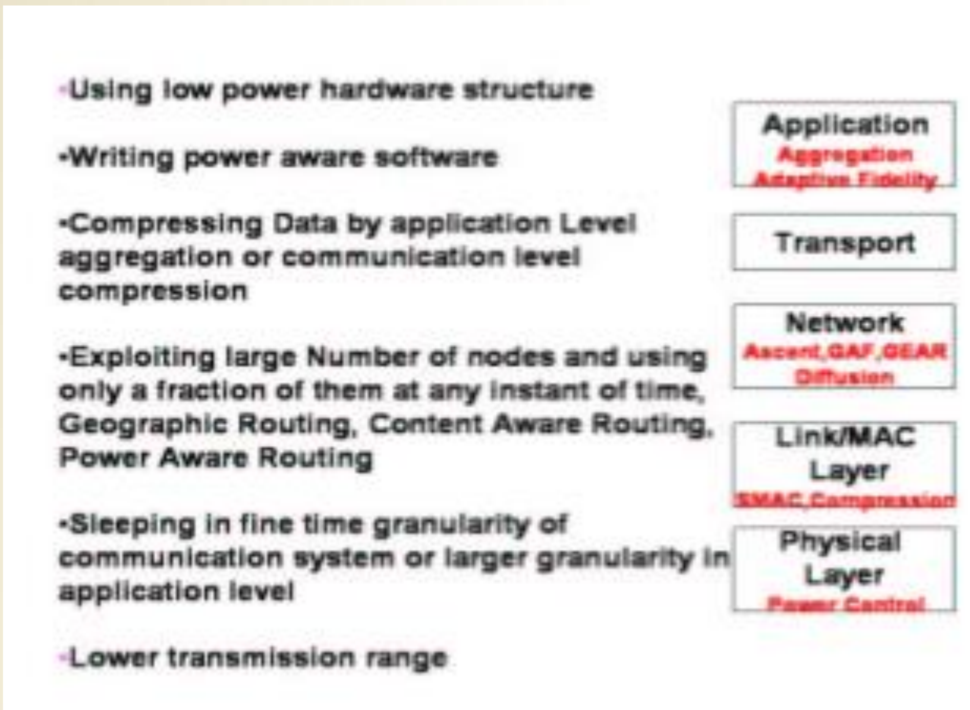
Energy Harvesting in Wireless Sensor and ActuatorNetwork

