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Topology Control from Bottom to Top

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Cross-Layer Design

Cognizance of behavior of other control functions:

- fosters synergistic interaction
- reduces redundant functionality

Exchange of information between control functions:

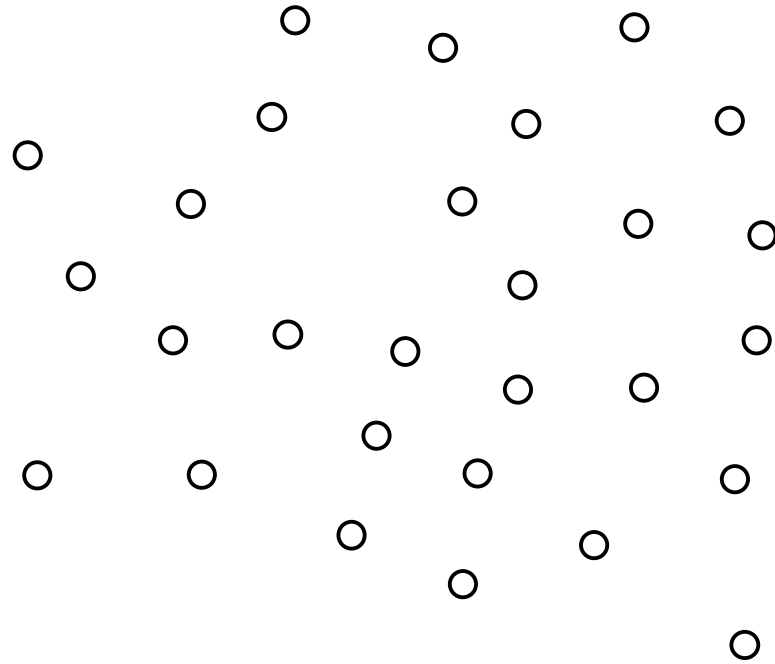
- directives as well as state information
- level of abstraction may affect accuracy of control

Integrated design of multiple control functions:

- tight coupling for optimization
- specific combinations intended for use together

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Mobile Wireless Network



Communications

Conditions:

- heterogeneous, mobile wireless devices
- operating in time-varying, unpredictable, and potentially hostile environment

Objective:

- must be consistent with service needs of traffic, capabilities of devices, and policies for resource use

Topology Control

Network topology:

time-dependent directed multigraph representing devices (nodes) and their ability to communicate directly with each other (links with different properties)

Goal:

determine which links between node pairs should be made available for transporting traffic from sources to destinations

Approaches:

- complete or partial view of network state
- global optimization for slowly-varying network conditions
- local optimization and heuristics for dynamic network conditions
- centralized, decentralized, distributed

History

Wireline networks:

- network design problem
- ordering of additional capacity based on predictions of load
- dial-up links for temporary replacement of lost connectivity and for additional capacity under heavy load

Wireless networks:

- minimize (maximum, total, average) transmit power for link closure while maintaining k -connectivity of network graph, $k \geq 1$
- use of node mobility to enable communication between nodes
- quality of service and interference considered secondary

Topology Control Functions

Node advertisement:

node announces presence and parameters for communication

Neighbor discovery:

node determines which nodes are within its transmission and reception ranges

Graph formation:

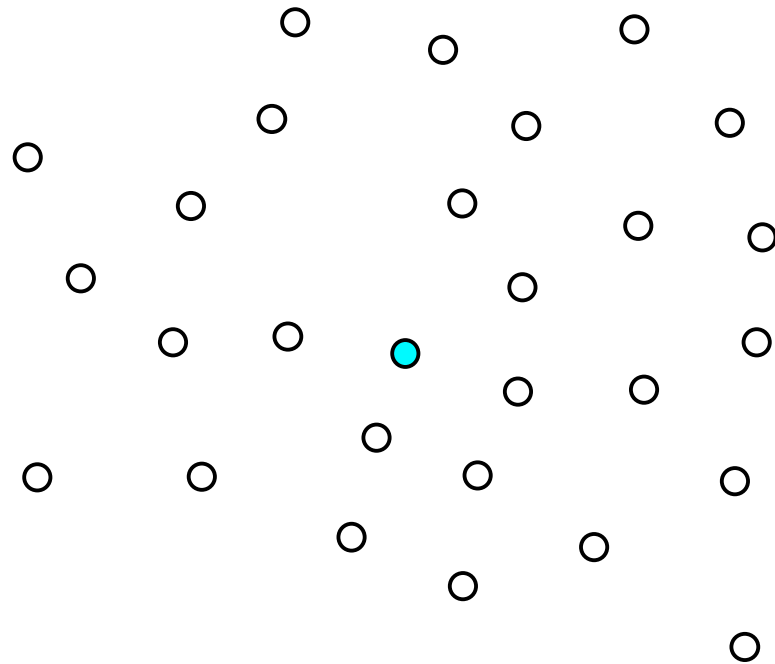
nodes negotiate and select persistent links for routing according to desired network properties and ephemeral links for specific sessions according to service needs

Graph maintenance:

nodes adjust graph according to perceived changes in channel conditions and mission directives

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Single Node's Perspective



Topology Control Functions

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node announces presence and parameters for communication

Neighbor discovery:

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Graph formation:

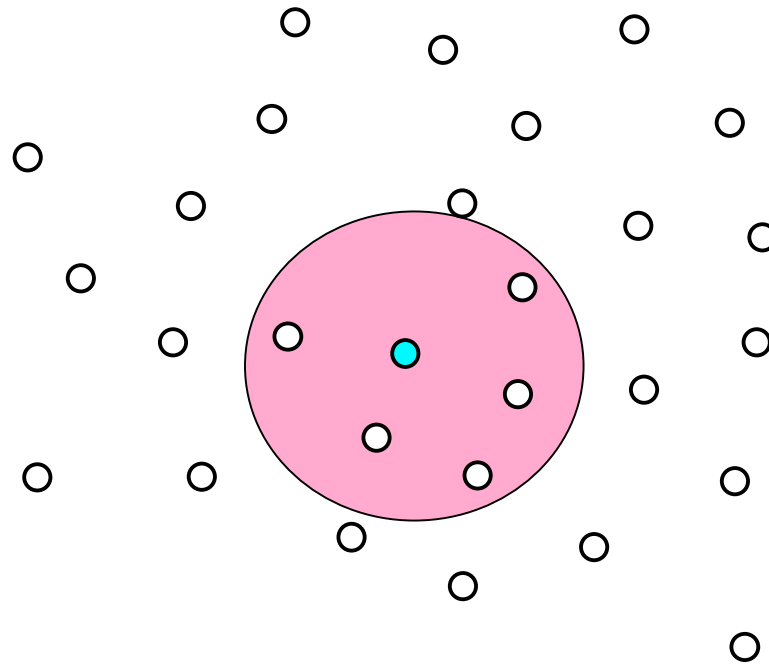
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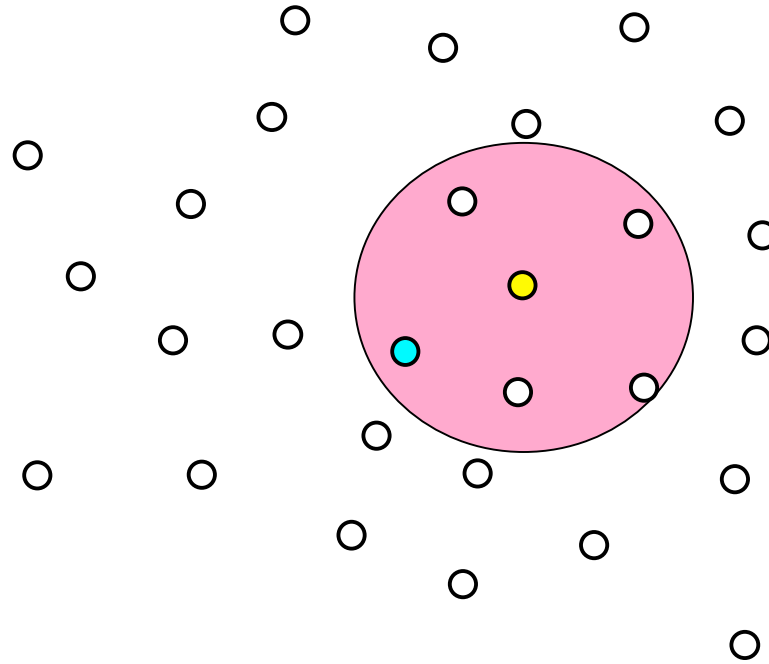
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Low-Power Transmission Range



