Institute for the Wireless Internet of Things
at Northeastern University

EECE 5155
Wireless Sensor Networks (and The Internet of Things)

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Network Layer

Routing in WSNs

- Routing in Ad Hoc Networks
  - Id-based routing
  - Reactive protocols, proactive protocols
  - Energy-efficient routing
  - Multicast and broadcast
- Routing in Sensor Networks
  - Data-centric protocols
  - Hierarchical routing protocols
  - Geographical routing protocols

Unicast, ID-centric Routing

- General problem: Given a network (*i.e.*, a graph)
  – Where each node has a unique identifier (ID)
- Objective: Derive a mechanism that allows a packet sent from an arbitrary node to arrive at some arbitrary destination node
- Routing & Forwarding
  – Routing: Construct data structures (i.e., tables) that contain information on how a given destination can be reached
  – Forwarding: Consult tables to forward a given packet to its next hop
- Challenges
  – Optimization metric
  – Mobility changes neighborhood relations
  – Scalability

Ad-hoc Routing Protocols

- Standard routing approaches not applicable
  - Large overhead
  - 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
  - Overhead is prohibitive
    - Energy consumption
    - Waste bandwidth
    - Not scalable

Ad Hoc Routing Protocols – Classification

- ***When*** does the routing protocol operate?

- ***Proactive*** Protocols
  - Routing protocol ***always*** tries to keep its routing data up-to-date
  - Active before tables are actually needed
  - Also known as ***table-driven***

- ***Reactive*** Protocols
  - Route is only determined when actually needed
  - Protocol operates ***on-demand***

- ***Hybrid*** protocols
  - Combine these behaviors

Ad Hoc Routing Protocols – Classification

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

Proactive Protocols - DSDV

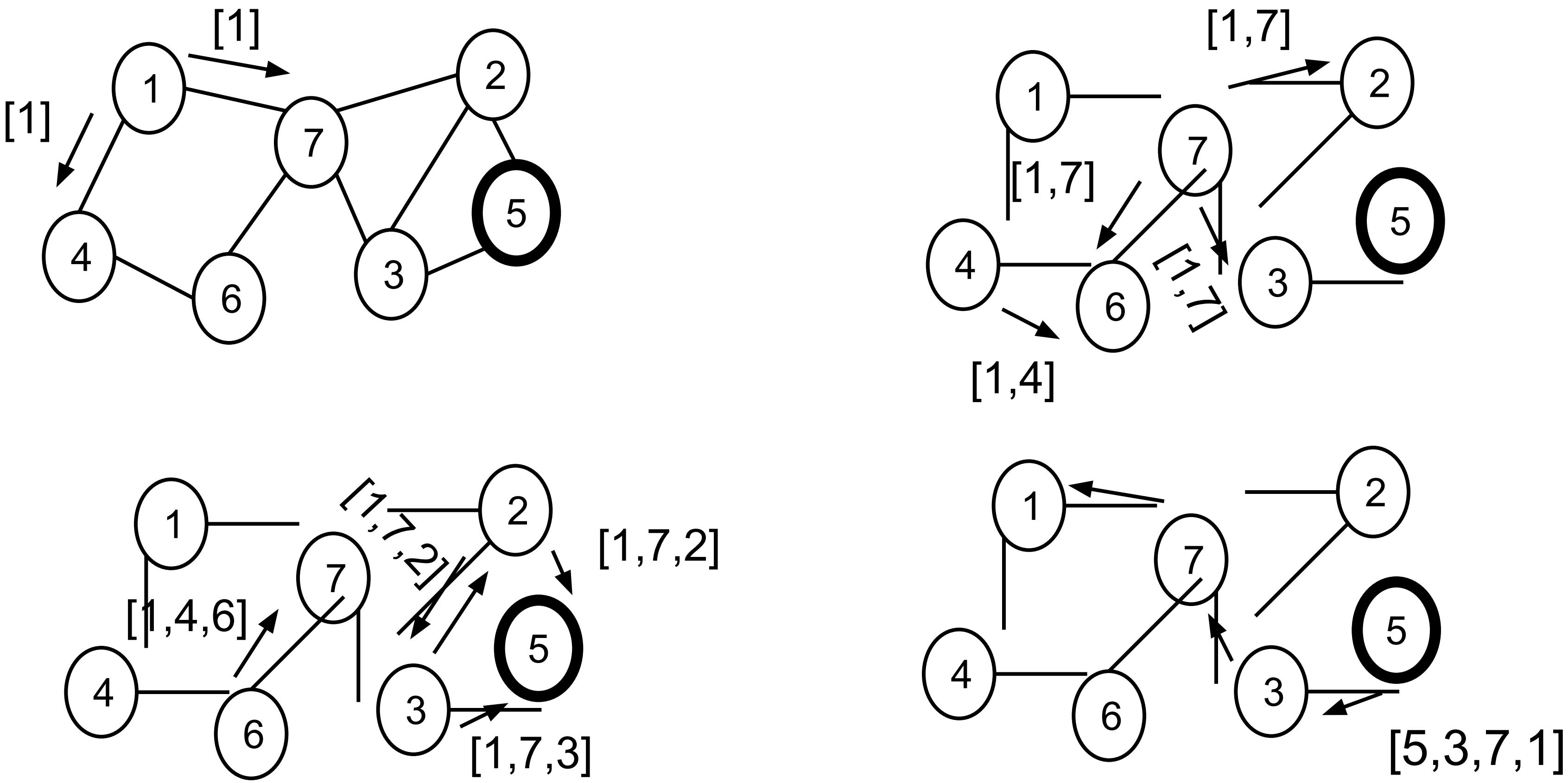
- Adapted distance vector:
  Destination Sequence Distance Vector (DSDV)
  - Based on distributed Bellman Ford procedure
  - Periodically send full route updates
  - On topology change, send incremental route updates
  - Unstable route updates are delayed

Reactive Protocols – DSR

- ***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

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
- Cache management mechanisms
  - To remove stale cache entries quickly

