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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starhome

(Science, Technology And Research home)

"Technology for living, experience of a lifetime"

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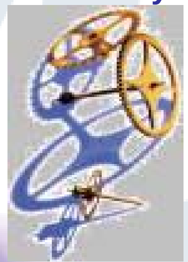
What is STARhome?

NANYANG TECHNOLOGICAL UNIVERSITY

NUS National University of Singapore

Industry



starhome

Agency for Science, Technology and Research

- 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.

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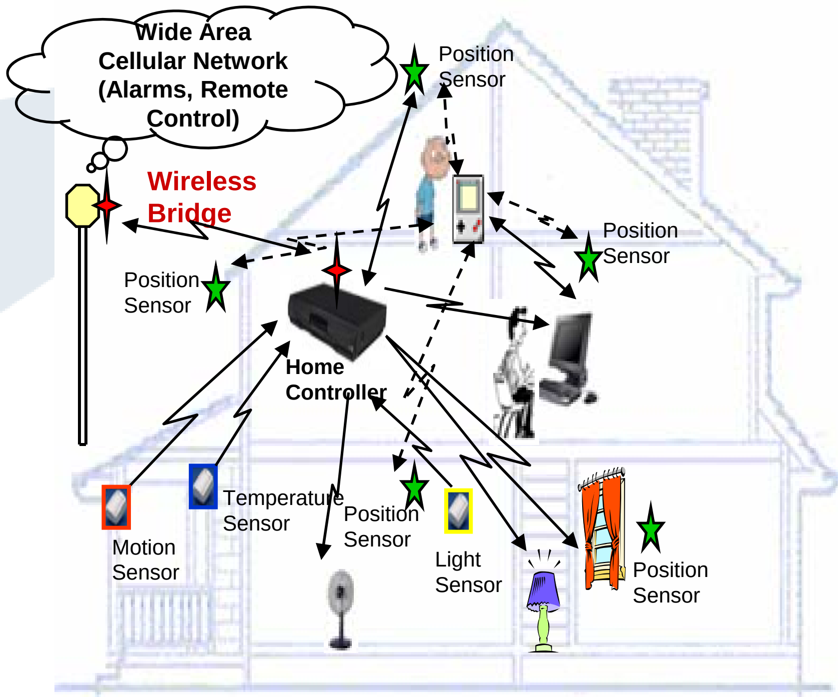
Mission & Vision

- 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

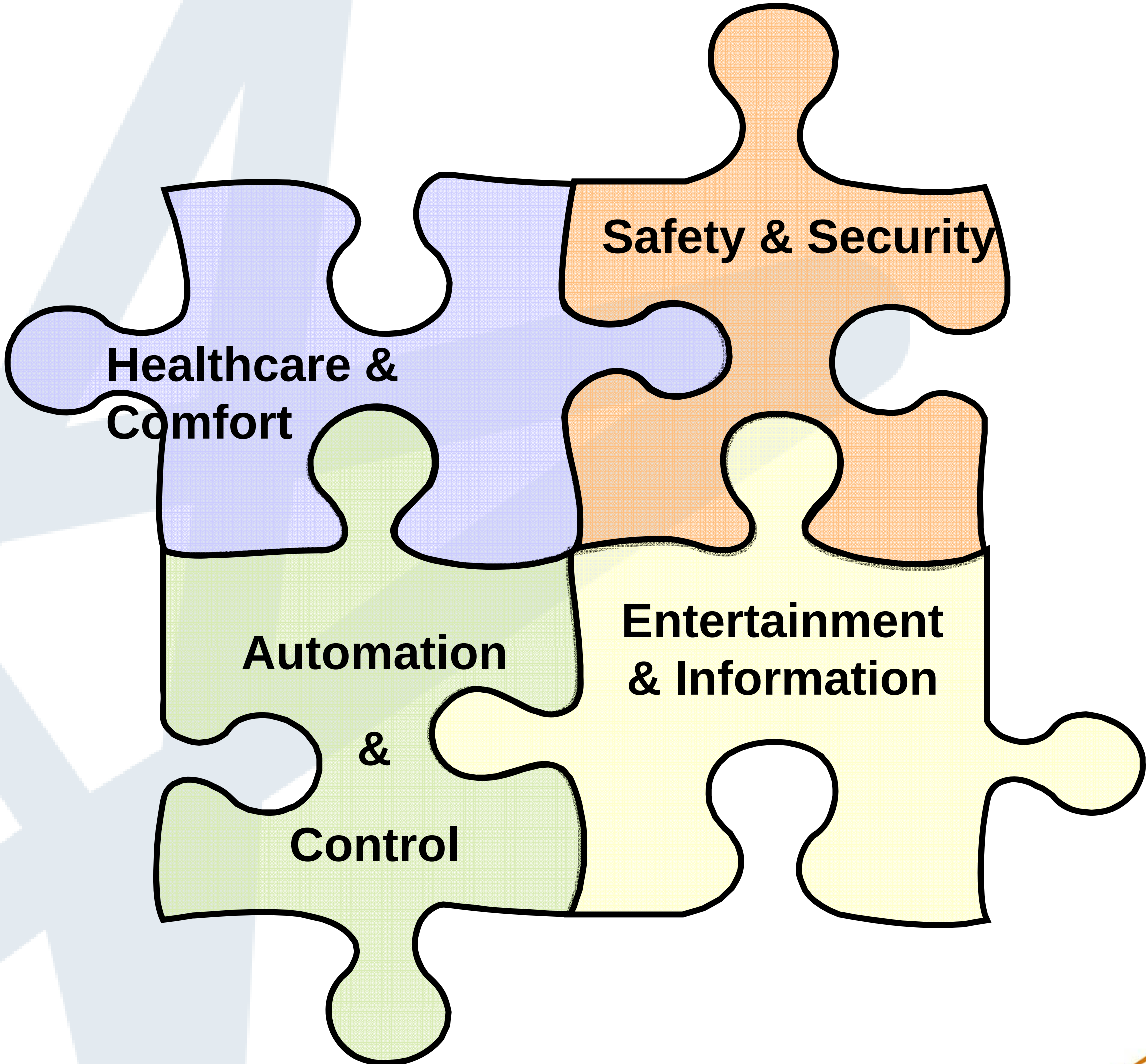
- Test bed for technology showcase
  - Realistic platform with extensive infrastructure
  - Neutral platform where diverse technologies coexist
- Innovative technologies to showcase new smart home concepts
- Resources to transform concepts into integrated prototypes
- High visibility & exposure for networking,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



