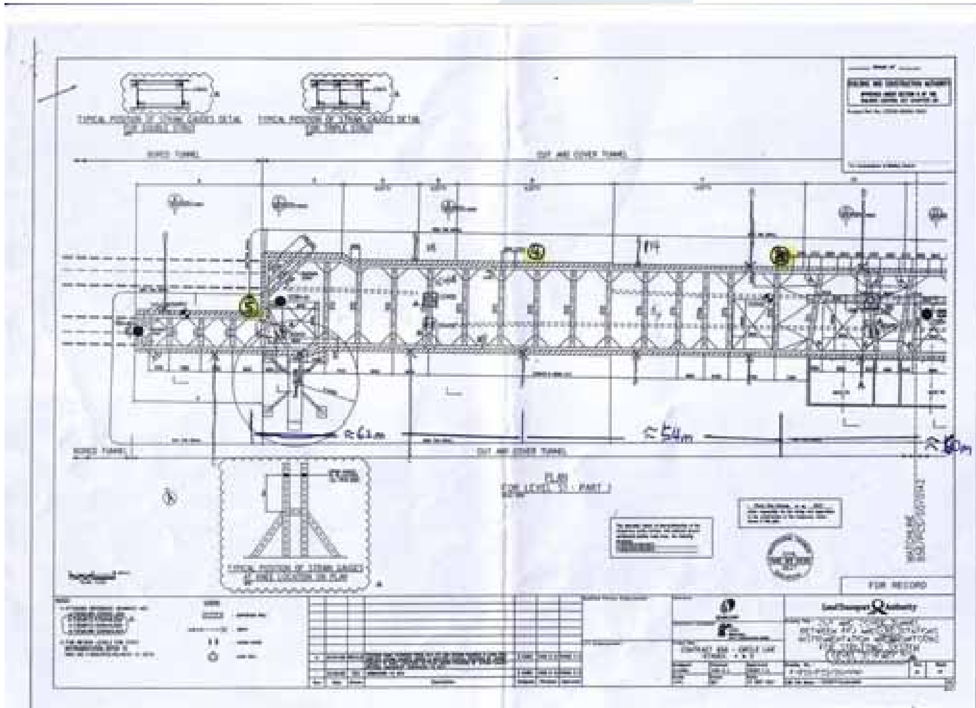
Observations (2)

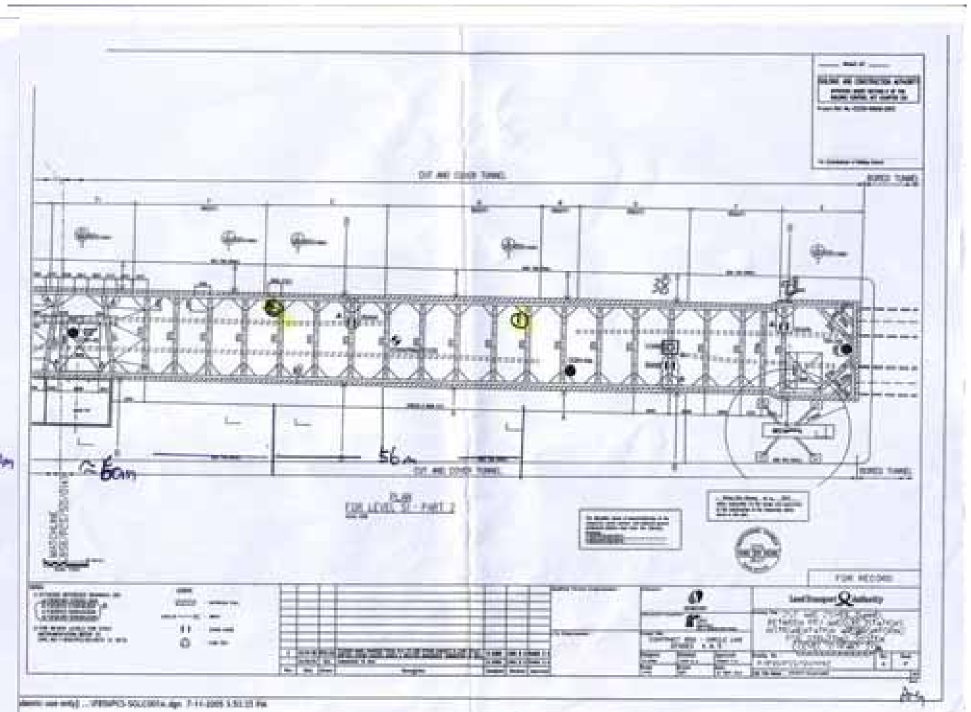




- Best performance occurs when t=8s, PDR > 0.97 at both 79mW and 42mW
- minimum average e2e delay – 5s
- highest data rate achieved is 0.25KB/s or 150KB/10mins