Reactive Protocols – AODV

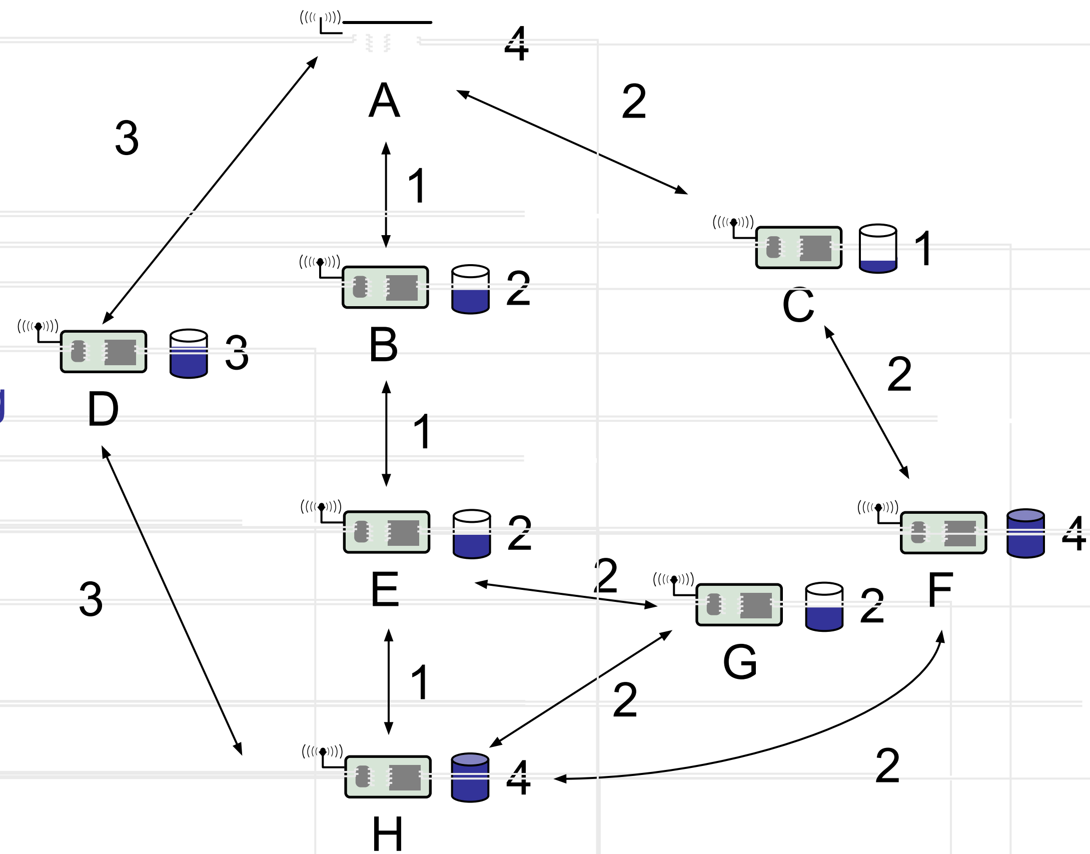
- ***Ad hoc On Demand Distance Vector*** routing (AODV)
  - Very popular routing protocol
  - Essentially same basic idea as DSR for discovery procedure
  - Nodes maintain routing tables instead of source routing
  - Sequence numbers added to handle stale caches
  - Nodes remember from where a packet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

Energy is (almost) always the most important thing in WSNs!!!

Energy-efficient Unicast: Goals

- Performance metric: Energy efficiency

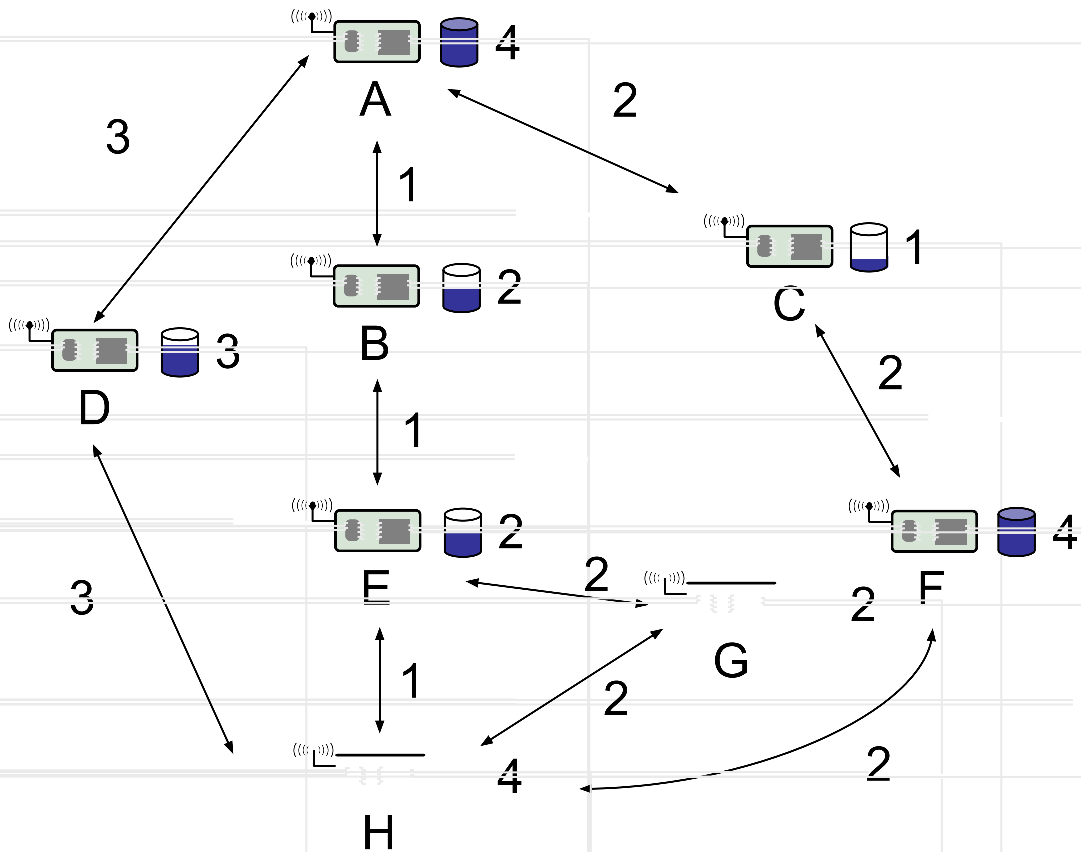
- Goals
  - Maximize network lifetime
    - Time until first node failure, loss of coverage, partitioning



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



Routing Protocols for WSNs

Taxonomy of Routing Protocols for WSN

K. Akkaya and M. Younis, “A Survey on Routing Protocols for Wireless Sensor Networks,” Ad Hoc Networks (Elsevier) Journal, 2005

- **LOCATION-BASED (GEOGRAPHIC) PROTOCOLS**
  - MECN, SMECN (Small Minimum Energy Com Netw), GAF (Geographic Adaptive Fidelity), GEAR, Distributed Topology/Geographic Routing Algorithm (PRADA), ...
- **DATA CENTRIC PROTOCOLS**
  - Flooding, Gossiping, SPIN, Directed Diffusion, SAR (Sequential Assignment Routing) , Rumor Routing, Constrained Anisotropic Diffused Routing, COUGAR, ACQUIRE,...
- **HIERARCHICAL PROTOCOLS**
  - LEACH, PEGASIS, TEEN (Threshold Sensitive Energy Efficient Sensor Network Protocol), APTEEN,...

Geographic Routing

- Routing tables contain information to which next hop a packet should be forwarded
  - Explicitly constructed
- Alternatively, we implicitly *infer* this information from physical placement of nodes
  - If position of current node, current neighbors, destination known -> send to a neighbor in the right direction as next hop
  - ***Geographic routing (also position-based 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

- "**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

Energy Efficiency of Geo Routing

- Question: Can we optimize the energy efficiency of Geographical Routing?

- T. Melodia, D. Pompili, Ian F. Akyildiz,
  "Optimal Local Topology Knowledge for Energy Efficient Geographical Routing in Sensor Networks,"
  in Proceedings of **IEEE INFOCOM 2004**, Hong Kong SAR, PRC.

