Wireless and Sensor Networks - Routing

3rd Class

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Outline

- Introduction
- Motivation and Design Issues in WSN Routing
- Routing Challenges in WSNs
- Flat Routing
- Hierarchical Routing
- Adaptive Routing
- Multipath Routing
- Query-Based Routing
- Negotiation-Based Protocols
- Future Directions
- Conclusions

Introduction

- WSNs contain hundreds or thousands of sensor nodes equipped with sensing, computing and communication abilities.
- Deployment can be in random fashion or planted manually.
- Some application examples:
  - Target field imaging
  - Intrusion detection
  - Weather monitoring
  - Security and tactical surveillance
  - Distributed computing
  - Detecting ambient conditions such as temperature, movement, sound, light or presence of certain objects
  - Inventory control
- Sensor networks can be categorized as time-driven or event-driven networks.
- WSNs can involve single-hop or multihop communication.
- WSNs have several restrictions:
  - Limited energy supply
  - Limited computation
  - Communication

Classical View of Routing

- Connectivity between nodes defines the *network graph*.
  - Topology formation
- A Routing algorithm determines the sub-graph that is used for communication between nodes.
  - Route formation, path selection
- Packets are forwarded from source to destination over the routing subgraph
  - At each node in the path, determine the recipient of the next hop

Motivation and Design Issues in WSN Routing

- Prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques.
- Nodes are expected to perform sensing and communication with no continual maintenance or human attendance and battery replenishment. → Limits the amount of energy available to the sensor nodes.
- Extensive collaboration between sensor nodes is required to perform high-quality sensing and to behave as fault-tolerant systems.

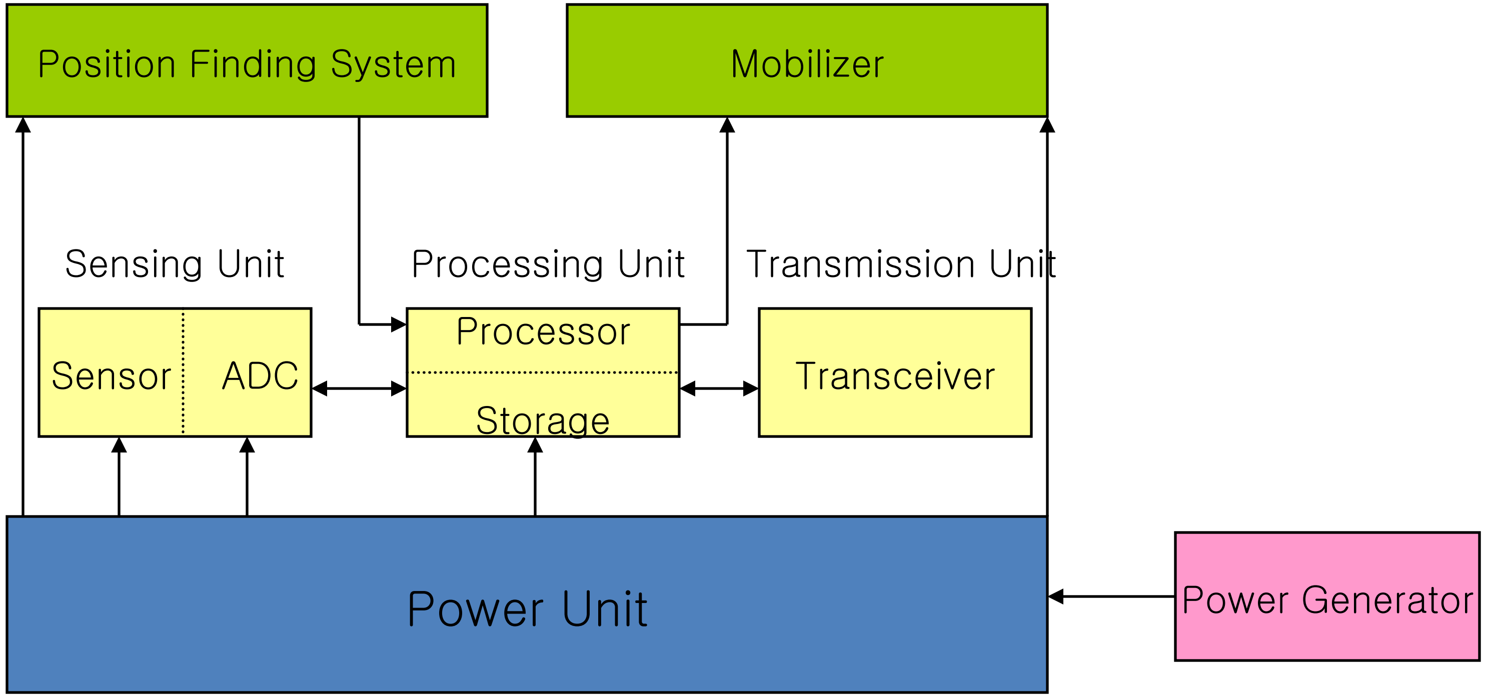
Motivation/Design Issues in WSN Routing

- Sensor nodes should be self-organizing.
- In most application scenarios, sensor nodes are stationary.
- Sensor networks are application specific.
- Data collected by many sensors in WSNs are based on common phenomena; there is a high probability that these data have some redundancy. → In-network aggregation of data is needed to yield energy-efficient data delivery before dispatch to destinations.
- Sensor networks are data-centric networks.
- WSNs have relatively large numbers of sensor nodes.
- WSNs use attribute-based addressing.
- Position awareness of sensor nodes is important because data collection is based on the location.

Routing Challenges in WSNs

- Ad hoc deployment
- Energy consumption without losing accuracy
- Computation capabilities
- Communication range
- Fault tolerance
- Scalability
- Hardware constraints
- Connectivity
- Control overhead
- Quality of service

Components of a sensor node



Protocol Classification (1)

- Proactive –

  First Compute all Routes;
  Then Route

- Reactive –

  Compute Routes On-Demand

- Hybrid –

  First Compute all Routes;
  Then Improve While Routing

Protocol Classification (2)

- Direct –

  Node and Sink Communicate Directly
  (Fast Drainage; Small Scale)

- Flat (Equal) – Random Indirect Route
  (Fast Drainage Around Sink; Medium Scale)

- Clustering (Hierarchical) –

  Route Thru Distinguished Nodes

Protocol Classification (3)

- Location Aware –
  Nodes knows where they are
- Location-Less –
  Nodes location is unimportant
- Mobility Aware –
  Nodes may move –
  Sources; Sinks; All

Protocol Classification (4)

Query Models:

- Historical Queries: Analysis of historical dat
  a
  "What was the watermark 2h ago in the southeast?"
- One-time Queries: Snapshot view
  "What is the watermark in the southeast?"
- Persistent Queries: Monitoring over time
  "Report the watermark in the southeast for the next 4h"

Routing Protocols in WSNs

- In general, routing in WSNs can be divided into:
  - Flat-based routing (all nodes plays an equal role.)
  - Hierarchical-based routing (different role)
  - Adaptive-based routing (to adapt network current status)
- Furthermore, depending on the protocol operation these protocols can be classified into:
  - Multipath-based routing
  - Query-based routing
  - Negotiation-based routing

I. Flat routing

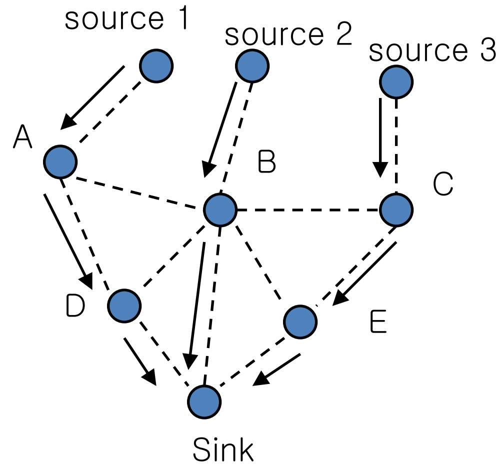
- Directed Diffusion
- Minimum Cost Forwarding Algorithm
- Coherent/Noncoherent Processing

Direct Diffusion: Motivation

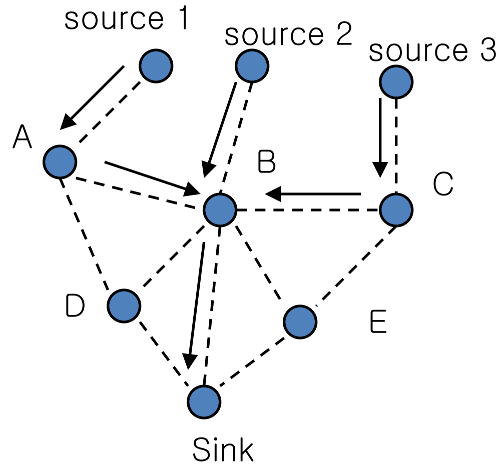
- Properties of Sensor Networks
  - Data centric
  - No central authority
  - Resource constrained
  - Nodes are tied to physical locations
  - Nodes may not know the topology
  - Nodes are generally stationary
- How can we get data from the sensors?

