Maximizing α-Lifetime for Wireless Sensor Networks

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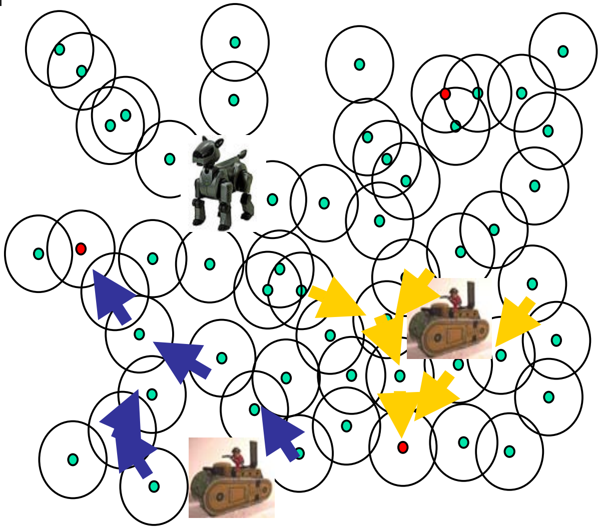
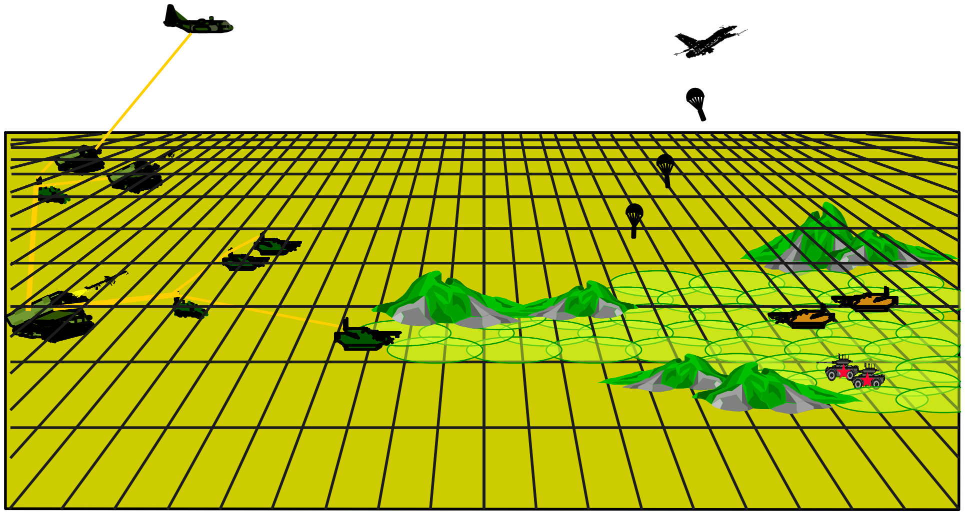
Wireless Sensor Networks (WSNs)

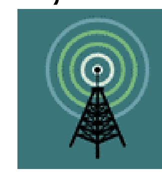




- WSN are emerging technologies for gathering dynamic information.
  - Inexpensive, airborne wireless nodes with acoustic sensors for target tracking and situational awareness for battlefield apps.
  - Statically/dynamically deployed sensor network for environmental monitoring (e.g., traffic, habitat, security).
  - Critical infrastructure protection (e.g., power grids, water distribution, waste disposal) in homeland security.

Critical Issues of WSNs

- Two fundamental tasks of WSNs
  - Sensing – sense changes in the temperature, pressure, acoustic/magnetic signal, chemical density, etc.
  - Communications – transmit the sensed signal



- Power is a scarce resource
  - How to perform the sensing and communication tasks using the minimal possible power, and prolonging the network lifetime?

Density Control

- As it is impractical to replace batteries on these sensors, a sensor network is usually deployed with a reasonably high density.
- In a high-density sensor network, only a subset of sensors nodes operate in the active mode to meet the following two requirements:
  - Coverage: the region that can be monitored is not smaller than the region that can be monitored by a full set of sensors.
  - Connectivity: the sensor network remain connected.
- Our Goal:
  - Explore the fundamental limit of sensor network lifetime that all algorithms can possibly achieve.
  - Explore to what extent the limit can be achieved.

Our Work Answers....

Given a sensor network of certain node density in a finite region,

> What is the upper bound on the lifetime under the scenario that only α portion of the region is required to be covered?
>
> Can the upper bound be achieved? To what extent?

Outline

- Problem formulation
- Major results
  - Upper bounds of α-lifetime
  - Algorithms approaching the derived bounds.
- Lessons learned in the performance evaluation
- Related work
- Conclusion and future work

We Consider Coverage Only, Because....

- We proved in [zheng:04]
  - If sensing range <= ½ transmission range, coverage implies connectivity.

