School of Computing Science
Simon Fraser University, Canada

Efficient *k*-Coverage Algorithms for Wireless Sensor Networks

Mohamed Hefeeda

(joint work with Majid Bagheri)

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Motivations

- **Wireless sensor networks have been proposed for many real-life monitoring applications**
  - Habitat monitoring, early forest fire detection, …
- ***k*-coverage is a measure of quality of monitoring**
  - ***k*-coverage ≡ every point is monitored by *k*+ sensors**
  - Improves reliability and accuracy
- ***k*-coverage is essential for some applications**
  - E.g., intruder classification, object tracking

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Our *k*-Coverage Problem

- **Given *n* already deployed sensors in a target area, and a desired coverage degree $k \geq 1$, select a minimal subset of sensors to *k*-cover all sensor locations**

- **Assumptions**
  - **Sensing range of each sensor is a disk with radius *r***
  - **Sensor deployment can follow any distribution**
  - **Nodes do not know their locations**
  - **Point coverage approximates area coverage (dense sensor network)**

Our *k*-Coverage Problem (cont'd)

- ***k*-coverage problem is NP-hard [Yang 06]**

- **Proof: reduction to minimum dominating set problem**
  - **Model network as graph**
  - **An edge between any two nodes if they are within the sensing range of each other**
  - **Finding the minimum number of sensors to 1-cover yields a minimum dominating set**

Our Contributions: *k*-Coverage Algorithms

- **We propose two approximation algorithms**
  - **Randomized *k*-coverage algorithm (RKC)**
    - **Simple and efficient ➔**
  - **Distributed RKC (DRKC)**
- **Basic idea:**
  - **Model *k*-coverage as a hitting set problem**
  - **Design an approximation algorithm for hitting set**
    - **Prove its correctness, verify using simulations**
  - **Decentralize it**

Set Systems and Hitting Set

- **Set system *(X,R)* is composed of**
  - **set *X*, and**
  - **collection *R* of subsets of *X***

- ***H* is a hitting set if it has a nonempty intersection with every element of *R*:**

$$H \subseteq X$$

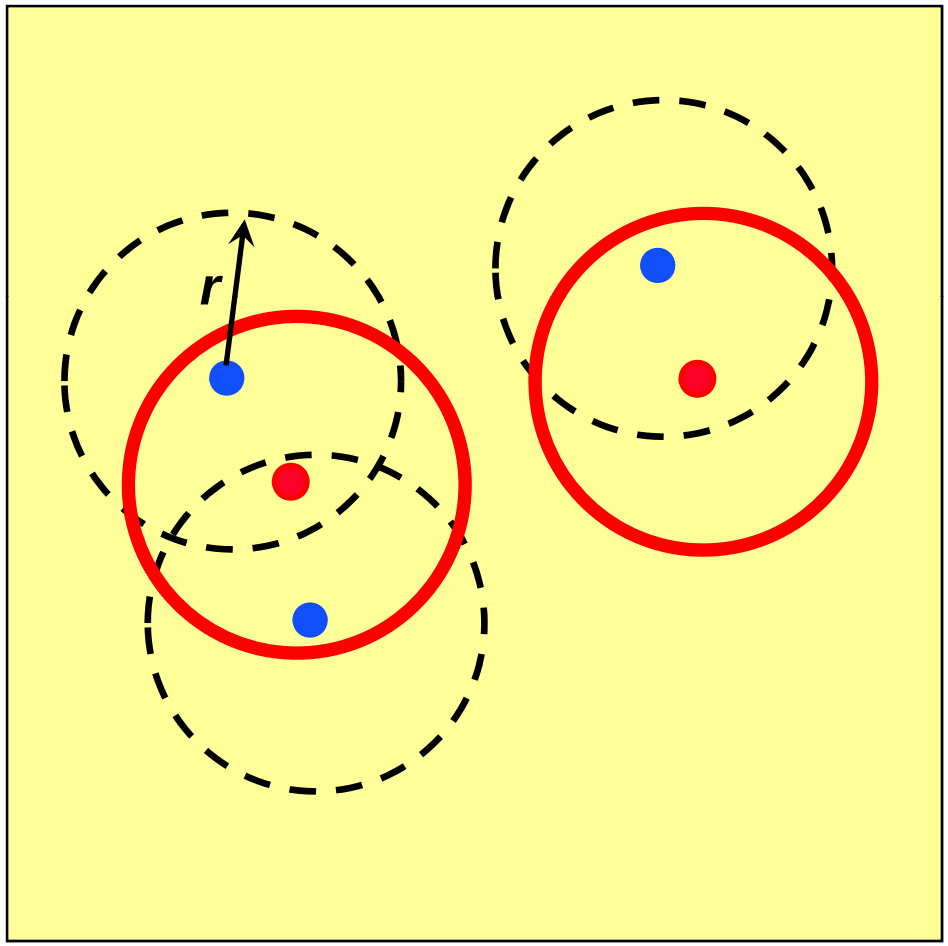
$$\forall s \in R, \quad H \cap s \neq \phi$$

