WSN-HEAP

Wireless **S**ensor **N**etworks **P**owered by **A**mbient **E**nergy **H**arvesting

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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

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
- 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

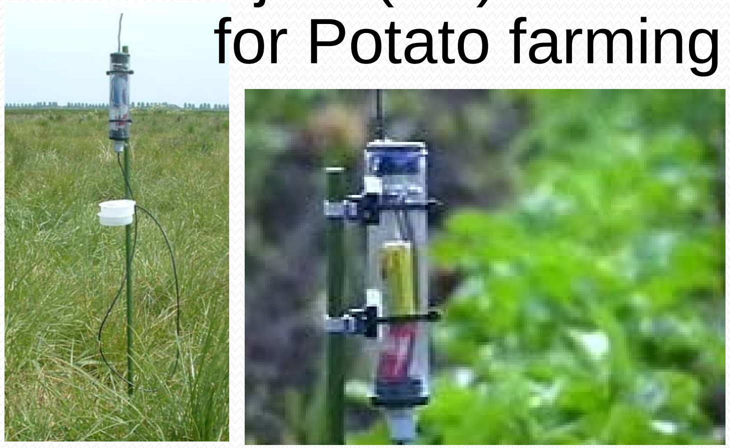
WSN for Agriculture

Grape Networks (US)

SoilWeather (FI)

CSIRO (AU)

Lofar Project (NL) - WSN for Potato farming



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(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

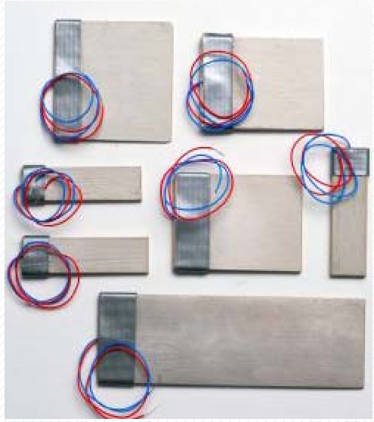
Energy Harvesting for Agriculture

Why Ambient Energy Harvesting?

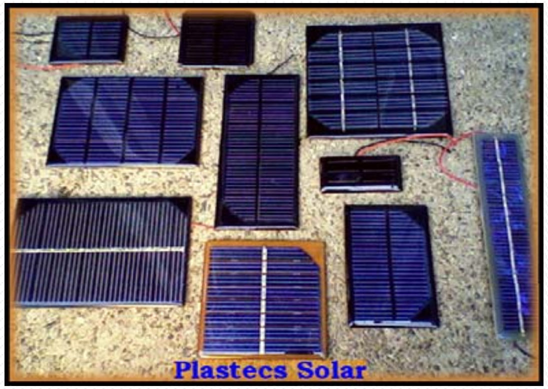
- Batteries in sensor nodes in plantation are not easily replaceable → high risk of damaging crops
- No batteries → no danger of battery leakage and polluting the environment
- Operate perpetually without need for human intervention

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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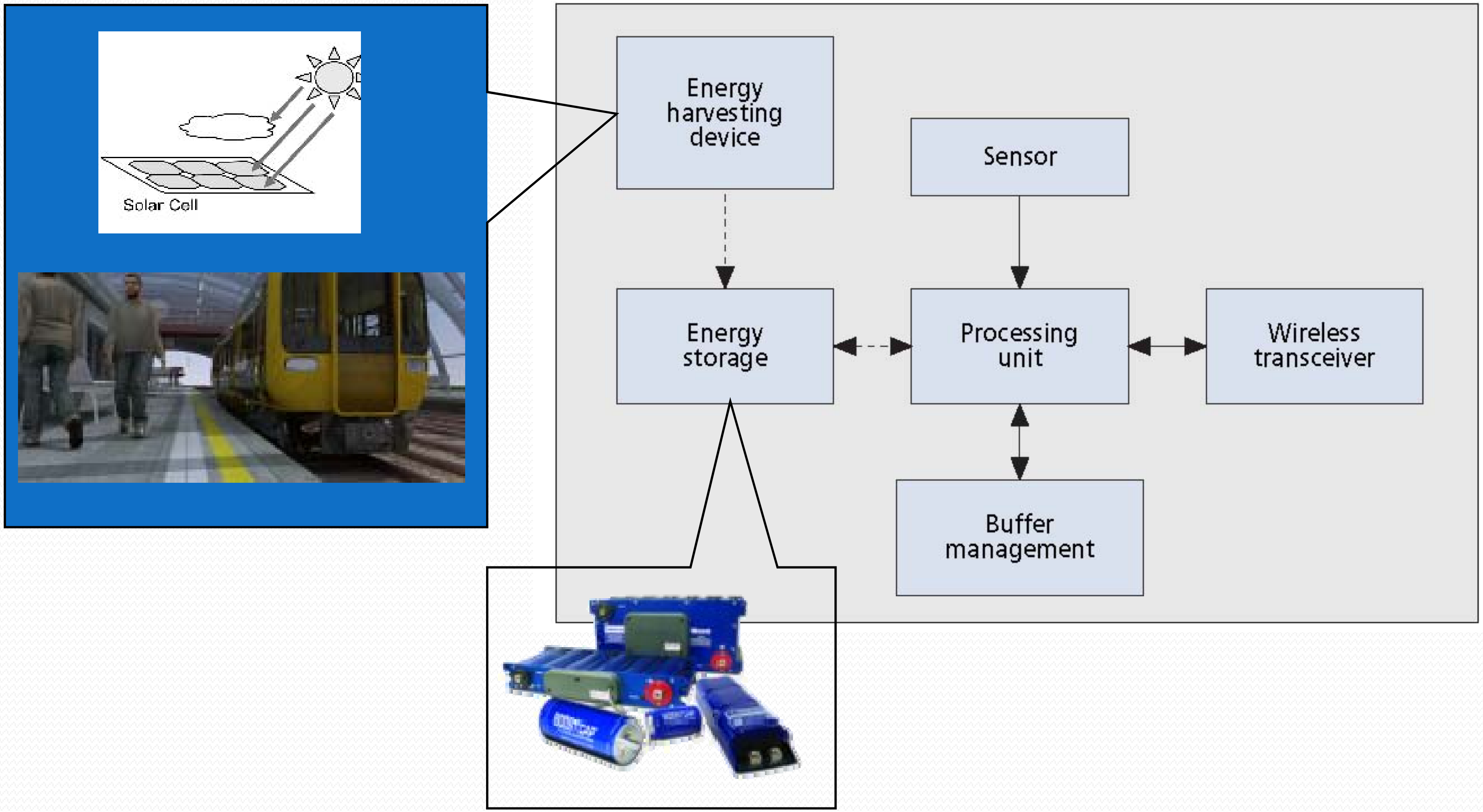
WSN-HEAP