Unifying theme

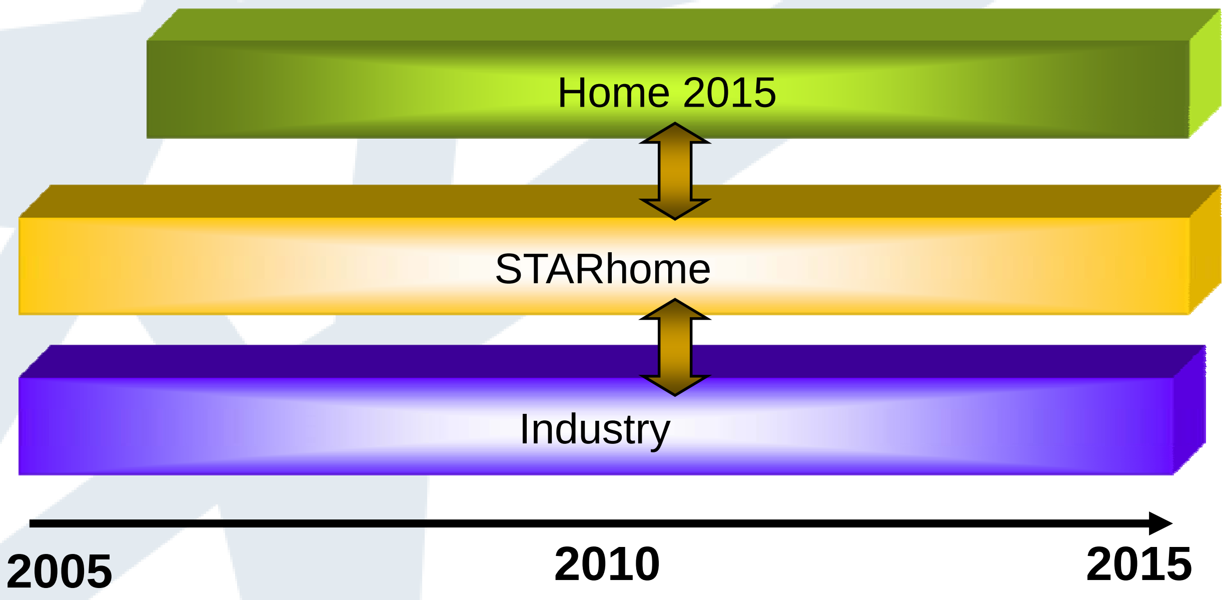
A smart home providing a safe, healthy and entertaining environment that you and your family would love to live in.

Areas of focus



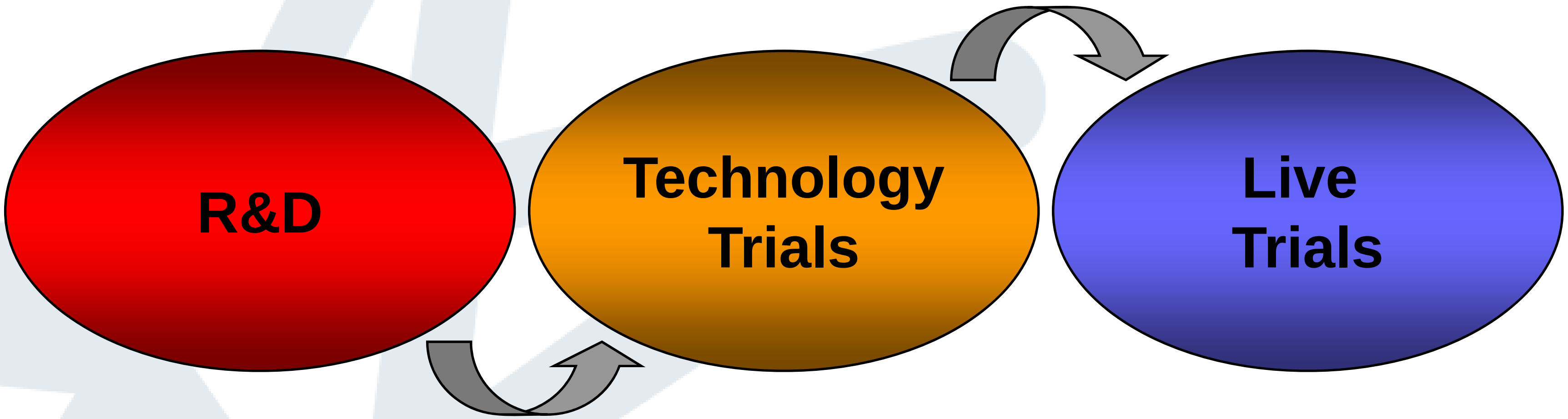
STARhome vis-à-vis Home2015

STARhome	Home2015
Technology showcase	National research programme
Industry/commercialisation focused	Research focused
Short-term deliverables	Long-term deliverables
Anchored on UWB as wireless platform	Futuristic with no technological restrictions