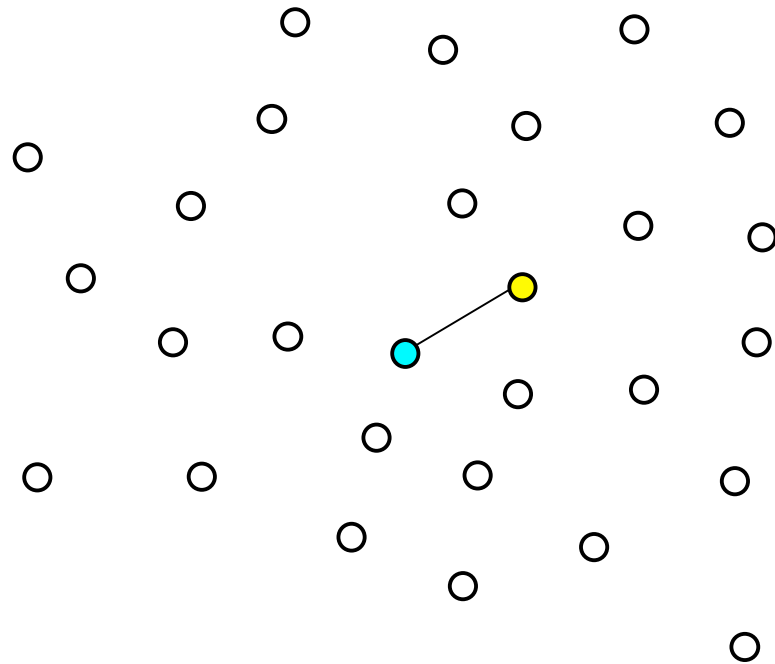
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Low-Power Transmission Range



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Achievable Low-Power Link



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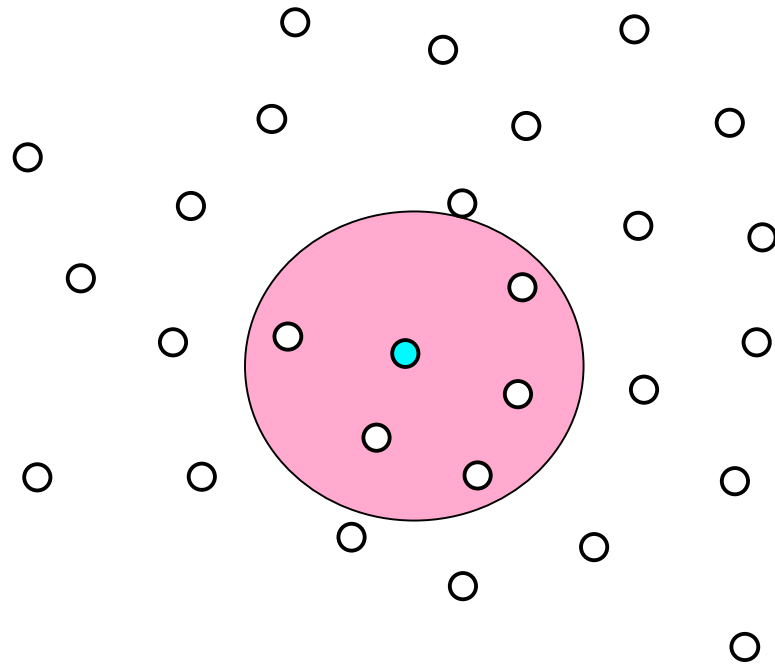
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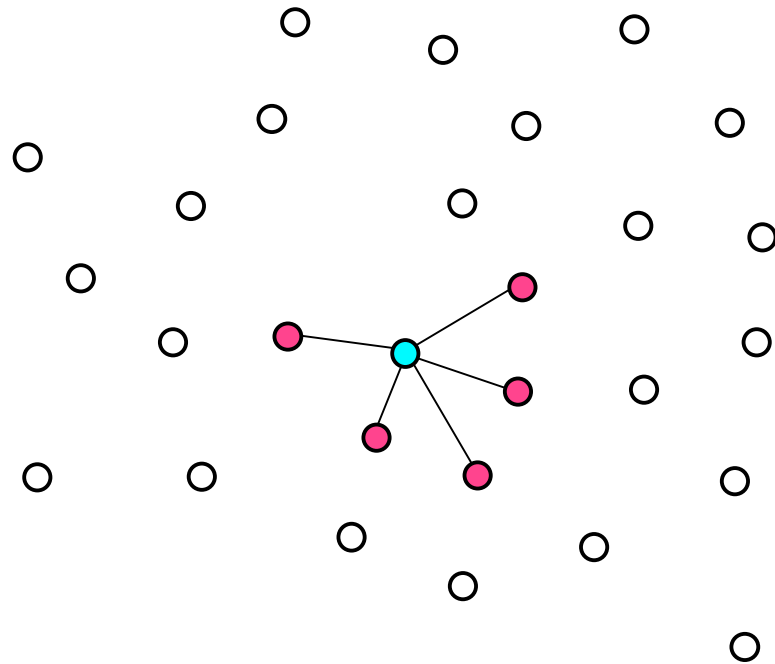
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Low-Power Transmission Range



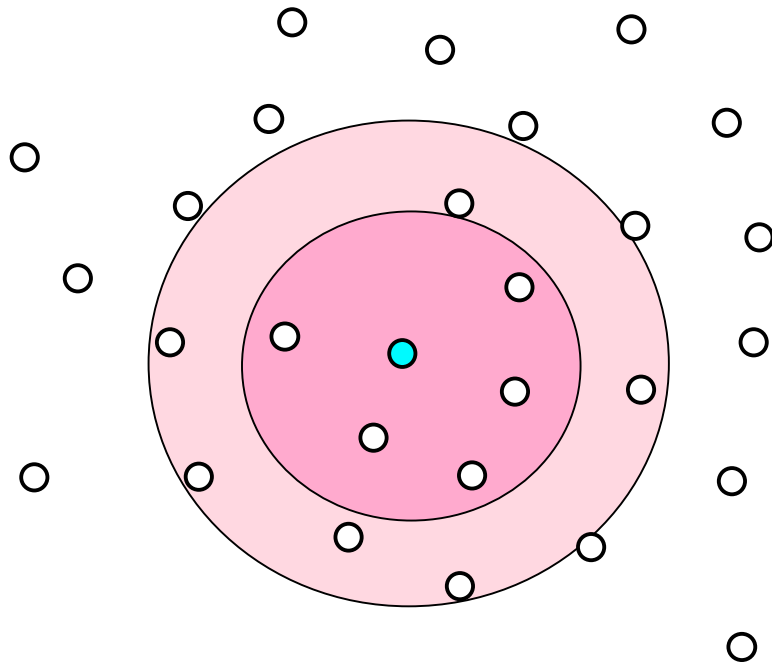
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Achievable Links at Low Power



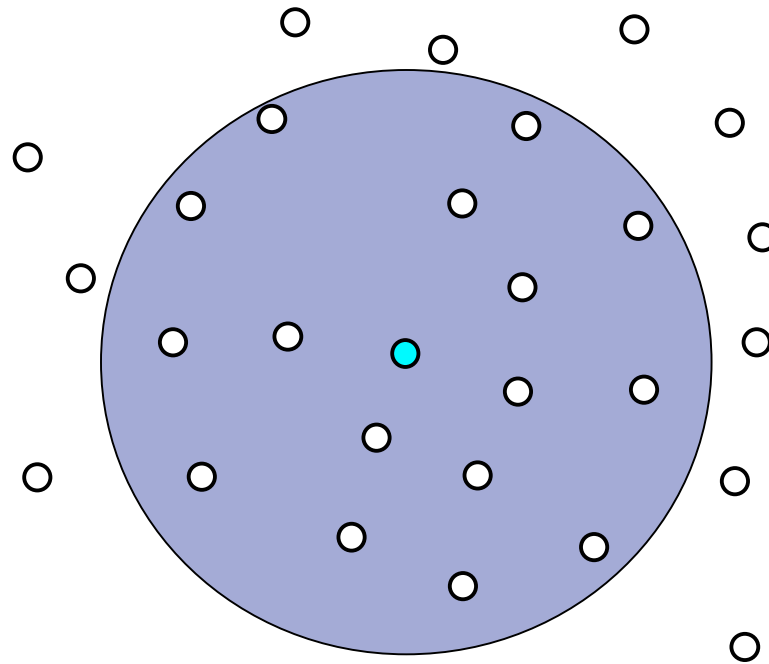
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Low-Power Interference Range