Set System for *k*-Coverage

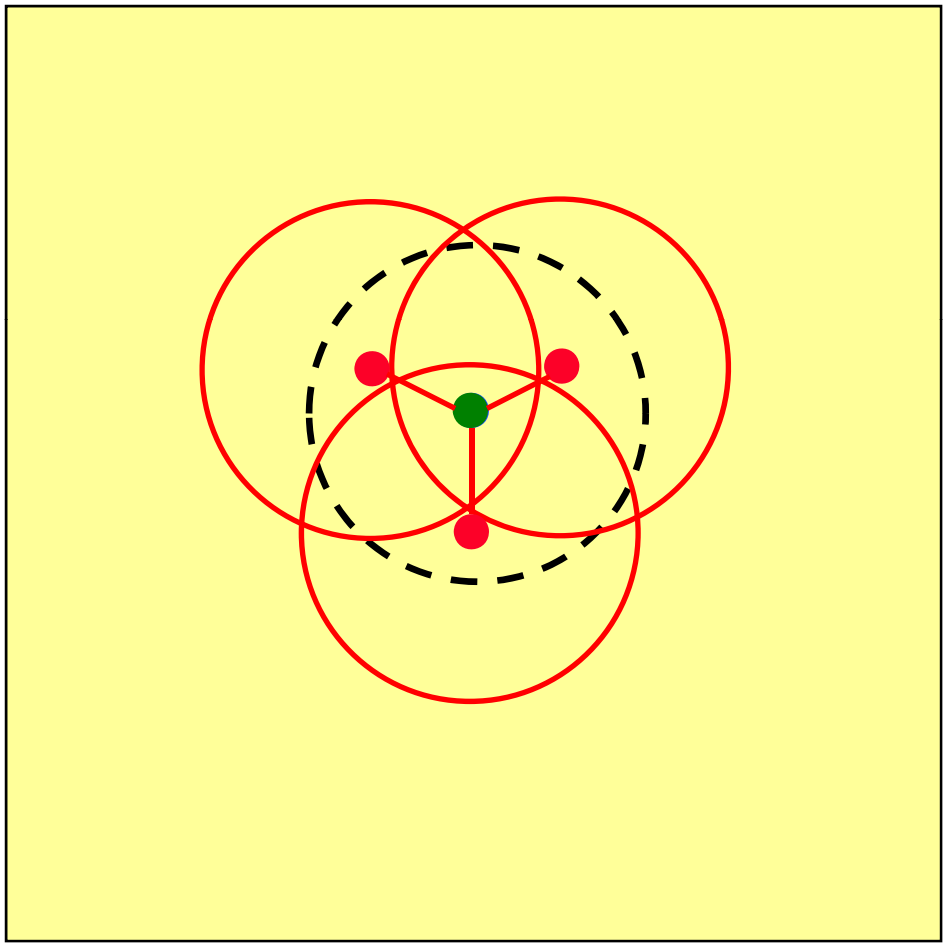
- *X:* set of all sensor locations
- For each point *p* in *X*, draw circle of radius *r* (sensing range) centred at *p*
- All points in *X* which fall inside that circle constitute one set *s* in *R*
- The hitting set must have at least one point in each circle

- Thus all points are covered by the hitting set

Example: 1-Coverage



Example: *k*-Coverage (*k* = 3)



