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A Heuristic Approach for K-Coverage Extension with Energy-Efficient Sleep Scheduling in Sensor Networks

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Outline

- Introduction
- Problem formulation
- Deployment of sensor nodes with "Gas Bubble" algorithm
  - Algorithm formulation
  - Performance evaluation
- Integration with dynamic sleep scheduling
- Conclusion and Outlook

Introduction

- Future ambient information infrastructures require huge number of sensors with redundant coverage
- "Coverage" encompasses two parts:
  - Sensing coverage (type of sensor)
  - RF communication range (connectivity)
- Deployment of sensor nodes is an NP-complete problem to obtain K-coverage, especially when a partially existing network is extended

K-Coverage Problem

- **Example scenario:**
  - Consider surveillance of a museum with sensors
  - Some objects require more reliable monitoring with redundant coverage
  - Failure of individual sensor can be compensated

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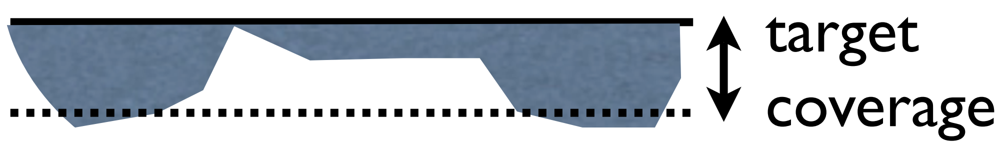
Assumptions and Definitions

- Rectangular monitoring window W
- Set of sensor nodes $\mathcal{S}$ with $|\mathcal{S}| = M$
- Sensing coverage radius r
- Circular sensing coverage areas, coverage degree:

$$C(x) = |\{s \in \mathcal{S} : \|s - x\| < r\}|$$

- **Definition**:
We say that a region W has obtained K-coverage, iff $\forall_{x \in W}\, C(x) \geq K$ where $C : \mathbb{R}^2 \rightarrow \mathbb{N}$ is the number of sensor nodes covering a point $x \in W$

Gas Bubble Algorithm



- Mimics the behavior of gas bubbles slowly rising in a liquid before changing its state to solid
- Heuristic method based on self-organizing feature maps, especially *Growing Neural Gas*
- Reaction of neurons to stimuli in the given area
- The distance of each neuron is indicator for suitability of "cooling down" (as in *Simulated Annealing*)

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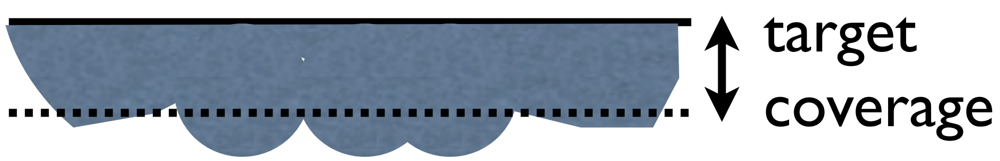

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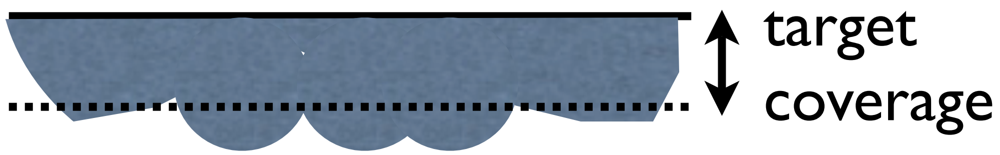

