Routing Protocols for Wireless Sensor Networks

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Introduction

- Sensors are micro-electro-mechanical systems (MEMS)
- Low power devices
- Data processing capable
- Communication capabilities

Introduction - Usage

- Gather data locally (Temperature, Humidity, Motion Detection, etc.)
- Send them to a command center (sink)
- Applications
  - Surveillance
  - Security
  - Disaster Management
  - Environmental Studies

Introduction - Constraints

- Limitations
  - Energy Constrains
  - Bandwidth
- All layers must be energy aware
- Need for energy efficient and reliable network routing
- Maximize the lifetime of the network

Differences of Routing in WSN and Traditional Networks

- No global addressing
  - Classical IP-based protocols cannot be applied to sensor networks
- Redundant data traffic
  - Multiple sensors may generate same data within the vicinity of a phenomenon.
  - Such redundancy needs to be exploited by the routing protocols to improve energy and bandwidth utilization.

Differences of Routing in WSN and Traditional Networks

- Multiple-source single-destination network
  - Almost all applications of sensor networks require the flow of sensed data from multiple regions (sources) to a particular sink.
- Careful resource management
  - Sensor nodes are tightly constrained in terms of:
    - Transmission power
    - On-board energy
    - Processing capacity
    - Storage

System architecture and design issues

- Network Dynamics
- Node Deployment
- Energy Considerations
- Data Delivery Models
- Node capabilities
- Data aggregation/fusion

Network Dynamics

- Mobile or Stationary nodes
- Static Events (Temperature)
- Dynamic Events (Target Detection)
- Dynamic events in most applications require periodic reporting and consequently generate significant traffic to be routed to the sink

Node Deployment

- Deterministic :
  - The sensors are manually placed and data is routed through pre-determined paths
- Self-organizing :
  - The sensor nodes are scattered randomly creating an infrastructure in an ad hoc manner.
  - Position of the sink or the cluster-head is also crucial in terms of energy efficiency and performance.

Energy Considerations

- Energy Considerations
  - Direct vs Multi-hop communication
    - Direct Preferred – Sensors close to sink
    - Multi-hop – unavoidable in randomly scattered networks
  - Since the transmission power of a wireless radio is proportional to distance squared
    - Multi-hop routing will consume less energy than direct communication.
  - Multi-hop routing introduces significant overhead for topology management and medium access control.
  - Direct routing would perform well enough if all the nodes were very close to the sink.

Data Delivery Models

- Different data delivery models depending on the application of the sensor network:
  - Continuous
    - Each sensor sends data periodically
  - Event-driven:
    - The transmission of data is triggered when an event occurs.
  - Query-driven:
    - The transmission of data is triggered when a query is generated by the sink
  - Hybrid
- The routing protocol is highly influenced by the data delivery model

Node Capabilities

- In a sensor network, different functionalities can be associated with the sensor nodes.
  - Homogenous:
    - All node have equal capacity in terms of computation, communication and power
  - Heterogeneous
    - Nodes dedicated to a particular task (relaying, sensing, aggregation)

Data Aggregation/Fusion

- Similar packets from multiple nodes can be aggregated
  - The number of transmissions would be reduced.
- Data aggregation
  - Combination of data using functions such as suppression (eliminating duplicates), min, max and average
  - Aggregation – Combination of data by eliminating redundancy
  - Data Fusion is Aggregation through signal processing techniques
  - Aggregation achieves energy savings

Classification of Routing Protocols

- Data Centric:
  - Data-centric protocols are query-based
- Hierarchical:
  - Aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy
- Location-based:
  - Utilize the position information to relay the data to the desired regions rather than the whole network.
- Network Flow & QoS Aware:
  - Are based on general network-flow modeling and protocols that strive for meeting some QoS requirements along with the routing function

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Data-centric Protocols

- In many applications of sensor networks, it is not feasible to assign global identifiers to each node
- Data-centric protocols are query-based.
- Sink sends queries to certain regions and waits data from sensors located in that region
- Attribute-based naming is necessary to specify properties of data

Data-centric Routing

- Sensor networks can be considered as a virtual database
- Implement query-processing operators in the sensor network
- Queries are flooded through the network (or sent to a representative set of nodes)
- In response, nodes generate tuples and send matching tuples towards the origin of the query
- Intermediate nodes may merge responses or aggregate

Data-centric Protocols

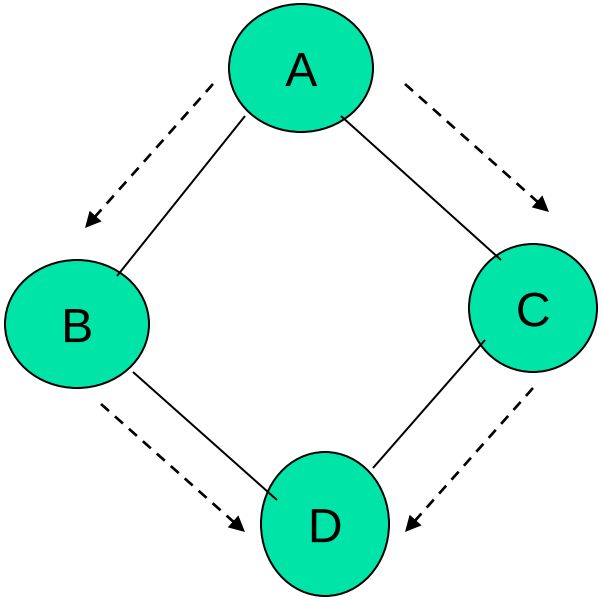
- Flooding
- Gossiping
- Sensor Protocols for Information via Negotiation (SPIN)
- Directed Diffusion
- Energy-aware Routing
- Rumor Routing
- Gradient-Based Routing (GBR)
- Constrained Anisotropic Diffusion Routing (CADR)
- COUGAR
- ACtive QUery forwarding In sensoR nEtworks (ACQUIRE)

Data-centric Protocols

- **Flooding**
  - Sensor broadcasts every packet it receives
  - Relay of packet till the destination or maximum number of hops
  - No topology maintenance or routing
- **Gossiping**
  - Enhanced version of flooding
  - Sends received packet to a randomly selected neighbor

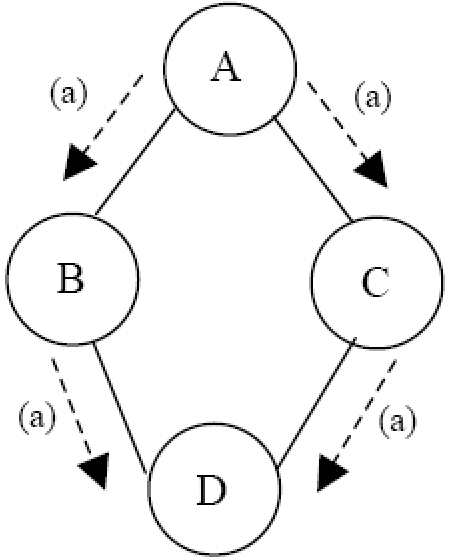
Classic Flooding Problems

- **Implosion Problem:**
  - A starts by flooding its data to all of its neighbors.
  - Two copies of the data eventually end at node D.
  - The system wastes energy and bandwidth.
- **Overlap Problem:**
  - Two sensors cover an overlapping graphic region.
  - Node receives two copies of the Data.
- **Resource Blinding:**
  - Resources do not modify their activities based on the amount of energy they have.