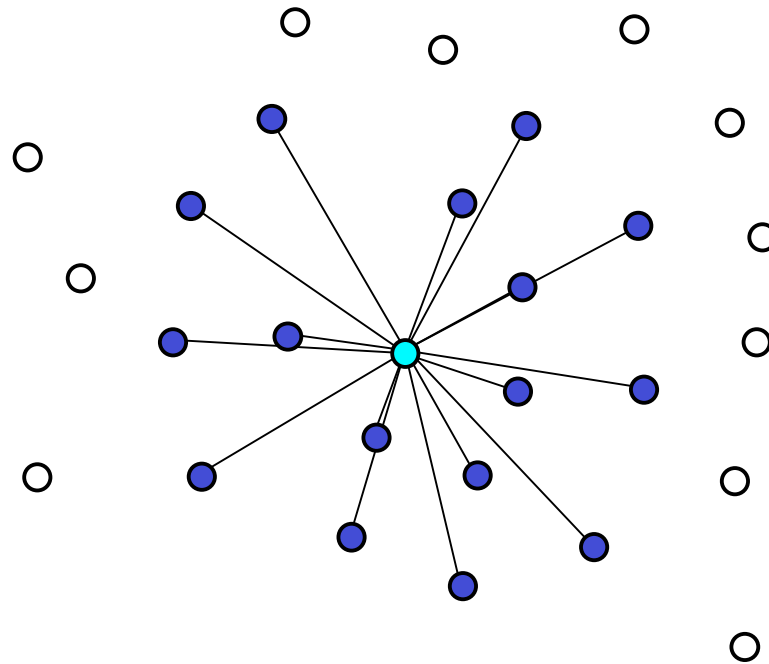
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High-Power Transmission Range



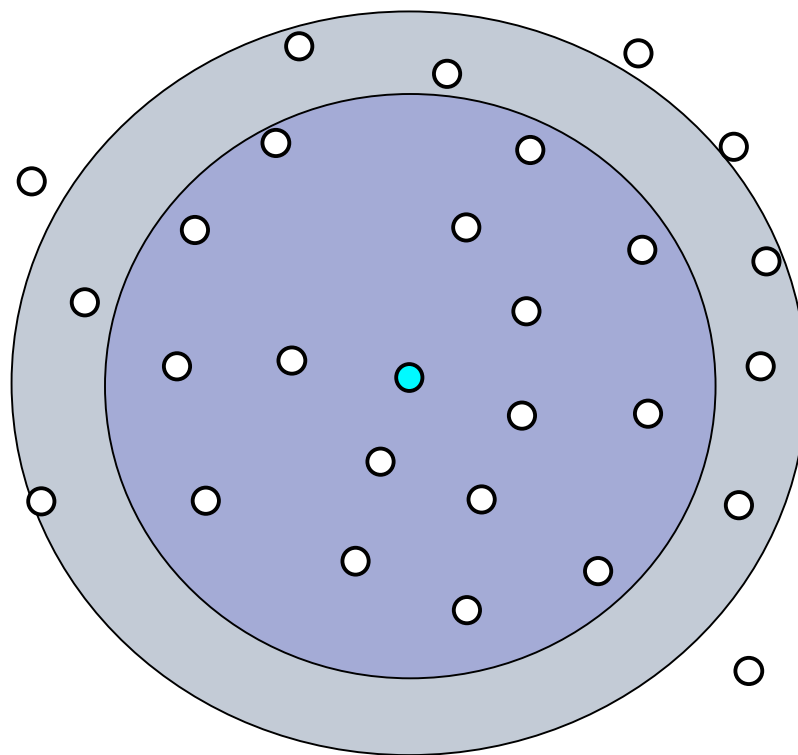
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Achievable Links at High Power

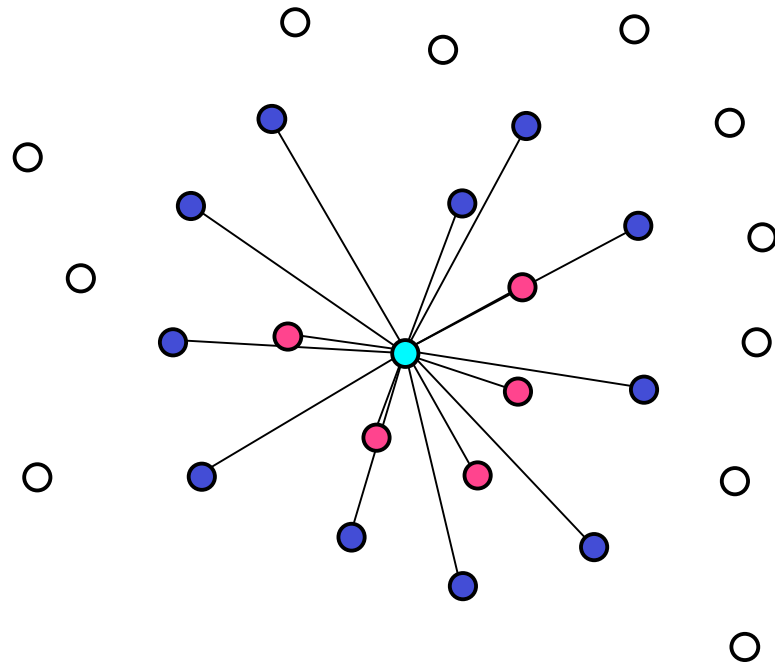


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High-Power Interference Range



All Achievable Links



Topology Control Functions

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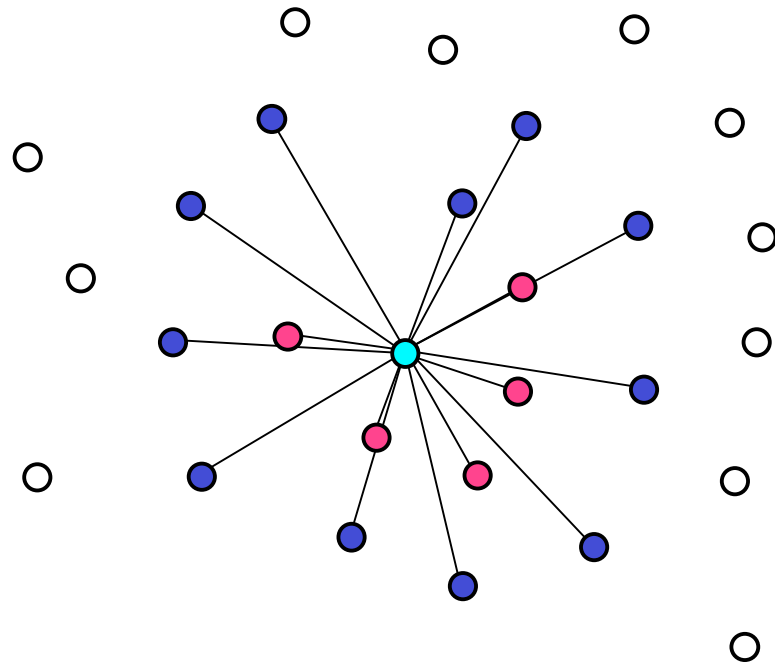
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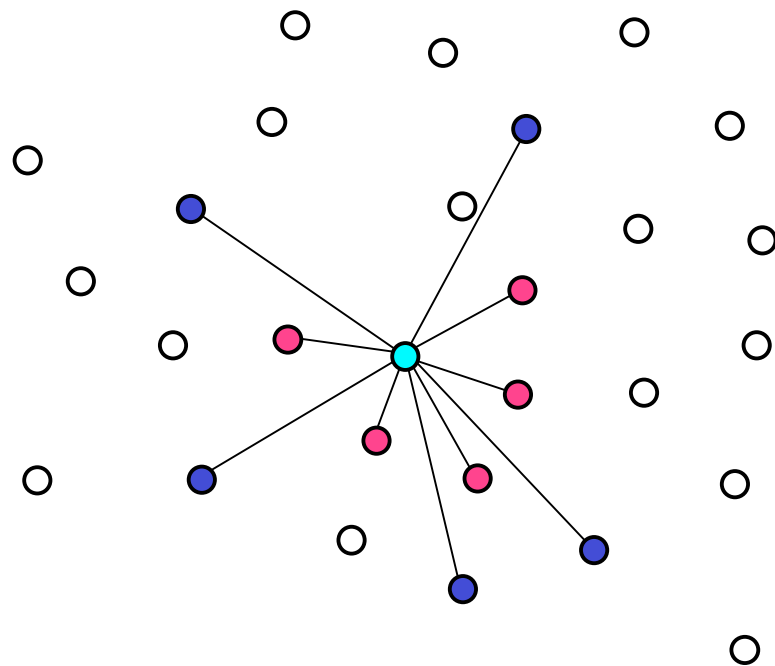
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All Achievable Links