Flat routing – AC vs DC

- It is data centric (DC) in the sense that all the data generated by sensor nodes are named by attribute-value pairs.
- DC perform in-network aggregation of data to yield energy-efficient data delivery.
- The main idea of the DC paradigm is to combine the data coming from different sources en route – eliminating redundancy, minimizing the number of transmissions, and thus saving network energy and prolonging its lifetime.
- The paradigm is different from the traditional paradigm, termed address centric (AC).



AC Routing



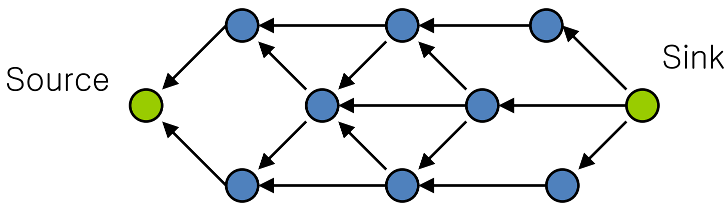
DC Routing

Differences between AC and DC routing

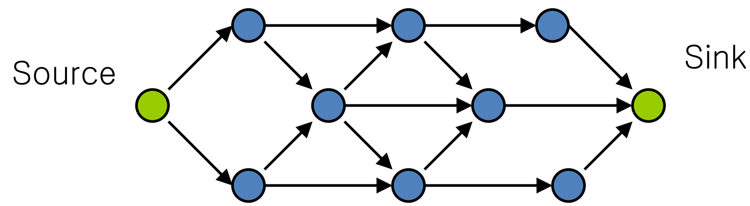
Directed Diffusion: Main Features

- Data centric
  - Individual nodes are unimportant
- Request driven
  - Sinks place requests as interests
  - Sources satisfying the interest can be found
  - Intermediate nodes route data toward sinks
- Localized repair and reinforcement
- Multi-path delivery for multiple sources, sinks, and queries

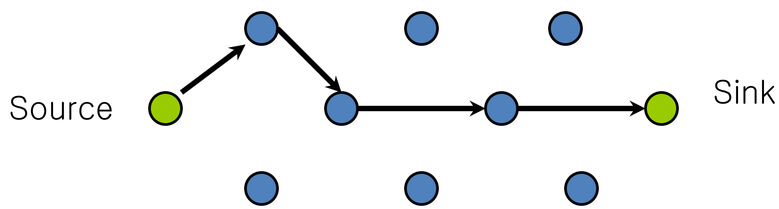
Directed Diffusion – Operation Sequence



Propagate Interest



Set up Gradients



Send data and Path Reinforcement

Interest diffusion in a sensor network

Directed Diffusion: Motivating Example

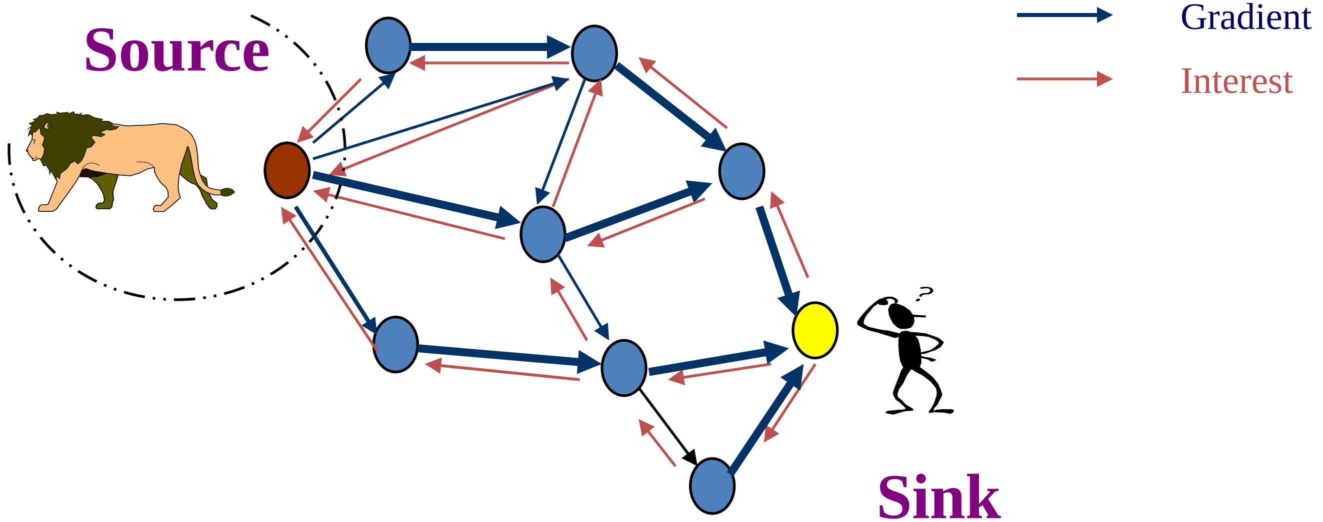
- Sensor nodes are monitoring animals
- Users are interested in receiving data for all 4-legged creatures seen in a rectangle
- Users specify the data rate

Directed Diffusion: Interest and Event Naming

- Query/interest:
  1. Type=four-legged animal
  2. Interval=20ms (event data rate)
  3. Duration=10 seconds (time to cache)
  4. Rect=[-100, 100, 200, 400]
- Reply:
  1. Type=four-legged animal
  2. Instance = elephant
  3. Location = [125, 220]
  4. Intensity = 0.6
  5. Confidence = 0.85
  6. Timestamp = 01:20:40
- Attribute-Value pairs, no advanced naming scheme

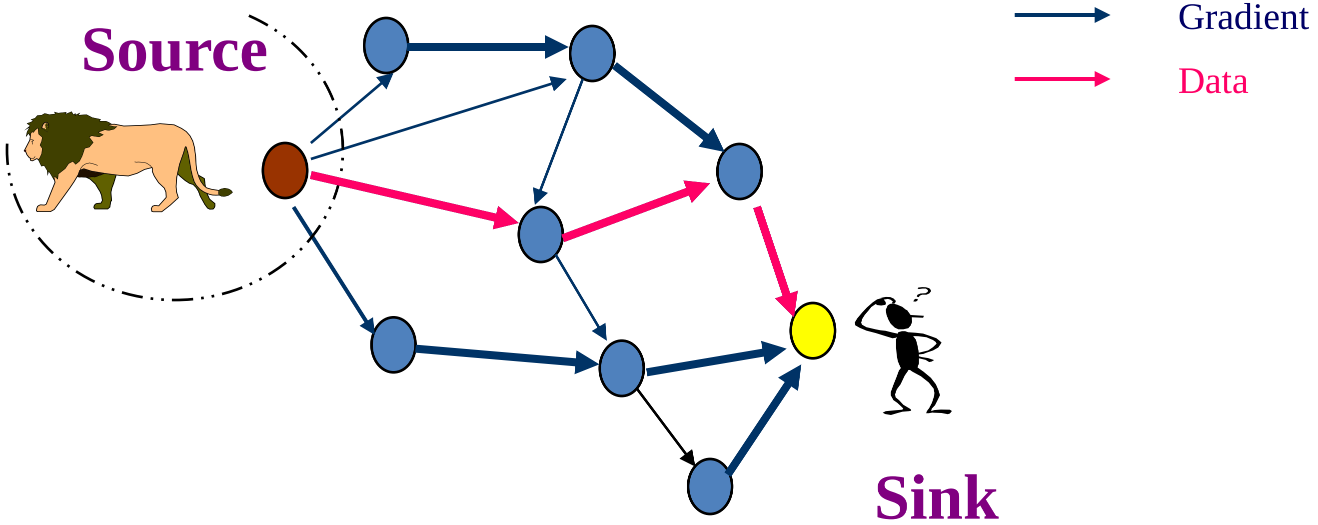
Directed Diffusion: Interest Propagation

- Flood interest
- Constrained or Directional flooding based on location is possible
- Directional propagation based on previously cached data



