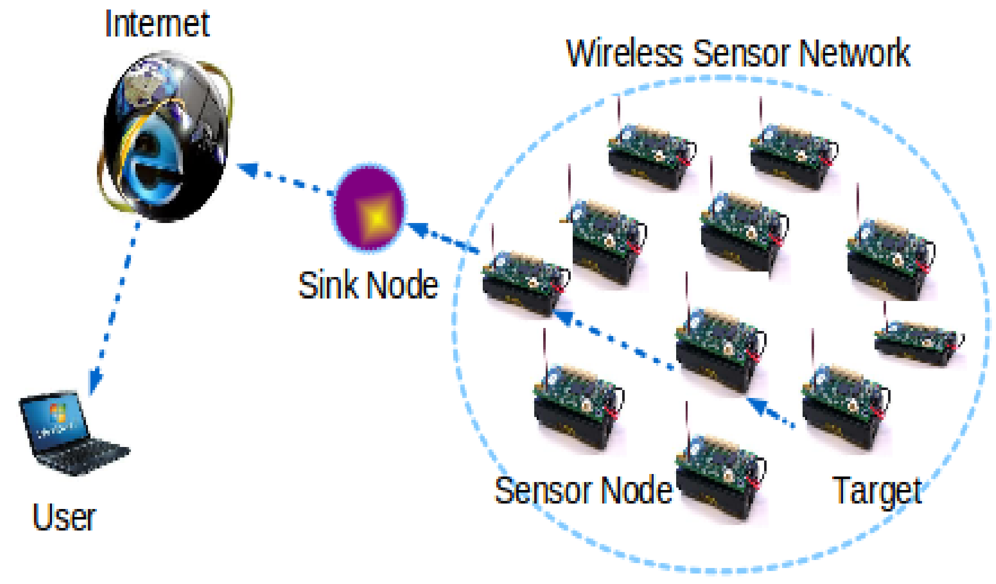
Mobile Computing

Wireless Sensor Networks (WSN)

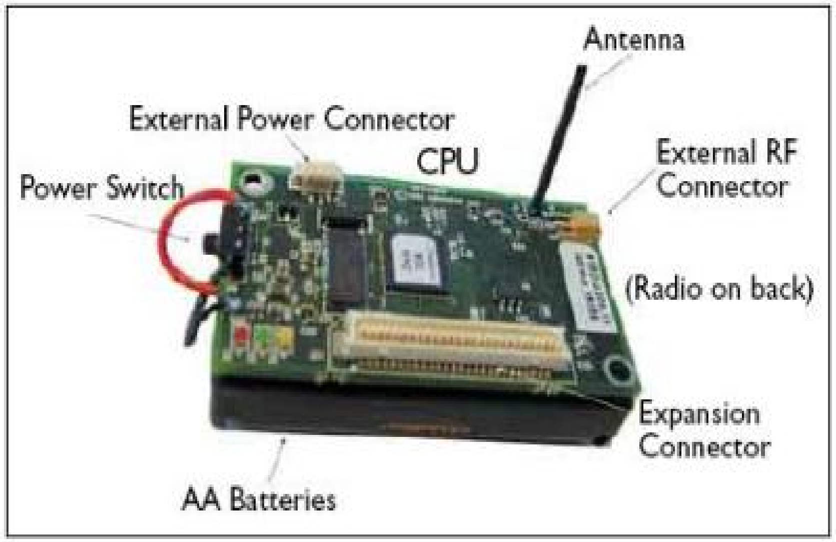
WSN Applications

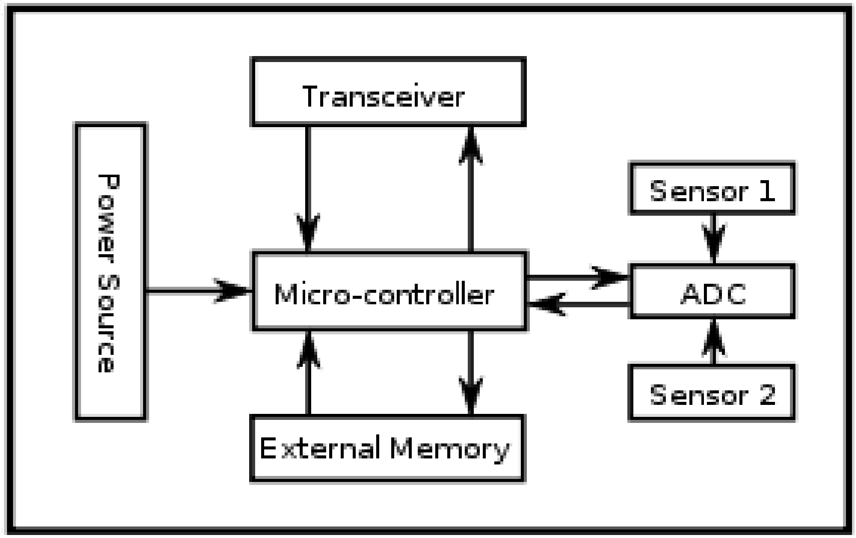
A WSN consists of hundreds or thousands of low cost and low power sensor nodes communicating together to achieve assigned tasks:

- Environmental/Habitat monitoring
- Acoustic detection
- Military surveillance
- Inventory tracking
- Medical monitoring
- Smart cities, homes,
- ....



