Wireless Sensor Networks

23rd Lecture

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Options for topology control

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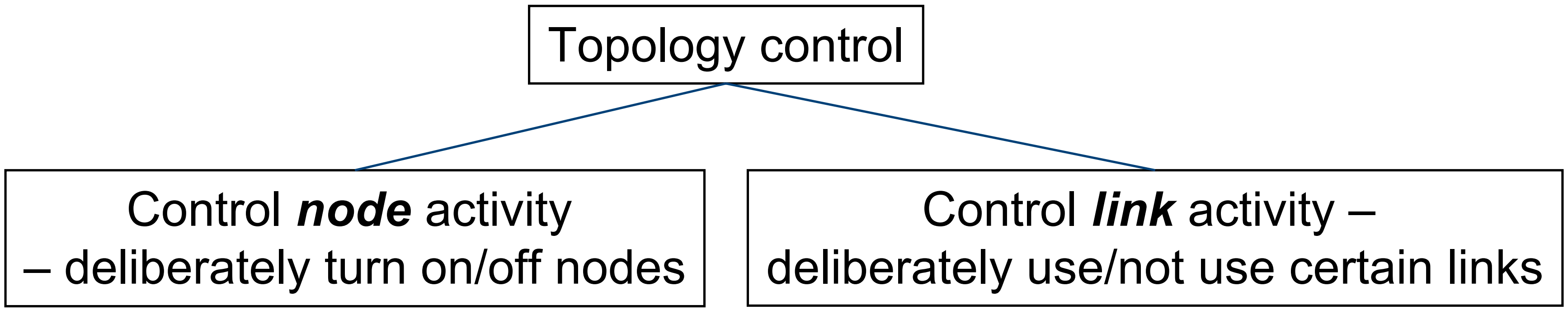

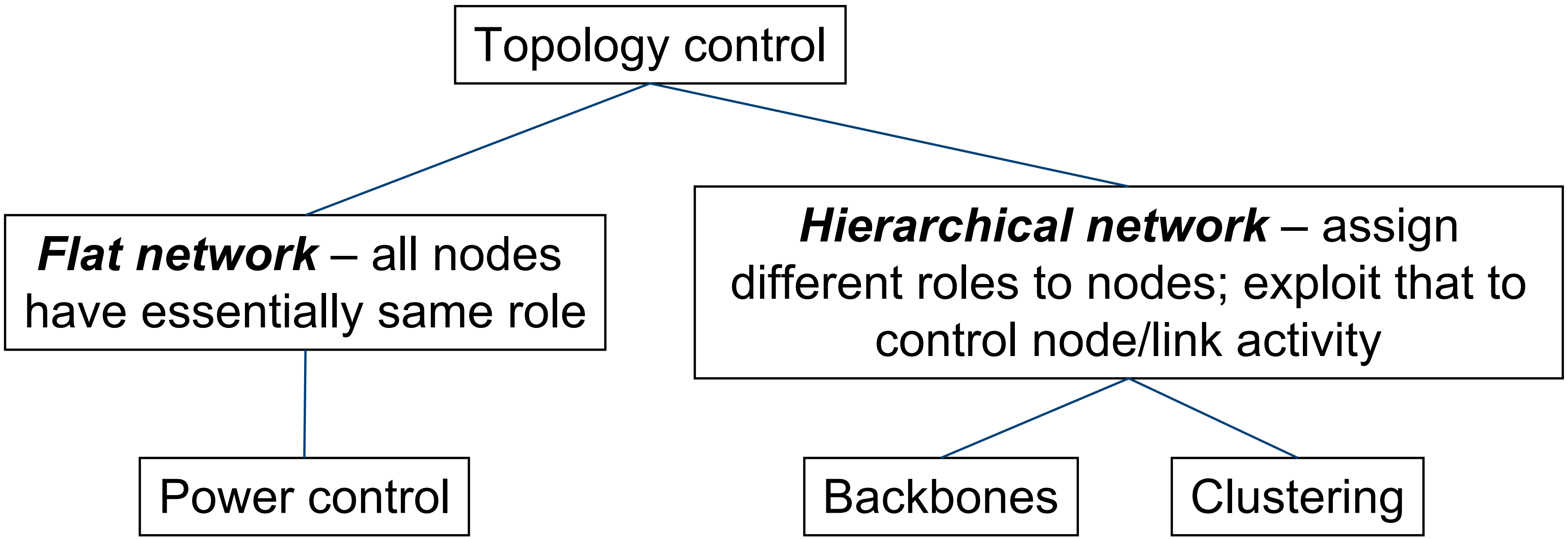

Hierarchical networks – backbones

- **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)
- **Dominating Set:**
  - Given an undirected graph G=(V,E)
  - Find a minimal subset $W \subseteq V$ such that for all $u \in W$ there exists $v \in V$ with $\{u,v\} \in V$
- **Problem: MDS is an NP-hard problem**
  - Hard to approximate, and even approximations need quite a few messages
  - Polynomial approximable within c log n for some $c > 0$ only if P=NP
  - Polynomial approximable within a factor of 1 + log n.

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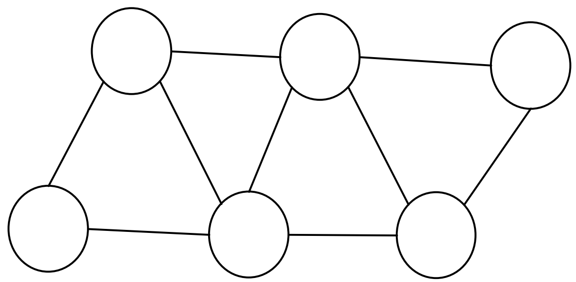
Backbone by growing a tree

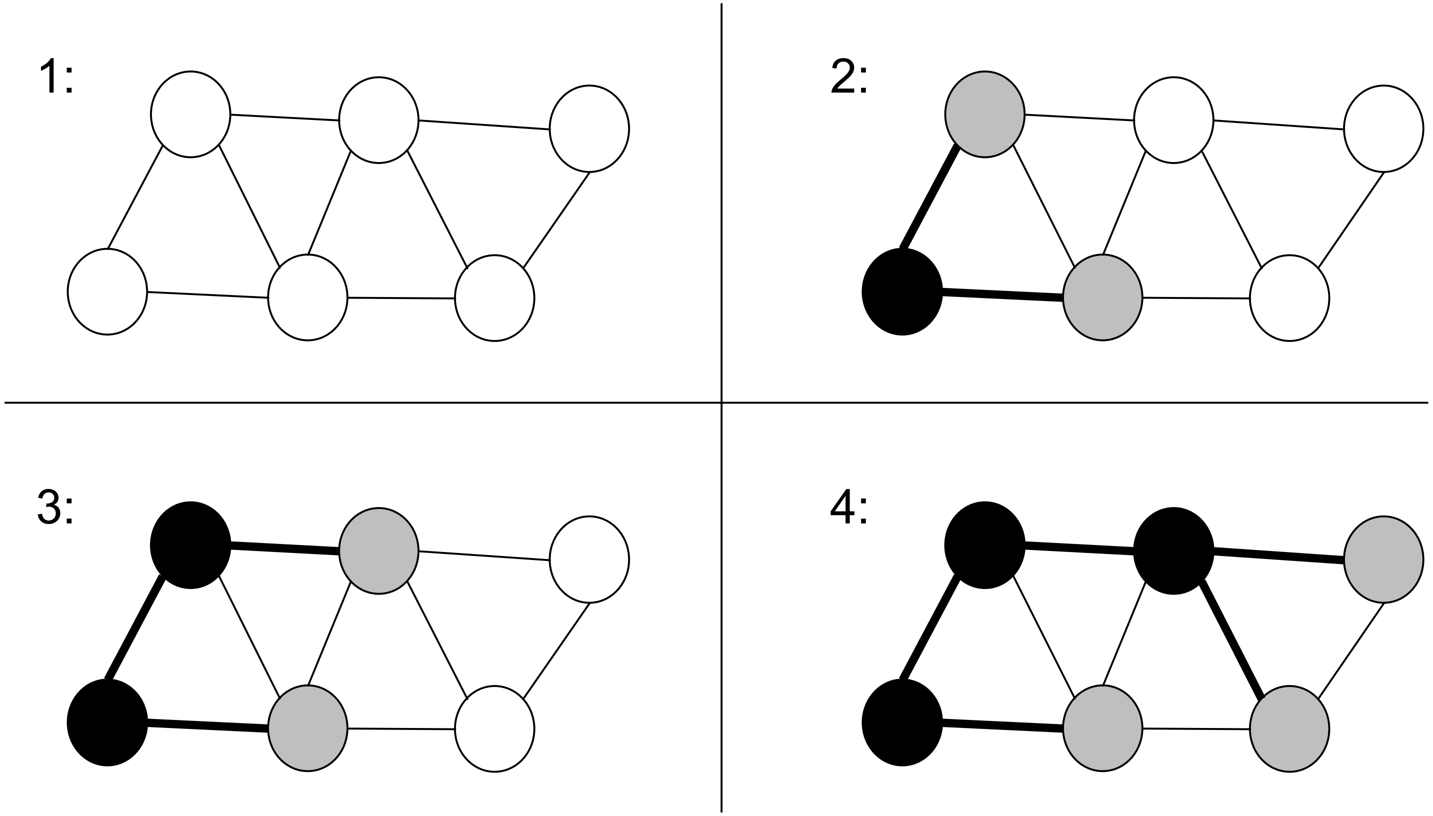
- **Construct the backbone as a tree, grown iteratively**

```
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 white neighbor u of v {
    color u grey
    add (v,u) to tree T
  }
}
```



Backbone by growing a tree – Example



Problem: Which gray node to pick?