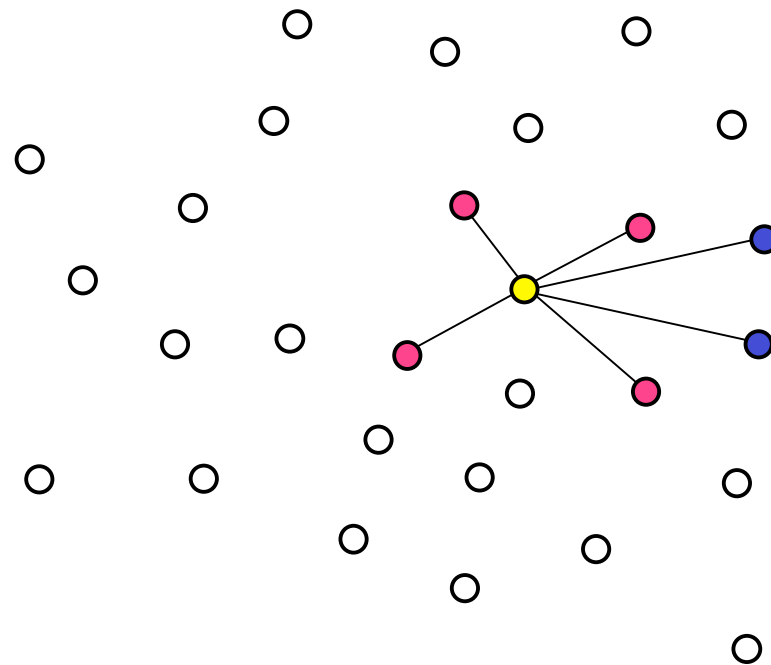
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Selected Links



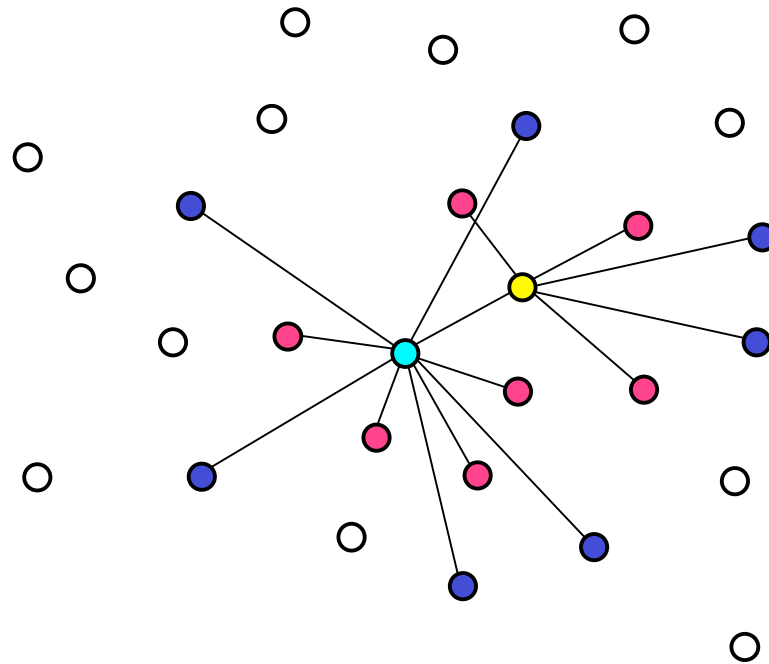
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Selected Links



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Partial View of Network Topology



Topology Control Functions

Advertisement:

node announces presence and parameters for communication

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Graph formation:

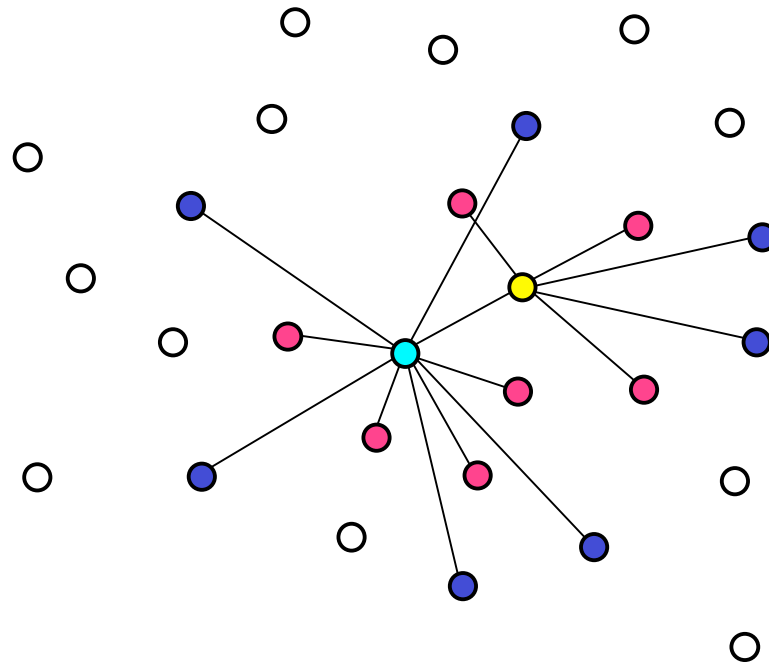
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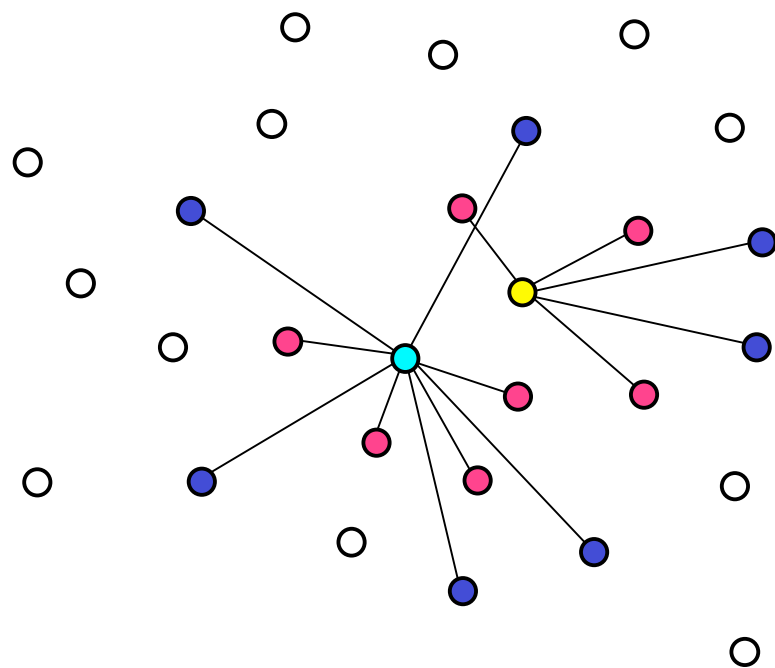
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Partial View of Network Topology



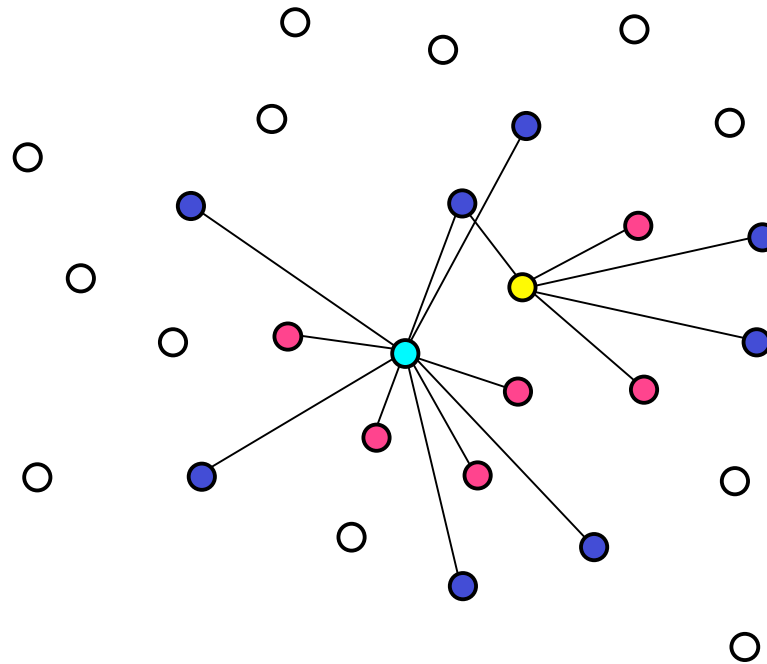
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Partitioned Topology