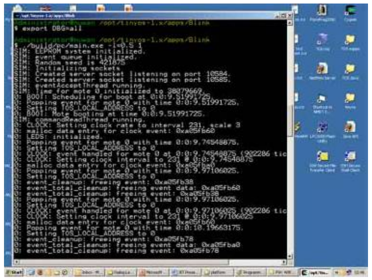
Mote (wireless sensor node)





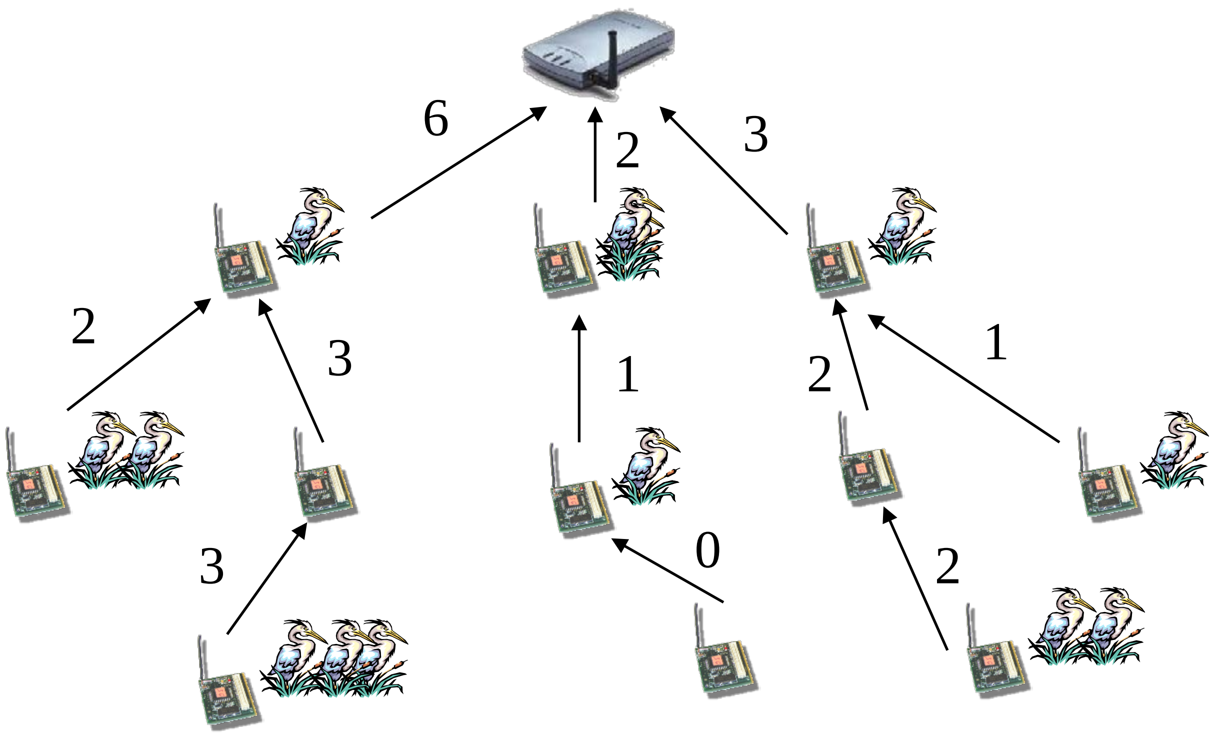
- A low cost and low power CPU
- One or more sensors
- A radio transceiver
- A battery (power module)

Different types of sensor nodes

mica	mica2	mica2dot	micaz
			
telos	telosb	rene2	pc
			

Data Centric in WSNs

- WSNs are "data centric" networks, i.e., the interest is in "*what* is the data?" rather than "*where* is the data?".
- Sensor nodes rely on their peers to pass sensed data to the data sink (sometimes with in-network processing).



TinyOS

- What is TinyOS
  - Open-source operating system, developed at UCBerkeley in collaboration with Intel Research
  - Written in nesC – network embedded systems C
  - Wireless embedded sensor networks
  - Component-based architecture
- Main Features –
  - Low complexity
  - Conserving power – sleep as frequently as possible
  - Application programs are compiled and linked with the TinyOS code into a single executable file, which is uploaded to sensor nodes for execution
    - No OS code pre-installed into sensor nodes

Query Types in Sensor Networks

There are three types of user queries:

- **Historical queries**: Used for analysis of historical data stored at the BS
  - e.g., “What was the temperature 2 hours back in the northwest quadrant?”
- **One time query**: Used to get a snapshot of the network
  - e.g., “What is the current temperature in the northwest quadrant?”
- **Periodical query**: Used to monitor the network over a time interval with respect to some parameters
  - e.g., “Report the temperature every 10 minutes for the next 2 hours”

Working Modes of Sensor Networks

- Periodical (Proactive Networks)

