WSN-HEAP

Wireless Sensor Networks
Powered by Ambient Energy Harvesting

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Outline

- Quick Introduction of Wireless Sensor Networks (WSN)
- Energy Harvesting for WSN
- WSN-HEAP
- Research Challenges
- Application Examples and Ongoing Research
- Concluding Remarks
What are WSNs?

Wireless Sensor Networks

- Originated from military/security applications, many new potential applications have emerged in areas such as medical, industrial, automotive, agriculture, environmental and structural health monitoring.
- Consists of sensor nodes distributed over an area monitoring some phenomena.
- Sensors monitor temperature, pressure, sound, vibration and motion.
- Typically powered by on-board batteries.
Old Assumptions

- Deployed randomly, e.g. air dropped
- Operational lifetime limited by battery
- Densely deployed to provide redundancy
- No concern for environmental implications caused by hardware, especially batteries
- Predominantly driven by military and/or short-term surveillance oriented applications
- Communications subsystem design is driven primarily by need to extend the limited battery lifetime
New Applications

- Structural Health Monitoring – monitoring bridges, tunnels, dams, ancient monuments, construction sites, buildings, roads, railways, land masses, etc.
- Agriculture and food industry – environmental monitoring, precision agriculture, facility automation (greenhouse control, animal-feeding system), etc
- Industrial automation – M2M-based machine and process control
- Building automation, smart homes, smart offices, smart spaces
- Environmental monitoring for conservation
Structural Health Monitoring

Compelling need for SHM because

- Earthquakes can shake buildings, even in Singapore (e.g. Sumatran earthquakes)
- Soil movement from construction and excavation works may cause buildings to become unstable (e.g. MRT/subway Tunneling Works)

April 2004
Structural Health Monitoring

Compelling need for SHM because

- Structures may weaken over time (e.g. bridges, building foundations, elevated roads) due to bacterial, chemical, or (sea) water damage
- Wear-and-tear may result in structural deformation and mechanical faults (e.g. bridges, railway tracks, etc.)
Deficiencies of current SHM approaches

- Sensors welded / embedded into critical structures
  - Infeasible / hazardous to replace / recharge batteries
- Sensors are wired to data loggers (sinks)
  - Cabling is expensive, messy, prone to damage, hazardous, non-recyclable and has limited coverage
- Offline data collection (non real-time)
  - Early warning signals may not be detected in time
WSN for SHM

Why use WSN?

- Prevalent transmission technology
  - IEEE 802.15.4, 802.11, 802.15.1
- Higher availability and wider coverage
- Reduced costs and wastage
  - Typical wiring costs US$130-650 per metre
  - Wireless tech can eliminate 20-80% of costs
- Reduce interferences from electrical sources
- Less vulnerable to disruptions arising from cable damage
WSN for Agriculture

Grape Networks (US)

SoilWeather (FI)

CSIRO (AU)

Lofar Project (NL) - WSN for Potato farming

(TH)
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Energy Harvesting

- Power has been and remains the key WSN issue
- Alternative source of energy for WSNs
- Gather energy that is present in the environment, i.e. ambient energy
- Convert the energy into a form that can be used to power devices
- Assumes energy source is well characterized, regular and predictable
- Energy scavenging refers to scenarios where energy source is unknown and highly irregular
Energy Harvesting for SHM

Why Ambient Energy Harvesting?

- Batteries in sensor nodes embedded in structures are not easily replaceable
- No danger of battery leakage (corrosive to structure) and environmentally-friendly
- Operate perpetually without need for human intervention
- Can be used in emergencies when power supply is not available
Energy Harvesting for Agriculture

Why Ambient Energy Harvesting?

