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PCP: A Probabilistic Coverage Protocol for Wireless Sensor Networks

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ICNP 07

17 October 2007

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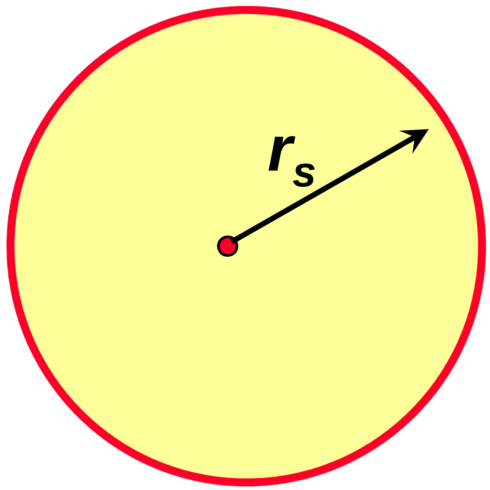
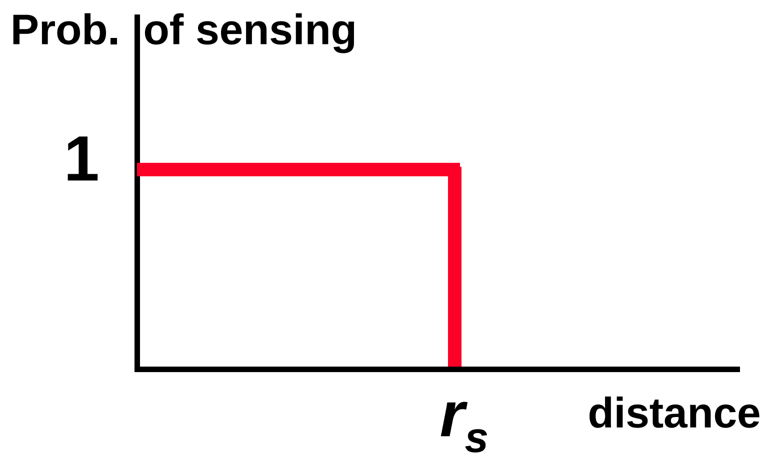
Motivations

- Sensor networks have been proposed for many apps: surveillance, forest fire detection, …
- Common in most apps:
  - Each sensor detects events within its *sensing range*
  - Sensors collaborate to deliver data to processing centre
- Many previous works assume *disk* sensing model





Motivations (cont'd)

- **Why disk sensing model?**
  - Easier to design and analyze coverage protocols

- **What is wrong with it?**
  - Not too realistic [Zou 05, Ahmed 05, Cao 05, …]
  - Wastes sensor capacity: signals don't fall abruptly ➔ chance to detect events after r_s
  - Activates more sensors ➔ more interference, shorter network lifetime
  - Protocols my not function in real environments

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Our Work

- **New coverage protocol for *probabilistic sensing models* (denoted by PCP)**
  - **Simple, energy efficient**
  - **Robust against clock drifts, failures, location inaccuracy**

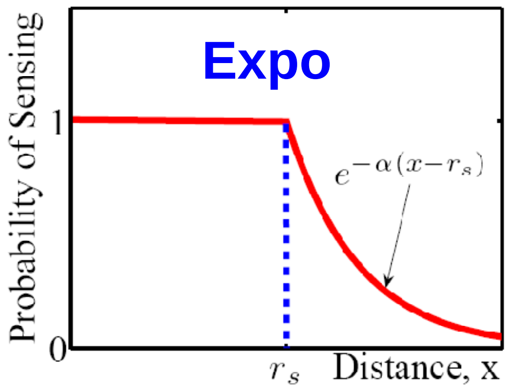
- **One model does not fit all sensor types ➔**
  - **PCP is designed with limited dependence on sensing model ➔ can be used with various sensor types**