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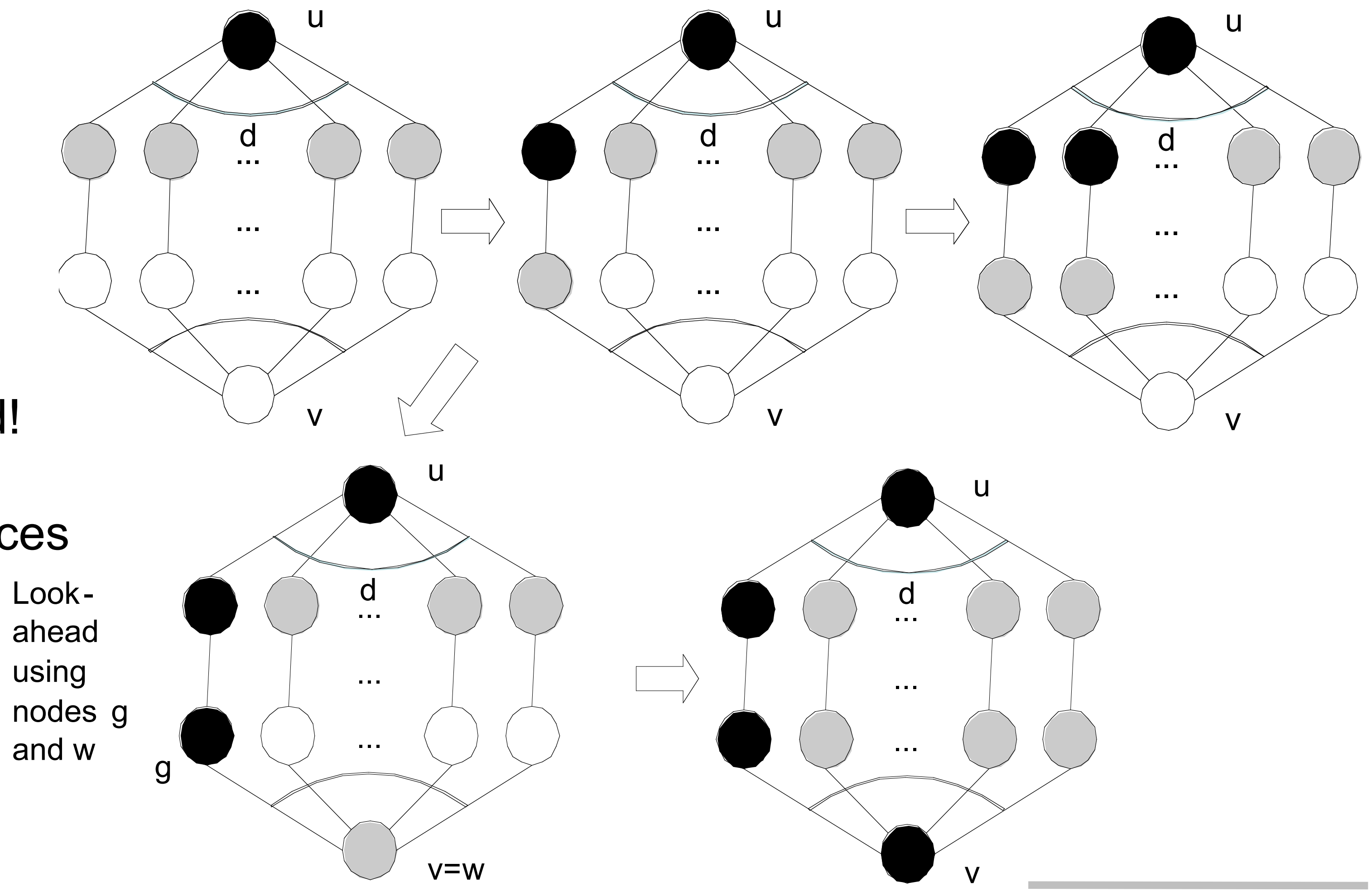
- **When blindly picking any gray node to turn black**
  - resulting tree can be very bad



Solution:
Look ahead!
Here,
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(Δ)) larger than MDS**
  - H(·) harmonic function, $H(k) = \sum_{i=1}^{k} 1/i \leq \ln k + 1$
  - Δ is maximum degree of the graph
- **It is automatically connected**
- **Can be implemented in a distributed fashion as well**

Start big, make lean

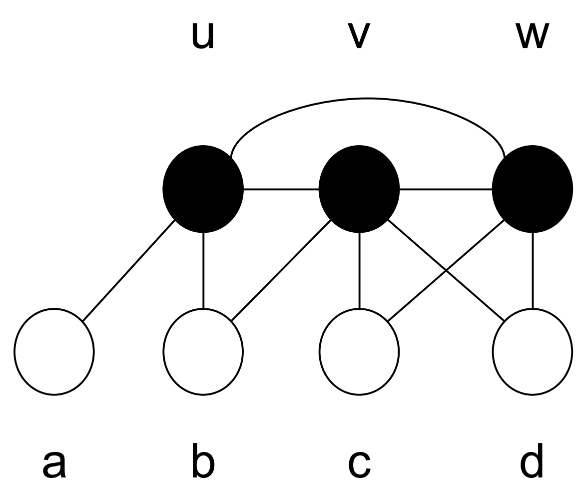
- **Idea: start with some, possibly large, connected dominating set, reduce it by removing unnecessary nodes**
- **Initial construction for dominating set**
  - All nodes are initially white
  - Mark any node black that has two neighbors that are not neighbors of each other (they might need to be dominated)

  $\rightarrow$ 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**



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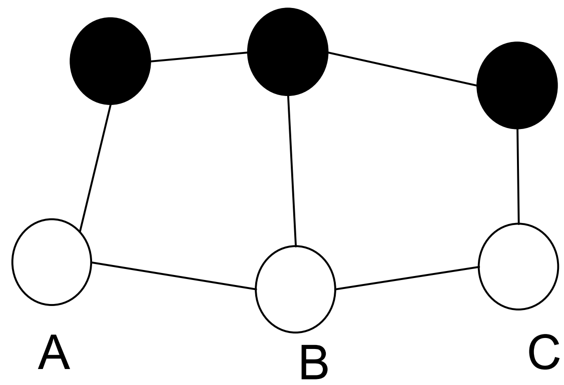
One more distributed backbone heuristic: Span

- **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



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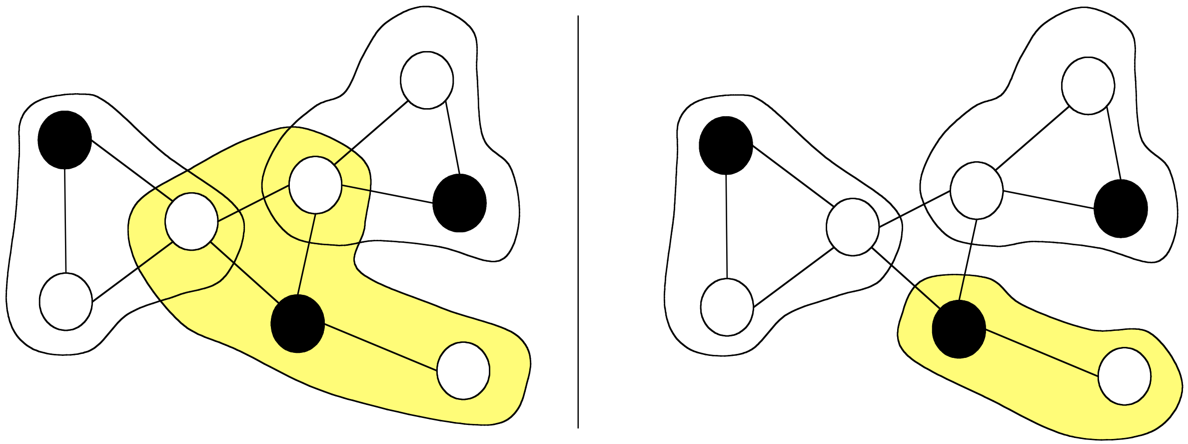
Overview