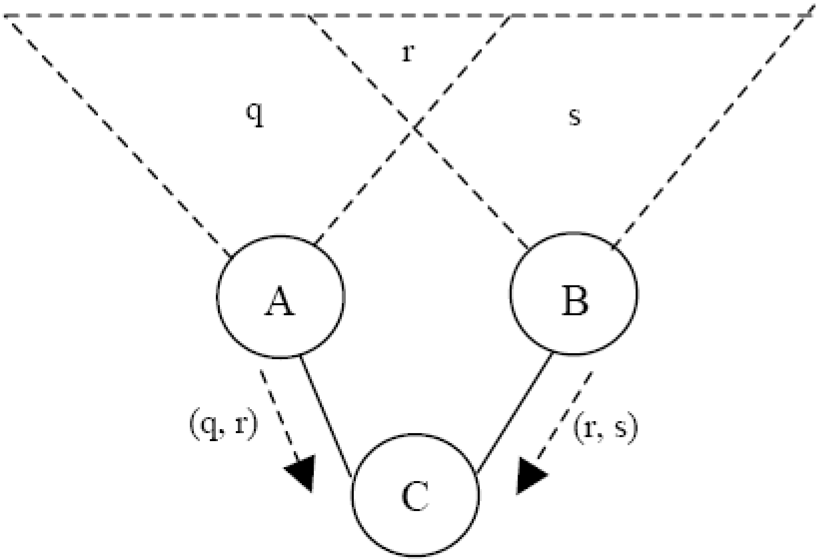


Data-centric Protocols – Flooding, Gossiping Problems

- Problems of Implosion, Overlap, Resource Blindness



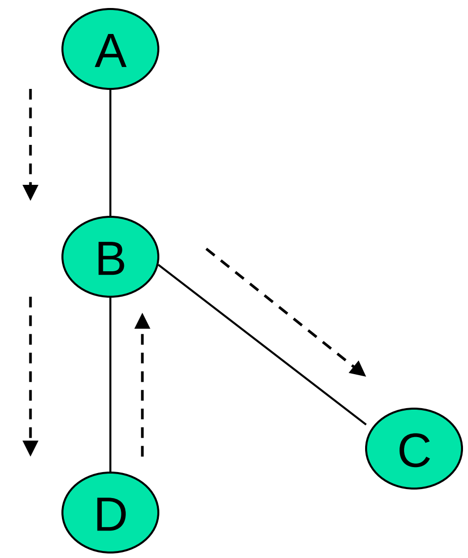
Implosion Problem



Overlap Problem

Gossiping

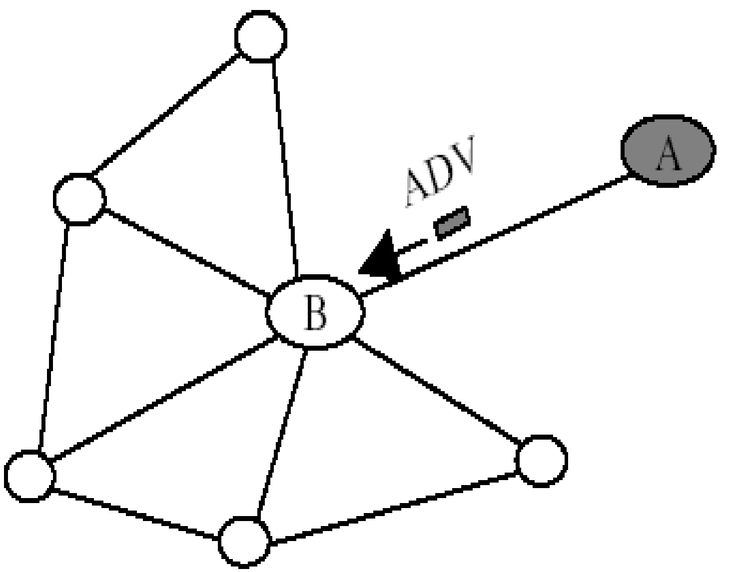
- An alternative to the classic flooding
- Uses randomization to conserve energy.
- Each node only forwards data on to one neighbor
  - Is selected randomly.
- After node D receives the data, it must forward the data back to sender (B)
  - Otherwise the data would never reach node C



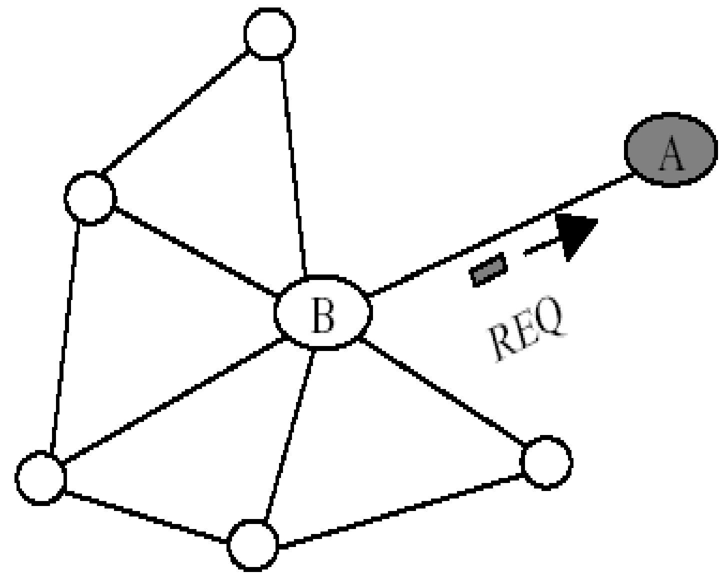
SPIN: Sensor Protocols for Information Negotiation

- One of the most dominant form of routing in the wireless sensor networks.
- Name data, using meta-data
  - Meta Data for each sensor data
  - Same senor data -> same meta-data
  - Different sensor data -> different meta-data
- Size of meta-data << Size of actual data
- There is no standard meta-data format and it is assumed to be application specific
- Uses three types of messages:
  - ADV – advertise data
  - REQ – request for data
  - DATA – data message, contains actual sensor data

SPIN Protocol Example



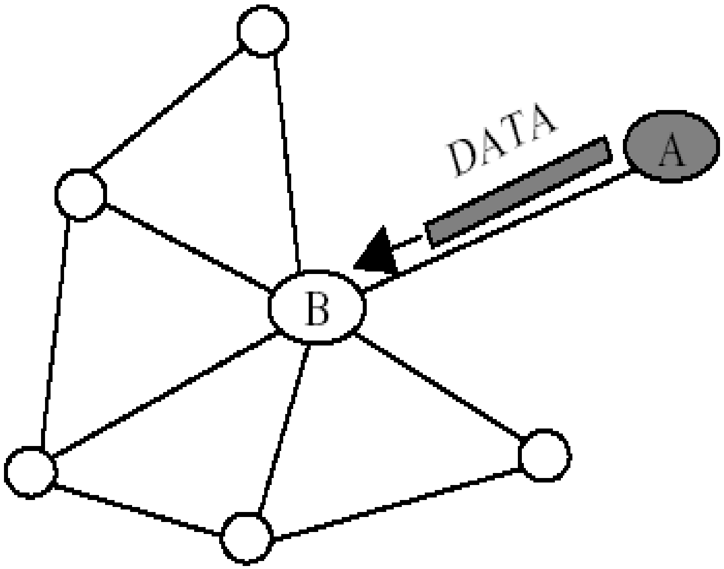
(a)

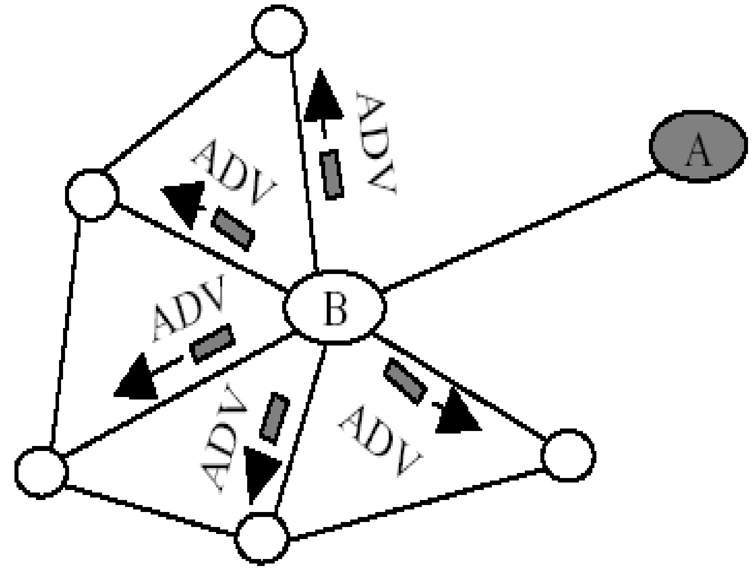


(b)

- A sends an ADV message to B
- B sends a REQ listing all of the data it would like to acquire.

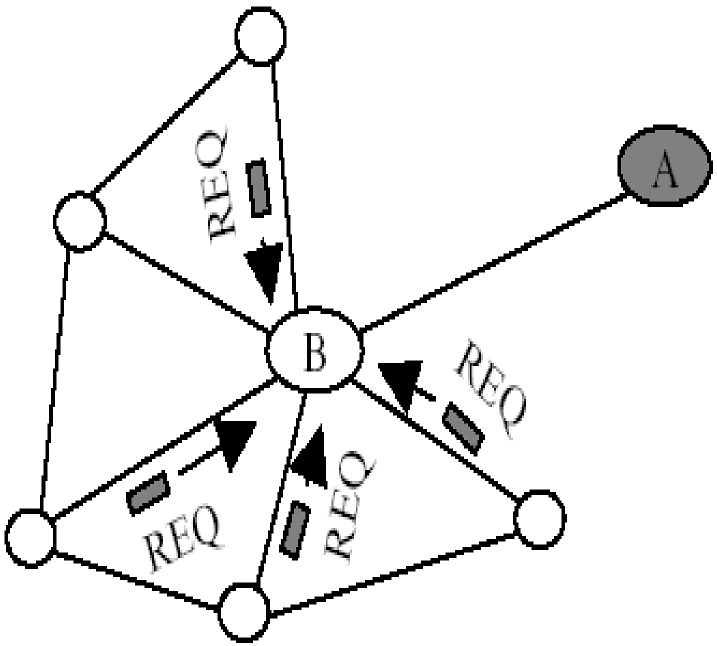
SPIN Protocol Example





•If node B had its own data, it could aggregate this with the data of node A and advertise.