- **PCP can use disk sensing model as well**

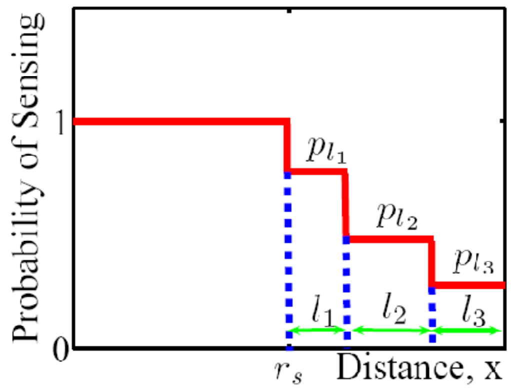
Related Works

- Lots of coverage protocols assuming disk model
  - PEAS [Ye 03], OGDC [Zhang 05], CCP [Xing 05], …
  - We compare PCP (with disk model) vs. OGDC, CCP
- Analysis of probabilistic sensing models
  - [Liu 04] studies implications of adopting prob. models
  - [Lazos 06] analyzes prob. of coverage under general sensing modes and heterogeneous sensors
  - Neither presents distributed coverage protocols
- Coverage protocols using probabilistic models
  - CCANS [Zou 05] assumes exponential sensing model
  - We show that PCP (with expo model) outperforms CCANS by wide margins

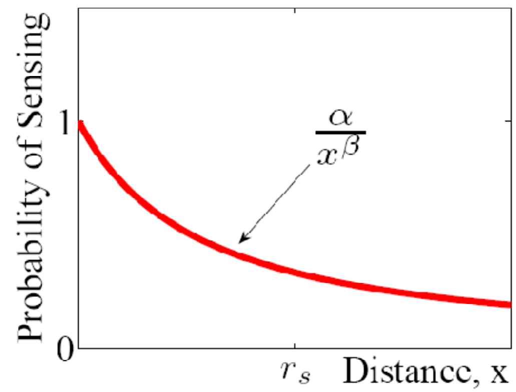
Probabilistic Sensing Models



[Zou 05]



[Ahmed 05]



[Liu 05]

- **Several models have been proposed in literature**
- **Our protocol can work with various models**

Probabilistic Coverage: Definitions

- **Def 1: An area *A* is probabilistically covered with threshold *θ* if for every point *x* in *A*:**

$$P(x) = 1 - \prod_{i=1}^{n} \left(1 - p_i(x)\right) \geq \theta$$

  - **where $p_i(x)$: prob. that sensor *i* detects events at *x***

- **That is, the collective probability of sensing events at *x* by all sensors is at least *θ***

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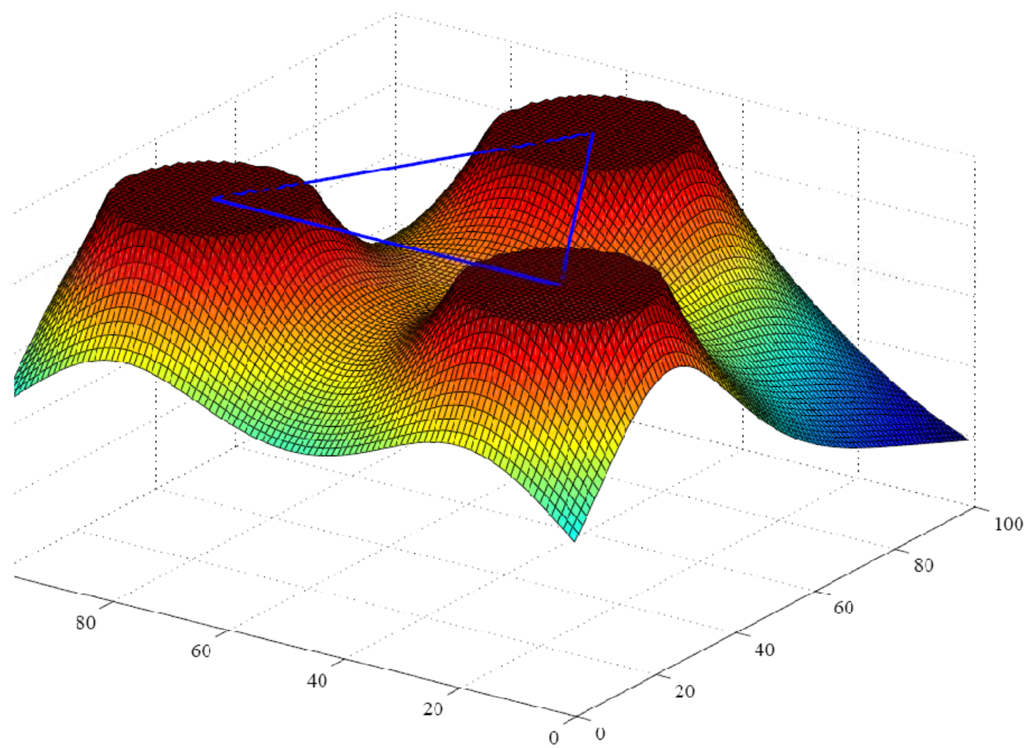
Probabilistic Coverage: Definitions (cont'd)