- T. Melodia, D. Pompili, I. F. Akyildiz,
  "On the Interdependence of Distributed Topology Control and Geographical Routing in Ad Hoc and Sensor Networks,"
  IEEE JSAC Special Issue on **Wireless Ad Hoc Networks**, March 2005, Vol. 23, Issue 3, pp. 520-532.

Motivation (1/3)

- Primary design constraints for sensor network protocols:

Energy Efficiency

- Optimize energy consumption of protocols at each layer

AND

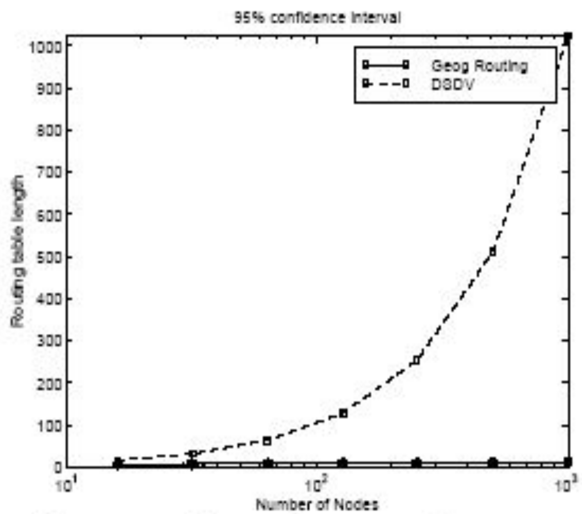
- Cross-Layer approach: jointly optimize networking functionalities at different layers

Scalability

- Performance should not be worsened with increasing number of nodes
- Scalable routing mechanism is crucial

Motivation (2/3)

- Traditional Ad hoc routing algorithms (AODV, DSDV) are not scalable since they do not use localization information
  - Too much memory is needed to store tables
  - Heavy reliance on flooding -> broadcast storm
- Two “Big Families” of scalable solutions:
  - Hierarchical Routing (e.g., LEACH)
  - **Geographical Routing**
    - **no routing tables are stored and maintained**
- Notion of *scalability* is related to notion of *loc*
  - in a scalable algorithm each node exchanges information only with its neighbors (*localized* information exchange)



(b) Comparison of GRA and DSDV

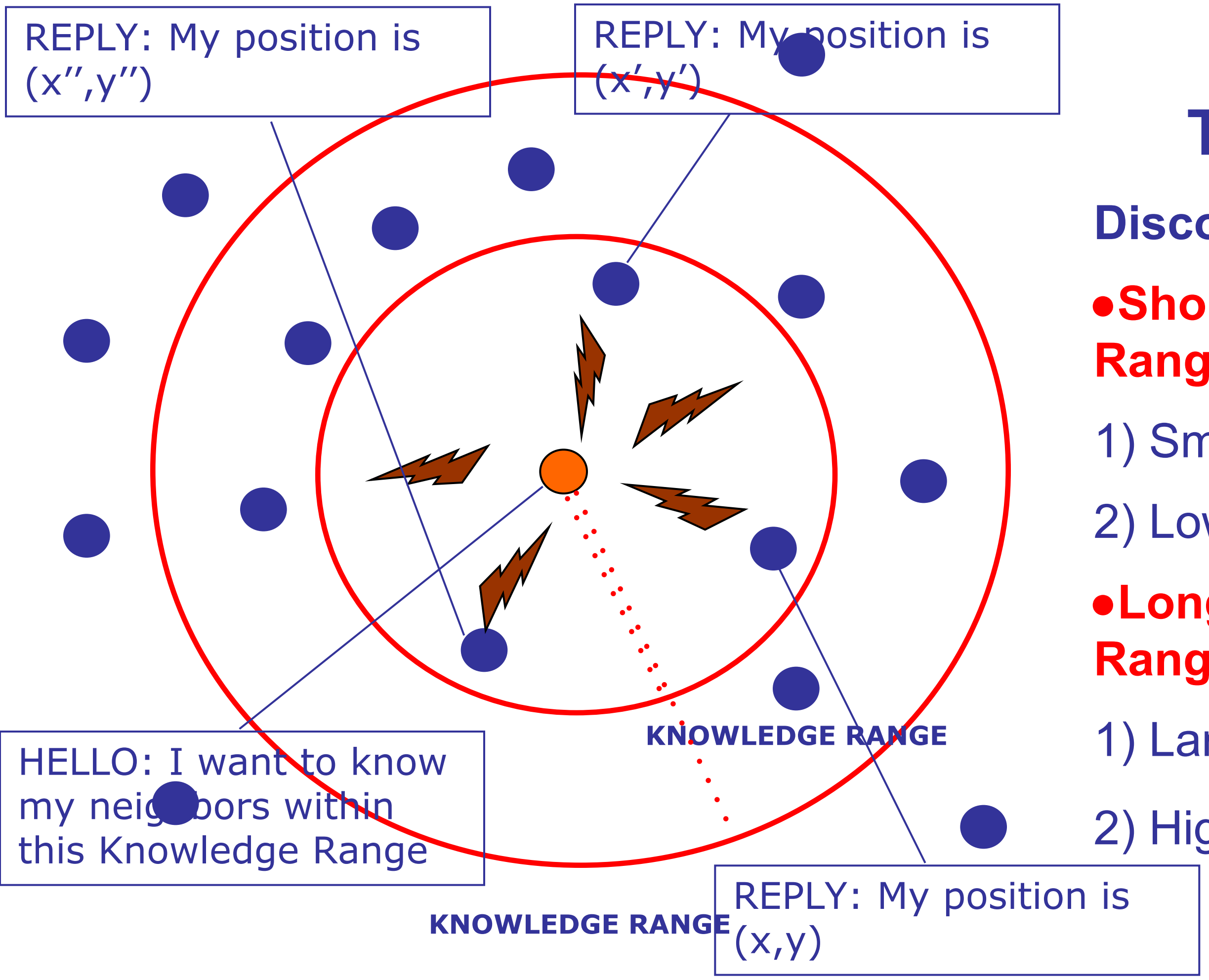
J. Li, J. Jannotti, D. De Couto, D. Karger, R. Morris, “A Scalable Location Service for Geographic Ad Hoc Routing,” Proc. IEEE/ACM Mobicom 2000, pp. 120-30.
R. Jain, A. Puri, R. Sengupta, “Geographical Routing Using Partial Information for Wireless Ad Hoc Networks,” IEEE Personal Communications, Feb. 2001, pp. 48-57.

Motivation (3/3)

- We consider interactions between
  - Energy Efficiency of Geographical Routing
  - Topology Control:
    - Given a node in a wireless setting, what are its neighbors, i.e., the nodes it can reach in one hop?
      - The number of neighbors can be adjusted by Power Control (**do you remember other algorithms that do the same?**)

Can we improve the Energy Efficiency of Geographical Routing with a cross layer approach by taking into account Topology Control?