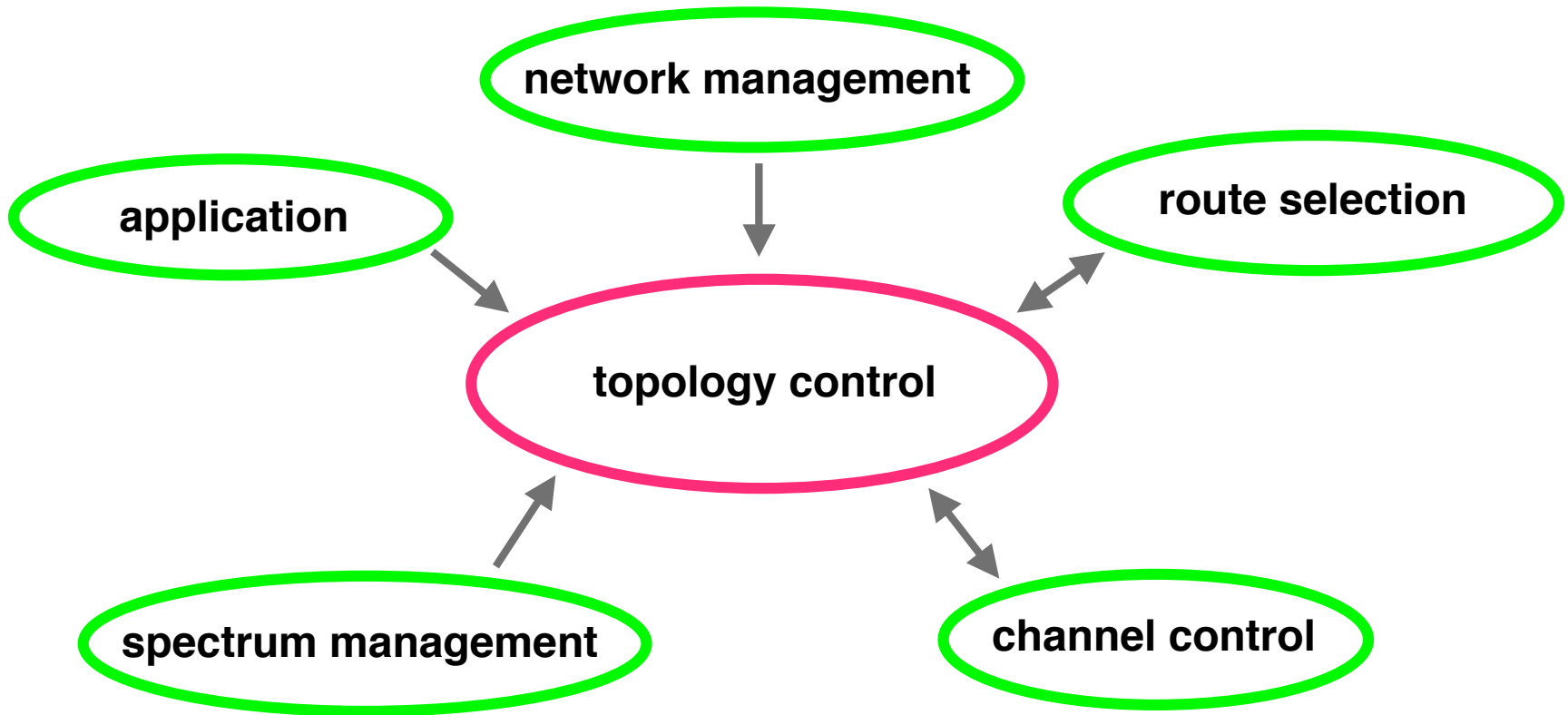


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Reconnected Topology

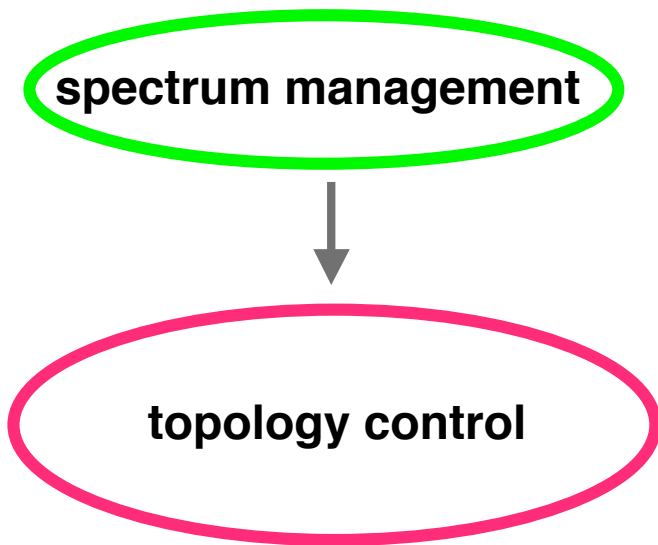


Explicit Interactions



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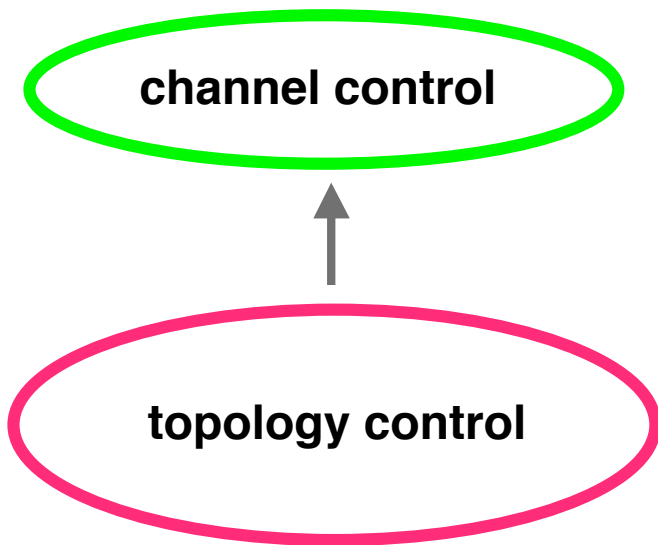
Available Spectrum



Spectrum opportunities:

- frequency bands
- tolerated interference
- expected lifetime

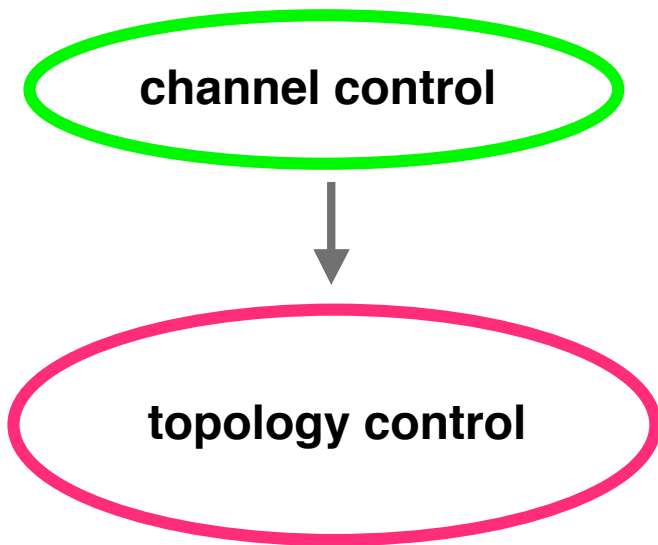
Probing and Scanning



Transceiver and antenna parameters:

- frequency
- transmit power
- modulation
- error-control coding
- beam width
- beam direction

Perceived Channel



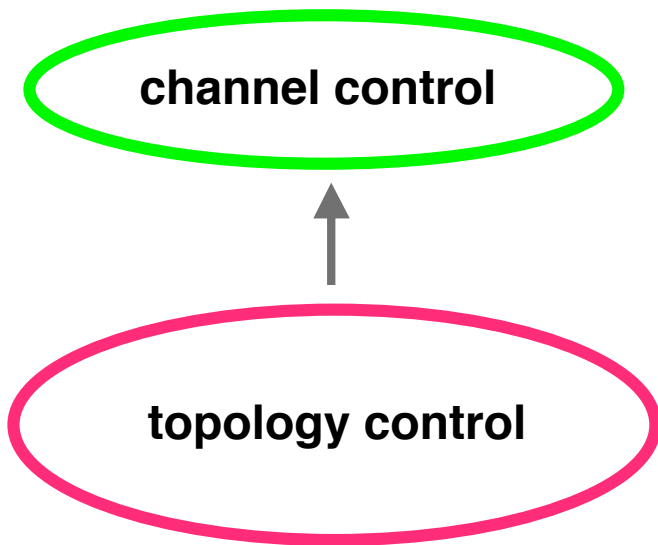
Channel properties:

- received signal strength
- signal-to-noise-plus-interference ratio
- bit error rate

Transceiver and antenna parameters:

- frequency
- transmit power
- modulation
- error-control coding
- beam width
- beam direction

