Analysis of Wired Short Cuts in Wireless Sensor Networks

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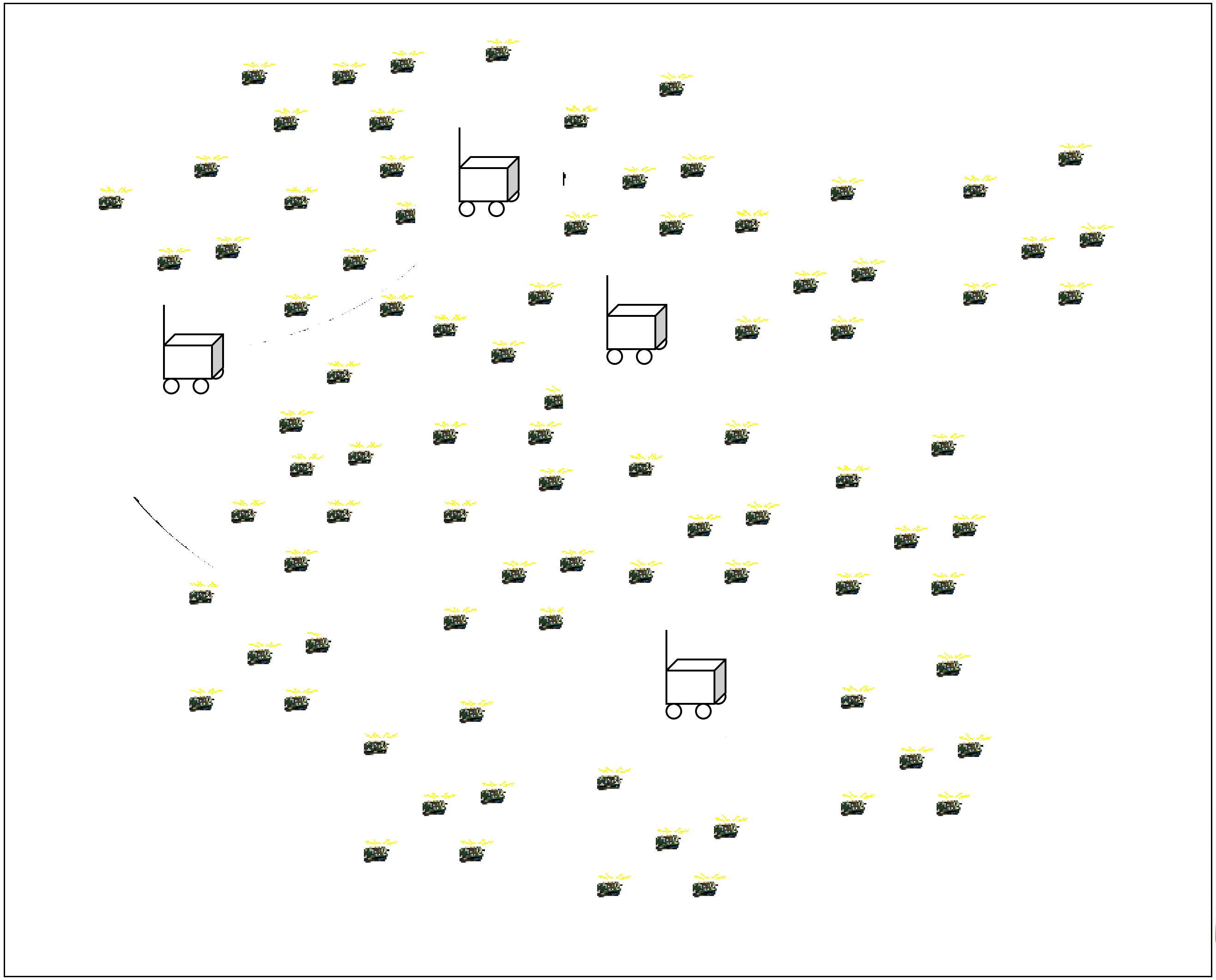
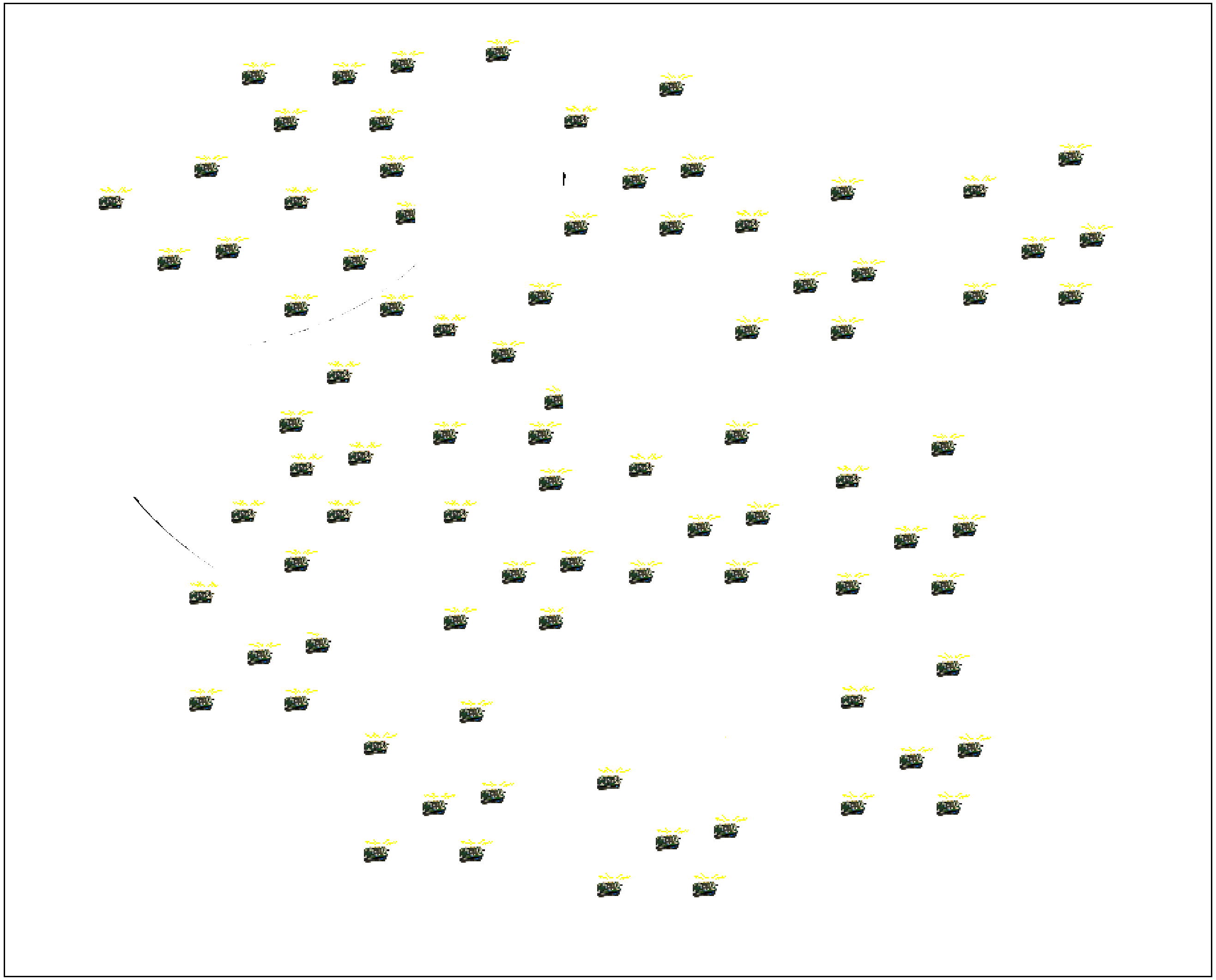
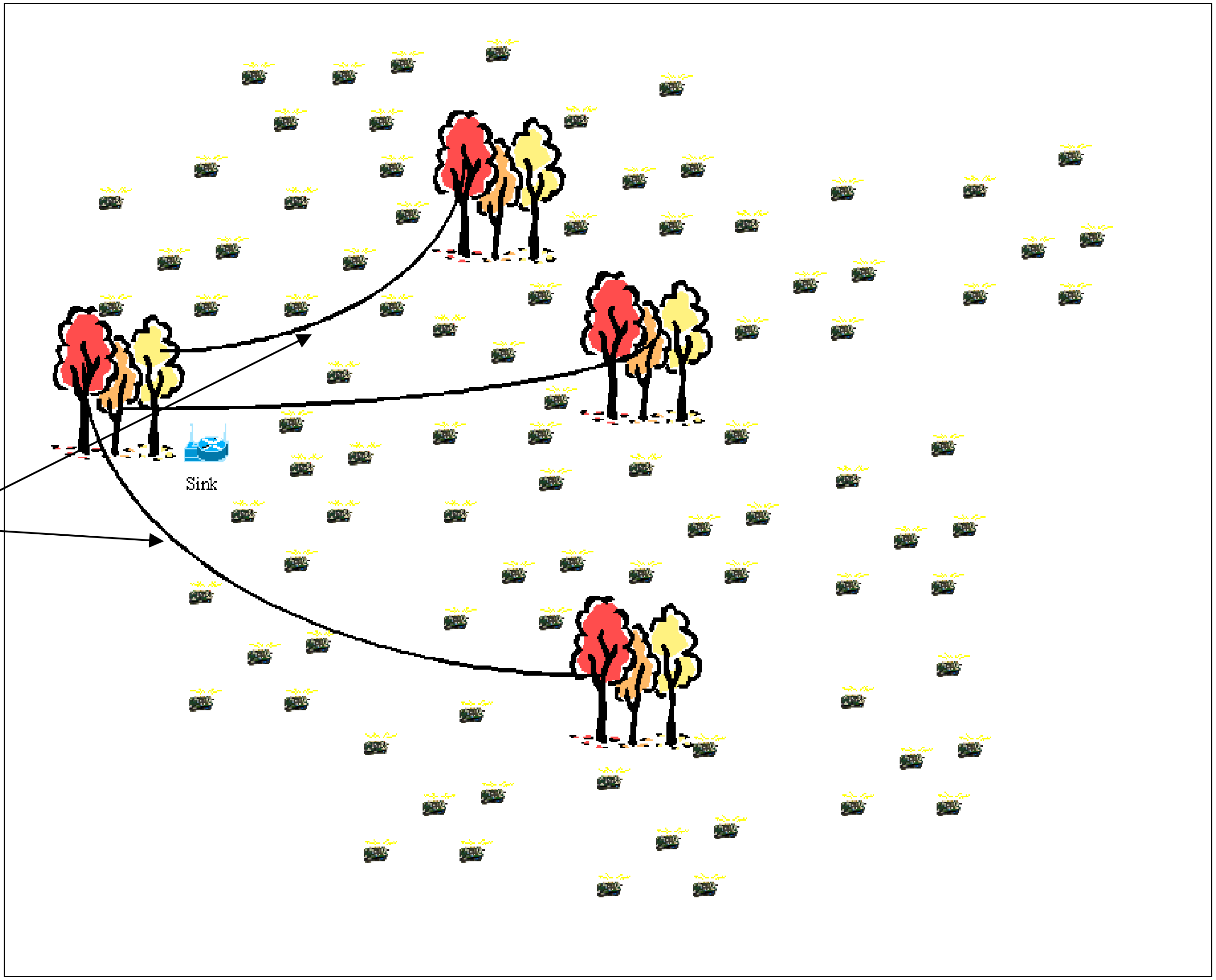