Geographical Routing (1/3)



Topology Discovery

Discover the position of neighbors

- **Short Topology Knowledge Range:**

1) Small Number of close Neighbors

2) Lower Energy Consumption

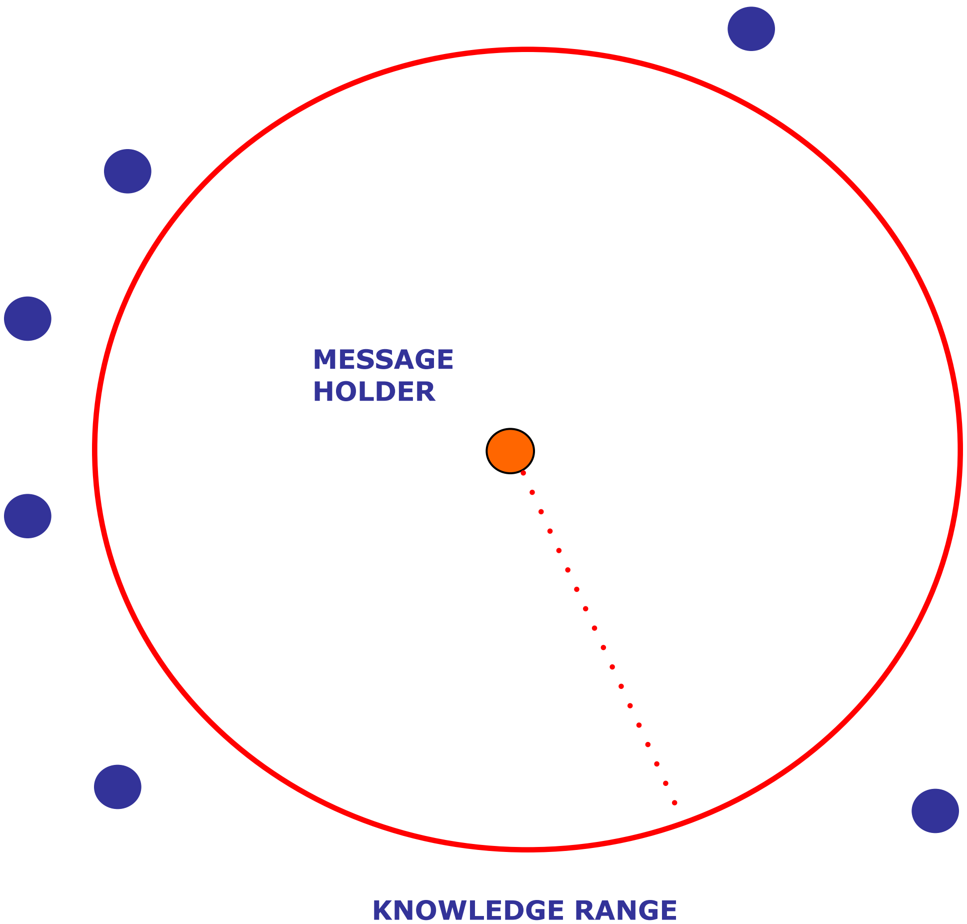
- **Long Topology Knowledge Range**

1) Large number of Neighbors

2) Higher Energy Consumption

In geographical routing algorithms, devices forward packets based on neighborhood information (topology information)

Geographical Routing (2/3)



Next Hop Selection

Given a Destination, the node that is holding the message selects the next hop according to

1) Its own position

2) The position of the destination node

3) The position of its neighbors (nodes in the knowledge range)

DIFFERENT FORWARDING RULES ARE POSSIBLE!

Geographical Routing (3/3)

- Two different notions of cost are defined

- ***Cost of Information:***
  - Energy needed to acquire *topology information*, i.e., the energy necessary to exchange the associated signaling traffic
- ***Cost of Communication:***
  - Energy needed to transmit data from source to destination on a given path in the network

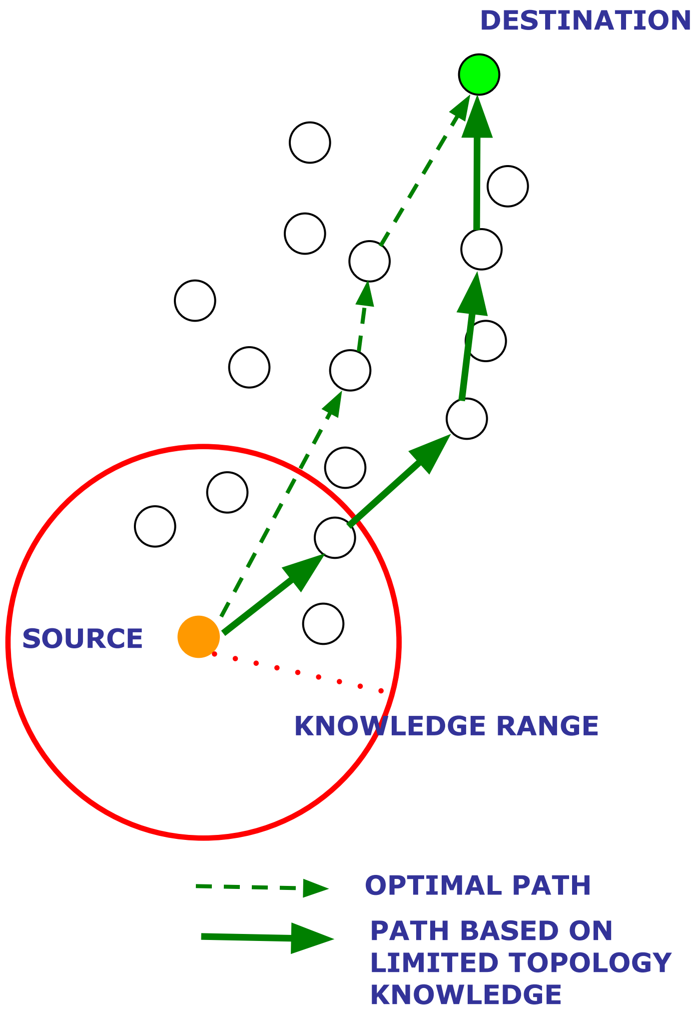
- With complete knowledge of the topology each sensor can compute the "globally" optimal path (i.e., minimum energy path)
- This way, the *cost of communication* is minimum but the *cost of topology information* is maximum

Cost of Communication vs Cost of Information (1/2)

- There is a tradeoff between:
  - *Cost of topology information*, increases with knowledge range
  - *Cost of communication*, usually decreases when the knowledge increases

- The question we try to answer is:
  - "How extensive the Local Knowledge of the global topology in each sensor node should be, so that an energy efficient geographical routing can be guaranteed?"