Table 1: Radio transmission range of Berkeley Motes [15]

Product	Transmission Range
MPR300*	30m
MPR400CB	150m
MPR410CB	300m
MPR420CB	300m
MPR500CA	150m
MPR510CA	300m
MPR520CA	300m

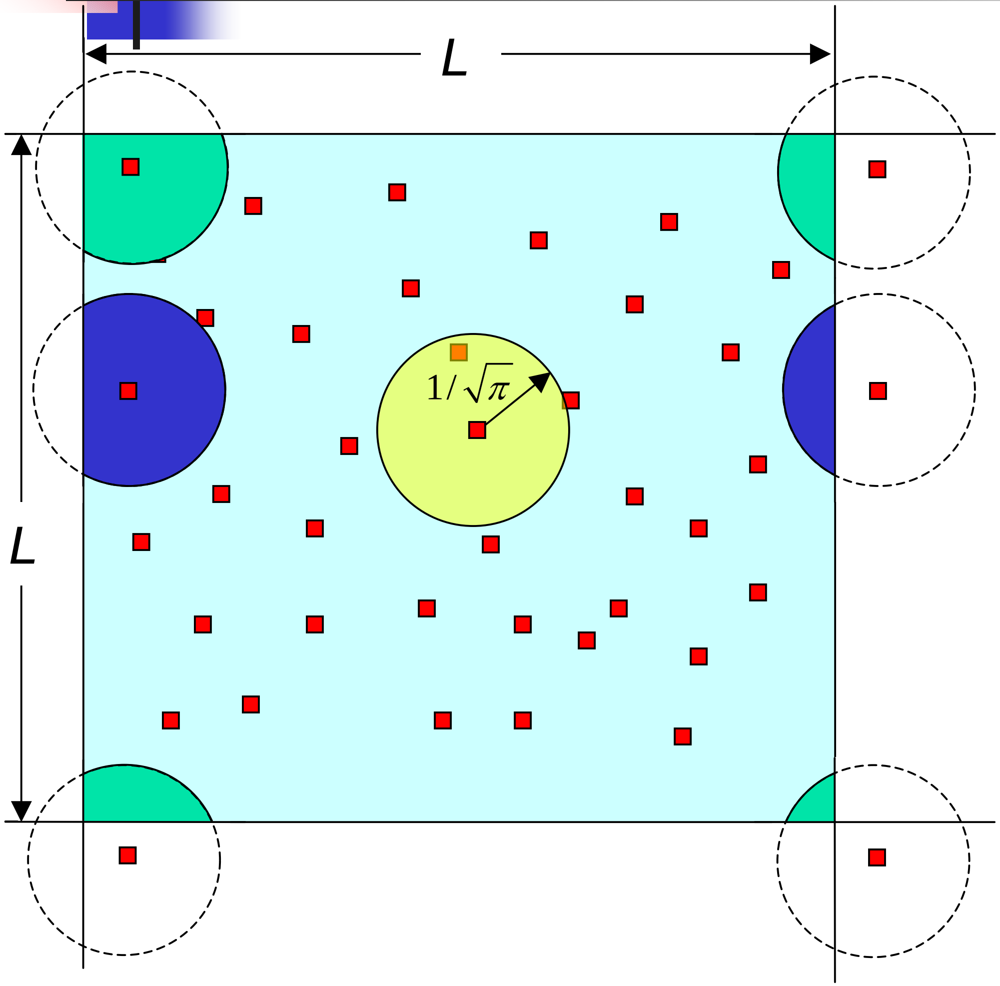
Table 2: Sensing range of several typical sensors

Product	Sensing Range	Typical Applications
HMC1002 Magnetometer sensor [5]	5m	Detecting disturbance from automobiles
Reflective type photoelectric sensor [13]	1m	Detecting targets of virtually any material
Thrubeam type photoelectric sensor [13]	10m	Detecting targets of virtually any material
Pyroelectric infrared sensor (RE814S) [10]	30m	Detecting moving objects
Acoustic sensor on Berkeley Motes * [5]	$\sim$ 1m	Detecting acoustic sound sources

* This result is based on our own measurement on Berkeley motes [5].

Honghai Zhang and Jennifer C. Hou, ``Maintaining sensing coverage and connectivity in large sensor networks,'' *Wireless Ad Hoc and Sensor Networks: An International Journal*, Vol. 1, No. 1-2, pp. 89--123, January 2005.