Distributed Wireless Sensor Networks



A. Helmy, “Small Worlds in Wireless Networks”, *IEEE Communications Letters*, October 2003.



Short Cuts

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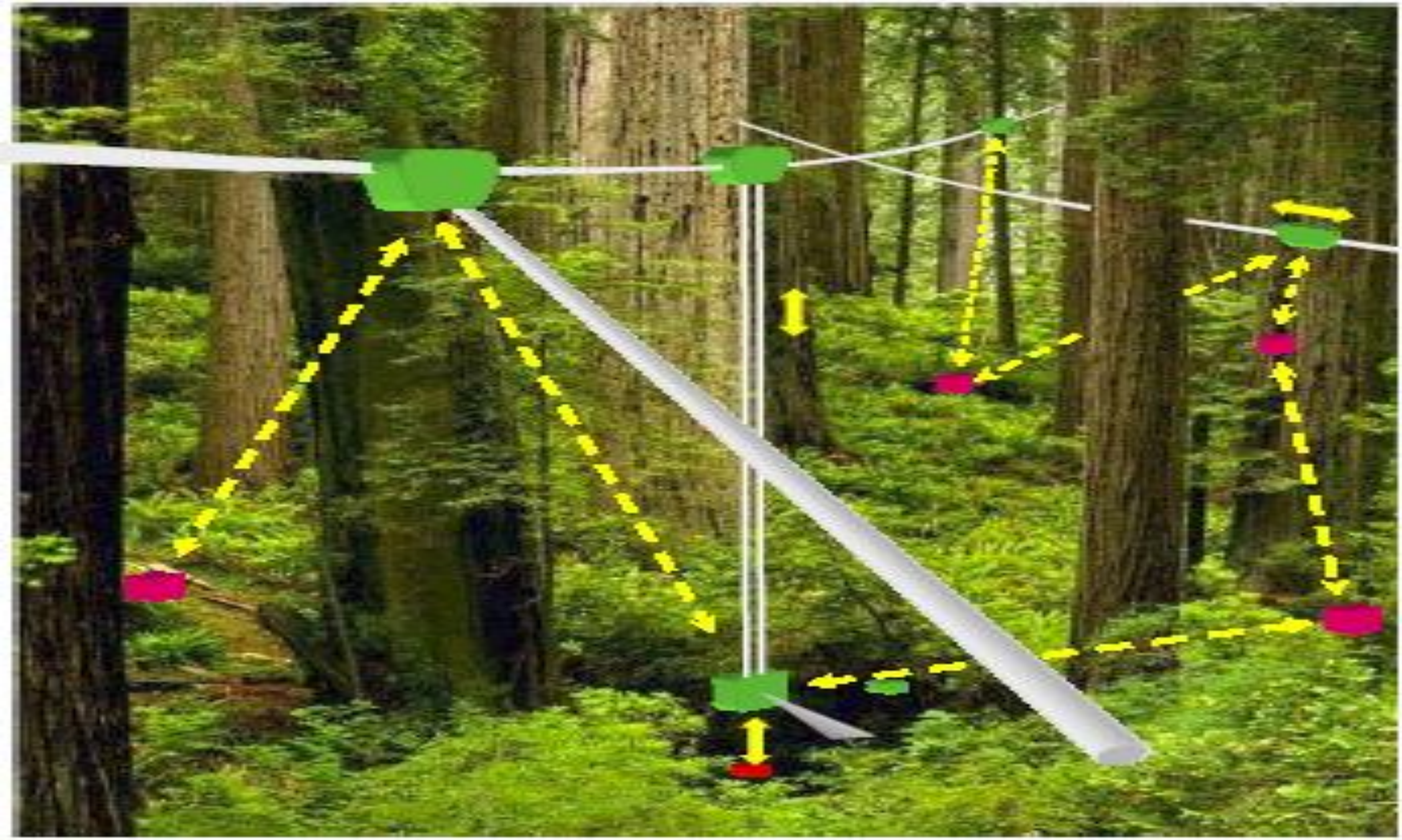


New Paradigm of Augmented Sensor Networks

NIMS Project (UCLA, USC, …)
Networked Infomechanical Systems

Outline

- Problem Statement and Approach
- System Model
  - Network Model
  - Routing Model
  - Analytical Model
- Simulation Setup
- Results and Analysis
- Conclusion and Future Work

Problem Statement

- Investigate the use of wired short cuts in sensor networks
  - Can a few wired short cuts improve the energy efficiency?
  - How can the short cuts extend network lifetime?
  - Can the short cuts change the fundamental limits of sensor networks?

Approach

- Energy efficiency achieved by reducing the path length
- Develop a simple analytical model to quantify the gain to be achieved
- Conduct Simulations to:
  - Validate the results
  - Vary the assumption of the simple model

Context of Wired-Wireless Sensor Networks

- Classes of sensor network applications include
  - habitat monitoring, environmental measurements, etc.
- Some challenges of deployment and operation
  - Limited network lifetime due to unattended operation by power constrained devices
  - Uneven energy consumption due to data collection
  - Uneven distribution of sensor nodes due to rugged terrain
- Potential Solutions
  - Energy efficient routing protocols
  - Mobility of sink or sensors
    - base station repositioning
    - using mobility to improve capacity
- Using mobility on a rugged terrain requires complex robotics which can be equally (or more) challenging !!

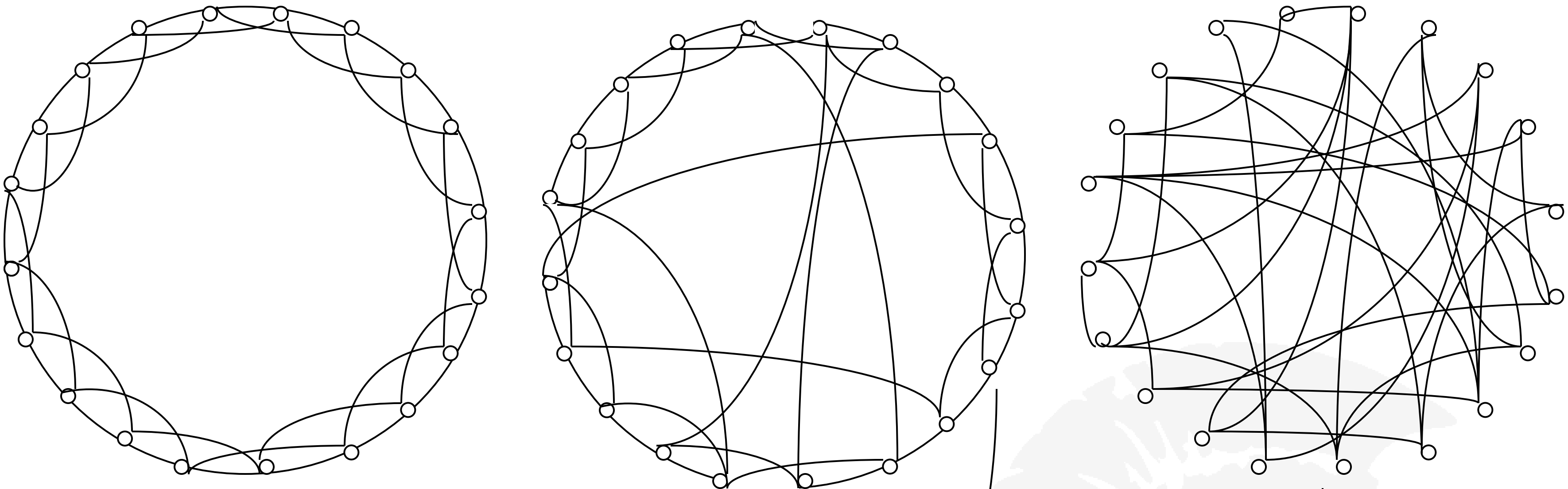
Wired-Wireless Sensor Networks: A New Paradigm