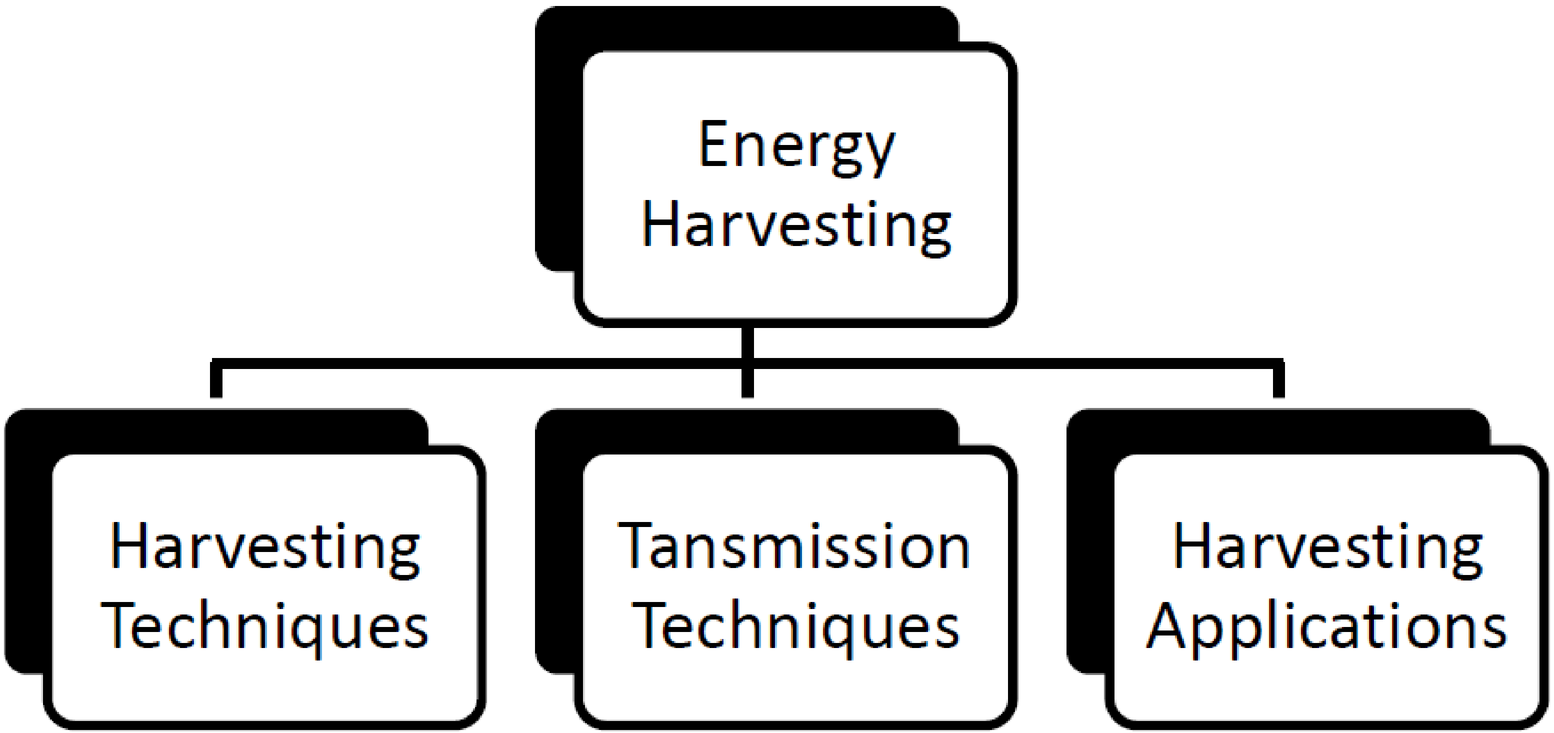
Contents

Low Power Architecture

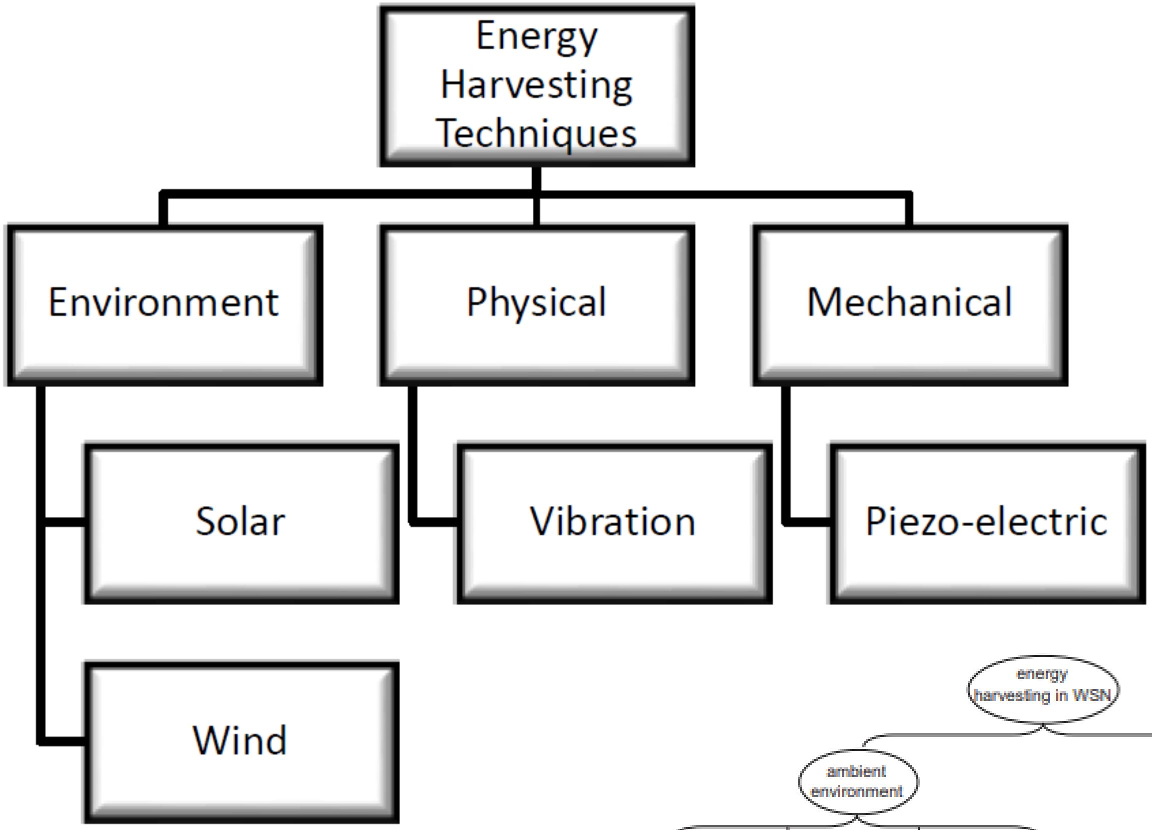
- Current approaches to energy management mainly focus on low power architecture and low power network design at different communication layers