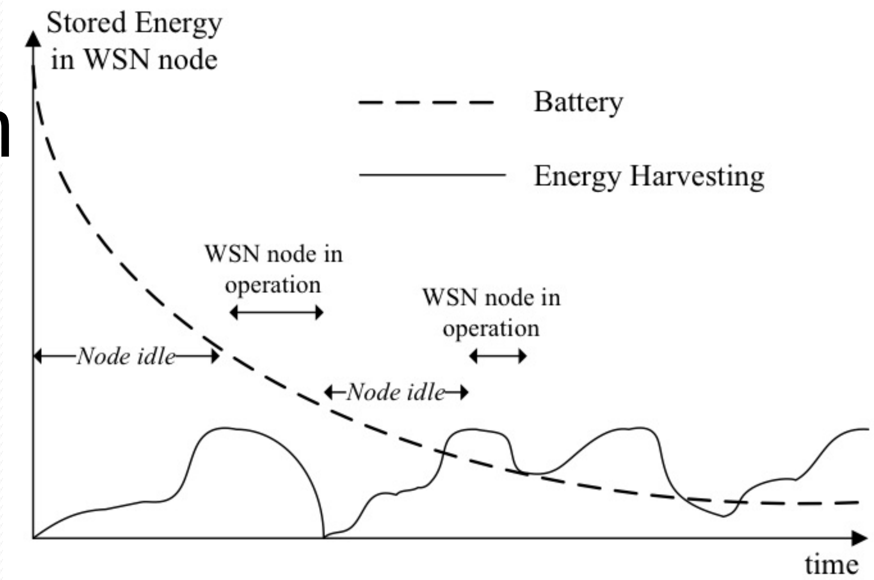
- Acronym for Wireless Sensor Networks Powered by Ambient Energy Harvesting
- Used for denoting WSNs that are solely powered by energy harvesting devices using capacitors/supercapacitors
  - excludes WSNs that use energy harvesters to supplement battery power