- In *some* scenarios it may be possible to instrument parts of the sensed field with cable-ways/wires (e.g., forests)
  - where the duration of deployment is long enough to make it feasible and practical
- Wires may be used for
  - Communication and data transmission
  - Support of simple robotics
  - Replenishing and deployment of new sensors
- But ...
  - How many wires should be installed and in what fashion?
  - What is the impact of those wires on the network performance?

The *Small World* Model

- In relational graphs:
  - It has been observed that by adding only few random links, average path length can be reduced drastically [Watts '98]
- In spatial graphs (e.g. wireless networks):
  - It has been shown that by adding limited length short cuts the average path length is reduced drastically [Helmy '03]
- The *Small world* model has been used to develop logical *contacts* to help in efficient resource discovery [Helmy '02, '03]

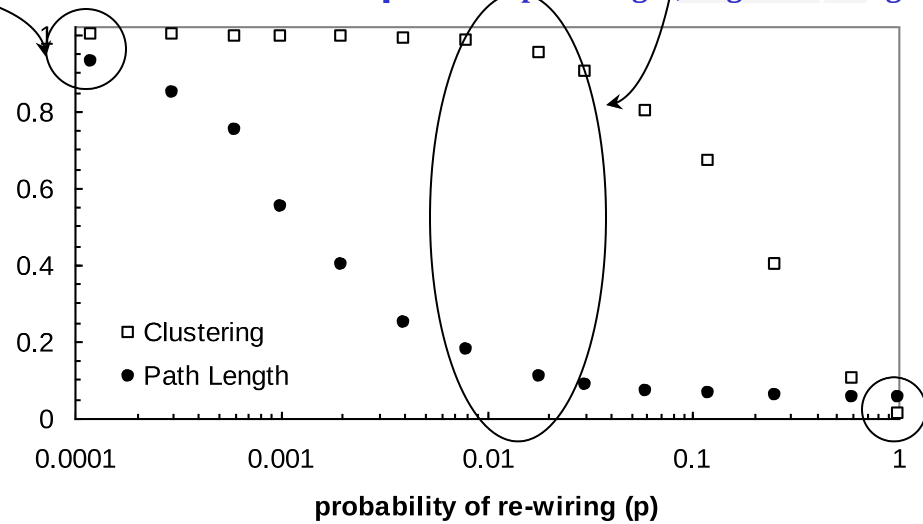
- Here we exploit the use of wires as physical contacts



Regular Graph
- High path length
- High clustering

Small World Graph: **Low path length, High clustering**

Random Graph
- Low path length,
- Low clustering



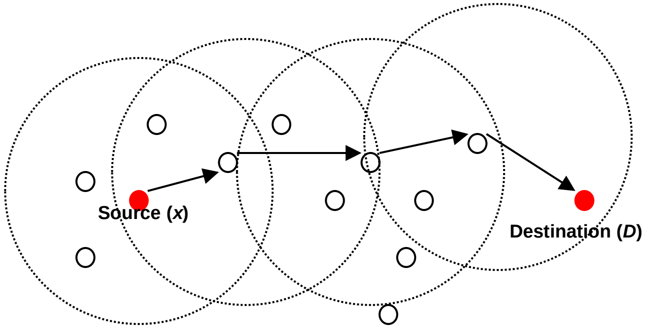
- In *Small Worlds*, a few *short cuts* contract the diameter (i.e., path length) of a regular graph to resemble diameter of a random graph without affecting the graph structure (i.e., clustering)

System Model: Assumptions & Limitations

- Network Model
  - Disk shaped topology
  - Sensor network with single sink, placed anywhere in the network
  - Uniformly distributed nodes, uniform traffic to/from the sink
- Wire Model
  - Wires are of equal length
  - One end of each wire is one hop from the sink
  - Other ends of the wires are equidistant on an arc centered at the sink
- Routing Model
  - Geographic based routing
  - Modified greedy geographic routing
    - Forwarding based on geographic location of neighbors and destination
    - Decision of whether or not to use the a wire is based on distance to the destination through the known wires

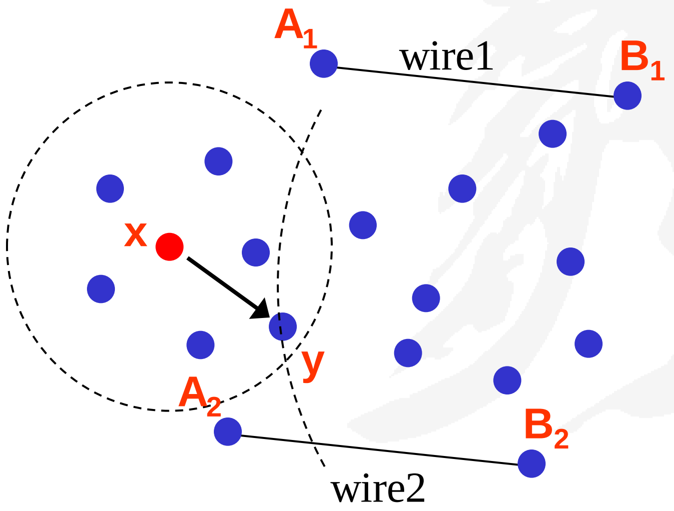
Greedy Geographic Routing

- A node knows its location and the locations of its neighbors
- A node *x* sending a packet to node *D* (the destination) would need to know *D*'s location
- The destination's location is included in the packet header
- Forwarding decision is taken based on local information
- Next hop is chosen to get packet closest to destination



