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Integrated Coverage and Connectivity Configuration in Wireless Sensor Networks

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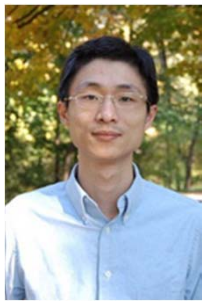
OUTLINE

- Introduction: Conserve Energy in WSNs through combined Coverage and Connectivity Configuration
- Relationship between Coverage and Connectivity: Geometric Analysis
- Coverage Configuration Protocol (CCP)
- Experiments and Results
- Conclusions

Introduction


Xiaorui Wang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Christopher Gill

- Washington University, St. Louis
- Lots of related work already available concerning coverage or connectivity in WSNs
  - **But**: both topics treated separately

- Published in ACM Transactions on Sensor Networks, 2005

Problem Formulation

- **Goal**: Energy conservation in wireless sensor networks
  - Longer lifetime
- **Solution**: Scheduling sleep intervals for some nodes
  - Which ones?
  - How many?
- **Problem**: Active nodes must provide continuous service
  - Coverage
  - Connectivity

Sensing Coverage

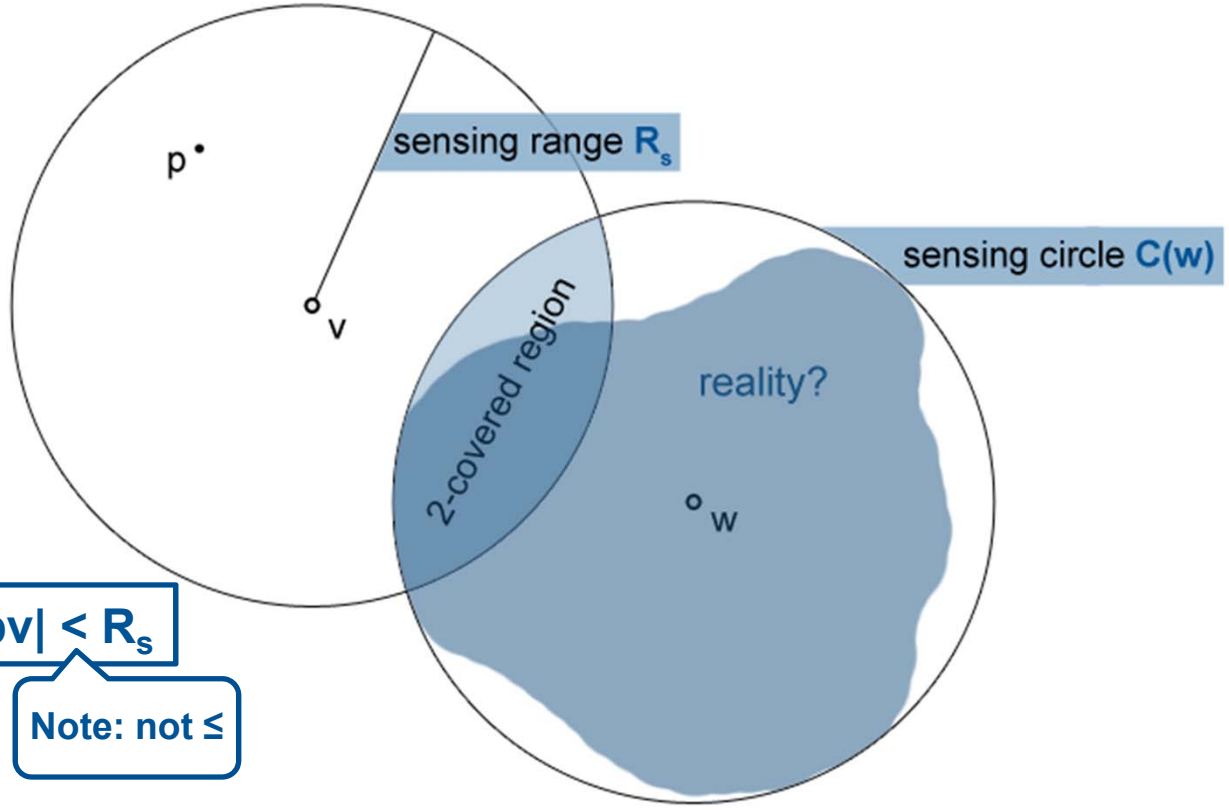
- Coverage describes the monitoring quality provided by a sensor network