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

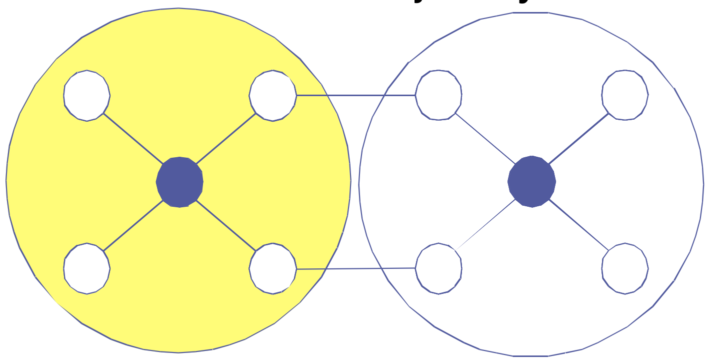
Clustering

- **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

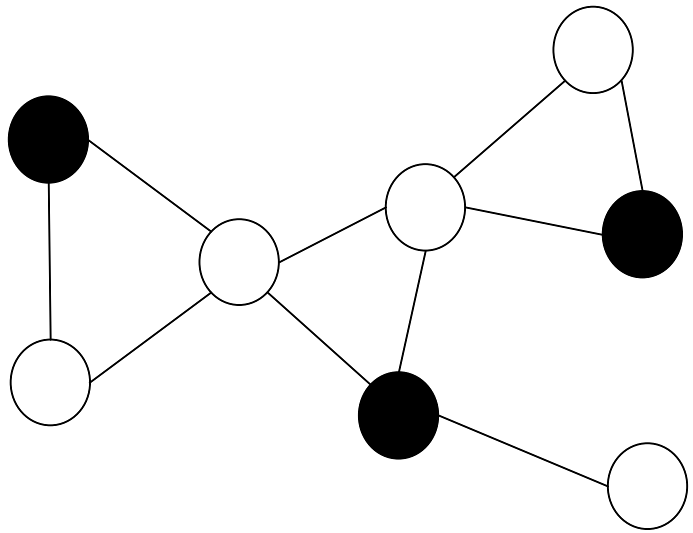
- **Further options**
  - How do clusters communicate? Some nodes need to act as ***gateways*** between clusters
    If clusters may not overlap, two nodes need to jointly act as a ***distributed gateway***



  - Many gateways may exist between clusters
    - active, 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 $\Delta/6 + o(1)$ and O(Δ/ log log Δ)**
  [Halldorsson Radhakrishnan]
- **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

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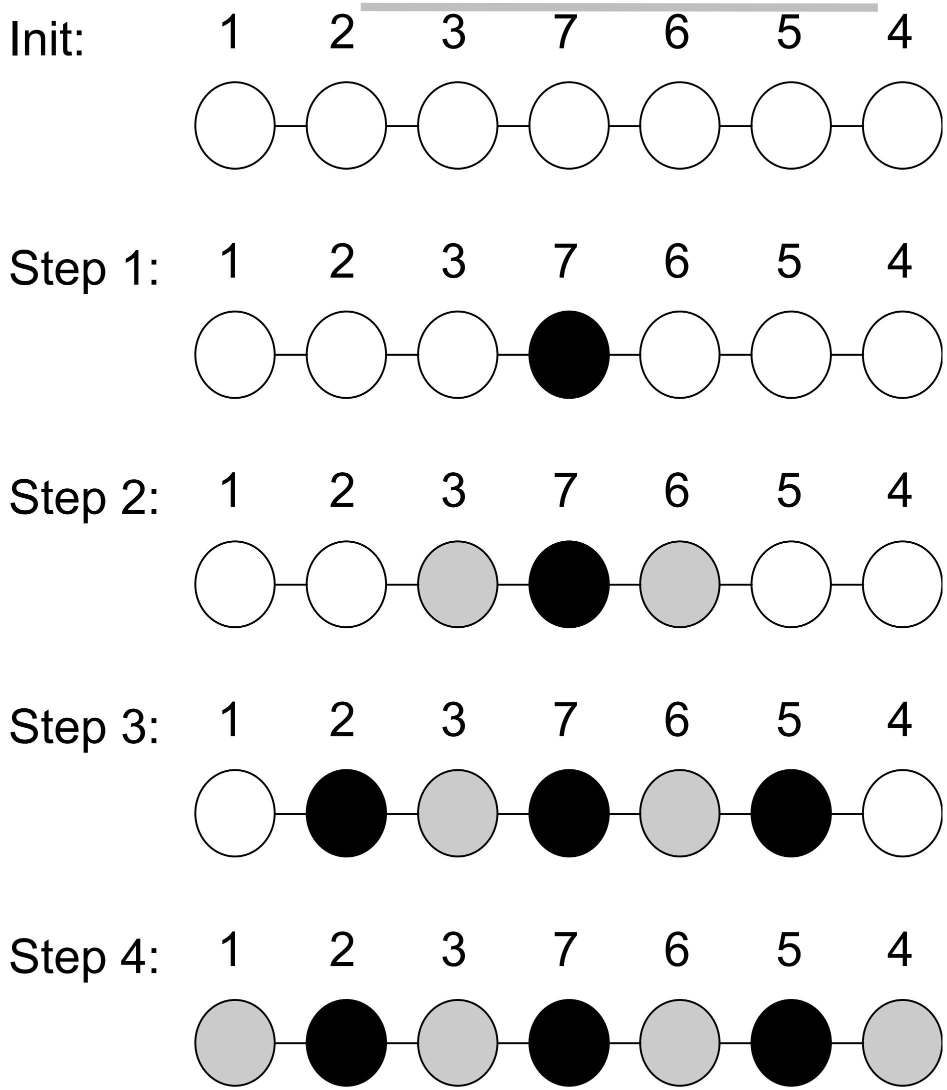
- **Use some attribute of nodes to break local symmetries**
  - Node identifiers, energy reserve, mobility, weighted combinations… - matters not for the idea as such (all types of variations have been looked at)
- **Make each node a clusterhead that locally has the largest attribute value**
- **Once a node is dominated by a clusterhead, it abstains from local competition, giving other nodes a chance**



Determining gateways to connect clusters

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- **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 $S \cup T$ is connected and $S \cup T$ 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

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- **Constructing a clustering structure brings overheads**
  - Not clear whether they can be amortized via improved efficiency
- **Question:**
  - 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

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Overview

- **Motivation, basics**
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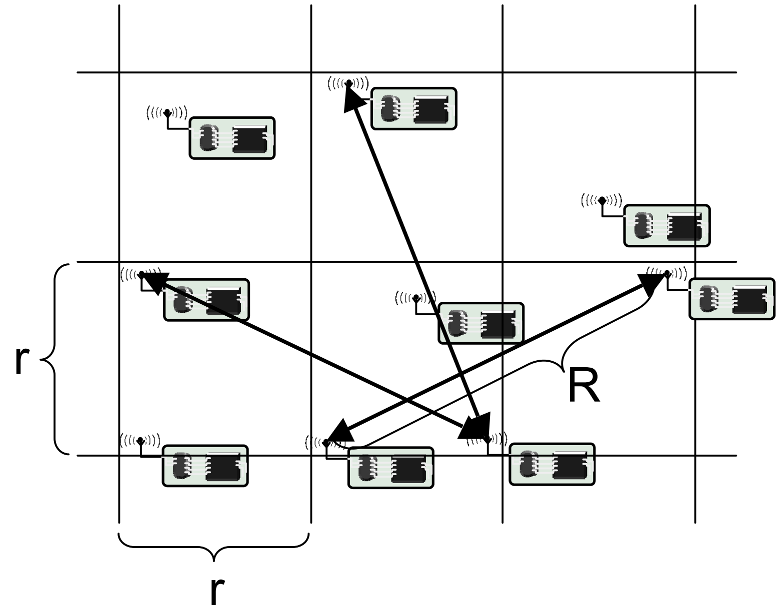
- *Adaptive node activity*

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 $r < R/5^{1/2}$ can replace each other with respect to forwarding**
  - R radio range
- **Keep only one such node active, let the other sleep**



Conclusion

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- **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**

Routing with IDs

- **In any network of diameter > 1, the routing & forwarding problem appears**
- **We will discuss mechanisms for constructing routing tables in ad hoc/sensor networks**
  - Specifically, when nodes are mobile
  - Specifically, with energy efficiency as an optimization metric
  - Specifically, when node position is available

Note: Presentation here partially follows Beraldi & Baldoni, Unicast Routing Techniques for Mobile Ad Hoc Networks, in M. Ilyas (ed.), The Handbook of Ad Hoc Wireless Networks

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Overview

- *Unicast routing in MANETs*
- **Energy efficiency & unicast routing**
- **Geographical routing**

Unicast, id-centric routing

- **Given: a network/a graph**
  - Each node has a unique identifier (ID)
- **Goal: Derive a mechanism that allows a packet sent from an arbitrary node to arrive at some arbitrary destination node**
  - The routing & forwarding problem
  - Routing: Construct data structures (e.g., tables) that contain information how a given destination can be reached
  - Forwarding: Consult these data structures to forward a given packet to its next hop
- **Challenges**
  - Nodes may move around, neighborhood relations change
  - Optimization metrics may be more complicated than “smallest hop count” – e.g., energy efficiency

Ad-hoc routing protocols

- **Because of challenges, standard routing approaches not really applicable**
  - Too big an overhead, too slow in reacting to changes
  - Examples: Dijkstra's link state algorithm; Bellman-Ford distance vector algorithm
- **Simple solution: Flooding**
  - Does not need any information (routing tables) – simple
  - Packets are usually delivered to destination
  - But: overhead is prohibitive

  → Usually not acceptable, either

→ **Need specific,** *ad hoc routing protocols*

Ad hoc routing protocols – classification

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- **Main question to ask:** *When* **does the routing protocol operate?**

- **Option 1: Routing protocol** *always* **tries to keep its routing data up-to-date**
  – Protocol is ***proactive*** (active before tables are actually needed) or ***table-driven***

- **Option 2: Route is only determined when actually needed**
  – Protocol operates ***on demand***

- **Option 3: Combine these behaviors**
  – ***Hybrid*** protocols

Ad hoc routing protocols – classification

- **Is the network regarded as flat or hierarchical?**
  - Compare topology control, traditional routing

- **Which data is used to identify nodes?**
  - An arbitrary identifier?
  - The ***position*** of a node?
    - Can be used to assist in ***geographic*** routing protocols because choice of next hop neighbor can be computed based on destination address
  - Identifiers that are not arbitrary, but carry some structure?
    - As in traditional routing
    - Structure akin to position, on a logical level?

