Wireless Sensor Networks
Chapter 10: Topology control

António Grilo

Courtesy: Holger Karl, UPB
Goals of this chapter

- Networks can be too dense – too many nodes in close (radio) vicinity
- This chapter looks at methods to deal with such networks by
  - Reducing/controlling transmission power
  - Deciding which links to use
  - Turning some nodes off
- Focus is on basic ideas, some algorithms
  - Complexity results are only very superficially covered
Overview

- Motivation, basics
- Power control
- Backbone construction
- Clustering
- Adaptive node activity
Motivation: Dense networks

- In a very dense networks, too many nodes might be in range for an efficient operation
  - Too many collisions/too complex operation for a MAC protocol, too many paths to chose from for a routing protocol, ...

- Idea: Make *topology* less complex
  - *Topology*: Which node is able/allowed to communicate with which other nodes
  - Topology control needs to maintain invariants, e.g., connectivity
Options for topology control

- **Topology control**
  - Control *node* activity – deliberately turn on/off nodes
  - Control *link* activity – deliberately use/not use certain links

**Flat network** – all nodes have essentially same role

- **Power control**

**Hierarchical network** – assign different roles to nodes; exploit that to control node/link activity

- **Backbones**
- **Clustering**
Flat networks

• Main option: Control transmission power
  • Do not always use maximum power
  • Selectively for some links or for a node as a whole
  • Topology looks “thinner”
  • Less interference, …

• Alternative: Selectively discard some links
  • Usually done by introducing hierarchies
Hierarchical networks – backbone

- Construct a **backbone** network
  - Some nodes “control” their neighbors – they form a (minimal) **dominating set**
  - Each node should have a controlling neighbor
  - Controlling nodes have to be connected (backbone)
  - Only links within backbone and from backbone to controlled neighbors are used

- Formally: Given graph $G=(V,E)$, construct $D \subseteq V$ such that
  \[
  \forall v \in V : v \in D \lor \exists d \in D : (v, d) \in E
  \]
Hierarchical network – clustering

- Construct **clusters**
  - Partition nodes into groups ("clusters")
  - Each node in exactly one group
    - Except for nodes “bridging” between two or more groups
  - Groups can have **clusterheads**
  - Typically: all nodes in a cluster are direct neighbors of their clusterhead
  - Clusterheads are also a dominating set, but should be separated from each other – they form an **independent set**

- Formally: Given graph $G=(V,E)$, construct $C \subseteq V$ such that

\[
\forall v \in V - C : \exists c \in C : (v, c) \in E
\]

\[
\forall c_1, c_2 \in C : (c_1, c_2) \notin E
\]
Aspects of topology-control algorithms

- **Connectivity** – If two nodes connected in $G$, they have to be connected in $G^0$ resulting from topology control

- **Stretch factor** – should be small
  - *Hop stretch factor*: how much longer are paths in $G^0$ than in $G$?
  - *Energy stretch factor*: how much more energy does the most energy-efficient path need?

- **Throughput** – removing nodes/links can reduce throughput, by how much?

- Robustness to mobility

- Algorithm overhead
Example: Price for maintaining connectivity

- Maintaining connectivity can be very “costly” for a power control approach
- Compare power required for connectivity compared to power required to reach a very big maximum component

![Graph showing the relationship between maximum transmission range and probability of connectivity.](image)
Overview

- Motivation, basics
- **Power control**
- Backbone construction
- Clustering
- Adaptive node activity
Power control – magic numbers?

- Question: What is a good power level for a node to ensure “nice” properties of the resulting graph?
- Idea: Controlling transmission power corresponds to controlling the number of neighbors for a given node
- Is there an “optimal” number of neighbors a node should have?
  - Is there a “magic number” that is good irrespective of the actual graph/network under consideration?
- Historically, k=6 or k=8 had been suggested as such “magic numbers”
  - However, they optimize progress per hop – they do not guarantee connectivity of the graph!!
    ! Needs deeper analysis
Controlling transmission range

