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Internet of Things

VI. Topology and Coverage Control

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Internet of Things: Topology and Coverage Control

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1. Introduction and Motivation

- Roles need to be assigned to each sensor.
- Nodes not needed at a given time should enter sleep state.

Issues

- Topology Control
  - Which sensors are required for communication connectivity ?
  - Which transmission power is needed for achieving connectivity ?
- Coverage Control / Sensing Mode Selection
  - Which sensors are needed to meet application requirements in terms of covering an area ?

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2. Topology Control

- Enough sensors must be active to provide network connectivity in order to deliver sensor data to the sink.
  - Sensors not needed can be switched off, also to avoid interference.
  - Transmission power should be adapted to avoid interference.
- Contradictory issues: connectivity, interference, and energy saving
- Optimized resource usage requires sophisticated scheduling of sensors.
- Application QoS to be considered

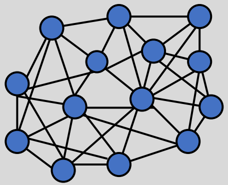
Requirements

- Energy efficient operation (sensing and routing)
- Scalability for large numbers of sensors
- Distributed control
- Low computation overhead
- Robustness to node failures

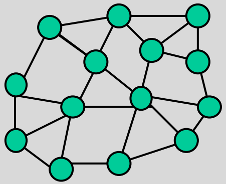
2. Topology Control

1. Topology Control Approaches

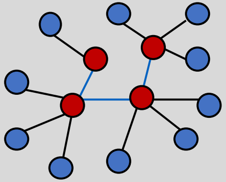
- Topology of a network consists of
  - set of active nodes (vertices, V)
  - set of active links along that nodes can communicate (edges, E)
  - $(v_1, v_2) \in E \subseteq V^2$ iff v_1 and v_2 can communicate with each other



- Topology control transforms (E, V) into (E_T, V_T) with $E_T \subseteq E$, $V_T \subseteq V$, e.g., by
  - switching off nodes $\in$ V or
  - limit a node's transmission power to adapt edges $\in$ E.
  - → flat network topology



- Active links can be arranged in a hierarchical fashion.
  - Nodes are selected for a backbone.
  - Only links within backbone and from other nodes to the backbone → Connected Dominating Set D
  - $D \subset V$ with $\forall\, v \in V: v \in D \vee \exists\, d \in D: (v, d) \in E$



2. Topology Control

2. Requirements to Topology Control Algorithms

- Connectivity
- Hop/energy stretch factor
  - relative increase in hops/energy of topology-controlled path for any pair of u and v compared to shortest path in original graph
- Throughput
- Robustness to mobility
- Algorithmic overhead

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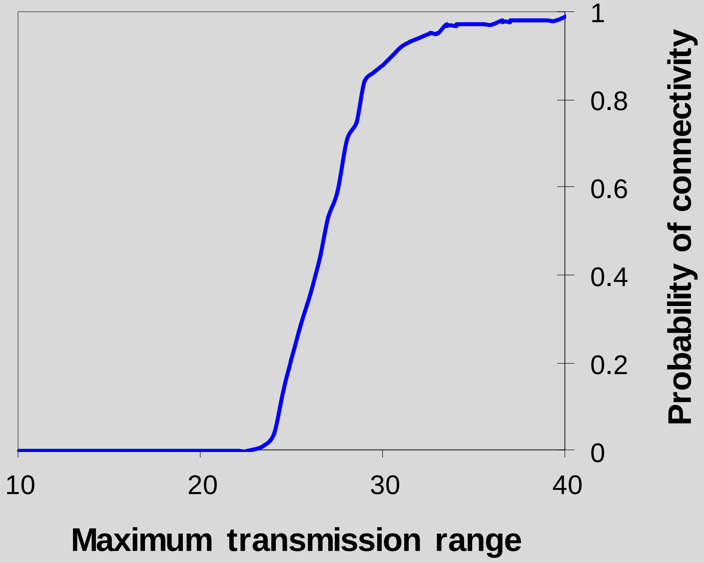
2. Topology Control