SPIN Protocol Example



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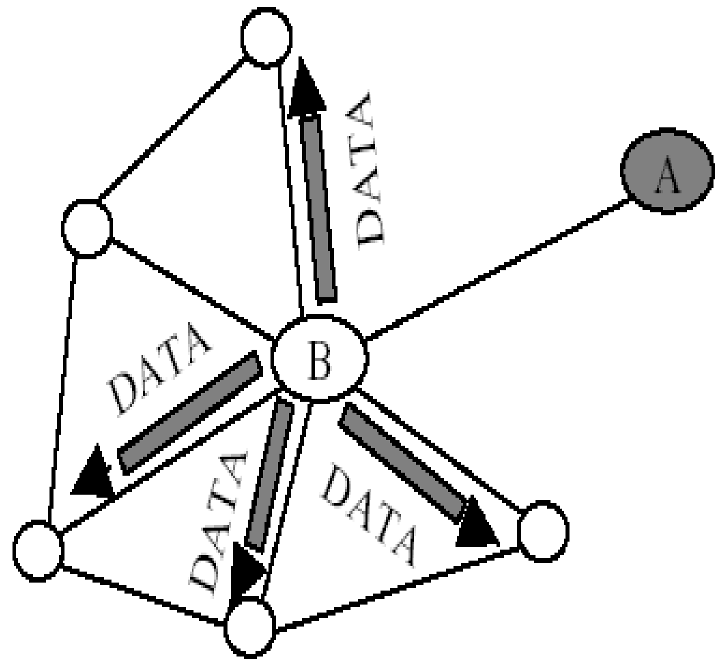


(f)

Nodes need not respond to every message

Data-centric Protocols - SPIN

- Topological changes are localized - Each node needs to know only its neighbors
- SPIN halves the redundant data in comparison to flooding
- Cannot guarantee data delivery
- SPIN **NOT** good for applications that need reliable data delivery

SPIN1 and SPIN2

SPIN1 : Three way handshaking protocol.

- ADV, REQ, DATA.

- Each sensor node has resource manager
  - Keeps track of resource consumption
  - Applications probe the manager before any activity
  - Cut down activity to save energy

SPIN2 : energy constraint

- Adds energy-conservative heuristic to the SPIN1 protocol.
- Node initiates three stage protocol, only if it has enough energy to complete it.
- If below energy threshold, node can still receive messages, cannot send/recv DATA messages

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?

Direct Diffusion

- Uses a naming scheme for the data to save energy
- Attribute-value pairs for data and queries on-demand (Interests)
- Interests are broadcasted by the sink (query) to its neighbors (caching), which can do in-network aggregation
- Gradients = reply links to an interest (path establishment)

Direct Diffusion

- Direct Diffusion suggests the use of attribute-value pairs for the data and queries the sensors in an on demand basis by using those pairs.
- In order to create a query, an interest is defined using a list of attribute-value pairs such as:
  - name of objects,
  - interval,
  - duration,
  - geographical area,
  - etc.

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

Direct Diffusion

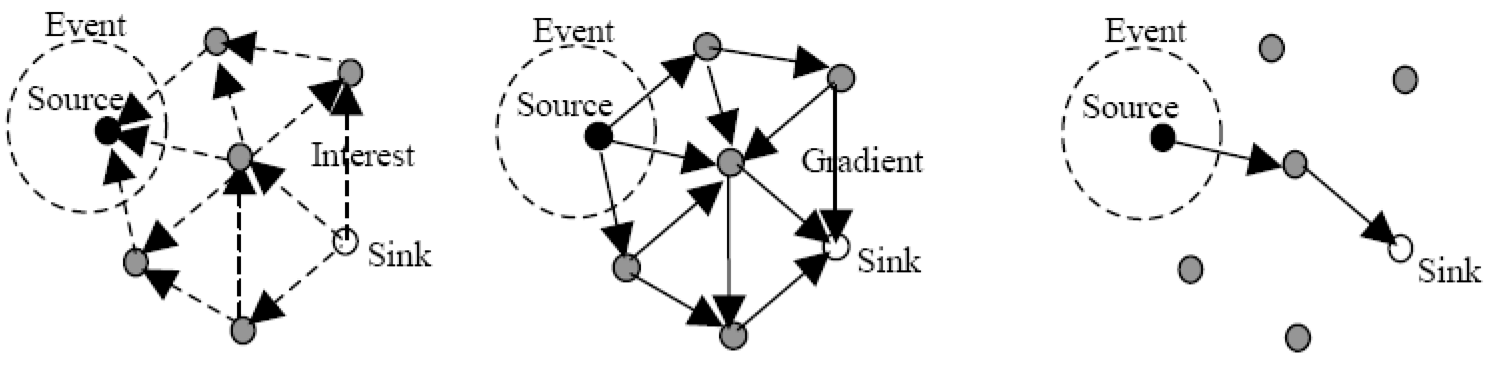
- The interest is broadcast by a sink through its neighbors.
- Each node receiving the interest can do caching for later use.
- The nodes also have the ability to do in-network data aggregation
- The interests in the caches are then used to compare the received data with the values in the interests.

Direct Diffusion

- The interest entry also contains several gradient fields.
- A gradient is a reply link to a neighbor from which the interest was received.
- It is characterized by the data rate, duration and expiration time derived from the received interests fields.
- By utilizing interest and gradients, paths are established between sink and sources.
- Several paths can be established so that one of them is selected by reinforcement.
- The sink resends the original interest message through the selected path with a smaller interval hence reinforces the source node on that path to send data more frequently

Data-centric Protocols – Direct Diffusion

- Energy saving and delay done with caching
- No need for global addressing (neighbor-to-neighbor mechanism)
- **Cannot** be used for continuous data delivery or event-driven applications



(a) Interest propagation (b) Initial gradients setup (c) Data delivery along reinforced

Directed Diffusion: Motivating Example

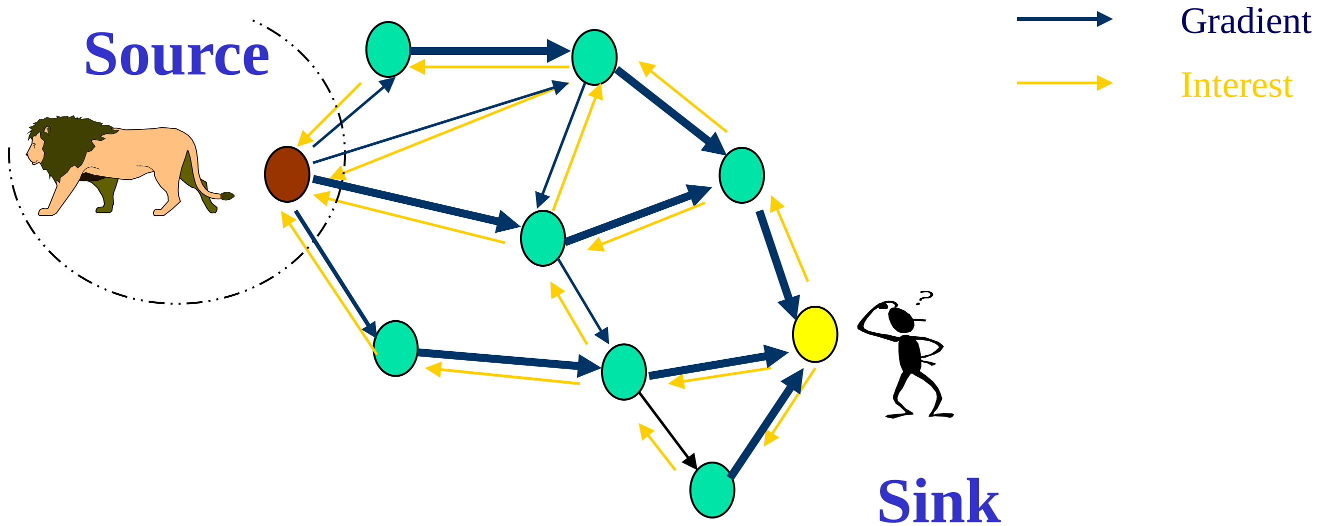
- Sensor nodes are monitoring animals
- Users are interested in receiving data for all 4-legged creatures seen in a rectangle
- Users specify the data rate

