Optimal Sleep-Wakeup Algorithms for Barriers of Wireless Sensors

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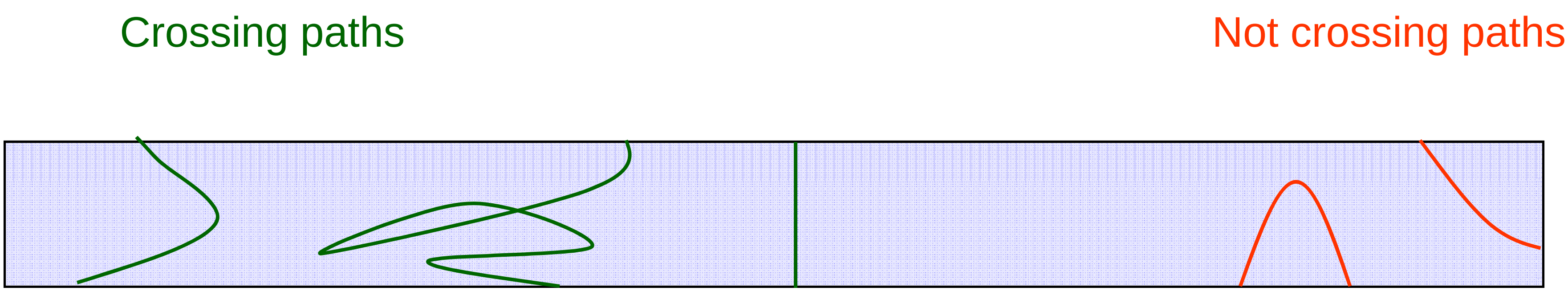
Outline

- A primer on Barrier Coverage
- The sleep-wakeup problem
- Homogeneous lifetime case
- Heterogeneous lifetime case
- Key learnings from simulation
- Conclusions

Intrusion Detection

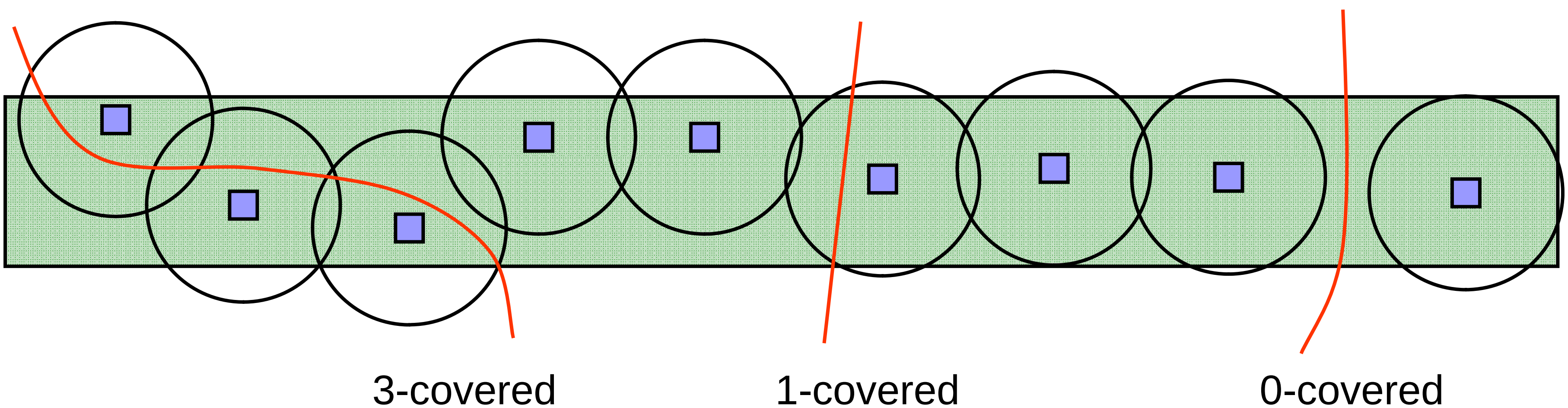
Crossing Paths

- A crossing path is a path that crosses the complete width of the belt region.



