II.3 Low Energy Clustering & Routing in Sensor Networks

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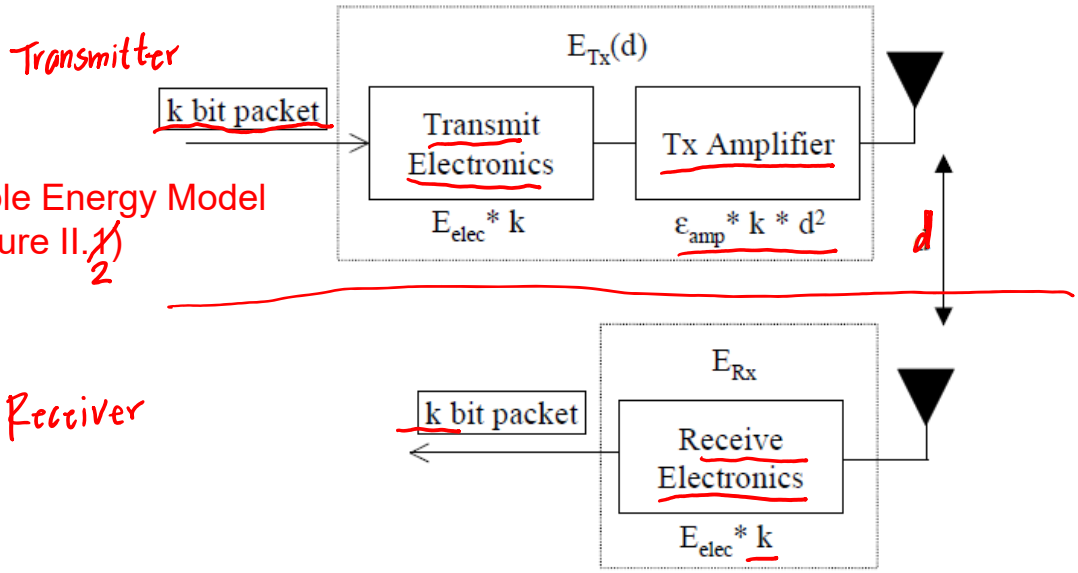
Outline of Lecture

- Motivation
  - Routing protocol: determines the path to transfer data from a sensor node to the sink
- WSN Routing and LEACH (Low Energy Adaptive Clustering Hierarchy) Protocol

WSN Routing and LEACH (Low Energy Adaptive Clustering Hierarchy) Protocol

Recap: Simple Energy Model (Lecture II.1/2)



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

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

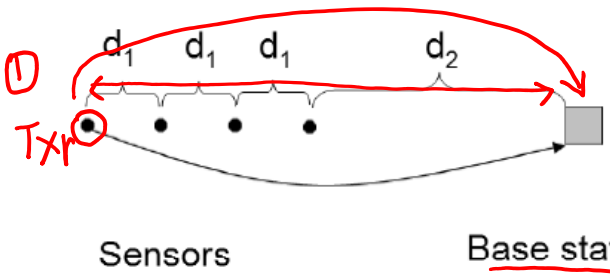
energy loss due to channel txn

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

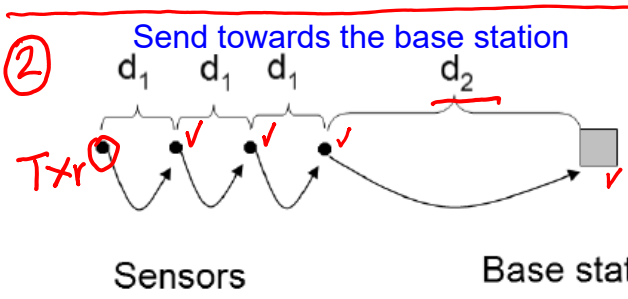
$$E_{Rx}(k) = E_{elec} * k$$

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

WSN Routing: ① Direct Transmission & ② Minimum Transmission Energy (MTE)