Proactive protocols

- **Idea: Start from a +/- standard routing protocol, adapt it**

- **Adapted distance vector:** *Destination Sequence Distance Vector (DSDV)*
  - Based on distributed Bellman Ford procedure
  - Add ***aging*** information to route information propagated by distance vector exchanges; helps to avoid routing loops
  - Periodically send full route updates
  - On topology change, send incremental route updates
  - Unstable route updates are delayed
  - … + some smaller changes

The Shortest Path Problem

- **Given:**
  - A directed Graph G=(V,E)
  - Start node
  - and edge weights $w : E \rightarrow \mathbb{R}$
- **Define Weight of Shortest Path**
  - δ(u,v) = minimal weight w(p) of a path p from u to v
  - w(p) = sum of all edge weights w(e) of edges e of path p
- **Find:**
  - The shortest paths from s to all nodes in G
- **Solution set:**
  - is described by a tree with root s
  - Every node points towards the root s

Shortest Paths of Edsger Wybe Dijkstra

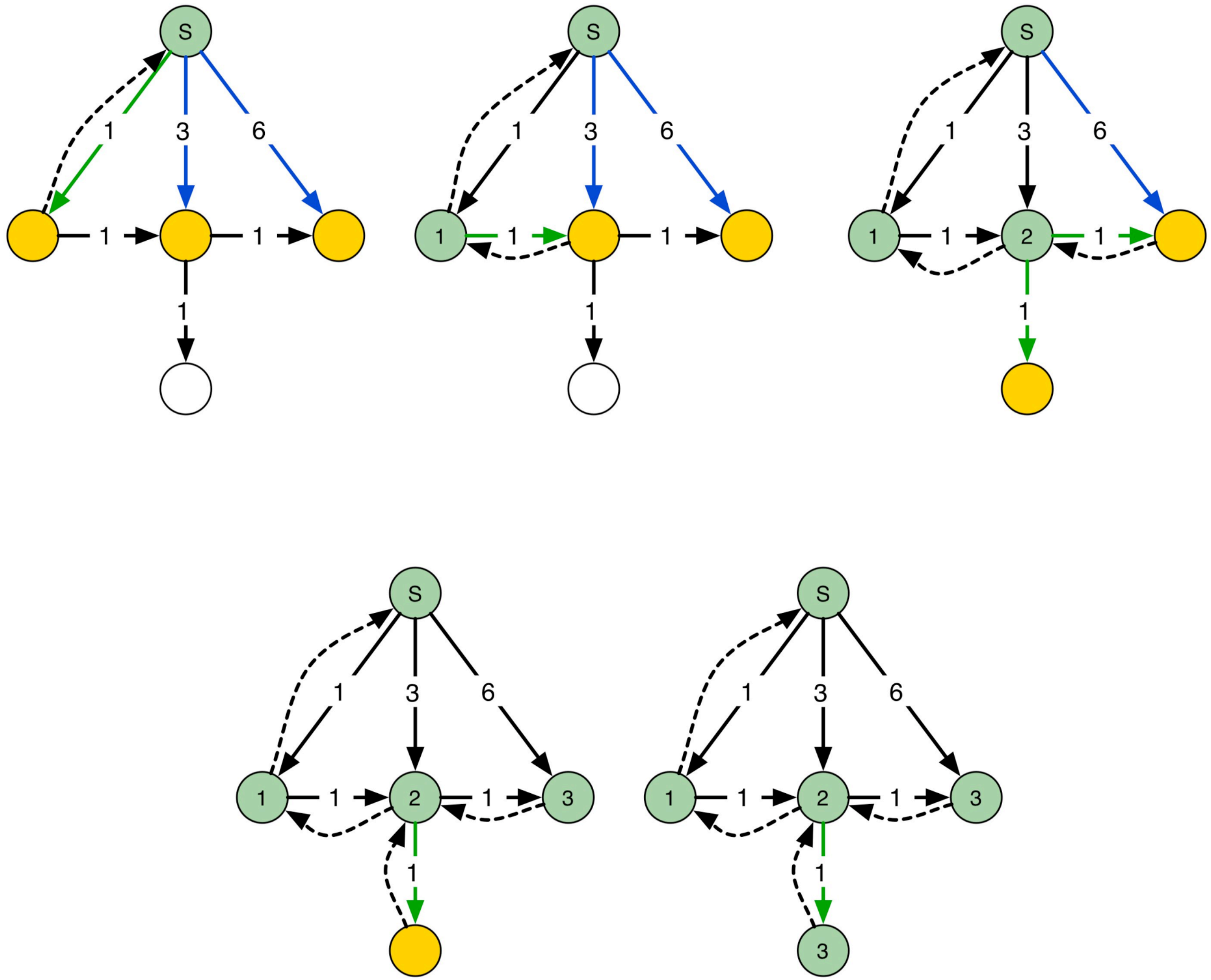
Dijkstra(G, w, s)
begin
  Init-Single-Source(G, w)
  $S \leftarrow \emptyset$
  $Q \leftarrow V$
  while $Q \neq \emptyset$ do
    $u \leftarrow$ Element aus Q mit minimalen Wert $d(u)$
    $S \leftarrow S \cup \{u\}$
    $Q \leftarrow Q \setminus \{u\}$
    for all $v \in$ Adj(u) do
      Relax(u, v)
    od
  od
end

Dijkstra's algorithm has runtime
$\Theta(|E| + |V| \log |V|)$

Init-Single-Source(G, w, s)
begin
  for all $v \in V$ do
    $d(v) \leftarrow \infty$
    $\pi(v) \leftarrow v$
  od
  $d(s) \leftarrow 0$
end

Relax(u, v)
begin
  if $d(v) > d(u) + w(u, v)$ then
    $d(v) \leftarrow d(u) + w(u, v)$
    $\pi(v) \leftarrow u$
  fi
end

Dijkstra: Example



Bellman-Ford

- Dijkstras Algorithm does not work for negative edge weights
- Bellman-Ford
  - solves shortest paths in runtime O(|V| |E|).

```
Bellman-Ford(G, w, s)
begin
    Init-Single-Source(G, w)
    loop |V| − 1 times do
        for all (u, v) ∈ E do
            Relax(u, v)
        od
    od
    for all (u, v) ∈ E do
        if d(v) > d(u) + w(u, v) then return false
    od
    return true
end
```

```
Init-Single-Source(G, w, s)
begin
    for all v ∈ V do
        d(v) ← ∞
        π(v) ← v
    od
    d(s) ← 0
end
```

```
Relax(u, v)
begin
    if d(v) > d(u) + w(u, v) then
        d(v) ← d(u) + w(u, v)
        π(v) ← u
    fi
end
```

Distance Vector Routing Protocol

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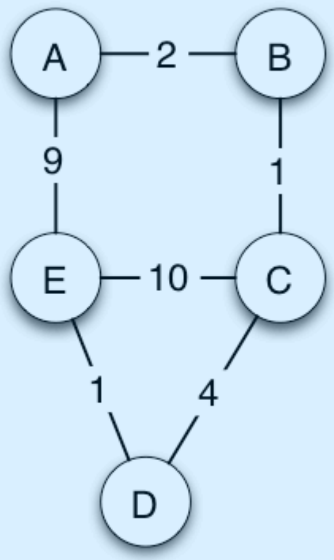
- **Distance Table Data Structure**
  - Every node has a
    - row for each target
    - column for each direct neighbor
- **Distributed Algorithm**
  - Every node communicates only with his neighbors
- **Asynchronous**
  - Nodes do not use a round model
- **Self-termination**
  - algorithm runs until no further changes occur



Distance Table für A

	von A	über B	über E	Routing Tabellen Eintrag
nach	B	2	15	B
	C	3	14	B
	D	7	10	B
	E	13	9	E

Distance Table für C

	von C	über B	über D	über E	Routing Tabellen Eintrag
nach	A	3	11	18	B
	B	1	6	16	B
	D	5	4	11	D
	E	7	5	10	D

The “Count to Infinity” - Problem

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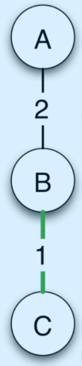
- **Good news travel fast**
  - A new connection is announced quickly.
- **Bad news travel slow**
  - Connection fails
  - Neighbors increase the distance counter
  - “Count to Infinity”-Problem