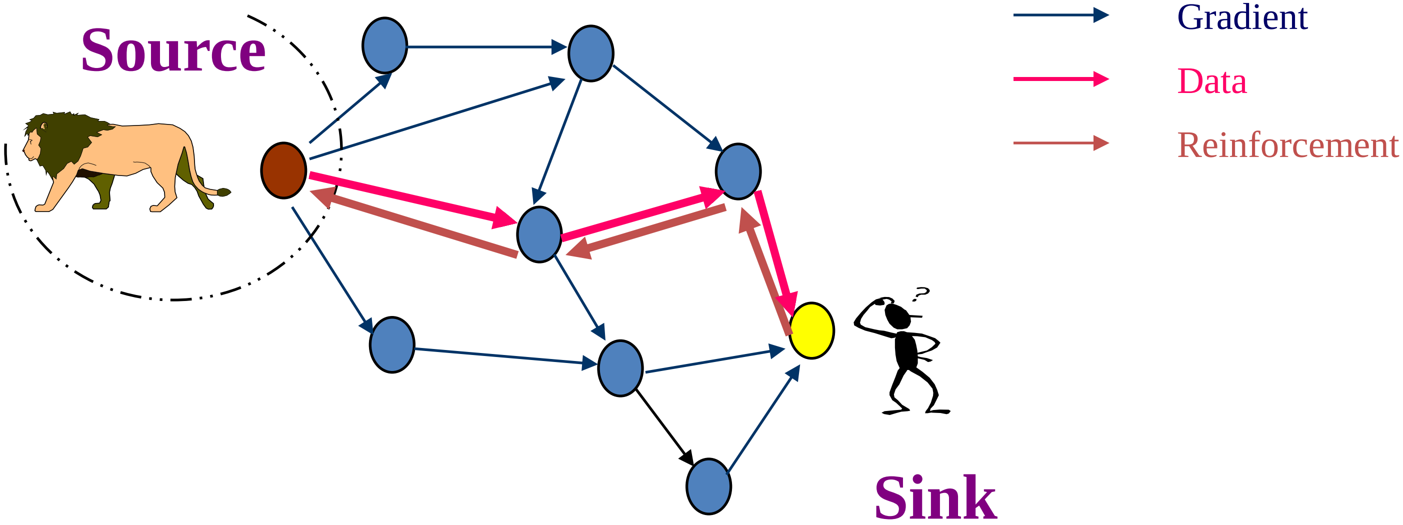
Directed Diffusion: Data Propagation

- Multipath routing
  - Consider each gradient's link quality



Directed Diffusion: Reinforcement

- Reinforce one of the neighbor after receiving initial data.
  - Neighbor who consistently performs better than others
  - Neighbor from whom most events received



Directed Diffusion: Pros & Cons

- Different from SPIN in terms of on-demand data querying mechanism
  - Sink floods interests only if necessary
    - A lot of energy savings
  - In SPIN, sensors advertise the availability of data
- Pros
  - Data centric: All communications are neighbor to neighbor with no need for a node addressing mechanism
  - Each node can do aggregation & caching
- Cons
  - On-demand, query-driven: Inappropriate for applications requiring continuous data delivery, e.g., environmental monitoring
  - Attribute-based naming scheme is application dependent
    - For each application it should be defined a priori
    - Extra processing overhead at sensor nodes

Flat routing – Minimum Cost Forwarding Algorithm

- MCFA exploits the fact that the direction of routing is always known (i.e. toward the fixed external base station).→ sensor nodes do not need to have a unique ID or to maintain a routing table.
- Each node maintains the least cost estimate from itself to the base station.
- Each message to be forwarded by the sensor node is broadcast to its neighbors.
- When a node receives the message, it checks if it is on the least cost path between the source sensor and the base station. If this is the case, it rebroadcasts the message to its neighbors.
- This process repeats until the base station is reached.
- Each node should know the least cost path estimate from itself to the base station.

MCFA

- Each node has to know the least cost path estimate to BS
  - BS broadcasts a message with cost set to 0
  - Every node initially sets its cost to BS to ∞
  - When a node receives the msg from BS, it checks if the estimate in the packet + 1 < the node's current estimate to BS
    - If yes, the current estimate & estimate in the msg are updated and resent
    - Else, delete the msg; Do nothing
  - A node far from BS may receive several msg's → A node will not send the updated msg until a * lc time where a is a constant & lc is the link cost from which the message was received
- Works well for fixed topologies

Flat routing – Coherent and Noncoherent Processing

- In noncoherent data processing routing, nodes will locally process the raw data before sending them to other nodes, called the aggregators, for further processing.
- Noncoherent cooperative processing contains 3 phases:
  - Target detection, data collection, and preprocessing
  - Membership declaration
  - Central node election
- In coherent routing, the data are forwarded to aggregators after minimum processing which typically includes tasks like time stamping, duplicate suppression, etc.

Flat routing – Coherent and Noncoherent Processing

- To perform energy-efficient routing, coherent processing is normally selected. Noncoherent functions have fairly low data traffic loading.
- Single and multiple winner algorithms are proposed for noncoherent and coherent processing, respectively:
  - Single winner algorithm (SWE): a single aggregator node is elected for complex processing. The election of a node is based on the energy reserves and computational capability of that node.
  - Multiple winner algorithm (MWE): limit the number of sources that can send data to the central aggregator node.

Ⅱ. Hierarchical routing

- LEACH
- PEGASIS
- TEEN/APTEEN
- SMECN
- Fixed size Clustering
- Virtual Grid Architecture
-Hierarchical Power-Aware Routing

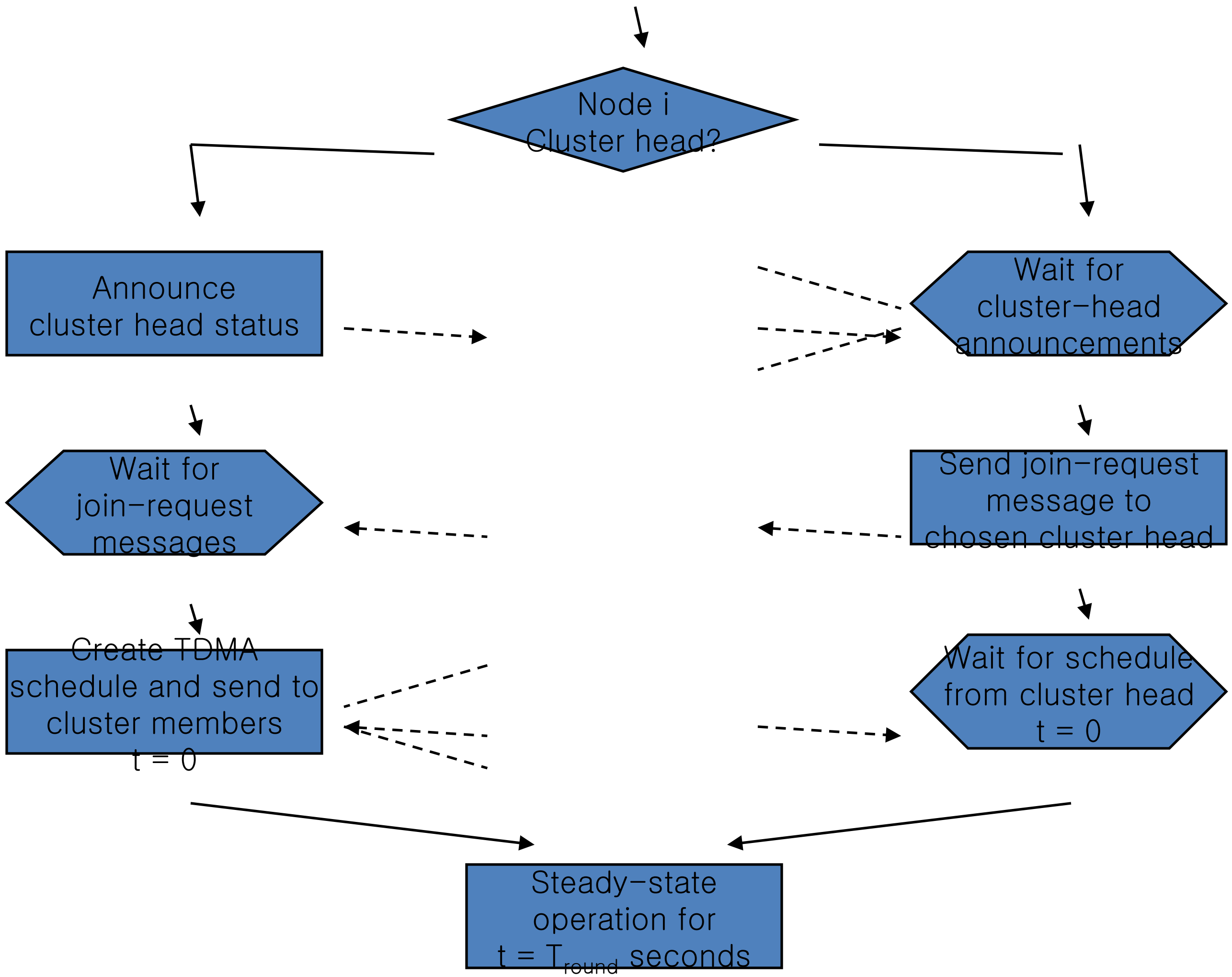
Hierarchical Routing – LEACH Protocol

- A hierarchical clustering algorithm for WSNs calls low energy adaptive clustering hierarchy (LEACH).
- Allowing a randomized rotation of the cluster head's role in the objective of reducing energy consumption and to distribute the energy load evenly among the sensors in the network.
- Using localized coordination to enable scalability and robustness for dynamic networks and incorporates data fusion into the routing protocol → reduce the amount of information that must be transmitted to the base station.
- Using TDMA/CDMA MAC to reduce inter-cluster and intra-cluster collisions.