(a) Direct transmission



(b) Minimum transmission energy

- The amount of energy used in figure (a) can be approximated by this formula:

$$ETX \sim \varepsilon_{amp}\, k(3d_1 + d_2)^2$$

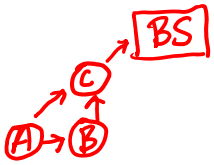
- whereas the amount of energy used in figure (b) can be approximated by this formula:

$$ETX \sim \varepsilon_{amp}\, k(3d_1^2 + d_2^2)$$

WSN Routing Protocols

- Minimum Transmission Energy (MTE) routing: neighbour selection
  - For 3 nodes A, B and C, A would transmit to node C through B

$$\text{iff } ETX(d=d_{AB}) + ETX(d=d_{BC}) < ETX(d=d_{AC})$$



[ETX = total transmit energy]

  - Assumes that position of each node wrt base station is known

- Question: is MTE routing always more efficient than Direct Transmission?
- Answer: No!
  - We have only considered transmitter amplifier energy and have neglected energy dissipation in the radio (tx and rx) electronics
  - Hence, answer depends on the energy cost of transmitter amplifier ε_{amp} wrt to radio electronics E_{elec} (read the paper)

WSN Routing Protocols

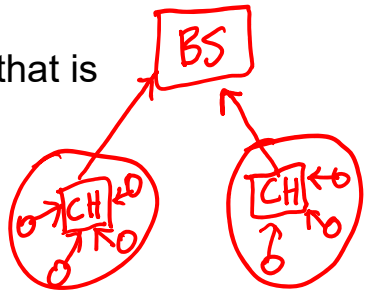
- Minimum Transmission Energy (MTE) routing: neighbour selection
  - For 3 nodes A, B and C, A would transmit to node C through B

    iff $ETX(d=d_{AB}) + ETX(d=d_{BC}) < ETX(d=d_{AC})$

    [ETX = total transmit energy]

  - Assumes that position of each node wrt base station is known
  - Only consider transmitter energy, neglects energy dissipation of the receivers (amplifier term)

- Static Clustering (fixed)
  - Nodes send data to an appointed cluster head that is well-distributed
  - Cluster head forwards data to base station
  - Cluster head has to be high energy node
  - Fixed infrastructure



Introduction to LEACH

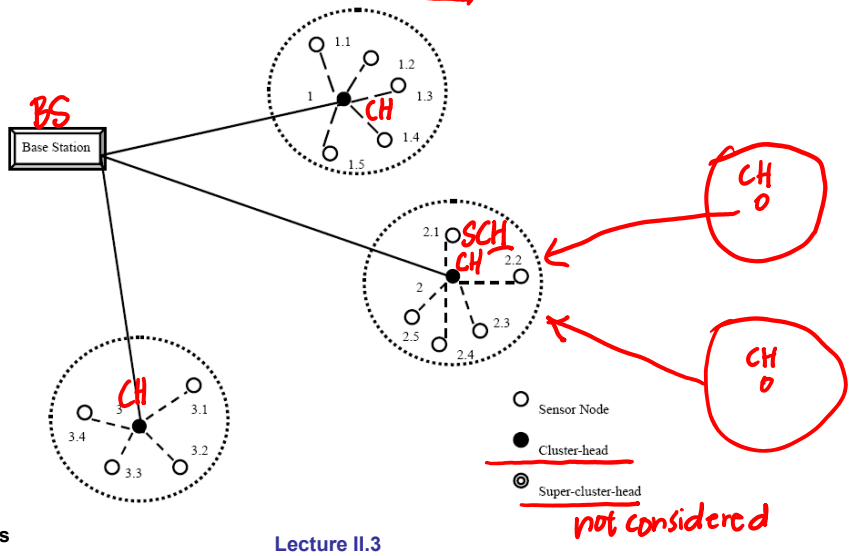
- The main vulnerability of a wireless sensor network is its limited energy supply
  - a node in the network is no longer useful when its battery dies
- We shall study an energy efficient routing protocol that extends the lifetime of the sensor network compared to the routing methods described earlier

References

- [Heinzelman00] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-Efficient Communication Protocol for Wireless Microsensor Networks. In The 33rd Hawaiian International Conference on Systems Sciences (HICSS), Maui, HA, January 2000.
- [Heinzelman02] An Application-Specific Protocol Architecture for Wireless Microsensor Networks by W. Heinzelman, A.P. Chandrakasan and H. Balakrishnan, IEEE Transactions on Wireless Communications, Vol. 1, No. 4, Oct 2002.