Distance Table für A

		über	
	von A	B	Routing Tabellen Eintrag
nach	B	**2**	B
	C	**-**	B

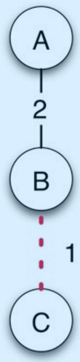
Distance Table für B

		über		
	von B	A	C	Routing Tabellen Eintrag
nach	A	2	-	A
	C	-	1	C

nach kurzer Zeit

		über	
	von A	B	Routing Tabellen Eintrag
nach	B	**2**	B
	C	**3**	B

		über		
	von B	A	C	Routing Tabellen Eintrag
nach	A	2	4	A
	C	5	1	C



		über	
	von A	B	Routing Tabellen Eintrag
nach	B	2	B
	C	3	B

		über		
	von B	A	C	Routing Tabellen Eintrag
nach	A	2	-	A
	C	5	-	A

		über	
	von A	B	Routing Tabellen Eintrag
nach	B	2	B
	C	7	B

		über		
	von B	A	C	Routing Tabellen Eintrag
nach	A	2	-	A
	C	5	-	A

		über	
	von A	B	Routing Tabellen Eintrag
nach	B	2	B
	C	7	B

		über		
	von B	A	C	Routing Tabellen Eintrag
nach	A	2	-	A
	C	9	-	A

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Link-State Protocol

- **Link State Routers**
  - exchange information using **link state packets** (LSP)
  - Every router uses a (centralized) shortest-path-algorithm
- **LSP contains**
  - ID of creator of LSP
  - Costs of all edges from the creator
  - Sequence no. (SEQNO)
  - TTL-entry (time to live)
- **Reliable Flooding**
  - The current LSP of every node are stored
  - Forwarding of LSPs to all neighbors
    - except sending nodes
  - Periodically new LSPs are generated
    - with incremented SEQNO
  - TTL is decremented after every transmission

Proactive protocols – OLSR

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- **Combine link-state protocol & topology control**
- *Optimized Link State Routing* **(***OLSR***)**

- **Topology control component: Each node selects a minimal dominating set for its two-hop neighborhood**
  - Called the ***multipoint relays***
  - Only these nodes are used for packet forwarding
  - Allows for efficient flooding

- **Link-state component: Essentially a standard link-state algorithms on this reduced topology**
  - Observation: Key idea is to reduce flooding overhead (here by modifying topology)

Proactive protocols – Combine LS & DS: Fish eye

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- **Fisheye State Routing (FSR) makes basic observation: When destination is far away, details about path are not relevant – only in vicinity are details required**
  - Look at the graph as if through a fisheye lens
  - Regions of different accuracy of routing information

- **Practically:**
  - Each node maintains topology table of network (as in LS)
  - Unlike LS: only distribute link state updates locally
  - More frequent routing updates for nodes with smaller scope

Reactive protocols – DSR

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- **In a reactive protocol, how to forward a packet to destination?**
  - Initially, no information about next hop is available at all
  - One (only?) possible recourse: Send packet to ***all*** neighbors – flood the network
  - Hope: At some point, packet will reach destination and an answer is sent pack – use this answer for ***backward learning*** the route from destination to source

- **Practically:** *Dynamic Source Routing (DSR)*
  - Use separate ***route request/route reply*** packets to discover route
    - Data packets only sent once route has been established
    - Discovery packets smaller than data packets
  - Store routing information in the discovery packets

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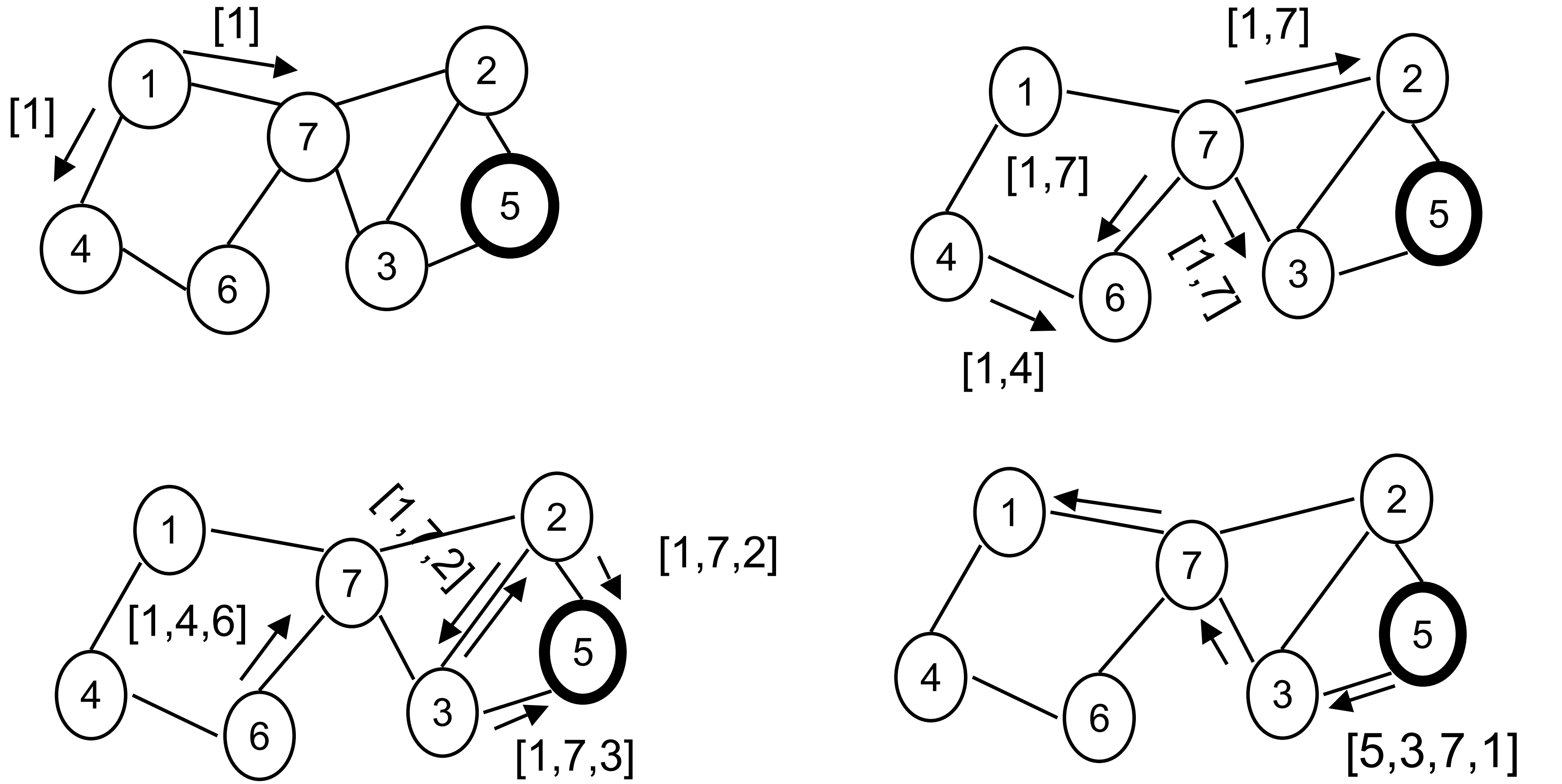
DSR route discovery procedure

Search for route from 1 to 5



Node 5 uses route information recorded in RREQ to send back, via ***source routing***, a route reply

DSR modifications, extensions

- **Intermediate nodes may send route replies in case they already know a route**
  - Problem: stale route caches
- **Promiscuous operation of radio devices – nodes can learn about topology by listening to control messages**
- **Random delays for generating route replies**
  - Many nodes might know an answer – reply storms
  - NOT necessary for medium access – MAC should take care of it
- **Salvaging/local repair**
  - When an error is detected, usually sender times out and constructs entire route anew
  - Instead: try to locally change the source-designated route
- **Cache management mechanisms**
  - To remove stale cache entries quickly
  - Fixed or adaptive lifetime, cache removal messages, …

