Energy Conservation in Wireless Sensor Networks with Mobile Elements

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Overview

- WSN-MEs
- Power Management & Node Discovery
  - Schedule-based
  - On demand
  - Asynchronous
    - Fixed
    - Adaptive (Learning-based, Hierarchical)
- Conclusions and Research Questions
Wireless Sensor Networks with Mobile Elements

Static Sensor Networks

Funneling Effect!
Other advantages of using WSN-MEs

- **Connectivity**
  - A sparse sensor network may be a feasible solution for a large number of applications

- **Cost**
  - Reduced number of sensor nodes \(\Rightarrow\) reduced costs

- **Reliability**
  - Single-hop communication instead of multi-hop communication
  - Reduced contentions/collisions and message losses

Components of a WSN-ME

- **Regular Sensor Nodes**
  - Sensing (source of information)
  - Data Forwarding
  - May be Static or Mobile

- **Sink Nodes (Base Stations)**
  - Destination of Information
  - Collect information directly or through intermediate nodes
  - May be Static or Mobile

- **Special Support Nodes**
  - Neither source nor destination of information
  - Perform a specific task (e.g., data relaying)
  - Typically mobile
Mobile Elements

- Relocatable Nodes
  - Limited mobility
  - Do not carry data while moving
  - Typically used in dense networks
- Mobile Data Collectors
  - Mobile Sinks
  - Mobile Relays
- Mobile Peers
  - Regular mobile nodes

Relocatable Nodes

Sink (Base station)

Relocatable node

Relocatable node
Mobile Sink/Relay: Potential Applications

- Air Quality Monitoring in Urban Areas
  - Sensors in strategic locations along streets.
  - Mobile Nodes are on board of buses
  - Collect data and transport to the sink node

- Urban Sensing Applications
  - Mobile nodes are personal devices
  - Sensor-to-vehicle communication
  - ...

Mobile Peers
Mobile Peers

Mobile Peers: Potential applications

- Mobile devices equipped with
  - (mobile) sensors
    - Camera, audio recorder, accelerometer, ...
  - Wireless communication
    - 3G, WiFi, Bluetooth, ...
- Can be used to implement
  - Personal Sensing applications (e.g., Cence me)
  - Group Sensing applications (e.g., garbage watch)
  - Participatory sensing applications
Data-driven approaches
- data compression
- data prediction
- ...

Power Management (duty cycling)
- The sensor duty cycle should be as low as possible
  - to maximize the lifetime
- Contacts could be missed
- Efficient ME Discovery
  - Maximize the number of detected contacts while minimize energy consumption

Power Management and Mobile Element Discovery
How to detect all potential contacts while minimizing the energy consumption at sensors?
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Ideal Scenario

Sensor Node

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In practice

- MDC arrival times are typically not known in advance
- Sensors nodes cannot be always active
  - Low duty cycle $\delta$ to save energy
- Discovery Protocol
  - Strictly related with power management
Power Management Schemes

- Scheduled rendezvous
- On-demand
- Asynchronous (Periodic Listening)

Scheduled Rendez-vous schemes

- Sensor nodes and ME agree on the visit time
  - at least with some approximation
- Simple to implement and energy Efficient
- Synchronization required
- Not applicable in some contexts

On-demand schemes

- The ME wakes up the static node when it is nearby

  - **Passive wakeup radio**
    - Use energy harvested by the wakeup radio (e.g., RFID)
  - **Active wakeup radio**
    - Low-power radio + high-power radio

### Passive Wakeup radio

- Use the energy **passively** received through the wakeup radio to activate the data radio
- Very limited distance
  - Few meters (suitable only for robotic networks)
  - The distance can be increased at the cost of
    - Increased complexity on the wakeup radio (increased cost)
    - Increased wakeup time
- Additional hardware required


Passive Wakeup Radio

WISP
- Wireless Identification and Sensing Platform
- Integration of Tmote Sky mote with a passive RFID tag
- RFID reader on the ME
- Maximum distance: few meters

Active Wakeup Radio

Radio Hierarchy
- Scenario
  - Mobile opportunistic network of handheld devices
- Multiple-radio strategy
  - Higher-level radio for data exchange, lower-level radio for discovery
    - Bluetooth and WiFi, Mote and WiFi
  - The lower-level radio is used to discover, configure and activate the higher-level radio
    - Bluetooth used to discover a nearby WiFi Access Point or node and configure the WiFi interface