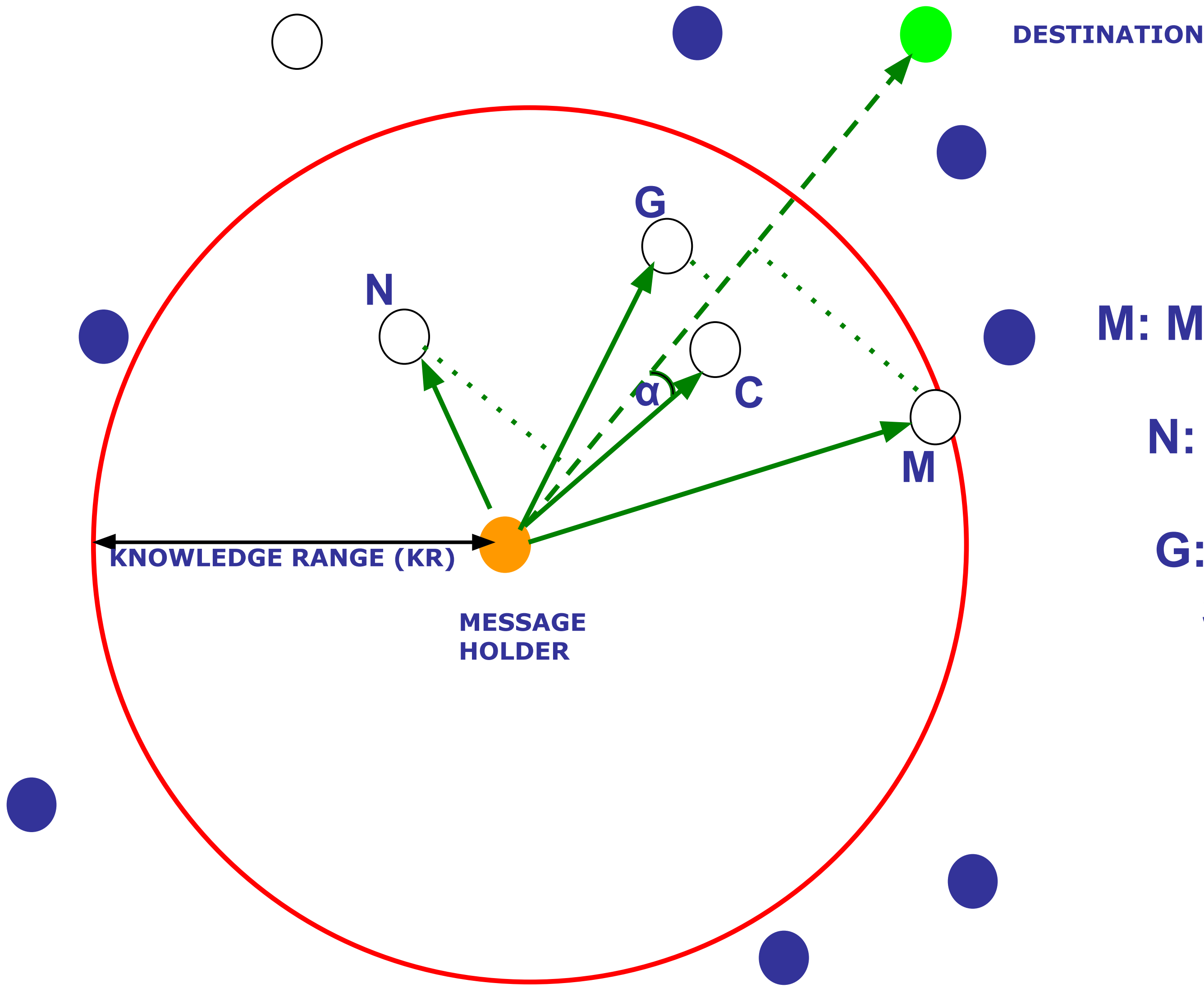
Cost of Communication vs Cost of Information (2/2)



- **Complete** topology knowledge
  - Each device can calculate the globally optimal path
  - High cost to acquire *topology information* (signaling)
- **Limited** topology knowledge
  - Can lead to suboptimal paths
  - Cost of topology information depends on the *Knowledge Range (KR)*

Which path is better if we also take the Cost of Information into account?

Geographical Routing: Greedy Forwarding Schemes



M: Most Forward Within Radius (MFR)

N: Nearest Forward Progress (NFP)

G: Greedy Routing Scheme (GRS)

C: Compass

Topology Knowledge Range Problem

Total number of nodes

$$C^*(\underline{R}^*) = \min_{\underline{R}} \left\{ \sum_{k=1}^{N} \left[C_k^{INF}(r_k) + C_k^{COM}(\underline{R}) \right] \right\}$$

$C_k^{INF}(r_k)$ **Cost of Information:** **energy needed for node k to acquire *topology information* with a knowledge range r_k**

$C_k^{COM}(\underline{R})$ **Cost of Communication:** **energy needed by node k to transmit user data given:**

- **the vector of knowledge ranges:** $\underline{R} = [r_1, r_2, .., r_N]$
- **a forwarding rule**

OBJECTIVE: Find the OPTIMAL VECTOR $\underline{R}^*$ of Knowledge Ranges that minimizes the overall cost of the network

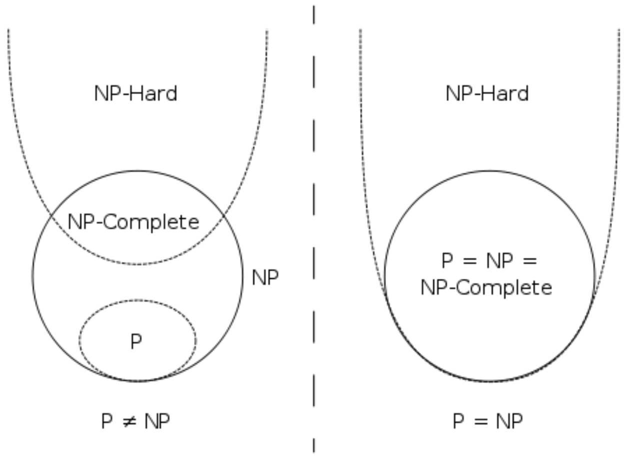
Compare different forwarding rules

P vs. NP
The fundamental problem of Computer Science

NP vs. P

- There are problems that we know are solvable in polynomial (POLY) time:
  - Maximum/minimum element of an array →O(n)
  - Sorting Array → O(nlog(n))
  - Minimum Spanning Tree → O(V^2)
  - Shortest Path in a Graph → O(E + V log V)
  - Greatest Common Divisor (GCD) → O(5*d)
  - ...

- For other problems, we **don't know** if the problem is solvable in POLY time!
- These problems are in the so-called Non-deterministic Polynomial (NP) computation class



P vs. NP and the Computational Complexity Zoo

https://www.youtube.com/watch?v=YX40hbAHx3s

Energy Model

$$c_{ij} = \underbrace{2 \cdot E_{elec}}_{\text{DISTANCE INDEPENDENT FACTOR}} + \underbrace{E_{amp} \cdot d_{ij}^{\alpha}}_{\text{DISTANCE DEPENDENT FACTOR}}$$

- Energy needed to transmit one bit between node i and node j
  - **$2 \le \alpha \le 5$**
  - **E_{elec}: the energy needed by the transmitter [receiver] to transmit [receive] one bit**
  - **E_{elec}: [Joule/bit]**
  - **E_{amp} : [Joule/bit/m$^{\alpha}$]**

ILP Formulation (1/5)

- Integer Linear Programming Formulation
- Discrete values of the knowledge ranges KR:
  - Example [0, 5, 10, 15, 20, 25] m

- Based on binary variables:

Given

$$\begin{cases} f_{kd}^{ij} = 1 \\ a_{im}(k) = 1 \end{cases}$$

iff j is the next hop of i towards the destination d with the k-th knowledge range (FORWARDING RULE)

iff node m is a neighbor of node i with k-th KR

Unknown (found by the solver)

$$\begin{cases} y_i^k = 1 \\ x_{ij}^{sd} = 1 \end{cases}$$

iff node i selects the k-th KR

iff connection between source s and destination d uses the link between node i and node j, according to the rule selected

ILP Formulation (2/5)

Minimize:

$$C^{TOT} = \sum_{i \in V} \left(C_i^{COM} + C_i^{INF} \right)$$

Set of Nodes

Subject to the following constraints:
Cost of Information for node i:

Number of Neighbors of node i with k-th KR

$$C_i^{INF} = L_N \cdot E_{amp} \cdot \sum_{k \in R} y_i^k \cdot r^{\alpha}(k) + \left(\sum_{k \in R} (y_i^k \cdot N_i(k)) + 1 \right) \cdot L_N \cdot E_{elec} +$$

Length of the HELLO message

(bits)

Energy needed to transmit HELLO message with knowledge range k

Energy needed for the neighbors to receive the HELLO message

$$+ \sum_{m \in V} \left(L_U \cdot E_{amp} \cdot d_{mi}^{\alpha} + 2 \cdot L_U \cdot E_{elec} \right) \sum_{k \in R} y_i^k \cdot a_{im}(k))) \cdot \frac{1}{T_M}, \quad \forall i \in V$$

Length of the REPLY message

(bits)

Energy needed for the neighbors to send their REPLY message

Period between two consecutive HELLO messages

ILP Formulation (3/5)

Constraint on cost of communication for node i:

$$C_i^{COM} = \sum_{s \in S} \sum_{d \in D} \sum_{j \in V} \left(x_{ij}^{sd} \cdot p^{sd} \cdot \left(2 \cdot E_{elec} + E_{amp} \cdot d_{ij}^{\alpha} \right) \right) \quad \forall i \in V$$

Set of Source nodes

Set of Destination nodes

Data rate of the connection between s and d (0= no connection)

For all source-destination pairs, for each node j (possibly neighbor of i), if the connection between s and d passes through the link (i,j) ($x_{ij}^{sd} = 1$), then the formula includes the cost of the link (i,j) $(2 \cdot E_{elec} + E_{amp} \cdot d_{ij}^{\alpha})$ in the cost of communication for node i

ILP Formulation (4/5)

- Impose that paths are built according to the forwarding rule expressed by the f variables

$$x_{ij}^{sd} \leq \sum_{k \in R} \left(y_i^k \cdot f_{dk}^{ij} \right) \; \forall s \in S, \; \forall d \in D, \; \forall i, j \in V$$

$$x_{sj}^{sd} = \sum_{k \in R} \left(y_s^k \cdot f_{dk}^{sj} \right) \; \forall s \in S, \; \forall d \in D, \; \forall j \in V \; s.t. \; s \neq d$$

- Imposes that each node selects only one KR

$$\sum_{k \in R} y_i^k = 1, \; \forall i$$

ILP Formulation (5/5)

3 FLOW CONSERVATION CONSTRAINTS

- Each source generates one flow

$$\sum_{j \in V} \left(x_{sj}^{sd} - x_{js}^{sd} \right) = 1, \forall s \in S, \forall d \in D, s.t. s \neq d$$

- Each destination receives one flow

$$\sum_{j \in V} \left(x_{dj}^{sd} - x_{jd}^{sd} \right) = -1, \forall s \in S, \forall d \in D, s.t. s \neq d$$

- Each other node retransmits exactly the flows that it receives

$$\sum_{j \in V} \left(x_{ij}^{sd} - x_{ji}^{sd} \right) = 0, \forall s \in S, \forall d \in D, \forall i \in V \; s.t. s \neq d, i \neq s, i \neq d$$

Online solution: PRADA

- ILP problem: can be solved with a centralized algorithm
- ILP is NP-complete -> Limited number of nodes with state-of-the-art workstations
- For online solution of the problem, use PRADA:
  - A PRobe bAsed Distributed algorithm for knowledge rAnge adjustement
- PRADA allows nodes to **distributedly** select their Knowledge Range by means of feedback information from the network
- The Optimal Solution is used as a comparison for the performance of PRADA, whose performance should be as close as possible to the optimum

PRADA can be found in **Melodia, Tommaso, Dario Pompili, and Ian F. Akyildiz. "On the interdependence of distributed topology control and geographical routing in ad hoc and sensor networks."** ***IEEE Journal on Selected Areas in Communications*** **23.3 (2005): 520-532.**

- What are the advantages/disadvantages of GeoRouting?

Think-Share!

Data-Centric Protocols

Data-centric Protocols

- Apart from routing protocols that use a direct identifier of nodes (unique id or position of a node), networking can be based on *content of data*

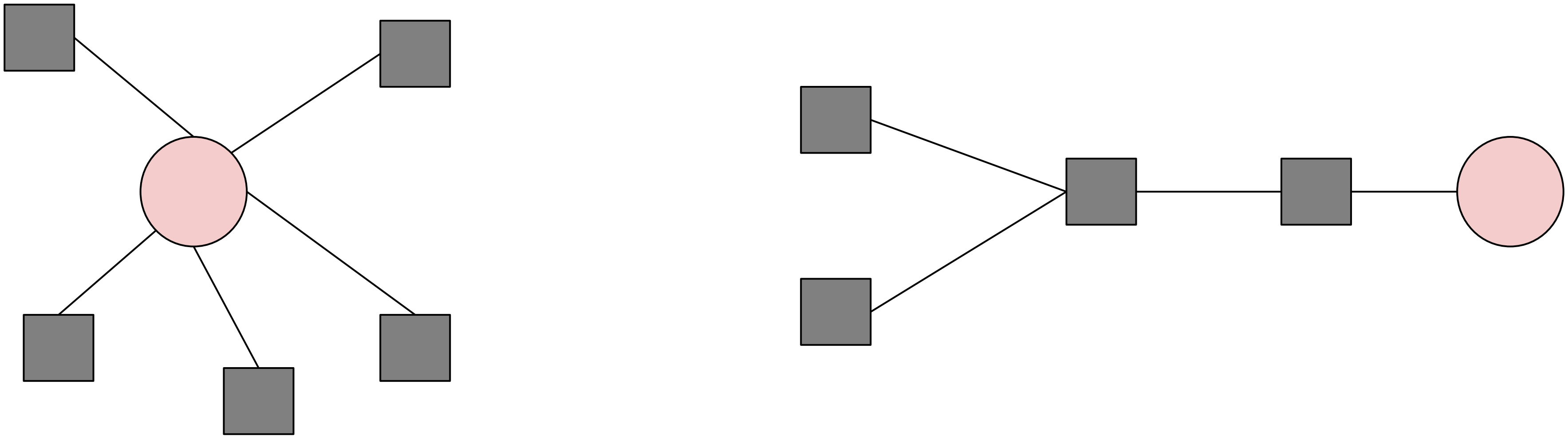
- Content can be collected from the network, processed in the network, and stored in the network

- This is also known as *content-based networking*

- Studied in connection with *data aggregation* mechanisms

Data Aggregation

- Any packet not transmitted does not need energy
- To still transmit data, packets need to combine their data into fewer packets -> ***aggregation*** is needed
- Depending on network, aggregation can be useful or pointless



Metrics for data aggregation

- ***Accuracy***: Difference between value(s) the sink obtains from aggregated packets and from the actual value (obtained in case no aggregation/no faults occur)
- ***Completeness***: Percentage of all readings included in computing the final aggregate at the sink
- ***Latency***
- ***Message overhead***

How to Express Aggregation Requests?