LEACH Overview - 1

- The job of the cluster head is to collect data from their surrounding nodes and pass it on to the base station
- Cluster head role is rotated to share energy load



LEACH Overview - 2

- Nodes organize themselves into local clusters, with one node as cluster head
- All non-cluster head nodes transmit data to their cluster head
- Cluster head receives this data and performs signal processing functions on the data and transmits data to the remote base station

data aggregation: avg, variance, sum ...

reduce amount of data sent to BS

LEACH Protocol Assumptions

- Assumptions
  - All nodes can transmit with enough power to reach the base station if needed
  - Each node has computational power to support different MAC protocols and data aggregation/fusion operations
  - Nodes always have data to send
  - Nodes located close to each other have correlated data

LEACH - Two Phases

- The LEACH network has two phases:
  - The Set-Up Phase
    - Cluster Heads (CHs) are chosen
    - Nodes join clusters
  - The Steady-State Phase
    - The cluster heads and clusters are maintained
    - Data is transmitted from nodes to CHs
    - CHs may do some processing and data aggregation before sending the data to the base station (BS)

LEACH: Set-Up Phase

- LEACH is *dynamic* because the job of cluster head rotates among different nodes
- Cluster Head Selection
  - Each sensor node elects itself to be cluster head with a certain probability at the beginning of a round
  - Nodes that have not already been cluster heads recently may become cluster heads

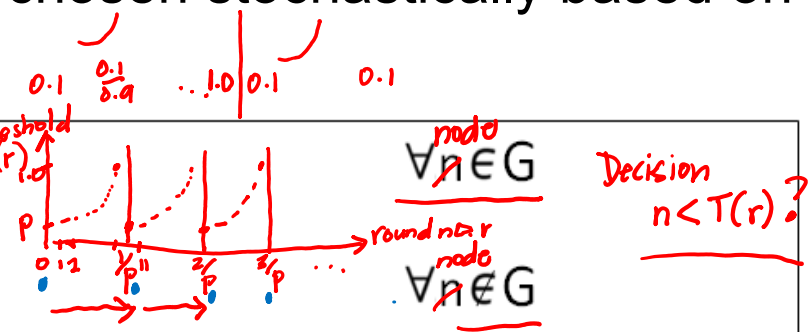
Decision to be Cluster Head

- Cluster head is chosen stochastically based on this algorithm:

$$T(n) = \frac{P}{1 - P \times (r \bmod P^{-1})}$$

$$T(n) = 0$$

Where n is a random number between 0 and 1
P is the cluster-head probability and
G is the set of nodes that weren't cluster-heads the previous rounds