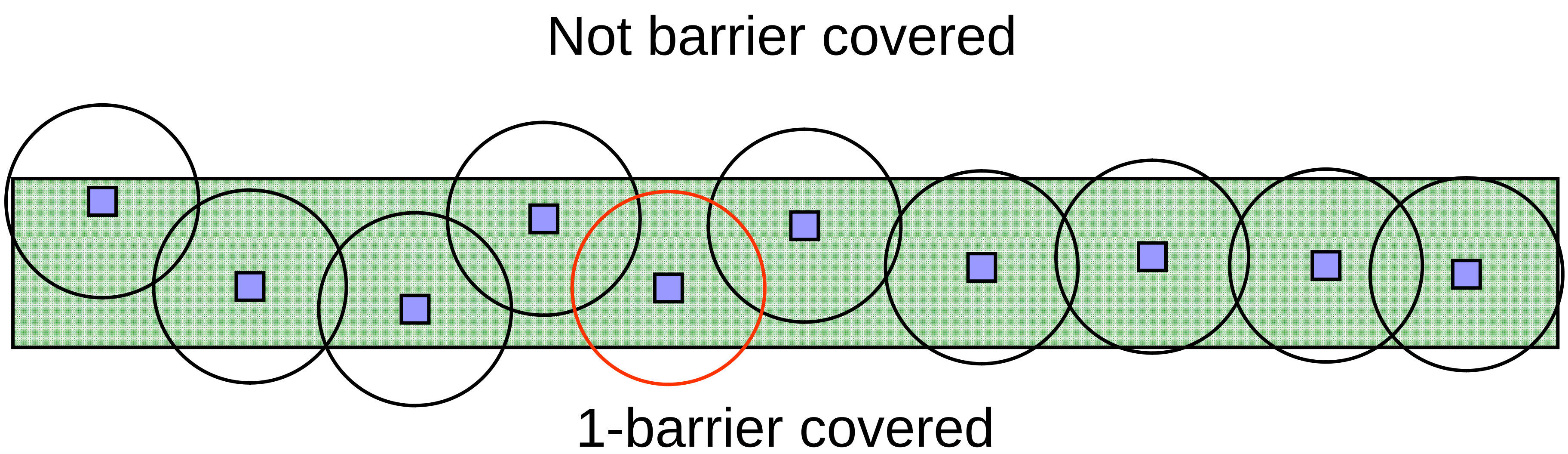
k-Coverage of a Path

- A crossing path is said to be *k*-covered if it intersects the sensing disks of at least *k* distinct sensors.



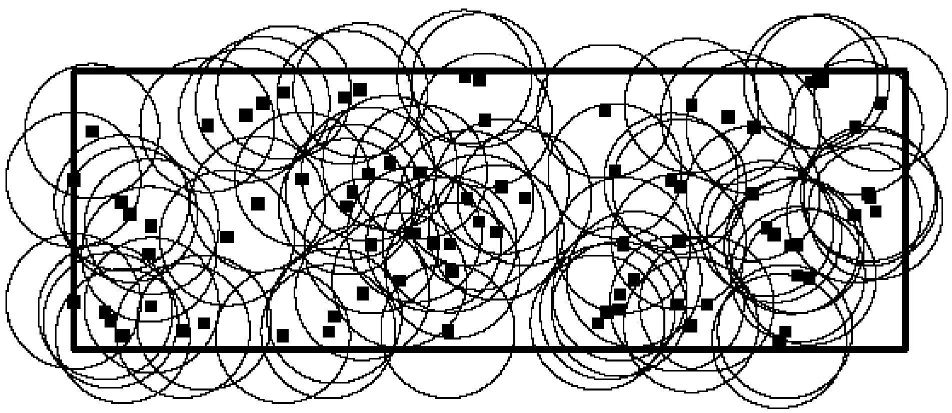
k-Barrier Coverage

- A belt region is *k*-barrier covered if all crossing paths are *k*-covered.



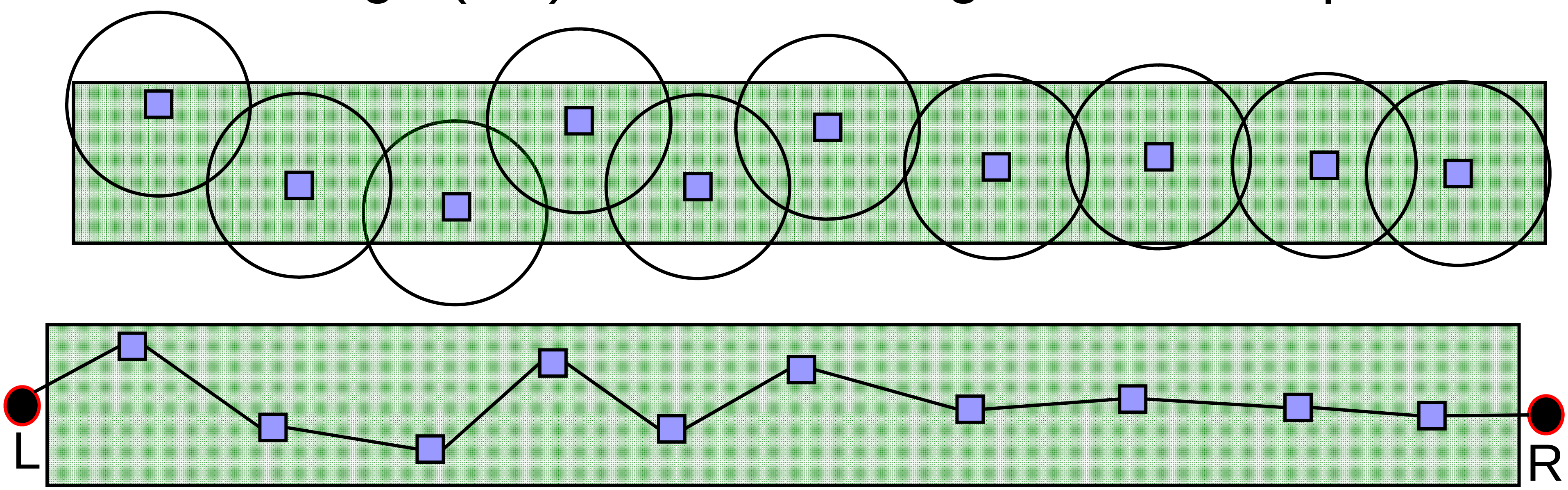
How to check for *k*-barrier coverage?