Integrated Smart Home Programme

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



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

STARhome
- Facilities
- Integration services
- HFE studies

Fusionopolis Service Apartment
- Subjects
- Usability studies

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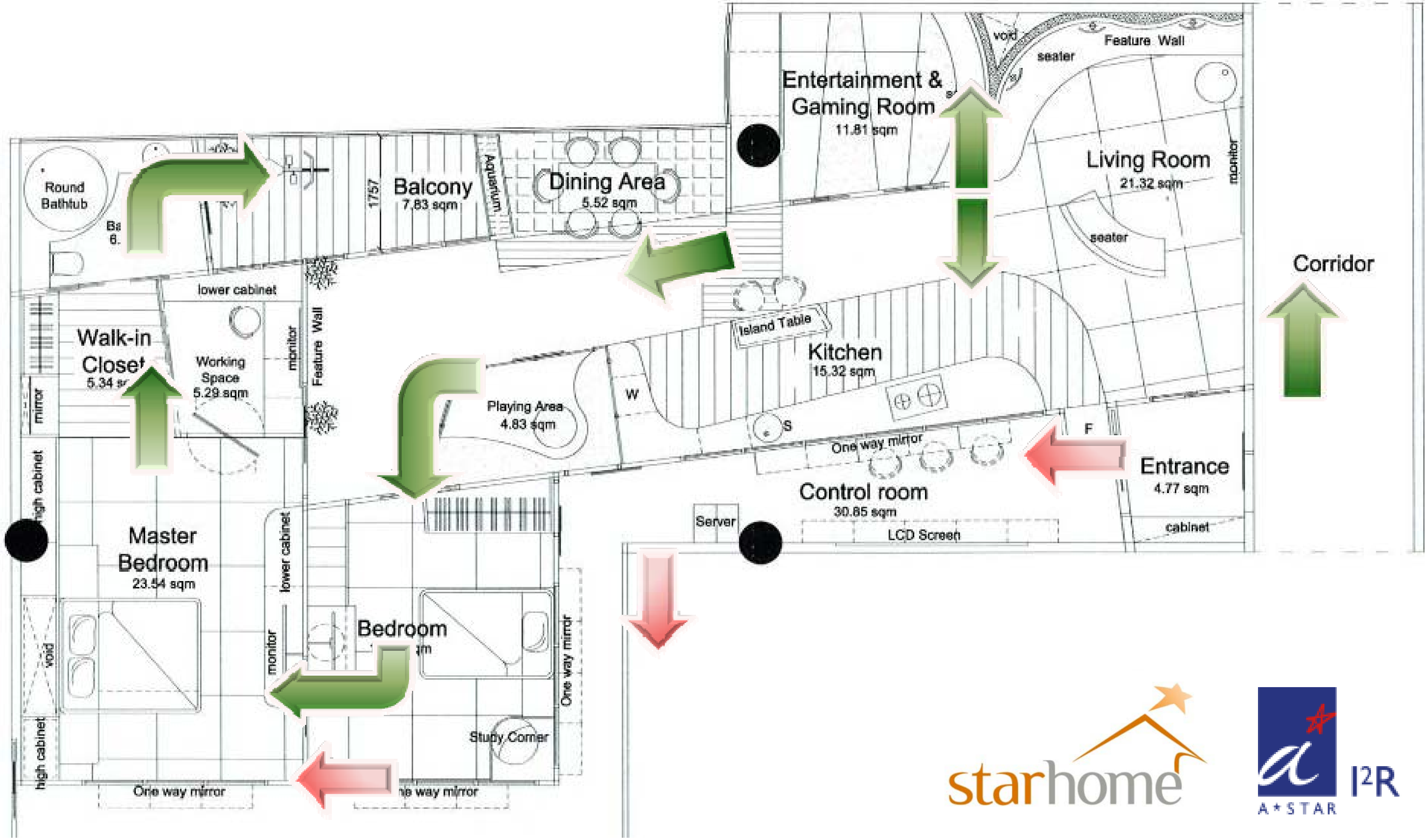
Layout



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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

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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**)

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Technologies & Projects

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- **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**)

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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**)