- **Definition**: Coverage degree of K (K-covered)
  - Every location is covered by at least K nodes

- Required degree of coverage can differ / change
  - Depending on region, application

Sensing Coverage

- R_s: sensing range



p is covered by v if $|pv| < R_s$

Note: not ≤

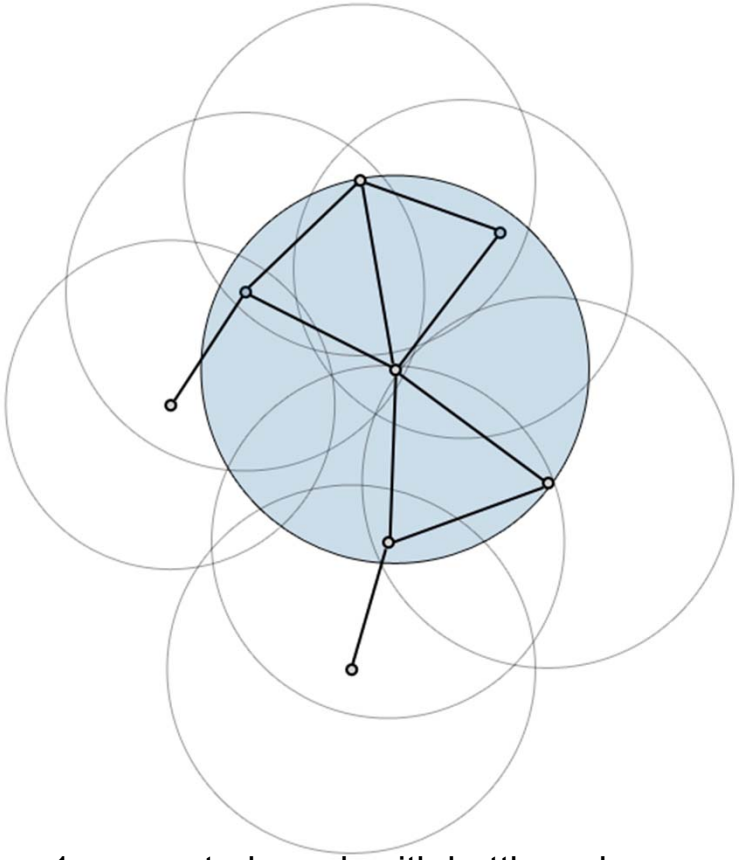
Connectivity

- Connectivity guarantees communication
- Affects robustness and achievable throughput
  - Avoid communication bottlenecks
- **Definition**: K-connected graph
  - If any possible K-1 nodes fail, network will remain connected

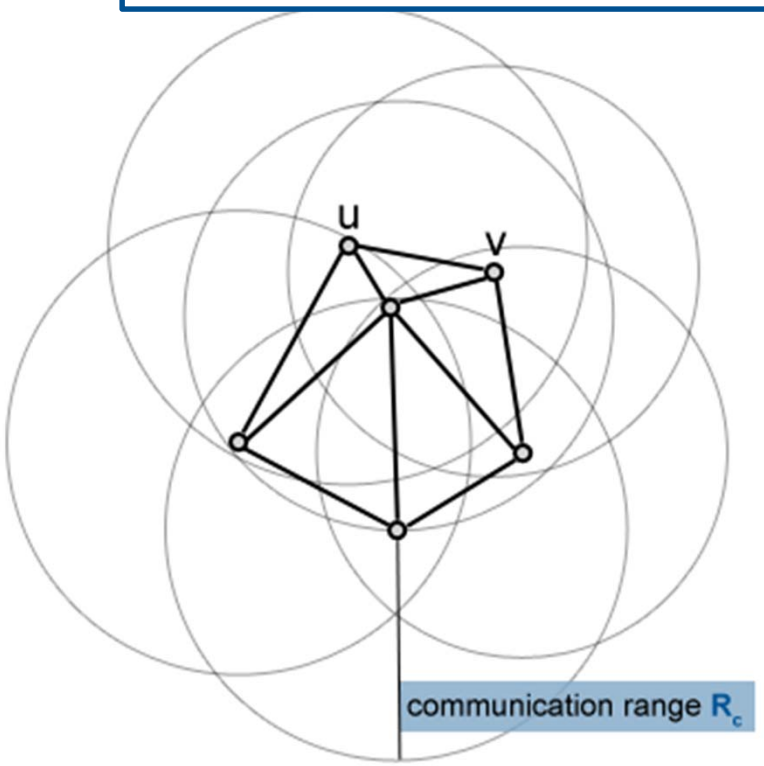
Connectivity

- R_c: communcation range

u and v can communicate if $|uv| < R_c$



1-connected graph with bottleneck



3-connected graph

Same Problem, new Formulation:

- Maximizing the number of passive nodes under the constraint that remaining nodes guarantee:
  - All active nodes are connected
  - Region is at least K-covered

Sensor coverage degree, configurable

RELATIONSHIP BETWEEN COVERAGE AND CONNECTIVITY

Does Coverage Imply Connectivity or Vice Versa?

- Connectivity does not guarantee coverage
  - Regardless of ranges
- But coverage guarantees connectivity
  - 1-covered sensor network guarantees 1-connectivity
  - **Condition**: $R_c \geq 2R_s$
  - Only configure network to guarantee coverage to satisfy both

Relationship between Degree of Coverage and Connectivity

- **Condition**: $R_c \geq 2R_s$
- Nodes that K-cover a convex region form a K-connected communication graph
- For set of nodes that K-cover a convex region, the interior connectivity is 2K

Number of sensors that must be removed to disconnect any two interior sensors

COVERAGE CONFIGURATION PROTOCOL (CCP)

CCP Key Benefits

- Variable coverage degree
  - As requested by application
- Decentralized protocol
  - Only depends on local states of sensing neighbors
  - Scales effectively
  - Change coverage degree at run-time
- Provides guaranteed degrees of coverage

All active nodes within twice its sensing range

Node States of CCP

- Node can be in one of three states:
  SLEEP, ACTIVE, LISTEN
- Initial state: ACTIVE

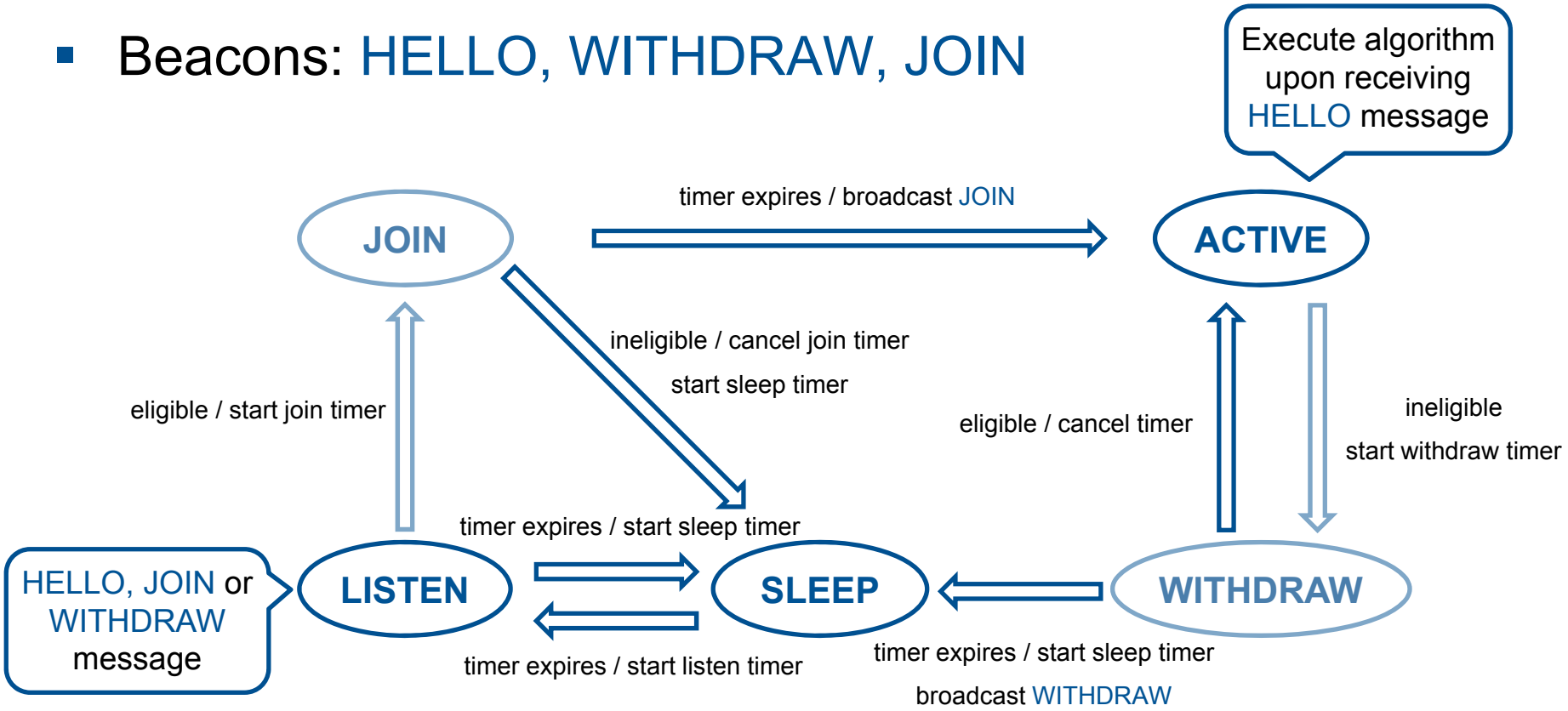
- Redundant nodes switch to SLEEP
  - If required degree of coverage exceeded