- Given a belt region deployed with sensors
  - Is it *k*-barrier covered?
  - Find the maximum value of *k*



Reduce to a graph problem

- Given a sensor network over a belt region
- Construct a coverage graph $G = (V, E)$
  - V: sensor nodes, plus two virtual nodes L, R
  - E: edge (u,v) if their sensing disks overlap



Reduction Theorem

- Theorem: Region is *k*-barrier covered iff there are *k* node-disjoint paths between *L* and *R* in *G*.
- Proof:
  - If *k* node-disjoint paths exist, then *k* disjoint sets of sensors exist each providing 1-barrier coverage
  - If not, there exists a set of (*k-1*) sensors, whose removal will disconnect *L* and *R.*
    - A crossing path through these sensors will be at most (*k-1*) covered.

Implications of the Reduction Theorem

- Standard max-flow algorithms can be used to check for the existence of *k*-barrier coverage.
- Further, the maximum value of *k* can also be determined using the same algorithm.

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Exploiting redundancy

- Reasons for redundancy
  - Protect against unanticipated failures
  - Random deployment
- In unattended outdoor deployments
  - Battery energy is precious
- Can exploit redundancy to increase the network lifetime

Lifetime distribution

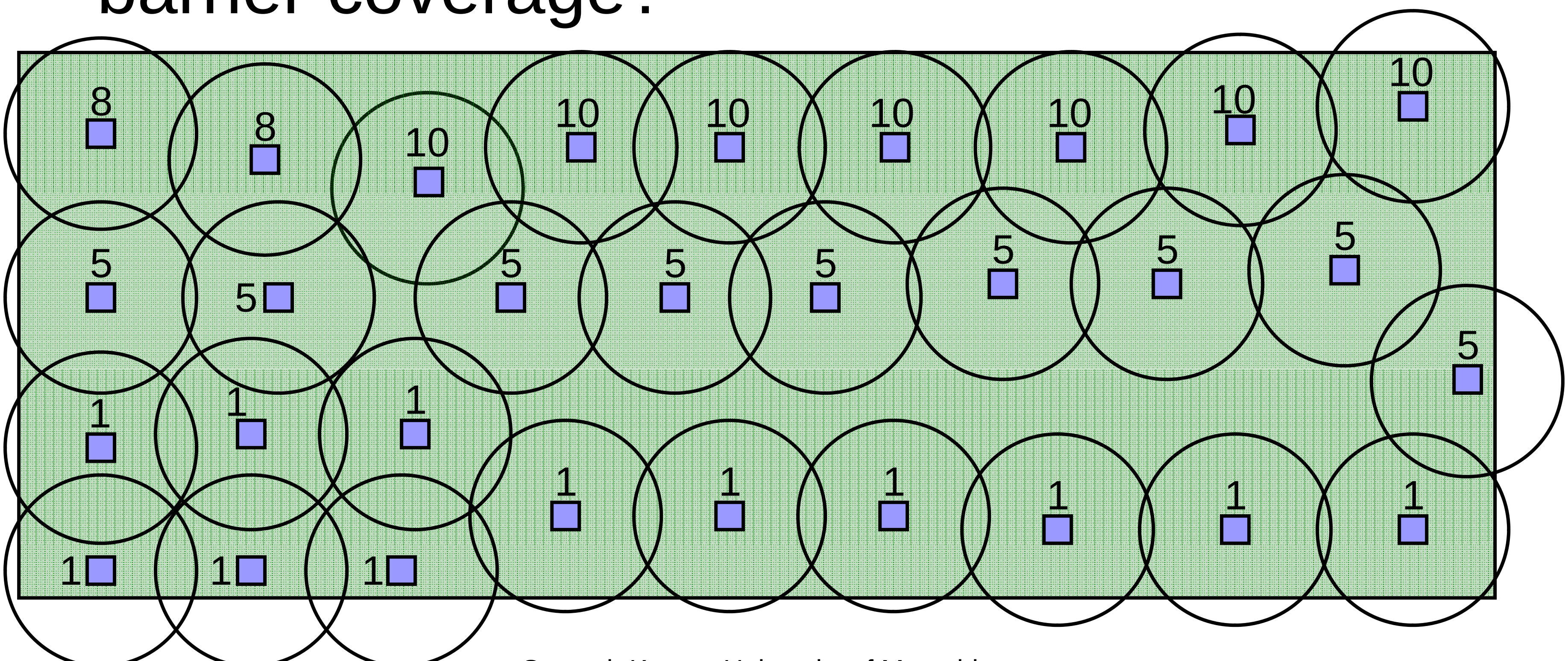
- Basic model
  - All sensors have homogeneous lifetime
- More practical
  - Sensors have distinct lifetimes due to
    - Uneven load
    - Sensor failures
    - Uneven recharging rates
    - Reinforcements – Additional sensor deployments