3. Connectivity

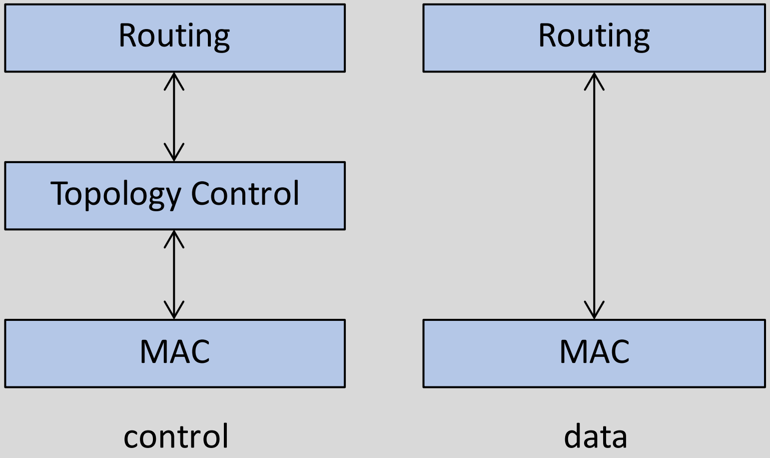
- Experiment
  - 5‘000 nodes in an area of 1000 m x 1000 m
  - Disk graph model with transmission radius r
  - Evaluation of connectivity for 100 random topologies
- Result
  - Connectivity increases sharply (percolation effect).



2. Topology Control

4. Protocol Stack

- Interaction between routing and topology control layers
  - Routing layer triggers topology control execution.
  - Topology Control layer triggers routing updates.
- Topology Control is not involved in data transfer.



2. Topology Control

5. Flat Topology Control Protocols

Flat topology:
All nodes have the same tasks.

Examples

1. Relative Neighborhood Graph
2. Gabriel Graph
3. Delaunay triangulation
4. Local Minimum Spanning Tree
5. Cone-based Topology Control
6. COMPOW

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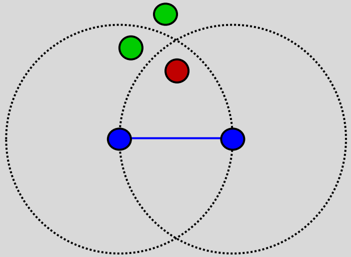
2. Topology Control

5.1 Relative Neighborhood Graph

- RNG T of G (V, E) is defined as

  $T = (V, E'), \forall\, u, v \in V: (u, v) \in E',$
  $\text{iff} \nexists\, w \in V: \max\{d(u,w), d(v,w)\} < d(u,v),$
  d: Euclidean distance
- T can be computed locally.
- T is connected if G is also connected.
- Problem: Hop stretch can become large.



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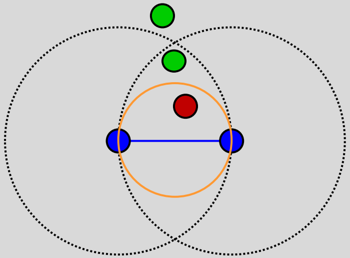
2. Topology Control

5.2 Gabriel Graph

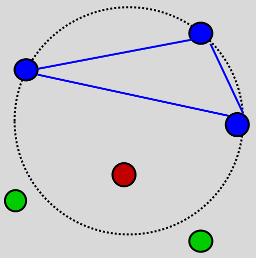
- GG T of G (V, E) is defined as T = (V, E'), $\forall$ u, v $\in$ V : (u, v) $\in$ E' iff $\nexists$ w $\in$ V: $d^2(u,w) + d^2(v,w) < d^2(u,v)$, d: Euclidean distance
- RNG is a sub-graph of GG, since the circle is included in the lune.