- Reenter ACTIVE if coverage below desired level

- Changes based only on local information

State Transitions of CCP – Detailed View

- Beacons: HELLO, WITHDRAW, JOIN



- Randomized timers
  - Avoid collisions

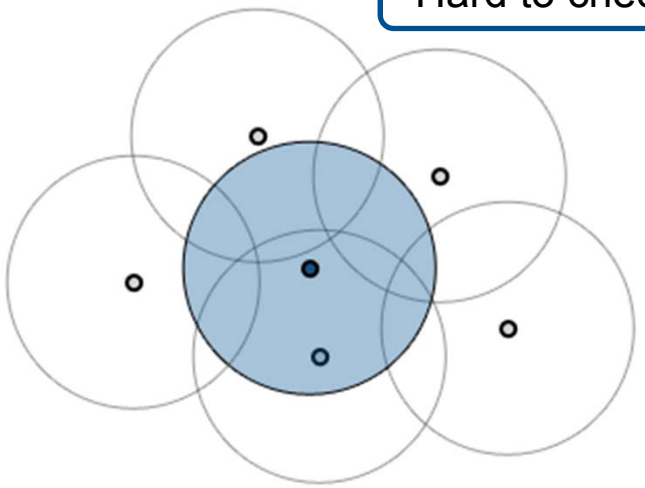
K-Coverage Eligibility Algorithm

- Each node runs algorithm
  - Determine if it is necessary to become active

can stay passive

- With requested coverage of degree K, node ineligible if:
  - Its whole coverage range is already K-covered

Hard to check



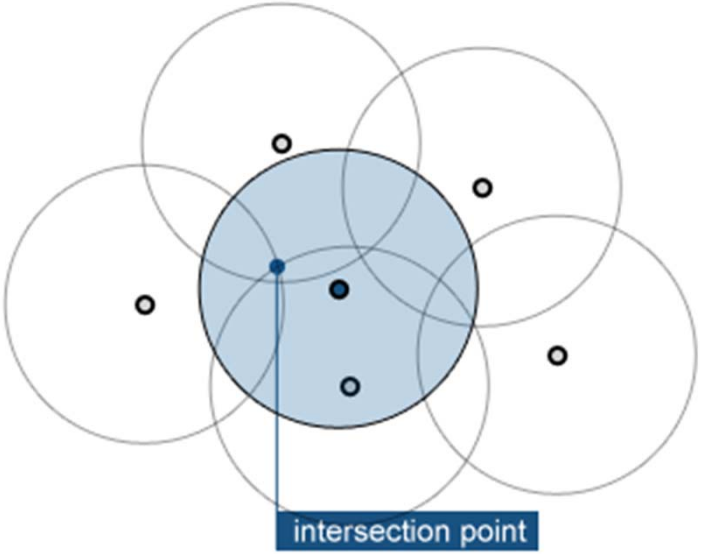
Blue node

- Ineligible for K = 1
- Eligible for K > 1

Simpler Argument for Ineligibility

- Assumption: $R_c \geq 2R_s$

- Sensor is ineligible if all intersection points inside its sensing range are at least K-covered