Problem Setting

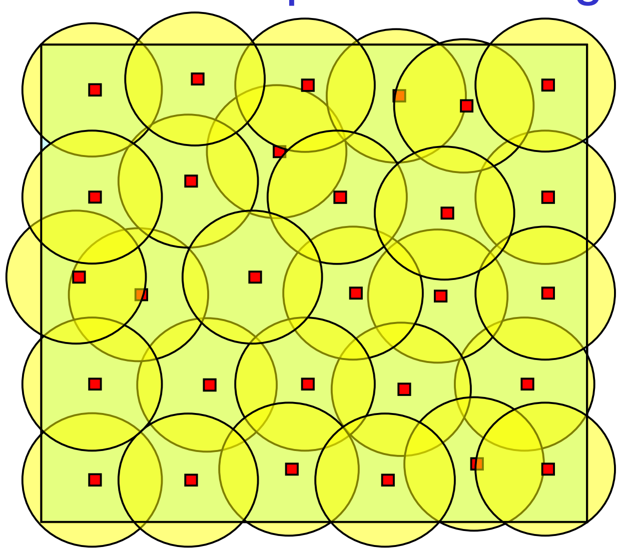


- Target region R: $[0,L]^2$
- Sensors form a Poisson point process with density λ
- Each sensor monitors a unit-area disk
- Each sensor has lifetime T
- Torus convention
  - Simplifies the calculation
  - Can be removed

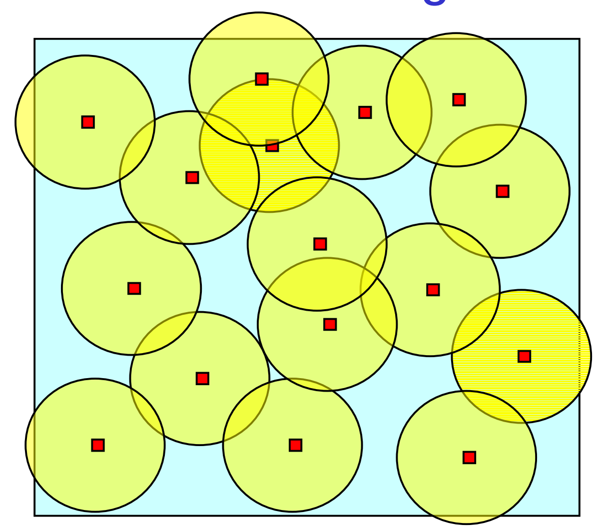
Sensor Network Lifetime

- Definition of α-lifetime
  - Length of time intervals during which at least α portion of the region is monitored by at least one sensor

- α=1: complete coverage



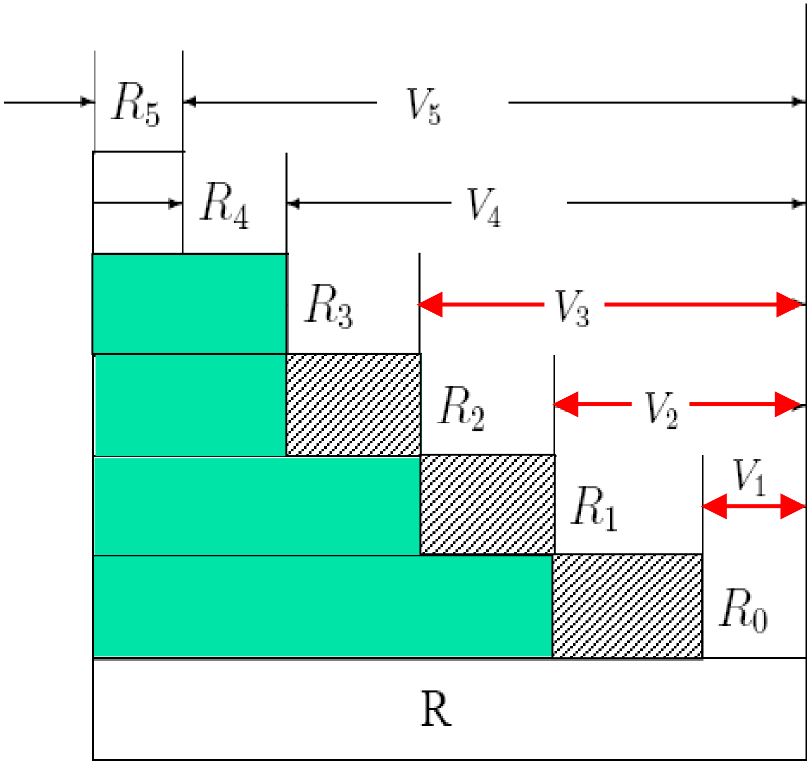
- α<1: α-coverage



Upper bounds of α-Lifetime

- Two upper bounds of α-Lifetime
  - For a special class of algorithms which maintain maximum possible coverage until the coverage ratio drops below α
  - For all possible algorithms which may provide α-coverage from the beginning of the network operation

Upper Bound of α-Lifetime for a Special Class of Algorithms



R_k: the area covered by exactly k nodes
V_k: the area covered by less than k nodes