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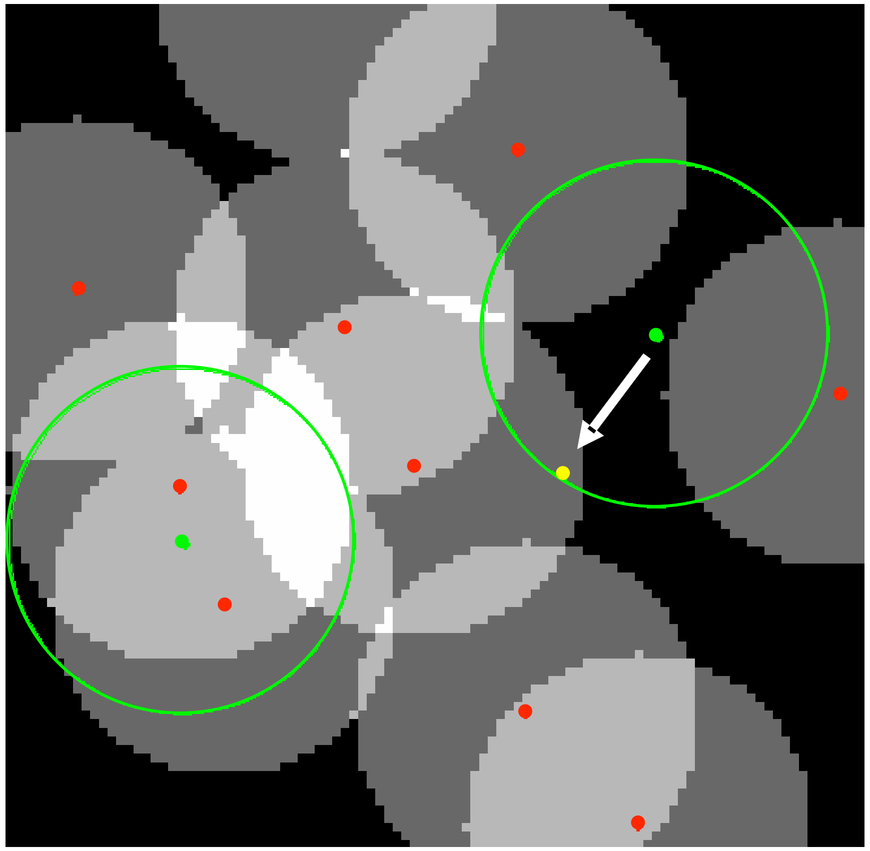

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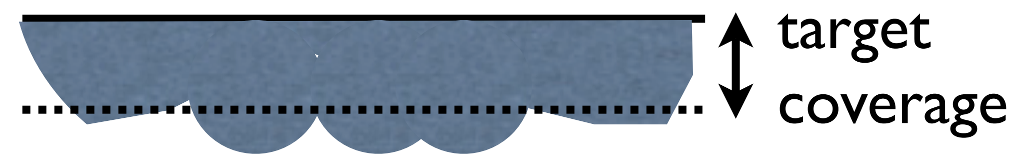
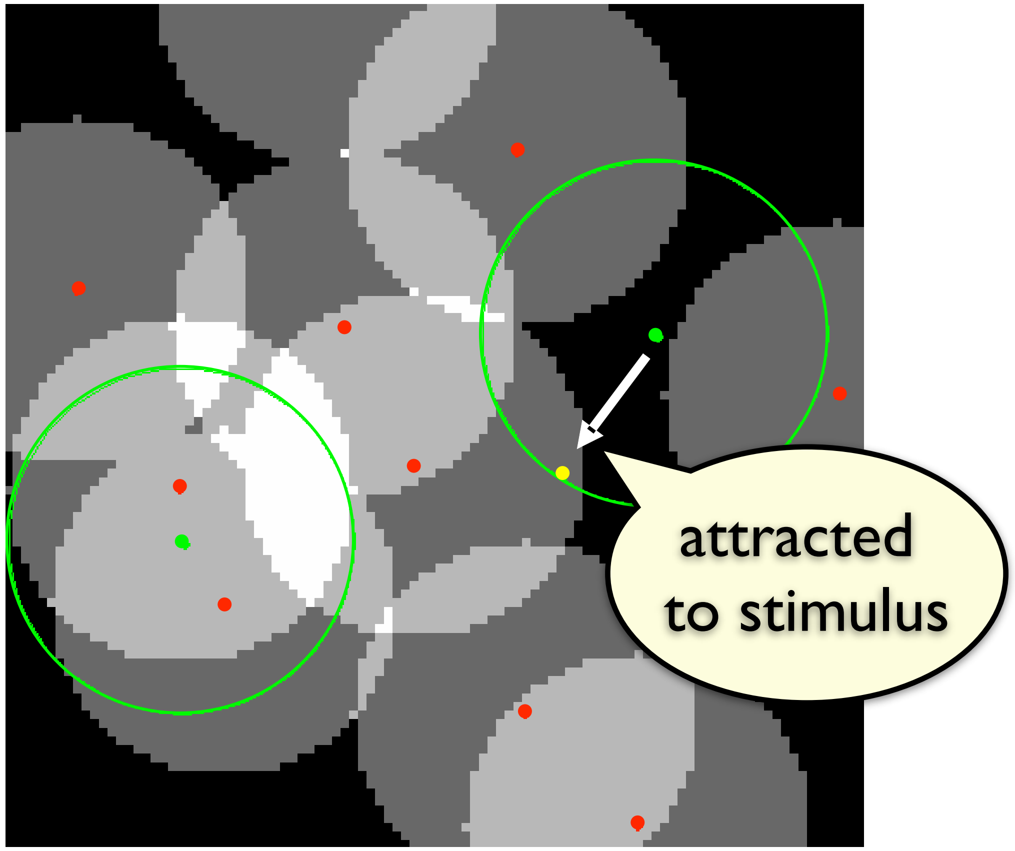




Formulation of Bubble Algorithm

1. Initialize $step = 0$
2. While there are still locations with coverage less than K
   - 2.1. $step = step + 1$
   - 2.2. Start with two neurons n_1 and n_2 at random positions in the window
   - 2.3. Generate input stimulus ξ randomly among all uncovered points in W proportional to $K - C(\xi)$
   - 2.4. Find the nearest neuron b to ξ and update its error value and reset its age.