Desired Channel



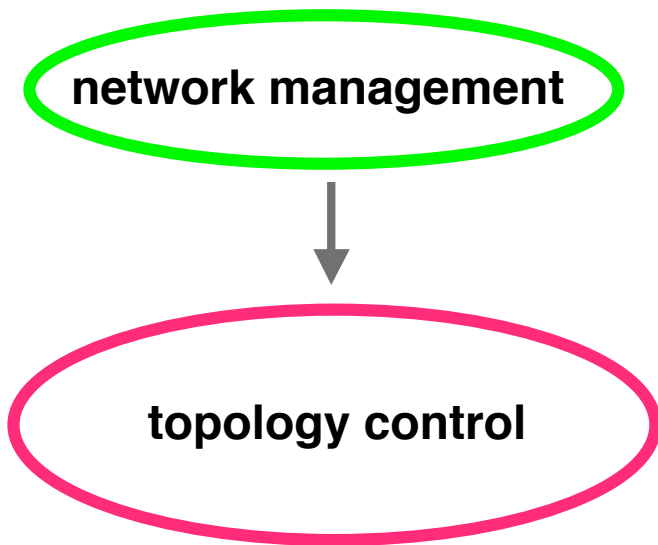
Channel properties:

received signal strength
signal-to-noise-plus interference ratio
bit error rate

Limits on cost:

transmit power
energy for transmission
air time for transmission

Admissible Links



Desired graph properties:

- degree
- diameter
- connectivity
- cut capacity

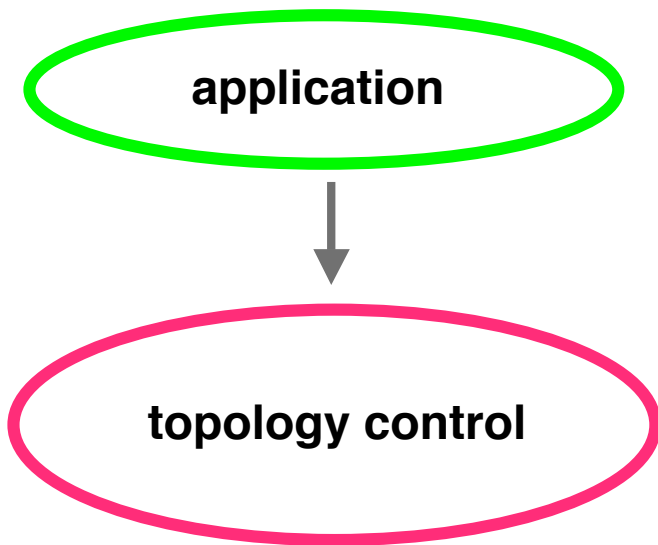
Desired network properties:

- interference
- energy consumption
- detection probability

Positional information:

- node trajectories
- probable location of detectors

Ephemeral Links



Quality of service:

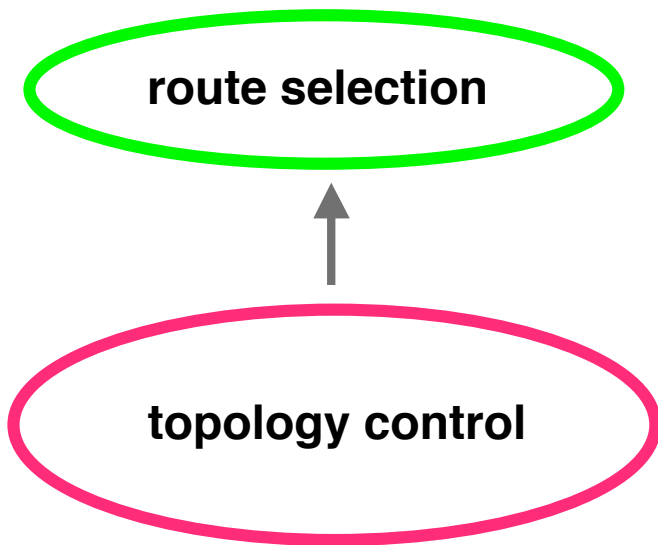
delay
throughput
loss

Session properties:

source and destinations
priority
expected lifetime

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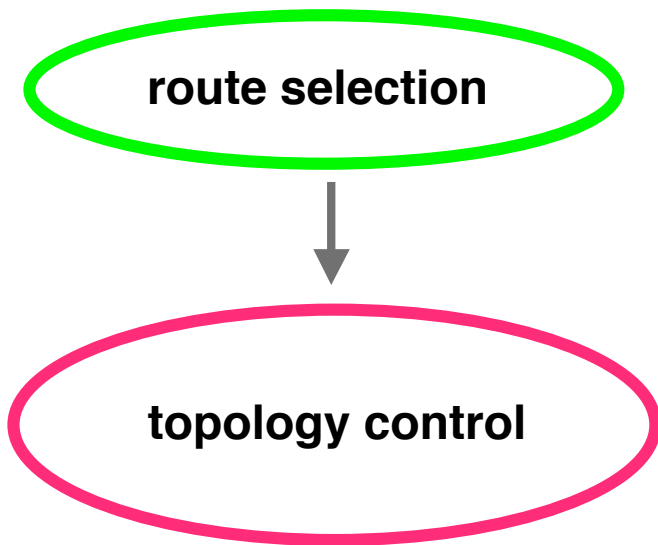
Network Topology



Links:

performance metrics
costs
expected lifetime

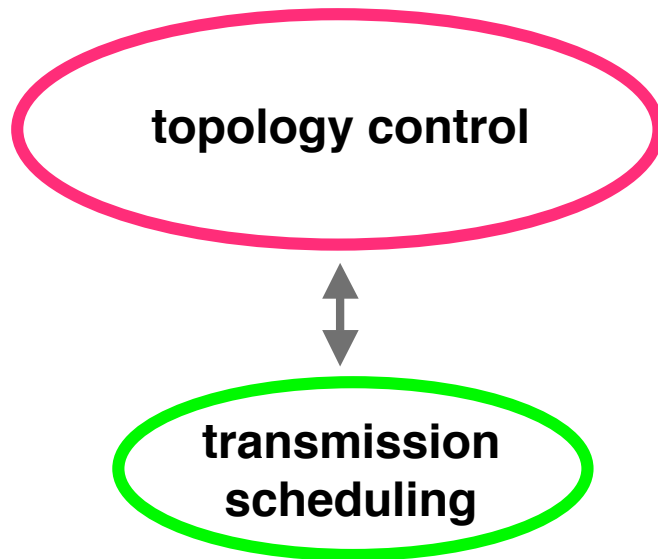
Routes for Updating Topology



Routes:

sequence of nodes
performance metrics
costs

Implicit Interactions



**Efficient use of channel
versus rich connectivity:**

interference
route length

Example: Link Activation

Assumptions:

- stationary network
- traffic flows known
- achievable links known
- slotted medium access

Objective:

- minimize total delay to send all traffic

Approach:

- flow scheduling: for each time slot determine which links to activate for which traffic flows
- combined topology control, route selection, and slot scheduling

Examples: Ephemeral Links

Direct link versus multihop path:

- performance benefits
- costs

High-priority application requests:

- low delay
- high throughput
- low packet loss

Network management desires:

- low interference
- low probability of detection

Example 1

Assumptions:

- omnidirectional transmissions
- transmit power adjustable in discrete levels
- no malicious detectors
- objective: minimize potential interference

Cost:

$$\sum_{i=1,h} r_i^2 \rho_i (\tau_i / \tau_{\min})$$

h : number of hops from source to destination

r_i : omnidirectional interference range for hop i

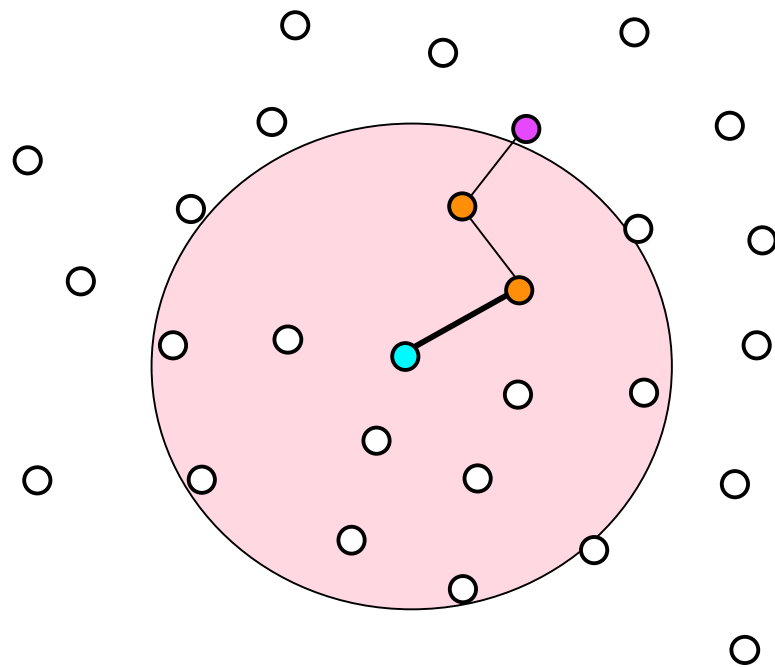
ρ_i : expected density of nodes around hop i