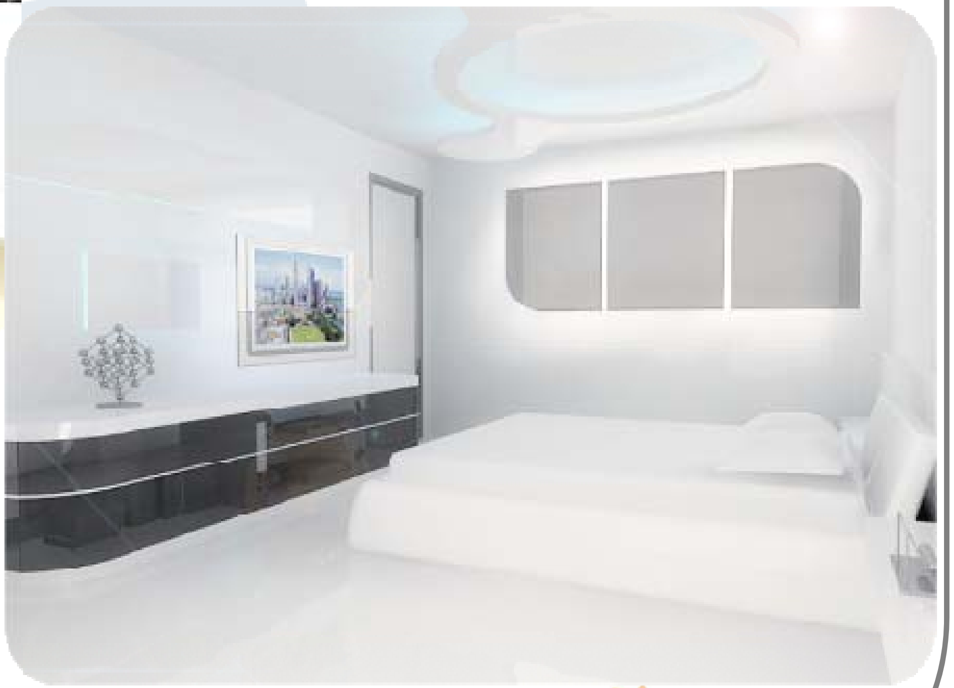
Living room & Kitchen area

Entertainment & Gaming room

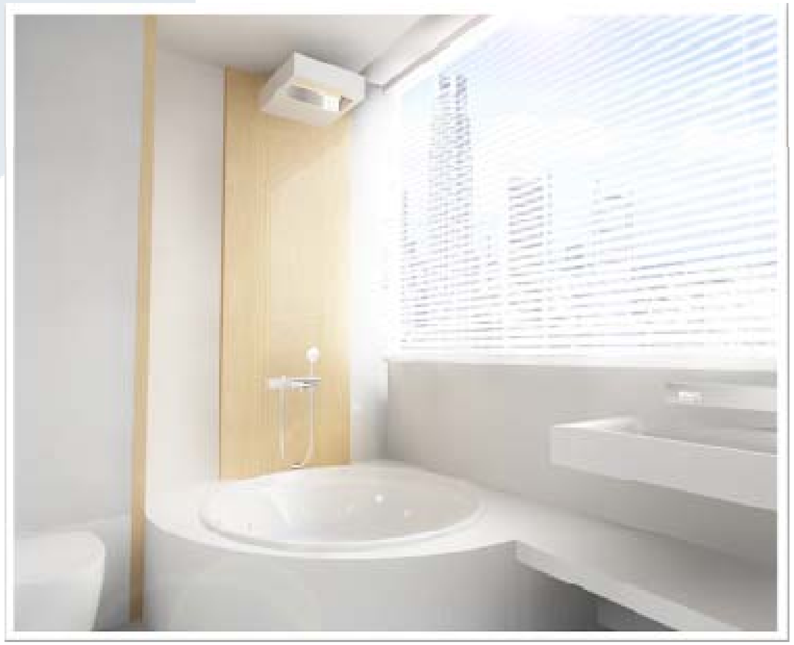
Playing area and Dining room

Balcony

Children room and Master bedroom



Study room, Walk-in closet and Bathroom



Control Room

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Where is STARHome?

Visit starhome at

1 Fusionopolis Way
13 Floor Connexis (North Tower)
Singapore 138632

Environmentally-Friendly Sensing with WSN-HEAP

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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…

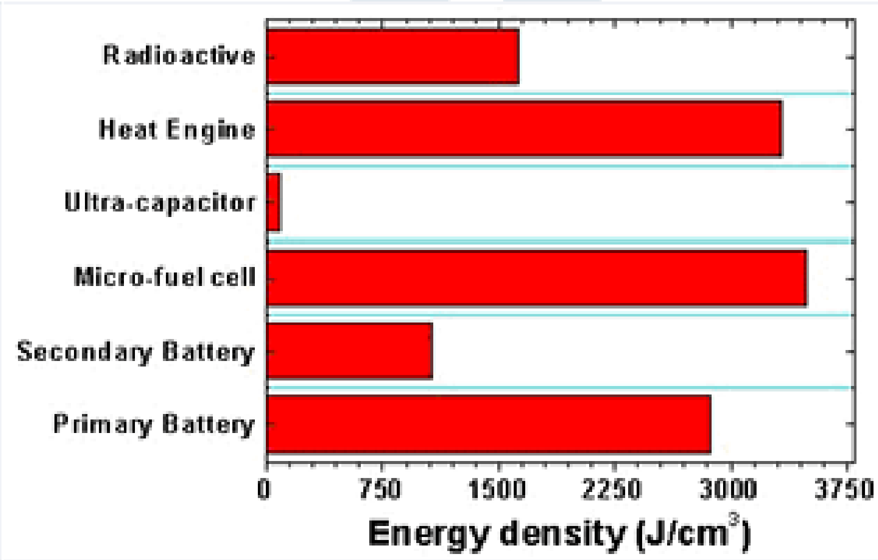
- fluctuations of magnetic field
- vibrations on machinery, body of aircraft
- pressure or linear motion of pushing button
- strain on structures
- waves in ocean

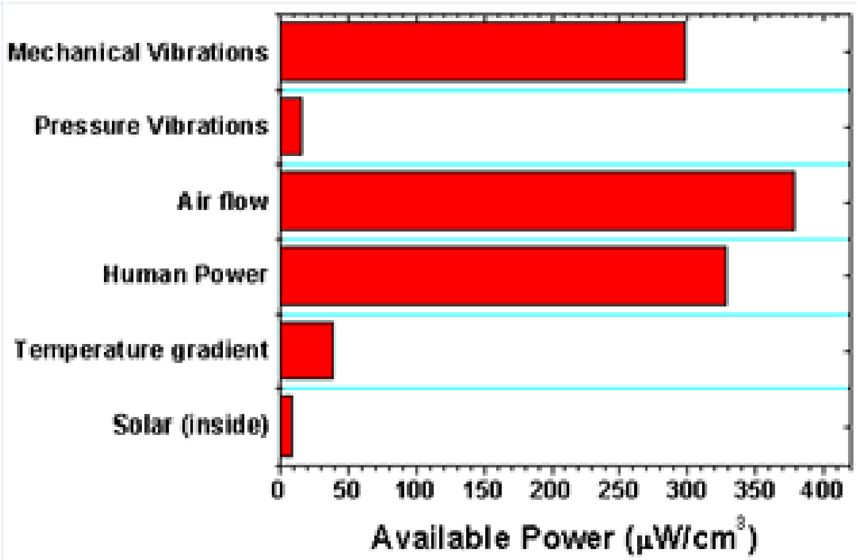
Harvesting Ambient Energy

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

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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/cm3 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

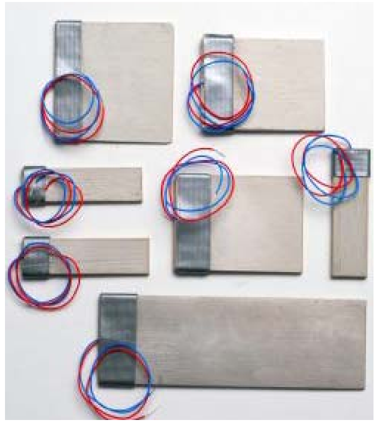
- Need an alternative (and perpetual) source of energy to power such WSNs which may be installed:
  - for long durations (up to decades) of uninterrupted usage
  - embedded in structures where battery replacement is unfeasible or impractical without damaging the structure and/or facade

