An Application-Specific Protocol Architecture for Wireless Microsensor Networks

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Microsensor Networks

- Remote monitoring of the environment
  - Surveillance
  - Machine diagnostics

- Relevant parameters:
  - System lifetime (energy efficiency)
  - Quality
  - Latency
The MIT $\mu$-AMPS Project

• Develop energy-optimized solutions
  – Node architecture and radio hardware
  – OS, algorithms and protocols

• Assumptions:
  – Base station far from nodes
  – All nodes energy-constrained
  – Locally, data correlated

Goal: Design protocols for high quality and energy and spectrum efficiency
General-Purpose Protocol Architectures

- **Direct transmission**
  - Power scales as $R^n$
  - Bandwidth limitations

- **Routing**
  - MTE (Min. Trans. Energy) Routing
  - Multi-step communication
  - Short lifetimes for close nodes

- **Clustering**
  - Cellular model
  - Needs high-energy cluster-head

\[ d_{AB}^2 + d_{BC}^2 < d_{AC}^2 \]
LEACH: Energy-Efficient Protocol Architecture

- **Low-Energy Adaptive Clustering Hierarchy**
  - Adaptive, self-configuring cluster formation
  - Localized control for data transfers
  - Low-energy medium access
  - Application-specific data aggregation
Dynamic Clusters

- Cluster-head rotation to evenly distribute energy load
- Adaptive clusters
  - Clusters formed during set-up
  - Scheduled data transfers during steady-state

Cluster-heads = •
Distributed Cluster Formation Algorithm

Choose CH with “loudest” announcement

Using $P_i(t)$

Node $i$ cluster-head?

Yes

Cluster-head Nodes

Announce cluster-head status

Wait for Join-Request messages

Steady-state operation for $t = T_{round}$ seconds

No

Non-CH Nodes

Wait for cluster-head announcements

Send Join-Request message to chosen cluster-head

Choose CH with “loudest” announcement

Autonomous decisions lead to global behavior

• No global control
• Flexible, fault-tolerant
Distributed Cluster Formation

- Assume nodes begin with equal energy
- Design for $k$ clusters per round
- Want to evenly distribute energy load
  ⇨ Each node CH once in $N/k$ rounds

$$E[\# \text{CH}] = \sum_{i=1}^{N} P_i(t) \times 1 = k$$

$k = \text{system param.}$
(Analytical optimum)

$$P_i(t) = \begin{cases} \frac{k}{N - k \ast r \text{ mod}(N/k)} & C_i(t) = 0 \\ 0 & C_i(t) = 1 \end{cases}$$

$C_i(t) = 1 \text{ if node } i \text{ a CH in last } r \text{ rounds}$

- Can determine $P_i(t)$ with unequal node energy
Unequal Initial Energies

\[ P_i(t) = \frac{E_i(t)}{E_{total}(t)} k \]

- \( E_i(t) \) = energy of node \( i \) at time \( t \)
- \( E_{total}(t) \) = total energy in system at time \( t \)

High-energy nodes CH more often than low-energy nodes

If nodes begin with \( E_o \)

**Cluster-head nodes**

- \( E_i(t) \approx E_o - X \)
- \( E_{total} \approx E_o(N-kr) + (E_o-X)kr \)
- \( P_i(t) \approx 0 \)

**Non-cluster-head nodes**

- \( E_i(t) \approx E_o \)
- \( P_i(t) \approx k/(N-kr) \)
LEACH Steady-State

- Cluster-head coordinates transmissions
  - Time Division Multiple Access (TDMA) schedule
  - Node i transmits once per frame
- Cluster-head broadcasts TDMA schedule
- Low-energy approach
  - No collisions
  - Maximum sleep time
  - Power control
Inter-Cluster Interference

- Transmission in different clusters can collide
  - Nodes minimize transmission power
  - Each cluster has unique spreading code
  - Distributed solution to minimize interference
LEACH Medium Access

ADV
• CSMA
• Large power, small messages

Join-REQ
• CSMA
• Large power, small messages

SCH
• DS-SS code
• Power to reach all members

Data Transfer to Cluster-Head
• TDMA slot (with DS-SS)
• Power to reach CH, large messages
Application-Specific Data Aggregation

- Clusters exhibit spatial locality
  - Local data aggregation
  - Common signal enhanced/noise reduced
- Computation vs. communication tradeoff
  - Depends on cost of computation and communication
  - Signal processing within the network
Base Station Cluster Formation (LEACH-C)

- Get optimal clusters for comparison
- Requires communication with base station
- Need GPS or other location-tracking method

All Nodes
- Send \{ (x_i, y_i, E_i) \} to BS
- Wait for cluster information

Base Station
- Wait for information from nodes
- Determine optimal clusters and send info to nodes
- Clusters Formed

- Only nodes with $E_i > \mu_E$ eligible

- Small packets
- Large energy
Simulation Framework

• Extensions to *ns* network simulator
  – Computation and communication energy models
    • Radio energy
  – StrongARM processor beamforming [A. Wang]
    – New node states
    – Medium access
    – LEACH, LEACH-C, MTE routing, static clustering

\[ E_{\text{elec}} \times k \quad \varepsilon_{\text{amp}} \times k \times d^2 \]

Transceiver \quad Tx\ Amplifier \quad Receiver
Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing delay</td>
<td>50 $\mu$s</td>
</tr>
<tr>
<td>Bit rate</td>
<td>100 kbps</td>
</tr>
<tr>
<td>Radio electronics</td>
<td>50 nJ/bit</td>
</tr>
<tr>
<td>Transmit amplifier</td>
<td>100 pJ/bit/m$^2$</td>
</tr>
<tr>
<td>Beamforming cost</td>
<td>5 nJ/bit/signal</td>
</tr>
<tr>
<td>Data size</td>
<td>500 bytes</td>
</tr>
</tbody>
</table>
Optimum Number of Clusters

- Too few clusters ⇒ cluster-head nodes far from sensors
- Too many clusters ⇒ not enough local signal processing
Analytical Optimum

k clusters $\Rightarrow$ N/k nodes/cluster:

$E_{CH} = \alpha \frac{N}{k} + \beta$

$E_{non-CH} = \gamma \frac{1}{k} + \delta$

$k_{opt} = \frac{\sqrt{N} \ M}{\sqrt{6} \ d_{toBS}}$

$N=100$
$M=100$
$75 < d_{toBS} < 185$

$\Rightarrow 2 < k_{opt} < 6$

• Simulation agrees with theory
Data per Unit Energy

- LEACH achieves order of magnitude more data per unit energy
  - 2 hops v. 10 hops average
  - Data aggregation successful
- LEACH delivers over 10 times amount of data for any number of node deaths
- Rotating cluster-head effective
Summary

- Microsensor network protocols must be designed for
  - Bandwidth efficiency
  - Energy efficiency
  - High quality

- Application-specific protocol architecture beneficial
  - Most efficient use of limited resources
  - Ideas extendable to other application spaces