- Algorithms: always maintain maximum possible coverage

time	maximum possible coverage
$0 \cdot T$	$1 - V_1 / L^2$
$1 \cdot T$	$1 - V_2 / L^2$
$2 \cdot T$	$1 - V_3 / L^2$
$\cdots$	$\cdots$
$(k-1) \cdot T$	$1 - V_k / L^2$

- In order to provide α-lifetime kT, it requires

$$1 - V_k / L^2 \geq \alpha$$

- α-Lifetime upper bound

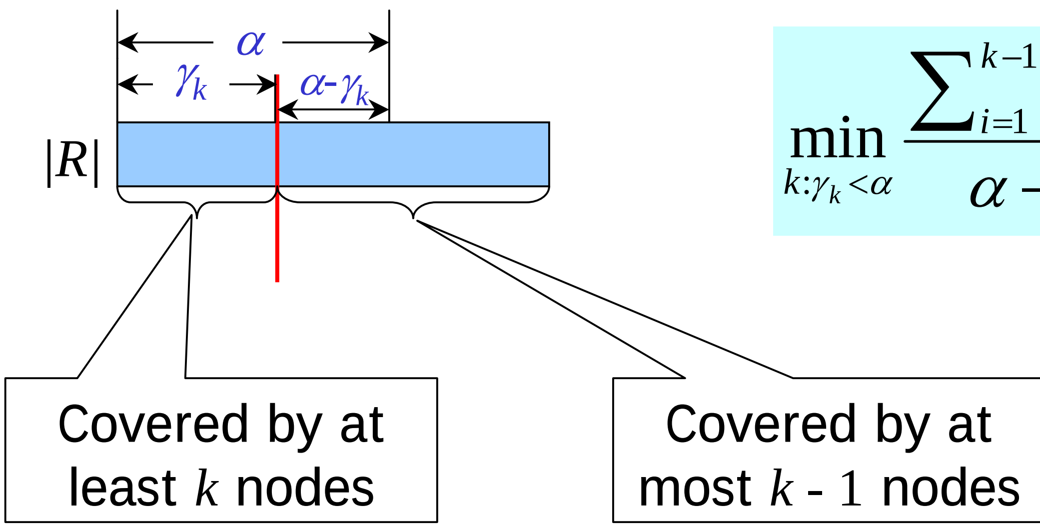
$$\max\{k : 1 - V_k / L^2 \geq \alpha\} \cdot T$$