- **Def 2: *x* is called the least-covered point in *A* if:**

$$P(x) \le P(y) \quad \forall x, y \in A \text{ and } x \neq y$$

- **Ex.: least-covered point by three sensors using expo model**



Probabilistic Coverage: Basic Ideas

- Activate sensors such that the least-covered point in A has prob of sensing $\geq \theta$
- To do this in distributed manner, we
  - divide A into smaller subareas,
  - determine location of the least-covered point,
  - activate sensors to meet θ coverage in each subarea
- We choose subareas to be equi-lateral triangles
  - Activate sensors at vertices, others sleep ➔
  - Yields optimal coverage in disk sensing model [Bai 06]

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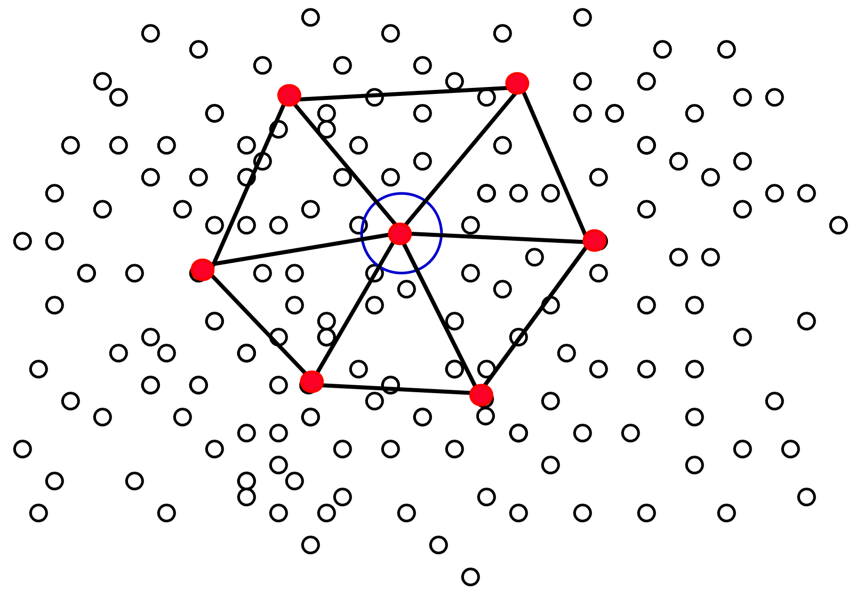
Probabilistic Coverage: Basic Ideas (cont'd)

