Power Management under Coverage and Connectivity Constraints in Sensor Networks

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Outline

- Motivation
- Coverage vs. Connectivity: Geometric Analysis
- Coverage Configuration Protocol (CCP)
- Applying CCP to realistic applications
- Routing performance
- Conclusion

Motivation

- Many sensor networks require long lifetime
  - Several months to years: habitat monitoring, civil structure monitoring, surveillance
- Energy is scarce
  - Low cost energy supply, e.g., AA batteries
  - Wireless communication is energy costly
- Continuous service
  - Sensing
  - Communication: network connectivity, routing ....

Approaches

- Duty cycle schedule
  - Example: SMAC
  - Cons: Long communication delay
- Active backbone
  - Use a small number of active nodes to provide “sufficient” service
  - Schedule other nodes to sleep
  - Examples: SPAN, CCP

“Sufficient” Service

- Sensing
  - N-coverage: every point in a region is covered (monitored) by at least N active sensors
- Communication
  - K-Connectivity: network is connected if (K-1) nodes fail
  - Routing quality: how many hops between two nodes?

Limitations of Existing Protocols

- Treat connectivity and coverage in isolation
  - Connectivity only: ASCENT, SPAN, AFECA, GAF, ...
  - Coverage only: exposure, Ottawa’s protocol, ...
  - Density: PEAS
- Lack flexibility: only provide fixed degree of coverage
**Goals**
- Design a protocol that guarantees desired **coverage** and **connectivity**
- Requirements
  - **Integrated**: must guarantee both coverage and connectivity
  - **Flexible**: can re-configure the network to different coverage degrees and connectivity
    - Meet diverse application requirements
  - **Decentralized**: achieve scalability

**Assumptions**
- The region to be covered is convex
- Disc models for coverage and communication
  - A point p is covered by a node v if |pv| < Rs
  - Rs: Sensing range
  - Nodes u and v are connected if |uv| < Rc
  - Rc: Communication range
- Intuition: range ratio Rc/Rs is important!

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**Implication of Geometric Analysis**
- Given a required coverage degree of Ks, and a required connectivity of Kc
- If Rs ≥ 2Rs, the protocol only needs to guarantee max(Ks, Kc) coverage configuration
  - Solution: Coverage Configuration Protocol (CCP)
- If Rs < 2Rs, the protocol must address both coverage and connectivity.
  - Solution: CCP + SPAN

**Connectivity vs. Coverage**
- A connected network does not guarantee coverage
  - Connectivity only concerns with node locations
  - Coverage must cover all locations in a region
  - True for any Rc/Rs
  - If Rc/Rs ≥ 2
    - K-coverage → K-connectivity for all nodes
    - K-coverage → 2K-connectivity for interior nodes
  - Interior node: a node whose sensing circle fully contained by the region

**A Sufficient Condition for K-Coverage**
- A convex region B is K-covered if all the intersection points among sensing circles and/or B’s boundary inside B are K-covered
- Implication: a coverage configuration protocol only needs to worry about intersection points!
**K-Coverage Eligibility Rule**

- All intersection points inside the sensing circle are K-covered?
- To evaluate eligibility, a node only needs to know the locations of active nodes within $2R_s$.

![Diagram of active nodes and intersection points](image)

**Coverage Configuration Protocol (CCP)**

- Active nodes periodically broadcast and receive beacon messages.
- Sleeping nodes periodically wake up and receive beacons.
- Change state based on the eligibility rule:
  - Active $\Rightarrow$ sleeping if the eligibility rule is true.
  - Sleeping $\Rightarrow$ active if the eligibility rule is false.

**Simulation: Coverage Configurability**

![Graph showing coverage configurability](image)

- CCP strictly enforces desired coverage degrees!

**SPAN**

- All nodes periodically broadcast/receive beacons.
- Change state based on the eligibility rule:
  - Active $\Rightarrow$ sleeping if the eligibility rule is false.
  - Sleeping $\Rightarrow$ active if the eligibility rule is true.
- Eligibility rule:
  - At least one pair of my neighbors cannot reach each other either directly or via one or two active nodes.
  - Every sleeping node is within one hop of at least one active node.

**CCP+SPAN**

- When $R_c < 2R_s$, CCP cannot guarantee connectivity.
- Solution: CCP + SPAN
- Combined eligibility rule:
  - Sleeping $\Rightarrow$ active if either CCP or SPAN activates the node.
  - Active $\Rightarrow$ sleeping if both CCP and SPAN put the node to sleep.

