Energy-Efficient Communication Protocol for Wireless Microsensor Networks

Wendi Rabiner Heinzelman
Anatha Chandrasakan
Hari Balakrishnan

Massachusetts Institute of Technology

Presented by Rick Skowyra
Overview

- Introduction
- Radio Model
- Existing Protocols
  - Direct Transmission
  - Minimum Transmission Energy
  - Static Clustering
- LEACH
- Performance Comparison
- Conclusions
LEACH (Low-Energy Adaptive Clustering Hierarchy) is a routing protocol for wireless sensor networks in which:

- The base station (sink) is fixed
- Sensor nodes are homogenous

LEACH conserves energy through:

- Aggregation
- Adaptive Clustering
Radio Model

- Designed around acceptable $E_b/N_0$
  - $E_{elec} = 50\text{nJ/bit}$
    - Energy dissipation for transmit and receive
  - $\varepsilon_{amp} = 100\text{pJ/bit/m}^2$
    - Energy dissipation for transmit amplifier
- $k =$ Packet size
- $d =$ Distance

\[
E_{Tx}(k, d) = E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^2
\]

\[
E_{Rx}(k) = E_{elec} \cdot k
\]
Existing Routing Protocols

- LEACH is compared against three other routing protocols:
  - Direct-Transmission
    - Single-hop
  - Minimum-Transmission Energy
    - Multi-hop
  - Static Clustering
    - Multi-hop
Direct-Transmission

- Each sensor node transmits directly to the sink, regardless of distance
- Most efficient when there is a small coverage area and/or high receive cost

Sensor Status after 180 rounds with 0.5J/node
Minimum Transmission Energy (MTE)

- Traffic is routed through intermediate nodes
  - Node chosen by transmit amplifier cost
  - Receive cost often ignored
- Most efficient when the average transmission distance is large and $E_{elec}$ is low

Sensor Status after 180 rounds with 0.5J/node
MTE vs Direct-Transmission

When is Direct-Transmission Better?

\[ E_{\text{direct}} = k(E_{\text{elec}} + \varepsilon_{\text{amp}} n^2 r^2) \]

\[ E_{\text{MTE}} = k((2n - 1)E_{\text{elec}} + \varepsilon_{\text{amp}} nr^2) \]

For MTE, a node at distance \( nr \) requires \( n \) transmits of distance \( r \), and \( n-1 \) receives.

\[ E_{\text{direct}} < E_{\text{MTE}} \text{ when:} \]

\[ \frac{E_{\text{elec}}}{\varepsilon_{\text{amp}}} > \frac{r^2 n}{2} \]

- High radio operation costs favor direct-transmission
- Low transmit amplifier costs (i.e. distance to the sink) favor direct transmission
- Small inter-node distances favor MTE
MTE vs. Direct-Transmission (cont)

- 100-node random network
- 2000 bit packets
- $\epsilon_{amp} = 100\text{pJ/bit/m}^2$
Static Clustering

- Indirect upstream traffic routing
- Cluster members transmit to a cluster head
  - TDMA
- Cluster head transmits to the sink
  - Not energy-limited
- Does not apply to homogenous environments
LEACH

- Adaptive Clustering
  - Distributed
- Randomized Rotation
  - Biased to balance energy loss
- Heads perform compression
  - Also aggregation
- In-cluster TDMA
LEACH: Adaptive Clustering

- Periodic independent self-election
  - Probabilistic
- CSMA MAC used to advertise
- Nodes select advertisement with strongest signal strength
- Dynamic TDMA cycles
LEACH: Adaptive Clustering

- Number of clusters determined *a priori*
  - Compression cost of 5nj/bit/2000-bit message
- “Factor of 7 reduction in energy dissipation”
  - Assumes compression is cheap relative to transmission
  - Overhead costs ignored
LEACH: Randomized Rotation

- Cluster heads elected every round
  - Recent cluster heads disqualified
  - Optimal number not guaranteed
- Residual energy not considered
- Assumes energy uniformity
  - Impossible with significant network diameters

\[ T(n) = \begin{cases} 
  \frac{P}{1 - P \times (r \mod \frac{1}{P})} & \text{if } n \in G \\
  0 & \text{otherwise}
\end{cases} \]

- \( P \) = Desired cluster head percentage
- \( r \) = Current Round
- \( G \) = Set of nodes which have not been cluster heads in 1/P rounds
LEACH: Operation

- Periodic process
- Three phases per round:
  - Advertisement
    - Election and membership
  - Setup
    - Schedule creation
  - Steady-State
    - Data transmission
LEACH: Advertisement

- Cluster head self-election
  - Status advertised broadcast to nearby nodes

- Non-cluster heads must listen to the medium
  - Choose membership based on signal strength
    - RSSI
    - $E_b/N_0$
LEACH: Setup

- Nodes broadcast membership status
  - CSMA
- Cluster heads must listen to the medium
- TDMA schedule created
  - Dynamic number of time slices
LEACH: Data Transmission

- Nodes sleep until time slice
- Cluster heads must listen to each slice
- Cluster heads aggregate/compress and transmit once per cycle
- Phase continues until the end of the round
  - Time determined *a priori*
LEACH: Interference Avoidance

- TDMA intra-cluster
- CDMA inter-cluster
  - Spreading codes determined randomly
    - Non-overlapping modulation may be NP-Complete
  - Broadcast during advertisement phase
LEACH: Hierarchical Clustering

- Not currently implemented
- $n$ tiers of clusters of cluster heads
- Efficient when network diameters are large
Performance: Parameters

- MATLAB Simulator
- 100-node random network
- $E_{elec} = 50\text{nj/bit}$
- $\varepsilon_{amp} = 100\text{pJ/bit/m}^2$
- $k = 2000$ bits
Performance: Network Diameter

- LEACH vs. Direct Transmission
  - 7x-8x energy reduction
- LEACH vs. MTE
  - 4x-8x energy reduction
Performance: Energy and Diameter

- LEACH performs in most conditions
- At low diameters and energy costs, performance gains negligible
  - Not always same for costs
- Comparable to MTE for some configurations
Performance: System Lifetime

- Setup costs ignored
- 0.5J of energy/node
- LEACH more than doubles network lifetime
- Static clusters fail as soon as the cluster head fails
  - Can be rapid
Experiments repeated for different maximum energy levels

- LEACH gains:
  - 8x life expectancy for first node
  - 3x life expectancy for last node
Performance: Coverage

- **LEACH**
  - Energy distributed evenly
  - All nodes serve as cluster heads eventually
  - Deaths randomly distributed

- **MTE**
  - Nodes near the sink die first

- **Direct Transmission**
  - Nodes on the edge die first
Conclusions

- LEACH is completely distributed
  - No centralized control system
- LEACH outperforms:
  - Direct-Transmission in most cases
  - MTE in many cases
  - Static clustering in effectively all cases
- LEACH can reduce communication costs by up to 8x
- LEACH keeps the first node alive for up to 8x longer and the last node by up to 3x longer
Future Work

- Extend ns to simulate LEACH, MTE, and Direct Transmission
- Include energy levels in self-election
- Implement hierarchical clustering
Areas for Improvement

- LEACH assumes all cluster heads pay the same energy cost
  - Death model incorrect
- Compression may not be as cheap as claimed
  - Unclear how much savings are from compression assumptions and how much from adaptive clustering
- Optimal number of cluster heads must be determined in simulation, before implementation
- Round durations never specified or explained
Questions