Modified Greedy Geographic Routing

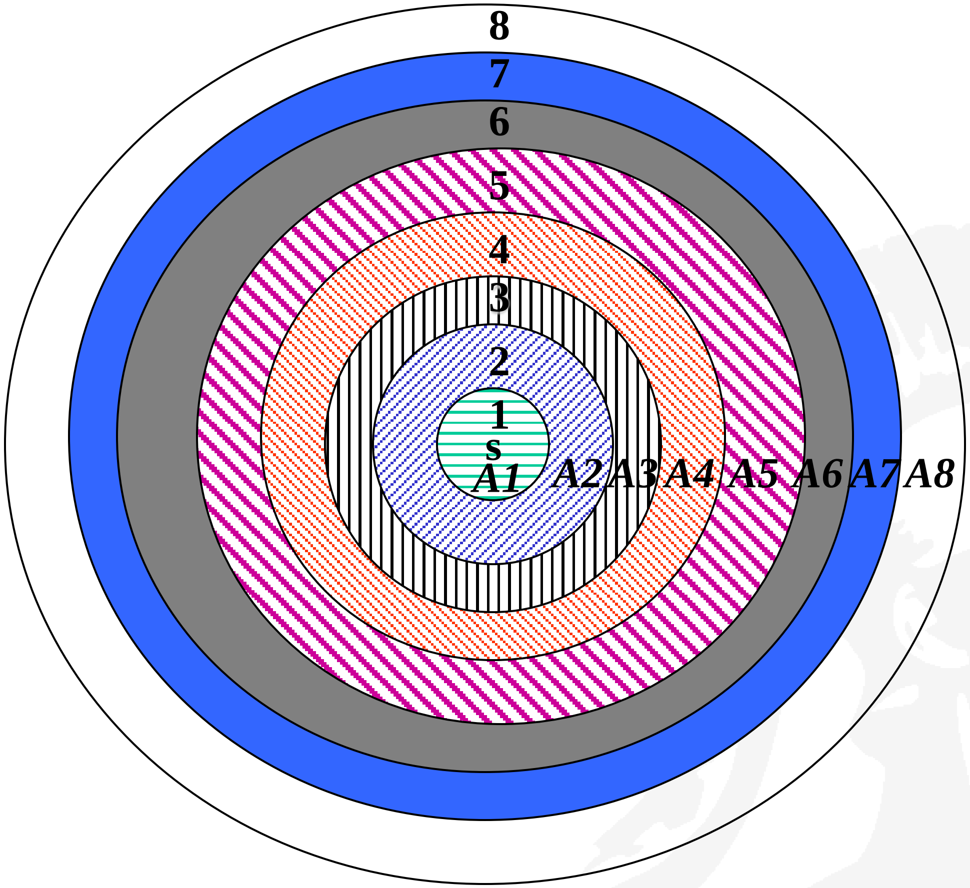
- Node *x* sending a packet to node *D* knows locations of wire1 (A_1,B_1) and wire2 (A_2,B_2)
- Let *d(a,b)* be the Euclidean distance between *a* and *b*
- *x* calculates min($d(x,A_i)+d(B_i,D)$ $\forall i$, $d(x,D)$) and decides the shortest Euclidean path accordingly



System Model (contd.)

- Two information models considered
  - 1) Nodes have information of all the wires
  - 2) Each wired node propagates its reachability to *k* hops
- Energy efficiency obtained by reducing the average path length
- Evaluation Metric:
  - Let $\ell(0)$ be the average path length (in hops) when no wires are used
  - Let $\ell(i)$ be the average path length when wires of length i are used
  - Define the Path Length Ratio $PLR(i)$
    - $PLR(i) = \ell(i)/\ell(0)$

Analytical Model: No wires



Average path length (in hops) for a pure wireless disk network (sink in center)