Upper Bound of α-Lifetime for All Algorithms

β_i : portion of the area that is covered by exactly i nodes

γ_k : portion of the area that is covered by at least k nodes

- α-Lifetime upper bound for arbitrary algorithms

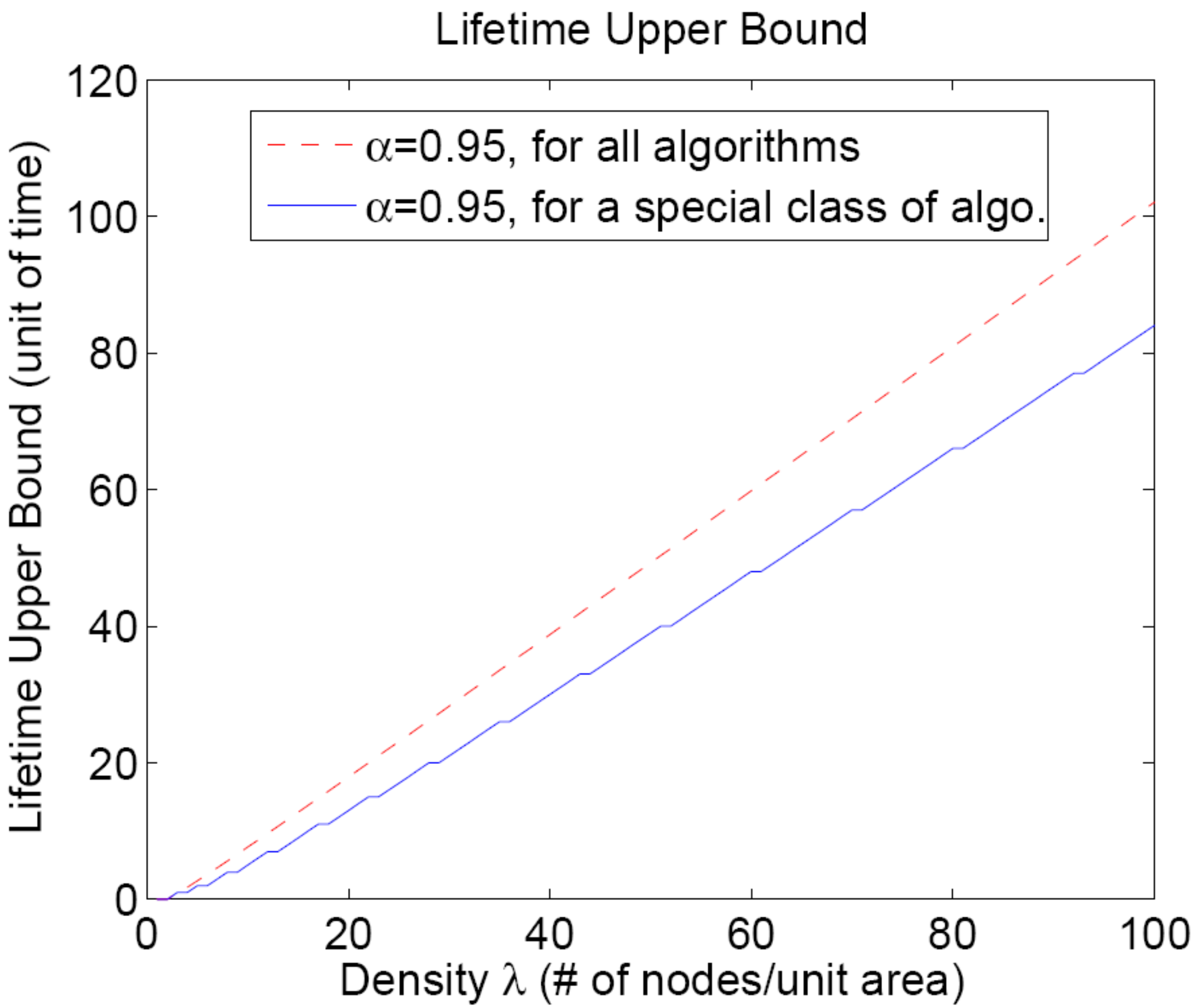


$$\min_{k:\gamma_k<\alpha} \frac{\sum_{i=1}^{k-1} \beta_i \cdot iT}{\alpha - \gamma_k}$$

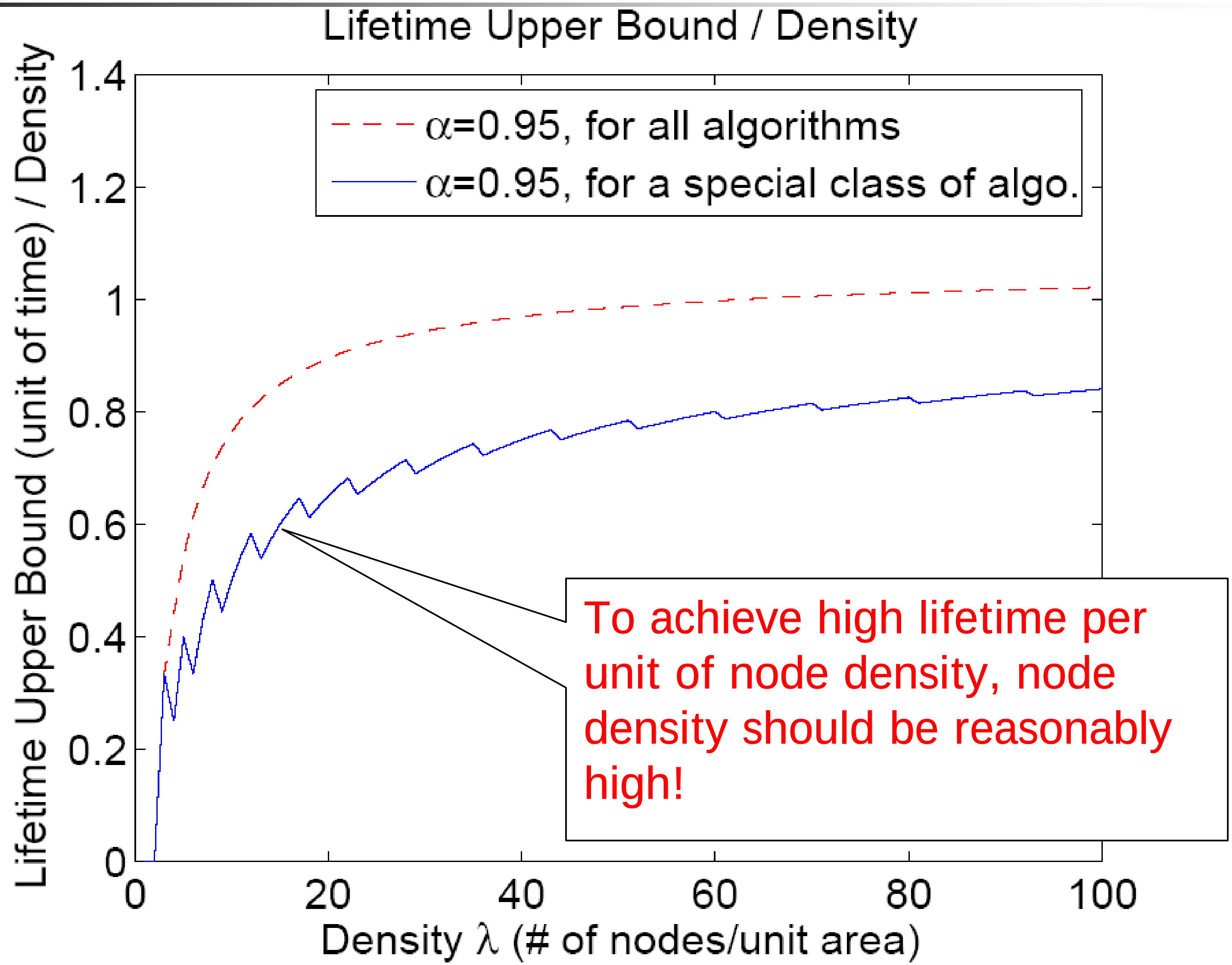
Total maximum contribution of coverage x lifetime by the right side