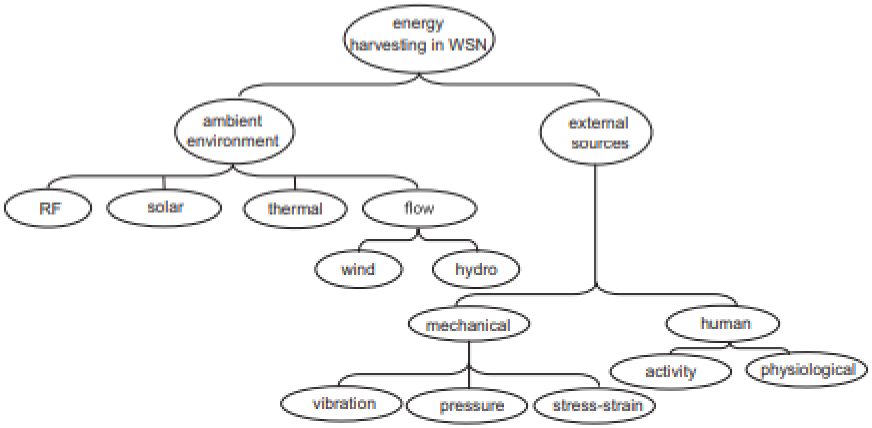


Energy Harvesting Domains



Energy Harvesting Techniques





Introduction

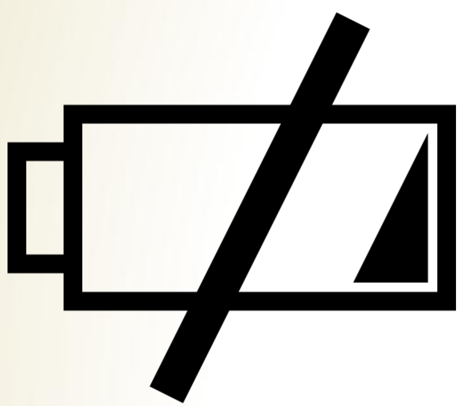
- What is energy harvesting?
  - The process by which energy is derived from external sources
- Why use energy harvesting?
  - Renewable source
  - Allows for remote charging in applications