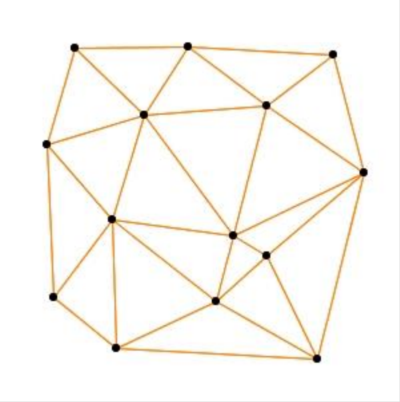


2. Topology Control

5.3 Delaunay Triangulation

- Delaunay Triangulation of a set of n points P is the unique triangulation DT of P such that the circumcircle of every triangle contains no points of P in its interior.
- Complexity: O(n log n)



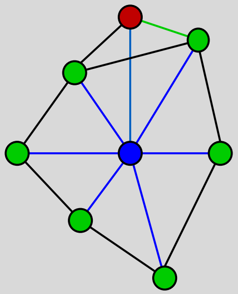


2. Topology Control

5.4 Local Minimum Spanning Tree

Phases

1. Information exchange
   – Beacon transmission with maximum transmission power
2. Topology construction
   – Each node calculates its local minimum spanning tree for the 1-hop-neighbors based on received beacon messages and Euclidean distance / energy costs as link weights. (minimized sum of edge lengths)
   – Node v is kept in the neighbor list of node u, if v is a 1-hop-neighbor of u in its minimum spanning tree.
3. Determination of transmit power
   – Estimation of transmit power by comparing the received power of beacon message (sent with maximum transmission power).



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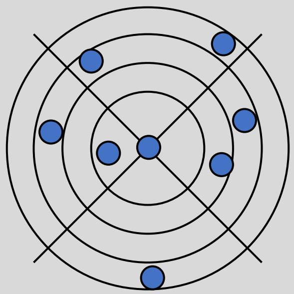
2. Topology Control

5.5 Cone-based Topology Control

Phases

1. Construction of a connected topology
   – Each node u starts with a small transmission power.
   – The node sends beacons to discover neighbor nodes v_i.
   – The node increases the transmission power until there is a neighbor in each cone with angle α or the maximum transmission power has been achieved.



2. Removal of redundant edges
   – If there are two edges (u, v_1) and (u, v_2), the longer edge of these can be removed, if $d(v_1, v_2) < \max\{d(u, v_1), d(u, v_2)\}$

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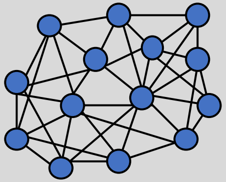
5.6 COMPOW

– Assumption: All nodes have a certain set of power levels.

– Nodes run a routing protocol for each power level with corresponding control message exchange. Maintenance of routing table for each power level.

– Nodes select the lowest power level that has the same number of reachable nodes as the maximum power level.

– Problem: overhead by several routing protocols



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2. Topology Control

6. Hierarchical Topology Control Protocols

Approach: select virtual backbone of nodes that remain active and can serve other nodes. Packets are routed along backbone.

Examples for distributed approximations

1. Minimum Connected Dominating Sets
2. SPAN
3. Geographic Adaptive Fidelity

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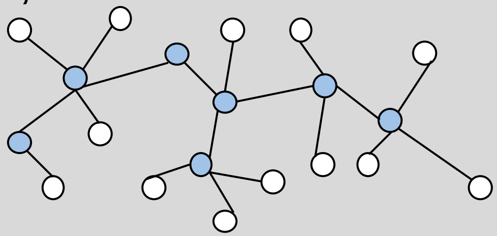
2. Topology Control

6.1 Minimum Connected Dominating Sets

- The dominating set D of a graph (V, E) is a subset $D \subset V$, where each node in $V - D$ is adjacent to some node in D; $D \subseteq V$ with $\forall\, v \in V : v \in D \vee \exists\, d \in D: (v, d) \in E$
- A connected dominating set is a dominating set that builds a connected sub-graph of G.
- Minimizing the nodes in D results in a MCDS.
- Finding a MCDS is NP complete.
  $\rightarrow$ Heuristics must be applied,
  e.g., Multipoint-Relay-based
  CDS construction.