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

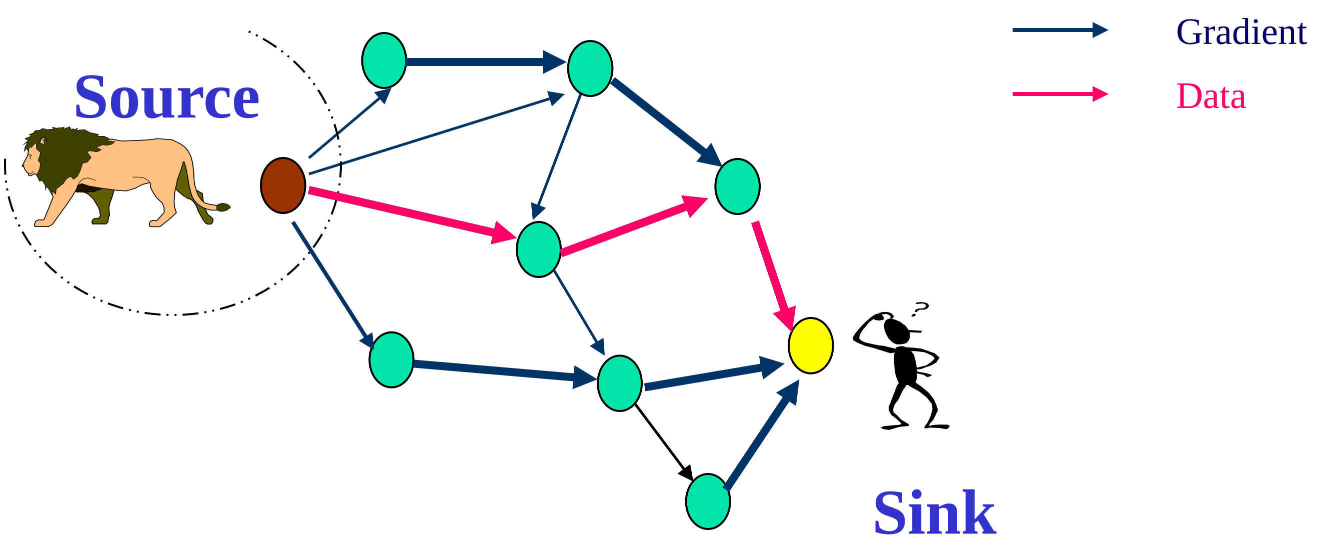
Directed Diffusion: Interest Propagation

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



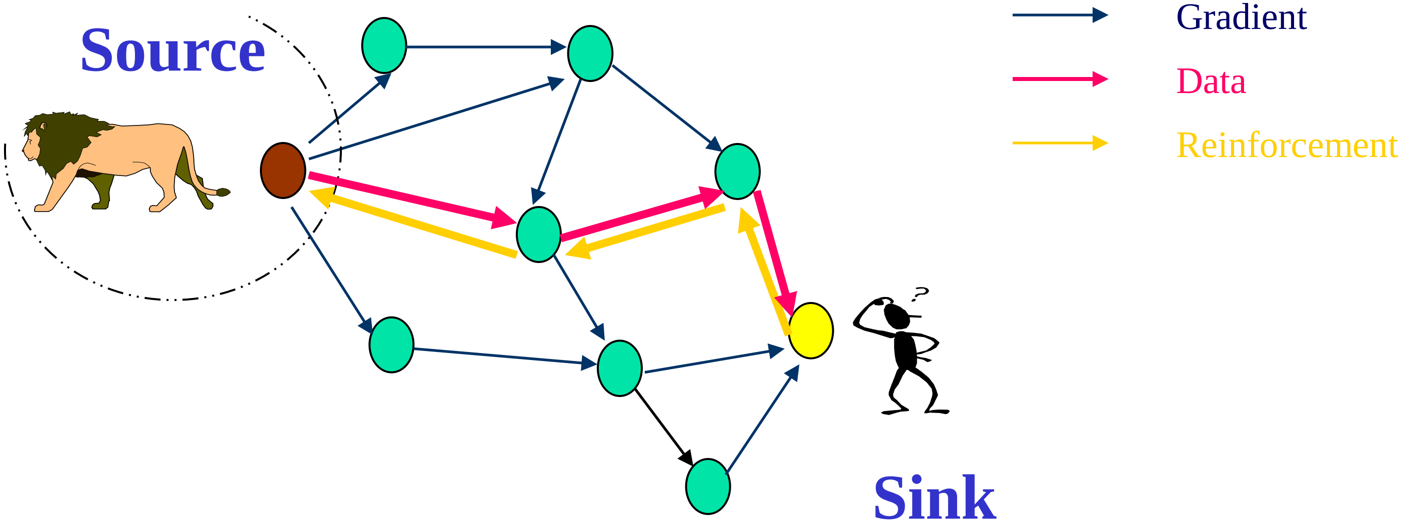
Directed Diffusion: Data Propagation

- Multipath routing
  - Consider each gradient's link quality



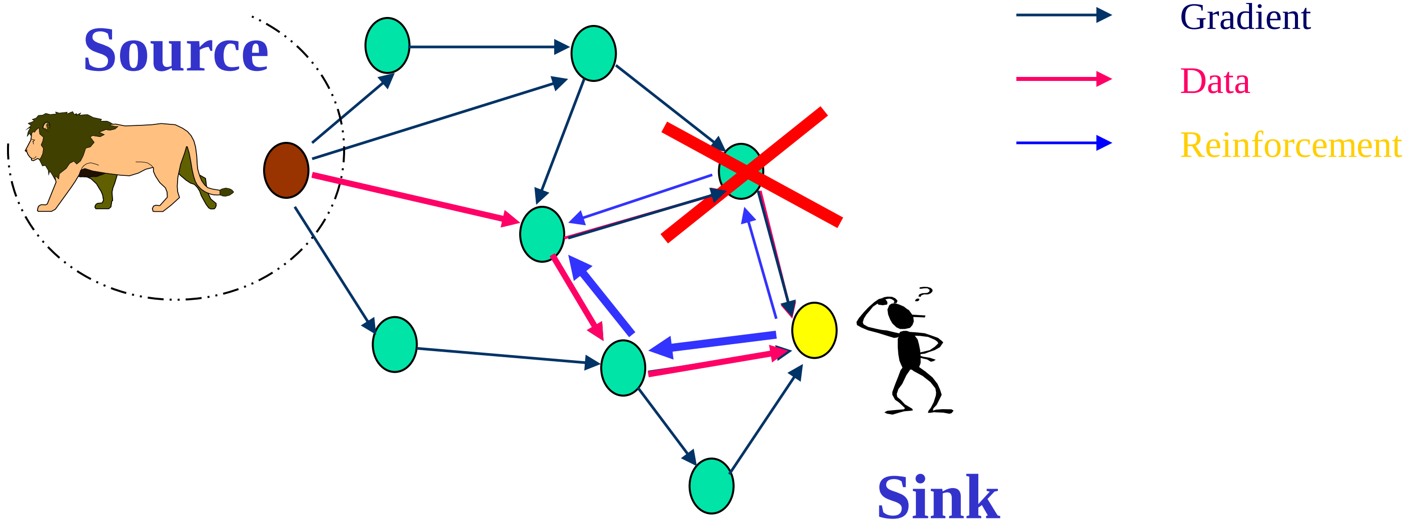
Directed Diffusion: Reinforcement

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



Directed Diffusion: Negative Reinforcement

- Explicitly degrade the path by re-sending *interest* with lower data rate.
- Time out: Without periodic reinforcement, a gradient will be torn down



Directed Diffusion Conclusion

- 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
- Characteristics
  - Data centric:
    - All communications are neighbor to neighbor with no need for a node addressing mechanism
  - Each node can do aggregation & caching
  - 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

Energy-aware Routing

- Chose paths base on a probability function, which depends on the energy consumption of each path.
- Network survivability is the main metric
- Using the minimum energy path all the time will deplete the energy of nodes on that path.
- Instead, one of the multiple paths is used with a certain probability so that the whole network lifetime increases.
- The protocol assumes that each node is addressable through a class-based addressing which includes the location and types of the nodes.

Energy-aware Routing

- Occasional use of a set of sub-optimal paths
- Multiple paths used with certain probability
- Increase of the total lifetime of the network
- Hinders the ability for recovering from node failure
- Requires address mechanism ➔Complicate setup

Energy-aware routing

- There are 3 phases in the protocol.
  - Setup phase:
    - Localized flooding occurs to find the routes and create the routing tables.
  - Data communication phase:
    - Each node forwards the packet by randomly choosing a node from its forwarding table using the probabilities.
  - Route maintenance phase:
    - Localized flooding is performed infrequently to keep all the paths alive.

Setup Phase (Cost Function)

- If the request is sent from node Ni to node Nj, Nj calculates the cost of the path as follows:

$$C_{N_j,N_i} = \mathrm{Cost}(N_i) + \mathrm{Metric}(N_j, N_i)$$

- Paths that have a very high cost are discarded
- The node assigns a probability to each of its neighbors in routing (forwarding) table (FT) corresponding to the formed paths
- The probability is inversely proportional to the cost

$$P_{N_j,N_i} = \frac{1/C_{N_j,N_i}}{\sum_{k \in \mathrm{FT}_j} 1/C_{N_j,N_k}}$$

Setup Phase (Cost Function)

- Nj then calculates the average cost for reaching the destination using the neighbors in the forwarding table (FTj) using the formula:

$$\mathrm{Cost}(N_j) = \sum_{i \in \mathrm{FT}_j} P_{N_j,N_i} C_{N_j,N_i}$$

- This average cost for Nj is set in the cost field of the request and forwarded.