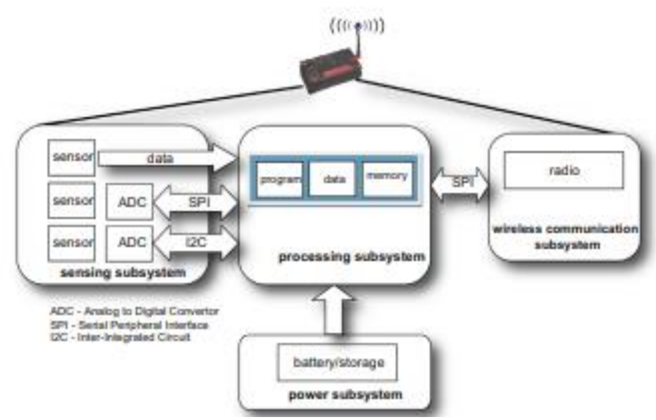
Energy Harvesting Background

- Energy harvesters provide a very small amount of power for low-energy electronics
- The energy source for energy harvesters is present as ambient background and is free
  - As opposed to large-scale energy generation which costs money

Why Use Energy Harvesting Technology?

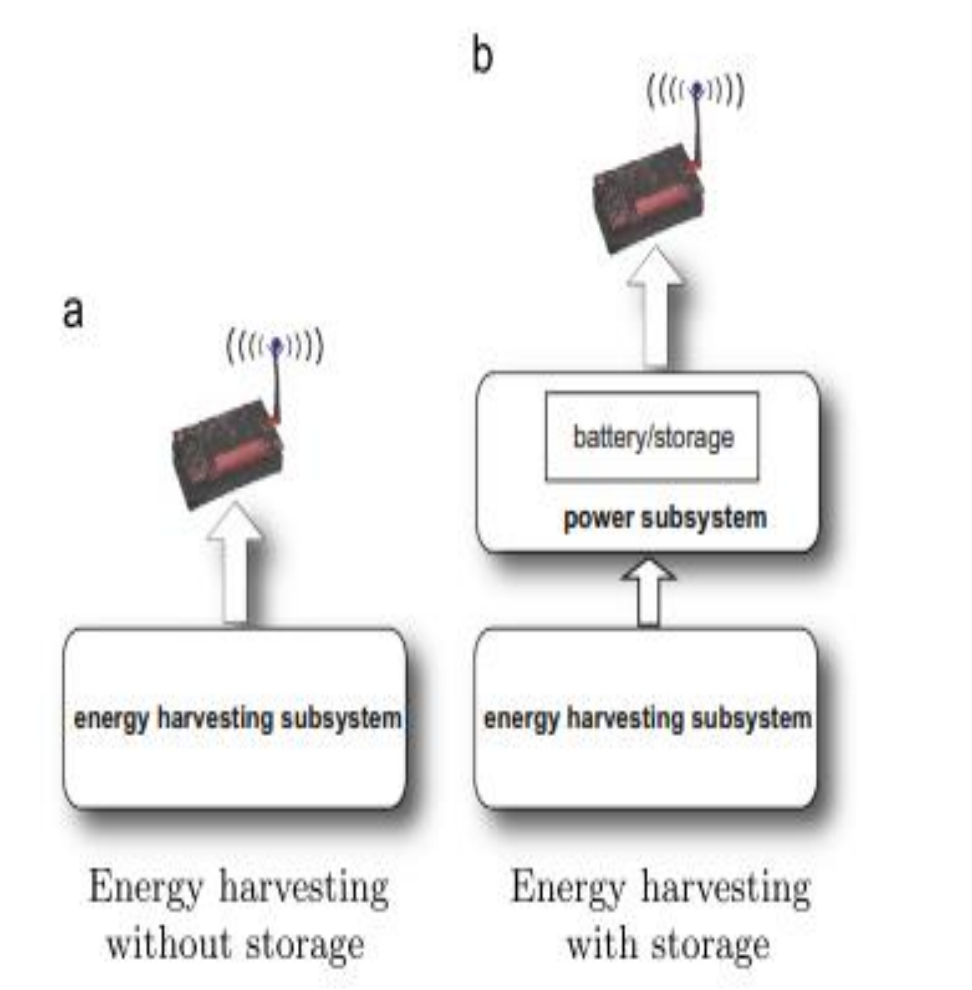
- Converted energy can be stored in a capacitor for short-term use or a battery for long-term use.
- Allows for the battery (or a charger) to be taken out of the equation of an application since it sources energy from the environment