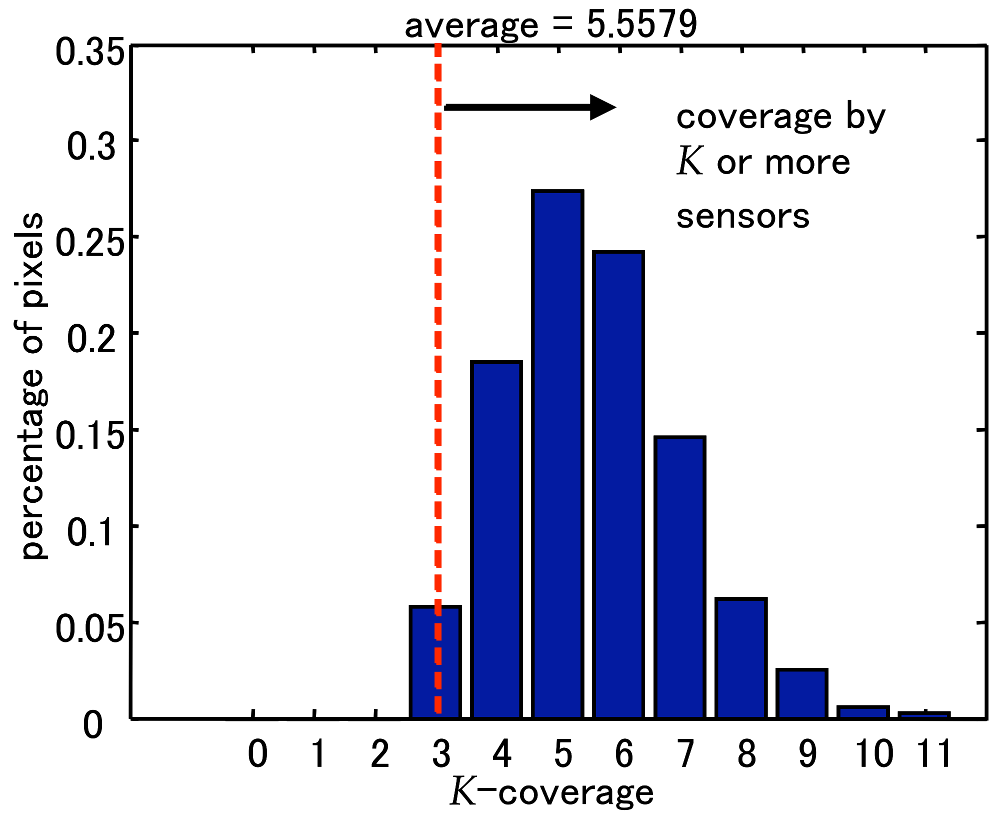
$$\begin{aligned} error(b) &= error(b) + \|b - \xi\| \\ age(b) &= 0 \end{aligned}$$

   - 2.5. Move b by ϵ towards ξ: $b = b + \epsilon\,(\xi - b)$
   - 2.6. If $t_{add} \bmod step == 0$, add a neuron at the location of the neuron with the highest error and split this total error among the old and new neuron.
   - 2.7. If $s_{add} \bmod step == 0$, the neuron with lowest error becomes a sensor node if there is a coverage gain.
   - 2.8. Remove all neurons n_i with $age(n_i) > t_{age}$
   - 2.9. Decrease the error of each neuron n_j by a decay factor δ and increment its age

$$\begin{aligned} error(n_j) &= \delta\ error(n_j) \\ age(n_j) &= age(n_j) + 1 \end{aligned}$$