Ring hop *x* Ring area = $\Sigma i.Ai$

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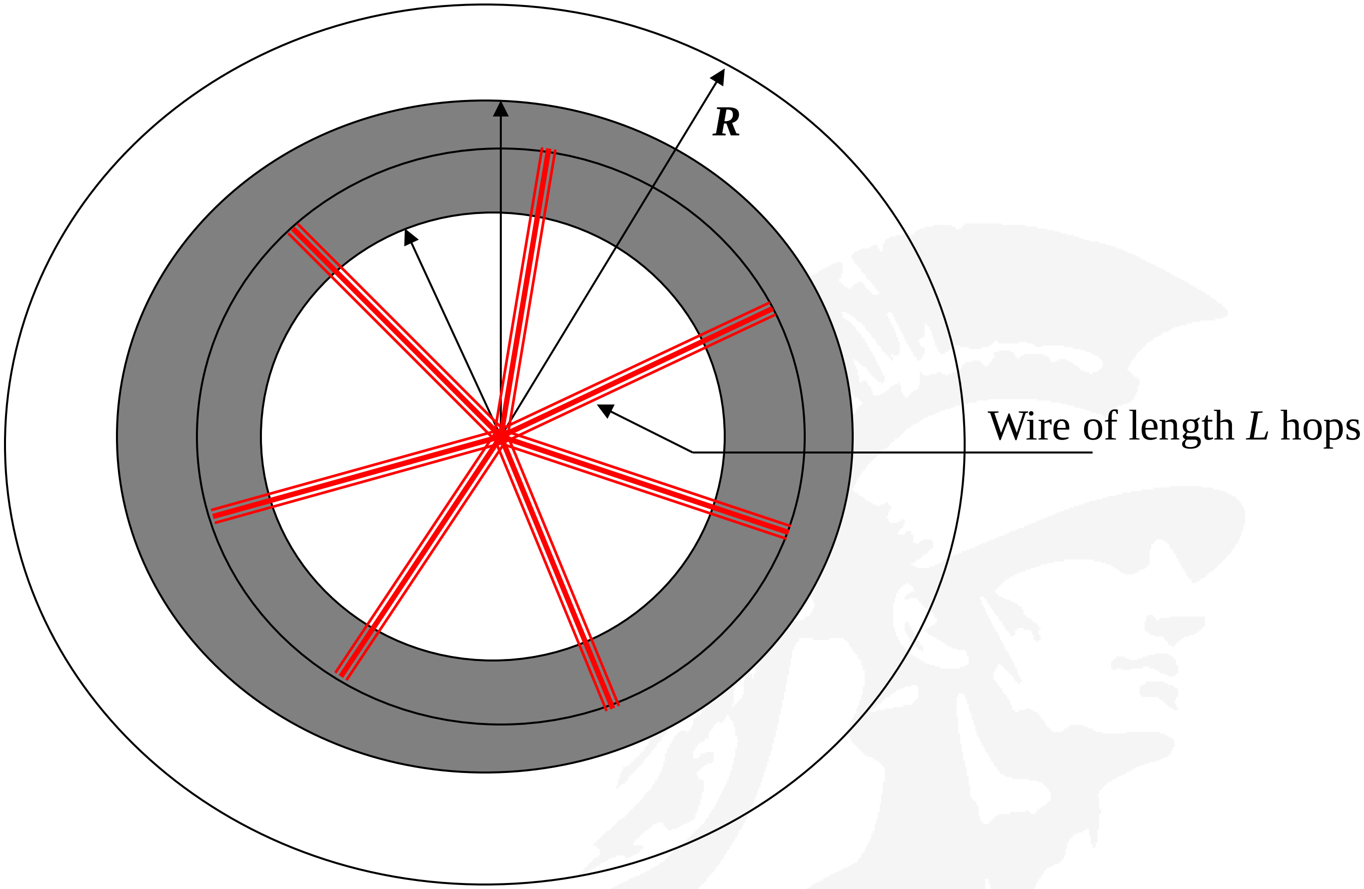
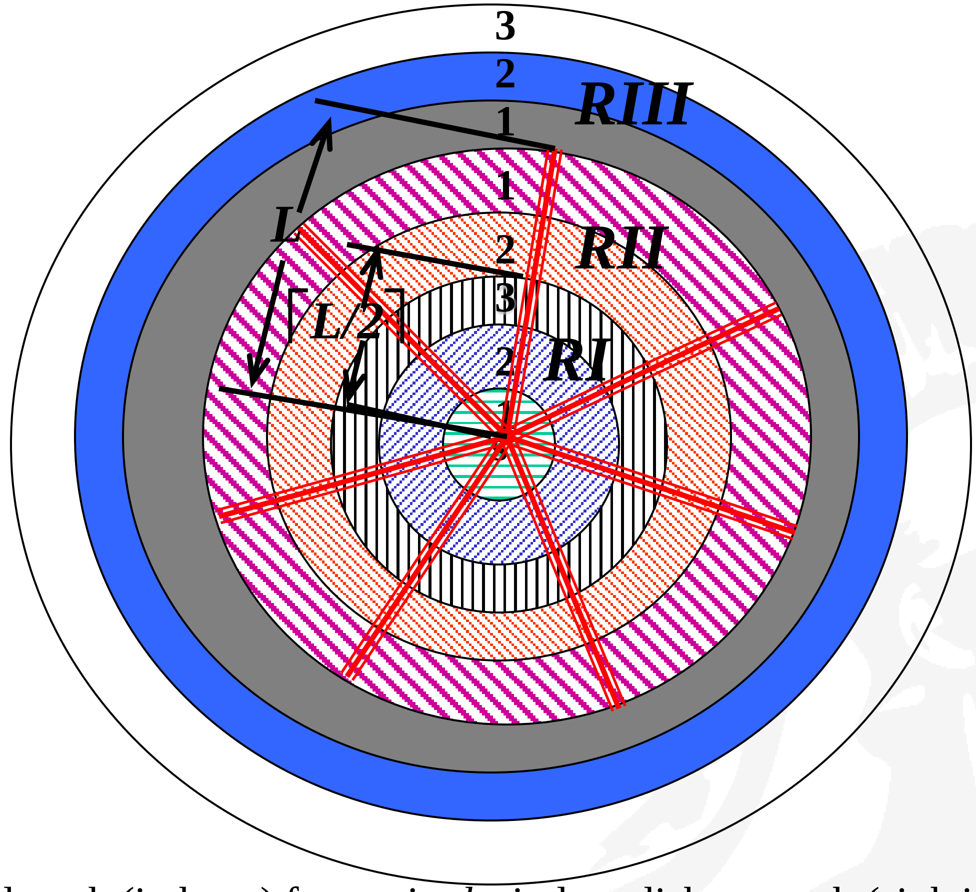
Analytical Model: With Wires



All nodes in grey area can reach wire end in 1 hop. Nodes have information of all wires. Infinite number of wires.

Analytical Model

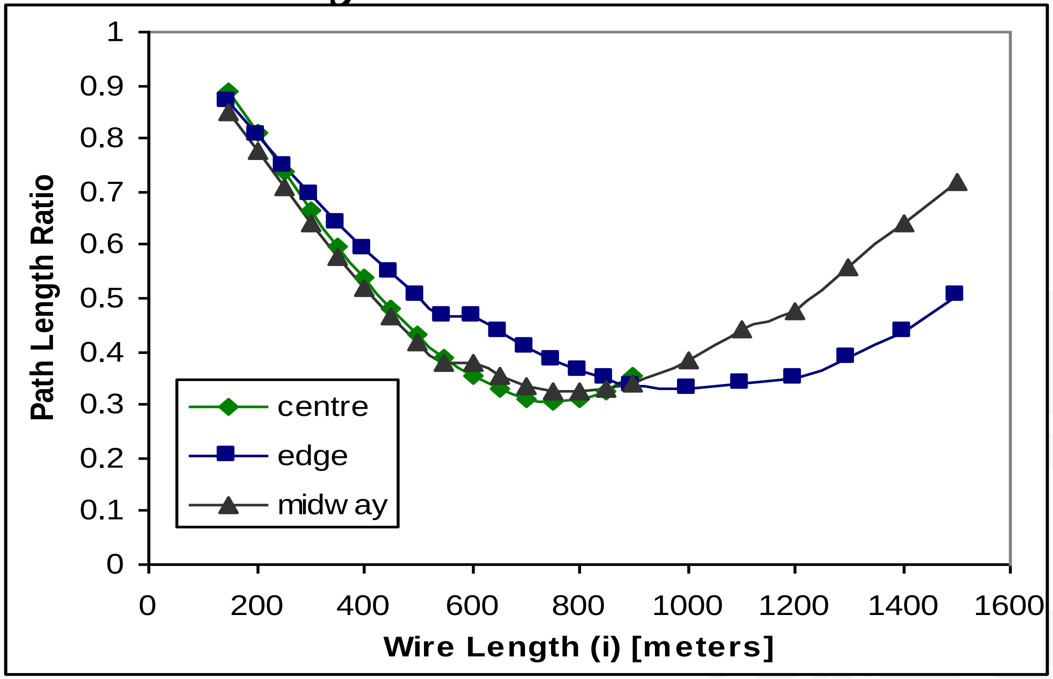


Average path length (in hops) for a *wired* wireless disk network (sink in center)

