Home of the Future
and
Environmentally-Friendly Sensing

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Overview of Presentation

• STARHome – Science, Technology And Research Home
• Environmentally-Friendly Sensing with Wireless Sensor Networks Powered by Ambient Energy Harvesting
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(Science, Technology And Research home)

“Technology for living, experience of a lifetime”
What is STARhome?

- STARhome is an A*Star initiative to showcase state-of-the-art & innovative future home technologies from A*Star research institutes, universities and industry partners.

- A unique, flexible and fully functional “living lab” facility (in the form of a stand-alone apartment) built from scratch to enable in-depth study on future home technologies and concepts.
Mission & Vision

- To transform cutting-edge research into innovative & integrated future home technologies that will help accelerate the development of a digital home industry in Singapore.

- A model smart home showcase integrating innovative technologies into the lifestyle of choice for every member of the family.
Our value propositions

- Test bed for technology showcase
  - Realistic platform with extensive infrastructure
  - Neutral platform where diverse technologies coexist
- Innovative technologies to showcase new smart home concepts
- Resources to transform concepts into integrated prototypes
- High visibility & exposure for networking, marketing & promotions
Unifying theme

A smart home providing a safe, healthy and entertaining environment that you and your family would love to live in.
Areas of focus

- Safety & Security
- Healthcare & Comfort
- Automation & Control
- Entertainment & Information
<table>
<thead>
<tr>
<th>STARhome</th>
<th>Home2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology showcase</td>
<td>National research programme</td>
</tr>
<tr>
<td>Industry/commercialisation focused</td>
<td>Research focused</td>
</tr>
<tr>
<td>Short-term deliverables</td>
<td>Long-term deliverables</td>
</tr>
<tr>
<td>Anchored on UWB as wireless platform</td>
<td>Futuristic with no technological restrictions</td>
</tr>
</tbody>
</table>

Home 2015

STARhome

Industry

2005 2010 2015
Integrated Smart Home Programme

Home2015/STARhome:
- an Integrated A*STAR Smart Home Programme

R&D

Technology Trials

Live Trials

HOME2015
- R&D resources
- R&D expertises
- IPs

STARhome
- Facilities
- Integration services
- HFE studies

Fusionopolis Service Apartment
- Subjects
- Usability studies
3 Complementary Thrusts

Environment
An ENVIRONMENT that protects and promotes physical and mental well-being

Freedom
FREEDOM to choose & decide

Experience
A user-centric, non-intrusive and immersive EXPERIENCE
Specific Thrusts

- Low-maintenance home
- RFID-enabled home
- Interactive home
- Green home
Technologies & Projects

• Automation
  - Voice Command & Control (Speech-to-Text, I²R)
  - Smart Cabinet (RFID, I²R)
  - Smart Media Player (Reader IC, IME)

• Entertainment
  - News Indexing (Video Extraction & Categorization, I²R)
  - News Subtitling (Speech-to-Text, I²R)
  - News Subtitling Translation (Language Translation, I²R)
  - A*STAR Intelligent Media (CE Group, DSI)
  - Smart Mobile Storage (Wireless Hard Disk, DSI)
  - 3D Personal Gaming (Gesture Recognition, I²R)
  - Attention Training Game (Brain Computer Interface, I²R)
  - Interactive Table (Multi-Touch, I²R)
  - Digital Jukebox (AAZ Audio Coding, I²R)
  - Sports Highlights (Event Detection, I²R)
Technologies & Projects

- Healthcare
  - Fall Detection (Visual Event Understanding, I²R)
  - Smart Bed Sleeping Pattern Monitoring (Fiber Bragg Sensors, I²R)
  - Smart Bed Vital Signs Detection (Home 2015 Research)

- Security
  - Voice Verification (Voice ID, I²R)
  - Face Verification (Face Recognition, I²R)
  - Fingerprint Matching on Smart Card (Biometric, I²R)
Projects

- New Projects in the pipeline
  - Anti-Scratch Surface (SIMTech)
  - Color Tunable LEDs (IMRE)
  - Organic Solar Cell (IMRE)
  - Configurable Multimodal Robot (HOME2015)
  - Scalable Multimedia Platform (HOME2015)
  - Urine Protein Detection (HOME2015)
  - 3-D Holographic Display for Mobile Devices (HOME2015)
  - Powerline Communications with Cognitive Intelligence (HOME2015)
  - Wireless Health Monitoring (HOME2015)
  - Low-power UWB transceiver for WPAN (HOME2015)
  - Intelligent mmWave Platform (HOME2015)
Living room & Kitchen area
Playing area and Dining room
Balcony
Children room and Master bedroom
Study room, Walk-in closet and Bathroom
Where is STARHome?