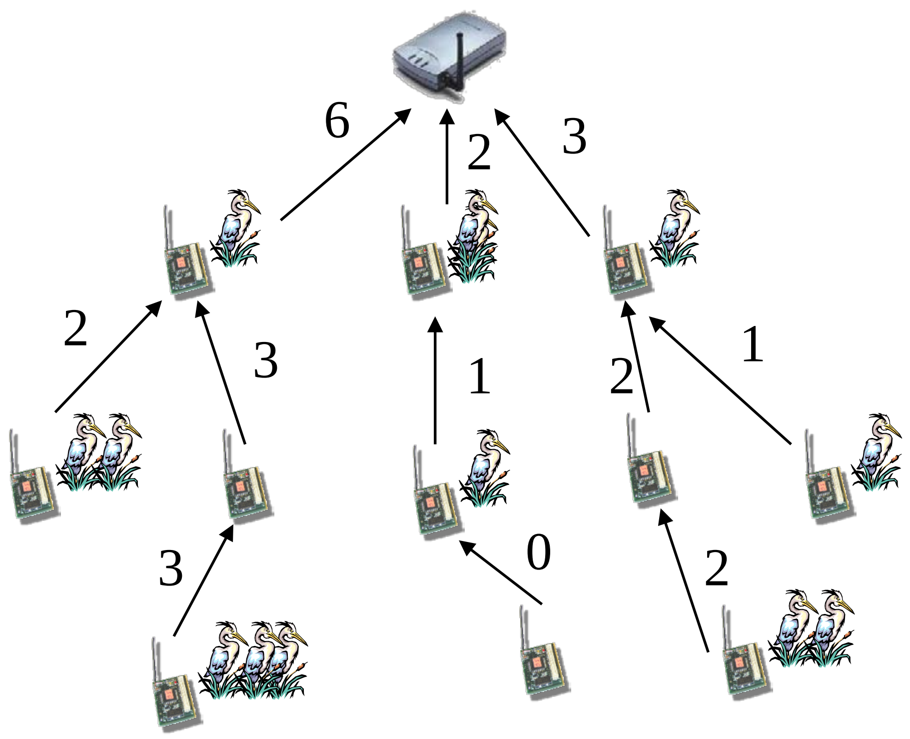
  The nodes in the network periodically switch on their sensors and transmitters, sense the environment and transmit the data of interest.

- Event Driven (Reactive Networks)

  In this scheme the nodes react immediately to sudden and drastic changes in the value of the sensed attribute.

Data Aggregation in Sensor Networks

- In traditional networks each node is identified by an IP address, which is used for routing. Sensor networks, in general, do not require routing between sensor nodes
- In most of sensor network applications, data can be aggregated (e.g., min, max, avg, etc) at internal node before passing it up further to the sink
- Data aggregation takes a tree structure



Routing in Sensor Networks – Flat Routing

- **Directed Diffusion**
  - The query (interest) is flooded throughout the network
  - Data is moved outwards to reach the query node
- **Sensor Protocols for Information via Negotiation** (SPIN)
  - Data ADV (advertisement) is broadcast throughout the network by the data source
  - Anybody interested in the data sends REQ to the data source
  - DATA is sent from the source to the requester
- None of Directed Diffusion or SPIN considers data aggregation

Directed Diffusion: interest and data matching

- Data-centric
  - A sensing task is described as an ***interest***, defined in a list of "attribute-value" pairs.
  - The ***data*** matching the attributes are returned by event source node in response to interests.
  - Example of interest: every 20 ms for the next 10 seconds, send me an estimates location of any four-legged animal in subregion R of the sensor field.

interest

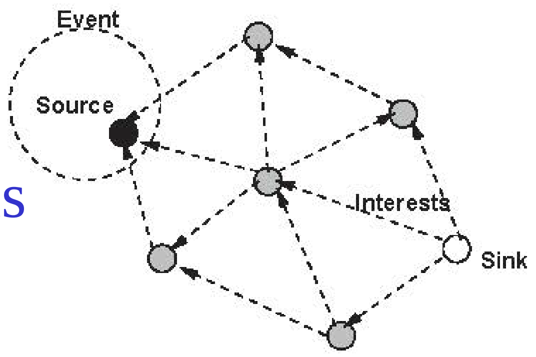
```
type = four-legged animal    // detect animal location
interval = 20 ms             // send back events every 20 ms
duration = 10 seconds        // .. for the next 10 seconds
rect = [-100, 100, 200, 400] // from sensors within rectangle
```

data

```
type = four-legged animal // type of animal seen
instance = elephant       // instance of this type
location = [125, 220]     // node location
intensity = 0.6           // signal amplitude measure
confidence = 0.85         // confidence in the match
timestamp = 01:20:40      // event generation time
```

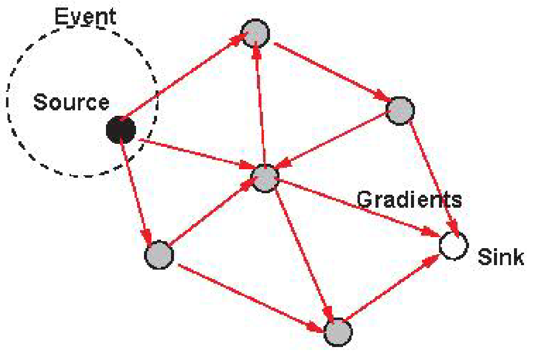
Directed Diffusion: interest broadcast

- Interest Propagation
  - The sink broadcasts an interest, which is flooded throughout the network.