τ_i : expected air time for packet over hop i

$\tau_{\min}$: minimum expected air time over all hops considered

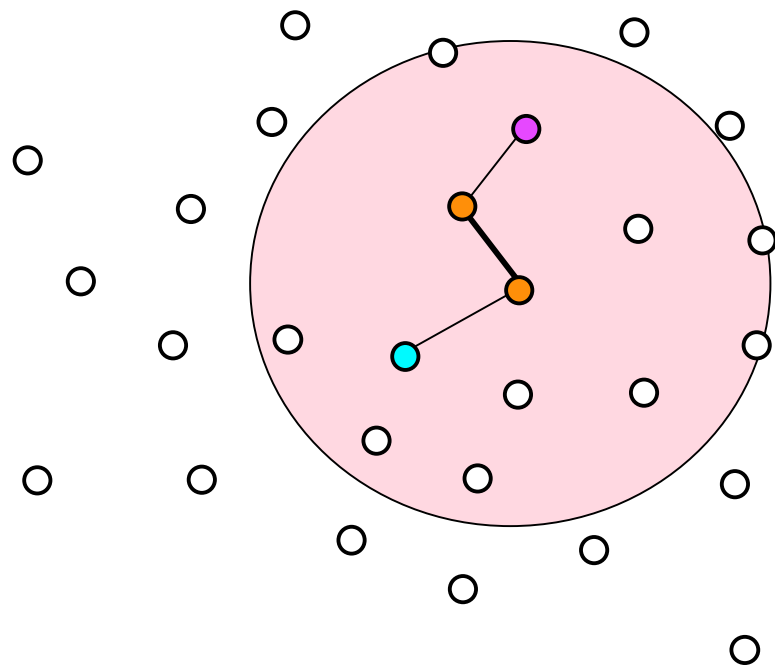
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Low-Power Transmission



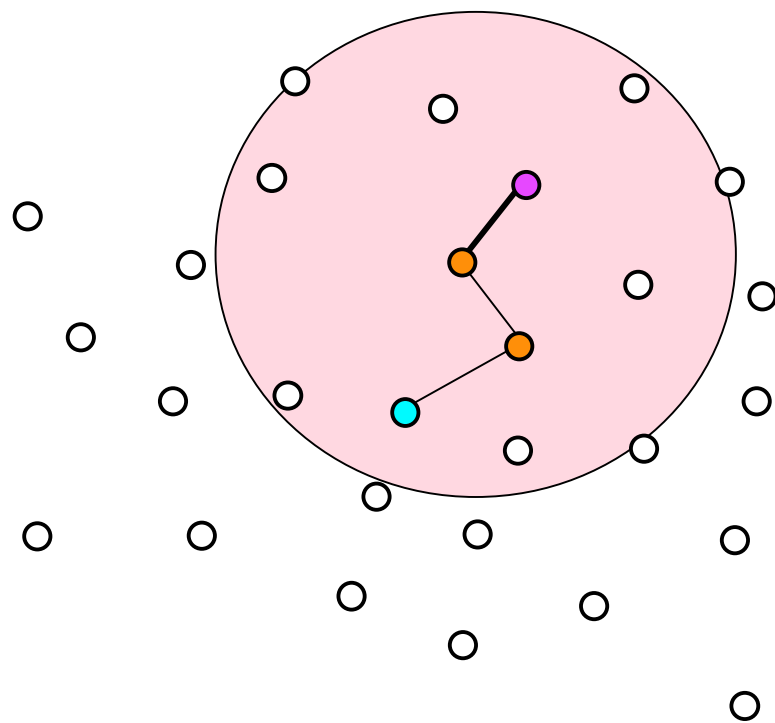
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Low-Power Transmission



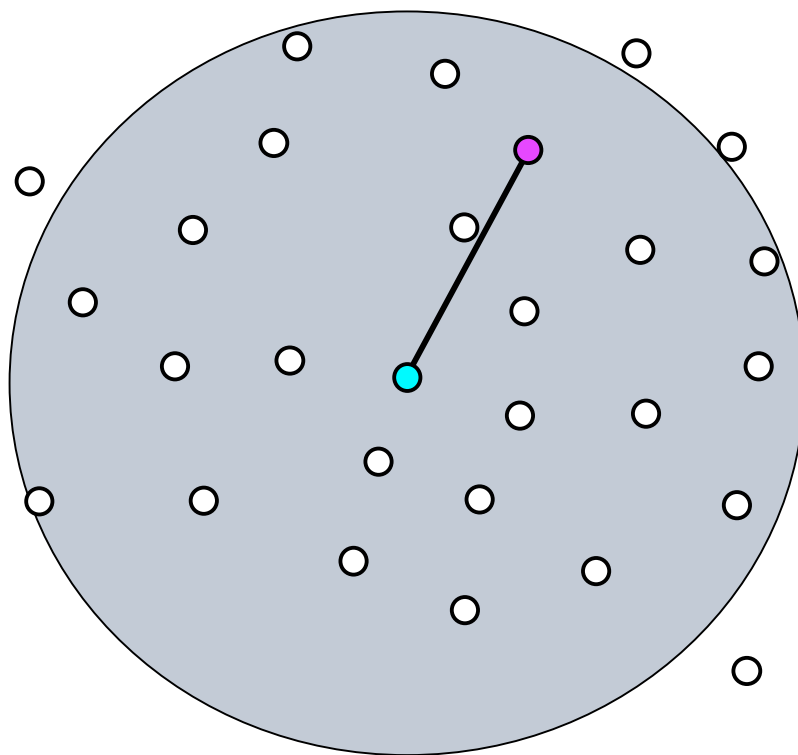
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Low-Power Transmission



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High-Power Transmission



Example 2

Assumptions:

- directional transmissions
- transmit power adjustable in discrete levels
- no malicious detectors
- objective: minimize potential interference

Cost:

$$\sum_{i=1,h} (r_i (2^{\beta/\alpha_i})^{1/\alpha_i})^2 (\alpha_i/2\pi) \alpha_i (\alpha_i/\alpha_{\min})$$

h : number of hops from source to destination

r_i : omnidirectional interference range for hop i

α : pathloss exponent

α_i : beam width for hop i

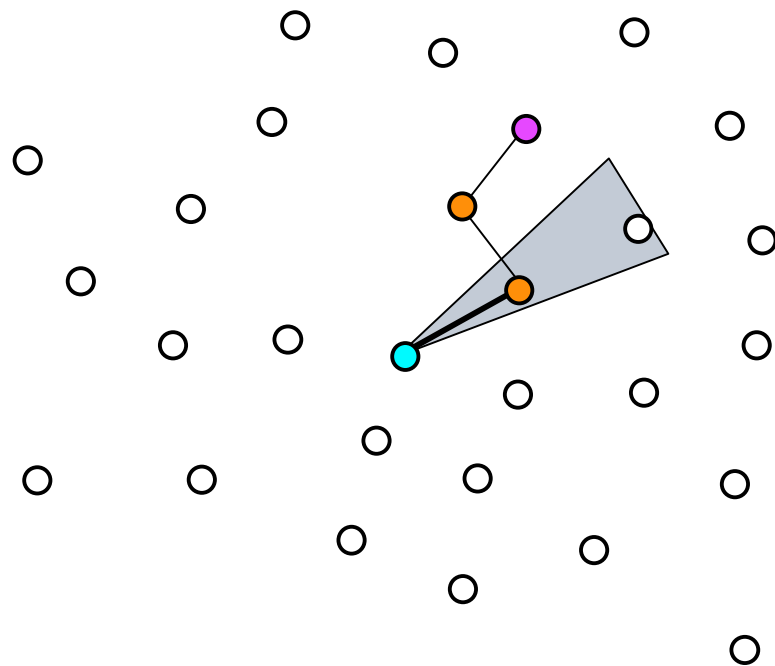
α_i : expected density of nodes around hop i