Visit at

1 Fusionopolis Way
13 Floor Connexis (North Tower)
Singapore 138632
Environmentally-Friendly Sensing with WSN-HEAP

Winston Seah
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Leader, Wireless Sensor Networks Group
Overview

• Harvesting Ambient Energy
• Wireless Sensor Networks (WSNs)
• WSN Powered by Ambient Energy Harvesting – WSN-HEAP
• Research Challenges
• The Road Ahead
• Conclusions & Ongoing Work
Harvesting Ambient Energy

Has been going on for many decades
  – hydro-electric, solar, geothermal, wind

More recently…
  – fluctuations of magnetic field
  – vibrations on machinery, body of aircraft
  – pressure or linear motion of pushing button
  – strain on structures
  – waves in ocean
Harvesting Ambient Energy

Yet to come...

– the radio waves that fill the air
– ever-present environmental gradients such as changes in temperature
What is the state-of-the-art?

Source: Centre for Energy Harvesting Materials and Systems
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.

IRIS mote

MICAz mote
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

• Assisted Living and Healthcare
Motivation

• Ambient intelligence requires a good sense of the environment → spatial sensing capabilities
• High costs of wiring and replacing batteries
• For nodes to be conveniently placed and efficiently utilized → as small as possible; e.g. electronic device with a 1 cm$^3$ of non-rechargeable lithium battery (at max energy density of 2880 J/cm$^3$ or 800 watt hour per liter) were to consume 100 µW of power on average, the device would last 333 days.
• “How to power the sensors?” “Who will replace billions of batteries?”
Motivation

• Need an alternative (and perpetual) source of energy to power such WSNs which may be installed:
  – for long durations (up to decades) of uninterrupted usage
  – embedded in structures where battery replacement is unfeasible or impractical without damaging the structure and/or facade
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 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