Parameter Settings

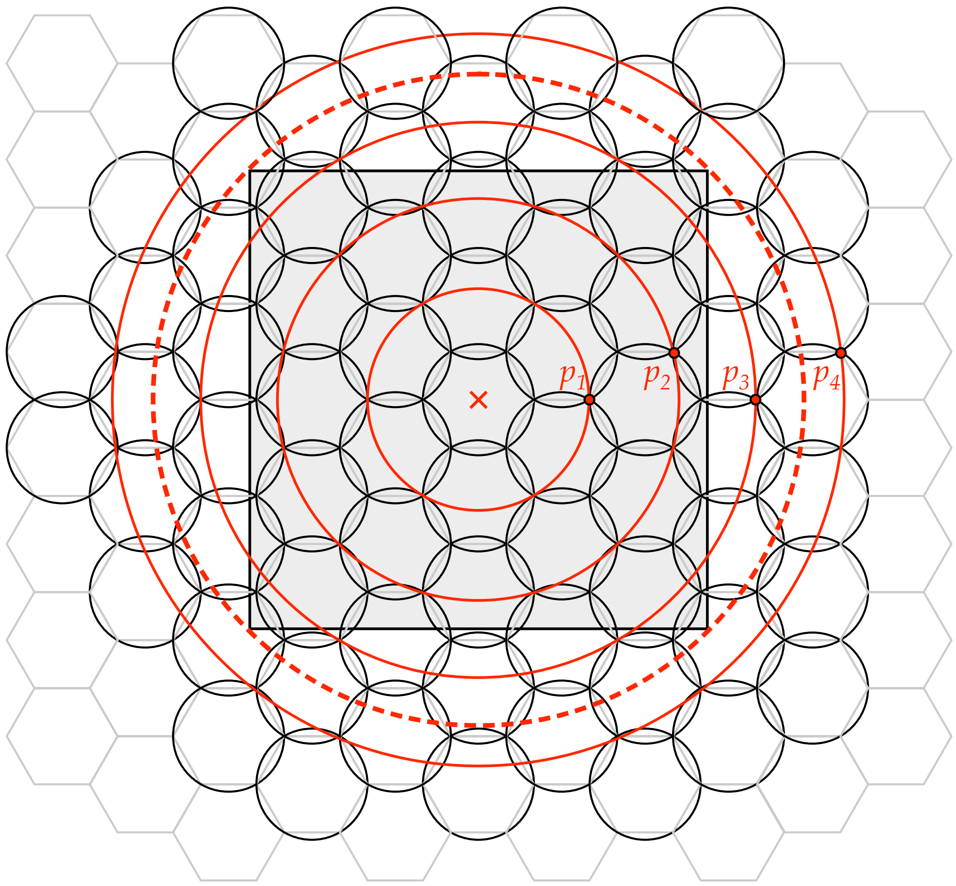
- Starting with 2 neurons, their error is indicator for adding new neurons
- Every t_{add} time steps a new neuron is added by splitting the node with the highest error value
- Every s_{add} time steps a neuron becomes fixed
- Circular sensor coverage areas cause much overlap, especially for large K



$$t_{add} = 200 \qquad s_{add} = 500$$
$$\epsilon = 0.2 \qquad t_{age} = 200$$
$$\delta = 0.95 \qquad w = 100$$
$$r = 13 \qquad K = 3$$

Approximation of Optimal Coverage

- Best approximation of circular coverage areas by hexagon with superposition of K layers
- Beginning from center ('x'), calculate p_i and their radius y_i
- Number of nodes L_i for tier i



$$y_i = \begin{cases} r\,(2+3\,(i-1)) & \text{if } i \text{ is odd} \\ \frac{r}{2}\sqrt{(7+6\,(i-2))^2+3} & \text{if } i \text{ is even} \end{cases}$$