K-Coverage Eligibility Algorithm

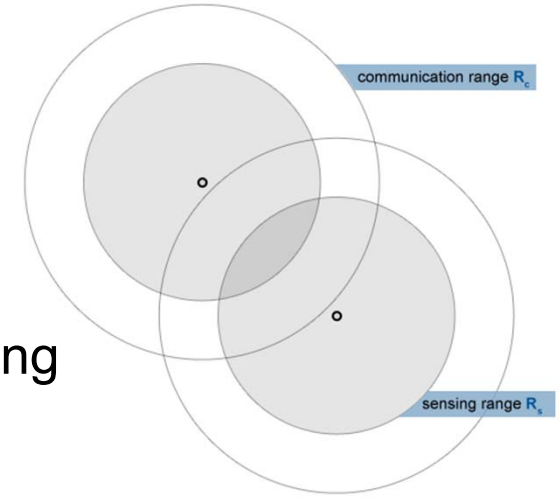
- Important steps in the algorithm
  - Find all intersection points inside node's sensing circle
  - For each intersection point compute its coverage degree
  - If one intersection point is not K-covered, node is eligible
  - Otherwise, node becomes ineligible

- Computational complexity: $O(N^3)$

Number of nodes in sensing neighbor set

CCP When $R_c < 2R_s$

- CCP does not guarantee connectivity if $R_c < 2R_s$



- **SPAN** [1]
  - Existing connectivity maintenance protocol
  - Decentralized coordination protocol
  - Turning off unnecessary nodes while maintaining communication backbone

  - **SPAN's eligibility rule**: Become eligible if at least one pair of its neighbors can't reach each other either directly or via one or two active nodes

Combination of SPAN and CCP

- Eligibility rule for inactive nodes
  - Become active if eligible according to eligibility rule of SPAN or CCP
- Eligibility rule for active nodes
  - Withdraw if node satisfies eligibility rule of neither SPAN nor CCP
- CCP guarantees coverage
  - Active nodes might not communicate with each other
  - SPAN activates extra nodes (if needed)

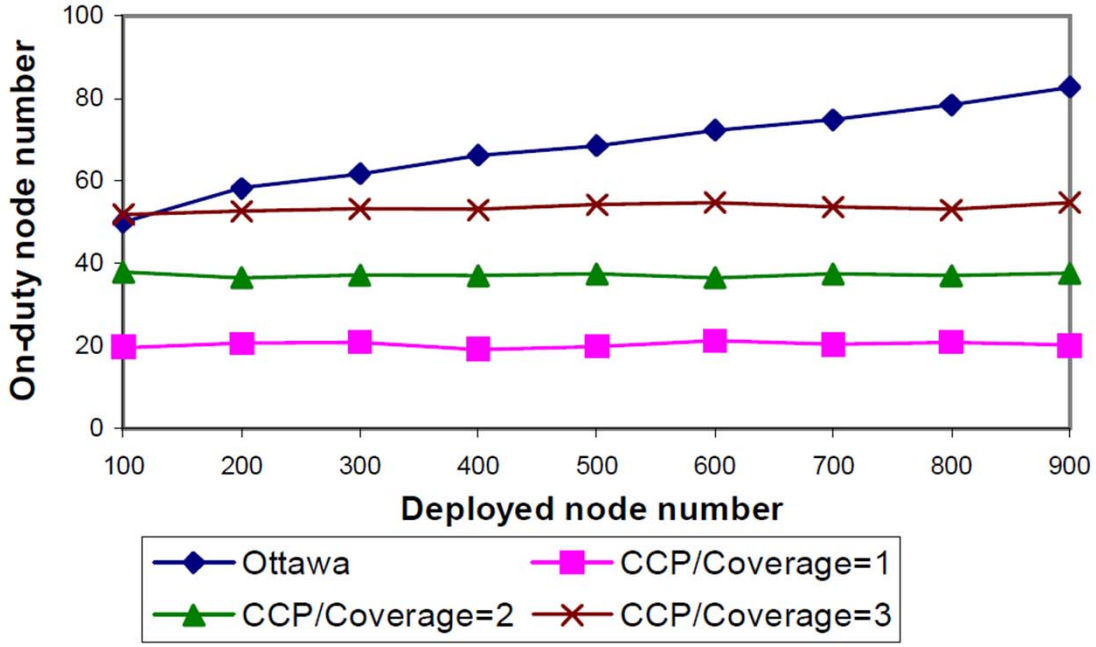
EXPERIMENTS

Experiment: Coverage Configuration

- Performed on Coverage Simulator
  - Assumes perfect wireless communication
- Compared to Ottawa Protocol [2]
  - Preserves coverage while turning off redundant nodes
  - Does not support different coverage configurations
- CPP makes decisions based on twice the sensing range, Ottawa only within sensing range