α : expected air time for packet over hop i

$\alpha_{\min}$: minimum expected air time over all hops considered

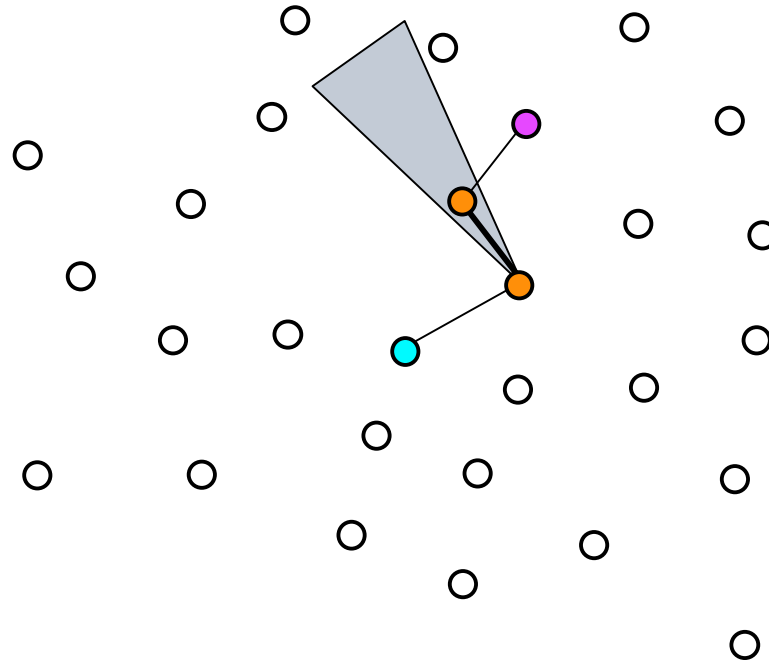
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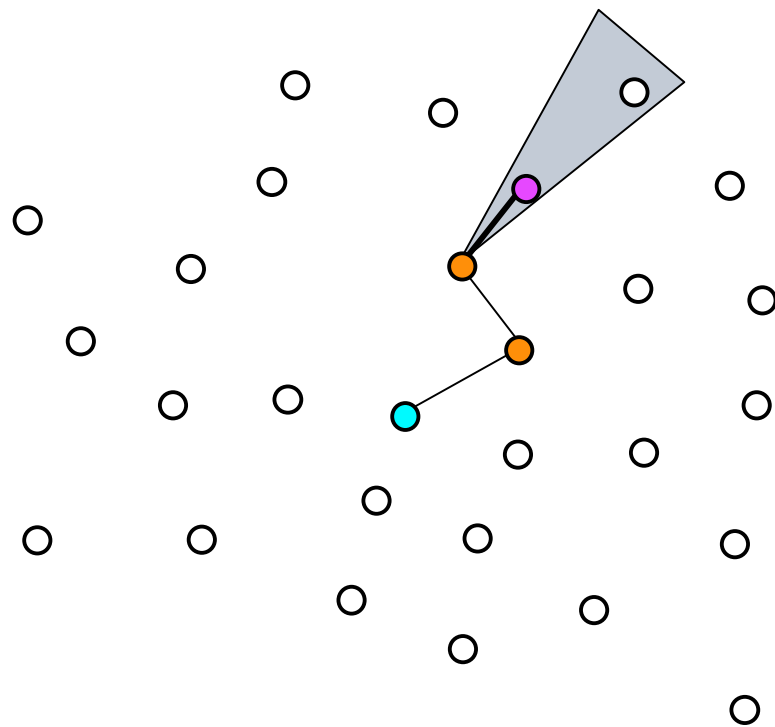
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Low-Power Transmission



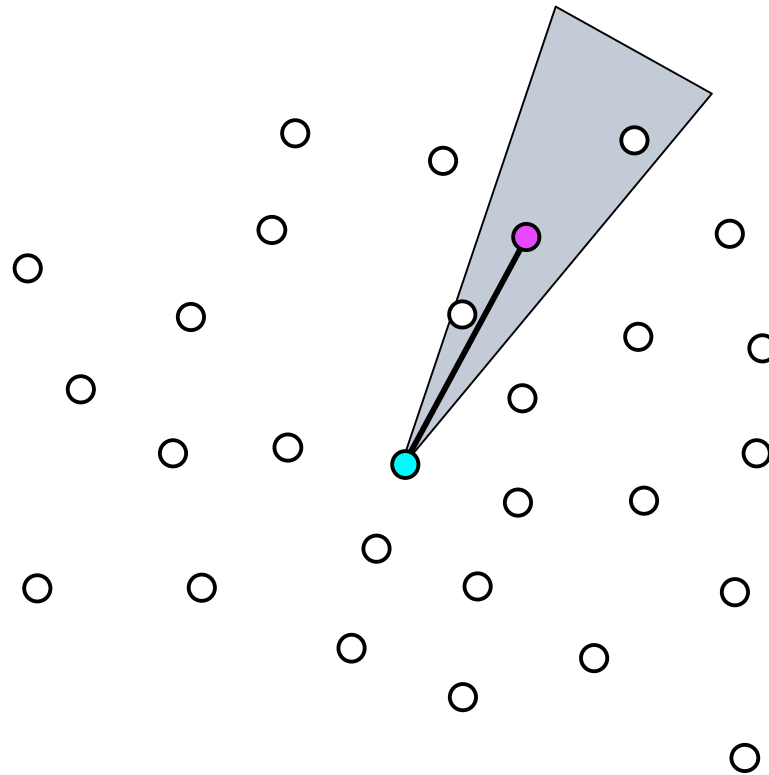
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Low-Power Transmission



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High-Power Transmission



Example 3

Assumptions:

- omnidirectional transmissions
- transmit power adjustable in discrete levels
- malicious detectors require few samples
- objective: minimize probability of detection

Cost:

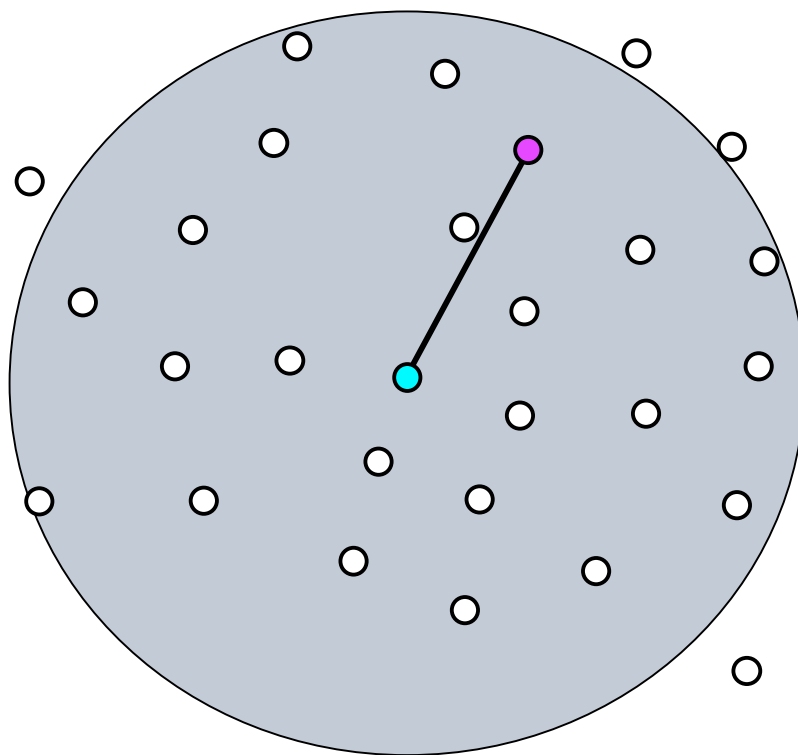
$$\sum_{i=1,h} r_i^2$$

h : number of hops from source to destination

r_i : omnidirectional interference range for hop i

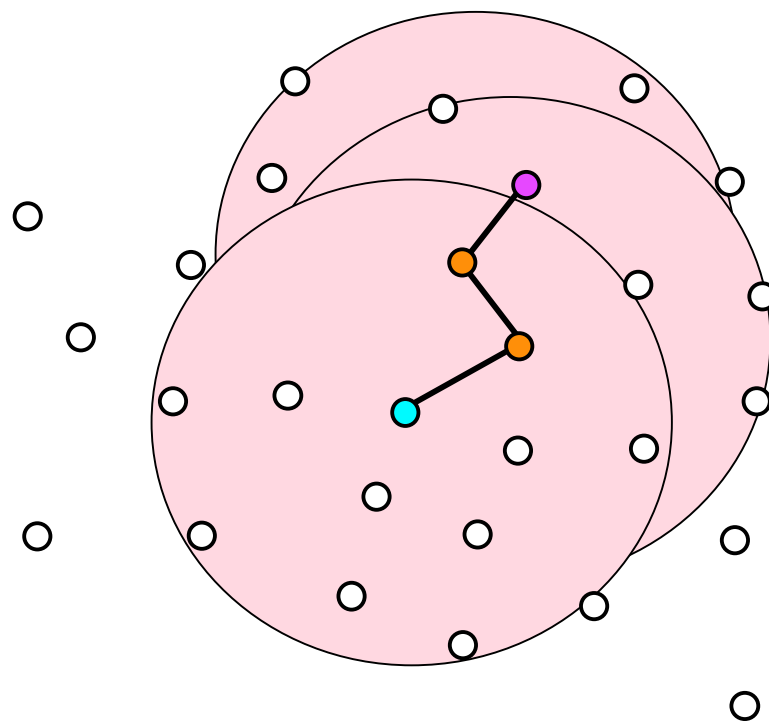
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High-Power Transmission



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Low-Power Transmissions



Summary

Topology control:

- network design and on demand
- uses information from both physical and application layers
- explicit interactions with other layers increases probability of meeting objectives
- knowledge of behavior of link layer (medium access) is critical for efficiency
- algorithms depend on communications context