Analysis of Wired Short Cuts in Wireless Sensor Networks

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Distributed Wireless Sensor Networks
New Paradigm of Augmented Sensor Networks
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
- 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 $\min(d(x,A_i)+d(B_i,D) \quad \forall i, d(x,D))$ 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 × Ring area = \( \sum i \cdot Ai \)
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)

\[ \sum_i A_i + \sum (L+1-i).A_i + \sum (i-L).A_i \]

RI \ ((0 < i \leq \lceil L/2 \rceil) \quad RII \ ((\lceil L/2 \rceil < i \leq L)) \quad RIII \ (L < i \leq R) \]
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
Simulation Results: 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 $PLR \sim 40\%$ by having wires of 0.75 $R$ in length

Sink at Edge:
- Gain Saturation at 5 wires
- Maximum gain (PLR~40%) is obtained at $\sim R$ 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 $\ell$, 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)

k=3hops gives same performance as complete knowledge

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

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 $0.75R - R$ 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?