Comparison with Directed Diffusion

- Like Directed Diffusion, potential paths from data sources to the sink are discovered.
- In Directed Diffusion, data is sent through multiple paths, one of them being reinforced to send at higher rates.
- Energy aware routing protocol selects a single path randomly from the multiple alternatives in order to save energy.
- It provides an overall improvement of 21.5% energy saving and a 44% increase in network lifetime.
- It hinders the ability of recovering from a node or path failure as opposed to Directed Diffusion.
- It requires gathering the location information and setting up the addressing mechanism for the nodes.
- More complicate route setup compared to the Directed Diffusion.

Rumor Routing

- Variation of Directed Diffusion
- Flood the events instead of the queries
- Creation of an event ➔ generation of a long live packet travel through the network (agent)
- Nodes save the event in a local table
- When a node receives query ➔ checks its table and returns source – destination path

Rumor Routing

- Variation of directed diffusion
  - Don't flood interests (or queries)
  - Flood events when the number of events is small but the number of queries large
  - Route the query to the nodes that have observed a particular event
  - Long-lived packets, called agents, flood events through the network
  - When a node detects an event, it adds the event to its events table, and generates an agent
  - Agents travel the network to propagate info about local events
    - An agent is associated with TTL (Time-To-Live)

Rumor Routing

- Advantages
  - Can handle node failure
  - Significant energy savings
- Disadvantages
  - Works well **only** with small number of events
  - Overhead through adjusting parameters, like the time to live of the agent

Gradient-Based Routing (GBR)

- Slightly changed version of Directed Diffusion
- Keep the number of hops when the interest is diffused through the network.
- Hence, each node can discover the minimum number of hops to the sink, which is called height of the node.
- The difference between a nodes height and that of its neighbor is considered the gradient on that link.
- A packet is forwarded on a link with the largest gradient.

GBR

- It uses traffic spreading and data aggregation to balance uniformly the network traffic
- The data spreading schemes strives to achieve an even distribution of the traffic throughout the whole network.
  - helps in balancing the load on sensor nodes and increases the network lifetime.
- Outperforms Directed Diffusion in terms of total communication energy

Traffic Spreading Methods in GBR

- Stochastic scheme:
  - When there are two or more next hops with the same gradient, the node chooses one of them at random.
- Energy-based scheme:
  - When a nodes energy drops below a certain threshold, it increases its height so that other sensors are discouraged from sending data to that node.
- Stream-based scheme:
  - The idea is to divert new streams away from nodes that are currently part of the path of other streams.

Constrained Anisotropic Diffusion Routing (CADR)

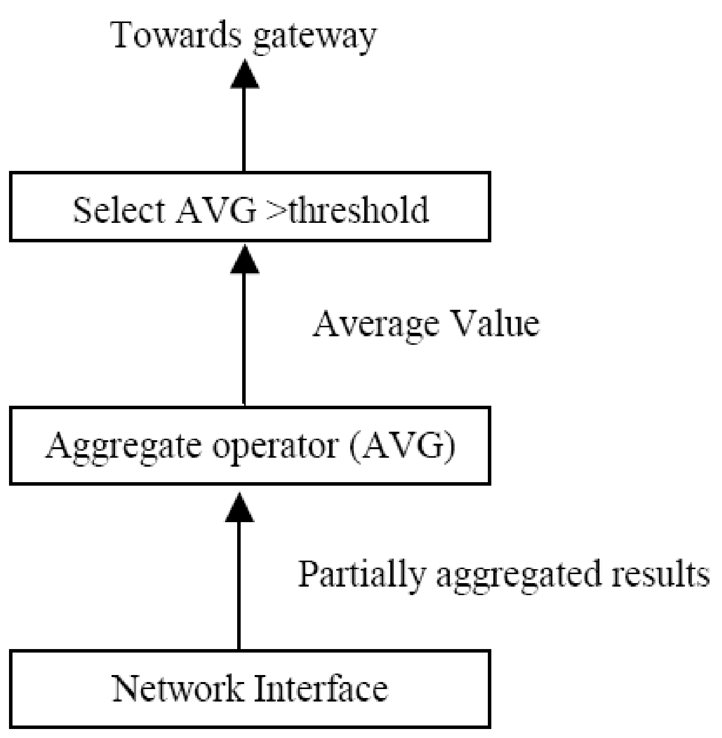
- A general form of Directed Diffusion.
- The idea is to query sensors and route data in a network in order to maximize the information gain, while minimizing the latency and bandwidth.
- This is achieved by activating only the sensors that are close to a particular event and dynamically adjusting data routes.
- The major difference from Directed Diffusion is the consideration
- of information gain in addition to the communication cost.
- Each node evaluates an information/cost objective and routes data based on the local information/cost gradient and end-user requirements.

Constrained Anisotropic Diffusion Routing (CADR)

- General form of Directed Diffusion
- Query Sensors
- Route data in the network
- Activates sensors close to the event and dynamically adjusts routes
- Routing based on a local information/cost gradient
- More energy efficient than Directed Diffusion

Data-centric Protocols

- **COUGAR**
  - Views the network as a huge distributed database
  - Declarative queries to abstract query processing from network layer functions
  - Introduces a new query layer
  - Leader node performs data aggregation and transmits to the sink



Query plan at a leader node

Data-centric Protocols - COUGAR

- Disadvantages
  - Additional query layer brings overhead in terms of energy consumption and storage
  - In network data computation requires synchronization (i.e. wait for all data before sending data)
  - Dynamically maintenance of leader nodes to prevent failure

ACtive QUery forwarding In sensoR nEtworks (ACQUIRE)

- Views network as a distributed database
- Node receiving a query from the sink tries to respond partially and then forwards packet to a neighbor
- Use of pre-cached information
- After the query is answered, result is returned to the sink by using the reverse path or the shortest path
- If cache information is not up to date ➔ node gathers information from neighbors within look ahead of d hops

ACQUIRE

- Motivation: Deal with one shot complex queries
- Efficient routing by adjusting parameter d
- If d equals network size → behaves similar to flooding
- If d too small the query has to travel more hops

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Hierarchical Routing Protocols

- Scalability is one of the major design attributes of sensor networks.
- A single-tier network can cause the gateway to overload with the increase in sensors density
  - Such overload might cause latency in communication and inadequate tracking of events.
- The single-gateway architecture is not scalable for a larger set of sensors covering a wider area of interest.

Hierarchical Protocols

- Maintain energy consumption of sensor nodes
  - By multi-hop communication within a particular cluster
  - By data aggregation and fusion → decrease the number of the total transmitted packets

Hierarchical Protocols

- LEACH : Low-Energy Adaptive Clustering Hierarchy
- PEGASIS: Power-Efficient GAthering in Sensor Information Systems
  - Hierarchical PEGASIS
- TEEN: Threshold sensitive Energy Efficient sensor Network protocol
  - Adaptive Threshold TEEN (APTEEN)
- Energy-aware routing for cluster-based sensor networks
- Self-organizing protocol

LEACH : Low-Energy Adaptive Clustering Hierarchy

- One of the first hierarchical routing protocols
- Forms clusters of the sensor nodes based on received signal strength
- Local cluster heads route the information of the cluster to the sink
- Cluster heads change randomly over time ➔ balance energy dissipation
- Data processing & aggregation done by cluster head

Cluster Head (CH)

- Each node randomly decides to become a cluster heads (CH)
- CH chooses the code to be used in its cluster
  - CDMA between clusters
- CH broadcasts Adv;
  - Each node decides to which cluster it belongs based on the received signal strength of Adv
- CH creates a transmission schedule for TDMA in the cluster
  - Nodes can sleep when its not their turn to transmit
- CH compresses data received from the nodes in the cluster and sends the aggregated data to BS
- CH is rotated randomly

Cluster Head Choosing

- All the data processing such as data fusion and aggregation are local to the cluster.
- CHs change randomly over time in order to balance their energy dissipation of nodes.
- This decision is made by the node choosing a random number between 0 and 1.
- The node becomes a cluster head for the current round if the number is less than a threshold.

LEACH Threshold Function

$$T(n) = \begin{cases} \dfrac{p}{1 - p * (r \bmod 1/p)} & \text{if } n \in G, \\ 0 & \text{otherwise,} \end{cases}$$

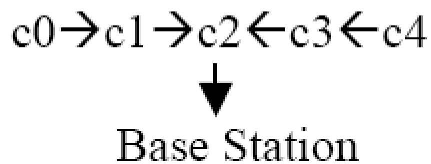
- p is the desired percentage of cluster heads (e.g. 0.05),
- r is the current round,
- G is the set of nodes that have not been cluster heads in the last 1/p rounds.