Energy Harvesting

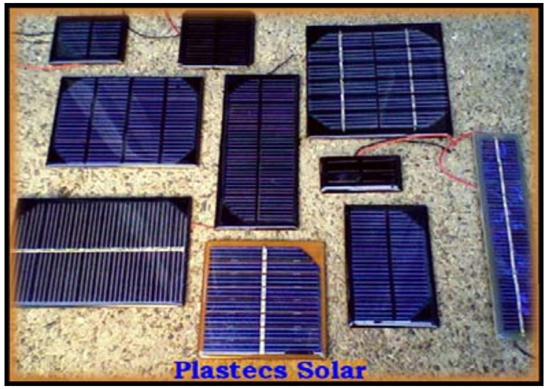
- Power has been and remains the key WSN issue
- Alternative source of energy for WSNs
- Gather energy that is present in the environment, i.e. ambient energy
- Convert the energy into a form that can be used to power devices
- Assumes energy source is well characterized, regular and predictable
- Energy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

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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)

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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)

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Current State-of-the-Art Energy Harvesting Rates

Technology	Power Density ($\mu W/cm^2$)	Energy Harvesting Rate (mW)	Duty Cycle (%)
Vibration – electromagnetic	4.0	0.04	0.05
Vibration – piezoelectric	500	5	6
Vibration – electrostatic	3.8	0.038	0.05
Thermoelectric	60	0.6	0.72
Solar – direct sunlight	3700	37	45
Solar – indoor	3.2	0.032	0.04

Source: B. H. Calhoun et. al., "Design Considerations for Ultra-Low Energy Wireless Microsensors Nodes", IEEE Transactions on Computers, Vol. 54, No. 6, June 2005

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

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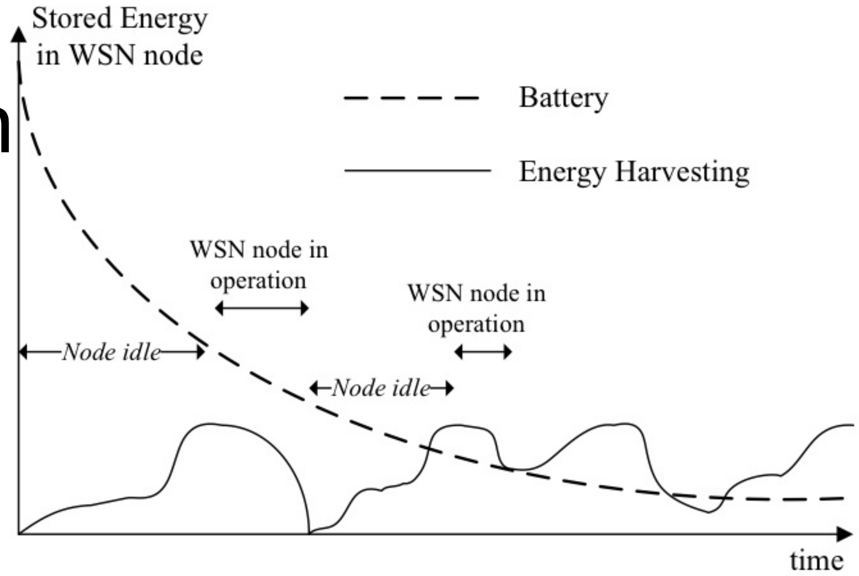
Energy Model of WSN-HEAP node

- 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



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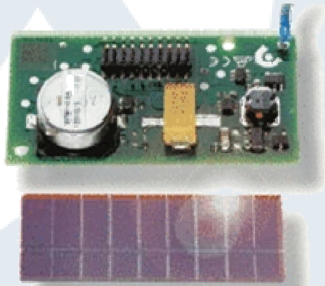
Sensor Nodes with Energy Harvesting

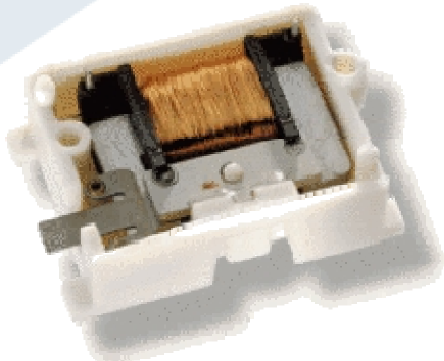
- Commercial
  - Ambiosystems
  - Microstrain
  - Enocean
  - Crossbow