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

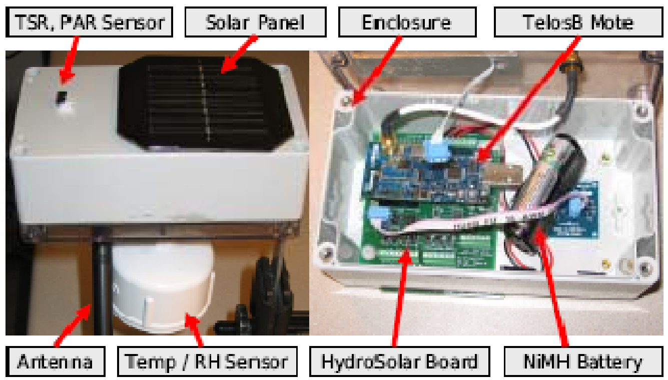


Major Research Groups

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

Heliomote by UCLA

EPFL

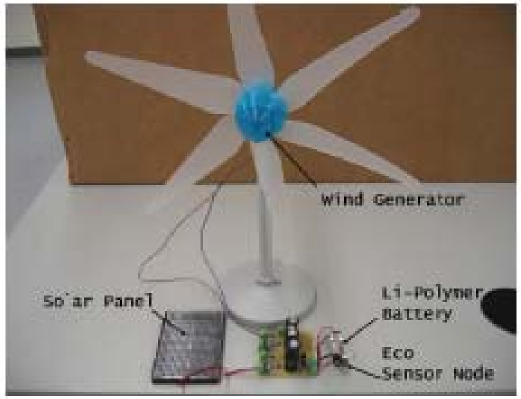


UC Berkeley

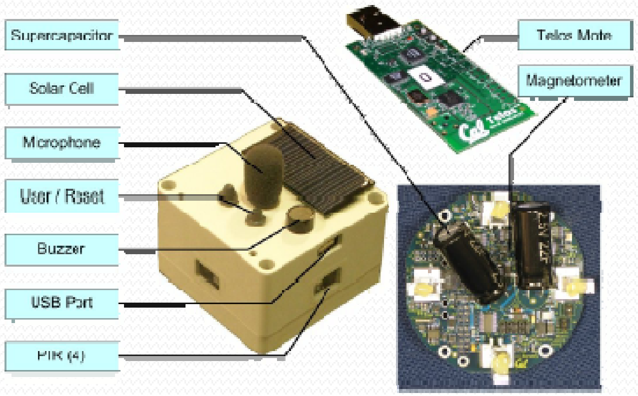
Sensor Nodes with Energy Harvesting

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

Heliomote



AmbiMax

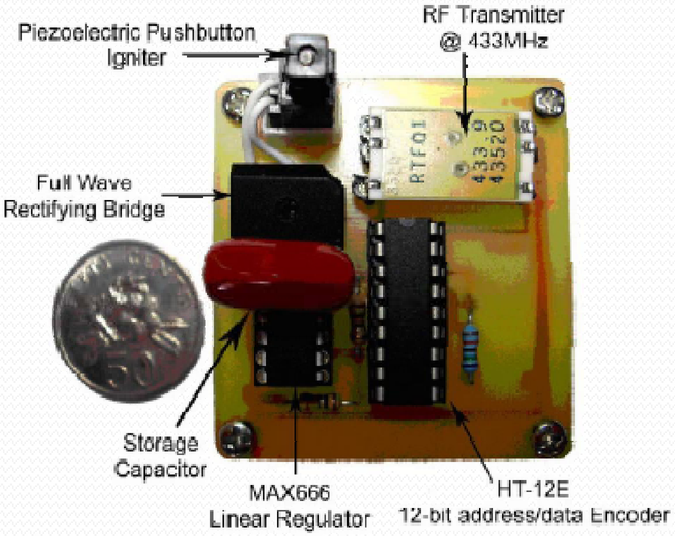


Trio Mote

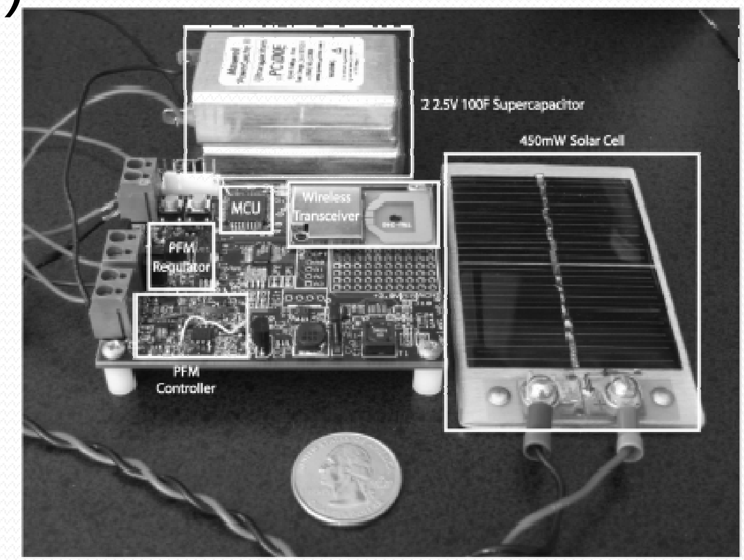
Sensor Nodes with Energy Harvesting

Research

- Piezoelectric Igniter (Y. K. Tan and S. K. Panda, IEEE ICIT 2006)
- Everlast (F. I. Simjee and P. H. Chou, IEEE Trans. on Power Electronics, 2008)



Piezoelectric Igniter



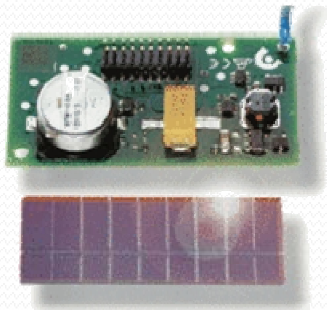
Everlast

Sensor Nodes with Energy Harvesting

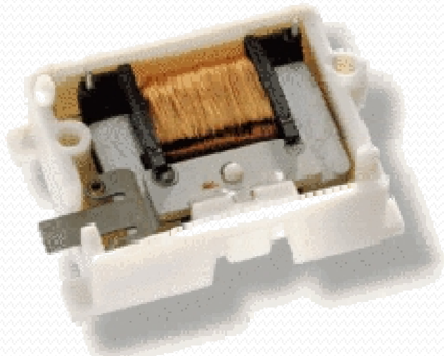
- Commercial
  - Ambiosystems
  - Microstrain
  - Enocean
  - Crossbow