LEACH Conclusion

- Advantages
  - Completely distributed
  - No global knowledge of the network
  - Increases the lifetime of the network
- Disadvantages
  - Uses single-hop routing within cluster →**not** applicable to networks in large regions
  - Dynamic clustering brings extra overhead (advertisements, etc)

PEGASIS: Power-Efficient GAthering in Sensor Information Systems

- Improvement of LEACH
- Forms chains from sensors rather than clusters



- Data aggregation in the chain → one node sends the data to the base station
- Outperforms LEACH
- Excessive delay for distant nodes in the chain

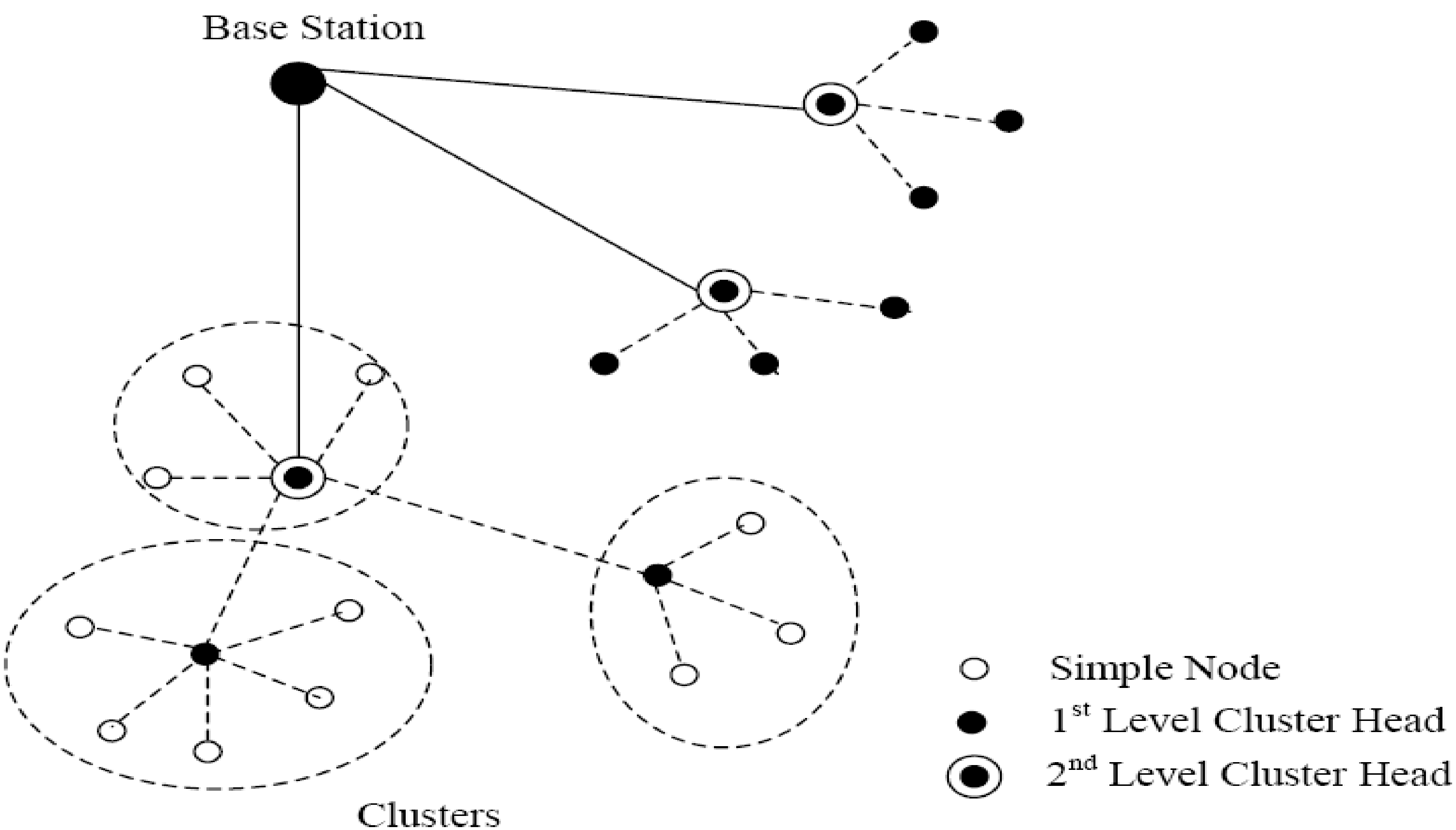
PEGASIS Characteristics

- Use multi-hop routing by forming chains.
- Selecting only one node to transmit to the base station instead of using multiple nodes.
- PEGASIS has been shown to outperform LEACH by about 100–300% for different network sizes and topologies.
- PEGASIS introduces excessive delay for distant node on the chain.
- The single leader can become a bottleneck.

TEEN: Threshold sensitive Energy Efficient Sensor Network Protocol

- Good for time-critical applications
- Hierarchical along with a data-centric approach
- Hierarchical grouping:
  - Close nodes form clusters and this process goes on the second level until sink is reached
- Not good for applications that need periodic reports

TEEN Example



TEEN Thresholds

- Cluster headers broadcast:
  - Hard Threshold
    - the minimum possible value of an attribute to trigger a sensor node to transmit to the cluster head
    - reducing the number of transmissions significantly
  - Soft Threshold
    - Once a node senses a value at or beyond the hard threshold, it transmits data only when the value of that attribute changes by an amount equal to or greater than the soft threshold

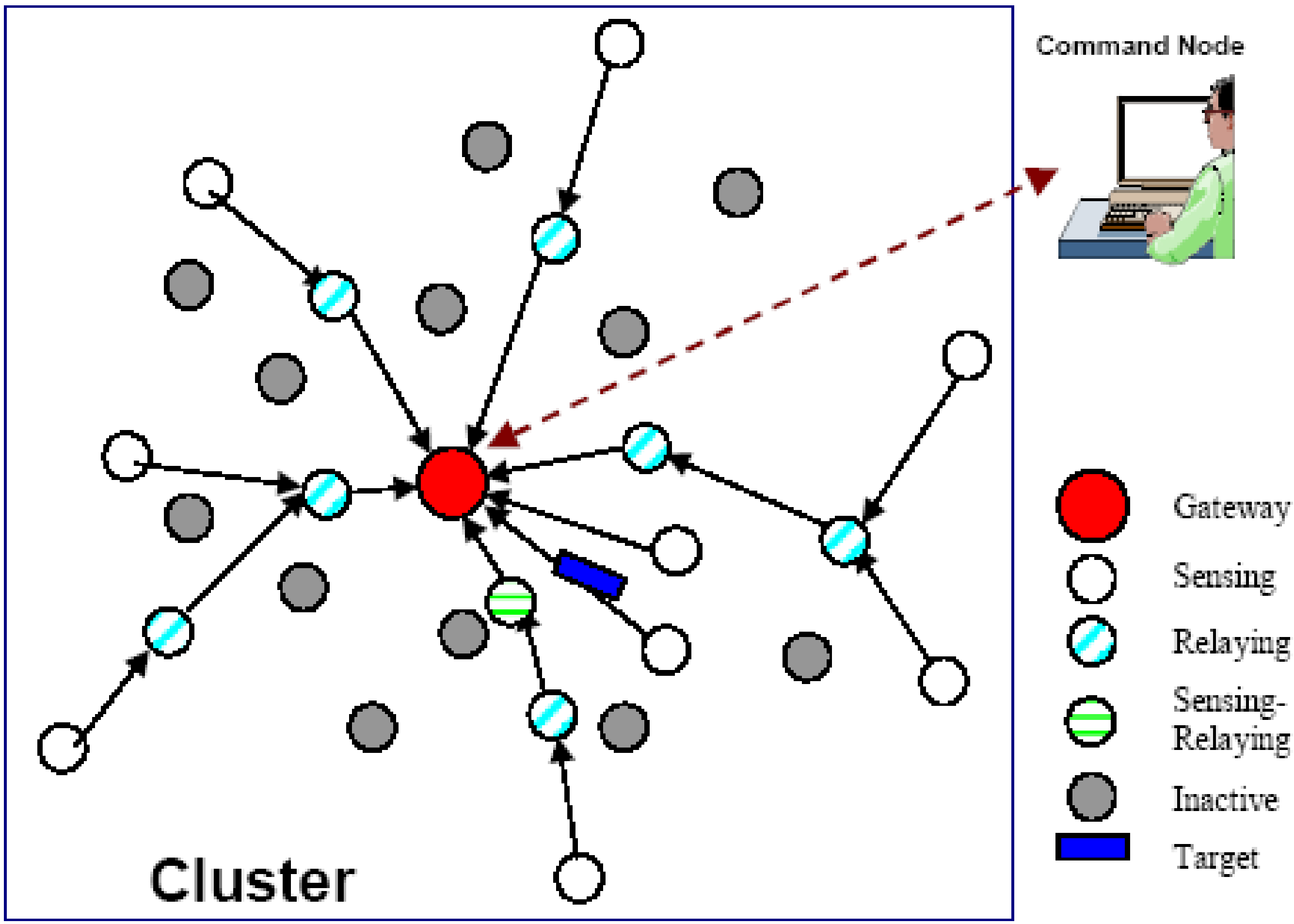
TEEN Conclusion

- Advantages
  - Outperform LEACH in terms of energy dissipation and total lifetime of the network
- Disadvantages
  - Overhead and complexity of:
    - Forming multiple level clusters
    - Implementing threshold-based functions
    - Dealing with attribute-based naming of queries

Energy-aware Routing For Cluster-based Sensor Networks

- Assumptions:
  - Sensors are grouped into clusters prior to network operation
  - Cluster Heads (Gateways) less energy constrained
  - Cluster Heads know the location of the sensors ➔ Known Multi-Hop routing to collect data
  - Communication node (sink) communicates only with gateways

Architecture



Stages of a Sensor

- Stages of a Sensor inside a cluster
  - Sensing only:
    - the node probes the environment and generates data at a constant rate.
  - Relaying only :
    - the node does not sense the target but its communications circuitry is on to relay the data from other active nodes.
  - Sensing-Relaying:
    - node is both sensing and relaying messages from other nodes
  - Inactive:
    - the node can turn off its sensing and communication circuitry.