• Batteries in sensor nodes in plantation are not easily replaceable → high risk of damaging crops
• No batteries → no danger of battery leakage and polluting the environment
• Operate perpetually without need for human intervention
Energy Harvesting for WSN usage

- Mechanical (Vibration or Strain) energy harvesters
  - Bridges, roads, railway tracks movement
  - Trains and vehicles cause vibration

- Solar films
  - Thin solar films that can be “pasted” on buildings are becoming a reality
  - Ambient light can also be harvested

- Water
  - Mini/Micro-hydroelectric generators in irrigation canals, streams, rivers, waterways, pipes, etc.
Energy Harvesting for WSN usage

- Ambient airflow
  - Besides natural airflow, wind is also generated by movement of vehicles, and even air conditioning
- Ambient RF
  - Available everywhere (e.g. from cell phones, WiFi)
  - 8 µW to 420 µW (IEEE Trans on Power Electronics, May 2008)
- Pressure
  - Energy is generated due to pressure (e.g. from movement of people)
Batteries vs Supercapacitors

- **Batteries**
  - Limited Recharge cycles
  - Higher storage density (30-120 Wh/kg)
  - Environmentally unfriendly and prone to leakage

- **Capacitors/Supercapacitors**
  - Virtually unlimited recharge cycles
  - Capacitors have lower storage density than batteries (0.5-10 Wh/kg)
  - Supercapacitors have potentially higher energy storage density than batteries/capacitors (30-300 Wh/kg)
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**WSN-HEAP**

- Acronym for **Wireless Sensor Networks Powered by Ambient Energy Harvesting**
- Used for denoting WSNs that are solely powered by energy harvesting devices using capacitors/supercapacitors
- Excludes WSNs that use energy harvesters to supplement battery power
WSN-HEAP node
Energy Model of WSN-HEAP node

- Energy harvesting is only energy source
- Different energy harvesting (charging) rate across time and physical domains
- Average energy charging rate is lower than the rate of energy consumption
- Short duty cycle
Major Research Groups

- UCLA CENS: Heliomote Energy Harvesting System
- EPFL Sensor Scope Project
- UC Berkeley WEBS (Wireless Embedded Systems)
Sensor Nodes with Energy Harvesting

- Research
  - Heliomote (V. Raghunathan et. al., IPSN 2005)
  - AmbiMax (C. Park and P. H. Chou, SECON 2006)
  - Trio (P. Dutta et. al, IPSN 2006)
Sensor Nodes with Energy Harvesting

Research

Sensor Nodes with Energy Harvesting

- Commercial
  - Ambiosystems
  - Microstrain
  - Enocean
  - Crossbow

- Solar-powered sensor node by Microstrain
- Battery-less motes by Ambiosystems
- Solar-powered sensor node by Enocean
- Energy converter for linear motion by Enocean
- Solar-powered (supplemented) sensor node by Crossbow
## Current State-of-the-Art Energy Harvesting Rates

<table>
<thead>
<tr>
<th>Technology</th>
<th>Power Density (µW/cm²)</th>
<th>Energy Harvesting Rate (mW)</th>
<th>Duty Cycle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration – electromagnetic</td>
<td>4.0</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Vibration – piezoelectric</td>
<td>500</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Vibration – electrostatic</td>
<td>3.8</td>
<td>0.038</td>
<td>0.05</td>
</tr>
<tr>
<td>Thermoelectric</td>
<td>60</td>
<td>0.6</td>
<td>0.72</td>
</tr>
<tr>
<td>Solar – direct sunlight</td>
<td>3700</td>
<td>37</td>
<td>45</td>
</tr>
<tr>
<td>Solar – indoor</td>
<td>3.2</td>
<td>0.032</td>
<td>0.04</td>
</tr>
</tbody>
</table>


Power consumption for MICAz sensor node is 83.1mW in the receive state and 76.2mW in the transmit state.
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Research Challenges

- WSN Architecture
- Power Management
- Modulation and Coding
- Medium Access Control (MAC) Schemes
- Routing Protocols
- Transport Protocols
WSN Architecture

- Single-Hop Single-Sink
- Architecture used by most WSNs with energy harvesters
WSN Architecture

