II.3 Low Energy Clustering & Routing in Sensor Networks

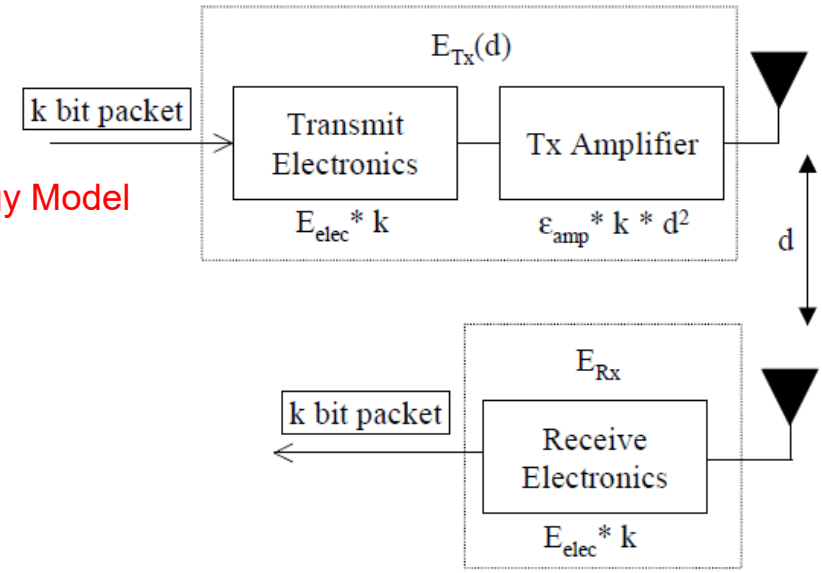
Assoc Prof THAM Chen Khong
E-mail: eletck@nus.edu.sg

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)



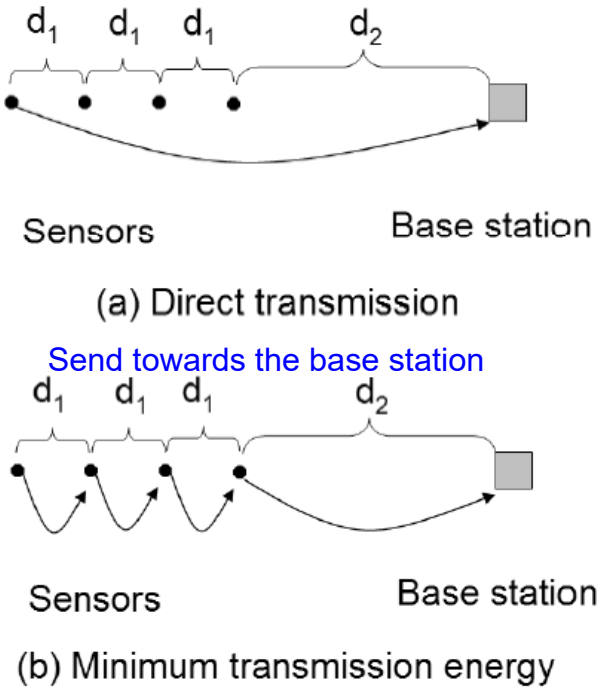
$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$
$$E_{Tx}(k,d) = E_{elec} * k + \epsilon_{amp} * k * d^2$$

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: Direct Transmission & Minimum Transmission Energy (MTE)



- 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

    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

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    [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