Reactive protocols – AODV

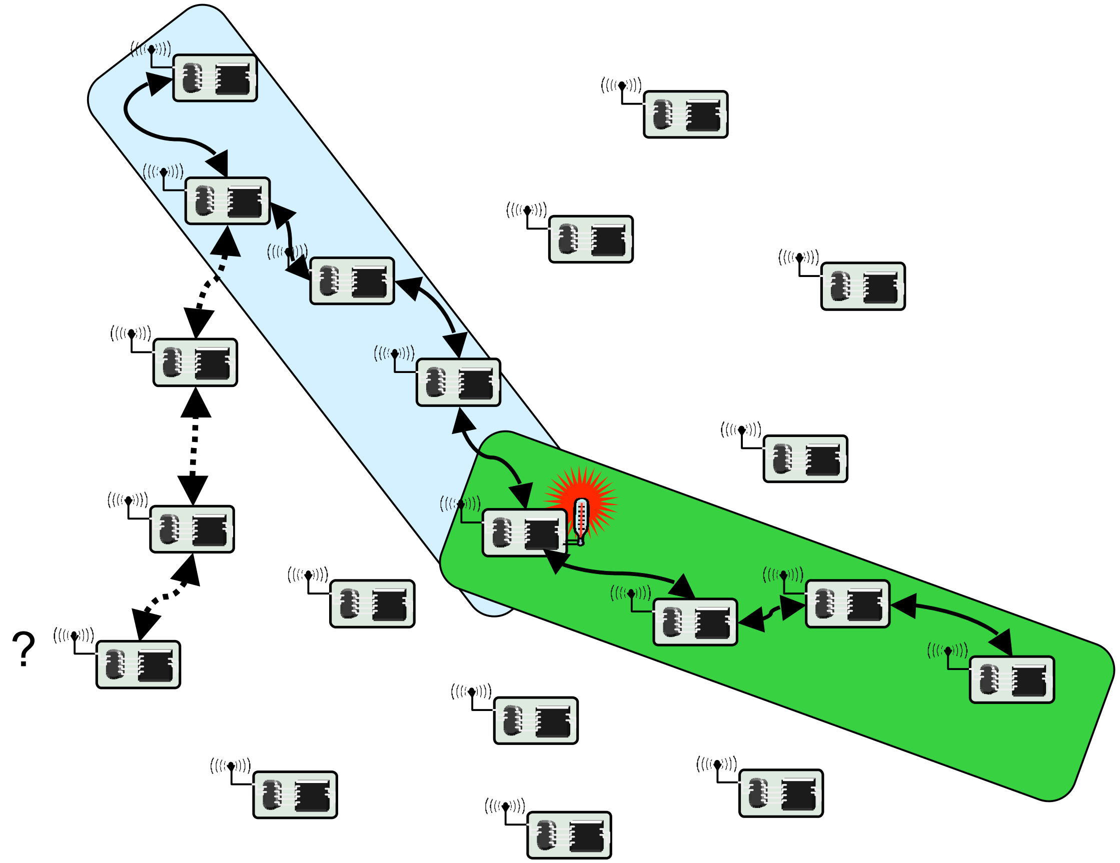
- **Ad hoc On Demand Distance Vector routing (AODV)**
  - Very popular routing protocol
  - Essentially same basic idea as DSR for discovery procedure
  - Nodes maintain routing tables instead of source routing
  - Sequence numbers added to handle stale caches
  - Nodes remember from where a packet came and populate routing tables with that information

Reactive protocols – TORA

- **Observation: In hilly terrain, routing to a river's mouth is easy – just go downhill**
- **Idea: Turn network into hilly terrain**
  - Different "landscape" for each destination
  - Assign "heights" to nodes such that when going downhill, destination is reached – in effect: orient edges between neighbors
  - Necessary: resulting directed graph has to be cycle free
- **Reaction to topology changes**
  - When link is removed that was the last "outlet" of a node, reverse direction of all its other links (increase height!)
  - Reapply continuously, until each node except destination has at least a single outlet – will succeed in a connected graph!

Alternative approach: Gossiping/rumor routing

- Turn routing problem around: Think of an "agent" wandering through the network, looking for data (events, …)
- Agent initially perform random walk
- Leave "traces" in the network
- Later agents can use these traces to find data
- Essentially: works due to high probability of line intersections



Overview

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- **Unicast routing in MANETs**
- *Energy efficiency & unicast routing*
- **Geographical routing**

Energy-efficient unicast: Goals

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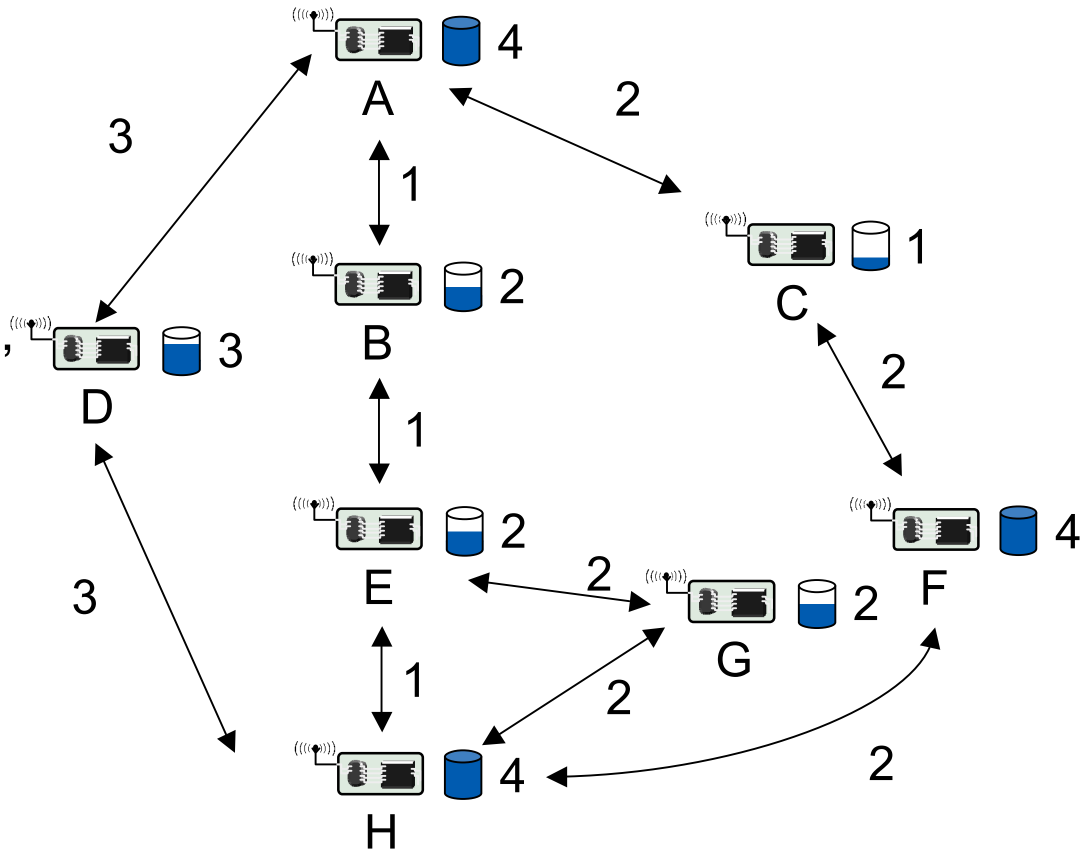
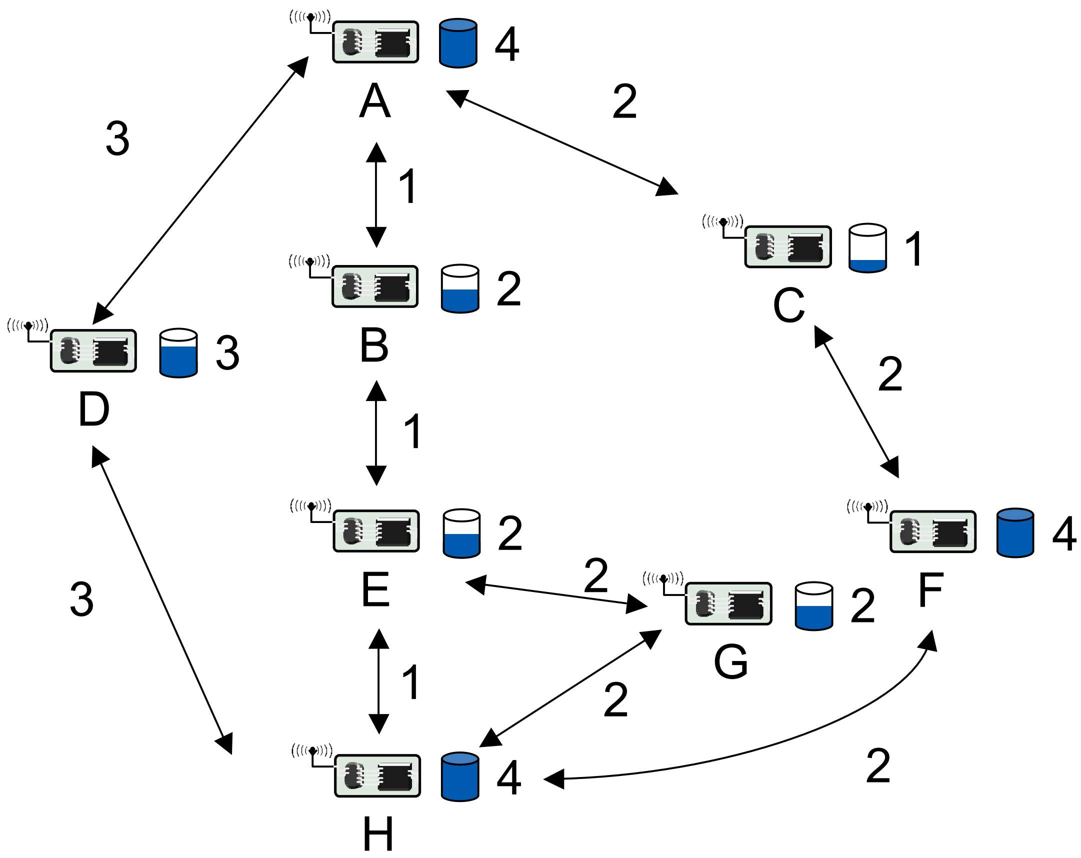
- **Particularly interesting performance metric: Energy efficiency**
- **Goals**
  - Minimize energy/bit
    - Example: A-B-E-H
  - Maximize network lifetime
    - Time until first node failure, loss of coverage, partitioning
- **Seems trivial – use proper link/path metrics (not hop count) and standard routing**