$\Sigma i.A_i$ + $\Sigma(L+1-i).A_i$ + $\Sigma(i-L).A_i$

RI $(0<i\leq\lceil L/2\rceil)$ **RII** $(\lceil L/2\rceil<i\leq L)$ **RIII** $(L<i\leq R)$

Analytical Results



Path length ratio obtained for the analytical model

- The path length ratio (*PLR*) decreases rapidly with increase in the wire length up to a point, after which the path length *increases*
  - Path length ratio reaches 0.5 for wire length of 0.4R
  - For sink placed at edge: we get minimum *PLR* for wire length of *R*
  - For sink placed at center: we get min *PLR* for wire length of 0.75 *R*

Simulation Setup and Experiments

- Simulation Parameters
  - Nodes N=1000, uniformly distributed
  - Radius R=1000m
  - radio range r =55m
- Dimensions investigated
  - Varying the number of wires
  - Varying the length of the wires
  - Varying the position of the sink
  - Limiting the information about wires locations to nodes k hops from the wire end

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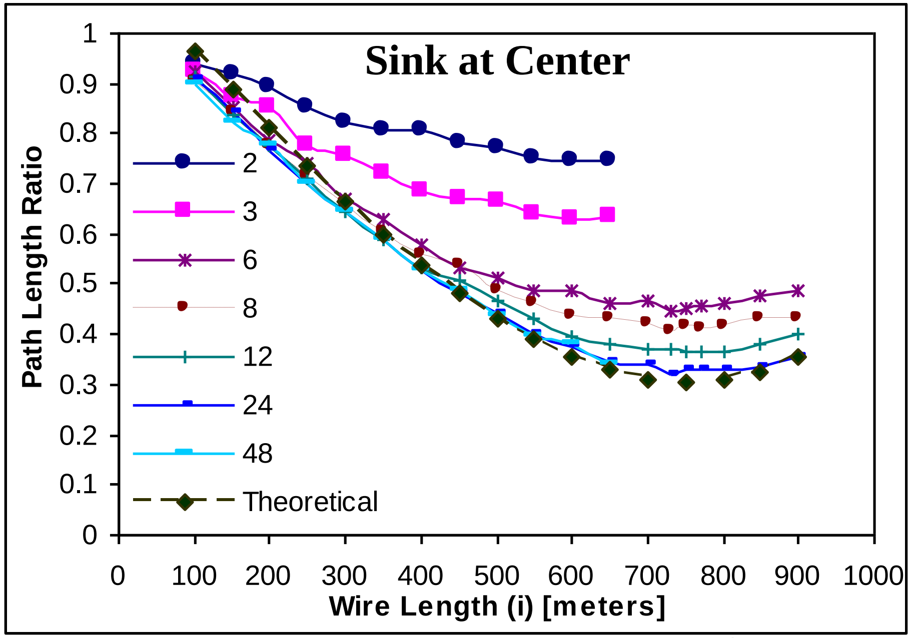
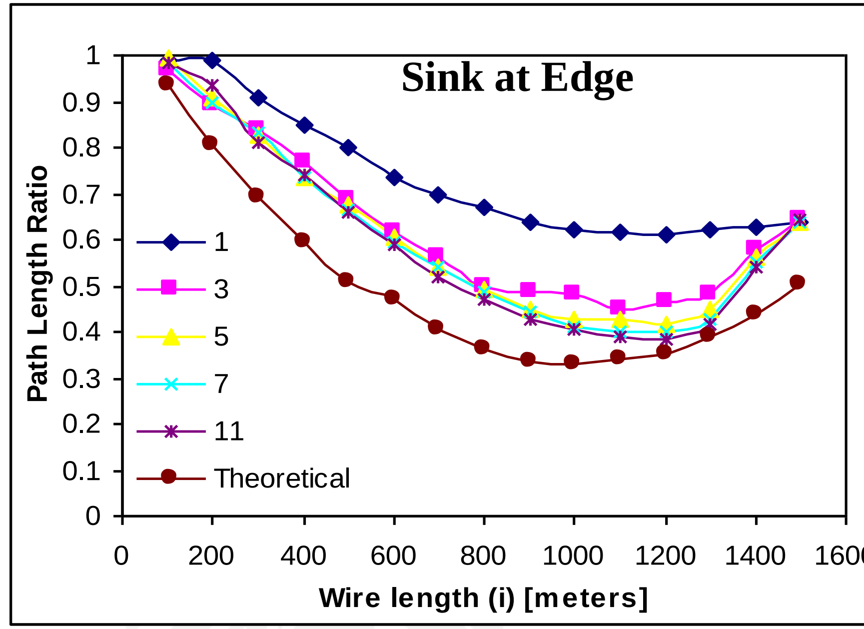
Simulation Results: Number of Wires



Path length ratio with Varying number of wires



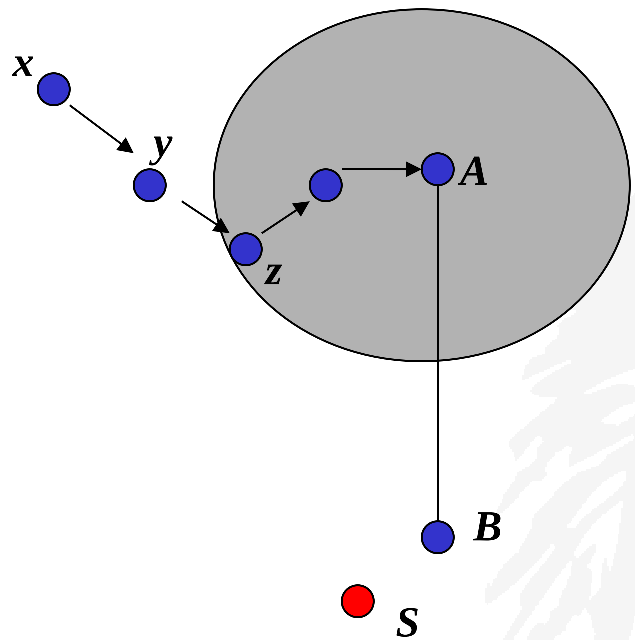
Path length ratio with Varying number of wires