Elements of the hitting set are centers of *k*-flowers

Centralized Algorithm (RKC)

- **Build an approximate hitting set**
  1. Assign weights to all points, initially 1
  2. Select a random set of points, referred to as *ε-net*
     - Selection biased on weights
  3. If current ε-net covers all points, terminate
  4. Else double weight of one under-covered point, goto 2 if number of iterations is below a threshold (~log |X|)
  5. Double size of ε-net, goto 1

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ε-nets

- N is an ε-net for set system (X,R) if it has nonempty intersection with every element T of R such as $|T| \geq \varepsilon |X|$
- Thus, ε-net is required to hit only large elements of R
  - (hitting set must hit every element of R)
- Idea:
  - Find ε-nets of increasing sizes (decreasing ε) till one of them hits all points

ε-net Construction

- **ε-nets can be computed efficiently for set systems with finite VC-dimension [Bronnimann 95]**
  - **We prove that our set system has VC-dimension = 3**

- **Randomly selecting**

  $$max\ \{4/\varepsilon \log 2/a,\ 8d/\varepsilon \log 8d/\varepsilon\}$$

  points of *X* constitutes an ε-net with probability *1-a* for *0<a<1* where *d* is the VC-dimension

Details of RKC

Randomized K-Coverage: RKC(X, r, k)

```
1.   c = 1; // sets the initial size of ε-net
2.   while (net-size(1/c) ≤ n) do
3.       set weights of all points to 1;
4.       ε = 1/c;
5.       for i = 1 to 4c log n/c
6.           N = net-finder(X, k, ε, r);
7.           u = verifier (X, N, k, r);
8.           if (u == null)
9.               return N;
10.          else
11.              double weight of u;
12.      c = 2 × c;
13.  return ∅;
```

Correctness and Complexity of RKC

- **Theorem 1: RKC …**
  - **ensures that very point is *k*-covered,**
  - **terminates in $O(n^2 \log^2 n)$ steps, and**
  - **returns a solution of size at most $O(P \log P)$, where *P* is the minimum number of sensors required for *k*-coverage**

Distributed Algorithm: DRKC

- **RKC maintains only two global variables:**
  - **size of ε-net**
  - **aggregate weight of all nodes**

- **Idea of DRKC: Emulate RKC by keeping local estimates of global variables**
  - **Nodes construct ε-net in distributed manner**
  - **Nodes double their weights with a probability**
  - **Each node verifies its own coverage**

DRKC Message Complexity

- **Theorem 2:**

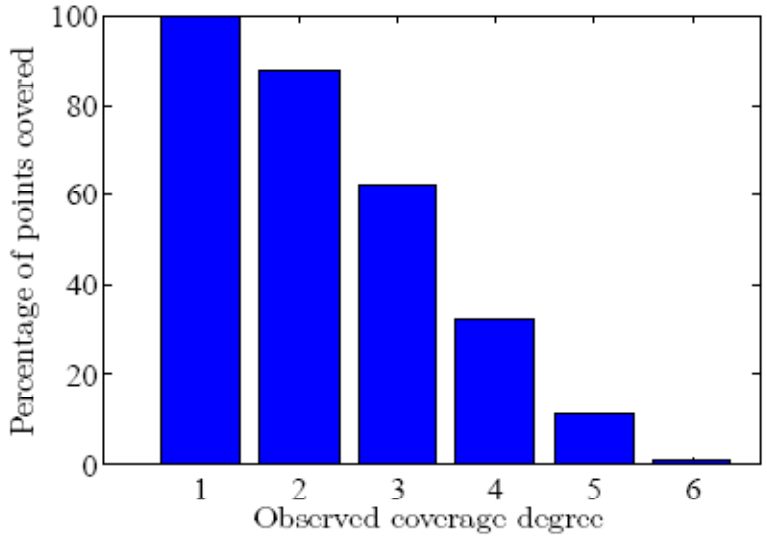
  The average number of messages sent by a node in DRKC is *O(1)*, and the maximum number is *O(log n)*