- **Rechargeable 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)
## 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.
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
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
<table>
<thead>
<tr>
<th>Type of business</th>
<th>Type of product</th>
<th>Description</th>
<th>Power source</th>
<th>Enabling technology</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Ceramics Inc.</td>
<td>OEM</td>
<td>Piezoelectric composite materials</td>
<td>Proprietary piezoelectric strips with a wide dynamic range—from the weight of a mosquito to hammer strike—generate voltage output proportional to force</td>
<td>Motion, vibration, pressure</td>
<td>Piezoelectric fibers in polymer strip</td>
</tr>
<tr>
<td>Advanced Linear Devices Inc.</td>
<td>Integrated circuits</td>
<td>Proprietary floating gate chip technology enables transistors to turn on with as little as 10 mV (normal transistors require 0.7 volts)</td>
<td>Charges battery with electrical current from piezoelectric or other transistor</td>
<td>CMOS</td>
<td>Battery replacement/recharging</td>
</tr>
<tr>
<td>Canstar Technologies</td>
<td>OEM modules</td>
<td>Variety of technologies, each of which convert motion into electricity</td>
<td>Linear motion, vibration</td>
<td>Voice-coil, piezoelectric, magneto</td>
<td>Battery replacement/recharging</td>
</tr>
<tr>
<td>Cidrasis Inc.</td>
<td>OEM modules</td>
<td>Inductive coil and piezoelectric transducers actuated by the linear motion of a pushbutton, as well as thermoelectric transistor that changes a capacitor when temperature changes</td>
<td>Linear motion, vibration, temperature</td>
<td>Inductive coil, piezoelectric, thermoelectric</td>
<td>Wireless lighting switches, battery elimination</td>
</tr>
<tr>
<td>Feero Solutions Inc.</td>
<td>OEM modules</td>
<td>Inductive coil, piezoelectric and proprietary ferromagnetic shape memory alloys generate electricity in response to vibration or magnetic-field changes</td>
<td>Vibration, pressure</td>
<td>Inductive coil, piezoelectric, actuator and ferromagnetic shape memory alloy (FSMA) transducer</td>
<td>Battery replacement</td>
</tr>
<tr>
<td>Mentor Industries Inc.</td>
<td>OEM modules</td>
<td>Thermoelectric generators as an alternative energy source</td>
<td>Temperature differential</td>
<td>Thermoelectric semiconductor material</td>
<td>Alternative energy source</td>
</tr>
<tr>
<td>MicroStrain Inc.</td>
<td>UCM modules</td>
<td>Piezoelectric transducers convert vibrations into electrical current*</td>
<td>Vibrations</td>
<td>Piezoelectric transducer</td>
<td>Sanitary elimination/recharging</td>
</tr>
<tr>
<td>Mite Technology Corp.</td>
<td>OEM modules</td>
<td>Piezoelectric transducers convert vibrations into electrical current</td>
<td>Vibration, strain</td>
<td>Piezoelectric wafer</td>
<td>Wireless sensor networks</td>
</tr>
<tr>
<td>Pangolin Ltd.</td>
<td>OEM modules</td>
<td>Vibration energy-harvesting microgenerator based on a magnet and coil transforms vibration into electrical current</td>
<td>Vibration</td>
<td>Inductive coil</td>
<td>Battery replacement</td>
</tr>
<tr>
<td>Powercase LLC</td>
<td>UCM modules</td>
<td>High frequency power transceivers and matched power receivers</td>
<td>Radio waves</td>
<td>Radio frequency transmitters/receivers</td>
<td>Wireless battery recharging/replacement</td>
</tr>
<tr>
<td>PolySwitch Systems</td>
<td>End-user wall-mounted pushbutton switch</td>
<td>Piezoelectric transducer actuated by a pushbutton that generates radio signal to power module, which turns on with light</td>
<td>Linear motion</td>
<td>Piezoelectric actuator</td>
<td>Wireless lighting switch</td>
</tr>
<tr>
<td>SmartMaterial</td>
<td>OEM modules</td>
<td>Piezoelectric composite materials generate electricity from motion</td>
<td>Linear motion, vibration ultrasound</td>
<td>Piezoelectric</td>
<td>Battery elimination</td>
</tr>
<tr>
<td>Thermopile Energy Corp.</td>
<td>OEM modules</td>
<td>Thermoelectric generator directly converts thermal energy into electricity</td>
<td>Temperature</td>
<td>Thermoelectric transducer</td>
<td>Battery elimination/recharging</td>
</tr>
</tbody>
</table>
WSN-HEAP node

- Energy harvesting device
- Energy storage
- Sensor
- Processing unit
- Wireless transceiver
- Buffer management

[Diagram showing the components of a WSN-HEAP node, including a solar cell and battery packs.]
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
Challenges in Power Management in WSN-HEAP

• In WSN-HEAP, higher transmission power means longer energy harvesting time
  – Reduced sending rate
• Higher transmission power also means:
  – More potentially awake neighbors to forward data packets to
  – More interference among nodes as energy harvesting tends to be spatially correlated
• What is the optimal transmit power to maximize throughput?
Modulation and Coding

IEEE 802.15.4
- Predominant WSN physical data transmission standard
- Commonly (and often incorrectly) 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

Not designed for energy harvesting scenarios
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-wakeup schedules
  - Not possible to know exactly when each node is awake
- Difficult to set duty cycles
  - Energy harvesting rates change with time and place
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?
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>
</table>
The Road Ahead

• Wireless communications and medium access issues are likely to dominate in the home environment.

• Possibility of hybrid storage approach that utilizes both supercapacitors (for periodic monitoring) and rechargeable batteries (for alarm situations that require packets to be sent immediately).
Conclusions & Ongoing 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

• Focus on maximizing throughput/goodput and minimizing delays given the amount of energy that we can harvest from the environment.
Conclusions & Ongoing Work

• 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.