The sleep-wakup problem

- Given a sensor network with
  - Sensor locations and
  - Lifetime distributions
- What is the **maximum** time for which the network can
  - Continuously provide *k*-barrier coverage?

An example

- For how long can this network provide 2-barrier coverage?



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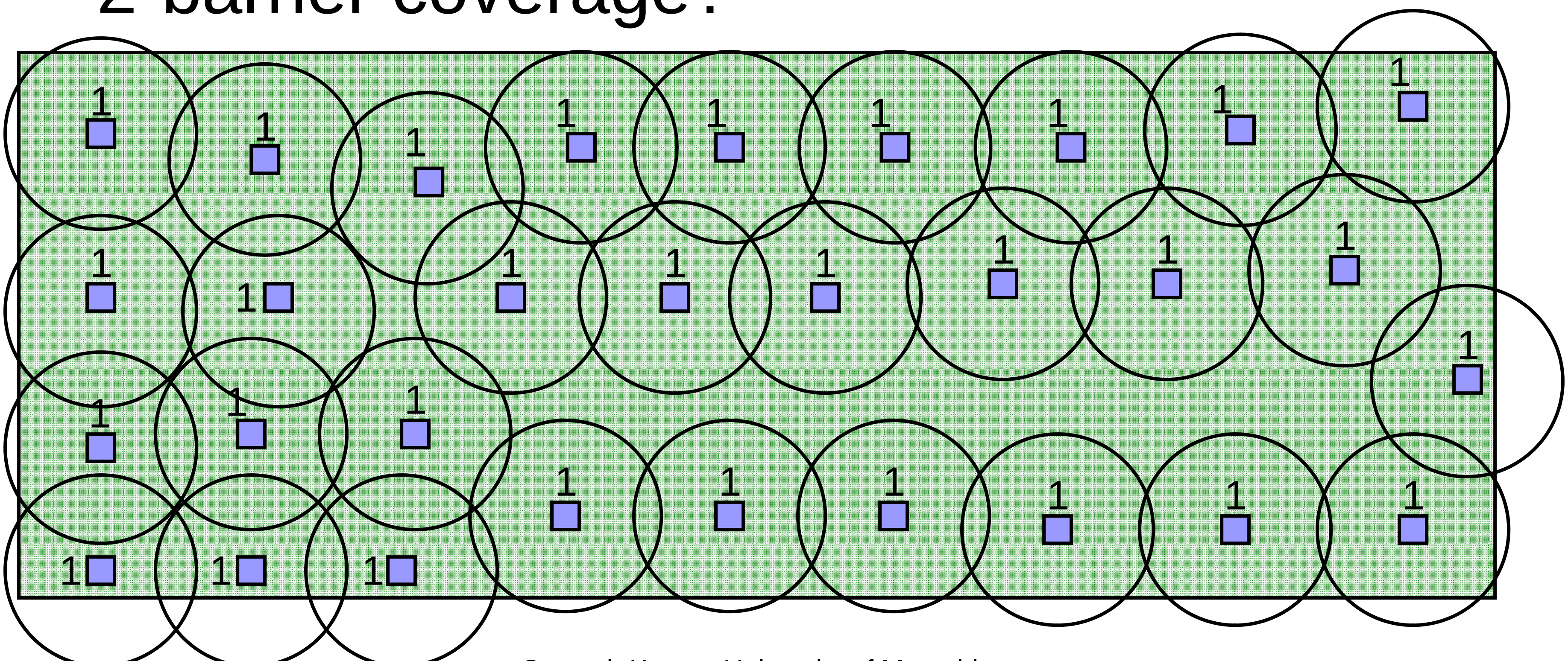
Homogeneous Lifetimes

- What is the maximum lifetime for providing 2-barrier coverage?