Active Wakeup Radio

Hierarchical Power Management

- Scenario
  - Opportunistic networks of handheld devices
  - WSNs with all mobile nodes
- Multiple radio’s strategy
  - Low-power radio for discovery
  - High-power radio for both discovery and data exchange
  - High-power radio is awakened by the low-power radio
    - E.g., mote radio and WiFi


Active Wakeup Radio

Network Interrupts

- Scenario
  - Sensor Networks (with MEs)
- Two different radios
  - A primary high-power radio usually in sleep mode
    - Used for data communication
  - Control Low-power radio always powered on
    - Used for control messages
  - A node can activate the high-power radio of a nearby node by sending it a beacon through the low-power radio

Limits of On-demand schemes

- On-demand schemes require multiple radios
  - which may not available in current sensor platforms
- The range of the wakeup radio is typically limited
  - Few meters for passive radios
- Active radios have a longer range, but they consume energy
  - The energy consumption should be below 50 $\mu$W
  - And the wakeup range should be as long as the communication range

Power Management Schemes

- Scheduled rendezvous
- On-demand
- Asynchronous
  - Active Wakeup
  - Passive Wakeup
Asynchronous schemes

- ME emits periodic beacons to announce its presence
- SN wakes up periodically (*period listening*), and for short periods
  - Very low duty cycle for saving energy

Asynchronous (Periodic Listening)

\[ T_{ON} = T_B + T_D \]
\[ \delta = T_{ON}(T_{ON} + T_{OFF}) \]
Classification of Periodic Listening Schemes

- **Fixed Schemes**
  - Both the beacon period and the sensor node’s duty cycle are fixed over time

- **Adaptive Schemes**
  - **Learning-based schemes**
    - The arrival time of the ME is predicted based on the past history, and the duty cycle is adjusted accordingly
  - **Hierarchical schemes**
    - Two different operation modes for sensor nodes
      - Low-power mode (most of the time)
      - High-power mode (when the ME is nearby)
Fixed Schemes

- Fixed Beacon Period
- Fixed Sensor’s Duty Cycle ($\delta$)
  - A low duty cycle saves energy, but contacts may be missed
  - A high duty cycle increases the % of detected contacts, but decreases the sensor’s lifetime

Key Question

- Which is the optimal duty cycle that allows to detect all contacts with the minimum energy expenditure?
- The optimal duty cycle depends on a number of factors that are difficult (if not impossible) to know in advance.


Fixed Schemes

- Fixed approach
  - Fixed Beacon Period
  - Fixed Sensor’s Duty Cycle ($\delta$) [Mat05] [Jai06]
    - A low duty cycle saves energy, but contacts may be missed
    - A high duty cycle increases the % of detected contacts, but decreases the sensor’s lifetime

This approach is quite inefficient, especially when sensor nodes spend a long time in the discovery phase


Learning-based approaches

Adaptive Beacon Rate

- Reference Scenario
  - All sensor nodes are mobile
  - Fixed sink with limited energy budget
  - Energy harvesting

- Basic idea
  - Adaptive beacon emission rate
    - Time is divided in slots (1-hour duration)
    - For each time slot the expected contact probability is derived and updated dynamically based on the past history
    - The beacon emission rate is varied according to the estimated probability and the available energy
  - Based on reinforcement learning


Learning-based approaches

Resource-Aware Data Accumulation (RADA)

- Reference Scenario
  - Static Sensor Nodes (with energy limitations)
  - MEs are resource-rich devices

- Basic idea
  - Fixed (Periodic) Beacon Emission by ME
  - The wake-up period (i.e., duty cycle) of the sensor node is adjusted dynamically, depending on the past history
  - Based on DIRL framework

- DIRL framework
  - Based on Q-learning
  - Autonomous and adaptive resource management
    - suitable to sparse WSNs

**DIRL framework**

- **Set of tasks to be executed**
  - Task priority
  - Applicability predicate

- **Set of states**
  - State representation includes system and application variables
  - Hamming distance used for deriving distance between states and aggregate similar states