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

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Energy on tap

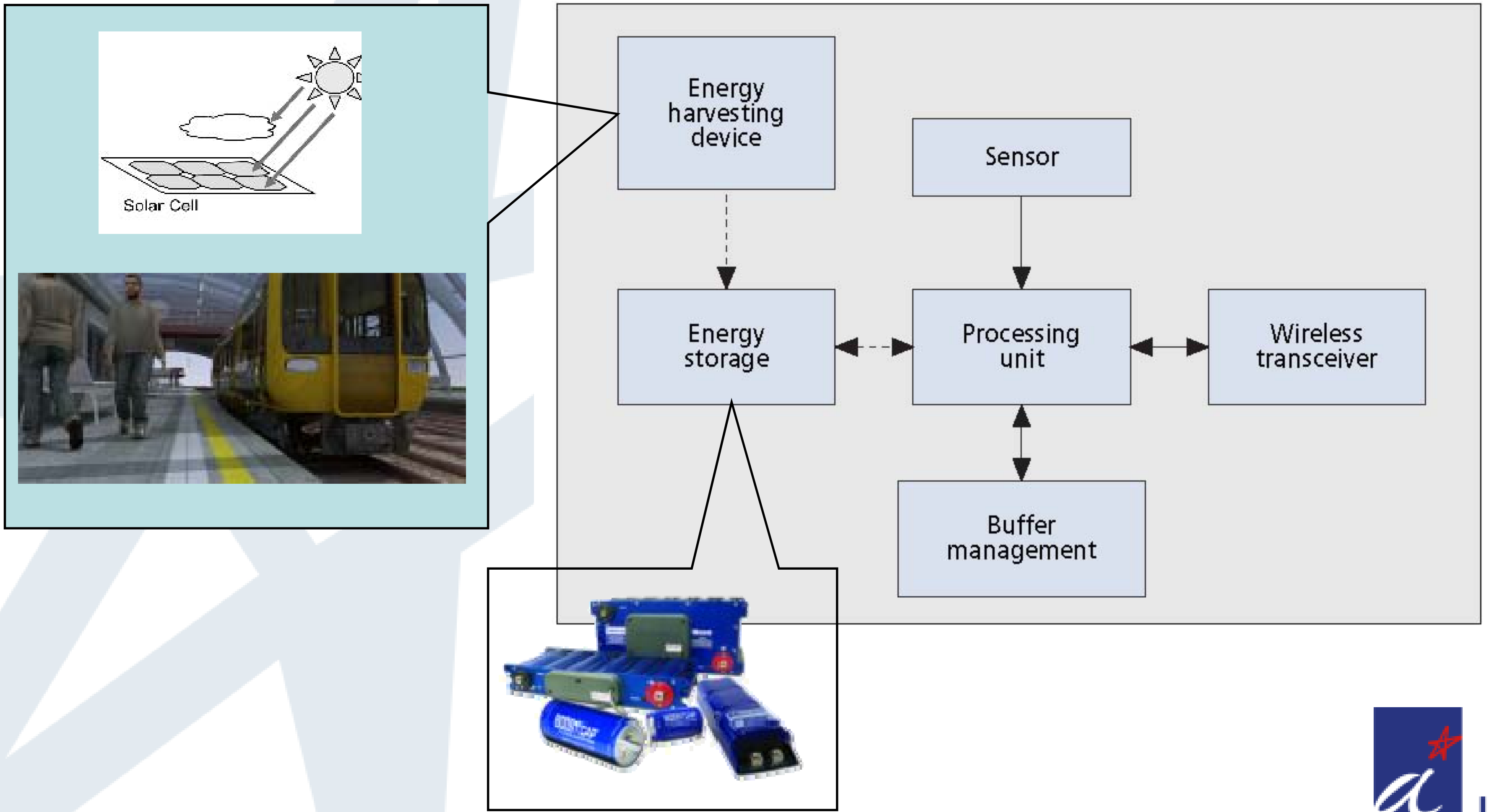
Available harvesting technology solutions

	Type of product	Description	Power source	Enabling technology	Application
Advanced Cerametrics Inc. *www.advancedcerametrics.com*	OEM piezoelectric-fiber composite materials	Proprietary piezoelectric strips with a wide dynamic range—from the weight of a mosquito to hammer strike—generate voltage output proportional to force	Motion, vibration, pressure	Piezoelectric fibers in polymer strip	Battery replacement/ recharging
Advanced Linear Devices Inc. *www.aldinc.com/*	Integrated circuits	Proprietary floating-gate chip technology enables transistors to turn on with as little as 10 mV (normal transistors require 0.7 volts)	Charges battery with electrical current from piezoelectric or other transducer	CMOS	Battery replacement/ recharging
Cedrat Technologies *www.cedrat.com*	OEM modules	Variety of technologies, each of which convert motion into electricity	Linear motion, vibration	Voice-coil, piezoelectric, magnetic	Battery replacement/ recharging
EnOcean Inc. *www.enocean.com*	OEM modules	Inductive coil and piezoelectric transducers actuated by the linear motion of a pushbutton, as well as thermocouple transducer that charges a capacitor when temperature changes	Linear motion, vibration, temperature	Inductive coil, piezoelectric stack, thermocouple	Wireless lighting switches, battery elimination
Ferro Solutions Inc. *www.ferrosi.com*	OEM modules	Inductive coil, piezoelectric and proprietary ferromagnetic shape memory alloys generate electricity in response to vibrations or magnetic-field changes	Vibration, pressure	Inductive coil, piezoelectric actuator and ferromagnetic shape memory alloy (FSMA) transducer	Battery replacement
Marlow Industries Inc. *www.marlow.com*	OEM modules/ subassemblies	Thermoelectric generators as an alternative energy source	Temperature differential	Thermoelectric semiconductor material	Alternative energy source
MicroStrain Inc. *www.microstrain.com*	OEM modules	Piezoelectric transducers convert vibrations into electrical current*	Vibrations	Piezoelectric strip	Battery elimination/ recharging
Midé Technology Corp. *www.mide.com*	OEM modules	Piezoelectric transducers convert vibrations into electrical current	Vibration, strain	Piezoelectric wafer	Wireless sensor networks
Perpetuum Ltd. *www.perpetuum.co.uk*	OEM modules	Vibration energy-harvesting microgenerator based on a magnet and coil transforms vibration into electrical current	Vibration	Inductive coil	Battery replacement
Powercast LLC *www.powercastco.com/*	OEM modules	Radio frequency power beacons and matched power receivers	Radio waves	Radio frequency transmitters/ receivers	Wireless battery recharging/ replacement
PulseSwitch Systems *www.lightningswitch.com*	End-user wall-mounted pushbutton switch	Piezoelectric transducer actuated by pushbutton sends radio signal to receiver module, which turns on the light	Linear motion	Piezoelectric actuator	Wireless lighting switch
Smart Material *www.smart-material.com*	OEM materials	Piezoelectric composite materials generate electricity from motion	Linear motion, vibration, ultrasound	Piezoelectric composite	Battery elimination
Thermolife Energy Corp. *www.poweredbythermolife.com*	OEM modules	Thermoelectric generator directly converts thermal energy into electricity	Temperature	Thermoelectric transducer	Battery elimination/ charging