- Multi-Hop Single-Sink
- Architecture used by many WSNs with on-board batteries
WSN Architecture

- Multi-Hop Multi-Sink
  - Increases network capacity
Power Management

- Most work on power management in WSNs using energy harvesting devices is done by M. Srivastava’s group in UCLA
- Their main focus is on estimating amount of energy that can be harvested in future to optimize duty cycles and scheduling of tasks
- Main assumption is that harvested energy is used in conjunction with battery power
  - Their energy model is different from ours
Challenges in Power Management in WSN-HEAP

- In WSN-HEAP, higher transmission power means longer energy harvesting time
  - Reduced sending rate
- However, higher transmission power also means that there are more potential awake neighbors to forward data packets to
- What is the optimal transmit power to maximize throughput?
Modulation and Coding

IEEE 802.15.4
- Most commonly used physical data transmission standard
- Commonly referred to as Zigbee
- Used in many popular sensor motes (e.g. MICAz, TelosB)

IEEE 802.11
- Widely used for WLANs
- Not power-efficient
- Used in some applications
Sensor MAC protocols

- **S-MAC** (W. Ye, Infocom 2002)
  - Periodic sleep and wakeup cycles
  - Latency is increased as a result
  - Variants include T-MAC and DSMAC to improve performance under specific scenarios

- **B-MAC** (J. Polastre, SenSys 2004)
  - Adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening
Sensor MAC protocols

- TRAMA (V. Rajendran, SenSys 2003)
  - TDMA-based algorithm
  - Time synchronization is required
- Sift (K. Jamieson, EWSN 2006)
  - Designed for event-driven WSN to minimize collisions when event occurs
Challenges in MAC for WSN-HEAP

- Difficult to use TDMA
  - Time synchronization is harder in WSN-HEAP than conventional WSNs
- Difficult to use sleep-and-wake-up schedules
  - Not possible to know exactly when each node is awake
- Difficult to set duty cycles
  - Energy harvesting rates change with time and place
Routing Protocols

- Flat routing
  - Directed Diffusion (C. Intanagonwiwat, Mobicom 2000); Solar-aware Directed Diffusion (T. Voigt, LCN 2003)
  - Variants include Rumor Routing, Gradient-Based Routing (GBR), Random Walks

- Hierarchical Routing
  - Makes use of clustering and data aggregation
  - LEACH (W. Heinzelman, HICSS 2000)
  - Variants include PEGASIS, TEEN, APTEEN
Routing Protocols

- Geographic Routing
  - GPSR (B. Karp, MOBICOM 2000)
  - Variants include GAF, GEAR, SPAN
Challenges in Routing for WSN-HEAP

- Difficult to determine next-hop neighbor
  - Not possible to determine exact wakeup schedules
  - Many sensor routing protocols assume knowledge of neighbors
- Complete routes may not be available when a data packet is sent
  - Delay-Tolerant Networking (DTN) may be a solution but be adapted to WSN-HEAP
Challenges in Routing for WSN-HEAP

- How to efficiently route data in WSN-HEAP when different nodes have different energy harvesting rates?
- How to aggregate or disseminate sensor data in WSN-HEAP?
Transport Protocols

- Variable Reliability
  - STCP (Y. G. Iyer, ICCCN 2005)
- Event-based Reliability
  - ESRT (Y. Sankarasubramaniam, MobiHoc 2003)
- Congestion Control
  - Flush (S. Ki, Sensys 2007)
  - CODA (C.-Y. Wan, Sensys 2003)
  - Fusion, CCF, PCCP, ARC, Siphon, Trickle
Challenges in transport protocols for WSN-HEAP

- How to detect congestion when a node is only awake for short periods of time?
- How to send the feedback from the sink to the source node when we do not know exactly when the source node would be awake?
- How to provide fairness if there are nodes with different energy harvesting rates?
Technical Challenges