Energy Storage

- Ambient energy is directly converted to electrical energy to power the sensor nodes (no battery storage is required)
- The converted electrical energy is first stored before being supplied to the sensor node



Ways to Harvest Energy

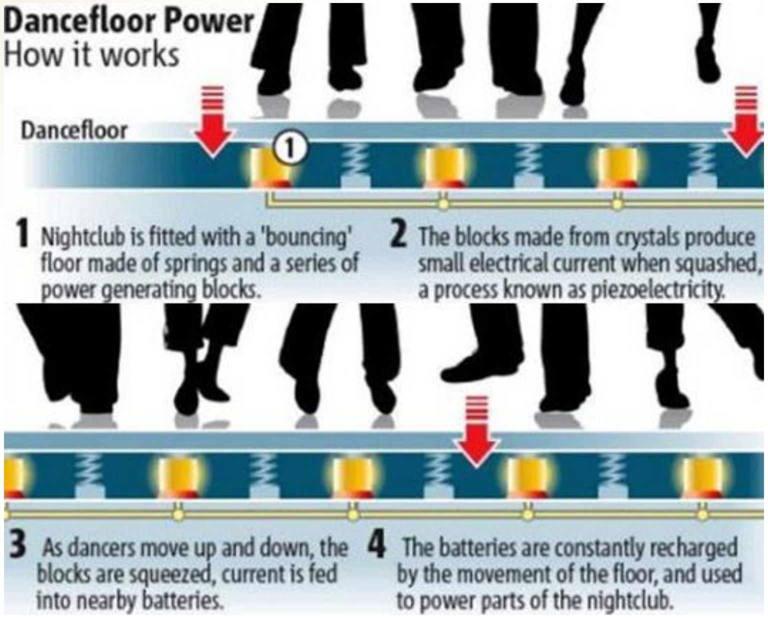
- Materials
  - Piezoelectric
  - Pyroelectric
  - Photovolatics
- Other
  - Kinetic Energy
  - RF Energy

Mechanical energy source

- Steady state mechanical source
  - Steady state: wind, flow, current..
- Intermittent mechanical source
  - Human activity(walking, typing.. 5.88J/2steps)
  - Vehicles passing
- Vibration
  - Energy depends on the amplitude and its freq.
  - Mass of harvesting device relative to the vibrating mass

Piezoelectric Effect (Pressure)

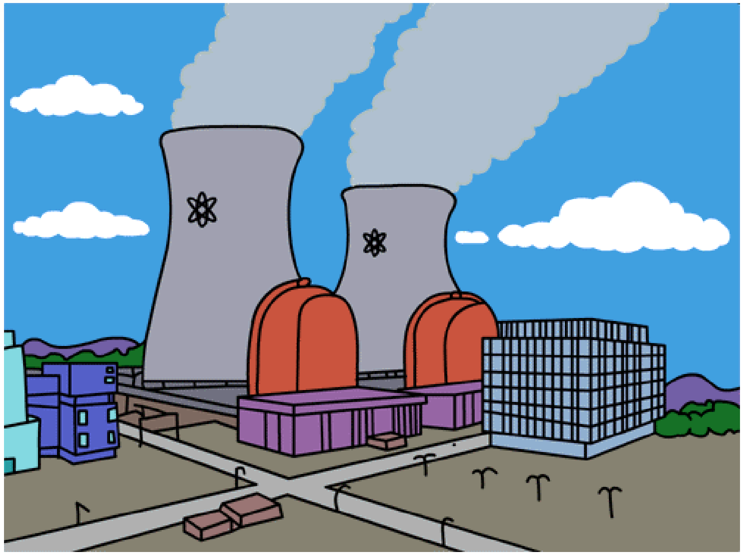
- Converts mechanical strain to electric current
- Produces power on the order of mW
- Useful for small applications
  - Handheld devices
  - Light bulbs