$$L_i = 1 + 6\sum_{k=1}^{i} k = 1 + 3\,i\,(i+1)$$

i	1	2	3	4	5	6	7
y_i	30.0	54.1	120.0	143.1	210.0	232.9	300.0

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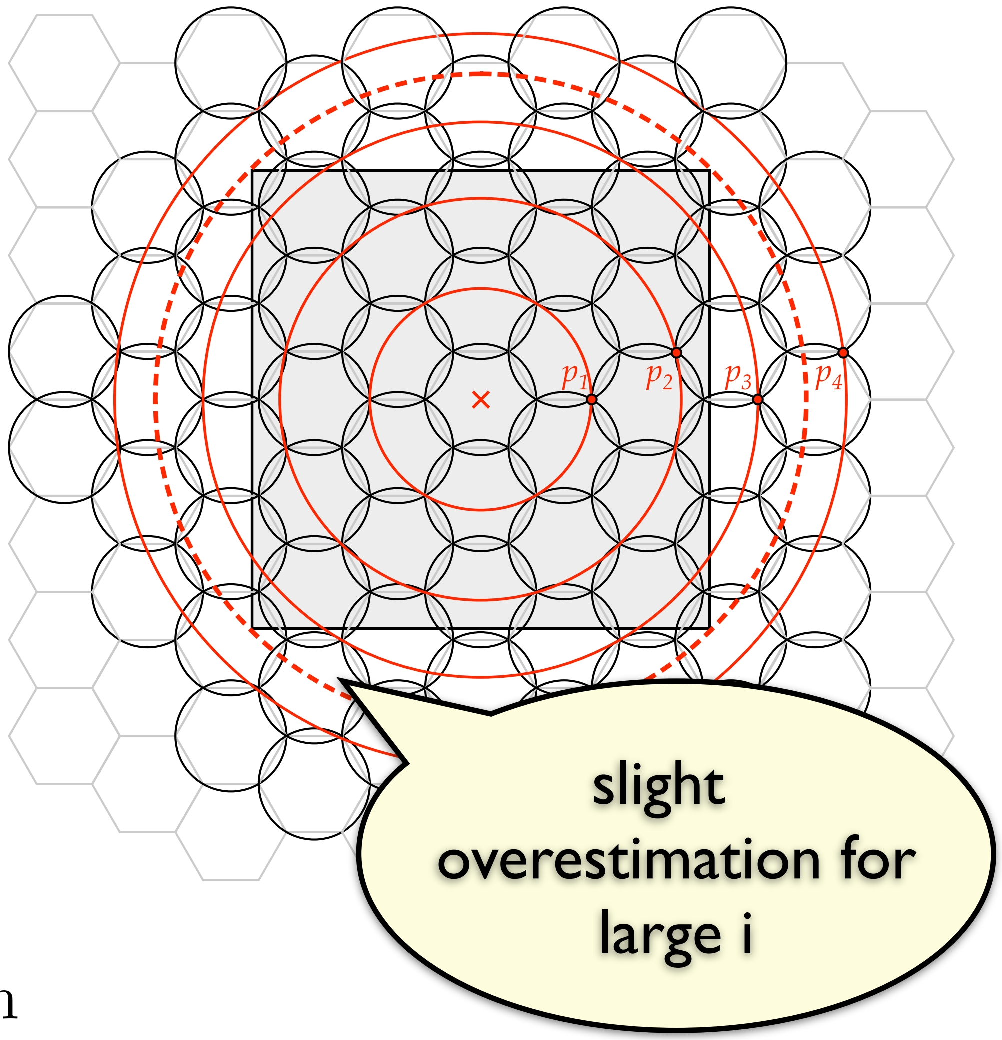