Self-organizing Protocol

- The architecture supports heterogeneous sensors that can be mobile or stationary
- Sensors probe the environment and forward the data to designated routers.
- Router nodes are stationary and form the backbone for communication.
- Collected data are forwarded through the routers to more powerful sink nodes.

Self-organizing Protocol

- The architecture requires addressing
  - Sensor identified by the router is connected to
- Sensing nodes are identifiable through the address of the router node it is connected to.
- The routing architecture is hierarchical where groups of nodes are formed and merge when needed.
- Utilizes router nodes to keep all sensors connected by forming a dominating set

Different Phases

- Discovery phase:
  - The nodes in the neighborhood of each sensor are discovered.
- Organization phase:
  - Groups are formed and merged by forming a hierarchy.
  - Each node is allocated an address based on its position in the hierarchy.
  - Routing tables are created for each node.
  - Broadcast trees that span all the nodes are constructed.
- Maintenance phase:
  - Updating of routing tables and energy levels of nodes is made.
  - Each node informs the neighbors about its routing table and energy level.
- Self-reorganization phase:
  - In case of partition or node failures, group reorganizations are performed.

Classification of Routing Protocols

- Data Centric:
  - Data-centric protocols are query-based
- Hierarchical:
  - Aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy
- Location-based:
  - Utilize the position information to relay the data to the desired regions rather than the whole network.
- Network Flow & QoS Aware:
  - Are based on general network-flow modeling and protocols that strive for meeting some QoS requirements along with the routing function

Location-based Protocols

- Most of the routing protocols for sensor networks require location information for sensor nodes.
- There is no addressing scheme for sensor networks like IP-addresses
- location information can be utilized in routing data in an energy efficient way.
- Protocols designed for Ad hoc networks with mobility in mind
  - Applicable to Sensor Networks as well
  - Only energy-aware protocols are considered.

Location-based Protocols

- MECN & SMECN
  - Minimum Energy Communication Network
- GAF
  - Geographic Adaptive Fidelity
- GEAR
  - Geographic and Energy Aware Routing

MECN & SMECN

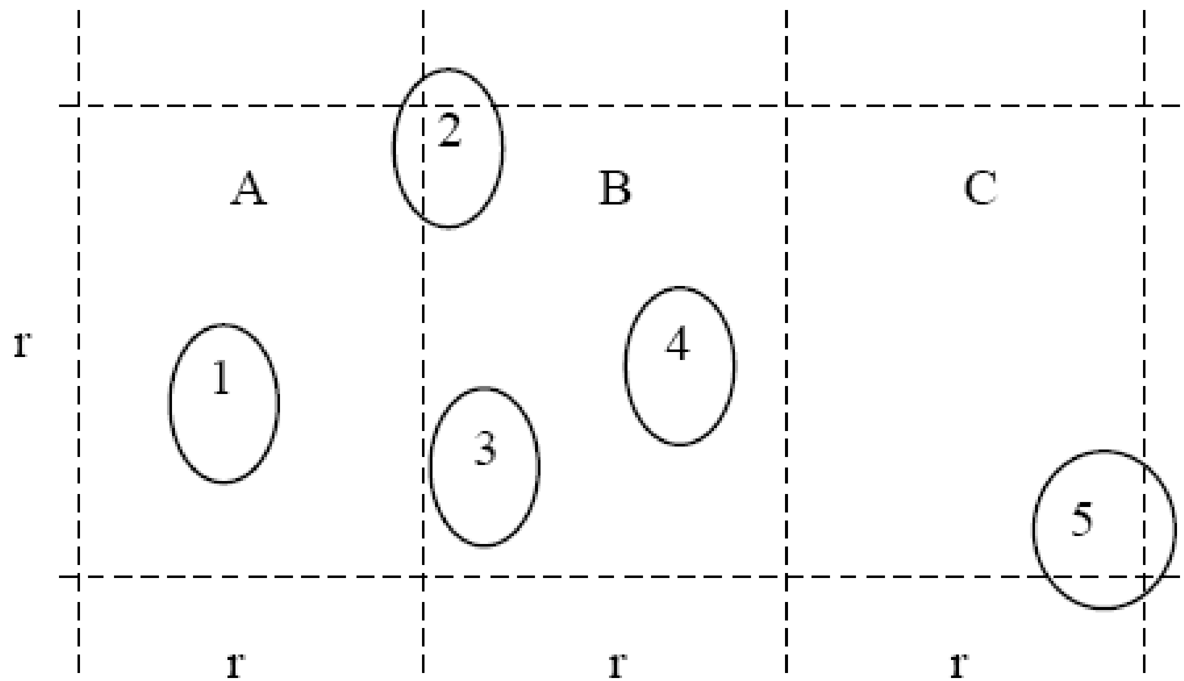
- Utilizes low power GPS
- Best applicable to non-mobile sensor networks
- Identifies a relay region for every node
  - The relay region consists of nodes in a surrounding area where transmitting through those nodes is more energy efficient than direct transmission.
- The main idea of MECN is to find a sub-network, which will have less number of nodes and require less power for transmission between any two particular nodes
- Self-reconfiguring
- Dynamically adaptive

GAF: Geographic Adaptive Fidelity

- GAF is an energy-aware location-based routing algorithm.
- GAF conserves energy by turning off unnecessary nodes in the network without affecting the level of routing fidelity.
- It forms a virtual grid for the covered area.
- Each node uses its GPS-indicated location to associate itself with a point in the virtual grid.
- Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing.

GAF Example

- Node 1 can reach any of 2, 3 and 4 and nodes 2, 3, and 4 can reach 5.
- Therefore nodes 2, 3 and 4 are equivalent and two of them can sleep.

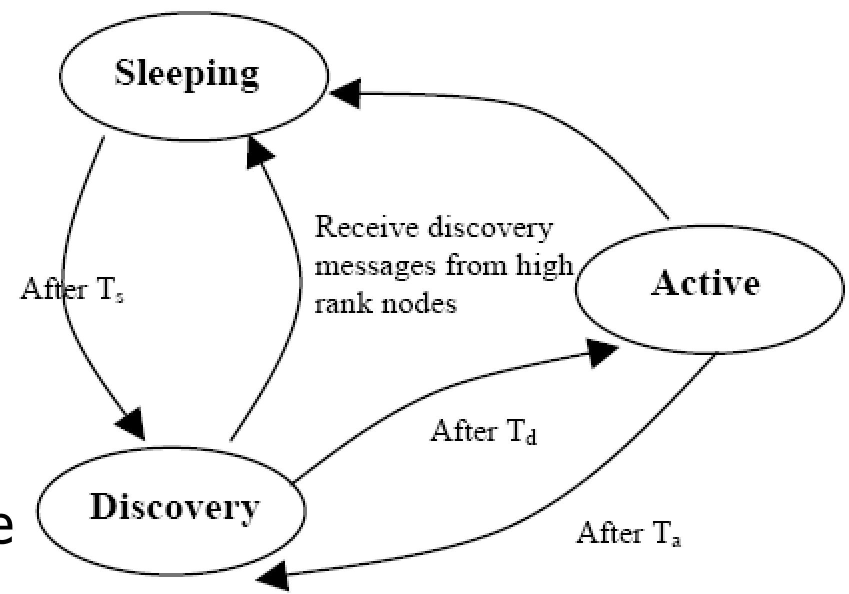


GAF States

- Three States
  - Discovery
  - Active
  - Sleep
- Discovery state is used for determining the neighbors in the grid.
- Nodes change states from sleeping to active in turn so that the load is balanced.
- Active reflecting participation in routing and sleep when the radio is turned off.
- As good as a normal Ad hoc in terms of latency and packet loss (saving energy)

GAF State Diagram

- Each node in the grid estimates its leaving time of grid and sends this to its neighbors.
- The sleeping neighbors adjust their sleeping time accordingly in order to keep the routing fidelity.
- Before the leaving time of the active node expires, sleeping nodes wake up and one of them becomes active.
- GAF strives to keep the network connected by keeping a representative node always in active mode for each region on its virtual grid.