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

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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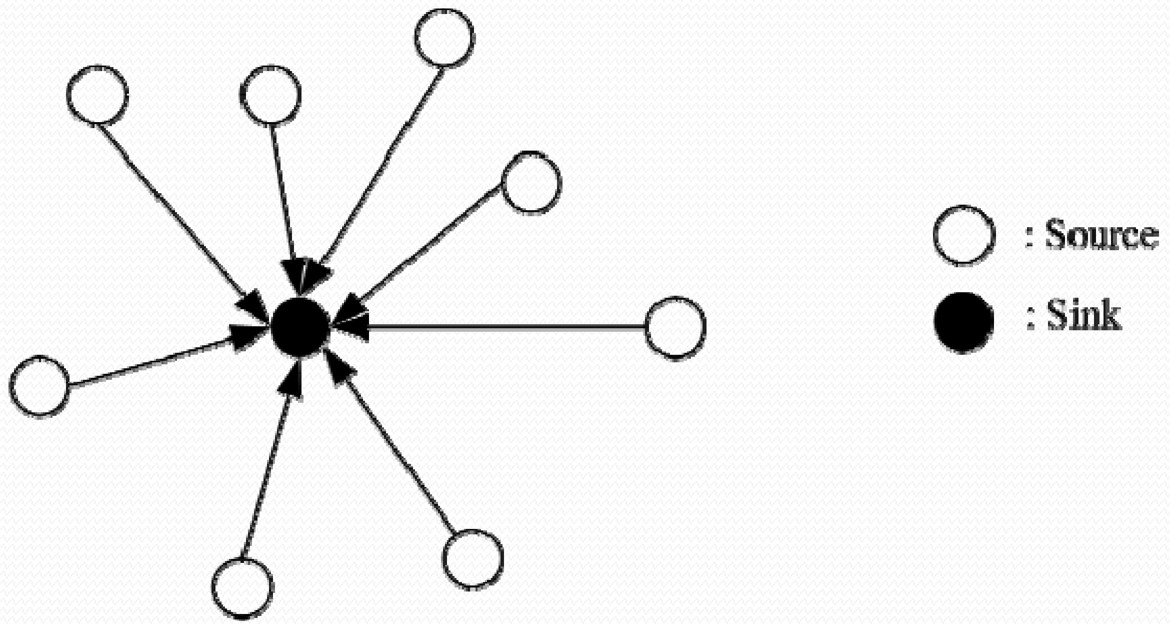
Research Challenges