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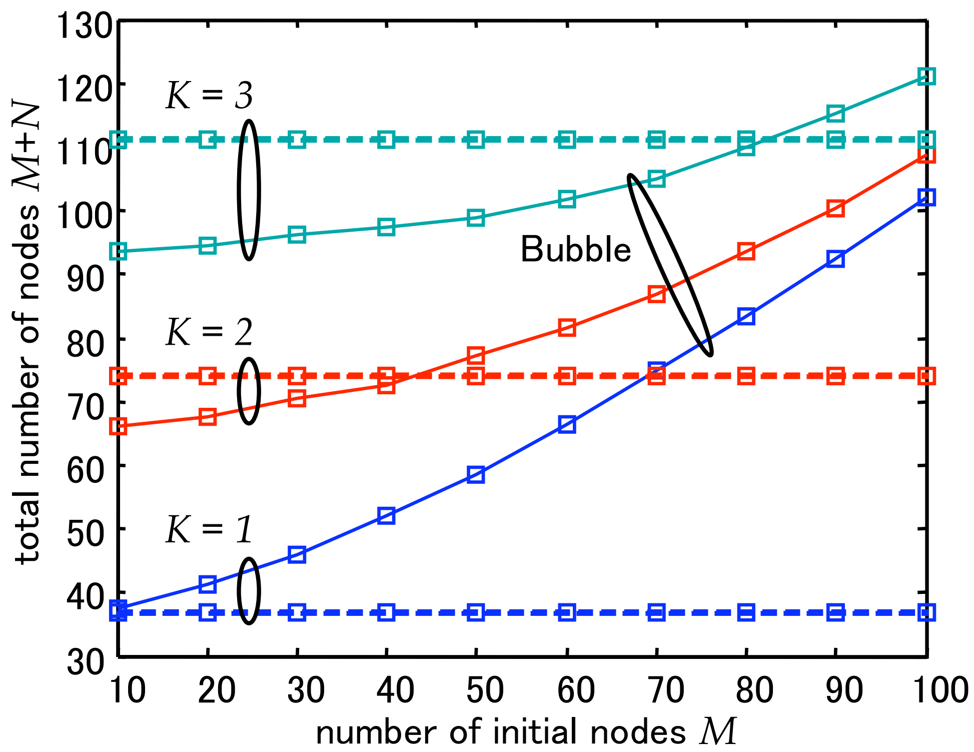
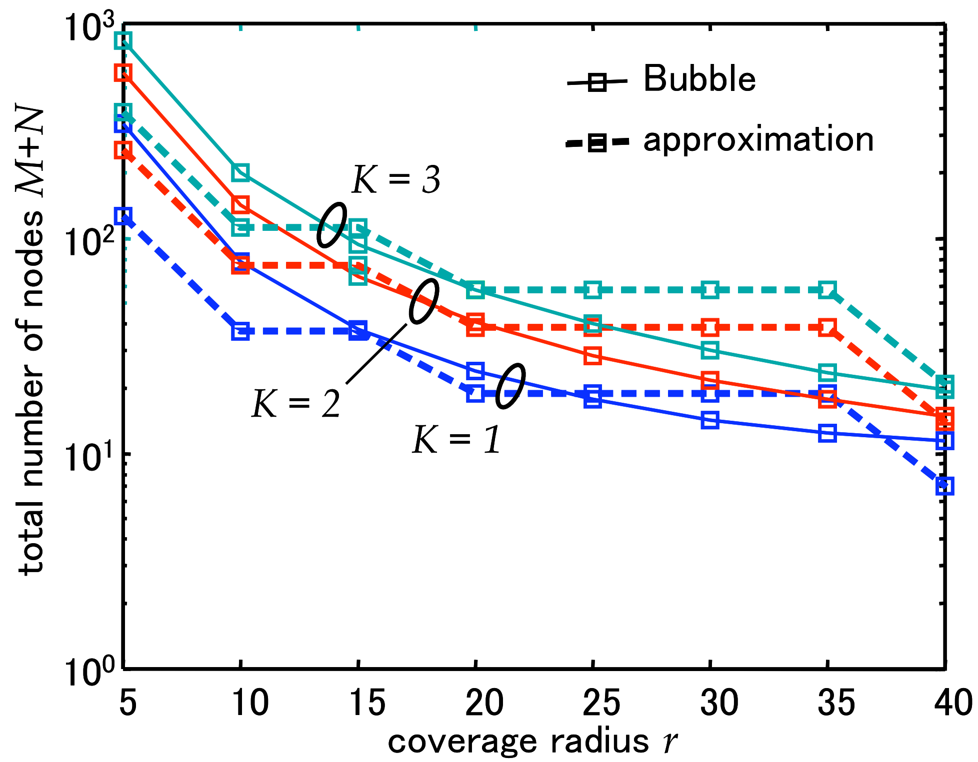
Comparison of Total Nodes





- Total nodes: M (initial nodes) + N (added nodes)
- Proposal is better when K gets larger, whereas total nodes remain constant for hexagonal approximation
- Similar benefit for variation of sensing radius r