P = desired percentage of cluster heads = no. of CH/no. of nodes = k/N

Decision to be Cluster Head

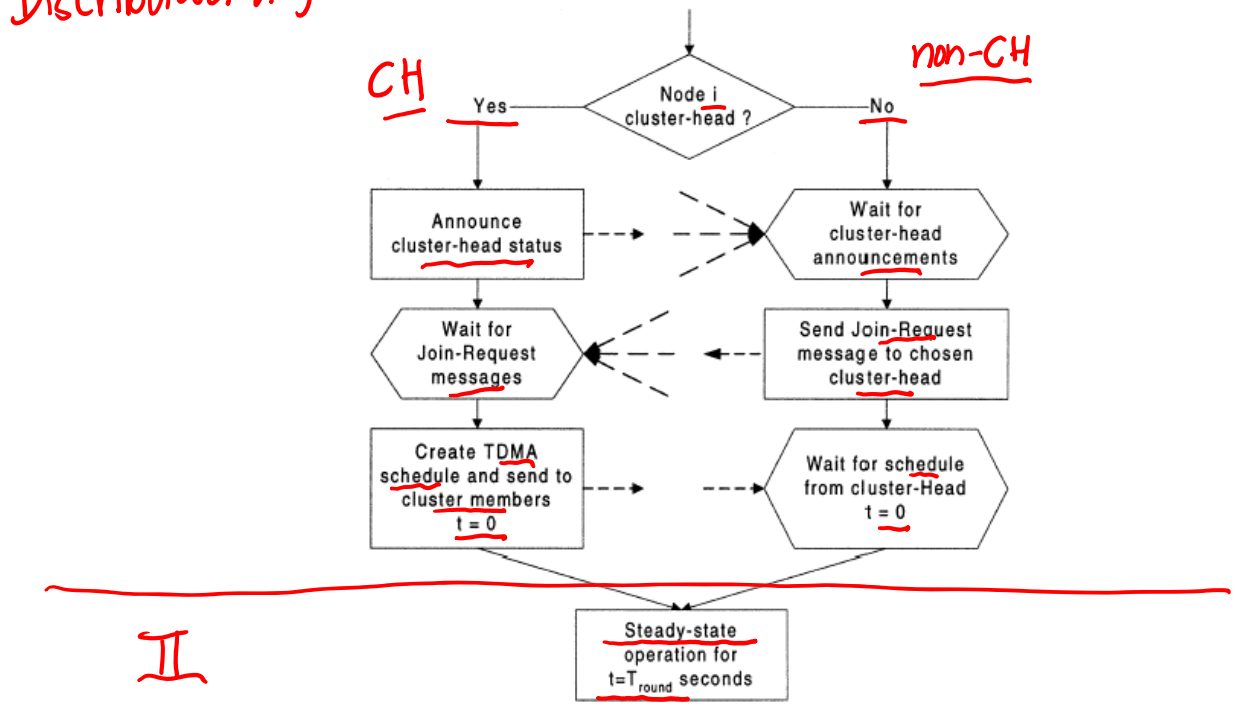
- If n < T(r), then that node becomes a cluster head
- Each node will be cluster head once in an interval of 1/P rounds
- Nodes that have already become cluster head cannot be a CH again in the current interval of 1/P rounds
- After each round, the probability to be cluster head for remaining nodes increases

LEACH Set-Up Phase contd…

- Cluster Formation
  - Each cluster head node broadcasts an advertisement message (ADV) using CSMA MAC Protocol
    - The message consists of the nodes' ID and a header that distinguishes it as an ADV message
  - Each non-cluster head node determines its cluster/cluster head that requires minimum communication energy
    - Largest signal strength, minimum transmit energy for communication
  - Each node transmits a join-request message (REQ) using CSMA MAC Protocol
    - The message consists of node's ID and cluster head ID
  - Each cluster head node sets up a TDMA schedule and transmits it
    - This ensures that there is no collision in data messages, radio components can be turned off at all times except during transmit time

Set-Up Phase complete

Flowchart for Set-Up Phase

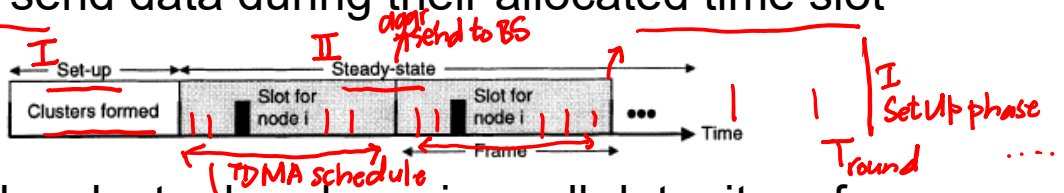


II. LEACH: Steady-State Phase

- Cluster head waits to receive data from cluster members
- Non-cluster heads will turn off radios when not sending while cluster head will have its radio turned on the whole round
- Cluster members will send data according to a TDMA schedule and DSSS (direct-sequence spread spectrum) code to minimize inter-cluster interference
- Members will use minimum energy to communicate with its cluster head based on the advertisement strength
- Cluster head aggregates data and sends to base station (BS)