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

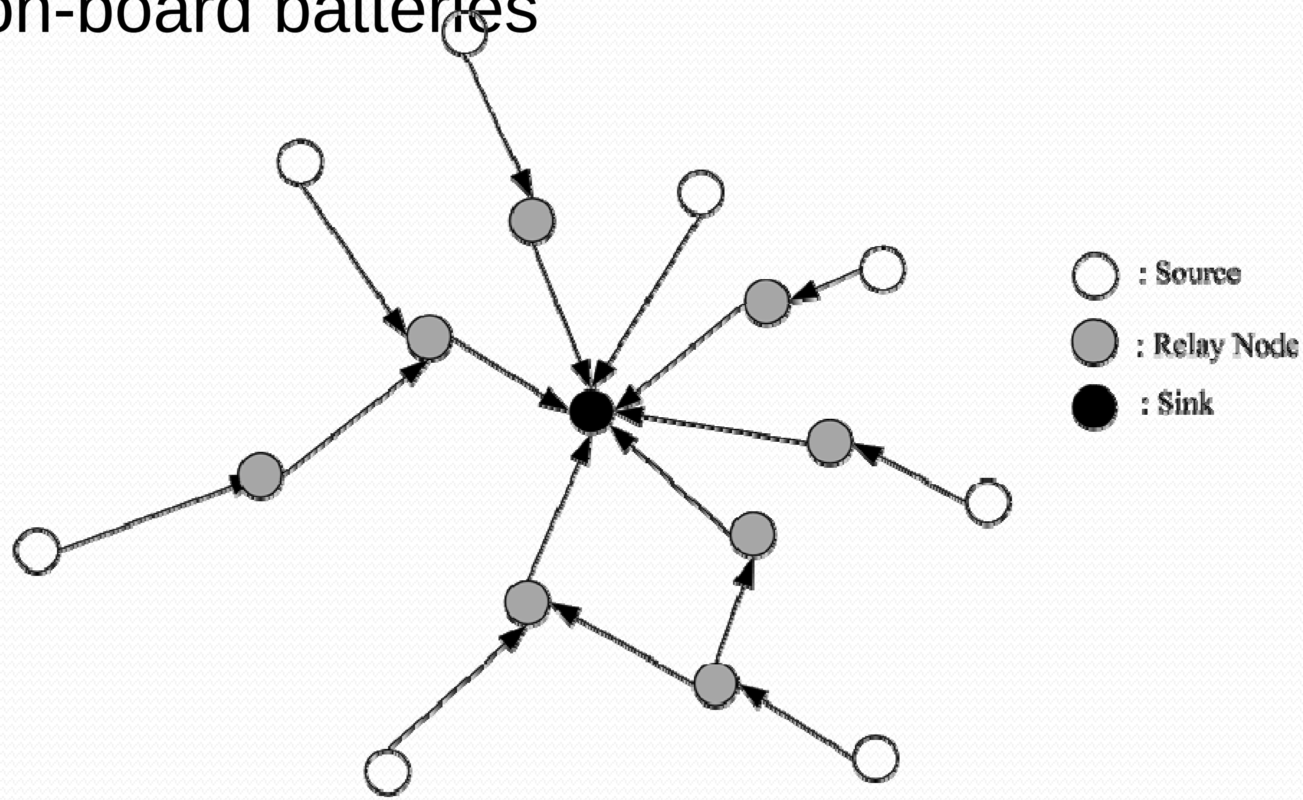
WSN Architecture

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



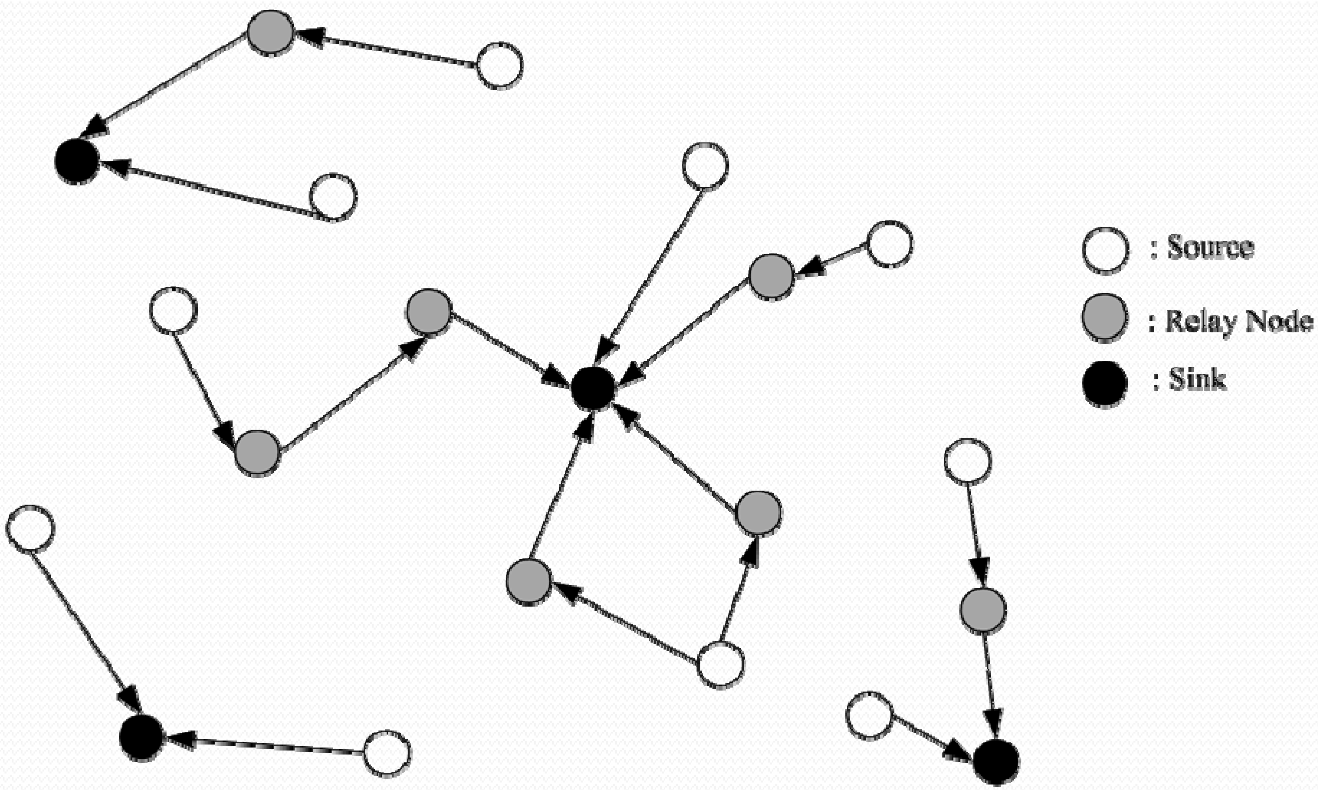
WSN Architecture

- 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
  - ISLPED 2003, SIGMETRICS 2004, IPSN 2005, DAC 2006, ISLPED 2006, ACM TECS 2007
- 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-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

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
  - GeRaF (M. Zorzi, IEEE Trans on Mobile Computing, 2003)
  - 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