- Human Motion
- Acoustic Noise
- Vibrations
- Pressure

Piezoelectric Effect

- Converts changes in temperatures to electric current
- Stable for temperatures above 1200 ^{o}C
- High thermodynamic efficiency
- Used in
  - Power Plants
  - Automobiles



Other Kinetic Energy

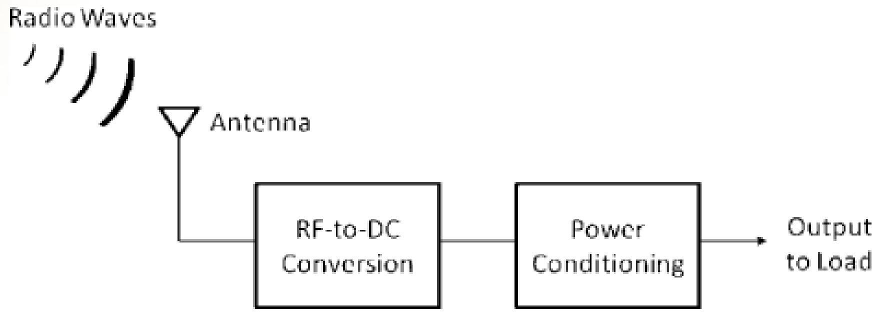
- Converts human and/or natural motion into electric current
- Found in
  - Wind Turbines
  - Ocean Wave Buoys
  - Human Motion

Photovoltaic Effect

- Also known as solar power
- Converts solar radiation into DC
- Found just about everywhere and gaining more popularity