- **Size of each triangle?**
  - Stretch the separation between active sensors to the maximum while maintaining θ coverage ➔
  - Minimize number of activated sensors
- **Theorem 1: Maximum Separation under the exponential sensing model is:**

$$\sqrt{3}\left(r_s - \frac{\ln\left(1-\sqrt[3]{1-\theta}\right)}{\alpha} \right)$$

PCP: Probabilistic Coverage Protocol

- One node randomly enters active state
- The node sends an activation message
- Closest nodes to vertices of triangular mesh activated
  - Using activation timers as function of proximity to vertex
- Activated nodes send activation messages



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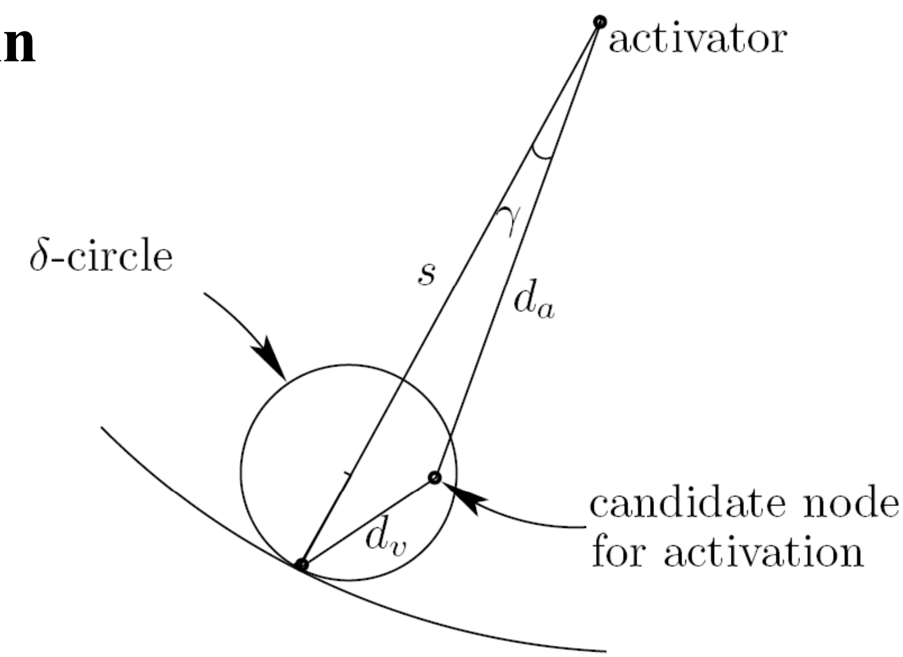
PCP: Further Optimization

- **Def 3: δ-circle is the smallest circle drawn anywhere in A s.t. there is at least one node inside it**

- **Minimizes number of nodes in WAIT state ➔ saves energy**
- **The diameter δ is computed based on node deployment**
- **Paper shows calculations for uniform and grid distributions**



PCP: Convergence and Correctness

- **Theorem 2: PCP converges in at most**

$$l(\tau_a \delta^2 + \tau_m)/(s - \delta)$$

steps with every point has a prob. of sensing ≥ θ

- **Convergence time depends *only* on area size (not number of sensors) ➔ PCP can scale**

PCP: Activated Nodes and Message Complexity

- **Theorem 3: PCP activates at most**

$$l^2/\sqrt{3}(s-\delta)^2$$

nodes to maintain coverage, and exchanges at most that number of messages

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PCP: Connectivity

- **Theorem 4: Nodes activated by PCP will be connected if communication range r_c is greater than or equal to maximum separation s**