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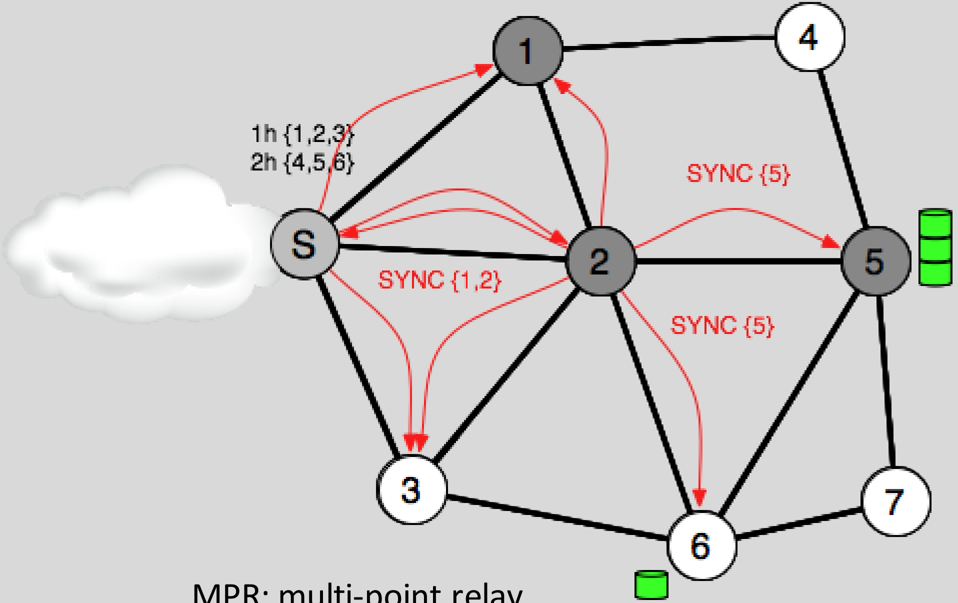
2. Topology Control

6.1.1 MPR-based CDS Construction

```
input:   2-hop neighbour list L2 of node x;
         1-hop neighbour list L1 of node x;
output:  MPR set of next-hop dominators of node x;
begin
      repeat
         If ∃ y ∈ L1 and y is the only node in L1 connecting to a node z in L2
            Add y to MPR set;
            Remove all nodes z in L2 that are now covered;
         else
            For each y in L1 do
               Compute number of nodes (δ(y)) in L2 that are not covered by an MPR node
               and that are connected to y;
            Select y with highest value for (δ(y)•remaining_energy_of_y) into MPR set;
            Remove all nodes z in L2 that are now covered;
      until all 2-hop neighbours are covered;
end
```

2. Topology Control

6.1.2 Example: MPR-based CDS Construction



MPR: multi-point relay

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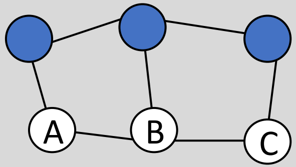
2. Topology Control

6.2 SPAN

- SPAN makes local decisions whether a node operates as coordinator.
- Node periodically announces willingness to become a coordinator, if it discovers that 2 neighbors can not communicate to each other via at most 2 backbone nodes, e.g., B becomes coordinator due to A and C
- Coordinator periodically checks whether to withdraw. By announcing itself as tentative, other nodes get a chance to become coordinator.
- Randomized back-off delay for announcements dependent on available energy and number of neighbors
  - N_i: # neighbors of node i
  - C_i: number of additional pairs among neighbors that can be connected by i
  - R: random number
  - $E_{r,i}$: remaining energy of node i
  - $E_{m,i}$: maximum amount of energy that node i can have
  - RTT: round trip time on wireless link



$$delay = \left(\left(1 - \frac{E_{r,i}}{E_{m,i}}\right) + \left(1 - \frac{C_i}{\binom{N_i}{2}}\right) + R \right) \cdot N_i \cdot RTT$$