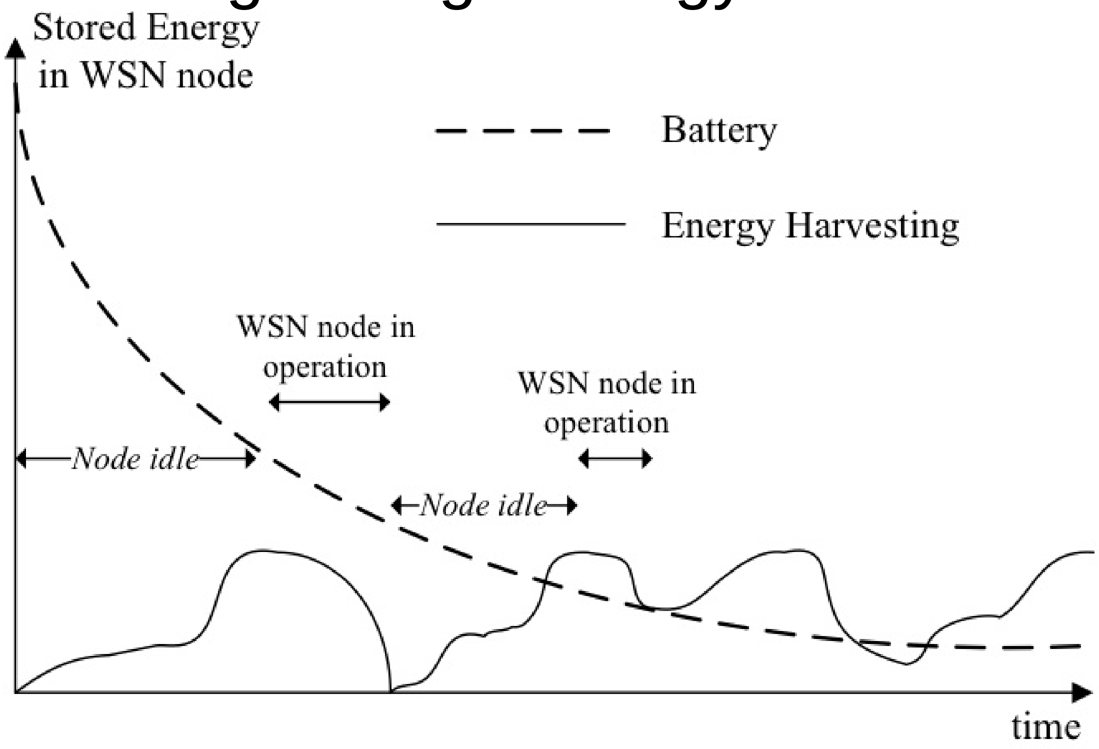
- Variable Reliability
  - STCP (Y. G. Iyer, ICCCN 2005)
- Event-based Reliability
  - ESRT (Y. Sankarasubramaniam, MobiHoc 2003)
- Congestion Control
  - Flush (S. Ki, Sensys 2007)
  - CODA (C.-Y. Wan, Sensys 2003)
  - Fusion, CCF, PCCP, ARC, Siphon, Trickle

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

	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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Application Examples

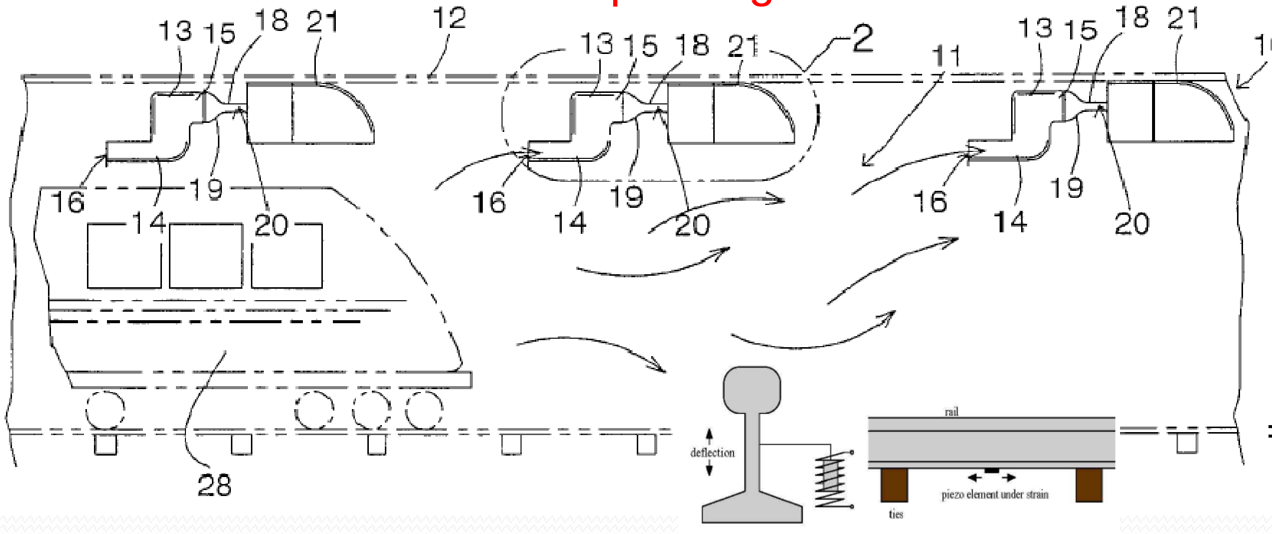
- Self-powered railway sleeper monitoring system
- Stability Monitoring of Bridges and Expressways

Wireless Monitoring Systems for Rail Systems

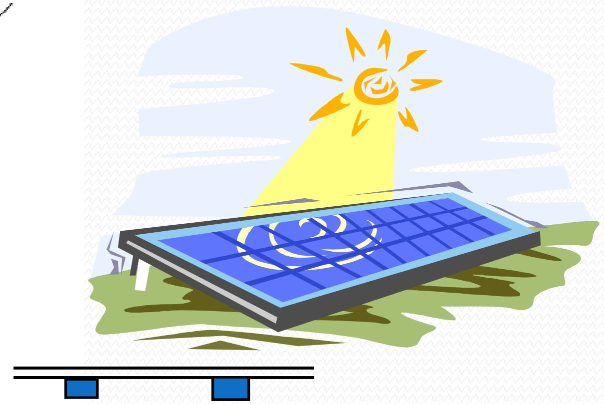
- Railway track and bridge monitoring
  - Remote (wireless) rail temperature preventive maintenance system in UK's high speed rail network since 2005
  - Next-generation wireless mesh for predictive maintenance demonstrated for Network Rail (UK) in 2007
- Battery-powered
  - Requires human intervention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

Self-Powering (Ambient Energy Harvesting)