- Static Clustering
  - 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

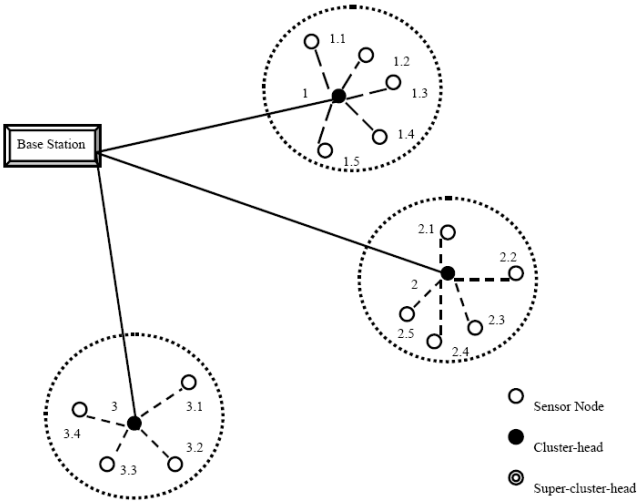
- The main vulnerability of a wireless sensor network is its limited energy supply
  - a node in the network is no longer useful when its battery dies
- We shall study an energy efficient routing protocol that extends the lifetime of the sensor network compared to the routing methods described earlier

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

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 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:

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

$$T(n) = 0 \qquad \forall n \notin G$$

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

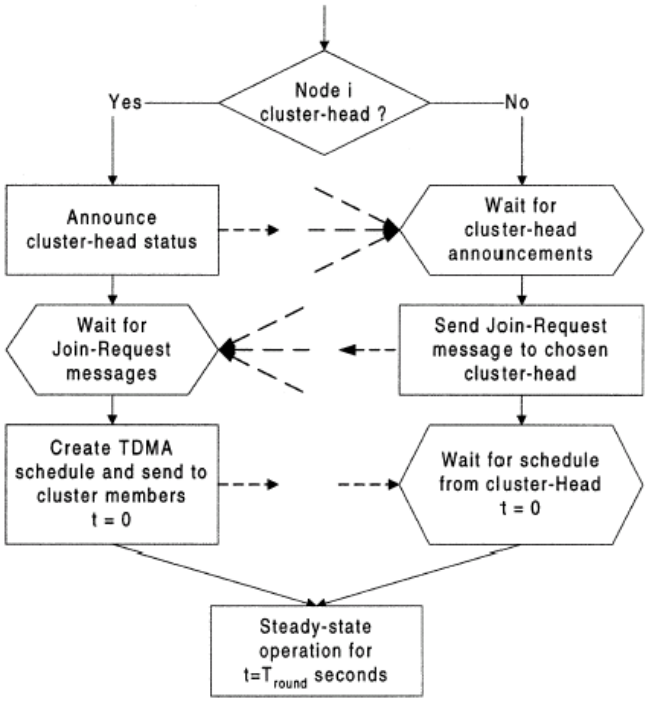
- If n < T(n), then that node becomes a cluster head
- Each node will be cluster head once in an interval of 1/P rounds
- Nodes that have already become cluster head cannot be a CH again in the current interval of 1/P rounds
- After each round, the probability to be cluster head for remaining nodes increases