(a) Interest propagation

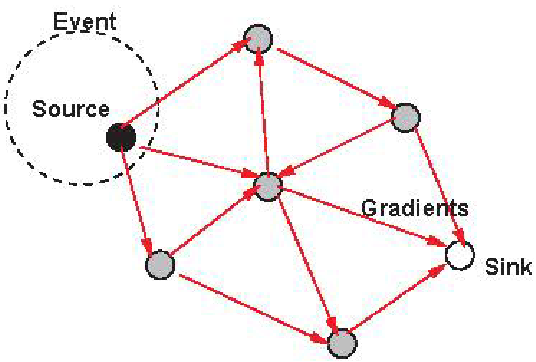
- Initial gradients set up
  - Each node sets gradients to upstream (towards the sink) neighbors for each received interest.
  - A node has several gradients (multiple path) towards the sink, one for each neighbor with a data rate.



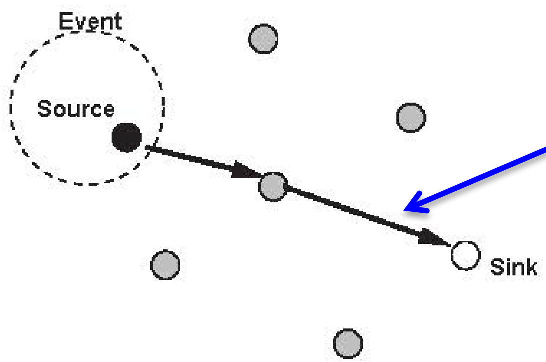
(b) Initial gradients set up

Directed Diffusion: data delivery

- Data Delivery
  - Data is diffused along the gradients, possibly along multiple paths.
  - Each node reinforces one particular neighbor in order to "draw down" higher data rate events, after start of sending back data.
  - A path is established from source to sink to transmit high data rate events.



(b) Initial gradients set up



(c) Data delivery along reinforced path

reinforced gradients

Sensor Protocols for Information via Negotiation (SPIN)

- Problems of flooding protocol.
  - Implosion: A node always broadcasts packets to its neighbors while the same packets may have been received by the neighbors from other nodes.
  - Overlapping: The nodes waste energy and bandwidth by sending packets multiple times.
  - Resource Blindness: Nodes do not change activities based on the energy availability.

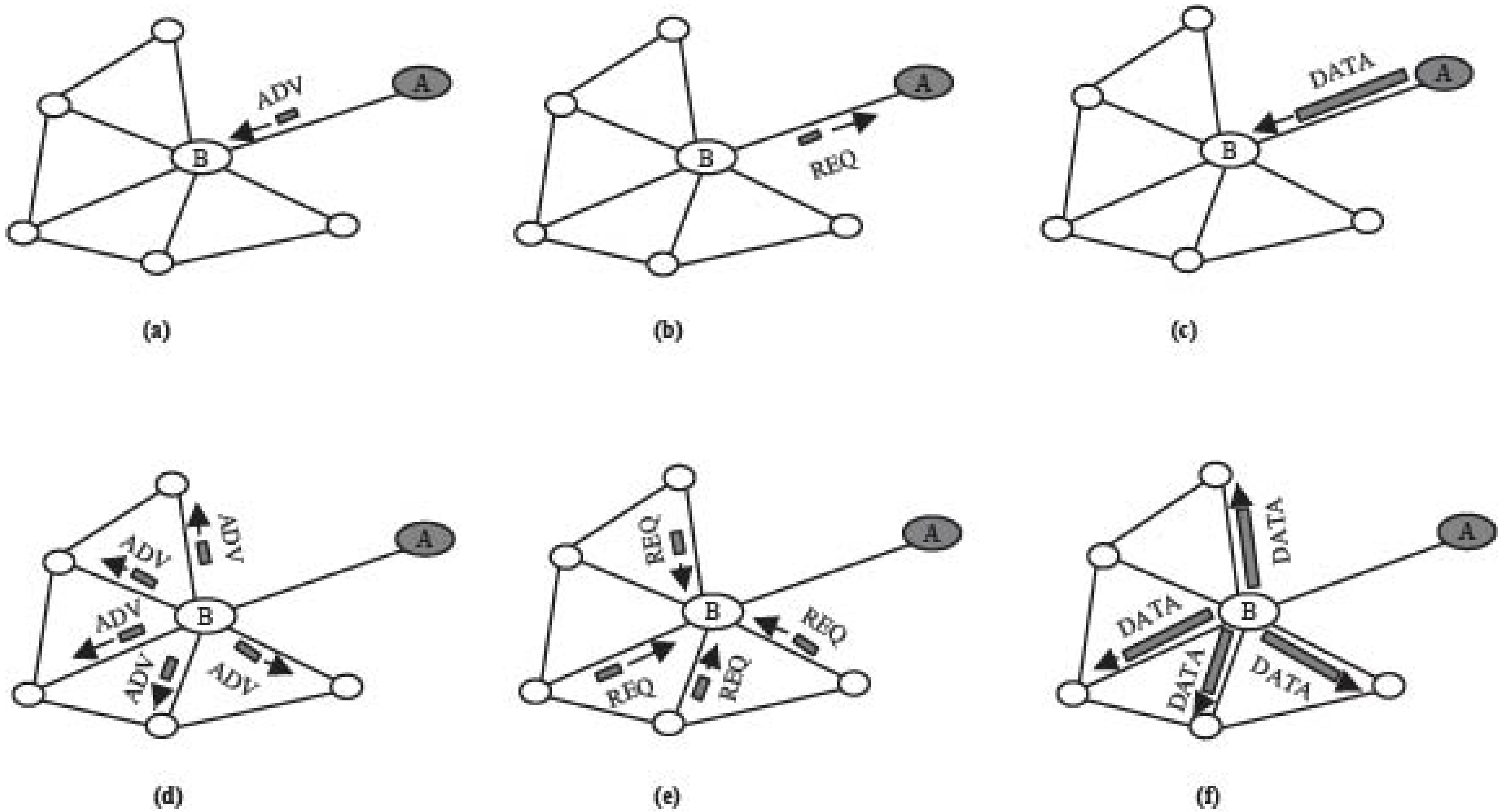
- SPIN addresses the deficiencies of classic flooding by *negotiation* and *resource-adaptation*.