Wind energy
from passing trains in tunnels

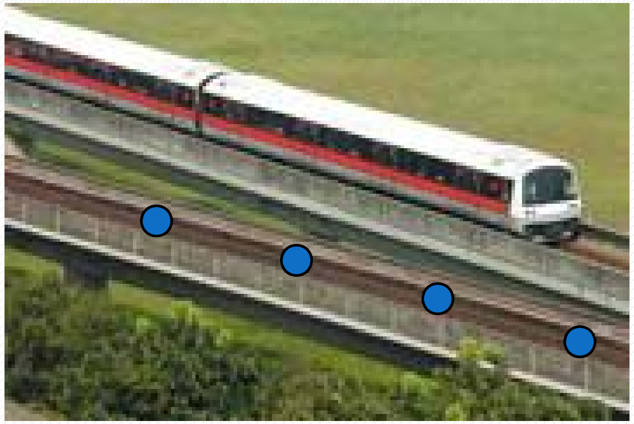


Vibrational energy
from track deflections



Solar energy
for outdoor tracks

Self-Powered, Online Rail-track Sleeper Monitoring



● Self-Powered, Wireless Monitoring Instrument (vibration, solar) on sleepers on viaduct and at-grade stations

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

Stability Monitoring of Bridges and Expressways using WSN-HEAP

Photo Source: SysEng (S) Pte Ltd

Pasir Panjang Semi-Expressway

Photo Source: SysEng (S) Pte Ltd

Ongoing Research

MAC Protocols for WSN-HEAP

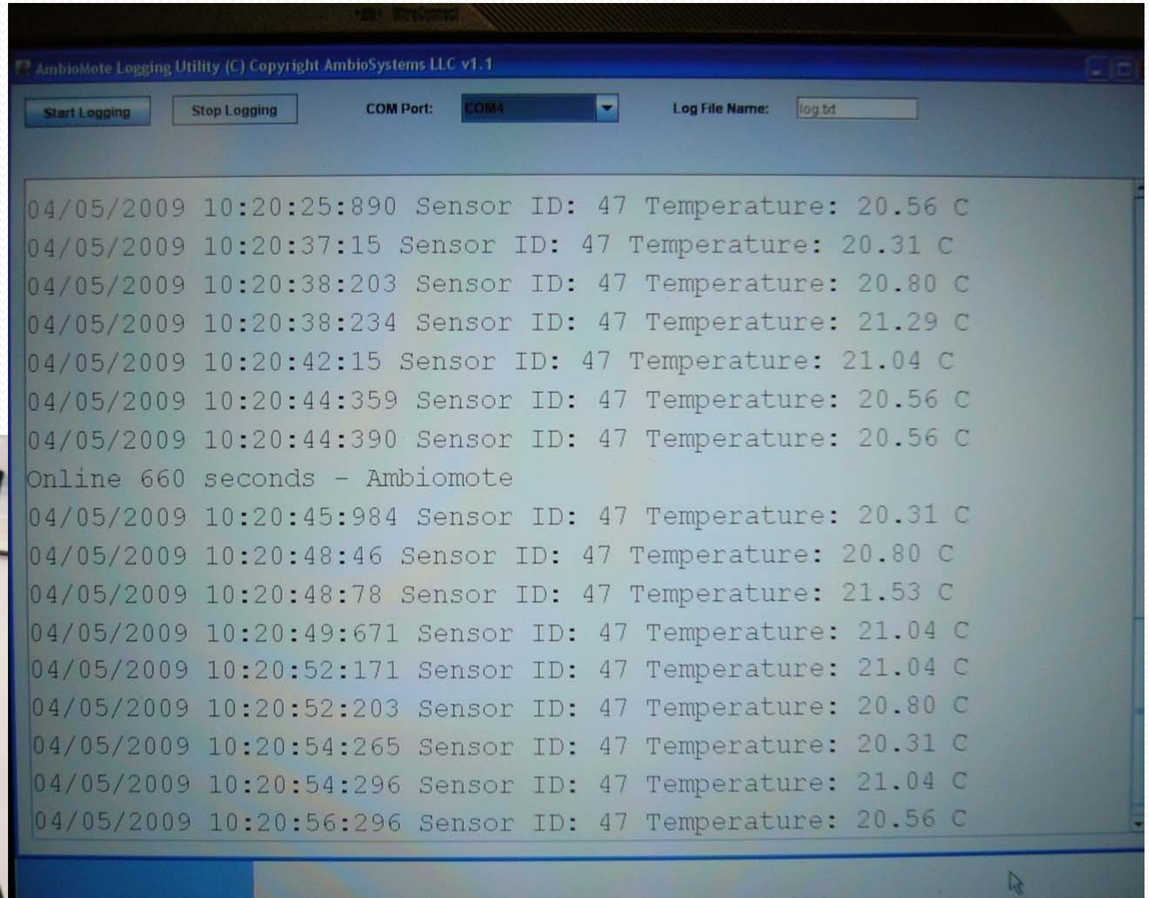
- Adapt and compare different MAC protocols for use in WSN-HEAP
- Design MAC scheme for WSN-HEAP
- Validated analytical and simulation results; working on experimentation
- Results enable network designers to determine the suitable MAC protocol to use to maximize throughput given the average energy harvesting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