Hierarchical Routing – LEACH Protocol

- It is most appropriate when constant monitoring by the WSNs is needed.
- Using adaptive clustering (re-clustering after a given interval with a randomized rotation of the energy-constrained cluster head) → energy dissipation in the network is uniform.
- The operation is separated into 2 phases:
  - Setup phase: the clusters are organized and cluster heads are selected.
  - Steady state phase: the actual data transfer to the BS takes place
- The duration of the steady state phase is longer than that of the setup phase to minimize overhead.

Hierarchical Routing – LEACH Protocol (cont)

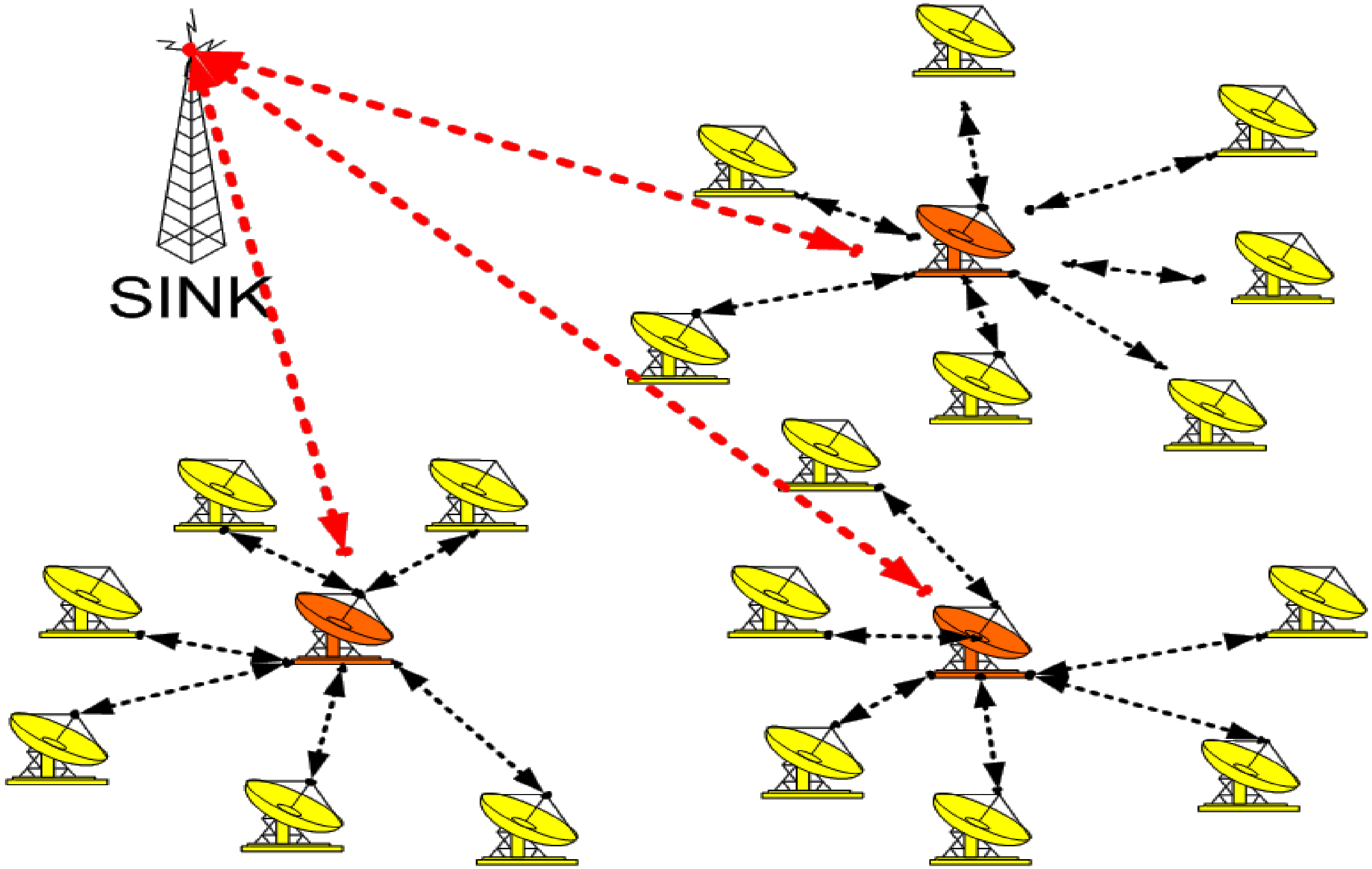


Flowchart of cluster head election in LEACH protocol

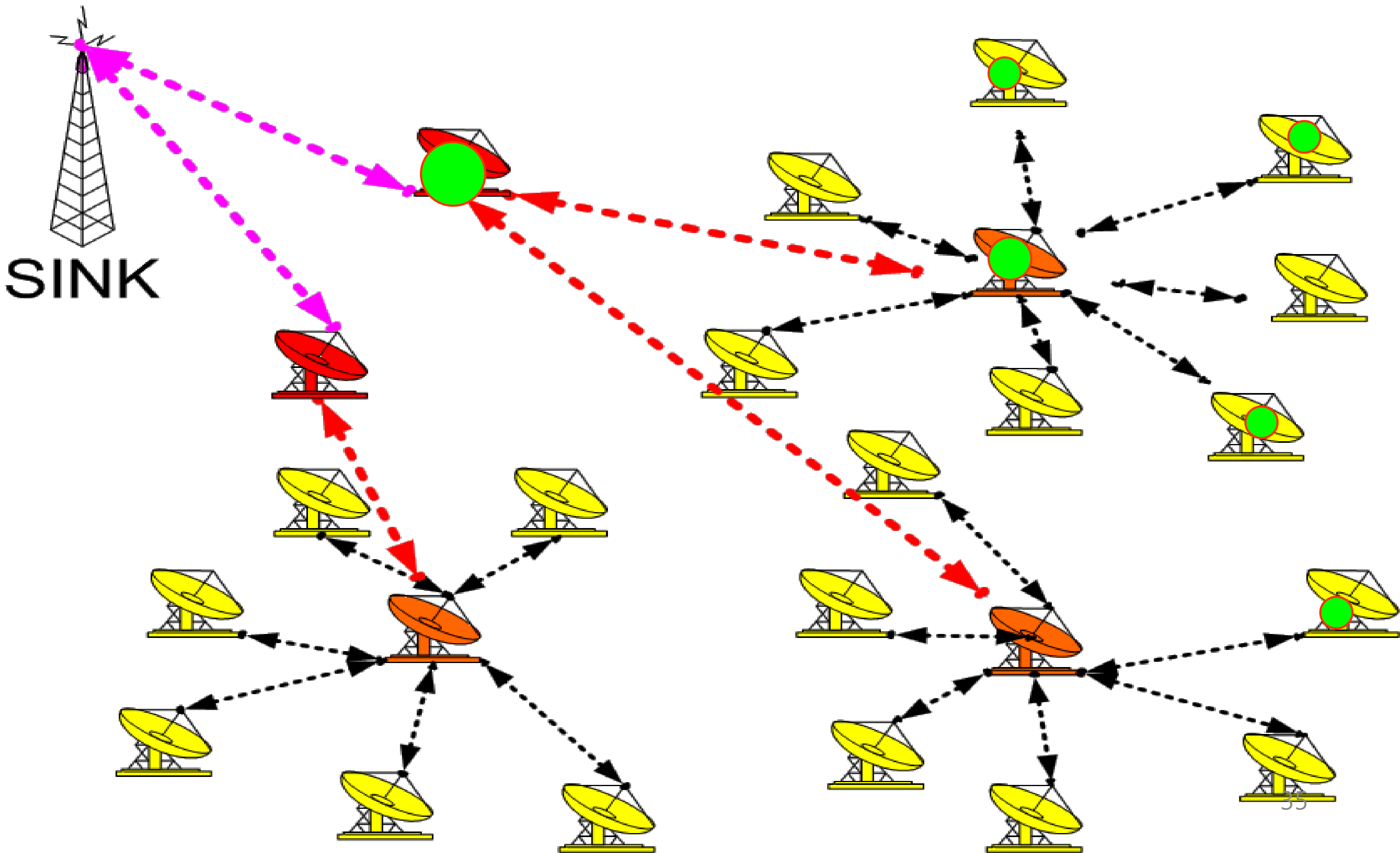
LEACH

- Works in Rounds, each with Set-Up (Short) and Steady-State (Long)
- Set-Up Phase - subdivided:
  - Advertisement (I am a Cluster-Head)
  - Cluster Set-Up (I am in your Cluster)
  - Schedule Creation (This is your slot)
- Steady-State Phase:
  - Data Transmission using TDMA