- Assume all nodes have identical transmission range \( r = r(|V|) \), network covers area \( A \), \( V \) nodes, uniformly distr.
- Fact: Probability of connectivity goes to zero if:
  \[
  r(|V|) \leq \sqrt{\frac{(1-\varepsilon)A \log |V|}{\pi |V|}}, \text{ for any } \varepsilon > 0
  \]
- Fact: Probability of connectivity goes to 1 for
  \[
  r(|V|) \geq \sqrt{\frac{A(\log |V| + \gamma |V|)}{\pi |V|}}
  \]
  if and only if \( \gamma |V| \neq 1 \) with \( |V| \)
- Fact (uniform node distribution, density \( \rho \)):
  \[
  P(G \text{ is } k\text{-connected}) \approx \left(1 - \sum_{l=0}^{k-1} \frac{(\rho \pi r^2)^l}{l!} e^{-\rho \pi r^2}\right)
  \]
Controlling number of neighbors

- Knowledge about range also tells about number of neighbors
  - Assuming node distribution (and density) is known, e.g., uniform

- Alternative: directly analyze number of neighbors
  - Assumption: Nodes randomly, uniformly placed, only transmission range is controlled, identical for all nodes, only symmetric links are considered

- Result: For connected network, required number of neighbors per node is $\Theta(\log |V|)$
  - It is not a constant, but depends on the number of nodes!
  - For a larger network, nodes need to have more neighbors & larger transmission range! – Rather inconvenient
  - Constants can be bounded
Some example constructions for power control

- Basic idea for most of the following methods: Take a graph \( G=(V,E) \), produce a graph \( G^0=(V,E^0) \) that maintains connectivity with fewer edges
  - Assume, e.g., knowledge about node positions
  - Construction should be local (for distributed implementation)
Example 1: Relative Neighborhood Graph (RNG)

- Edge between nodes $u$ and $v$ if and only if there is no other node $w$ that is closer to either $u$ or $v$
- Formally: $\forall u, v \in V : (u, v) \in E' \iff \not\exists w \in V : \max\{d(u, w), d(v, w)\} < d(u, v)$
- RNG maintains connectivity of the original graph
- Easy to compute locally
- But: Worst-case spanning ratio is $\Omega(|V|)$
- Average degree is 2.6

This region has to be empty for the two nodes to be connected.
Example 2: Gabriel graph

- Gabriel graph (GG) similar to RNG
- Difference: Smallest circle with nodes u and v on its circumference must only contain node u and v for u and v to be connected
- Formally:
  \[
  \forall u, v \in V : (u, v) \in E' \quad \text{iff} \quad \not\exists w \in V : d^2(u, w) + d^2(v, w) < d^2(u, v)
  \]
- Properties: Maintains connectivity, Worst-case spanning ratio $\Omega(|V|^{1/2})$, energy stretch $O(1)$ (depending on consumption model!), worst-case degree $\Omega(|V|)$
Example 3: Delaunay triangulation

- Assign, to each node, all points in the plane for which it is the closest node
  - Voronoi diagram
    - Constructed in $O(|V| \log |V|)$ time
- Connect any two nodes for which the Voronoi regions touch
  - Delaunay triangulation
- Problem: Might produce very long links; not well suited for power control
Example: Cone-based topology control

- Assumption: Distance and angle information between nodes is available
- Two-phase algorithm
- Phase 1
  - Every node starts with a small transmission power
  - Increase it until a node has sufficiently many neighbors
  - What is “sufficient”? – When there is at least one neighbor in each cone of angle $\alpha$
  - $\alpha = 5/6\pi$ is necessary and sufficient condition for connectivity!
- Phase 2
  - Remove redundant edges: Drop a neighbor $w$ of $u$ if there is a node $v$ of $w$ and $u$ such that sending from $u$ to $w$ directly is less efficient than sending from $u$ via $v$ to $w$
  - Essentially, a local Gabriel graph construction
Example: Cone-based topology control (2)

- Properties: simple, local construction
- Extensions for k-connectivity (Yao graph)

- Little exercise: What happens when $\alpha < \text{or} > \frac{5}{6}\pi$?
Centralized power control algorithm

- **Goal**: Find topology control algorithm minimizing the *maximum* power used by any node
  - Ensuring simple or bi-connectivity
  - Assumptions: Locations of all nodes and path loss between all node pairs are known; each node uses an individually set power level to communicate with all its neighbors
- **Idea**: Use a centralized, greedy algorithm
  - Initially, all nodes have transmission power 0
  - Connect those two components with the shortest distance between them (raise transmission power accordingly)
- **Second phase**: Remove links (=reduce transmission power) not needed for connectivity
- **Exercise**: Relation to Kruskal’s MST algorithm?
Centralized power control algorithm