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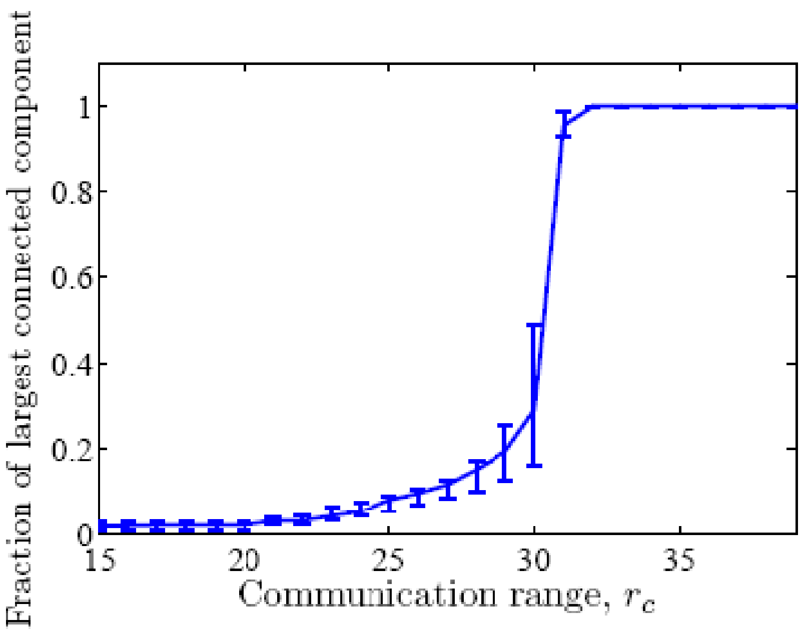
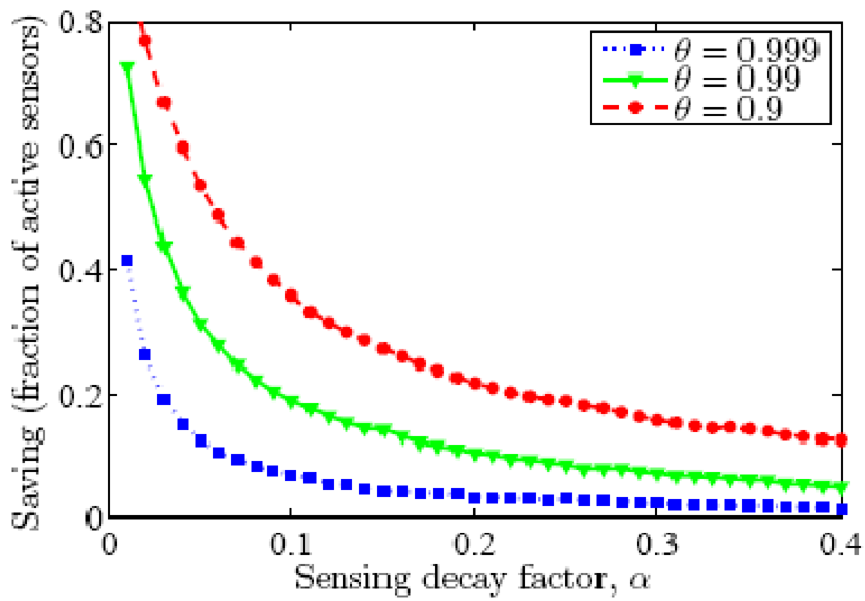
Evaluation: Setup

- **We implemented PCP**
  - **in NS-2; worked fine for up to 1,000 nodes, and**
  - **in our own packet level simulator; scaled to more than 20,000 nodes deployed in a 1 km x 1 km area**
  - **Implemented Expo and Disk sensing models**
- **Used elaborate energy model (Motes) in [Zhang 05][Ye 03]**
- **Rigorous evaluation to**
  - **Verify correctness**
  - **Show robustness**
  - **Compare PCP against the state-of-the-art protocols:**
    - **Probabilistic coverage protocol : CCANS**
    - **Deterministic coverage protocols : CCP, OGDC**
- **Only sample results are presented**

Evaluation: Correctness and Savings





- **Connectivity achieved when $r_c \geq s$**
- **Significant savings can be achieved by gauging coverage threshold θ**