Sink at Center:
- Gain Saturation at 24 wires
- Max gain (*PLR*~30%) is obtained at 0.75 *R* wire length
- 6 wires give *PLR* ~ 40% by having wires of 0.75 *R* in length

Sink at Edge:
- Gain Saturation at 5 wires
- Maximum gain (PLR~40%) is obtained at ~*R* wire length

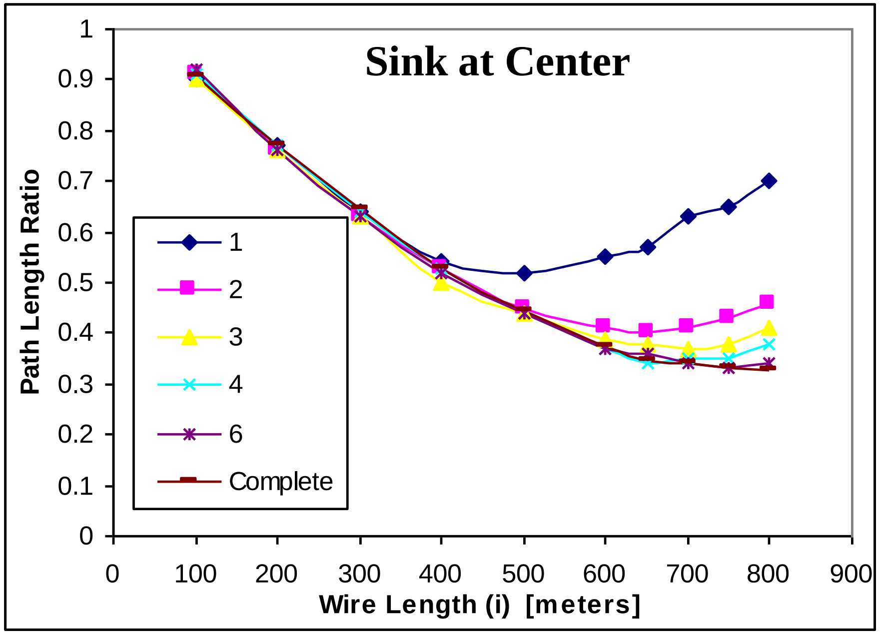
Adding 5-6 wires can provide up to 60% reduction in average path length

Routing decision when wire information is restricted to *k* hops from the wire

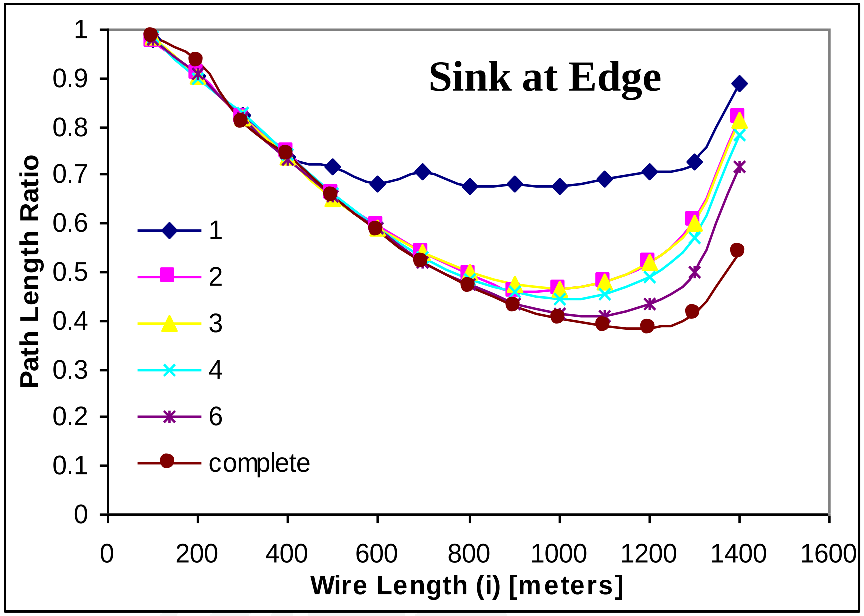


S*: sink, *A*-*B* is the wire of length ℓ, Nodes in shaded region know about the wire *A*-*B*. Node *x* uses wireless to reach *S*. Node *y* sends packet to *z* that knows about the wire. The packet is then forwarded to *A* and over the wire to *B* then to *S

Simulation Results: Wire Information



Effect of limiting the wire information to k hops.
k is varied from 1-6 (with 24 wires)



Effect of restricting wire information to k hops.
k is varied from 1-6 (with 5 wires)

k=3hops gives same performance as complete knowledge

k=2hops gives min *PLR* ~45%

Restricting the wire knowledge to 2-3 hops of the ends of the wire gives very good performance

Conclusions

- Introduced a new paradigm of wired-wireless sensor networks
- Developed routing and analytical models for the new paradigm
- Performed extensive simulations to study the new scheme using small worlds to help understand how to allocate wired resources
  - There is an optimal wire length for which the path length ratio is at its minimum, beyond which it *increases*
  - Adding 5-6 wires with 0.75*R* - *R* in length results in reduction of ~60% in average path length
  - Restricting wire information to 2-3 hops does not result in deterioration of performance
- This paradigm promises to decrease average path length drastically
- Does this scheme lead to better energy balance, network lifetime and fundamental limits?

On-going Work and Future Directions

- Energy Balancing and Lifetime of Sensor Networks
- Robots on wires
  - Controlled mobility for balanced communication/energy
  - Uncontrolled predictable scheduled mobility
  - Uncontrolled task-based mobility
- Uneven node and wire distribution
- Fundamental Limits
  - Can wires change the scaling and asymptotic limits of throughput and network lifetime of sensor networks?