Sensor Protocols for Information via Negotiation (SPIN)

- Basic ideas:
  - Negotiation: nodes communicate with each other about the data they have and the data still in need, via ADV-REQ messages.
    - ADV (data advertisement)
    - REQ (request for data)
  - Resource-adaptation: change activities based on energy availability.

SPIN: ADV-REQ-Data

- SPIN-1: a 3-stage handshake protocol.



SPIN: Energy Adaptation

- SPIN-2: SPIN-1 with a low-energy threshold.
  - When energy is plentiful, SPIN-2 acts as SPIN-1 protocol
  - A node will only participate in a stage of the protocol if it believes that it can complete all the other stages of the protocol without going below the low-energy threshold.

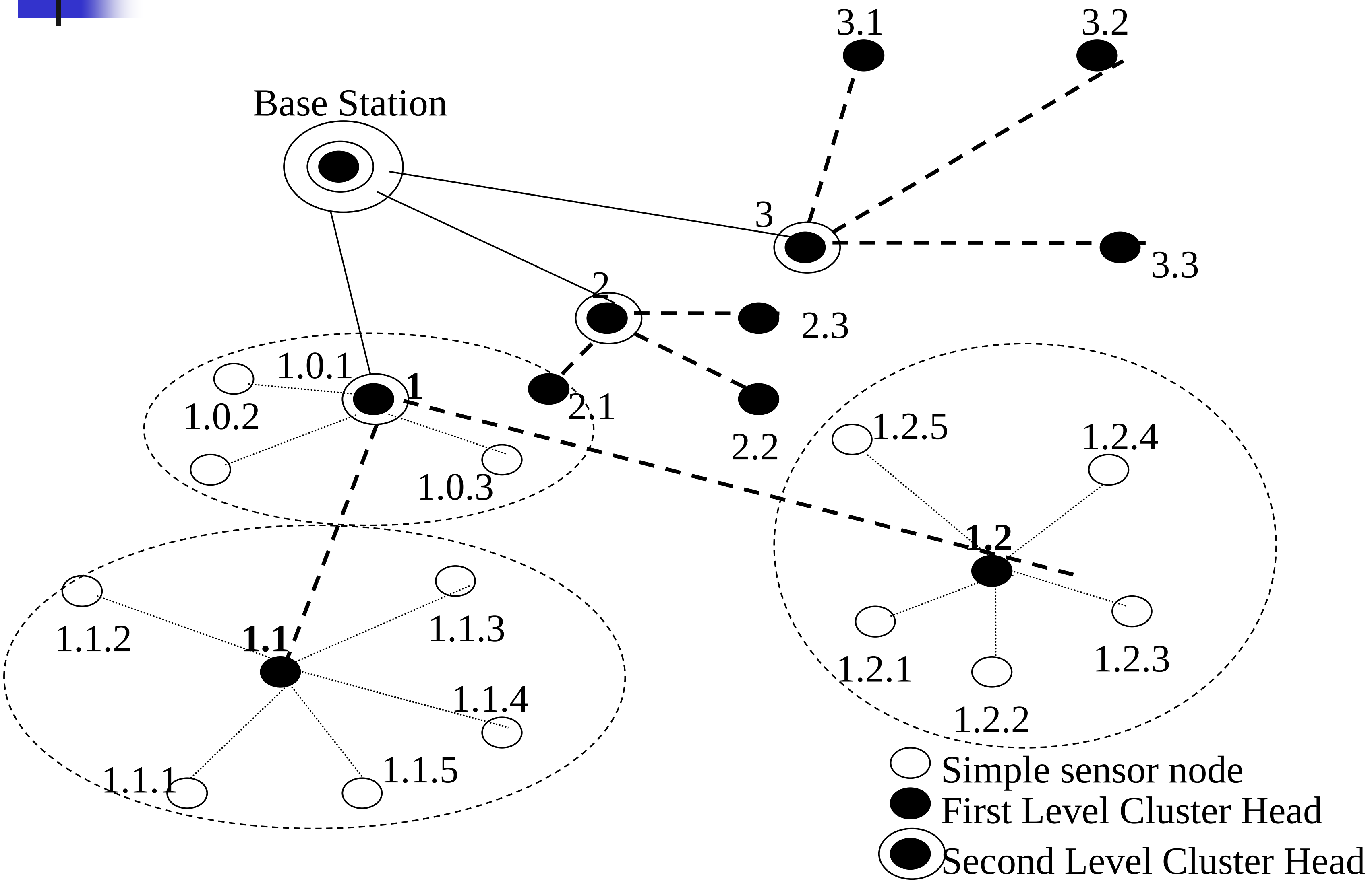
Hierarchical Routing in Sensor Networks

- Hierarchical clustering schemes are the most suitable for large scale wireless sensor networks.

- The network consists of a set of cluster heads (CHs) through which sensor nodes transmit data to (or receive commands from) the sink.

- CHs may have higher power than sensor nodes, resulting in asymmetric communication links.

Hierarchical Routing