**Simulation: Coverage+Connectivity ($R_c = 1.5R_s$)**

- Combination of SPAN & CCP is necessary for desired coverage and connectivity when $R_c < 2R_s$. 
Simulation: Coverage vs $R_c/R_s$

- CCP-based protocols guarantee coverage for all $R_c/R_s$
- SPAN's cannot guarantee coverage for any $R_c/R_s$

Simulation: Connectivity vs $R_c/R_s$

- SPAN-based protocols delivers more packets
- CCP cannot delivery all packets when $R_c/R_s < 2$

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Realistic Detection Applications

- Requirements: detection prob., false alarm rate
- Probabilistic sensing range
  - Stochastic signals/noises
  - Signal decay
  - Usually determined from empirical measurements
- Multi-sensor data fusion
  - Single sensor may be faulty and cause false alarms
  - Reliable detection decision should base on multiple sensor readings
  - Fusion rule: how to reach a final decision based on multiple sensor readings?

Applying CCP to Realistic Detection Applications

- Probabilistic sensing model
  - A point within the sensing range of a sensor is covered with prob. $P$
- Application requirement: ($K$, $\beta$) coverage
  - $\text{Prob}(\text{target is detected}) \geq \beta$
  - Target detected if sensed by at least $K$ sensors
- Solution: run CCP with coverage degree $K'$ given by:
  \[ 1 - \frac{\binom{K'}{i}}{\binom{K}{i}} P^i (1 - P)^{K - i} \geq \beta \]
Illustration: Applying CCP to Realistic Detection Applications

- The probability is sensed by 2 sensors must > 0.95
- Each sensor senses with prob. 0.9
- How many sensors are needed to cover?

\[ P = 0.9, K = 2, \beta = 0.95, K' = ? \]

Scalability and Performance

Impact of Sensing Coverage on Routing Performance

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Greedy Geographic Forwarding

- Forward packet to the neighbor with the shortest Euclidean distance to destination

Pros and Cons of Greedy Forwarding

- Local decision based on neighbor locations
  - Allow efficient implementation on constrained platforms
  - Match location-centric communication paradigm in WSN
- Fail when a packet reaches a local minima
  - A node cannot find a neighbor better than itself
  - Recovery schemes: face routing, flooding
  - Result in long routes
- Does greedy geo-routing perform better on sensing-covered networks?
- Can we establish analytical performance bounds?
Routing Metric: Network Dilation

- Network dilation of a graph under a routing algorithm
- Definition
  \[ D_n = \max_{u,v} \left( \frac{|u,v|}{R_{uv}} \right) \]
  - \# of hops found by a routing algorithm
  - \min \# of hops
- Low \( D_n \) means good routing algorithm
- For any two nodes \( u \) and \( v \), a path no longer than \( D_n \) hops can be found by a routing algorithm whose network dilation is \( D_n \)

Greedy Forwarding in Networks with Coverage

- GF always succeeds when \( R_c/R_s > 2 \)
- \# of hops between \( u \) and \( v \):
  \[ R - 2R_s \]

Do Better than Greedy Geo-routing

- Voronoi Diagram of a set of nodes \( V \) partitions the plane into Voronoi regions, one for each node.
- A point lies inside \( u \)'s Voronoi region if \( u \) is the closest node to the point.
- Delauney Triangulation (DT) is the dual graph of Voronoi diagram of \( V \)
  - An edge between \( u \) and \( v \) in DT iff Vor(u) and Vor(v) share a boundary
  - The Euclidean distance of shortest path from \( u \) to \( v \) in DT < 2.42 \( |uv| \)
- Theorem: DT is a sub-graph of the network with sensing coverage
- Good routing algorithm is possible by taking advantage of DT

Bounded Voronoi Greedy Forwarding (BVGF)

- A neighbor is eligible only if its Voronoi region intersects the line joining source and destination
- Greedy: choose the eligible neighbor closest to destination

Conclusion

- Geometric analysis on relationship between coverage and connectivity
  - Only need to worry about coverage when \( R_c \geq 2R_s \): Coverage Configuration Protocol
  - Must worry about both when \( R_c < 2R_s \): CCP + SPAN
  - CCP can be applied to realistic applications
  - Sensing coverage implies good routing property
  - Simple greedy geo-routing works well
  - Justifies power management protocols that maintain sensing coverage
  - Source can compute bound on network distance based on source/destination locations
  - Scalable real-time communication
Critiques

- Circular sensing/communication range
- Need more realistic sensing model (see CoGrid paper: www.cs.wustl.edu/~xing)
- Geometric routing may not work well when communication links are unreliable
- No evaluation on motes