The right side must contribute α-γ_k coverage anytime

Numerical Examples



Numerical Examples



Questions to Ask

- Can the upper bound of the α-lifetime be achieved?
- To what extent?

Approaching α-Lifetime Upper Bound

- A baseline algorithm: repeatedly chooses a minimum subset of nodes that can provide α-coverage to be active

- Our algorithm: repeatedly chooses as active nodes a set of nodes that
  (i) can provide α-coverage, and
  (ii) maximize the α-lifetime upper bound of the remaining nodes

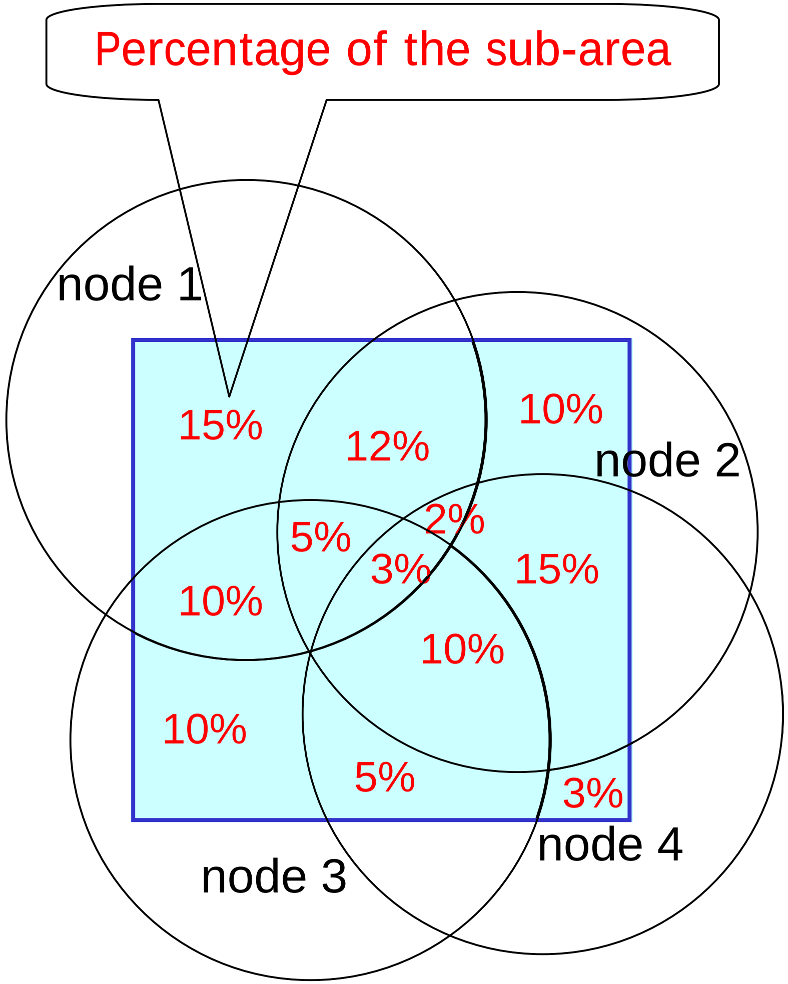
The Algorithm

α-Lifetime algorithm

1. the remaining set of nodes = the set of all nodes,
2. lifetime = 0,
3. **while** (the remaining set of nodes can provide α-coverage)
4. find an initial minimal α-cover C,
   search for a minimal α-cover which maximizes the lifetime upper bound for the remaining nodes,
   update the set of remaining nodes,
6. lifetime += T,
7. **endwhile**