Key Result

- *N* – Given sensor network
- *m* – maximum number of node disjoint paths in the coverage graph of *N*
- Lemma 3.1: The maximum time for which *N* can provide *k*-barrier coverage is *m*/*k*.
  - Proof using the Reduction Theorem and the Menger's Theorem

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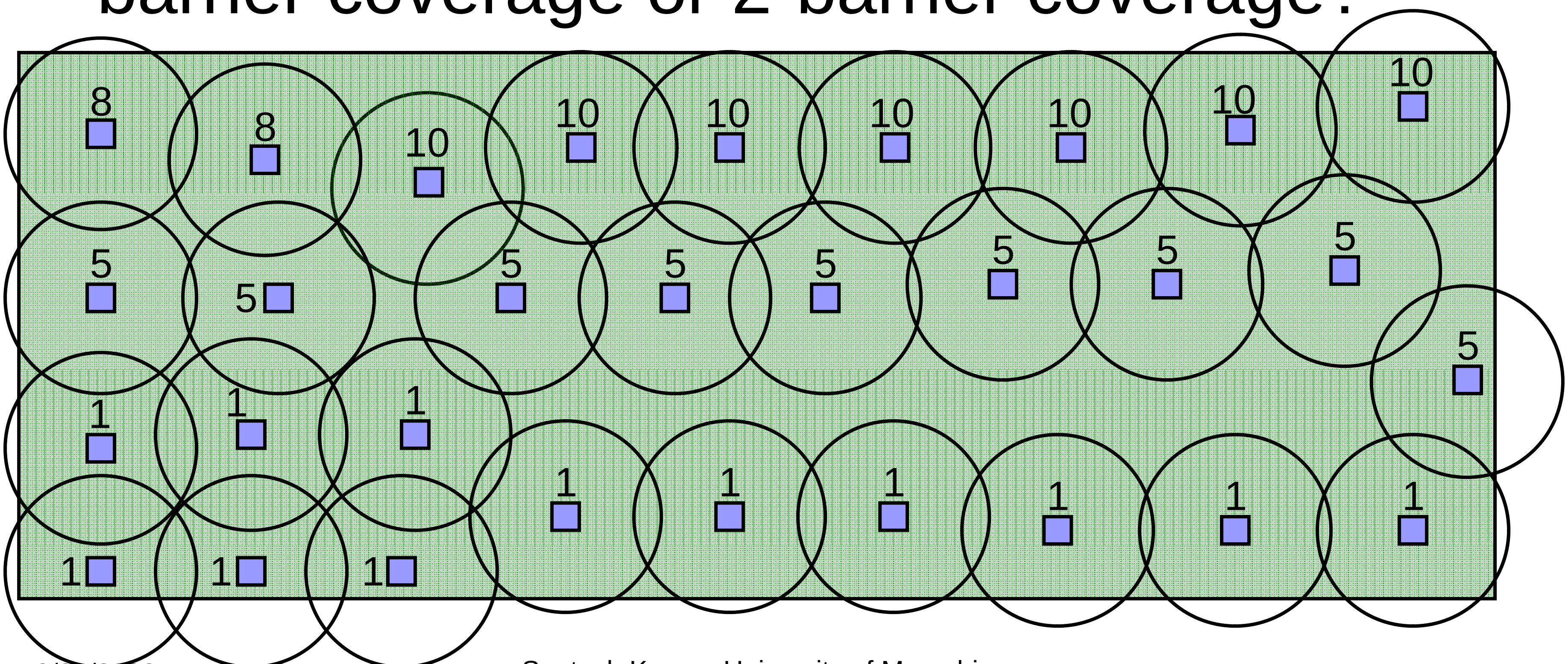
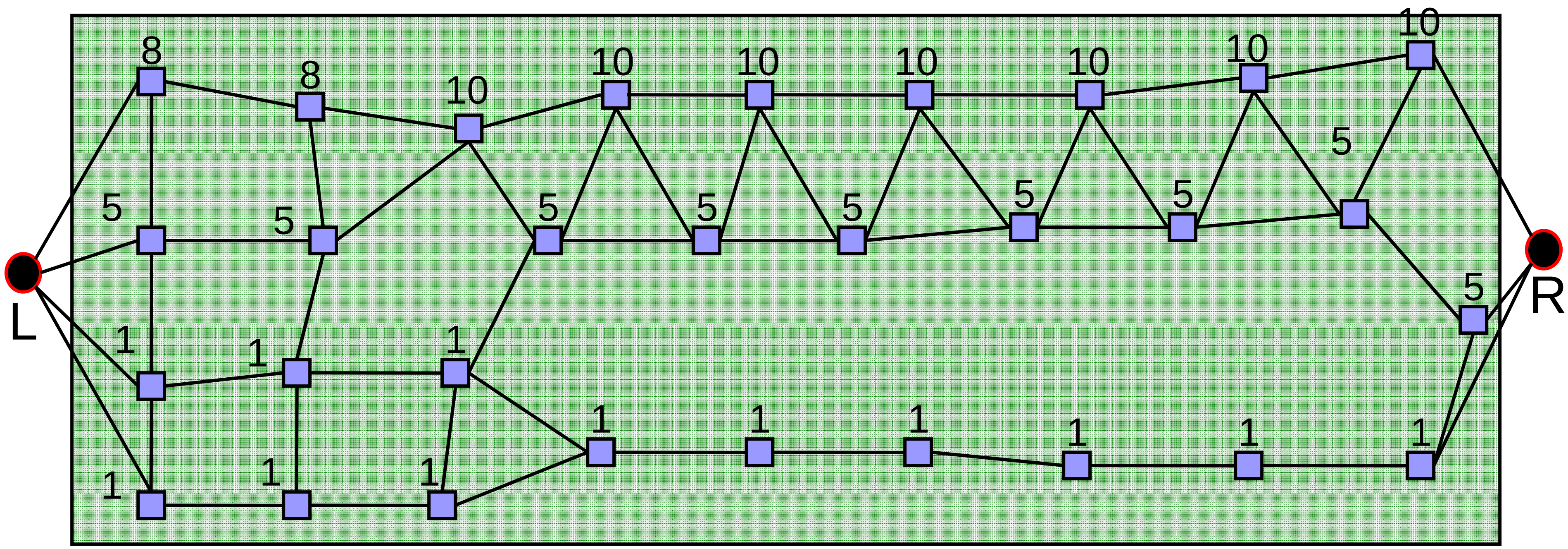
Heterogeneous Lifetime