1) Connect A-C and B-D

2) Connect A-B

3) Connect C-D

4) Connect C-E and D-F

5) Remove edge A-B

Wireless Sensor Networks: Topology Control
Overview

- Motivation, basics
- Power control
- **Backbone construction**
- Clustering
- Adaptive node activity
Hierarchical networks – backbones

- Idea: Select some nodes from the network/graph to form a backbone
  - A connected, minimal, dominating set (MDS or MCDS)
  - Dominating nodes control their neighbors
  - Protocols like routing are confronted with a simple topology – from a simple node, route to the backbone, routing in backbone is simple (few nodes)

- Problem: MDS is an NP-hard problem
  - Hard to approximate, and even approximations need quite a few messages
Backbone by growing a tree

- Construct the backbone as a tree, grown iteratively

```plaintext
initialize all nodes’ color to white
pick an arbitrary node and color it grey

while (there are white nodes) {
    pick a grey node \( v \) that has white neighbors
    color the grey node \( v \) black
    \foreach \( u \) white neighbor of \( v \) {
        color \( u \) grey
        add \((v, u)\) to tree \( T \)
    }
}
```
Backbone by growing a tree – Example

1:

2:

3:

4:
Problem: Which gray node to pick?

- When blindly picking any gray node to turn black, resulting tree can be very bad

Solution: Look ahead! One step suffices
Performance of tree growing with look ahead

- Dominating set obtained by growing a tree with the look ahead heuristic is at most a factor $2(1 + H(\Delta))$ larger than MDS
  - $H(\Delta)$ harmonic function, $H(k) = \sum_{i=1}^{k} 1/i \leq \ln k + 1$
  - $\Delta$ is maximum degree of the graph

- It is automatically connected

- Can be implemented in a distributed fashion as well
Start big, make lean

- Idea: start with some, possibly large, connected dominating set, reduce it by removing unnecessary nodes
- Initial construction for dominating set
  - All nodes are initially white
  - Mark any node black that has two neighbors that are not neighbors of each other (they might need to be dominated)
    - Black nodes form a connected dominating set (proof by contradiction); shortest path between ANY two nodes only contains black nodes

- Needed: Pruning heuristics
Pruning heuristics

- **Heuristic 1:** Unmark node v if
  - Node v and its neighborhood are included in the neighborhood of some node marked node u (then u will do the domination for v as well)
  - Node v has a smaller unique identifier than u (to break ties)

- **Heuristic 2:** Unmark node v if
  - Node v’s neighborhood is included in the neighborhood of two marked neighbors u and w
  - Node v has the smallest identifier of the tree nodes

- Nice and easy, but only linear approximation factor
One more distributed backbone heuristic: Span

- Construct backbone, but take into account need to carry traffic – preserve capacity
  - Means: If two paths could operate without interference in the original graph, they should be present in the reduced graph as well
  - Idea: If the stretch factor (induced by the backbone) becomes too large, more nodes are needed in the backbone
- Rule: Each node observes traffic around itself
  - If node detects two neighbors that need three hops to communicate with each other, node joins the backbone, shortening the path
  - Contention among potential new backbone nodes handled using random backoff
Overview

- Motivation, basics
- Power control
- Backbone construction
- **Clustering**
- Adaptive node activity
Clustering

- Partition nodes into groups of nodes – clusters
- Many options for details
  - Are there clusterheads? – One controller/representative node per cluster
  - May clusterheads be neighbors? If no: clusterheads form an independent set $C$: $\forall c_1, c_2 \in C : (c_1, c_2) \notin E$
    Typically: clusterheads form a maximum independent set
  - May clusters overlap? Do they have nodes in common?
Clustering

- Further options
  - How do clusters communicate? Some nodes need to act as *gateways* between clusters
    If clusters may not overlap, two nodes need to jointly act as a *distributed gateway*

  - How many gateways exist between clusters? Are all active, or some standby?
  - What is the maximal diameter of a cluster? If more than 2, then clusterheads are not necessarily a maximum independent set
  - Is there a hierarchy of clusters?
Maximum independent set