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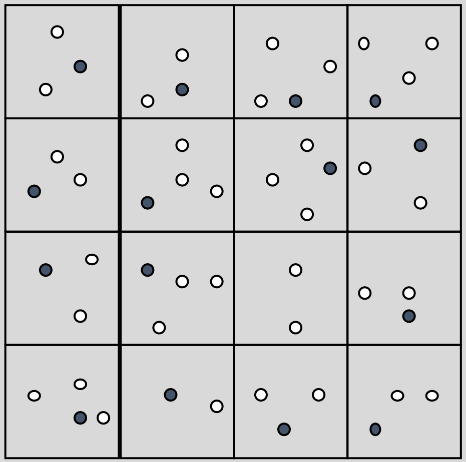
2. Topology Control

6.3 Geographic Adaptive Fidelity

- Formation of virtual grid. Two nodes in adjacent grids can communicate with each other.
- A single node in a grid cell is chosen to be active at any given time.
  Selection is based on estimated node lifetime.
- If a node detects another more suitable node, it falls into sleep and periodically reenters discovery state.



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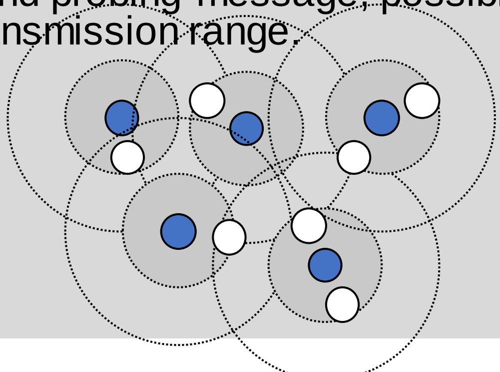
3. Coverage Control

- Activating too many sensors can be counter-productive.
  - Generation of data can congest and overload the network.
  - Energy waste by unnecessary sensors and data packet forwarding
- Sensing mode selection decisions
  - Which sensors to activate / deactivate?
  - Which sensing features to select? Examples:
    - Data resolution
    - Sensing time
    - Sensing frequency
- If (sensing range s > transmission range r): Active routers are sufficient. Otherwise: activation of additional sensors
- Main goal: preservation of coverage within an area

3. Coverage Control

1. Probing Environment and Adaptive Sleeping

- Threshold-based protocol enforcing that two sensing nodes are not closer than s
- Sensor nodes
  - initially sleep,
  - wake up periodically, and
  - send probing message, possibly with low transmission range.

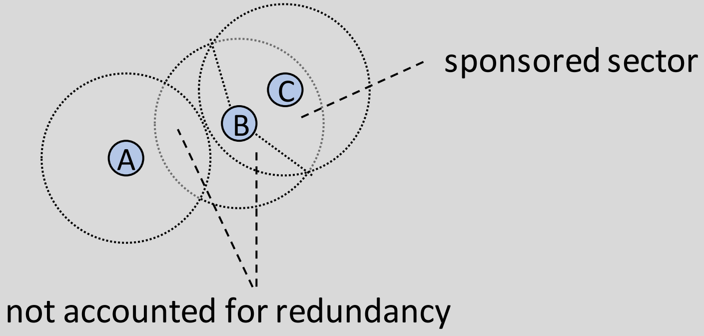


- Each receiving sensor should estimate (using localization mechanisms) whether (distance to probing sensor < s).
  - If so, activity should be indicated by receiving sensor and probing sensor can fall into sleep mode again.
  - Otherwise, probing sensor begins sensing.
- Probing range depends on desired density.
- Probing frequency must balance energy savings and robustness.