- For how long can this network provide 1-barrier coverage or 2-barrier coverage?



The Flow Graph

- Maximum lifetime achievable for
  - 1-barrier coverage; 2-barrier coverage?

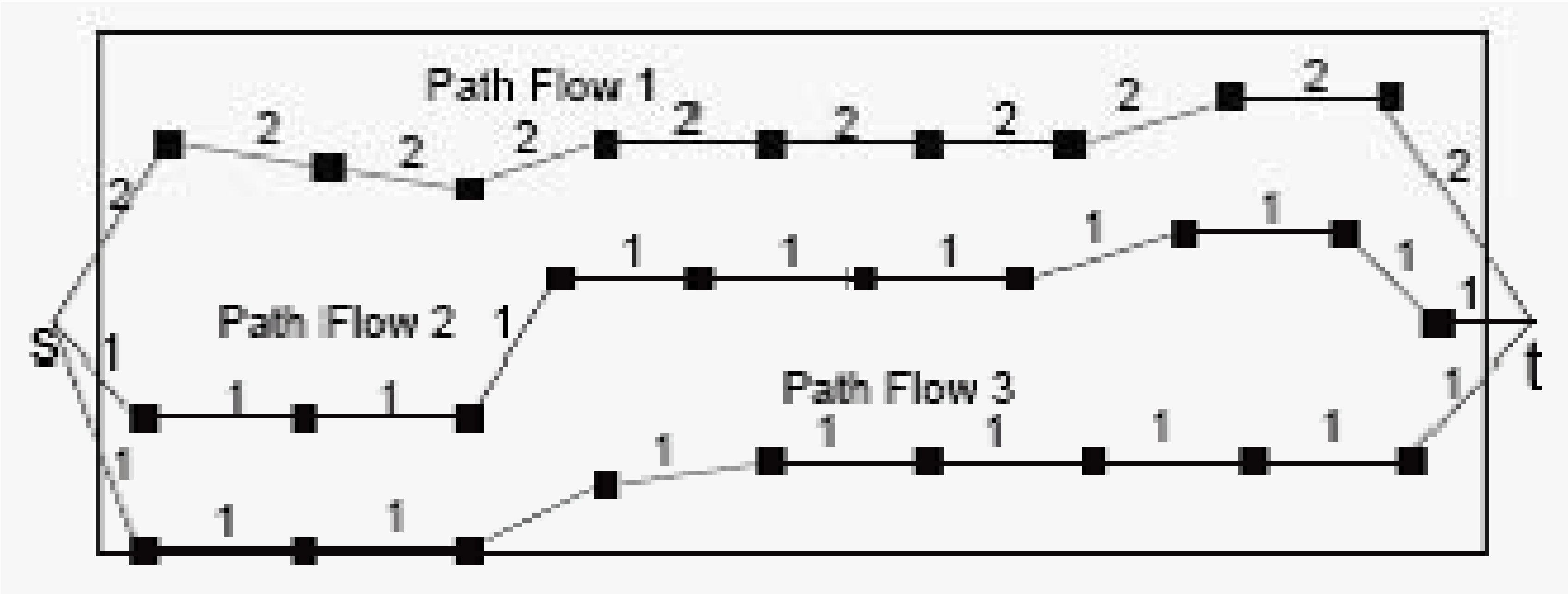


Multi-route Flow

- **Basic *k*-flow:** A set of node disjoint flows each of which has a value of *a*. The total value of the flow is *k*a*
- **Composite *k*-flow:** A set of flows that can be expressed as a linear combination of *basic k-flows.*

An Example

- Which ones are basic 2-flows?