Performance Evaluation

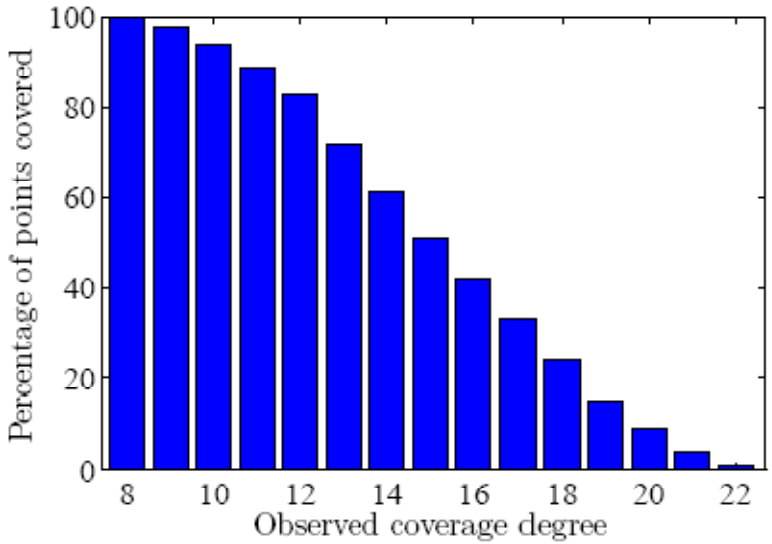
- Simulation with thousands of nodes
- Verify correctness (k-coverage is achieved)
- Show efficiency (output size compared optimal)
- Compare with other algorithms
  - LPA (centralized linear programming) and PKA (distributed based on pruning) in [Yang 06]
  - CKC (centralized greedy) and DPA (distributed based on pruning) in [Zhou 04]