Example: Send data from node A to node H

Basic options for path metrics

- **Maximum total available battery capacity**
  - Path metric: Sum of battery levels
  - Example: A-C-F-H
- **Minimum battery cost routing**
  - Path metric: Sum of reciprocal battery levels
  - Example: A-D-H
- **Conditional max-min battery capacity routing**
  - Only take battery level into account when below a given level
- **Minimize variance in power levels**
- **Minimum total transmission power**



A non-trivial path metric

- **Previous path metrics do not perform particularly well**

- **One non-trivial link weight:**

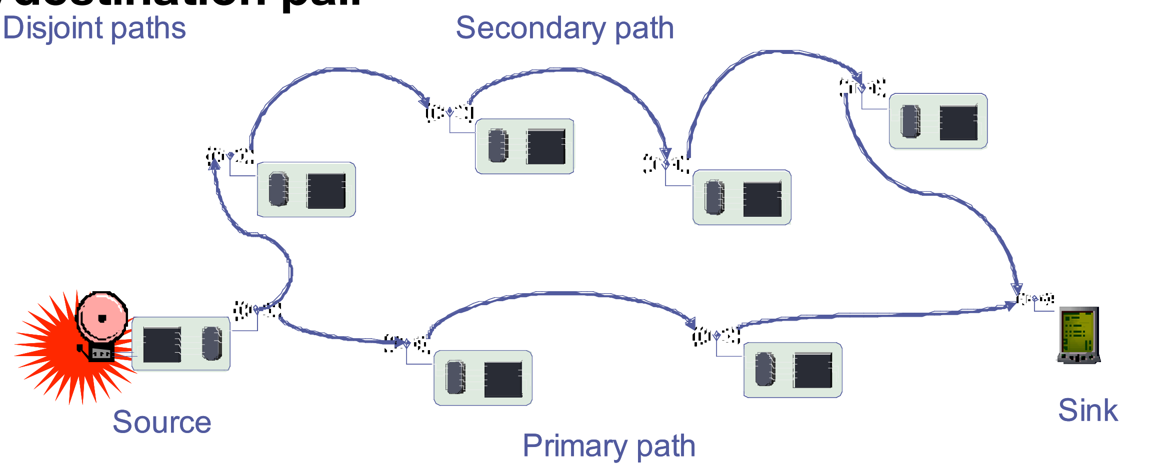
$$w_{ij} = e_{ij}(\lambda^{\alpha_i} - 1)$$

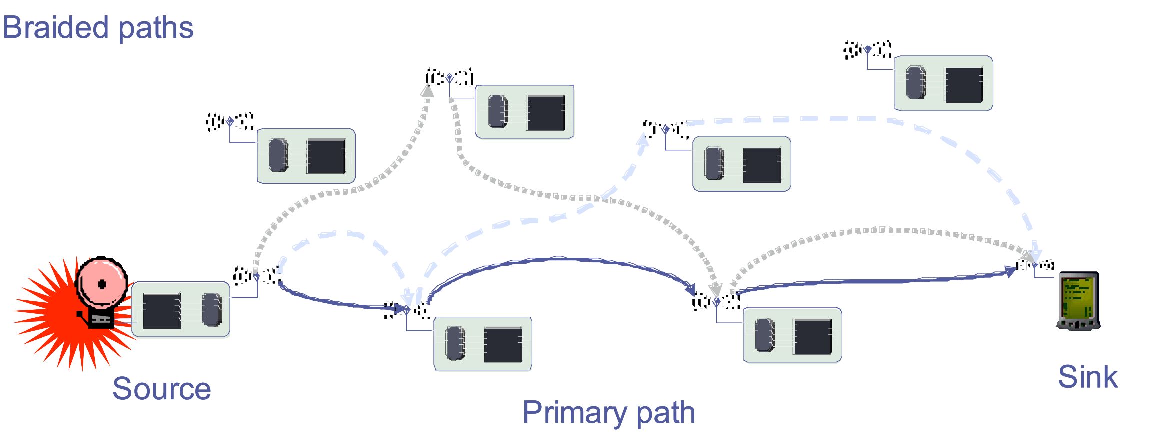
  – w_{ij} weight for link node i to node j
  – e_{ij} required energy, λ some constant, α_i fraction of battery of node i already used up
- **Path metric: Sum of link weights**
  – Use path with smallest metric

- **Properties: Many messages can be send, high network lifetime**
  – With admission control, even a competitive ratio logarithmic in network size can be shown

Multipath unicast routing

- **Instead of only a single path, it can be useful to compute multiple paths between a given source/destination pair**
  - Multiple paths can be ***disjoint*** or ***braided***
  - Used simultaneously, alternatively, randomly, …





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Overview

- **Unicast routing in MANETs**
- **Energy efficiency & unicast routing**
- *Geographical routing*
  - ***Position-based routing***
  - Geocasting

Geographic routing

- **Routing tables contain information to which next hop a packet should be forwarded**
  - Explicitly constructed
- **Alternative: Implicitly *infer* this information from physical placement of nodes**
  - Position of current node, current neighbors, destination known – send to a neighbor in the right direction as next hop
  - ***Geographic routing***
- **Options**
  - Send to any node in a given area – ***geocasting***
  - Use position information to aid in routing – ***position-based routing***
    - Might need a ***location service*** to map node ID to node position

Basics of position-based routing

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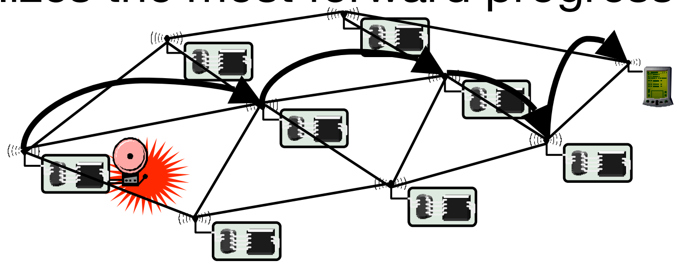
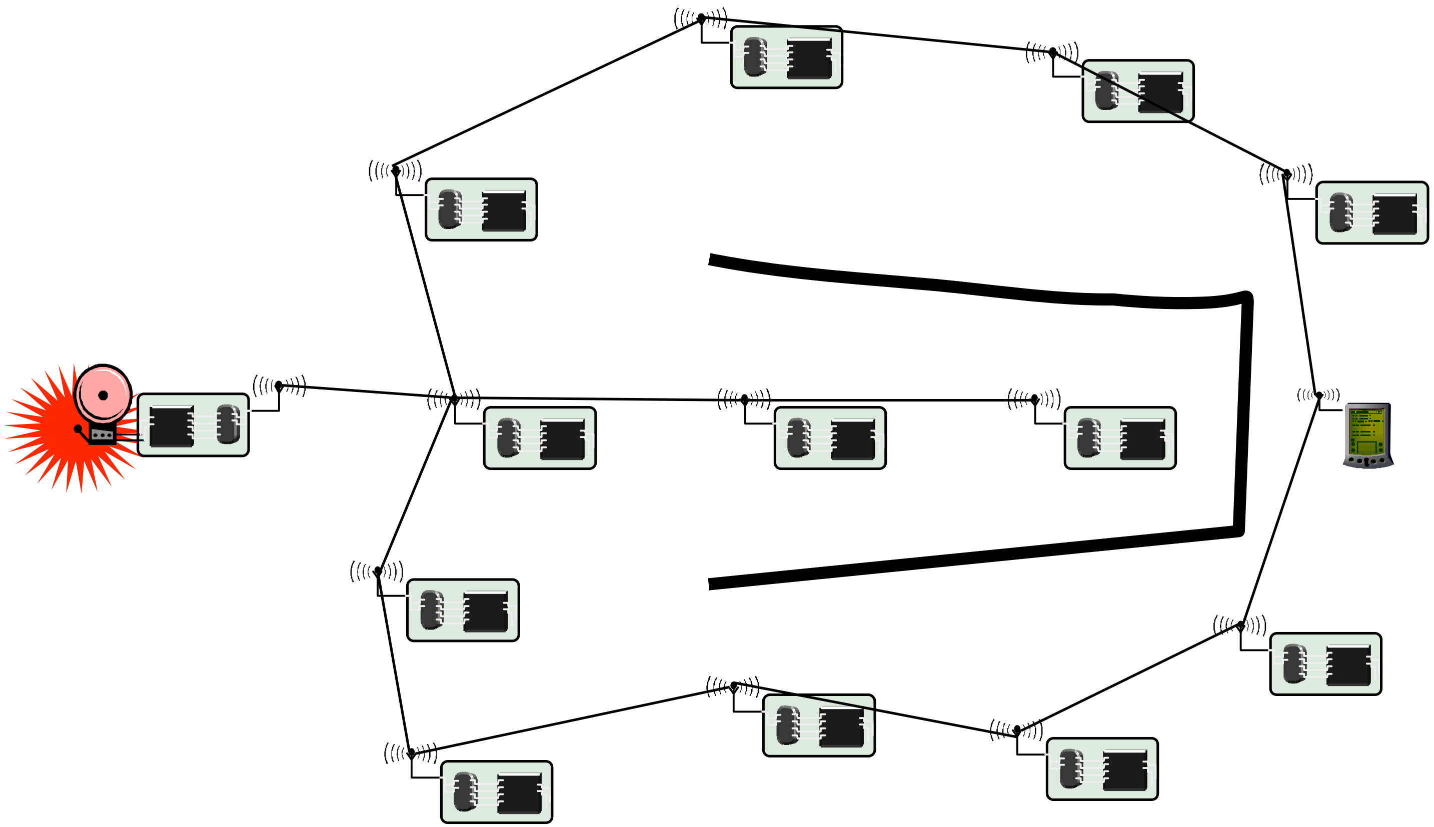
- **"Most forward within range r" strategy**
  - Send to that neighbor that realizes the most forward progress towards destination
  - NOT: farthest away from sender!