Reduction to Multi-route Flow

- Given a sensor network *N*, there exists a sleep-wakeup schedule to achieve a lifetime of *T* time units for providing *k*-barrier coverage iff
  - There exists a composite *k*-flow of value *k***T* in the corresponding flow graph.
- Can now use existing algorithms for finding max multiroute flow to maximize network lifetime for *k*-barrier coverage.

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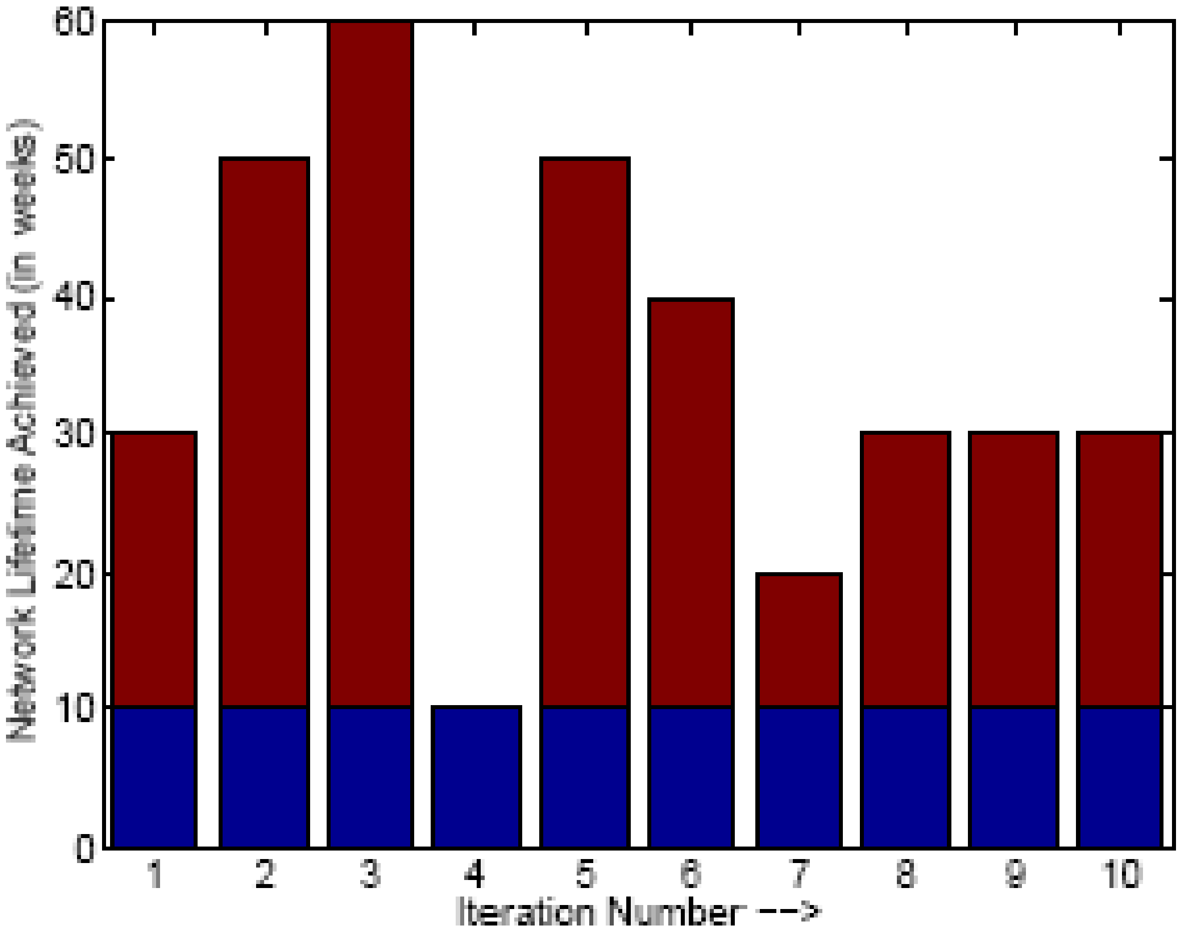
Exploiting statistical redundancy

- If sensors are deployed randomly but non-redundantly (i.e., optimally), then what level of lifetime increase may we get in practice?