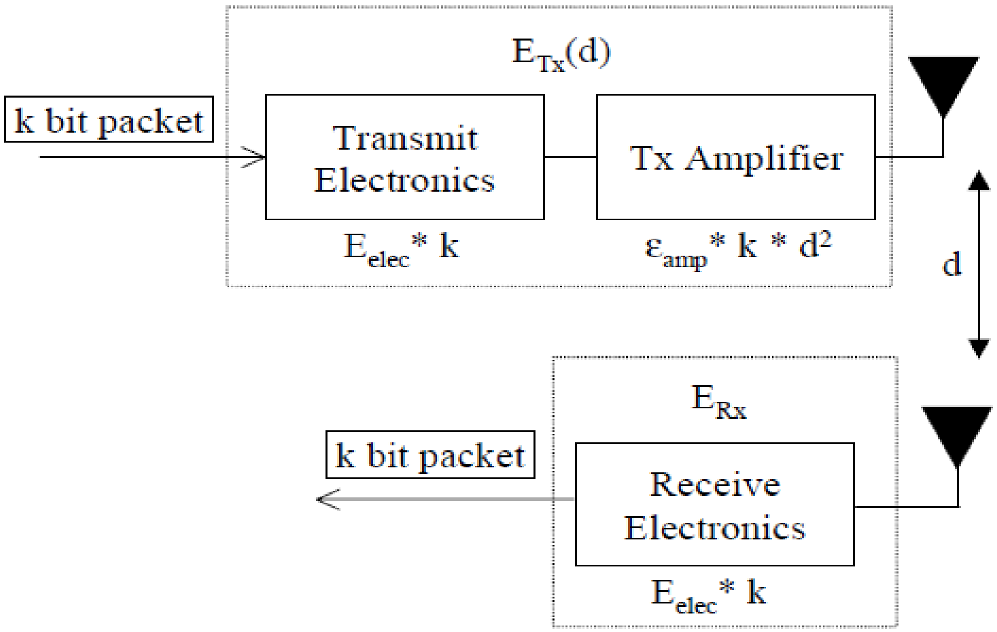
Cluster-Based Routing Protocol

- Cluster members send the data to the cluster head (CH), usually in 1-hop
- The CH routes the data to the destination (base-station)
- Not suitable for a highly mobile environment, as a lot of HELLO messages are needed to maintain the clusters (and the election of CH)

LEACH: Low-Energy Adaptive Clustering Hierarchy

- LEACH is a family of protocols containing both distributed and centralized schemes and using proactive updates
- The main features include:
  - Localized coordination and control for cluster set-up and operation
  - Randomized rotation of local cluster heads (CHs) to evenly distribute the energy load among sensors
  - Local data compression (aggregation) to reduce communication cost
  - Use of a TDMA/CDMA MAC scheme to reduce inter and intra-cluster collisions

Energy Consumption for Transmitting and Receiving over a Radio Set



Energy for transmitting a *k*-bit packet over distance *d*:

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$

$$E_{Tx}(k,d) = E_{elec} * k + \epsilon_{amp} * k * d^2$$

Energy for receive *k*-bits:

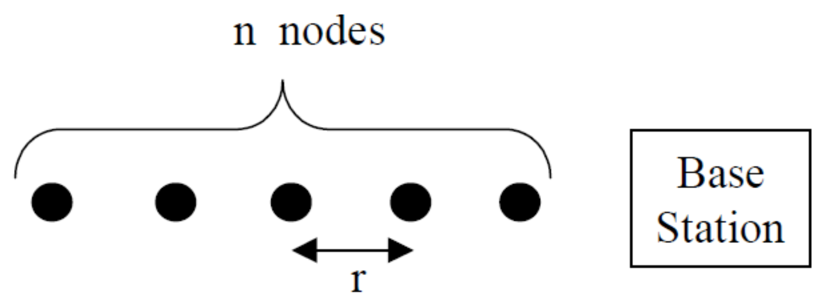
$$E_{Rx}(k) = E_{Rx-elec}(k)$$

$$E_{Rx}(k) = E_{elec} * k$$

Operation	Energy Dissipated
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec} = E_{Rx-elec} = E_{elec}$)	50 nJ/bit
Transmit Amplifier (ϵ_{amp})	100 pJ/bit/m^2

Energy Consumption for Transmitting and Receiving over a Network

Suppose a node is *n* hops away from the BS:



Energy required for a direct transmission (k-bits) over distance *n*r*:

$$
\begin{aligned}
E_{direct} &= E_{Tx}(k, d = n * r) \\
&= E_{elec} * k + \epsilon_{amp} * k * (nr)^2 \\
&= k(E_{elec} + \epsilon_{amp} n^2 r^2)
\end{aligned}
$$

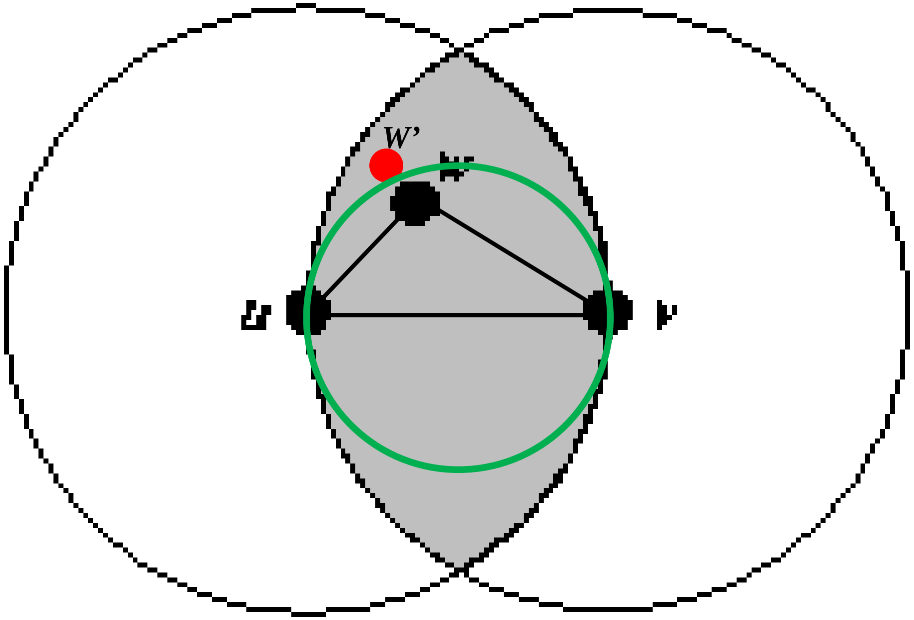
Energy required for transmission in *n* hops (each with distance *r*):

$$
\begin{aligned}
E_{MTE} &= n * E_{Tx}(k, d = r) + (n-1) * E_{Rx}(k) \\
&= n(E_{elec} * k + \epsilon_{amp} * k * r^2) + (n-1) * E_{elec} * k \\
&= k((2n-1)E_{elec} + \epsilon_{amp} n r^2)
\end{aligned}
$$

Multi-hop short distance transmissions cost less energy than a single long distance transmission

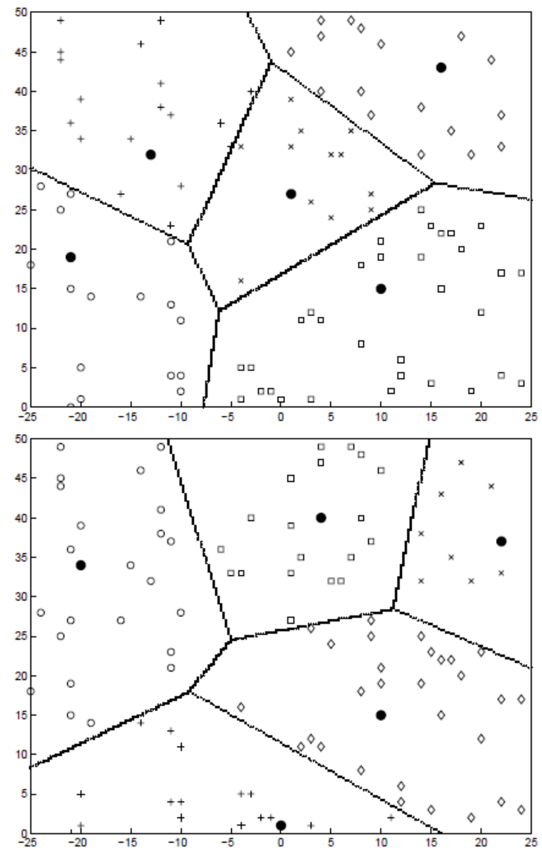
When should take multiple hops for energy saving?