- Computing a maximum independent set is NP-complete
- Can be approximate within \((\Delta + 3)/5\) for small \(\Delta\), within \(O(\Delta \log \log \Delta / \log \Delta)\) else; \(\Delta\) bounded degree
- Show: A maximum independent set is also a dominating set
- Maximum independent set not necessarily intuitively desired solution
  - Example: Radial graph, with only \((v_0,v_i) \in E\)
A basic construction idea for independent sets

- Use some attribute of nodes to break local symmetries
  - Node identifiers, energy reserve, mobility, weighted combinations… - matters not for the idea as such (all types of variations have been looked at)

- Make each node a clusterhead that locally has the largest attribute value

- Once a node is dominated by a clusterhead, it abstains from local competition, giving other nodes a chance

Init: 1 2 3 7 6 5 4

Step 1: 1 2 3 7 6 5 4

Step 2: 1 2 3 7 6 5 4

Step 3: 1 2 3 7 6 5 4

Step 4: 1 2 3 7 6 5 4
Determining gateways to connect clusters

- Suppose: Clusterheads have been found
- How to connect the clusters, how to select gateways?

- It suffices for each clusterhead to connect to all other clusterheads that are at most three hops
  - Resulting backbone (!) is connected

- Formally: Steiner tree problem
  - Given: Graph $G=(V,E)$, a subset $C \subseteq V$
  - Required: Find another subset $T \subseteq V$ such that $S \setminus T$ is connected and $S \setminus T$ is a cheapest such set
  - Cost metric: number of nodes in $T$, link cost
  - Here: special case since $C$ are an independent set
Rotating clusterheads

- Serving as a clusterhead can put additional burdens on a node
  - For MAC coordination, routing, …

- Let this duty rotate among various members
  - Periodically reelect – useful when energy reserves are used as discriminating attribute
  - LEACH – determine an optimal percentage P of nodes to become clusterheads in a network
    - Use 1/P rounds to form a period
    - In each round, nP nodes are elected as clusterheads
    - At beginning of round r, node that has not served as clusterhead in this period becomes clusterhead with probability $P/(1-p(r \ mod \ 1/P))$
Multi-hop clusters

- Clusters with diameters larger than 2 can be useful, e.g., when used for routing protocol support
- Formally: Extend “domination” definition to also dominate nodes that are at most d hops away
- Goal: Find a smallest set D of dominating nodes with this extended definition of dominance
- Only somewhat complicated heuristics exist

- Different tilt: Fix the size (not the diameter) of clusters
  - Idea: Use growth budgets – amount of nodes that can still be adopted into a cluster, pass this number along with broadcast adoption messages, reduce budget as new nodes are found
Passive clustering

- Constructing a clustering structure brings overheads
  - Not clear whether they can be amortized via improved efficiency
- Question: Eat cake and have it?
  - Have a clustering structure without any overhead?
  - Maybe not the best structure, and maybe not immediately, but benefits at zero cost are no bad deal…

! Passive clustering

- Whenever a broadcast message travels the network, use it to construct clusters on the fly
- Node to start a broadcast: Initial node
- Nodes to forward this first packet: Clusterhead
- Nodes forwarding packets from clusterheads: ordinary/gateway nodes
- And so on… Clusters will emerge at low overhead
Overview

• Motivation, basics
• Power control
• Backbone construction
• Clustering
• *Adaptive node activity*
Adaptive node activity

- Remaining option: Turn some nodes off deliberately
- Only possible if other nodes remain on that can take over their duties
- Example duty: Packet forwarding
  - Approach: Geographic Adaptive Fidelity (GAF)
- Observation: Any two nodes within a square of length $r < R/\sqrt{5}$ can replace each other with respect to forwarding
  - $R$ radio range
- Keep only one such node active, let the other sleep
Conclusion

- Various approaches exist to trim the topology of a network to a desired shape
- Most of them bear some non-negligible overhead
  - At least: Some distributed coordination among neighbors, or they require additional information
  - Constructed structures can turn out to be somewhat brittle – overhead might be wasted or even counter-productive
- Benefits have to be carefully weighted against risks for the particular scenario at hand