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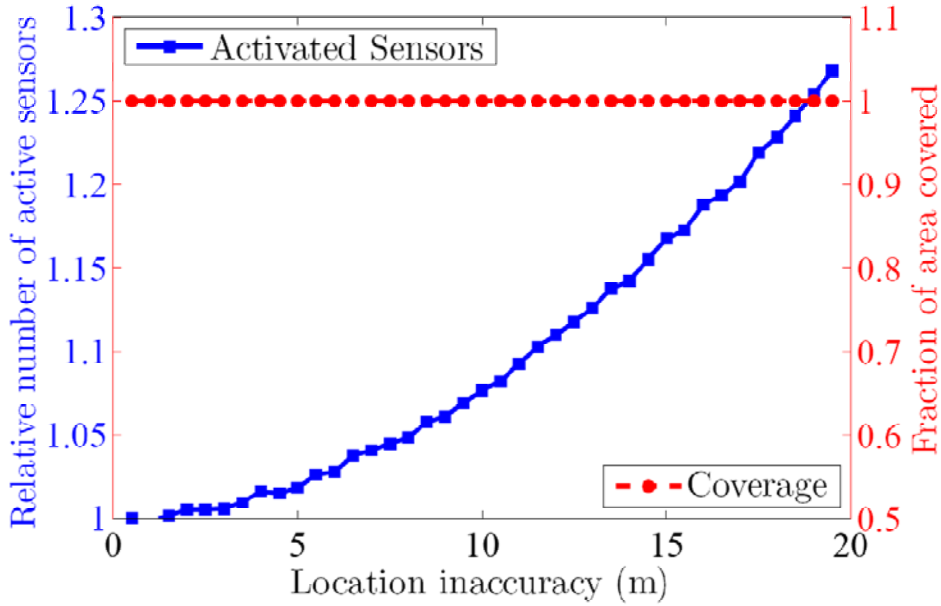
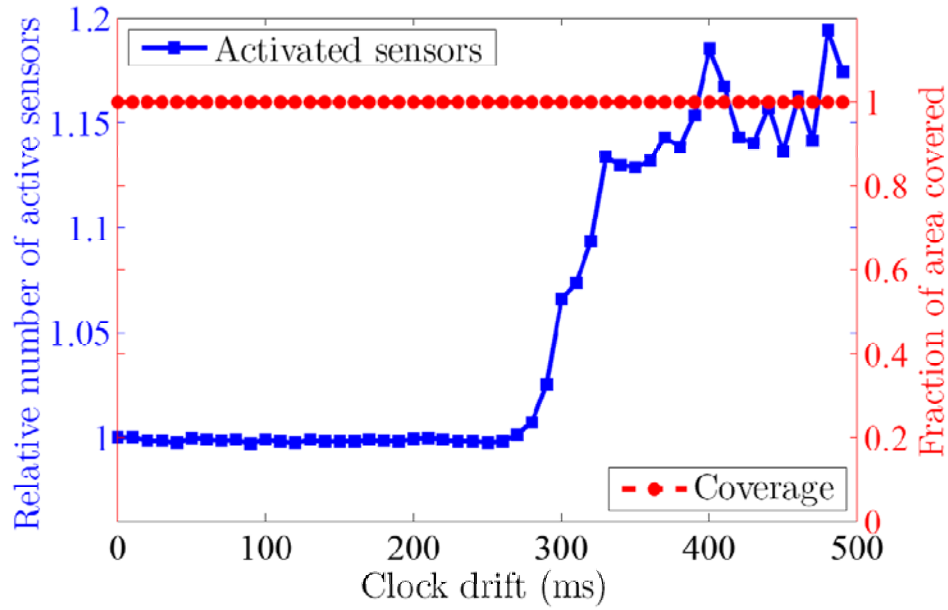
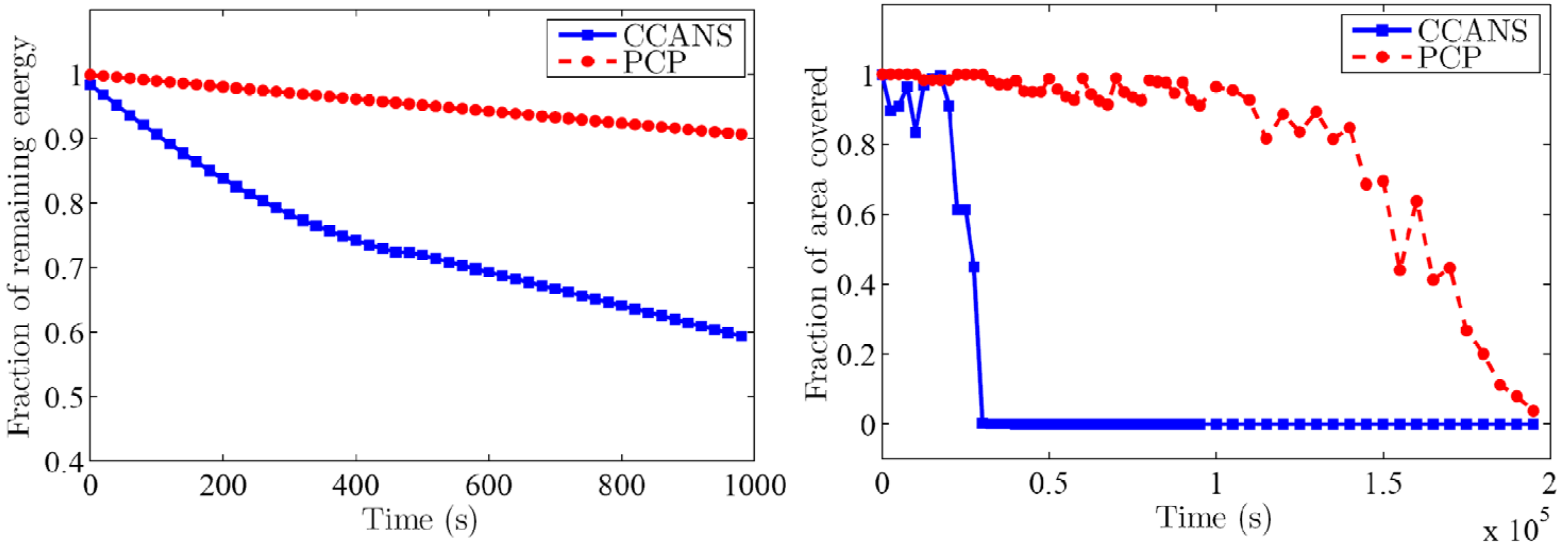
Evaluation: Robustness