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

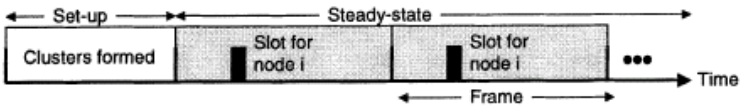


LEACH: Steady-State Phase

- 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…

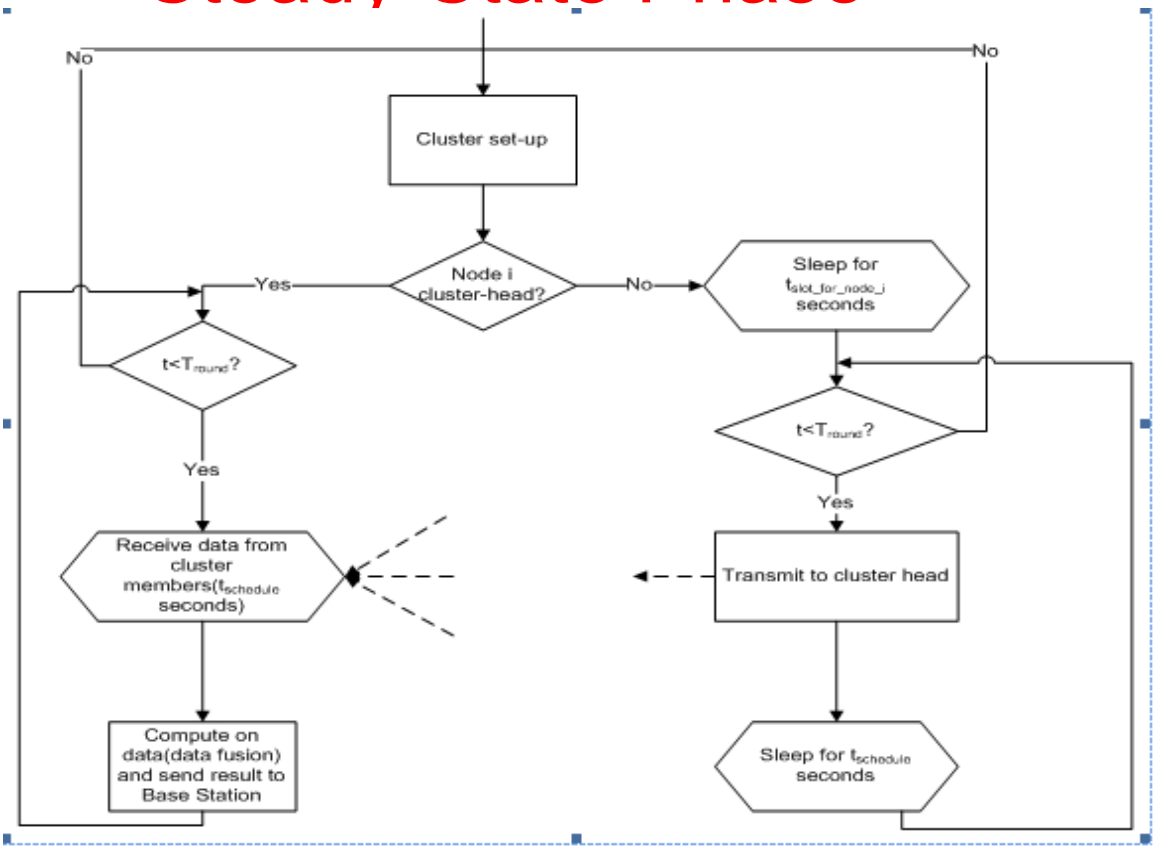
- Nodes send data during their allocated time slot



- 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



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

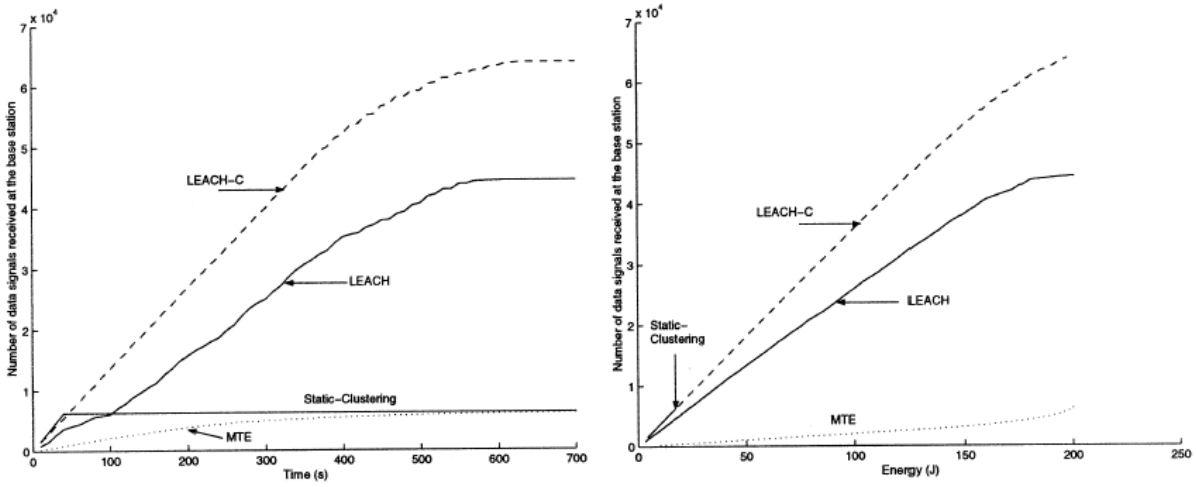
- Amount of energy dissipated by data transfer:
  [*note*: this energy model was covered in Lecture II.1]