Correctness of RKC

- **RKC achieves the requested coverage degree**



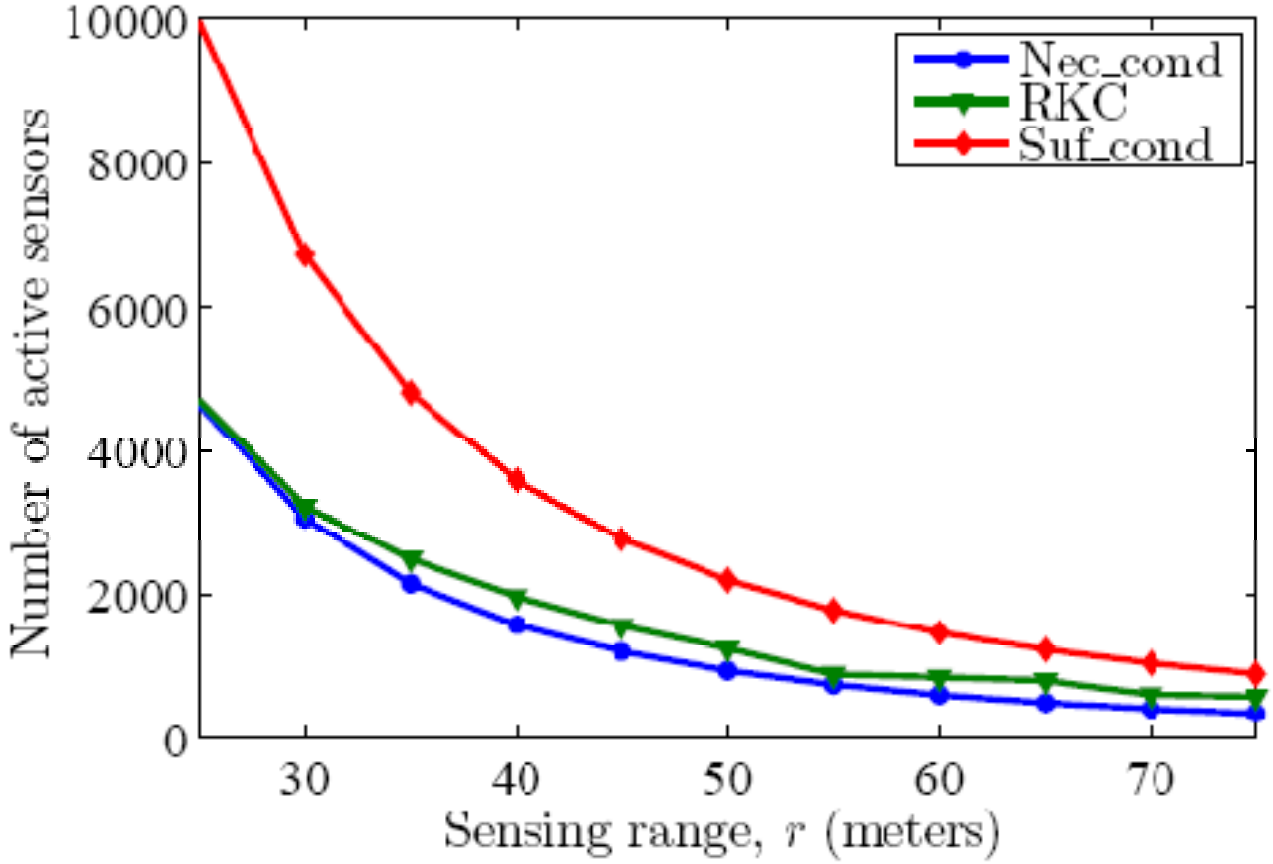
Requested k = 1



Requested k = 8

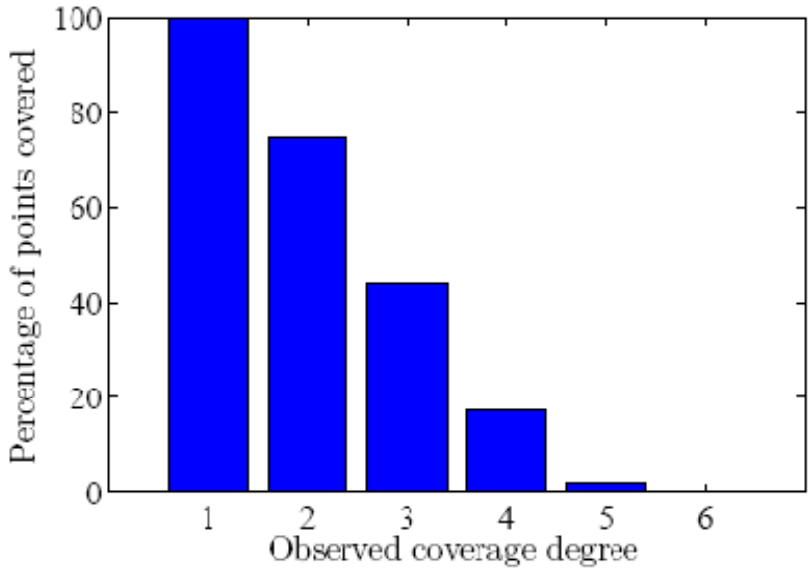
Efficiency of RKC

- **Compare against necessary and sufficient conditions for *k*-coverage in [Kumar 04]**

