Energy-efficient Data Collection in Wireless Sensor Networks

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Research Topics

- Pervasive and Mobile Computing
  - Wireless Sensor Networks
  - Opportunistic Networking
  - Ad Hoc and Mesh Networks
  - Power management for mobile computing
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Sensor Node Architecture

A Sensor Node

- Location Finding System
- Mobilizer
- Power Unit
- Power Generator
- Sensor ADC
- Processor Memory
- Transceiver

- Small
- Low power
- Low bit rate
- Low cost
Dense Sensor Networks

- Several thousand nodes
- Nodes are tens of feet of each other
- Densities as high as 20 nodes/m³
- Multi-hop communication

Sparse Sensor Networks

- Distance between nodes larger than transmission range
- Data collection through mobile nodes (data mules)
  - Part of the external environment (buses, cabs, …)
  - Part of the infrastructure (robots, …)
Data Collection through Data Mules

- **Pros**
  - Increased system lifetime
  - Increased reliability
  - Increased capacity
  - Increased flexibility

- **Cons**
  - Increased message latency (delay-tolerant applications)
  - Limited scalability (unless multiple mules are used)
  - Physical obstacles may limit mule’s movements
  - Costs of data mule(s)

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How to prolong the network lifetime?

- Dense Sensor Networks
- Sparse Sensor Networks
How to prolong the network lifetime?

- Dense Sensor Networks
- Sparse Sensor Networks

Possible approaches

- Energy Harvesting
- Low-Power Components and Design
- Topology Management
- Power Management Management
- Data compression/aggregation
- Optimal Sampling
- Predictive Monitoring
- …
Power Management

- **Sleep Wakeup Scheduling**
  - Switches off the radio subsystem during inactivity periods
  - Sleep/wakeup schedule needed for communication

- **Adaptive sampling**
  - Reduces the amount of data to be transmitted to the sink
  - Decreases the power consumption for sensing

Adaptive Sleep/Wake up

- **Goal:** minimize radio energy consumption
- **Basic Idea of Sleep/Wake up Schemes**
  - Nodes sleep for most of the time
  - Wake up periodically for transmitting/receiving data
  - MAC or Application-layer protocol

- **Our Scheme**
  - Application-layer protocol
  - Relies on a routing tree
  - Active periods dynamically adjusted
Multi-hop Network

Routing Tree
Data flow from leaves to the root (sink node)

Coordination scheme

Communication Period
Talk Interval
Silence Interval

Energy-efficient Data Collection in Wireless Sensor Networks

Fully Synch (TinyDB)

Pros
- Simplicity

Cons
- Static scheme
- Global duty-cycle (low efficiency)
- Requires clock synchronization

Energy-efficient Data Collection in Wireless Sensor Networks
Fixed Staggered (TAG)

- Parent-child talk intervals
  - Adjacent to reduce sleep-awake commutations
  - Clock synchronization (periodic timestamps sent by the sink node)
- Pros
  - Pipeline
  - Suitable to data aggregation
- Cons
  - Static scheme
  - Global parameters

Our Proposal: Adaptive Staggered

- Adaptive duty cycle
  - Variable-length talk intervals depending on
    - Number of children
    - Network traffic
    - Channel conditions
    - Node Joins/Leaves
    - ...
Simulation

- Simulation Setup
  - Ns-2 tool
  - IEEE 802.15.4 MAC protocol

- Network scenario
  - 50m×50m area
  - 30 nodes randomly deployed

- Performance Indices
  - Average Activity Time (in % wrt always on)
  - Delivery Ratio
  - Average Message Latency
  - Fairness (MRD)

Simulation Results

- Adaptation example

Sample topology

TX Range = 15m, CS Range = 30m, 50m x 50m grid, 30 nodes
Simulation Results

- Comparison with other approaches

Power Management

- Sleep Wakeup Scheduling
  - Switches off the radio subsystem during inactivity periods
  - Sleep/wakeup schedule needed for communication

- Adaptive sampling
  - Decreases the power consumption for sensing
  - Reduces the amount of data to be transmitted to the sink
Snow Sensor

An Embedded System to Evaluate the Snow Status
Adaptive Sampling Algorithm

Estimate $F_{max}$ by considering the initial $W$ samples and set $F_c = c \cdot F_{max}$.
Define $F_{up} = (1 + (c-2)/4) \cdot F_{max}$ and $F_{down} = (1 - (c-2)/4) \cdot F_{max}$.
$h_1 = 0$ and $h_2 = 0$.

for $(i=W+1; i < \text{DataLength}; i++)$

    Estimate the current maximum frequency $F_{curr}$ on the subsequence $(i-W, W)$

    if ($|F_{curr} - F_{up}| < |F_{curr} - F_{max}|$)
        $h_1 = h_1 + 1$;
    else if ($|F_{curr} - F_{down}| < |F_{curr} - F_{max}|$)
        $h_2 = h_2 + 1$;
    else
        $h_1 = 0$;
        $h_2 = 0$;

    if ($h_1 > h$) || ($h_2 > h$)
        $F_c = c \cdot F_{curr}$;
        $F_{up} = (1 + (c-2)/4) \cdot F_{curr}$;
        $F_{down} = (1 - (c-2)/4) \cdot F_{curr}$;
    }


Simulation

- Simulation Setup
  - MatLab
  - Experimental datasets

- Network Scenario
  - Star Topology
  - TDMA communication scheme
  - Adaptive sampling algorithm at Base Station