Deployment Site





Deployment Site

- ~300m in length → 5 nodes, 60m apart
- Construction site with numerous metallic structures is a very harsh environment for RF transmission → reduced transmission range
- Temporal/spatial interferences, e.g. welding, blockage from large metal objects, etc.
- Poor location and/or placement can easily result in high packet losses

Router 2 mounted on iron railings (right antenna meddled by passer-by)

Router 3 placed on concrete slab due to unavailability of mounting surfaces.

Router 4 being placed on top of metal box and blocked by aluminium wall.

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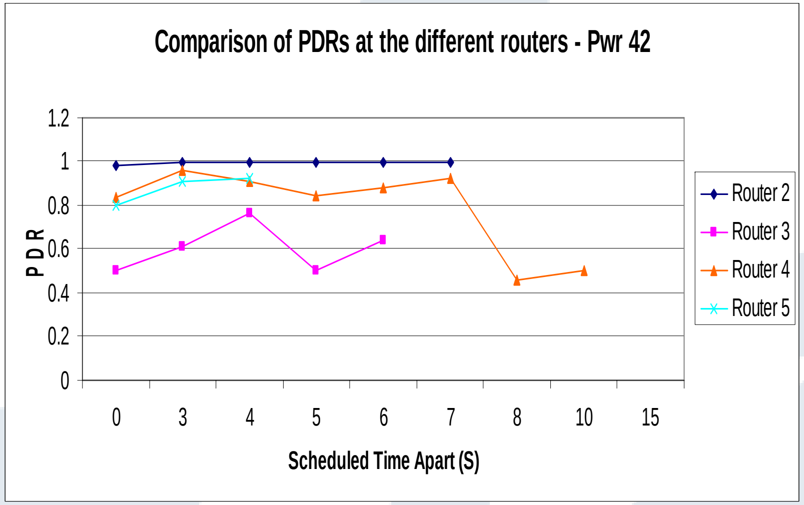
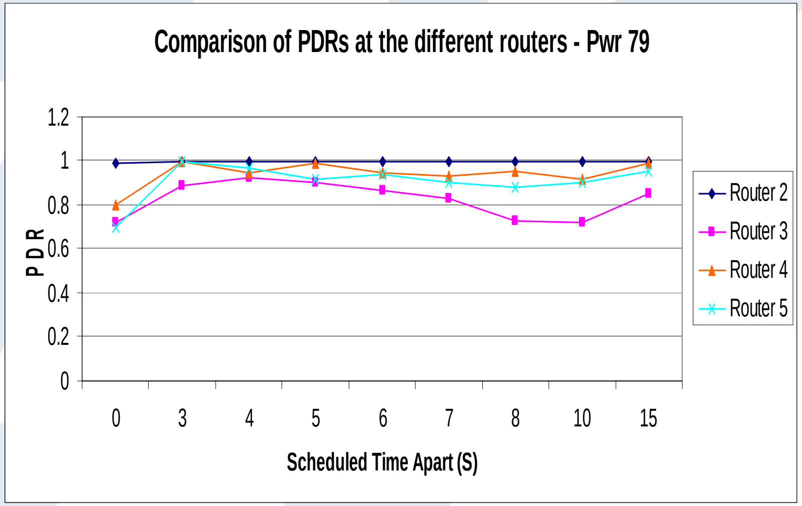
Findings





- What works in a open terrain performed poorly onsite
- Txn power of 42mW was barely enough to maintain the links between nodes
  - → Constant link breakages and route maintenance
  - → Need to use higher txn power, i.e. 79mW
- Nd 3 performed badly because its low lying location with many metal obstructions.

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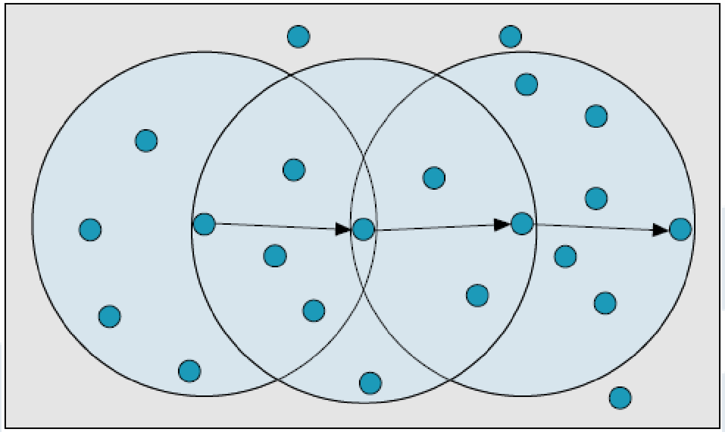
- Application of OR techniques in WSN design
- Reality of wireless communications – case study of a wireless sensor network deployment
- Concluding remarks – Bridging Theory and Reality