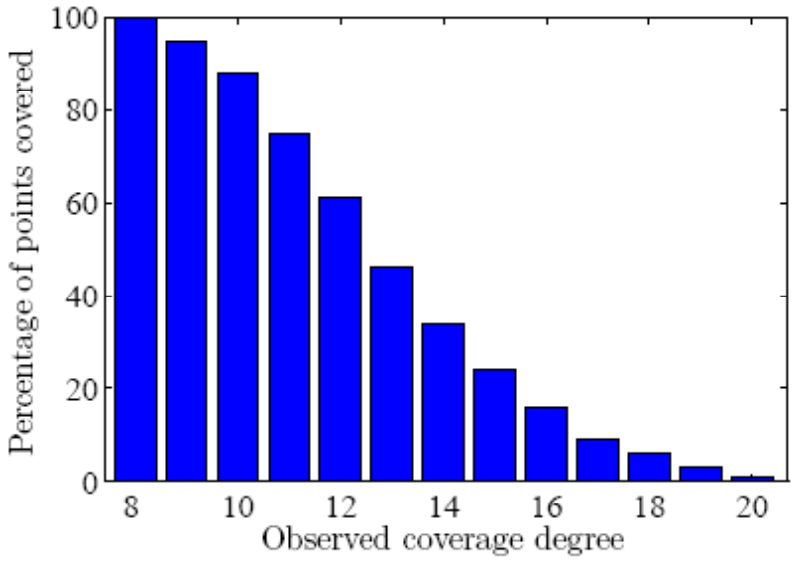


Correctness of DRKC

- **DRKC achieves the requested coverage degree**



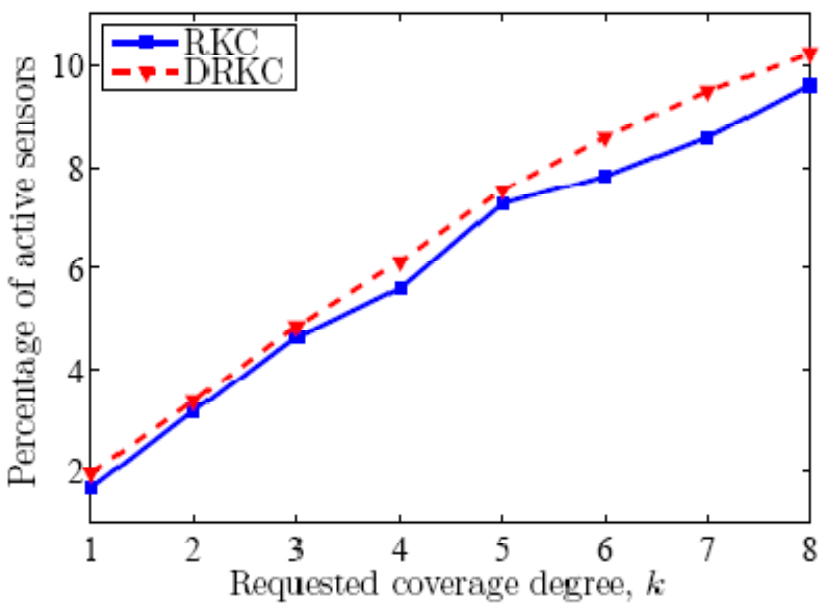
Requested k = 1

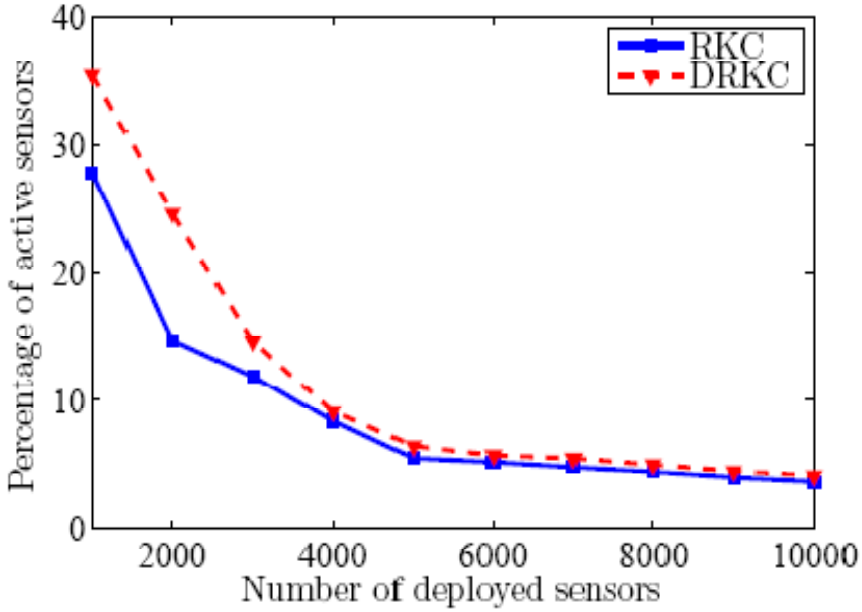


Requested k = 8

Efficiency of DRKC

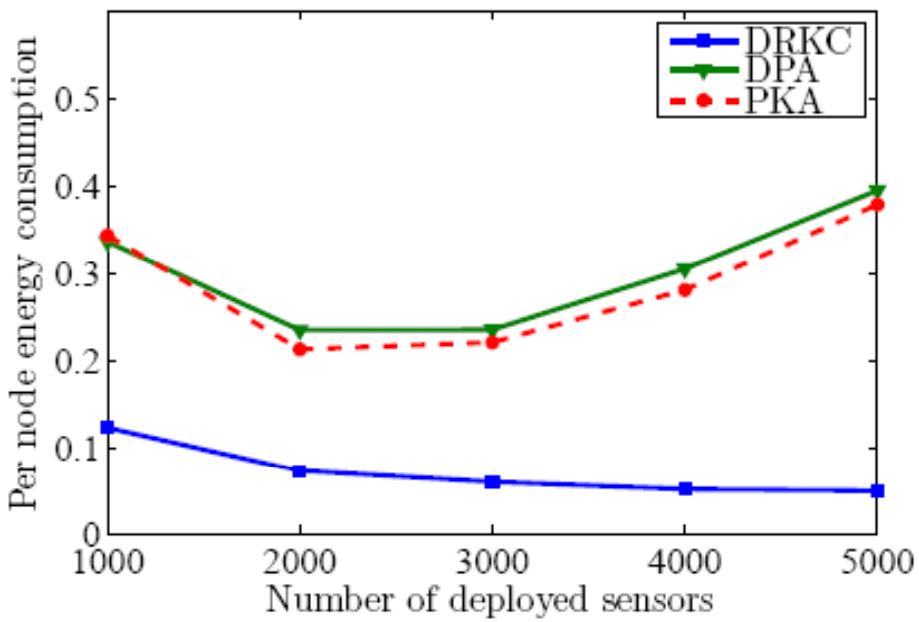
- **DRKC performs closely to RKC, especially in dense networks**

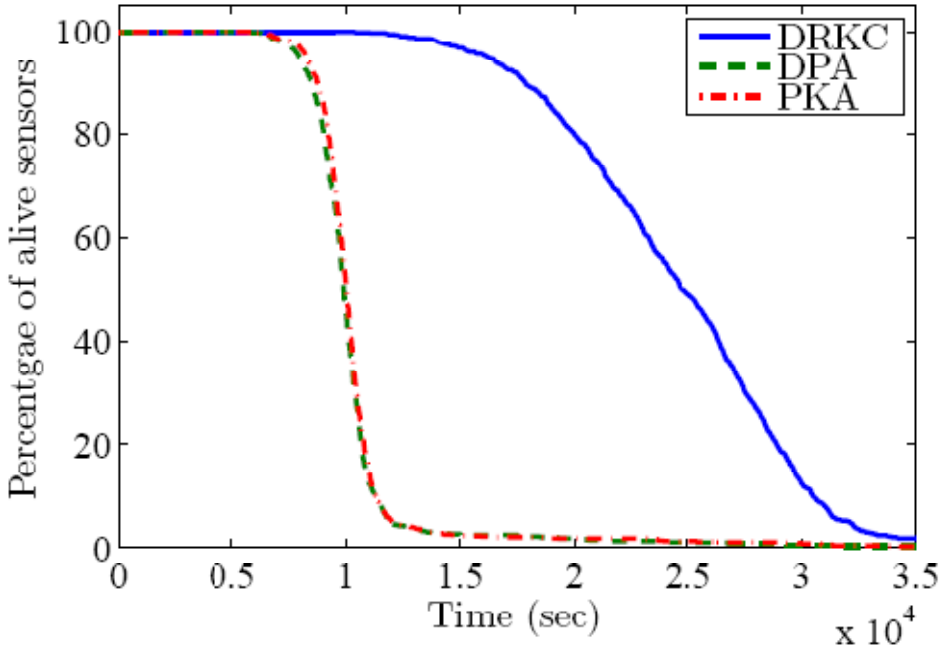




Comparison: DRKC, PKA, DPA

- **DRKC consumes less energy and prolongs network lifetime**





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Conclusions

- **Presented a centralized *k*-coverage algorithm**
  - Simple, and efficient (log-factor approximation)
  - Proved its correctness and complexity
- **Presented a fully-distributed version**
  - low message complexity, prolongs network lifetime
- **Simulations verify that our algorithms are**
  - Correct and efficient
  - Outperform other *k*-coverage algorithms

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Thank You!

Questions??

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

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