- One option: Use **database abstraction** of WSN
- Aggregation is requested by appropriate SQL clauses

```
SELECT {agg(expr), attributes} FROM sensors
WHERE {selectionPredicates}
GROUP BY {attributes}
HAVING {havingPredicates}
EPOCH DURATION i
```

- Agg(expr): actual aggregation function, e.g., AVG(temperature)
- WHERE: filter on value before entering aggregation process
  - Usually evaluated locally on an observing node
- GROUP BY: partition into subsets, filtered by HAVING
  - GROUP BY floor HAVING floor > 5

Placement of Aggregation Points

- What are *good* aggregation points?
  - **Ideally:** choose tree structure such that the size of the aggregated data to be communicated is minimized
  - A **Steiner tree problem** in disguise
  - Steiner trees can be viewed as a generalization of minimum spanning trees (MSTs).
  - A MST must includes all vertices of V, whereas a Steiner needs only to include the vertices of a given $S \subseteq V$
  - If $S = V$, then an MST is a Steiner tree for S.
  - If $S \subset V$, then a MST could be a Steiner tree for *S*, but not necessarily
- Good aggregation tree structure can be obtained through **heuristics**

Hierarchical Protocols

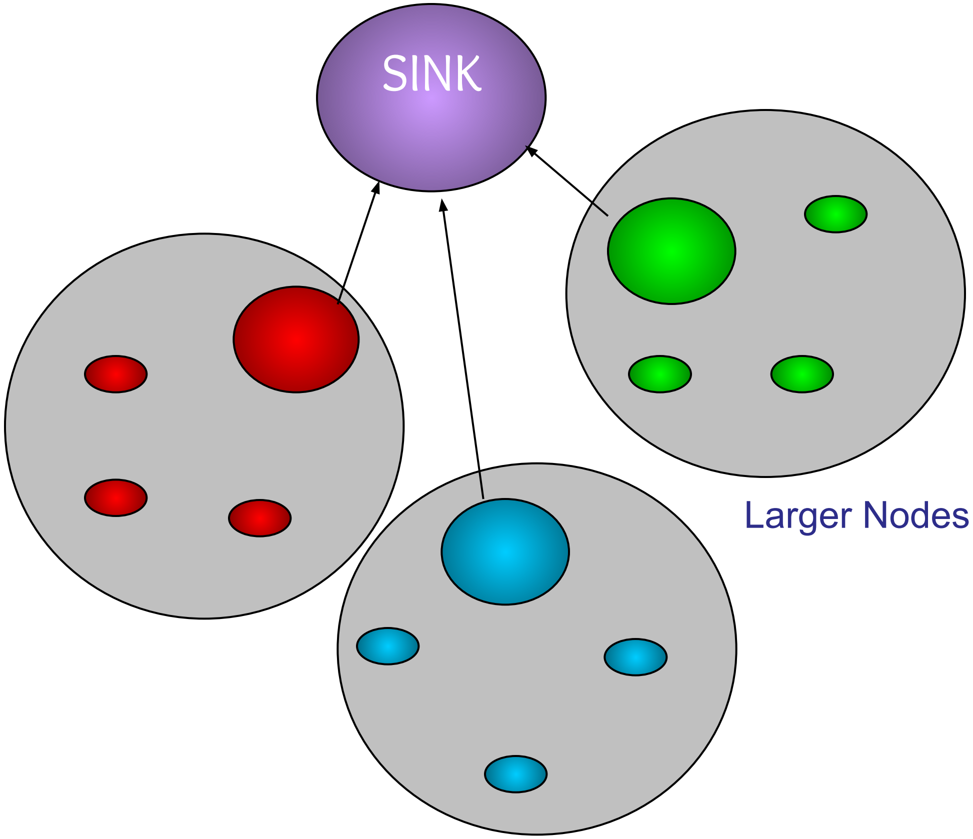
- Hierarchical-architecture protocols are proposed to address the scalability and energy consumption challenges of sensor networks
- Sensor nodes form clusters where the cluster-heads aggregate and fuse data to conserve energy
- The cluster-heads may form another layer of clusters among themselves before reaching the sink

Low Energy Adaptive Clustering Hierarchy

W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-Efficient Communication Protocol for Wireless Microsensor Networks," *IEEE Proc. of the Hawaii Int. Conf. on System Sciences*, January, 2000. Longer version in IEEE Tr. on Wireless Com., pp.660-670, Oct. 2002 (**20k+ citations!!!**)

- LEACH is a clustering-based protocol which minimizes energy dissipation in sensor networks
- Idea:
  - Randomly select sensor nodes as cluster heads, so the high energy dissipation in communicating with the base station is spread to all sensor nodes in the network
  - Forming clusters is based on the received signal strength
  - Cluster heads can then be used as routers (relays) to the sink