LEACH-*Low Energy Adaptive Clustering Hierarchy*



LEACH



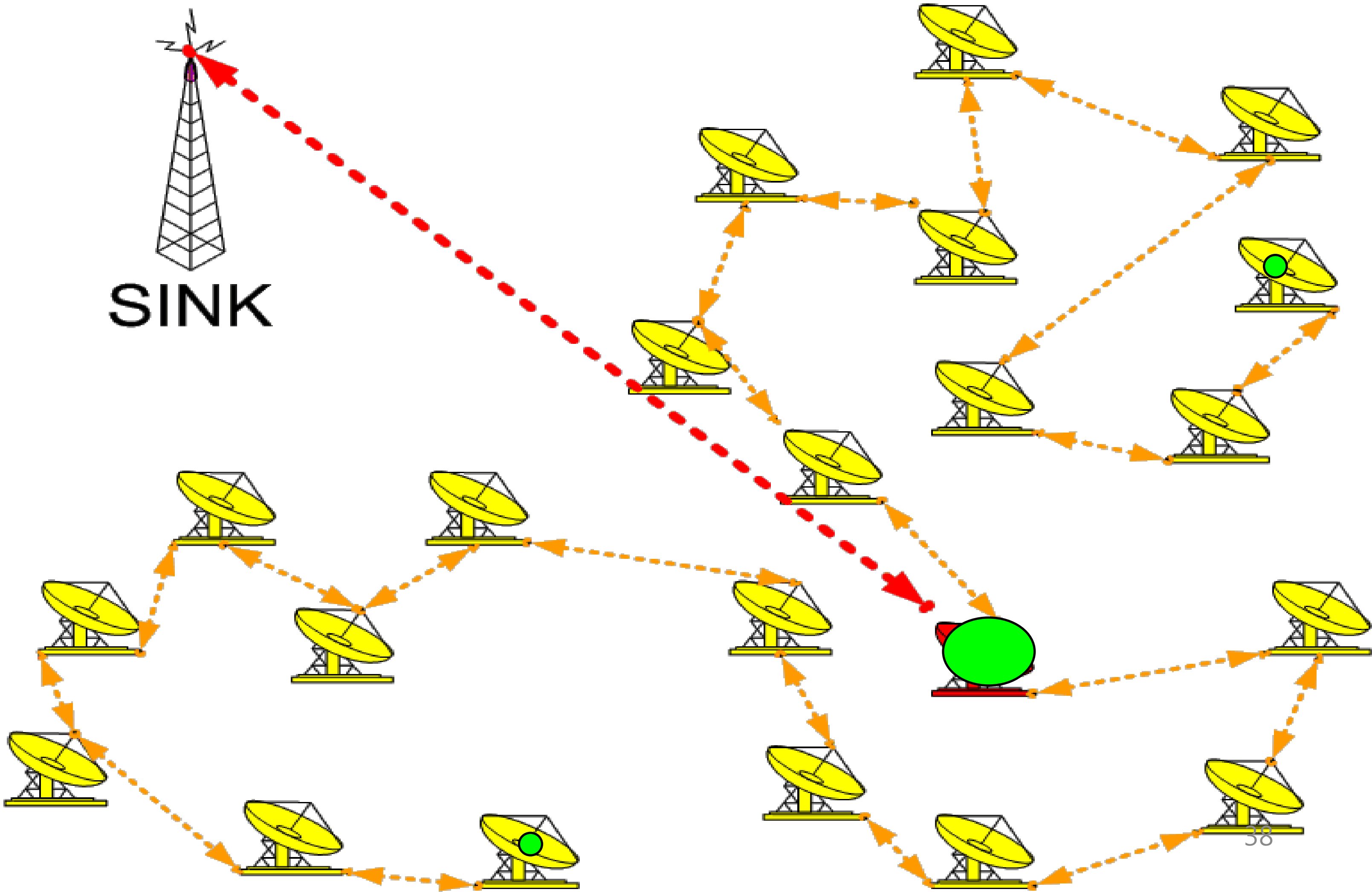
Hierarchical Routing – Power-Efficient Gathering in Sensor Information Systems (PEGASIS)

- In order to extend network lifetime, nodes need only communicate with their closest neighbors and take turns in communicating with the base station.
- When the round of all nodes communicating with the base station ends, a new round will start and so on. → reduces the power required to transmit data per round because the power draining is spread uniformly over all nodes.
- Two main objectives:
  - Increase the lifetime of each node by using collaborative techniques → increase network lifetime
  - Allow only local coordination between nodes that are close together → the bandwidth consumed in communication is reduced

PEGASIS

- Greedy Algorithm Construct Chain – Start at a node far from sink and ga ther everyone neighbor by neighbor
- Node $\boldsymbol{i}\ (\mathrm{mod}\ \mathrm{N})$ is the leader in roun d $\boldsymbol{i}$
- Each node fuse its data with the rest
- Leader transmit to sink

PEGASIS



Hierarchical Routing – Threshold-Sensitive Energy-Efficient Protocols (TEEN and APTEEN)

- In TEEN
  - Sensor nodes sense the medium continuously, but the data transmission is done less frequently.
  - A cluster head sensor sends its members
    - A hard threshold (HT): the threshold value of the sensed attribute.
    - A soft threshold (ST): a small change in the value of the sensed attribute that triggers the node to switch on its transmitter and transmit.

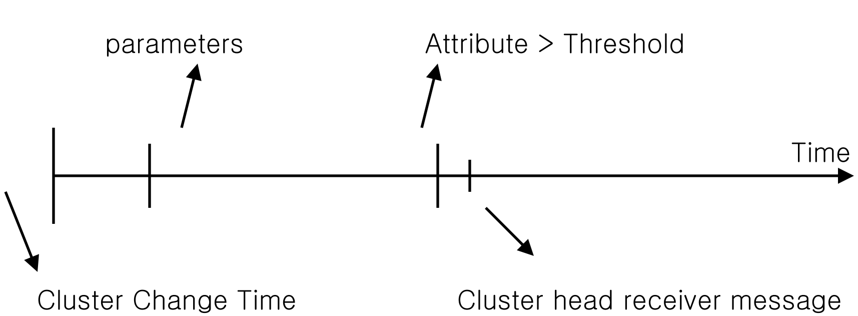
Hierarchical Routing – Threshold-Sensitive Energy-Efficient Protocols (TEEN and APTEEN)

- In TEEN
  - The HT reduces the number of transmissions by allowing the nodes to transmit only when the sensed attribute is in the range of interest.
  - The ST reduces the number of transmissions that might have otherwise occurred when little or no change occurs in the sensed attribute.
  - The user can control the trade-off between energy efficiency and data accuracy.
  - The main drawback is that, if the thresholds are not received, the nodes will never communicate and the user will not get any data from the network.