- Whenever $d(u,w)^2 + d(w,v)^2 < d(u,v)^2$, it always cost less energy to let intermediate node w to relay the message
- Node w is the node falling into the green circle with diameter of $d(u,v)$



LEACH: Adaptive Clustering Hierarchy

- Nodes organize themselves into local clusters, with one node acting as the local CH
- CHs compress (aggregate) data, reducing energy cost for further data transmission
- With fixed CH, if it runs out of battery, the useful lifetime of the cluster also ends
- LEACH enhances system lifetime by randomly rotating the CH among sensor nodes



LEACH clustering & data transmission

- Periodic process
- Four phases per round:
  - Advertisement
    - CH self-election
  - Set-up
    - Non-CH nodes inform membership
  - Schedule transmission
    - CHs create transmission schedule
  - Data transmission
    - TDMA/CDMA

LEACH: Cluster-Head self-election

- Each node n independently calculates threshold $T(n)$ at each round

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

P = Desired percentage of becoming CH ($P \in [0,1]$, given in priori)
r = Number of round
G = Set of nodes that have not been the CH in last $1/P$ rounds

- Node n chooses a random number p in [0, 1]. If $p < T(n)$, this node becomes a CH.
  - Each node will become a CH at some point within $1/P$ rounds
  - As increase of r, the chance of becoming CH increases
    - When $r = 1/P - 1$, $T(n) = 1$, the node surely becomes CH
  - A node with a larger P, the higher chance to become CH
    - Nodes have different P, depending on how much they want to be CH

LEACH: cluster formation

- Advertisement Phase
  - The node that has elected itself as the CH for the current round broadcasts an advertisement message to its neighboring nodes (1-hop)

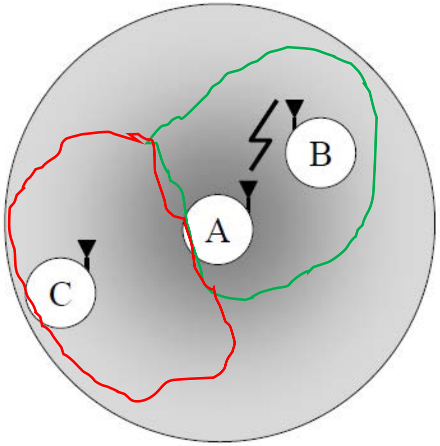
- Set-Up Phase
  - Each non-CH node chooses the CH with *the strongest signal strength of the advertisement* to join for this round (ties break randomly)
  - Each non-CH node informs the CH the membership by transmitting a message using a CSMA MAC protocol, after deciding which CH it joins to

LEACH: Scheduling of data transmissions

- TDMA Schedule by CH
  - The CH makes a TDMA schedule, specifying when each node can transmit
  - The CH broadcasts this schedule to all nodes in its cluster
- Data Transmission
  - Each non-CH node sends its data in the timeslot allocated it, and turns off its radio when transmission finishes
  - When all the data has been received, the CH compresses the data into a single packet, and sends it towards the BS
- A new round begins after a certain period of time
  - Repeat the CH election, cluster setup, transmit schedule,…

LEACH: Parallel transmissions of multiple clusters

- In multiple clusters, transmission in one cluster will interfere nearby clusters
  - node A's transmission to node B conflicts any transmission to node C.



- Solution: each CH communicates with its members using a different CDMA code.
  - when a node decides to become a CH, it chooses a CDMA code randomly from a list of spreading codes, and informs all member nodes of the code.

Hierarchical Vs Flat topologies

Hierarchical	Flat
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 multi-hop path aggregates incoming data from neighbors
Simple but non-optimal 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 that have data for transmission
Lower latency as multi-hop network formed by cluster-heads is always available	Longer latency in waking up intermediate nodes and setting up the multi-hop path
Energy dissipation is uniform	Energy dissipation depends on traffic patterns
Energy dissipation can not be controlled	Energy dissipation adapts to traffic pattern
Fair channel allocation	Fairness not guaranteed

Summary

- Data centric of WSN
  - Data queries in WSNs
  - Data aggregation in WSNs
- Flat Routing Structure
  - Directed Diffusion
  - Sensor Protocols for Information via Negotiation (SPIN)
- Hierarchical Routing (Cluster-Based Routing Protocol)
  - Low-Energy Adaptive Clustering Hierarchy (LEACH)
    - Energy efficient routing in WSNs
    - Distributed clustering and rotation of CH
    - CDMA/TDMA for parallel data transmission among clusters

Exercise

- List three differences between wireless sensor networks and the Mesh networks.
- Design a routing algorithm that the data sink can collect data from all n sensor nodes and the total energy cost for data transmission is minimized (data aggregation is used).
- In LEACH protocol, each node n calculates a threshold value $T(n)$ independently from others, and chooses a random number p between [0, 1]:

  If $p < T(n)$, node n declares itself as a CH.

  Prove each node in a cluster has the equal chance to become a CH in each round.