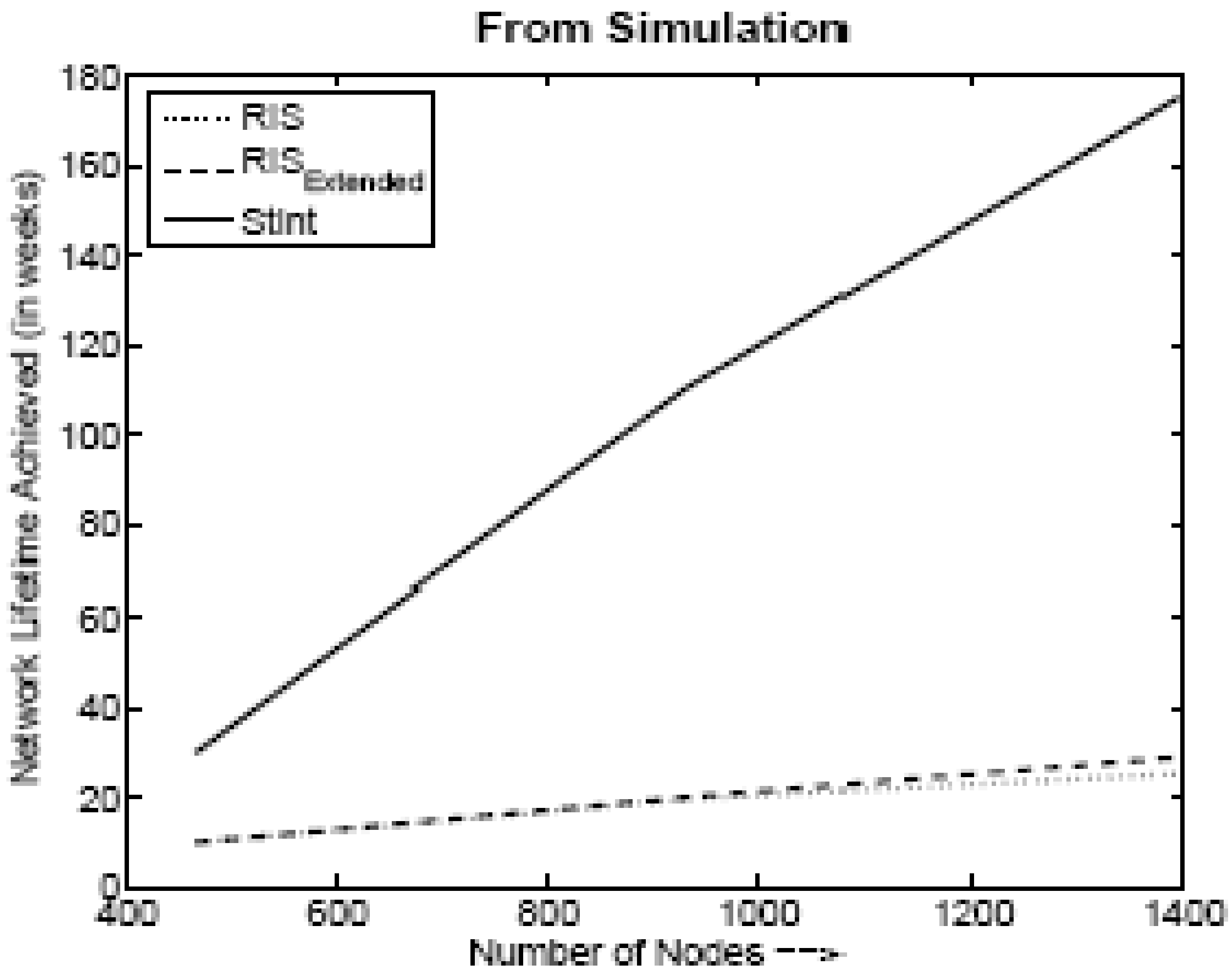
Random deployment



Homogeneous vs. Heterogeneous

- If lifetime distribution is sufficiently random, then median lifetime achieved in both cases are approximately the same
  - Provided an optimal algorithm for heterogeneous case is used

Improvement over RIS



Conclusions

- Showed that optimal sleep-wakeup scheduling is possible for a coverage model
  - Even the heterogeneous lifetime case is tractable
- Significant enhancement in lifetime is possible in randomized deployments even if the deployment is optimal

What about localized sleep-wakeup algorithms?

- Designing localized algorithms that provide deterministic guarantee is not possible (see our *MobiCom 2005* paper)
- It is, however, possible with suitable relaxation of the barrier coverage concept
  - See our *MobiCom 2007* paper
    - Ai Chen, Santosh Kumar, Ten H. Lai "**Designing Localized Algorithms for Barrier Coverage**"