- Not possible to know exactly which is the awake next-hop neighbor to forward data to
- Not possible to predict exactly when the node will finish harvesting enough energy
# WSN-HEAP vs battery-operated WSNs

<table>
<thead>
<tr>
<th></th>
<th>Battery-operated WSNs</th>
<th>Battery-operated WSNs with energy harvesters</th>
<th>WSN-HEAP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goal</strong></td>
<td>Latency and throughput is usually traded off for longer network lifetime</td>
<td>Longer lifetime is achieved since battery power is supplemented by harvested energy</td>
<td>Maximize throughput and minimize delay since energy is renewable and the concept of lifetime does not apply</td>
</tr>
<tr>
<td><strong>Protocol Design</strong></td>
<td>Sleep-and-wakeup schedules can be determined precisely</td>
<td>Sleep-and-wakeup schedules can be determined if predictions about future energy availability are correct</td>
<td>Sleep-and-wakeup schedules cannot be predicted</td>
</tr>
<tr>
<td><strong>Energy Model</strong></td>
<td>Energy model is well understood</td>
<td>Energy model can be predicted to high accuracy</td>
<td>Energy harvesting rate varies across time, space as well as the type of energy harvesters used</td>
</tr>
</tbody>
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Application Examples

- Self-powered railway sleeper monitoring system
- Stability Monitoring of Bridges and Expressways
Wireless Monitoring Systems for Rail Systems

- Railway track and bridge monitoring
  - Remote (wireless) rail temperature preventive maintenance system in UK’s high speed rail network since 2005
  - Next-generation wireless mesh for predictive maintenance demonstrated for Network Rail (UK) in 2007
- Battery-powered
  - Requires human intervention for battery replacement
  - Poses safety issues and may disrupt rail operations
Self-Powering (Ambient Energy Harvesting)

Wind energy from passing trains in tunnels

Vibrational energy from track deflections

Solar energy for outdoor tracks
Self-Powered, Online Rail-track Sleeper Monitoring

Benefits of wireless
- Mature and prevalent technology
  - WiFi, ZigBee
- Higher availability and wider coverage
- Reduced costs and wastage
- Online monitoring and remote control

Benefits of self-powering
- Sustainable
- Environmental friendliness
- Economical
- Safety
- Commercially available

Self-Powered, Wireless Monitoring Instrument (vibration, solar) on sleepers on viaduct and at-grade stations
Stability Monitoring of Bridges and Expressways using WSN-HEAP

Photo Source: SysEng (S) Pte Ltd

Pasir Panjang Semi-Expressway
Ongoing Research

MAC Protocols for WSN-HEAP

- Adapt and compare different MAC protocols for use in WSN-HEAP
- Design MAC scheme for WSN-HEAP
- Validated analytical and simulation results; working on experimentation
- Results enable network designers to determine the suitable MAC protocol to use to maximize throughput given the average energy harvesting rates and the number of WSN-HEAP nodes to deploy
Ongoing Research

Routing and Node Placement Algorithms

- Different node placement schemes affect network performance
- Optimal choice of a node placement scheme and routing algorithm is crucial in maximizing goodput
Lab Feasibility Study (Solar)
Lab Feasibility Study (Vibration)
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Conclusions and Future Work

- WSN-HEAP are viable solutions to making WSN more pervasive
  - Increase the commercial viability of wireless sensor networks since maintenance costs are reduced.
  - Since energy harvesters make use of energy that is otherwise wasted, WSN-HEAP contribute to environmental sustainability
- Increased structural monitoring capabilities will lead to more early warnings, thereby reducing the risk of deaths or injuries when structures collapse
Conclusions and Future Work

- Focus on maximizing throughput/goodput and minimizing delays given the amount of energy that we can harvest from the environment.
- Amount of sensor data should increase when energy harvesting rates increase and number of sensor nodes increase.
- Reliability issues are important in some sensor network applications.
- Set up a testbed to validate our ideas and protocols.
Thank you.

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