LEACH Steady-State Phase contd…

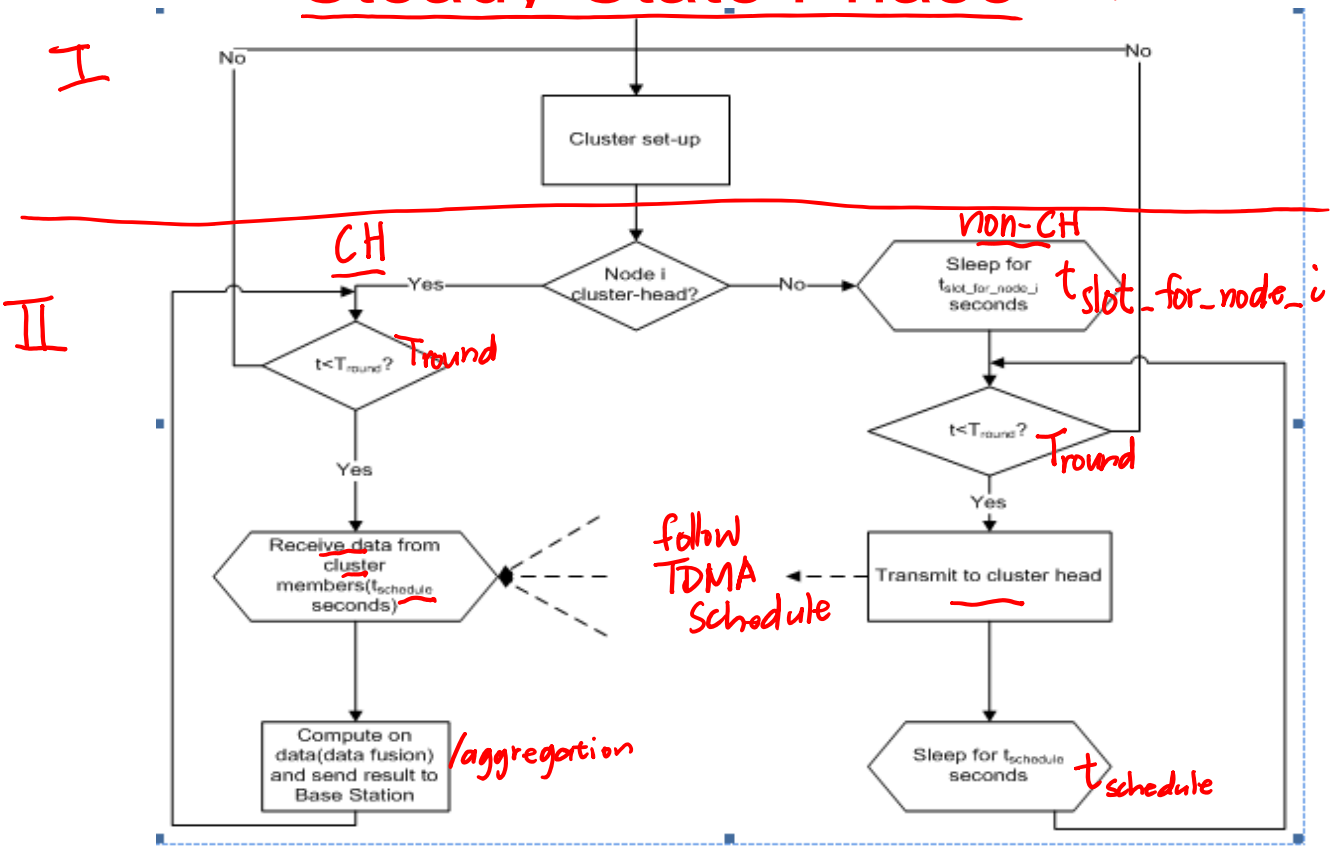
- Nodes send data during their allocated time slot