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 ($\lambda \geq 2$).

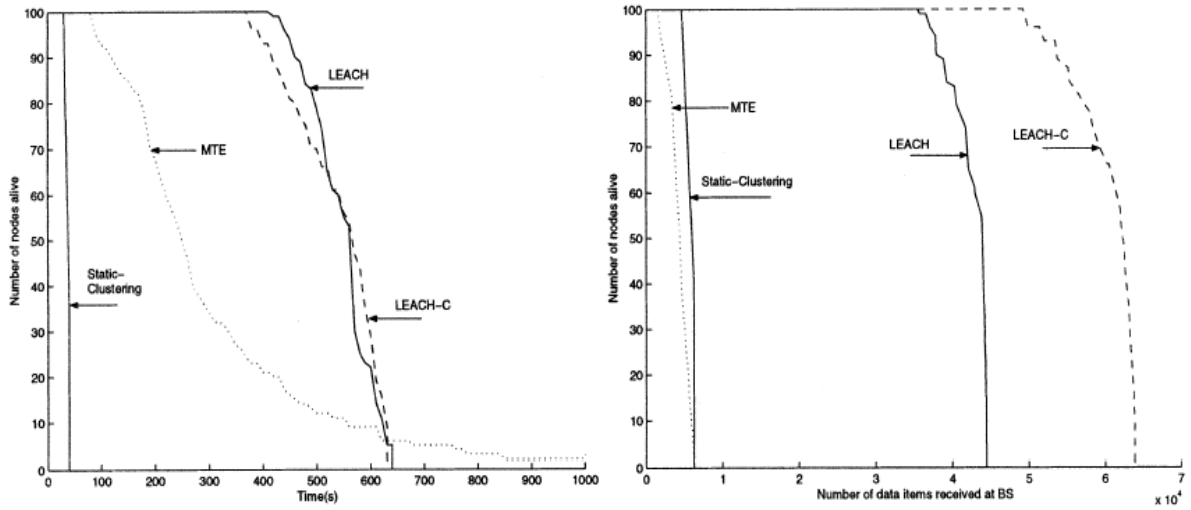
Results: Limited Energy Simulations



(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…

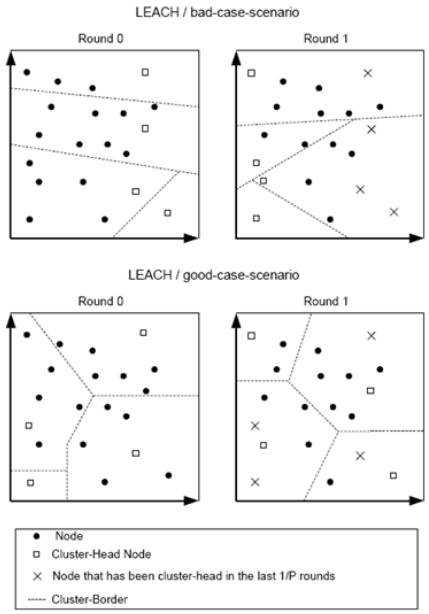


(a) Number of nodes alive over time.
(b) Number of nodes alive per amount of data sent to the BS.

- 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

- 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?