*Available in 2009

Source: EE Times

WSN-HEAP node

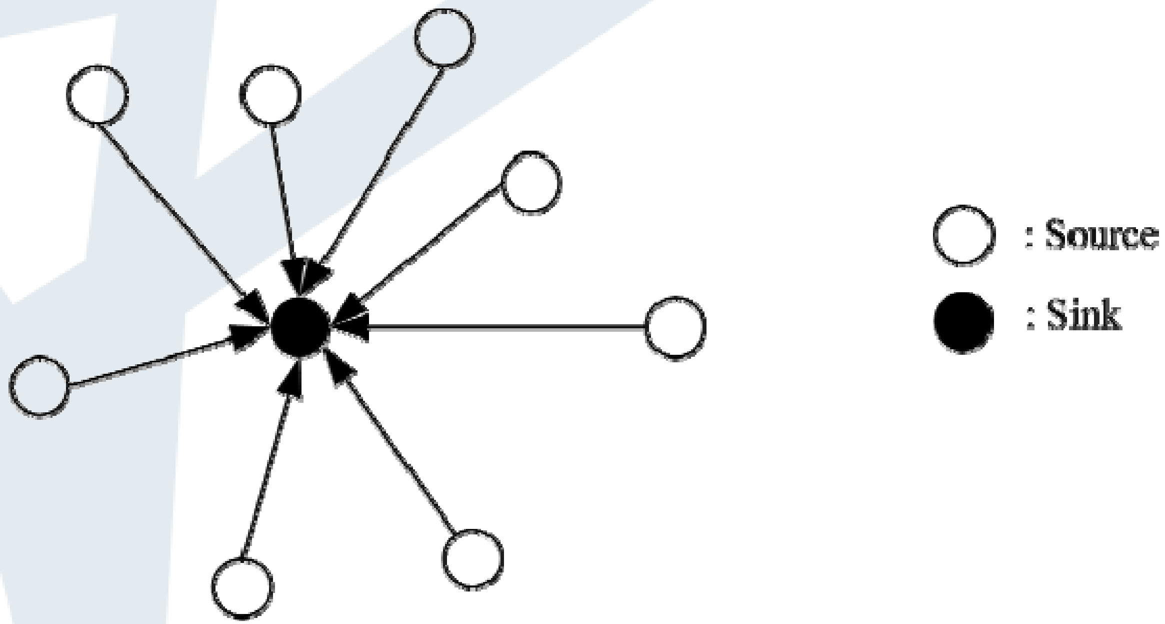


Research Challenges

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

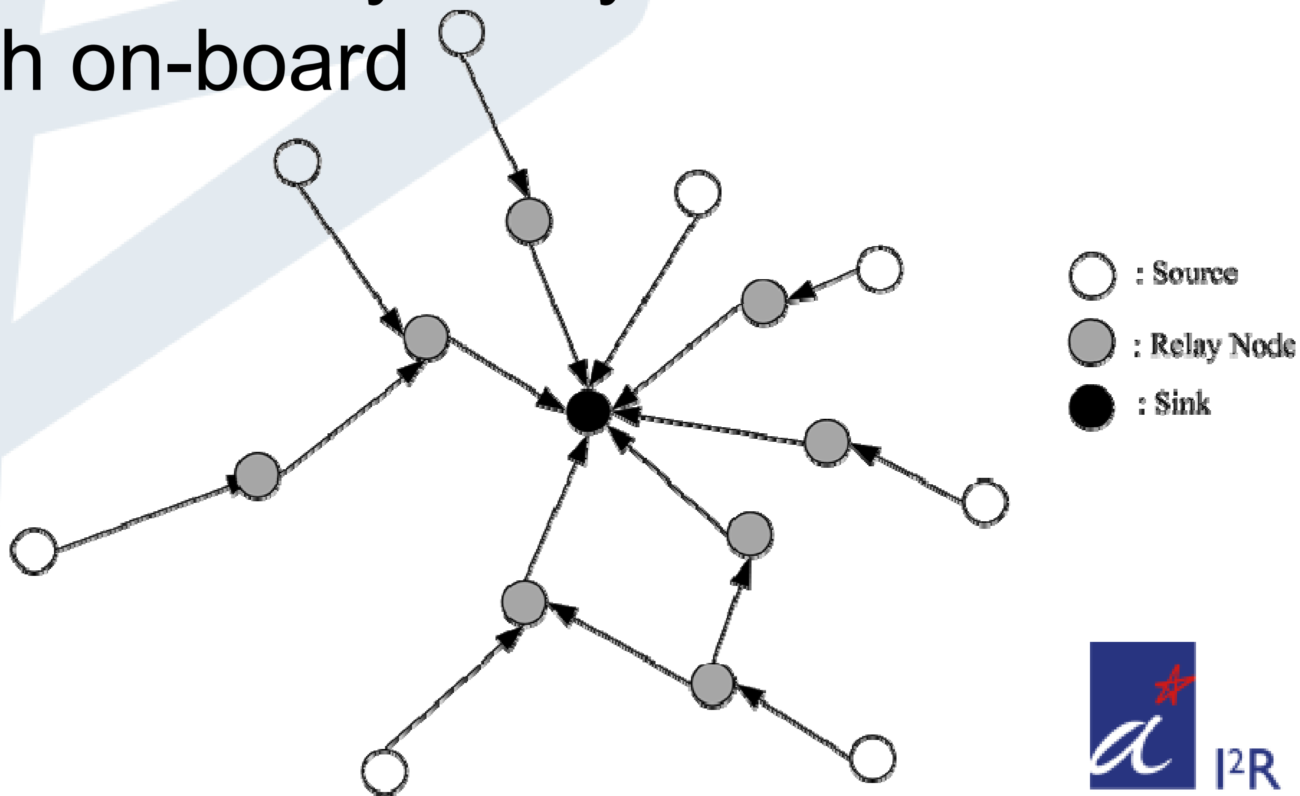
WSN Architecture

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



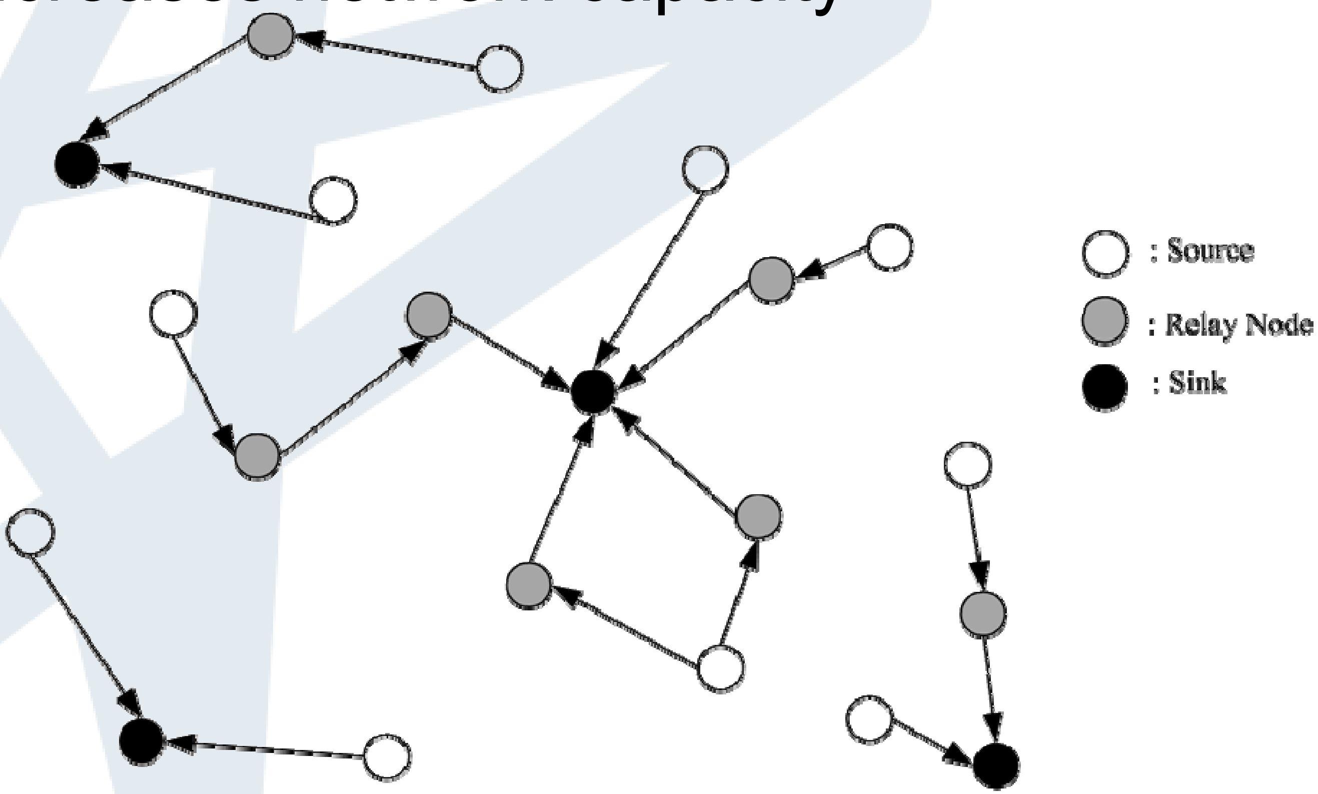
WSN Architecture

- 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?