- **Utility Lookup Table: Q(s, t)**
  - Q(s,t) gives the long-term utility of executing task t in state s

- **Exploration/Exploitation strategy**
  - Exploration with probability $\varepsilon$
    - A random task is executed
  - Exploitation with probability $1-\varepsilon$
    - The best task, according to Q-values, is selected


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**DIRL Algorithm**

1. Initialize $Q(s,t)$ for all $s$ and $t$
2. Observe current state $s$
3. Choose task $t$ to execute
4. Execute $t$ and observe new state $s'$
5. Compute reward $r$ for task $t$ in current state $s$ and move to state $s'$
6. Update $Q(s,t)$ based on reward $r$ and state $s'$
7. Make state $s'$
8. Yes: Is $s'$ similar to any existing state $s''$?
   - No: Add $s'$ to the list of known states
   - Yes: $Q(s,t)$
9. $Q(s,t) = (1-\alpha)Q(s,t) + \alpha(r + \gamma Q(s'))$

Simulation Results

Sparse Scenario

Limits of Adaptive Schemes

- Learning-based schemes perform well when the ME has a regular mobility pattern
  - The regularity can be learned and exploited for predicting next arrivals
- Performance degrades significantly as the randomness in the mobility pattern increases

Hierarchical Discovery schemes

- **Basic idea**
  - The duty cycle is adjusted dynamically (as in learning-based approaches)
    - **Low duty cycle** when the ME is far
    - **High duty cycle** when the ME is about to arrive
  - Information about the ME location are provided by the ME itself

- **Dual Radio**
  - **Low-power radio** for discovery and a **high-power radio** for data communication
  - Already considered as on-demand schemes

- **Dual Beacon**
  - **Long-range beacons** for announcing the presence of the ME in the area
  - **Short-range beacons** for informing that communication can take place

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**Dual Beacon Discovery (2BD)**

- **ME uses two different beacon messages**
  - Long-range beacons (LRB) for announcing the presence of the ME in the area
  - Short-range beacons for informing that communication can take place

- **Sensor nodes alternate between two duty cycles**
  - Typically in Low duty cycle
  - Switch to High duty cycle upon receiving a LRB
  - Enter the communication phase upon receiving a SRB
  - Switch back to Low duty cycle at the end of the communication phase

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2BD Protocol

Simulation Results

Sparse Scenario
False Activations

\[ E_{FA} = \left( \frac{R}{r} - 1 \right) \cdot T_{out} \cdot \left[ \delta_H \cdot P_{RX} + (1 - \delta_H) \cdot P_{ST} \right] \]

Simulation Results

Sparse Scenario
(false activations never occur)

Dense Scenario
(false activations may occur)
### Schedule-based power management

- **Can be used only in some special cases**

### On-demand wakeup

- **Interesting!**
- **However...**
  - Active wakeup radio consume energy
    - \( \text{Low power consumption} \times \text{long time} = \text{large energy consumption} \)
  - Passive wakeup radios do not consume additional energy, but they have very short ranges (few meters)
  - In both cases, special hardware is required

### Periodic Listening

- **Can be always used**
  - As it does not require special hardware
  - Finding the appropriate parameters may not be so easy
  - Using fixed parameters may result in inefficient solutions

- **Periodic Listening with adaptive parameters is more efficient**
  - Learning-based schemes are suitable for scenarios where ME moves with a regular pattern
  - Hierarchical schemes (based on dual beaconing) are more flexible
    - False activations may occur in dense scenarios
Is there any room for new research activities?

- **Adaptive strategies**
  - More complex (and efficient) adaptive strategies can be investigated
  - Adaptive strategies for
    - Energy conservation + energy harvesting = unbounded lifetime
- **Optimization over multiple parameters**
  - Data generation process
  - ME arrival pattern (next arrival)
  - Available space in the local buffer
  - Available energy (energy harvesting)

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Is there any room for new research activities?

- **WSN with all mobile nodes (opportunistc networks)**
- In opportunistic networks a lot of work has been done for data dissemination
- Less attention has been devoted to node discovery (related with power management)
  - Although nodes spend most of time for discovery (rather than for data dissemination).

Available at [http://info.iot.unipi.it/~anastasi/](http://info.iot.unipi.it/~anastasi/)