Ongoing Research

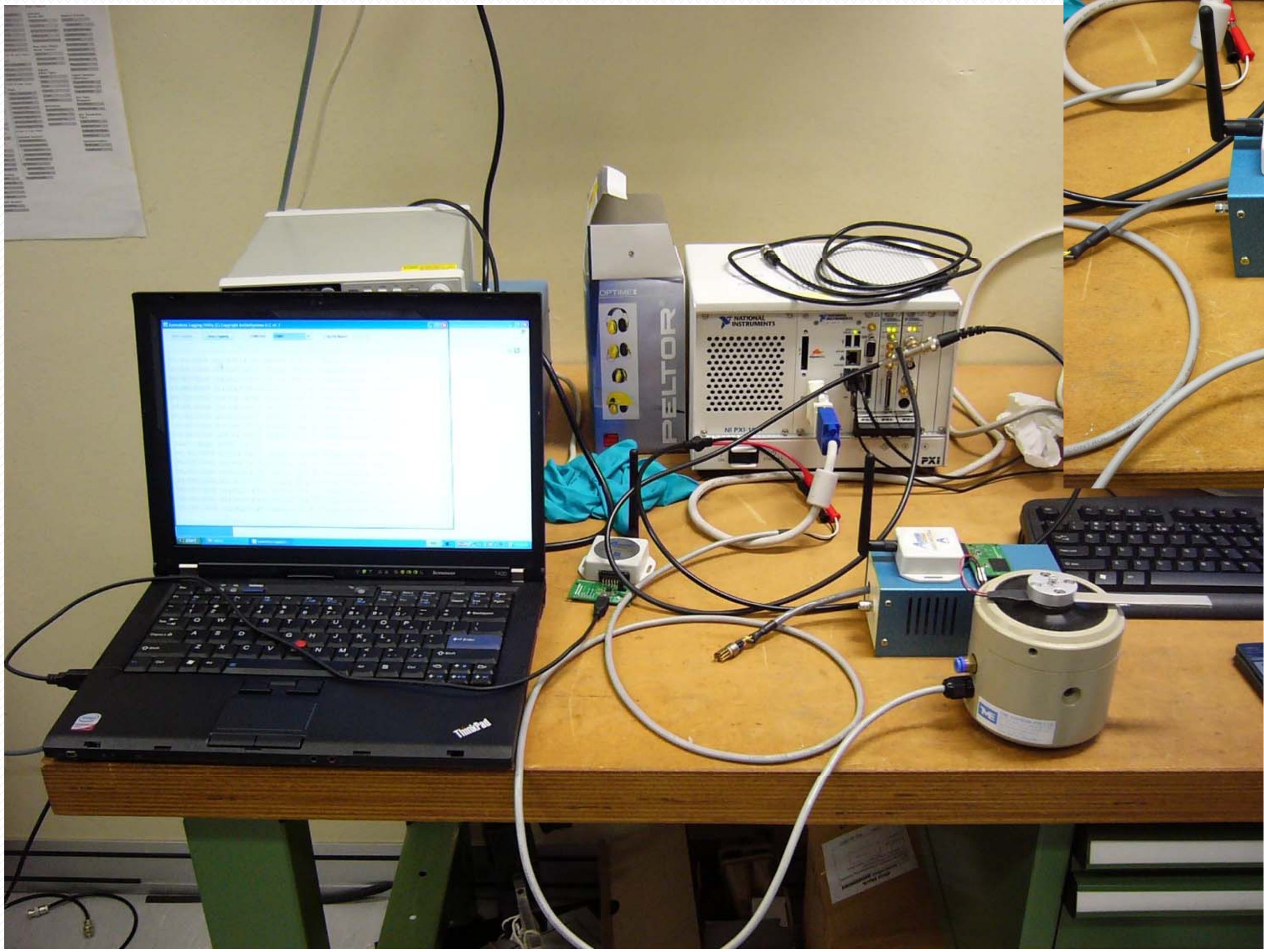
Routing and Node Placement Algorithms

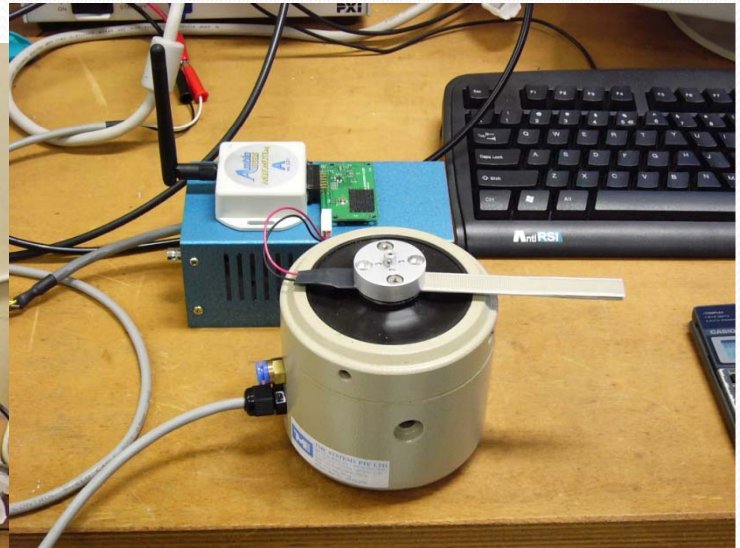
- Different node placement schemes affect network performance
- Optimal choice of a node placement scheme and routing algorithm is crucial in maximizing goodput

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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