Other findings

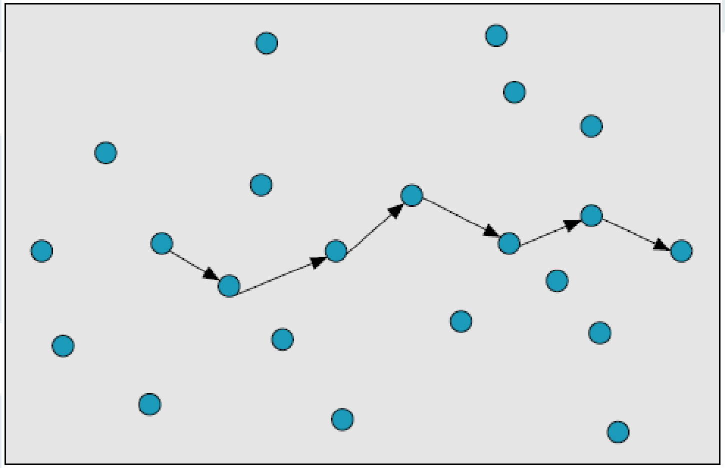
In current wireless communications:

- Heavy reliance on minimum-hop (shortest path) routing → lower received signal strength → poorer link stability and lower data rate.
- Inconsistency between control messaging and data transmission, e.g. RTS/CTS and broadcast packets sent at base (lowest) rate (longest range) → unnecessary exposed terminal problems

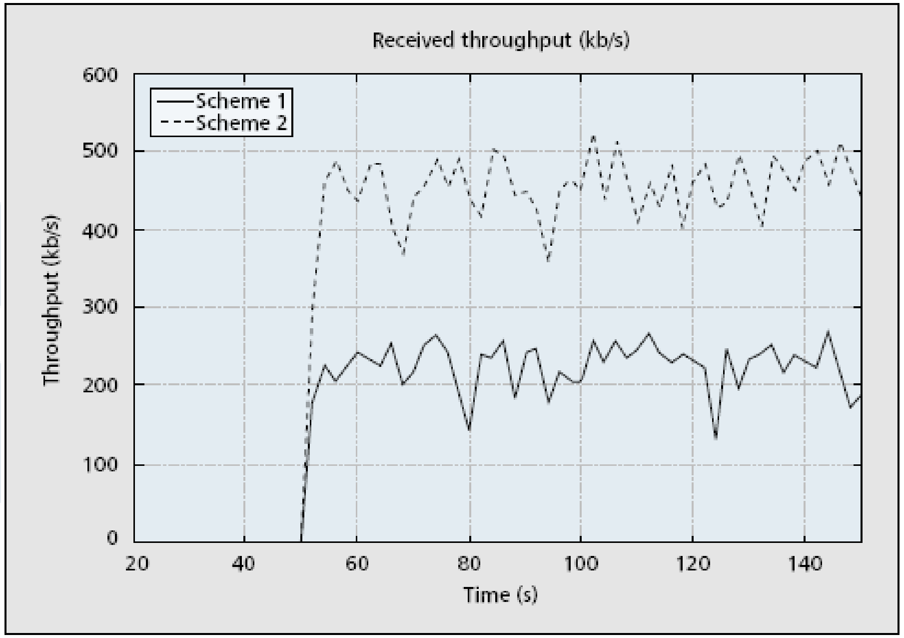
Minimum-Hop Routing is Bad



■ **Figure 5**. *DSDV chooses a small number of long hops, which give a lower data rate when an adaptive rate MAC is used.*



■ **Figure 6**. *Plain IEEE 802.11 causes short hops of higher data rate to be used.*



■ **Figure 7**. *Comparing scheme 1 (adaptive-rate MAC) and scheme 2 (plain IEEE 802.11) for the 18-node linear topology.*

Source: A. Kawadia and P.R. Kumar, "A Cautionary Perspective on Cross-Layer Design", *IEEE Wireless Communications*, Feb 2005.

What next?

- How to make routing protocol choose the best link?
- Static configuration is not viable; must have backup
- Extensive field tests under various environmental conditions, e.g. heavy rain

Thank you.

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