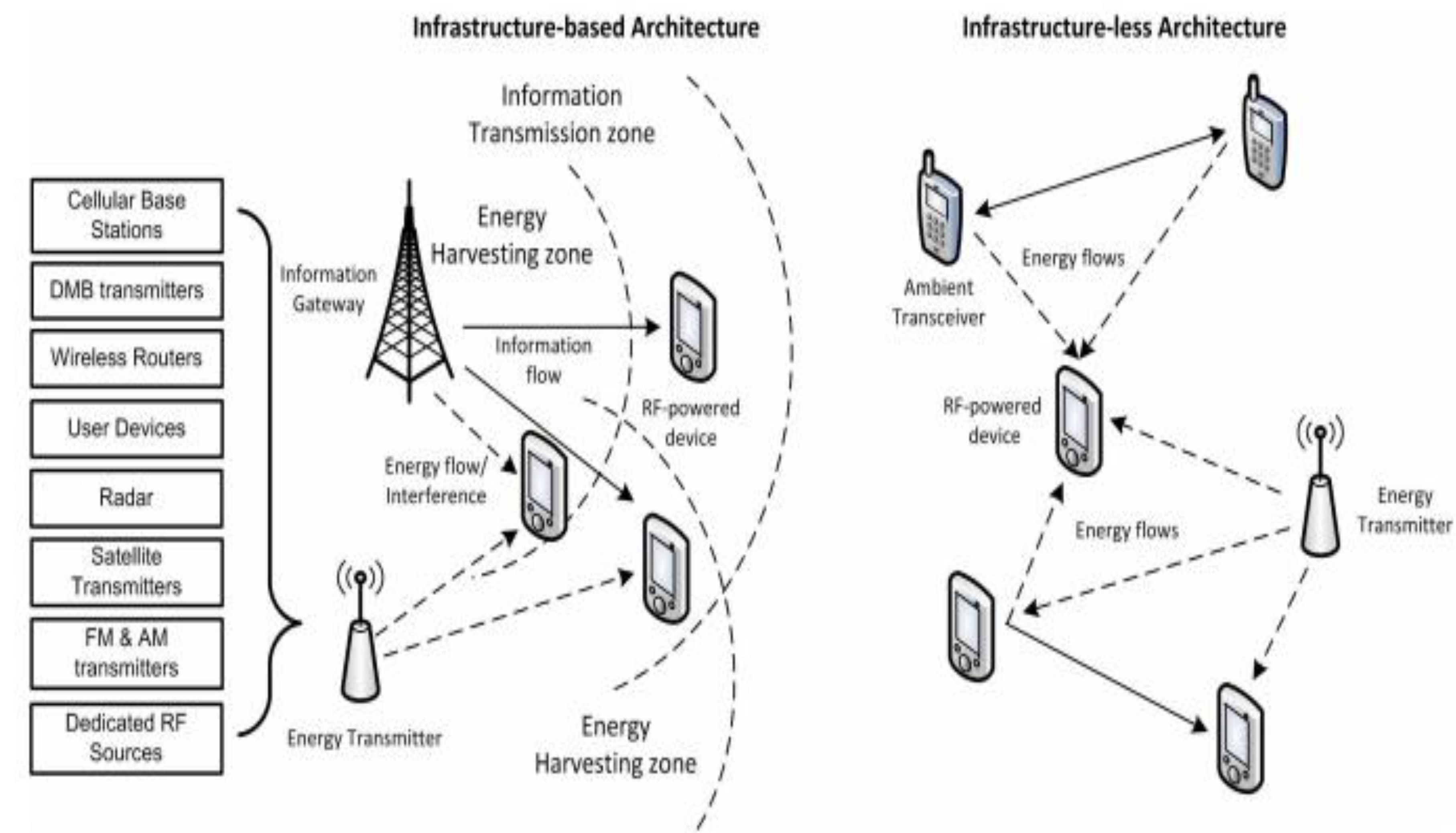
RF Energy Harvesting

- Converts RF signal energy into DC power
- RF energy is available in a wide array of frequency bands due to everyday technologies
  - Cell Phones
  - Radio Towers
  - WiFi Routers
  - Laptops
  - TV Signals