Example

α =80%



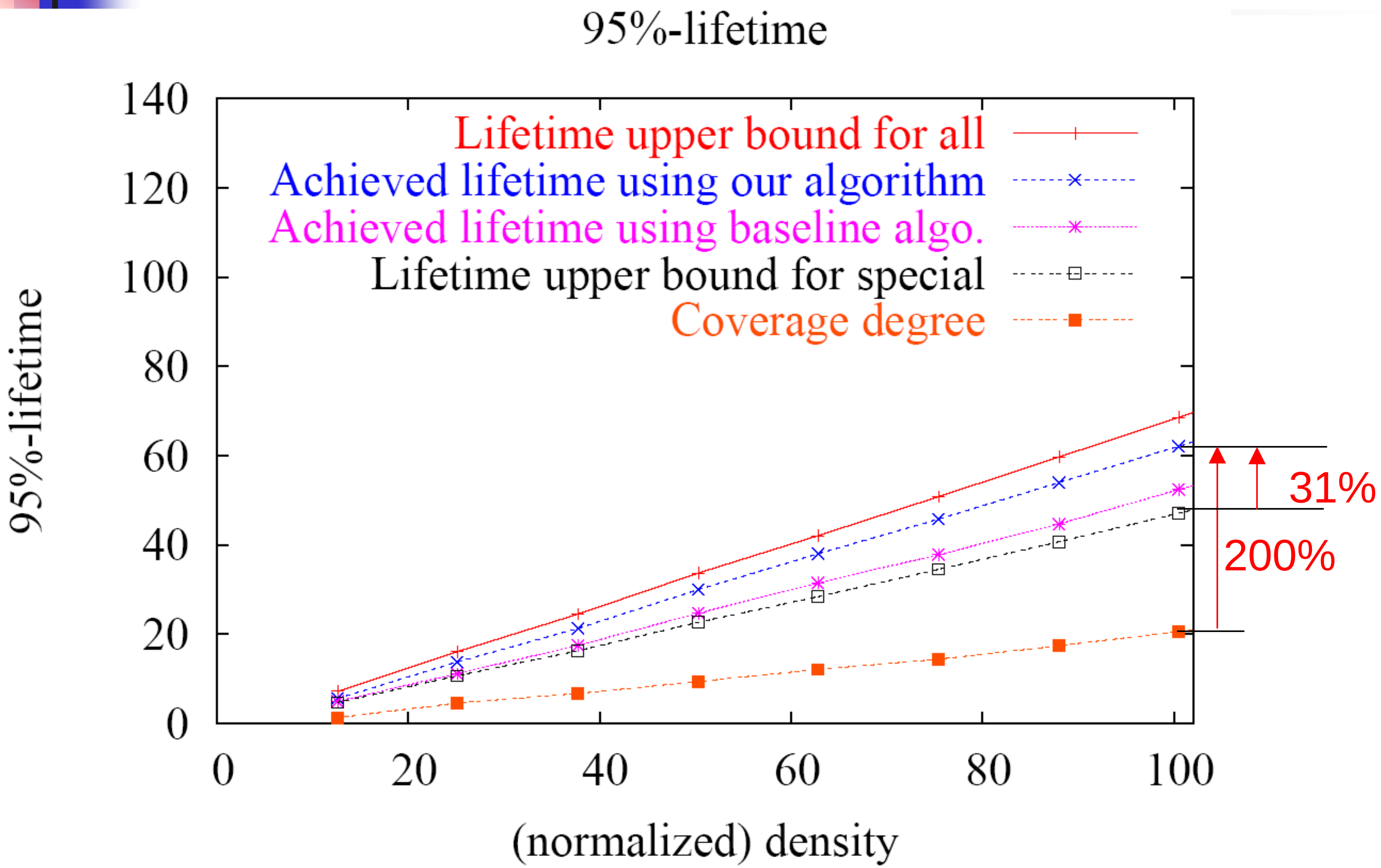
- ➢Nodes 1 & 2 cover 82%
- ➢Nodes 1 & 3 cover 72%
- ➢Nodes 1 & 4 cover 80%
- ➢Nodes 2 & 3 cover 82%
- ➢Nodes 2 & 4 cover 65%
- ➢Nodes 3 & 4 cover 63%

- Baseline algorithm:
  - At 0, choose 1 & 2
  - At T, stop
  - Lifetime T
- Our algorithm:
  - At 0, choose 1 & 4
  - At T, choose 2 & 3
  - Lifetime $2T$