- Performance Indices
  - % of samples wrt fixed over-sampling
  - Mean Relative Error (MRE)

Simulation Results

- Sampling Fraction (17-26%)

![Graph showing sampling fraction vs packet loss rate]
Simulation Results

- **Graphical Comparison**

![Graphical Comparison](image.png)

Simulation Results

- **Energy Consumption**

<table>
<thead>
<tr>
<th>Power management scheme</th>
<th>Power cons.</th>
<th>Activity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always On</td>
<td>880 mJ/sample</td>
<td>100%</td>
</tr>
<tr>
<td>Duty-cycle</td>
<td>150 mJ/sample</td>
<td>17%</td>
</tr>
<tr>
<td>Duty-cycle + Adaptive Sampling</td>
<td></td>
<td>3-5%</td>
</tr>
</tbody>
</table>
How to prolong the network lifetime?

- Dense Sensor Networks
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Sparse Sensor Networks

- Data Mules are resource rich
- Static sensors are energy-constrained
  - Power management
- Mule-sensor communication
  - Mule discovery protocol
  - Data transfer protocol
Experimental testbed

- Testbed environment
  - MULE collecting data packets sent by a static node
  - straight path and constant speed

- Investigated factors
  - mule distance
  - mule speed

- Performance measures
  - Contact time
  - Packet loss behavior
  - Number of successfully transmitted packets

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Experimental Measurements

Impact of distance between sensor and mule

Impact of the MULE’s speed on packet loss and contact time

<table>
<thead>
<tr>
<th>distance $D_y$</th>
<th>15 m</th>
<th>25 m</th>
<th>35 m</th>
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<tbody>
<tr>
<td>avg</td>
<td>928</td>
<td>526</td>
<td>417</td>
</tr>
<tr>
<td>min</td>
<td>875</td>
<td>499</td>
<td>372</td>
</tr>
<tr>
<td>max</td>
<td>994</td>
<td>569</td>
<td>456</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>speed</th>
<th>20 km/h</th>
<th>30 km/h</th>
<th>40 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>119</td>
<td>108</td>
<td>114</td>
</tr>
<tr>
<td>min</td>
<td>98</td>
<td>99</td>
<td>98</td>
</tr>
<tr>
<td>max</td>
<td>141</td>
<td>143</td>
<td>75</td>
</tr>
</tbody>
</table>
Energy-efficient Data Collection

- Many previous works assume
  - Circular transmission range
  - Packet loss negligible within the transmission range
- [Somasundara-2006] proposes a stop&wait approach
  - Uses acks for
    - Reliability (message received)
    - Beaconing (mule still within the transmission range)
  - No assumption about
    - Packet loss behavior
    - Mule position and mobility
  - Starts transmitting upon mule discovery
  - Robust but not efficient


Optimal vs. Naïve Approach

- Optimal approach
  
  minimize \( t_{\text{end}}^n - t_{\text{start}}^n \)

  subject to \( \int_{t_{\text{start}}^n}^{t_{\text{end}}^n} Th(t) \cdot dt = B \)

- Naïve approach
  
  \[ [t_{\text{start}}^n, t_{\text{end}}^n] \text{ such that } \]
  
  \( t_{\text{start}}^n = t_{\text{discovery}}^n \)

  \( \int_{t_{\text{start}}^n}^{t_{\text{end}}^n} Th(t) \cdot dt = B \)
Performance Comparison

- **Average data transfer delay**

![Graph showing data transfer delay comparison between naive and optimal methods for different weights.](image1)

- **Slowdown in the average data transfer delay**

![Graph showing slowdown comparison between naive and optimal methods for different weights.](image2)
Adaptive Data Transfer (ADT) protocol

- Feasible
- Approximates the optimal protocol
  - Window-based scheme
- Relies upon
  - Real measurements of the contact time
- Assumes that
  - Message loss probability is minimum around the middle of the contact time
  - Message loss probability function is (approximately) symmetric wrt the mid contact time

Simulation Results

Mule’s speed
- 40 Km/h (1-50)
- 20 Km/h (51-100)
- 40 Km/h (101-150)
Sparse Sensor Networks

- Data Mules are resource rich
- Static sensors are energy-constrained
  - Power management
- Mule-sensor communication
  - Mule discovery protocol
  - Data transfer protocol

Current Research Projects

- **ArtDecO**: Adaptive Infrastructures for Decentralized Organizations
  - Funded by: MIUR, FIRB Project (2006-2009)
- **WiSeMaP**: Wireless Sensor networks for Monitoring Natural Phenomena
  - Funded by: MIUR, PRIN Project (2006-2008)
- **GeoMon**: Monitoraggio delle opere ingegneristiche e prove geotecniche tramite l’utilizzo delle reti di sensori
  - Funded by: Engisud, Palermo (2007-08)
- **VirtusVini**: Monitoraggio della produzione vitivinicola con reti di sensori
  - Funded by: Engisud, Palermo (2007-08)
- **CityNet**: Progetto e realizzazione di un’infrastruttura per il monitoraggio dell’inquinamento dell’aria mediante sensori a terra fissi e collettori mobili
  - Funded by: TDGroup, Pisa (2007)
- **Nautilus**
  - Funded by: Consorzio di aziende toscane (2007)
- **Power Management in IEEE 802.16e (WiMax) Networks**
  - Funded by Nokia Research Center, Helsinki (2006-07)
Recent Publications on WSN