LEACH



Larger Nodes denote Cluster Heads

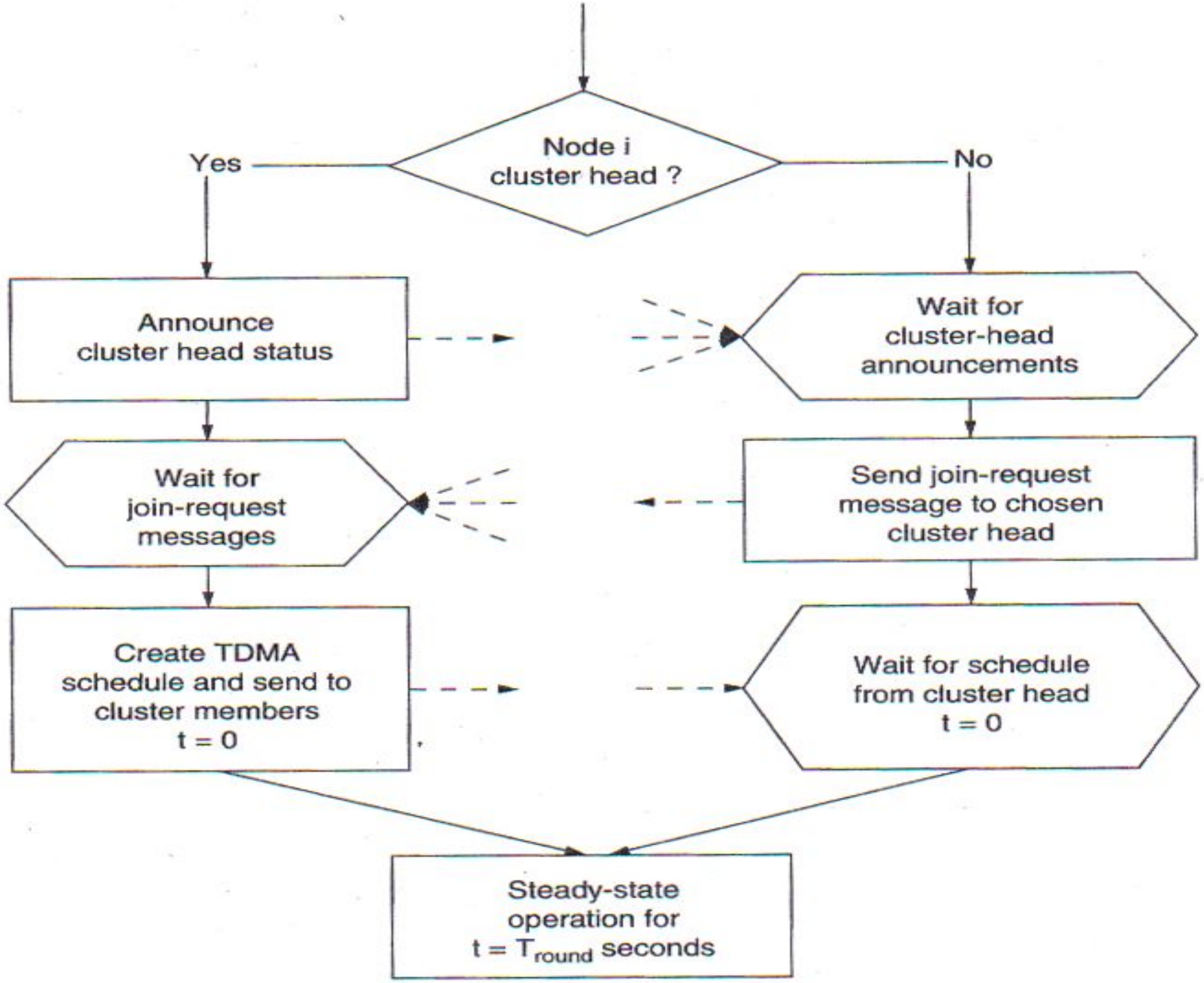
LEACH

- Two Phases: Setup Phase and Steady-Phase
- Setup Phase:
  - Sensors may elect themselves to be a local cluster head at any time with a certain probability (to balance the energy dissipation)
  - A sensor node chooses a random number between 0 and 1
  - If this random number is less than the threshold T(n), the sensor node becomes a cluster-head

$$T(n) = P / \{1 - P[r \bmod (1/P)]\} \quad \text{if } n \text{ is element of } G$$

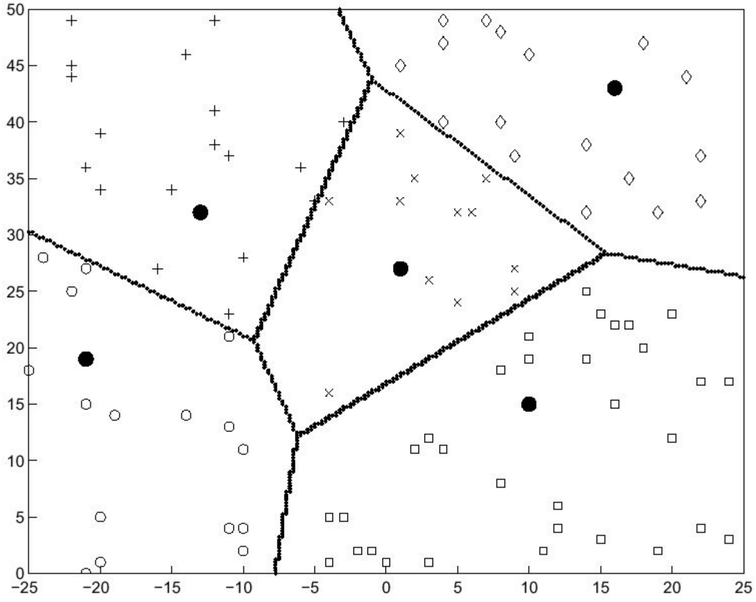
  - where
    - P is the desired percentage of cluster heads (e.g., 0.05)
    - r is the current round
    - G is the set of nodes that have not been a cluster head in the last 1/P rounds.

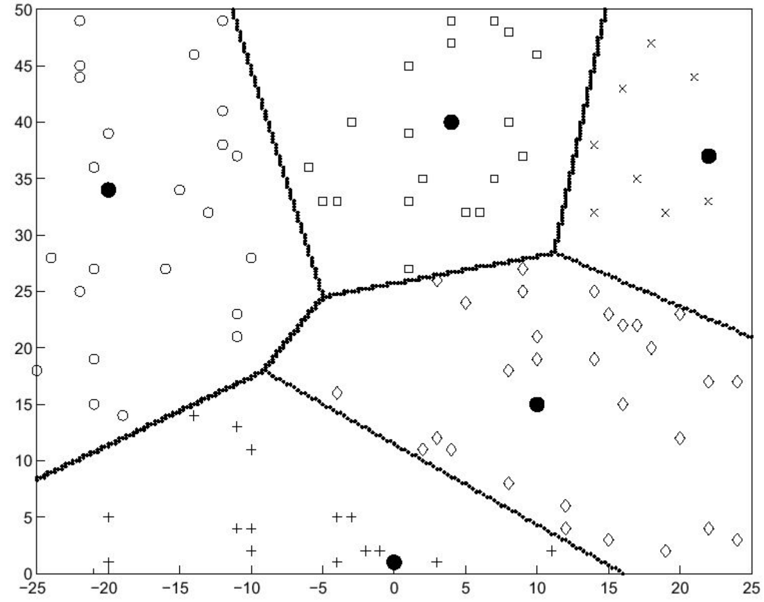
Cluster Head Selection



Flowchart of cluster head election in LEACH protocol.

Dynamic Clusters





LEACH

- After the cluster heads are selected, the cluster heads advertise to all sensor nodes in the network that they are the new cluster head

- Each node accesses the network through the cluster head that requires minimum energy to reach, based on the signal strength of the advertisement

- The nodes inform the appropriate cluster heads that they will be a member of the cluster

- Afterwards the cluster heads assign the time on which the sensor nodes can send data to them

LEACH

- Steady State Phase
  - Sensors begin to sense and transmit data to the cluster heads which aggregate data from the nodes in their clusters
  - After a certain period of time spent on the steady state, the network goes into start-up phase again and enters another round of selecting cluster heads

LEACH

- What is the Optimal Number of Clusters ?
  - Too few
    - Nodes far from cluster heads
    - Not much aggregation
  - Too many
    - Many nodes send data to sink
- Several variants and enhancements have been proposed
  - Multi-hopping from sensors to clusters
  - Multi-hopping among clusters

LEACH - Conclusions

- Achieves over a factor of 7 reduction in energy dissipation compared to direct communication
- The nodes die randomly and dynamic clustering increases the lifetime of the system
- It is completely distributed and requires no global knowledge of the network

- What are the advantages/disadvantages of LEACH?

Think-Share!

LEACH - Conclusions

- The idea of dynamic clustering brings extra overhead, e.g., head changes, advertisements etc. which may diminish the gain in energy consumption