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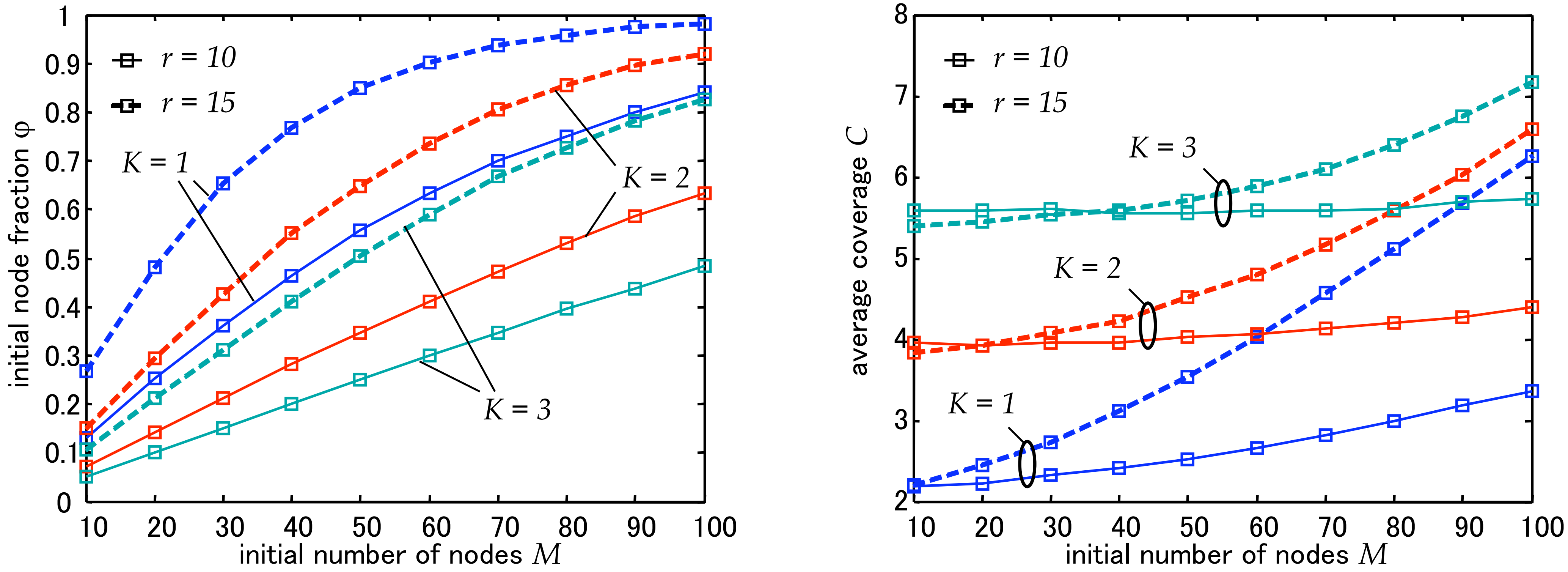
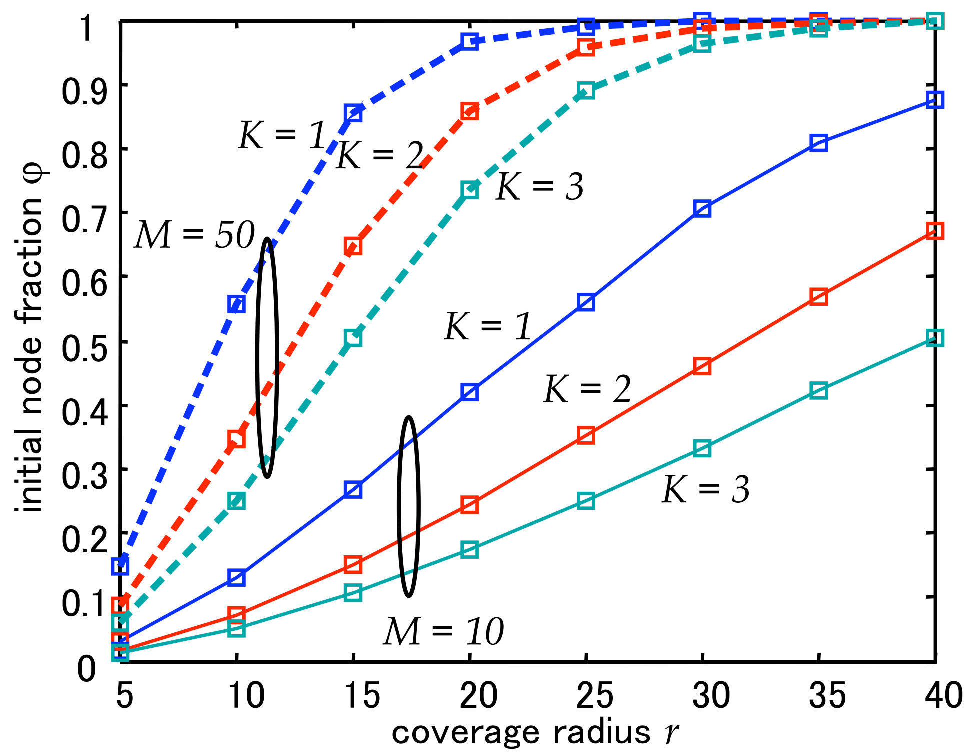
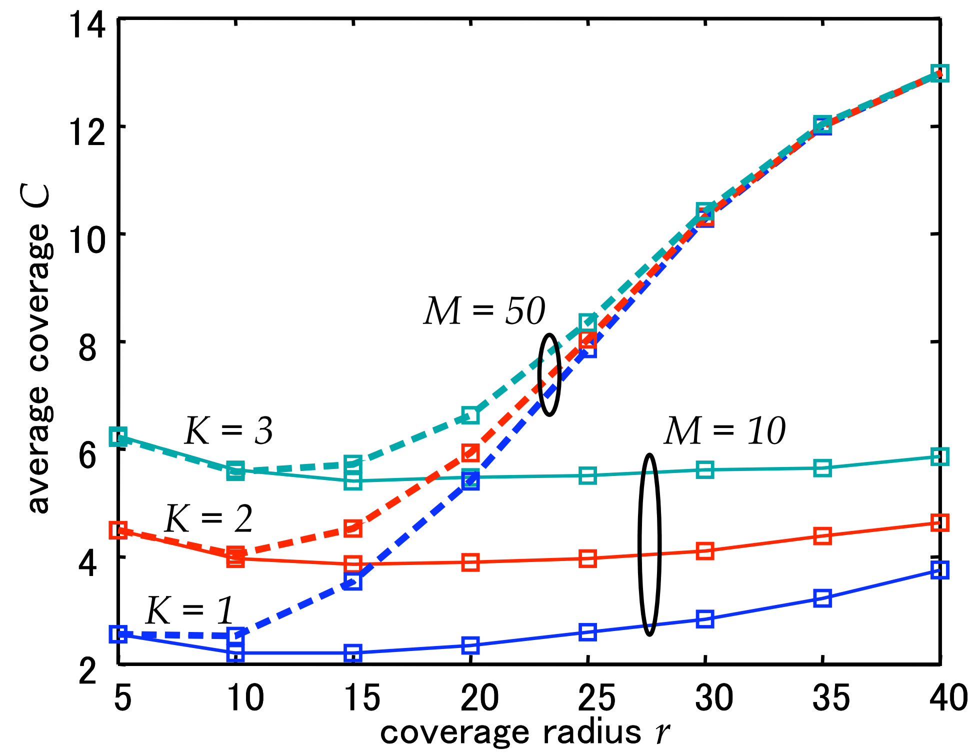
Influence of Initial Configuration