- Once the cluster head receives all data, it performs data aggregation
- Resulting data is sent from cluster head to BS (a high energy transmission)
- Transmit using fixed spreading code
- Cluster head senses the channel before transmission (CSMA)

Steady-State Phase complete

Flowchart for Steady-State Phase (II)



LEACH-C:BS Cluster Formation (LEACH Centralized)

- Uses a central control algorithm to form clusters
  - During set-up phase, each node sends its location and energy level to base station (BS)
  - BS tries to form good clusters and evenly distribute energy load
    - nodes that have below-average energy cannot be CH
  - Use simulated annealing algorithm to find *k*-optimal clusters (NP-hard)
    - minimize amount of energy for non-CH nodes to transmit data to the CH by minimizing the total sum of squared distances between all the non-CH nodes and the closest CH
  - BS broadcasts cluster head ID that each node belongs to
  - Non-CH determines TDMA slot for data transmission and goes to sleep until that time
  - Steady-state phase same as normal LEACH

Energy Dissipation

- Amount of energy dissipated by data transfer:
  [*note*: this energy model was covered in Lecture II.1]

The energy being dissipated to run the transmitter: $E_{elec} = 50$ nJ/bit
The energy dissipation of the transmission amplifier: $\varepsilon_{amp} = 100$ pJ/bit/m2

Transmission costs: $E_{Tx}(k,d) = E_{elec}\, k + \varepsilon_{amp}\, kd^{\lambda}$
Receiving costs: $E_{Rx}(k) = E_{elec}\, k$

Where k is the length of the message in bits
d is distance between nodes, and
λ represents the path-loss exponent ($\lambda \geq 2$).

Results: Limited Energy Simulations

Each node: 2J at start

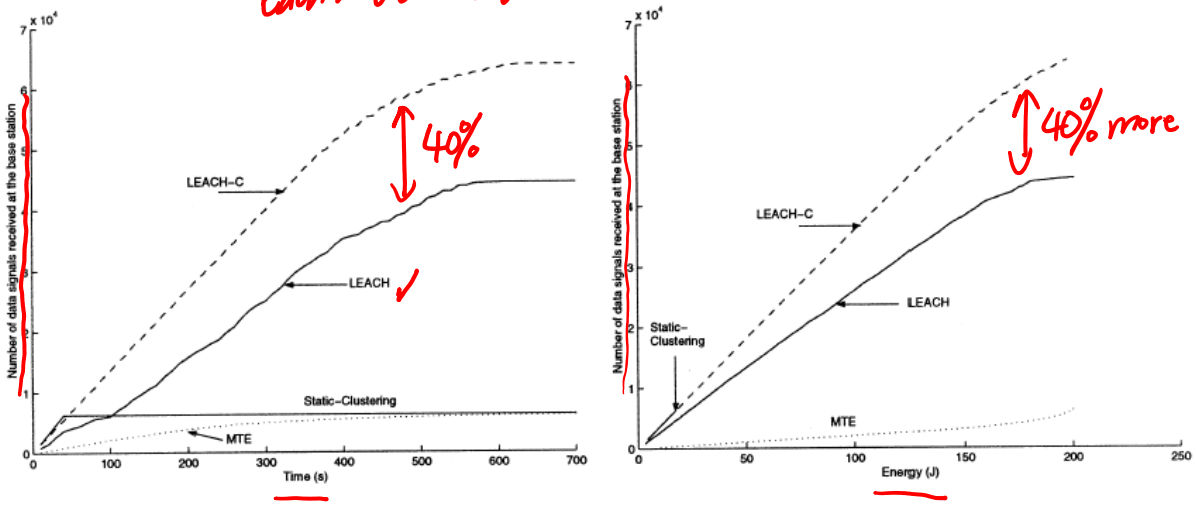


Fig.7 HW2 paper

(a) Total amount of data received at the BS over time.
(b) Total amount of data received at the BS per given amount of energy.