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  - Are based on general network-flow modeling and protocols that strive for meeting some QoS requirements along with the routing function

Network Flow & QoS-aware Protocols

- Network Flow:
  - Maximize traffic flow between two nodes, respecting the capacities of the links
- QoS-aware protocols:
  - Consider end-to-end delay requirements while setting up paths

Network Flow & QoS-aware Protocols

- Maximum Lifetime Energy Routing
- Maximum Lifetime Data Gathering
- Minimum Cost Forwarding
- Sequential Assignment Routing
- Energy Aware QoS Routing Protocol
- SPEED

Maximum Lifetime Energy Routing

- Maximizes network lifetime by defining link cost as a function of:
  - Remaining energy
  - Required transmission energy
- Tries to find traffic distribution (Network flow problem)
- The least cost path is one with the highest residual energy among paths

Maximum Lifetime Data Gathering

- Maximizes the Data-gathering schedule
- Maximum Lifetime Data Aggregation
  - Data aggregation plus setting up maximum lifetime of routes
- Maximum Lifetime Data Routing
  - When data aggregation is not possible
- Computational Expensive (scalability)
  - Clustering MLDA

Minimum Cost Forwarding

- Aims at finding the minimum cost path in a large network, simple and scalable
- Cost function captures delay, throughput, and energy metrics from node to sink
  - Back-off based algorithm
- Finds optimal cost of all nodes to the sink by using only one message per node
- Does not require addressing or forwarding paths

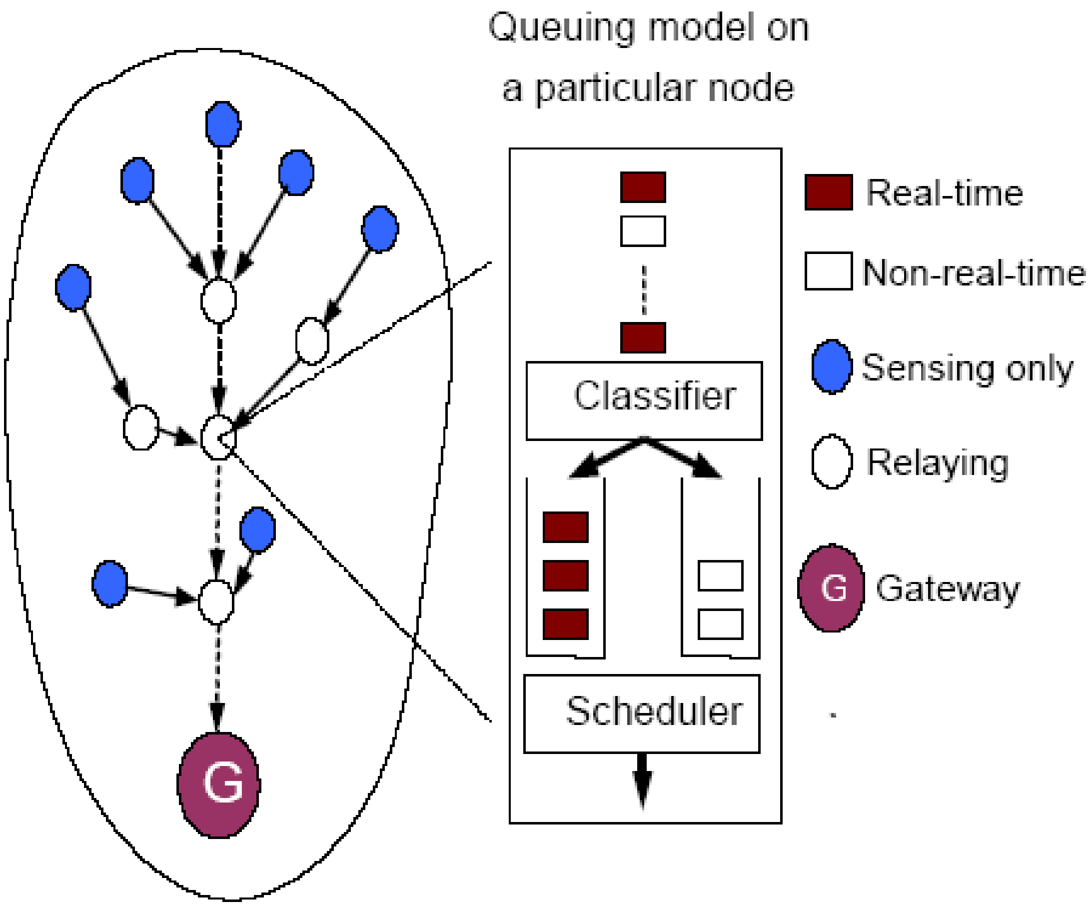
Sequential Assignment Routing

- Table-driven, multi-path protocol
- Creates trees rooted at immediate neighbors of the sink (multiple paths)
  - QoS metrics, energy resource, priority level of each packet
- Failure recoverable (done locally)
- High overhead to maintain tables and states at each sensor

Energy Aware QoS Routing Protocol

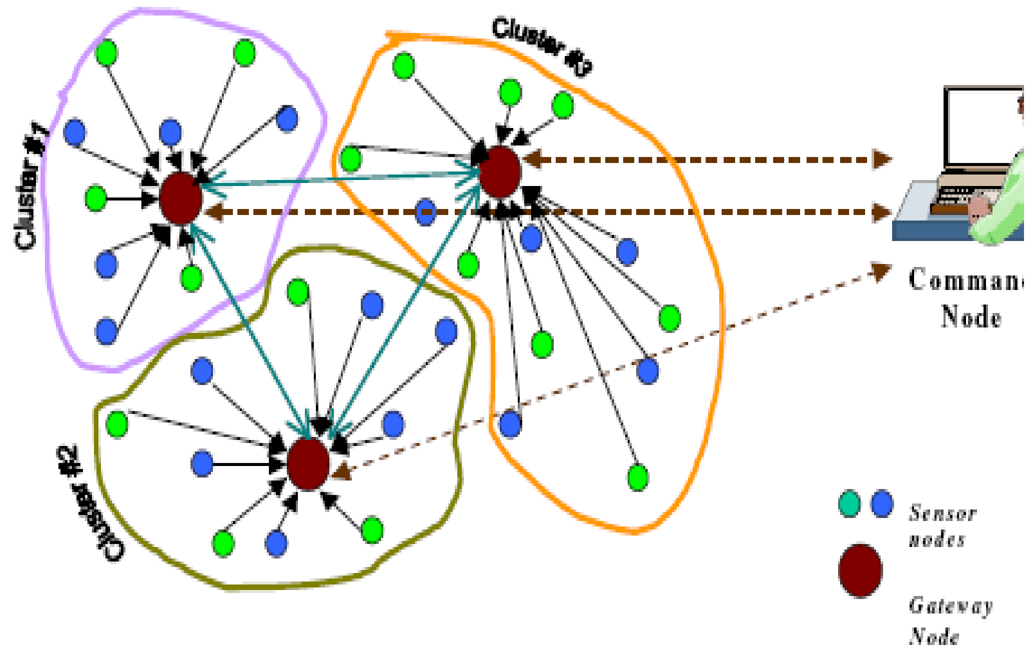
- Finds least cost and energy efficient paths that meet the end-to-end delay during connection
  - Energy reserve, transmission energy, error rate
- Class-based queuing model used to support best-effort and real-time traffic

Energy Aware QoS Routing Protocol



Energy Aware QoS Routing Protocol

- Basic settings
  - Base station
  - Gateways can communicate with each other
  - Sensor nodes in a cluster can only be accessed by the gateway managing the cluster
  - Focus on QoS routing in one cluster
  - Real-time & non-real-time traffic exist
    - Support timing constraints for RT
    - Improve throughput of non-RT traffic



SPEED

- The protocol requires each node to maintain information about its neighbors and uses geographic forwarding to find the paths.
- SPEED strive to ensure a certain speed for each packet in the network so that each application can estimate the end-to-end delay.
- SPEED can provide congestion avoidance when the network is congested.

Summary of Routing Protocols in Wireless Sensor Networks

Routing protocol	*Data-centric*	*Hierarchical*	*Location-based*	*QoS*	*Network-flow*	*Data aggregation*
SPIN	✓					✓
Directed Diffusion	✓					✓
Rumor Routing	✓					✓
Shah et al.	✓		✓			
GBR	✓					✓
CADR	✓					
COUGAR	✓					✓
ACQUIRE	✓					
Fe et al.					✓	
LEACH		✓				✓
TEEN&APTEEN	✓	✓				✓
PEGASIS		✓				✓
Younis et al.		✓	✓			
Subramanian et al.		✓				✓
MECN&SMECN			✓			
GAF		✓	✓			
GEAR			✓			
Chang et al.		✓			✓	
Kalpakis et al.			✓		✓	
Akkaya et al.		✓		✓		
SAR				✓		
SPEED			✓	✓		