Coverage Configuration: Results

- CCP guarantees requested degree of coverage without unnecessary redundancy
- CCP is proportional to degree of coverage



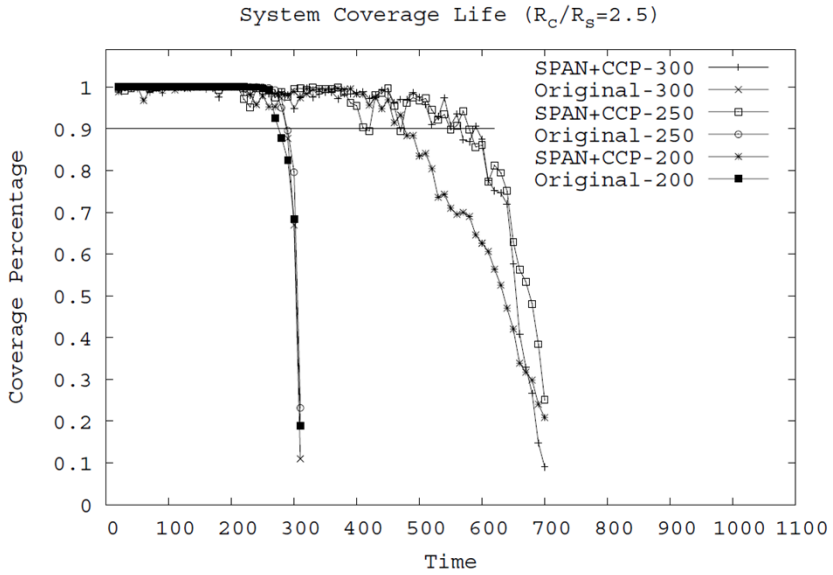
Experiment: System Life Time

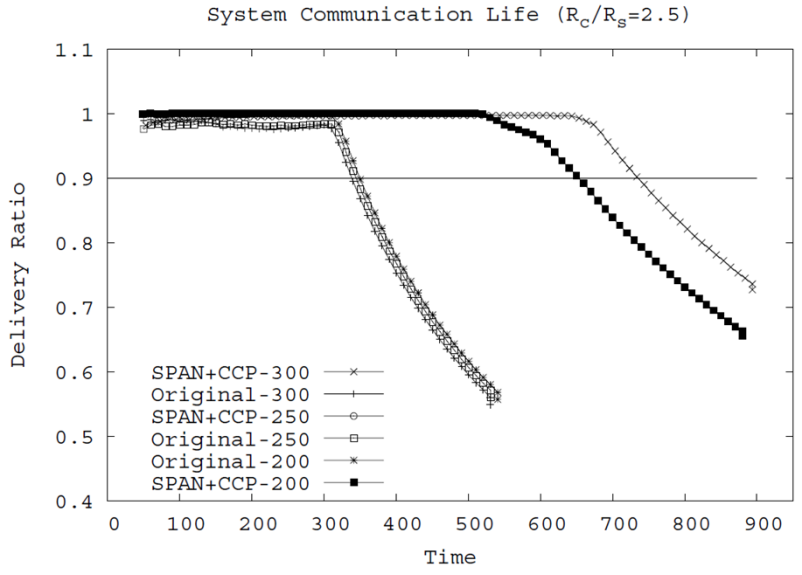
- SPAN+CCP compared to original network with all nodes on
  - Significant improvement expected

- Tested with different node deployment densities
  - Randomly distributed in area of same size

System Lifetime: Results

- Increases system lifetime as expected
- Coverage lifetime dominates overall system lifetime
- Lifetime doesn't increase much with higher node density
  - Wake up to listen to 802.11 beacons consumes considerable energy





CONCLUSIONS

Conclusions

- Sensing coverage implies connectivity
  - If $R_c \geq 2R_s$
- CCP can achieve different degrees of coverage on request
- CCP maintains both desired coverage and connectivity
  - $R_c \geq 2R_s$
  - CCP + SPAN

References

- [1]: B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks“

- [2]: D. Tian and N.D. Georganas, "A Coverage-preserved Node Scheduling scheme for Large Wireless Sensor Networks"