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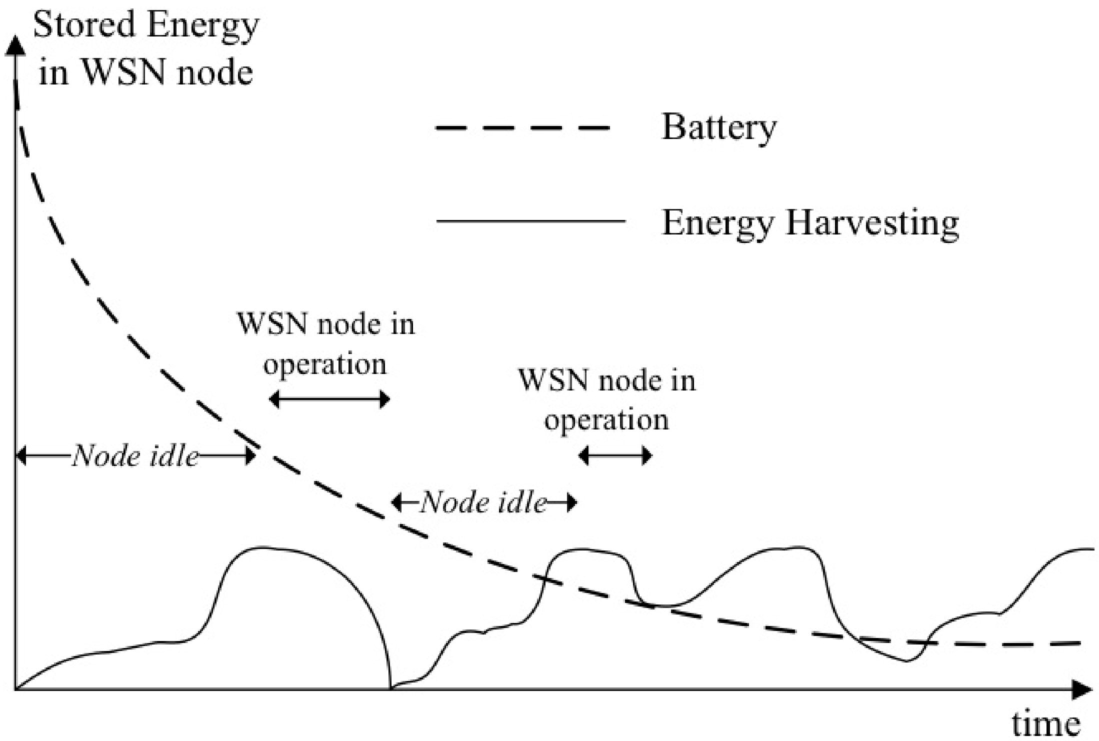
Challenges in transport protocols for WSN-HEAP

- 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

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

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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.