- **Nearest node with (any) forward progress**
  - Idea: Minimize transmission power
- **Directional routing**
  - Choose next hop that is angularly closest to destination
  - Choose next hop that is closest to the connecting line to destination
  - Problem: Might result in loops!

Problem: Dead ends

- Simple strategies might send a packet into a dead end

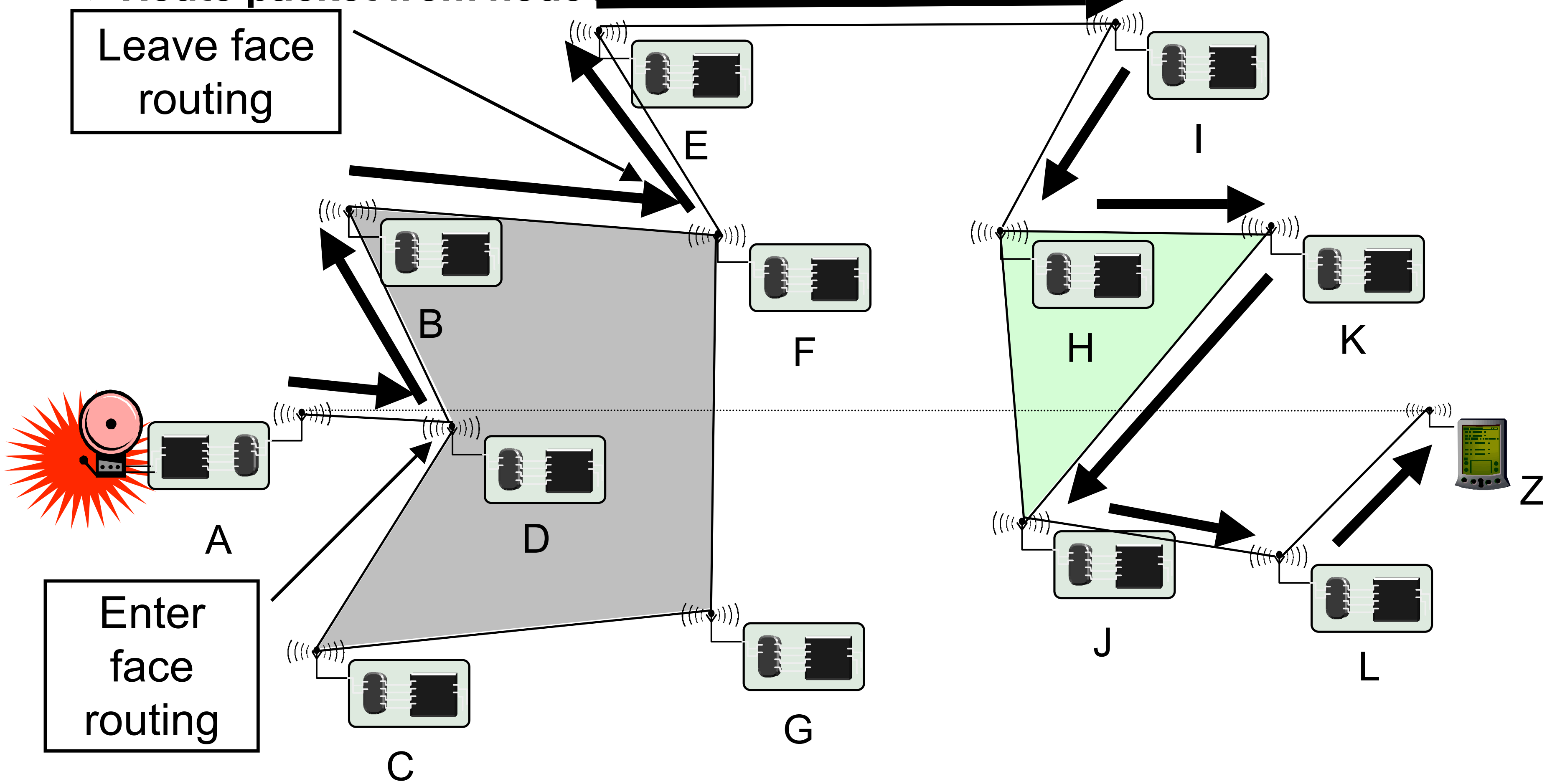


Right hand rule to leave dead ends – GPSR

- **Basic idea to get out of a dead end: Put right hand to the wall, follow the wall**
  - Does not work if on some inner wall – will walk in circles
  - Need some additional rules to detect such circles
- *Geometric Perimeter State Routing* **(***GPSR***)**
  - Earlier versions: Compass Routing II, face-2 routing
  - Use greedy, "most forward" routing as long as possible
  - If no progress possible: Switch to "face" routing
    - Face: largest possible region of the plane that is not cut by any edge of the graph; can be exterior or interior
    - Send packet around the face using right-hand rule
    - Use position where face was entered and destination position to determine when face can be left again, switch back to greedy routing
  - Requires: planar graph! (topology control can ensure that)

GPSR – Example

- Route packet from node A to node Z



Geographic routing without positions – GEM

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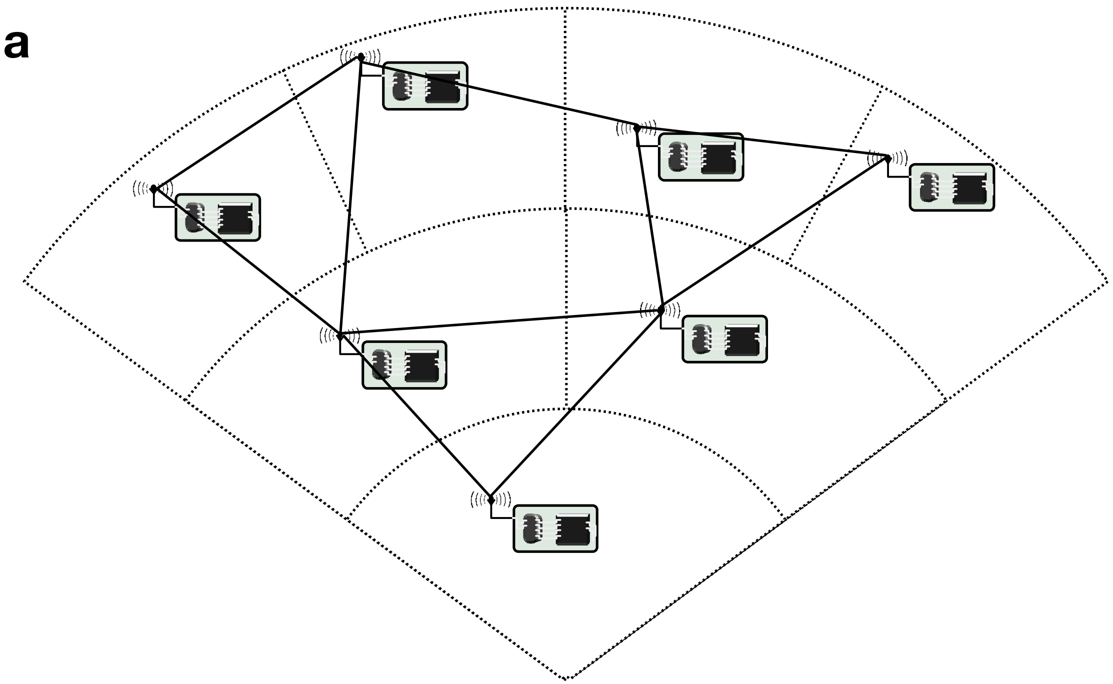
- **Apparent contradiction: geographic, but no position?**
- **Construct** *virtual coordinates* **that preserve enough neighborhood information to be useful in geographic routing but do not require actual position determination**

- **Use polar coordinates from a center point**
- **Assign "virtual angle range" to neighbors of a node, bigger radius**
- **Angles are recursively redistributed to children nodes**



Thank you

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