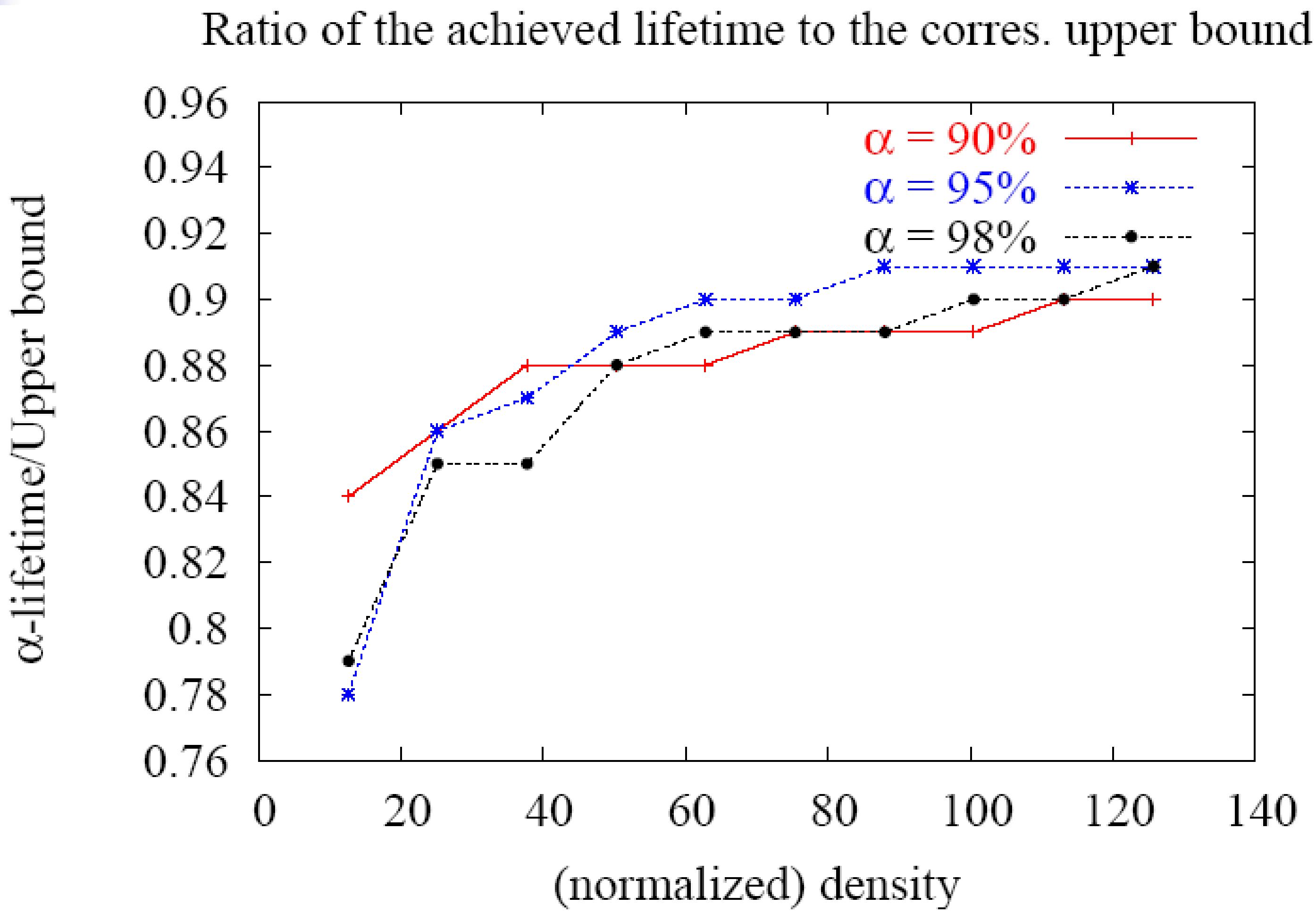
Performance Evaluation

- Methodology
  - Field size 100x100
  - Randomly distribute n nodes
  - Each has sensing radius r
  - Normalized density: $\frac{n\pi r^2}{10000}$
  - T=1

Simulation Results



Ratio of the Achieved α-Lifetime to the Upper Bound



Lessons We Learned

- Allowing a small portion of the area not covered can significantly increase the sensor network lifetime
- If the goal is to provide α-coverage, we should start with α-coverage from the beginning.
- For maximizing the lifetime, it is not always optimal to minimize the number of active sensors in each round, it is better to choose a set of nodes that can provide α-coverage and maximize the lifetime upper bound of the remaining nodes.

Related Works

- Bhardwaj et al. 2001, 2002
  - Analyzed the lifetime upper bound of data gathering networks.
  - Their model only considers power consumed when sensors sense active events and/or send/receive data.
- Blough and Santi 2002
  - Studied the network lifetime upper bound for cell-based algorithms.
  - Restricted to GAF-like schemes
- Coleri et al. 2002
  - Studied the lifetime of networked sensor nodes.
  - Primarily focused on the lifetime of individual nodes instead of that of the entire network.

Conclusions

- We derive the α-lifetime upper bounds
  - For a special class of algorithms
  - For all algorithms
- We design algorithms that maximize the lifetime upper bounds
  - To approach the derived upper bound

Future Work

- Jointly consider both coverage and connectivity
- Consider the issue of coverage and connectivity with an additional temporal dimension.
  - The set of working nodes needs not cover the entire region at all times, but only need to provide, for each point, intermittent coverage with the inactive period less than or equal to the given bound.