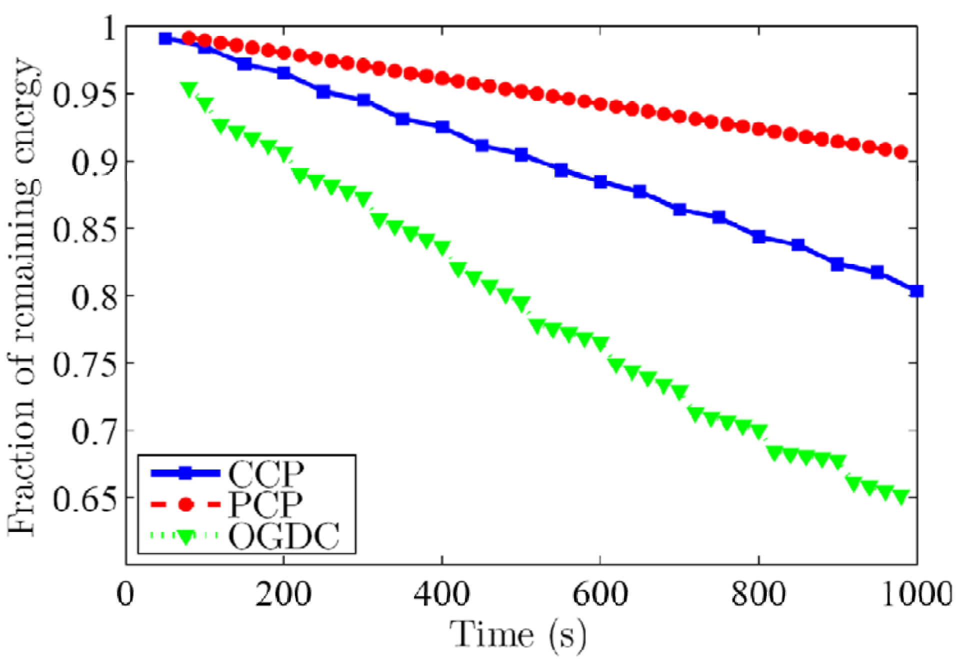
- **Coverage is maintained even with large: (i) location errors, and (ii) clock drifts**
- **Cost: slight increase in number of activated sensors**