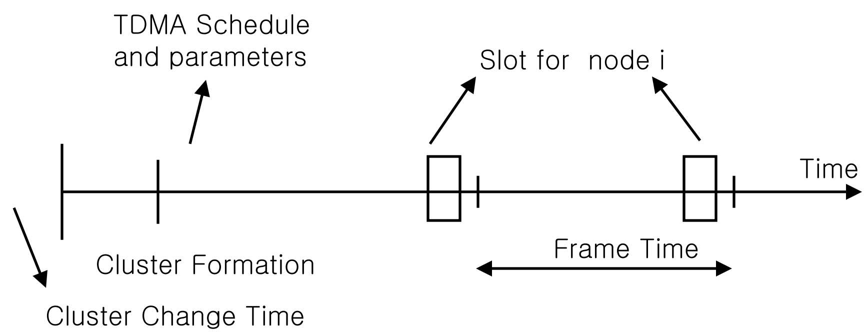
Hierarchical Routing – Threshold-Sensitive Energy-Efficient Protocols (TEEN and APTEEN) (cont)

- In APTEEN (Adaptive Periodic TEEN)
  - A hybrid protocol that changes the threshold values used in the TEEN protocol according to user needs and type of the application.
  - The cluster heads broadcast the following parameters:
    - Attributes
    - Thresholds
    - Schedule
    - Count time
  - Using a modified TDMA schedule to implement the hybrid network.
  - The main features of the APTEEN scheme include:
    - Combining proactive and reactive policies
    - Offering a lot of flexibility by allowing the user to set the CT interval
    - Controlling threshold values for the energy consumption by changing the CT and threshold values.
  - The main drawback is the additional complexity required to implement the threshold functions and the CT.

Hierarchical Routing – Threshold-Sensitive Energy-Efficient Protocols (TEEN and APTEEN) (cont)



Operation of TEEN



Operation of APTEEN

Time line for the operation of TEEN and APTEEN

Hierarchical Routing – Small Minimum Energy Communication Network (SMECN)

- Subgraph G′ of graph G, which represents the sensor network, minimizes the energy usage satisfying the following conditions:
  - The number of edges in G′ is less than in G while containing all nodes in G
  - The energy required to transmit data from a node to all its neighbors in subgraph G′ is less than the energy required to transmit to all its neighbors in graph G
- The subnetwork computed by SMECN helps to send messages on minimum-energy paths. However, it does not actually find the minimum-energy path; it just constructs a subnetwork where the path is guaranteed to exist.

Hierarchical Routing – Fixed-Size Cluster Routing

- The network area is first divided into fixed zones; inside each zone, nodes collaborate with each other to play different roles.
- Each sensor node is positioned randomly in a tow-dimensional plane.
- When a sensor transmits a packet with power for a distance r, the signal will be strong enough for other sensors to hear it within the Euclidean distance r from the sensor that originates the packet.
- In other word, to cover a range of r, the sensor that originates the signal must transmit with enough power to cover that range.

Hierarchical Routing – Virtual Grid Architecture Routing

- Based on the concept of data aggregation and in-network processing.
- The data aggregation is performed at 2 levels: local and global.
- Arranging nodes in a fixed topology due to the node stationary or extremely low mobility.
- Fixed, equal, adjacent, and nonoverlapping clusters with regular shapes are selected to obtain a fixed rectilinear virtual topology.
- Inside each zone, a node is optimally selected to act as cluster head.
- The set of cluster heads, local aggregators (LAs), performs the local aggregation.
- Several heuristics were formulated to allocate a subset of the cluster heads, master aggregators (MAs).

Hierarchical Routing – Hierarchical Power-Aware Routing

- Dividing the network into groups of sensors.
- Each group or sensors in geographic proximity is clustered together as a zone and each zone is treated as an entity.
- To perform routing, each zone is allowed to decide how it will route a message hierarchically across the other zones.
- Messages are routed along the path with maximal-minimal of the remaining power, called the max-min path.
- The motivation is that using nodes with high residual power may be expensive compared to the path with the minimal power consumption.
- The max-min zPmin algorithm combines the benefits of selecting the path with the minimum power consumption and the path that maximizes the minimal residual power in the nodes of the network.

Hierarchical vs. Flat Topology Routing

Hierarchical Routing	Flat Routing
-Reservation-based scheduling	-Contention-based scheduling
-Collisions avoided	-Collision overhead present
-Reduced duty cycle due to periodic sleeping	-Variable duty cycle by controlling sleep time of nodes
-Data aggregation by cluster head	-Node on multihop path aggregates incoming data from neighbors
-Simple but no nonoptimal routing	-Routing is complex but optimal
-Requires global and local synchronization	-Links formed on the fly without synchronization
-Overhead of cluster formation throughout the network	-Routes formed only in regions with data for transmission
-Lower latency because multiple hops network formed by cluster heads are always available	-Latency in waking up intermediate nodes and setting up multipath
-Energy dissipation is uniform	-Energy dissipation depends on traffic patterns
-Energy dissipation cannot be controlled	-Energy dissipation adapts to traffic pattern
-Fair channel allocation	-Fairness not guaranteed

Adaptive Routing

- A family of adaptive protocols, called sensor protocols for information via negotiation (SPIN), are proposed by Heizelman and Kulik.
- Disseminating all the information at each node to every node in the network, assuming that all nodes are potential base stations. → enable a user to query any node and get the required information immediately.
- Using data negotiation and resource-adaptive algorithms.
  - Assigning a high-level name to describe their collected data (metadata) completely and perform metadata negotiations before any data are transmitted. → no redundant data are sent throughout the network.
  - Accessing to the current energy level of the node and adapting the protocol it is running based on how much energy is remaining.
- These protocols work in a time-driven fashion and distribute the information over the network, even when a user does not request any data.

SPIN - (Sensor Protocols for Information via Negotiation)

- Network-wide Broadcast Limited by Negotiation and using Local Communication
- Flooding problems solved:
  - Implosion – same data from many neighbors
  - Detection of overlapping regions
  - Excessive resources consumption (Blindness)
- Needs only Localized Information
- Data Fusion
- Two main protocols SPIN-PP & SPIN-BC

SPIN-Drawbacks

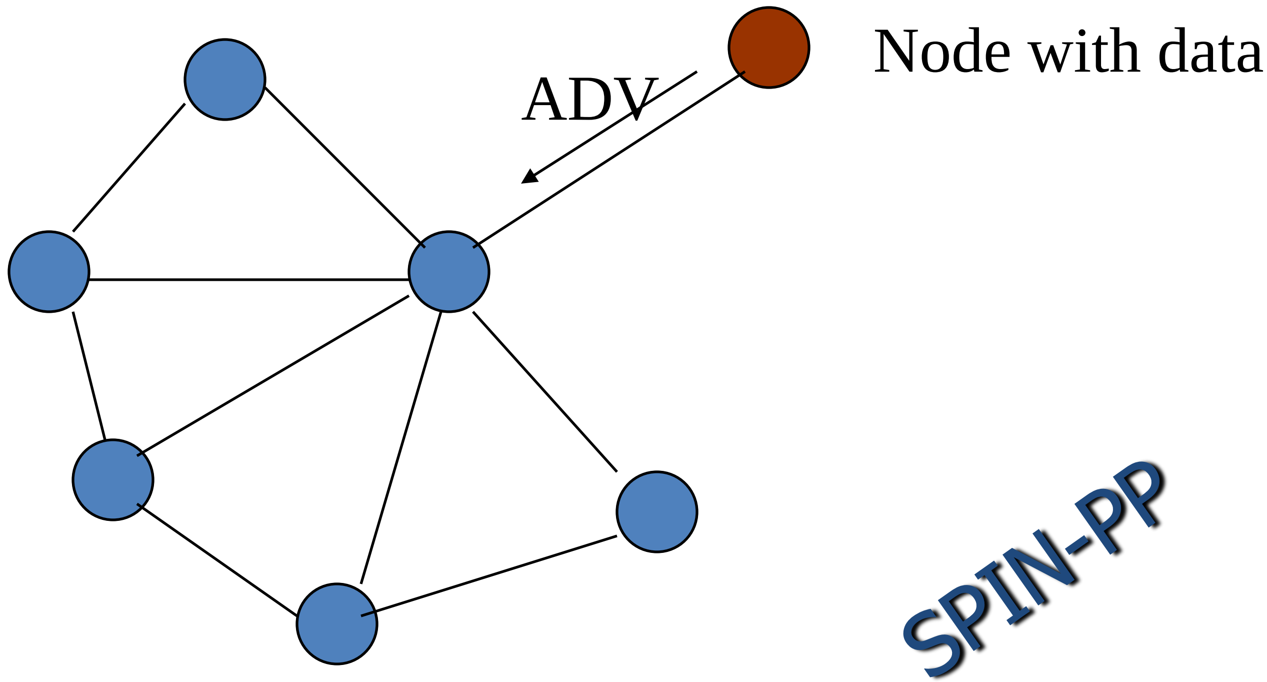
- Broadcast - Limited Scale – every node handles O(*n*) messages
- Data is updated throughout network – unnecessary in many cases
- Network lifetime - not clear
- High degree nodes = High power nee ds