- LEACH distributes more data per unit energy than MTE
- LEACH-C delivers 40% more data per unit energy than LEACH

Results contd…

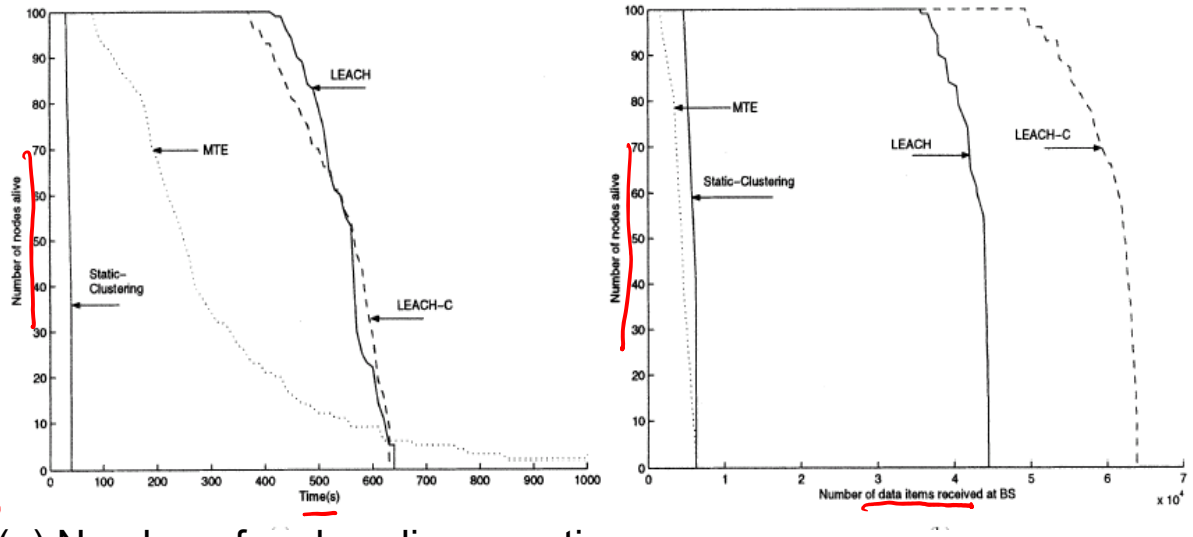


Fig.8 Hoz paper

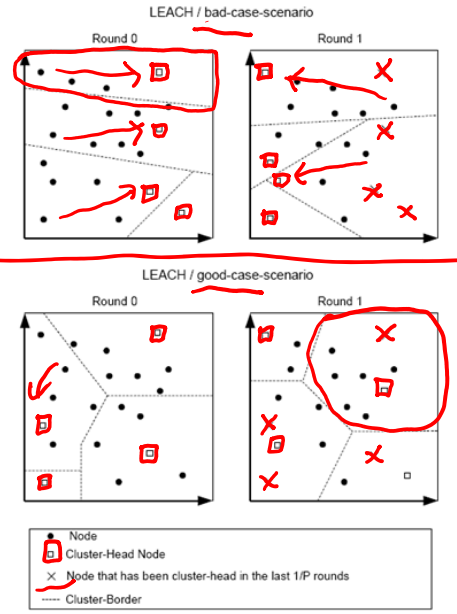
(a) Number of nodes alive over time.
(b) Number of nodes alive per amount of data sent to the BS.

- LEACH can deliver 10 times the amount of effective data to BS as MTE for the same number of node deaths
- Benefits of rotating cluster heads is seen

Shortcomings of LEACH

Distributed case

- Due to random manner in which clusters are formed, some clusters may be bad



- While neither of these shows the optimum scenario, the second is better because the cluster-heads are spaced out and the network is properly sectioned

LEACH: Discussion

- Advantages
  - LEACH helps to balance the load in the network as compared to direct transmission
  - LEACH is completely distributed, requiring no control information from the base station
  - Nodes do not need global topology information
- Disadvantages
  - Nodes must have data to send in the allotted time
  - Bad clusters can be formed due to the random nature of cluster formation
- Many researchers have proposed variations and enhancements to LEACH

Questions?