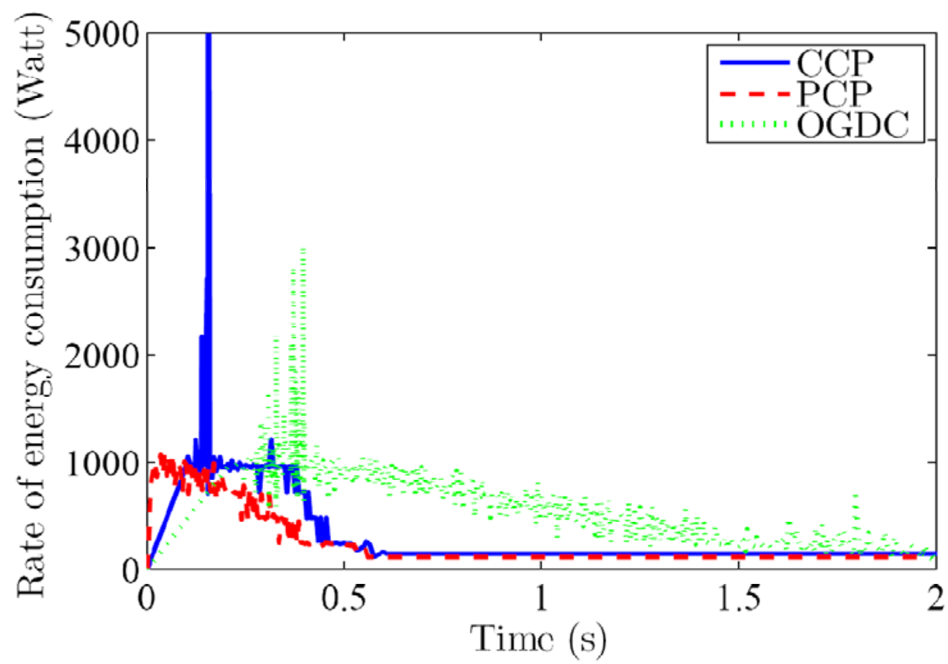
Evaluation: PCP vs. CCANS



- **Significant energy savings**
- **Much longer lifetime**

Evaluation: PCP vs. OGDC, CCP





- **PCP (with disk model) outperforms OGDC and CCP. Why?**
  - **Peak in CCP is due to many HELLO messages**
  - **OGDC takes longer time to converge**

Conclusions

- **Presented a distributed protocol (PCP) for maintaining coverage under probabilistic and deterministic sensing models**
  - **Robust, efficient, and outperforms others**
  - **More suitable for real environments than others**

- **PCP Limitation**
  - **Does not provide coverage with multiple degrees**

Thank You!

Questions??

- Details are available in the extended version of the paper at:

  http://www.cs.sfu.ca/~mhefeeda

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