3. Coverage Control

2. Node-Self Scheduling Scheme

- A node measures during a certain interval its neighborhood redundancy as the union of sectors covered by neighboring sensors.
- If the full 360° are covered, the node can decide at the end of the interval to distribute a withdrawal message and power off.
- Possible redundancy can be considered.
- Problem: node failures



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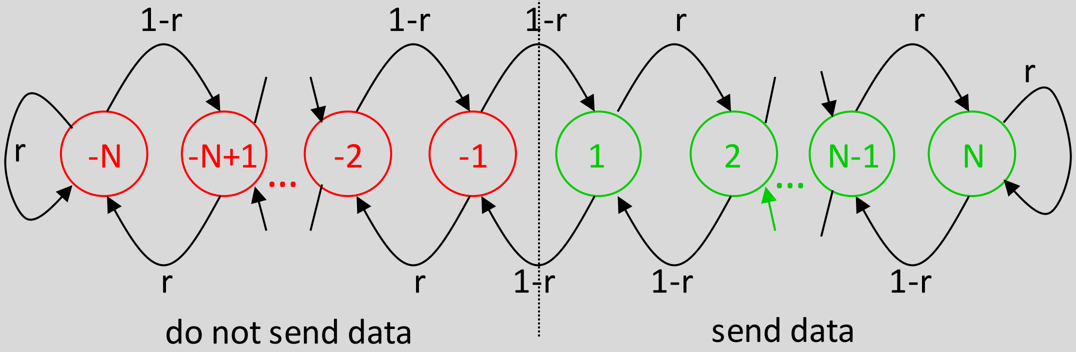
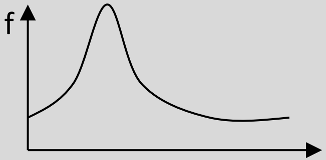
3. Coverage Control

3. Gur Game

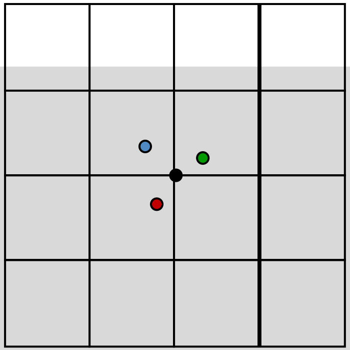
- Base station desires to receive a certain number of messages from sensors.
- Each sensor runs a finite state machine.
  - Left side: Sensor does not send data.
  - Right side: Sensor sends data.
- Base station calculates r = f(# of received packets) and broadcasts r.
  - f has a maximum at desired resolution.
- Each sensor moves
  - with probability r towards the edge and
  - with probability (1-r) towards the center.
- Good convergence to desired reporting rate



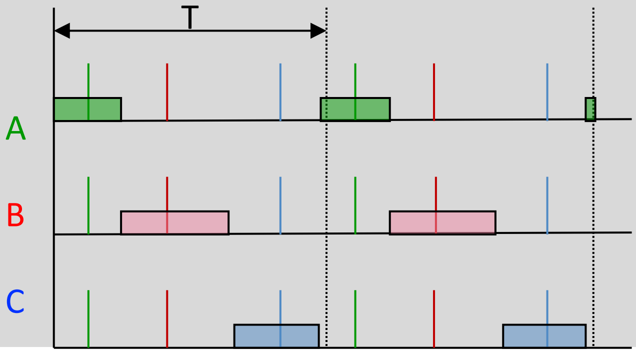


3. Coverage Control

4. Reference Time Based Scheduling Scheme



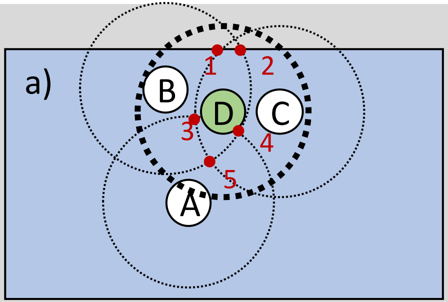
- Division of the environment into a grid
- Assumption: transmission radius > 2 · sensing radius
- Coverage is maintained at each grid point while minimizing the number of sensors.
- Each sensor node broadcasts a randomly chosen reference time (uniformly distributed on [0,T), T: round length).
- For each grid point: Each sensor
  - sorts reference times of all sensors able to monitor grid point
  - schedules its activity:
    - Start at time between reference time of predecessor node and own reference time
    - End of activity between its own reference time and reference time of successor node