- Initial coverage fraction defined as $\varphi = M/(M+N)$
- Smaller coverage radius results in less total nodes
- Larger target coverage has less influence in conjunction with radius on average coverage C

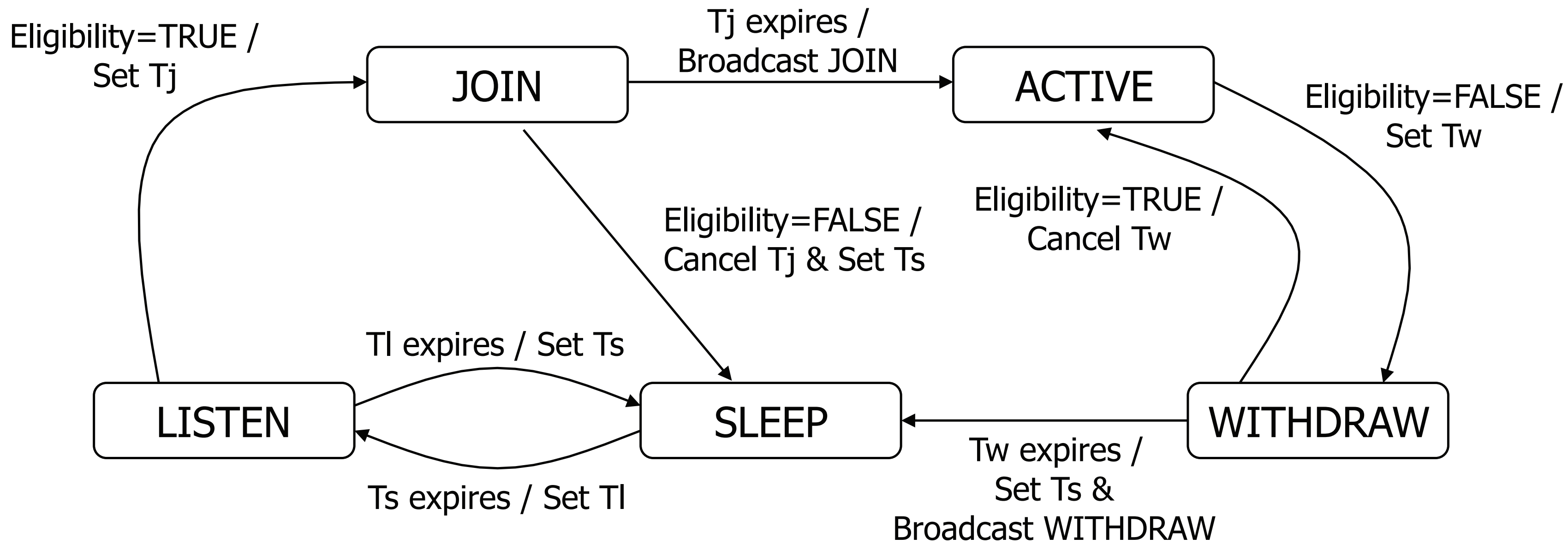
Influence of Sensing Coverage Radius





- If initial nodes M is large, only few additional nodes required, especially for large r
- Proposal is more efficient the less initial nodes exist. For large number of initial nodes and radius, we have much (unnecessary) overlap

Conclusion



- Fast Gas Bubble method for sensor node deployment
- Heuristic is based on Neural Gas/Simulated Annealing
- Redundant coverage planning permits unnecessary nodes to enter sleep state, prolonging network lifetime
- Combined with energy-dependent state sojourn timers and message filtering