PCP: A Probabilistic Coverage Protocol for Wireless Sensor Networks

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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 may not function in real environments
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
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 $\theta$ if for every point $x$ in $A$:

\[
P(x) = 1 - \prod_{i=1}^{n} (1 - p_i(x)) \geq \theta
\]

- 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 $\theta$
Def 2: \(x\) is called the least-covered point in \(A\) if:

\[ P(x) \leq P(y) \quad \forall x, y \in A \text{ and } x \neq y \]

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 $\theta$ 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]
Size of each triangle?
- Stretch the separation between active sensors to the maximum while maintaining $\theta$ coverage
- Minimize number of activated sensors

Theorem 1: Maximum Separation under the exponential sensing model is:

$$\sqrt{3}\left(r_s - \frac{\ln\left(1 - \frac{3}{\sqrt{1-\theta}}\right)}{\alpha}\right)$$
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
Def 3: $\delta$-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 $\Rightarrow$ saves energy
- The diameter $\delta$ 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

\[ l \left( \tau_a \delta^2 + \tau_m \right) / (s - \delta) \]

steps with every point has a prob. of sensing \( \geq \theta \)

- Convergence time depends only on area size (not number of sensors) \( \Rightarrow \) 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
Theorem 4: Nodes activated by PCP will be connected if communication range $r_c$ is greater than or equal to maximum separation $s$. 
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 $\theta$
**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