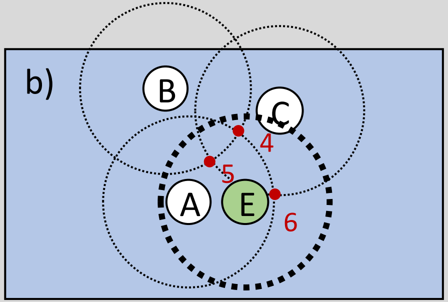


3. Coverage Control

5. Coverage Configuration Protocol

- Each node determines intersection points between borders of neighbor sensing radii and desired coverage area.
- A node is eligible for deactivation, if each intersection point is k-covered.
- Examples (k=1)
  - a)
    - B covers 1, 3
    - C covers 2, 4
    - A covers 5
    - → All intersection points of D are covered.
    - → D can remain inactive.
  - b)
    - Intersection point 6 is not covered by one of E's neighbors.
    - → E becomes active.





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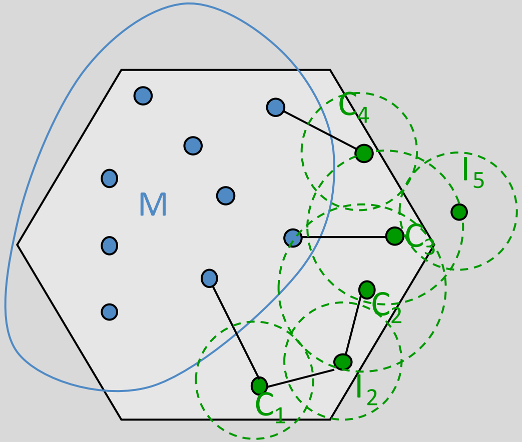
4. Integration of Topology and Coverage Control

- Problem
  - Topology control protocols do not use knowledge of traffic patterns.
  - Often, traffic is generated from a small subset of nodes only.
  - Many more nodes than necessary are activated to route data.
- Approach
  - Required topology can be tailored to the area to be covered, if appropriate coverage knowledge is available.
- Example Protocols
  - Connected Sensor Cover
  - Distributed Activation with Pre-Determined Routes

4. Integration of Topology and Coverage Control

1. Connected Sensor Cover

- Addressed problem: Find minimum set of sensors to cover desired area and additional routing nodes required to process query / data messages.
- M: set of sensors already covered
- Centralized algorithm: At each step
  - determine candidates with sensing regions intersecting with a sensing region of a node in M
  - for each candidate C_i find the path P_i with highest benefit (= additionally covered area / number of new hops along path)
  - add path P_i with highest benefit
  - select C_i with sensors along P_i
- Distributed algorithm: Most recently added candidate
  - broadcasts Candidate Path Search message and
  - receives Candidate Path Response messages.



4. Integration of Topology and Coverage Control

2. Distributed Activation with Pre-Determined Routes

- Approach: Sensors important for sensing and those with potentially short lifetimes should not be considered for routing.
- Each node assigns an application cost (measure for their value to the sensor application) based on remaining energy of the node and its neighbors.

Phases

1. Route discovery (using broadcasts from base station)
   - Nodes discover routes with minimal cumulative application costs.
2. Role discovery
   - Opt In: Nodes attempt to activate themselves after a back-off delay proportional to their cumulative application costs. No activation if neighborhood is already covered.
   - Opt Out: Activated nodes can deactivate themselves if they discover redundant nodes.

Thanks

for Your Attention

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