SPIN – Main Procedures

SPIN-PP (Point-to-Point Communication)

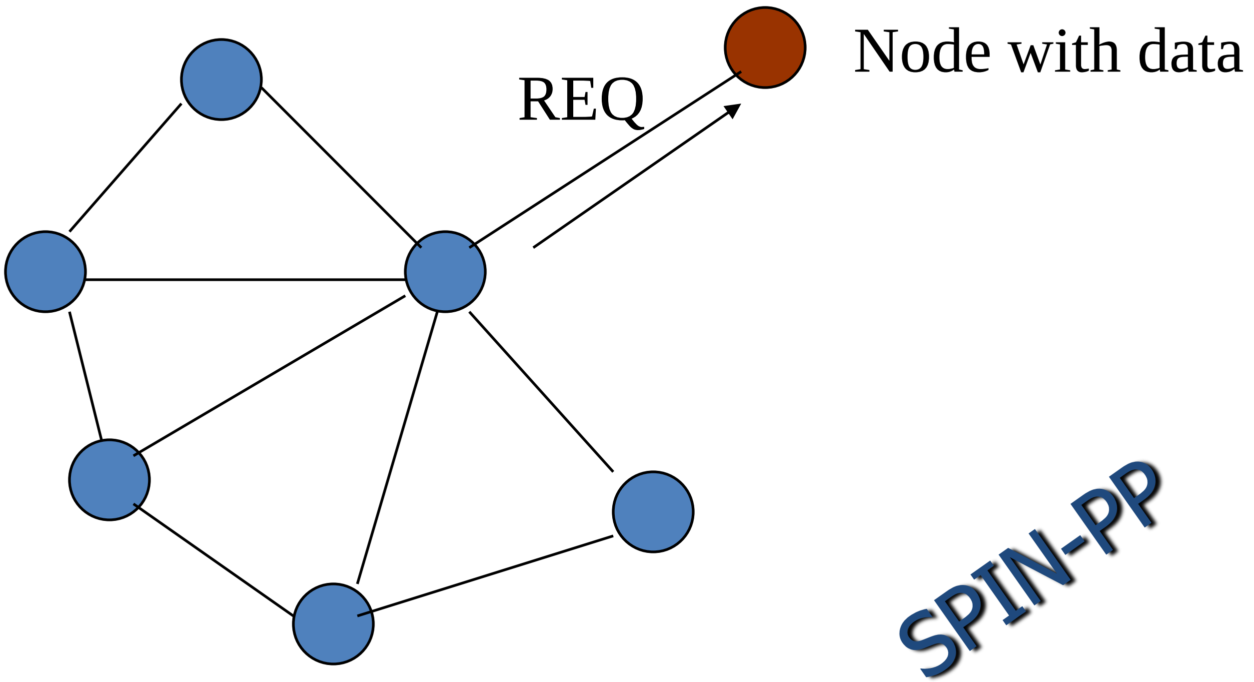
- Data is described by meta-data ADV msg.
- Node has data ⇒ sends ADV to neighbors
- If neighbor do not have data ⇒ sends REQ
- Node responds by sending the DATA
- This process continues around the network
- Nodes may aggregate their data to ADV
- In a Lossy Network ADV may be repeated pe riodically and REQ if not answered

SPIN – Illustrations



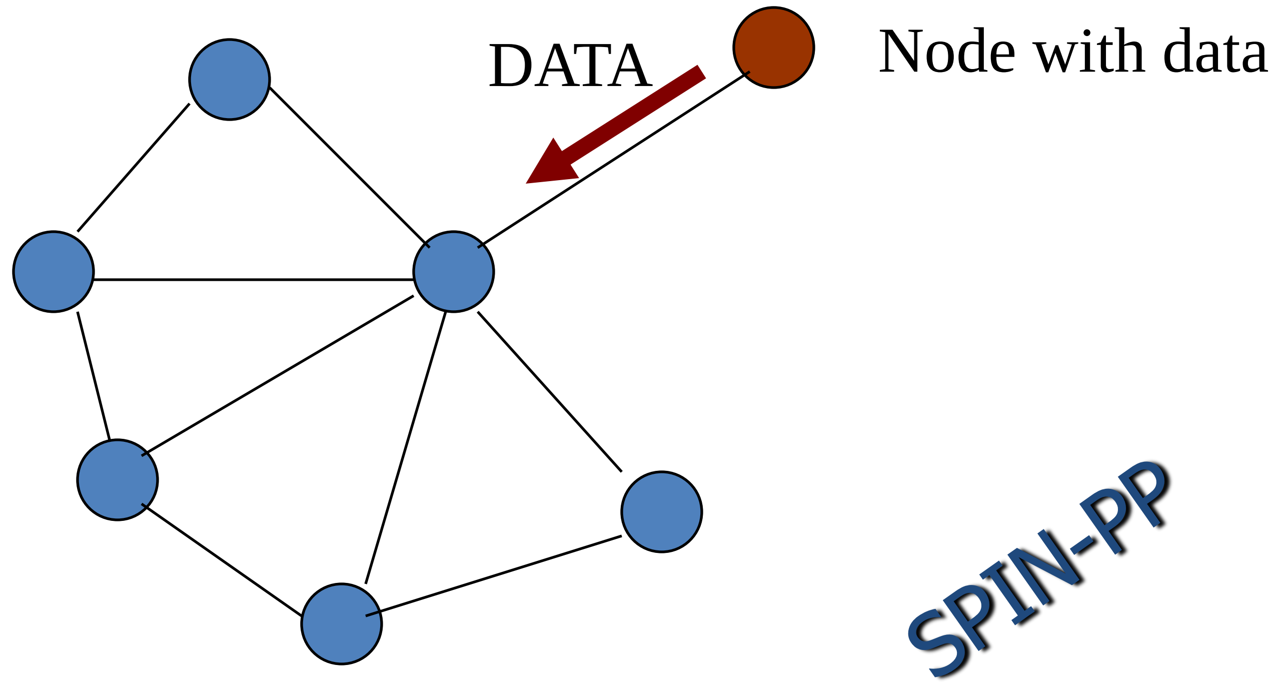
Node with data advertises to all its neighbors

SPIN – Illustrations



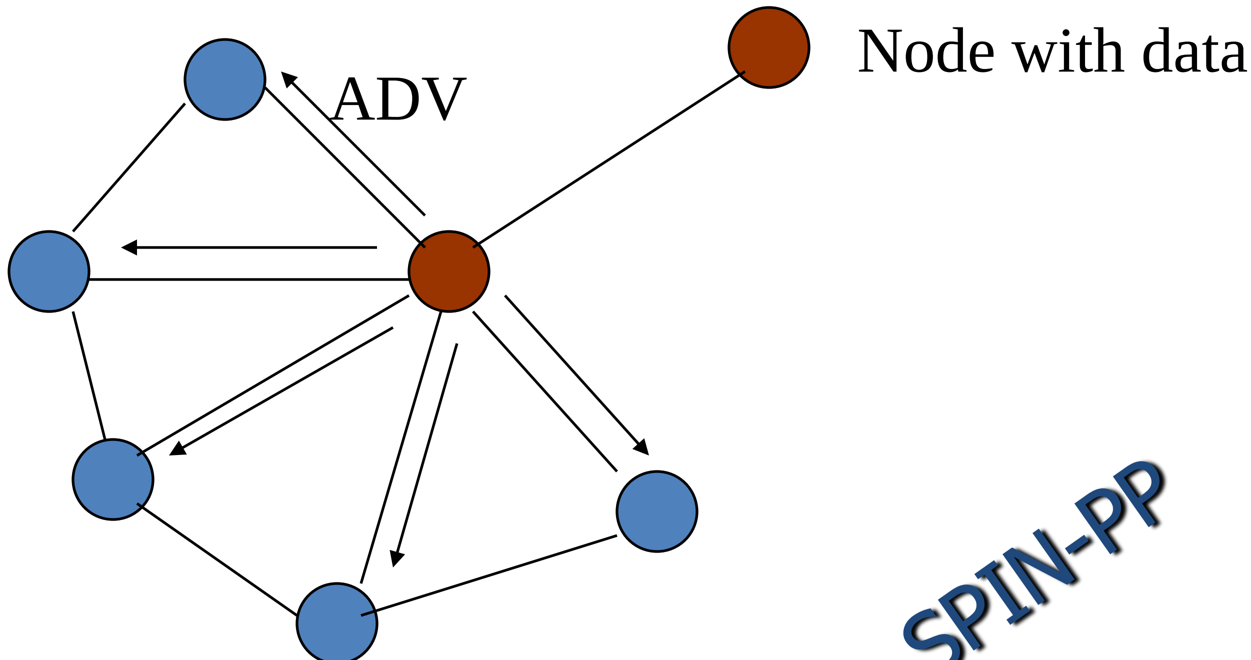
Neighbor requests for data and it is sent

SPIN –Illustrations



Node with data advertises to all its neighbors

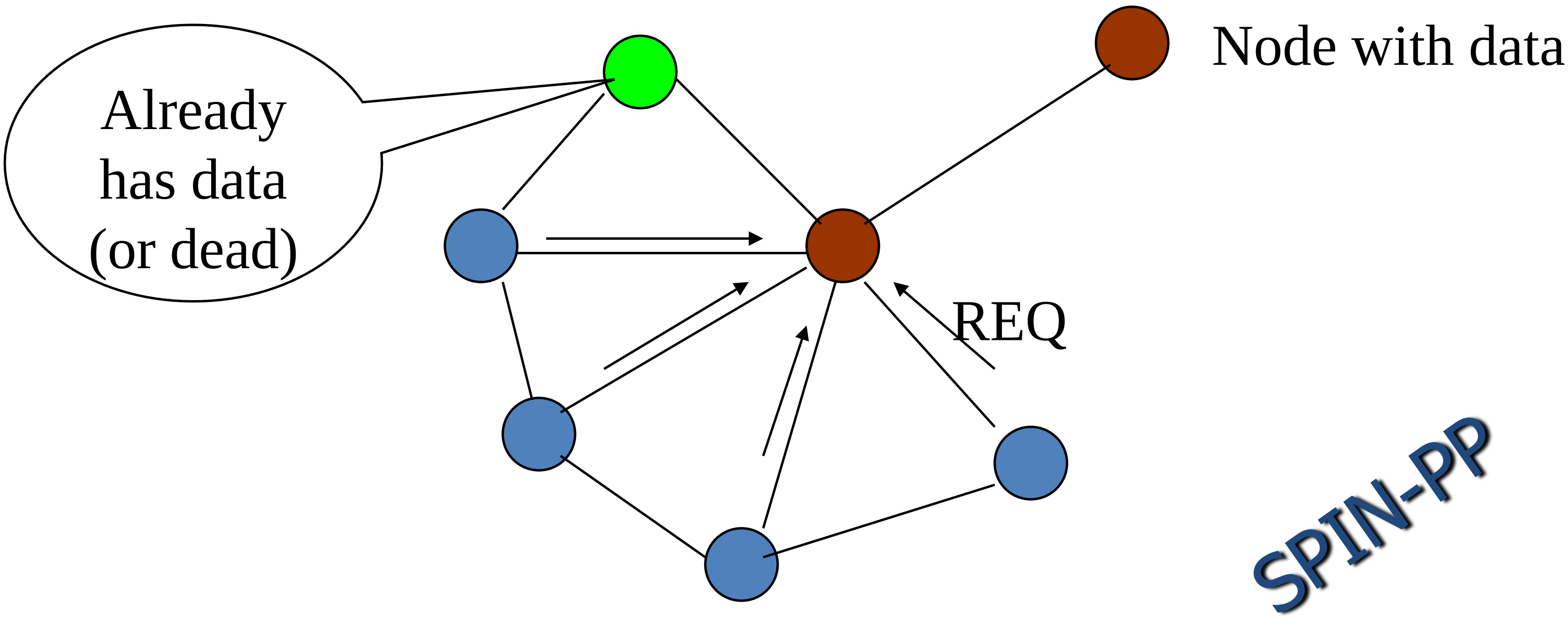
SPIN –Illustrations



SPIN-PP

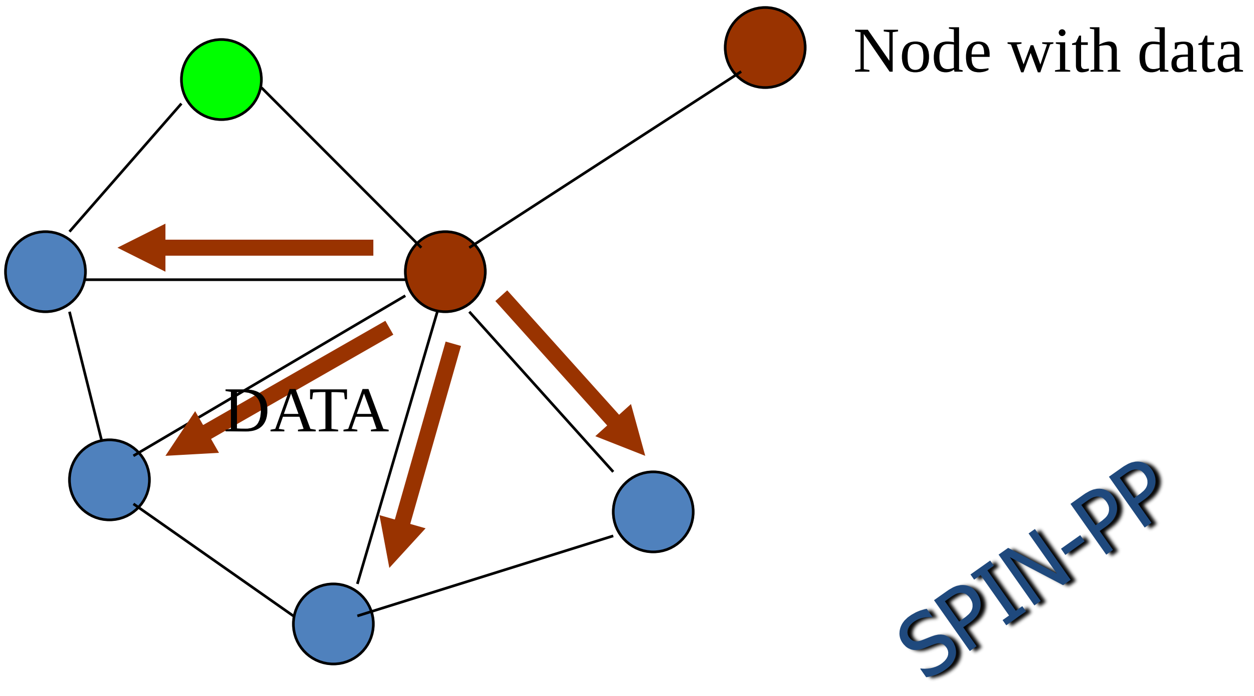
Receiving node sends ADV to neighbors

SPIN –Illustrations



Receiving neighbors requests for data.

SPIN –Illustrations



Receiving node sends ADV to neighbors

Multipath Routing

- Ganesan and coworkers have proposed an energy-efficient multipath routing protocols that uses braided multipaths instead of completely disjoint multipaths so as to keep the cost of maintenance low.
- The costs of such alternate paths are also comparable to the primary path because they tent to be much closer to the primary path.
- Chang and Tassiulas proposed an algorithm to route data through a path whose nodes have the largest residual energy. The path is changed whenever a better path is discovered.
- Rahul and Rabaey have proposed the use of a set of suboptimal paths occasionally to increase the lifetime of the network. These paths are chosen by means of a probability that depends on how low the energy consumption of each path is.

Query-Based Routing

- The destination nodes propagate a query for data from a node through the network and a node having these data sends data that match the query back to the node, which initiates the query.
- Usually these queries are described in natural language, in high-level query languages.
- All the nodes have tables consisting of the sensing task queries received, and hence they send data that match these queries when they receive them.

Negotiation-Based Protocols

- Using high-level data descriptors in order to eliminate redundant data transmissions through negotiation.
- Communication decisions are also taken based on the resources available to them.
- Suppressing duplicate information and preventing redundant data from being sent to the next sensor or the base station by conducting a series of negotiation messages before the real data transmission begins.
- SPIN family protocols are an example of negotiation-based routing protocols.

Future Directions

- Exploit redundancy
- Tiered architectures (mix of form/energy factors)
- Exploit spatial diversity and density of sensor/actuator nodes
- Achieve desired global behavior with adaptive localized algorithms
- Leverage data processing inside the network and exploit computation near data sources to reduce communication
- Time and location synchronization
- Self-configuration and reconfiguration

Conclusions

- The common objective is extending the lifetime of the sensor network.
- The routing techniques are classified
  - Based on the network structure
    - Flat routing
    - Hierarchical routing
    - Adaptive routing
  - Based on the protocol operation
    - Multipath-based routing
    - Query-based routing
    - Negotiation-based routing
- Design trade-offs between energy and communication overhead savings in some of the routing paradigm have been highlighted.