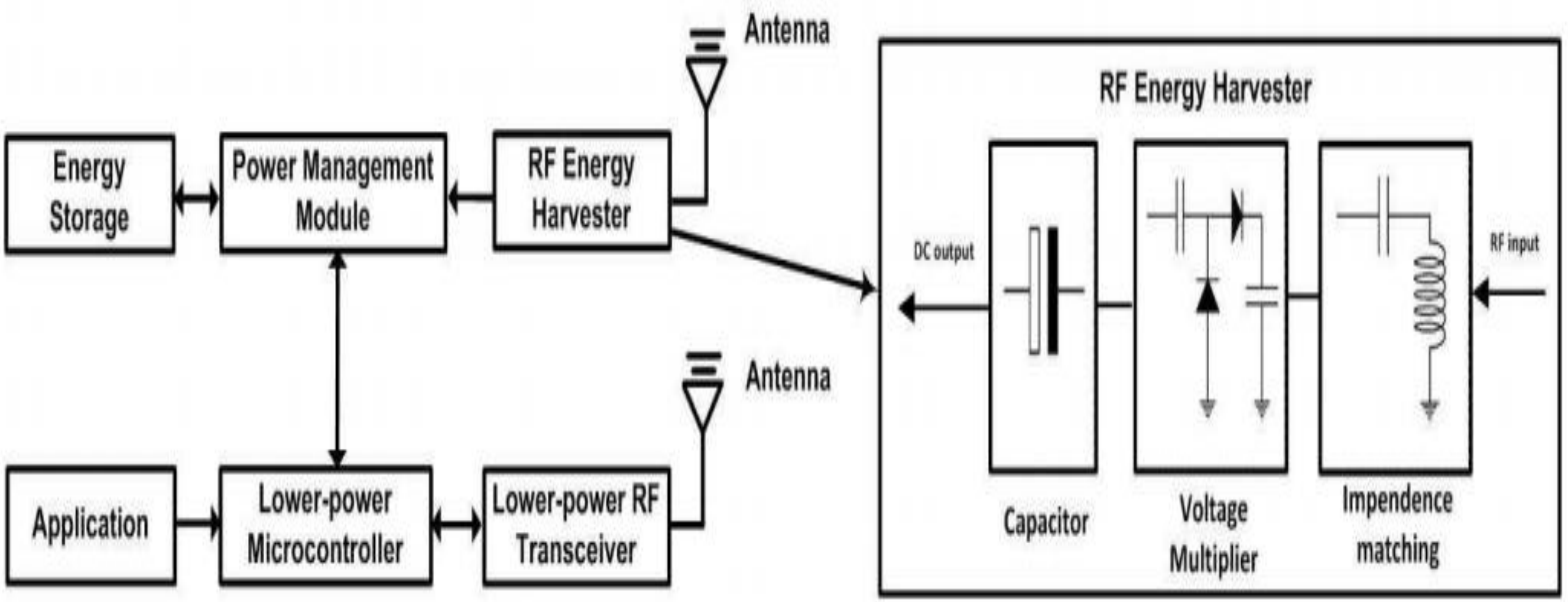


- Only a tiny amount of power can be harvested, good for low power applications (Ex: A WiFi router can transmit 50-100mW)
- Usually very short distance, however Powercast demonstrated energy harvesting at 1.5 miles

RF Energy Harvesting



RF Energy Harvesting Device



RF Energy Propagation Models

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi d)^2 L}, \quad (1)$$

where P_R is the received power, P_T is the transmit power, L is the path loss factor, G_T is the transmit antenna gain, G_R is the receive antenna gain, λ is the wavelength emitted, and d is the distance between the transmit antenna and the receiver antenna.

- The harvested RF power from a transmitter in free space can be calculated based on the Friis equation
- The power management module can adopt two methods to control the incoming energy flow, i.e., harvest-use and harveststore-use.

Ambient Energy

TABLE 1

Energy-harvesting opportunities and demonstrated capabilities.

Energy source	Performance[A]	Notes
Ambient radio frequency	< 1 μW/cm^2	Unless near a transmitter[3]
Ambient light	100 mW/cm^2 (directed toward bright sun) 100 μW/cm^2 (illuminated office)	Common polycrystalline solar cells are 16%–17% efficient, while standard monocrystalline cells approach 20%. Although the numbers at left could vary widely with a given environment's light level, they're typical for the garden-variety solar cell Radio Shack sells (part 276-124).
Thermoelectric	60 μW/cm^2	Quoted for a Thermo Life generator at $\Delta T = 5°C$[B]; typical thermoelectric generators ≤ 1% efficient for $\Delta T < 40°C$.[6]
Vibrational microgenerators	4 μW/cm^3 (human motion—Hz) 800 μW/cm^3 (machines—kHz)	Predictions for 1 cm^3 generators.[9] Highly dependent on excitation (power tends to be proportional to ω^3 and y_0^2, where ω is the driving frequency and y_0 is the input displacement), and larger structures can achieve higher power densities. The shake-driven flashlight of Figure 3, for example, delivers 2 mW/cm^3 at 3 Hz.
Ambient airflow	1 mW/cm^2	Demonstrated in microelectromechanical turbine at 30 liters/min.[29]
Push buttons	50 μJ/N	Quoted at 3 V DC for the MIT Media Lab Device.[20]
Hand generators	30 W/kg	Quoted for Nissho Engineering's Tug Power (vs. 1.3 W/kg for a shake-driven flashlight).[2]
Heel strike	7 W potentially available (1 cm deflection at 70 kg per 1 Hz walk)	Demonstrated systems: 800 mW with dielectric elastomer heel,[26] 250–700 mW with hydraulic piezoelectric actuator shoes,[24] 10 mW with piezoelectric insole.[25]

[A]These numbers depend heavily on the ambient excitation and harvesting technologies. By comparison, lithium-ion batteries can yield up to 0.52 W-hr./cm^3 (0.18 W-hr./g), and the Toshiba DMFC (direct methanol mini fuel cell) achieves 0.27 W-hr./cm^3. The theoretical energy available from methanol is 4.8 W-hr./cm^3 (6.1 W-hr./g).

[B]Quoted by Ingo Stark of Applied Digital Solutions' Thermo Life Energy Corp.

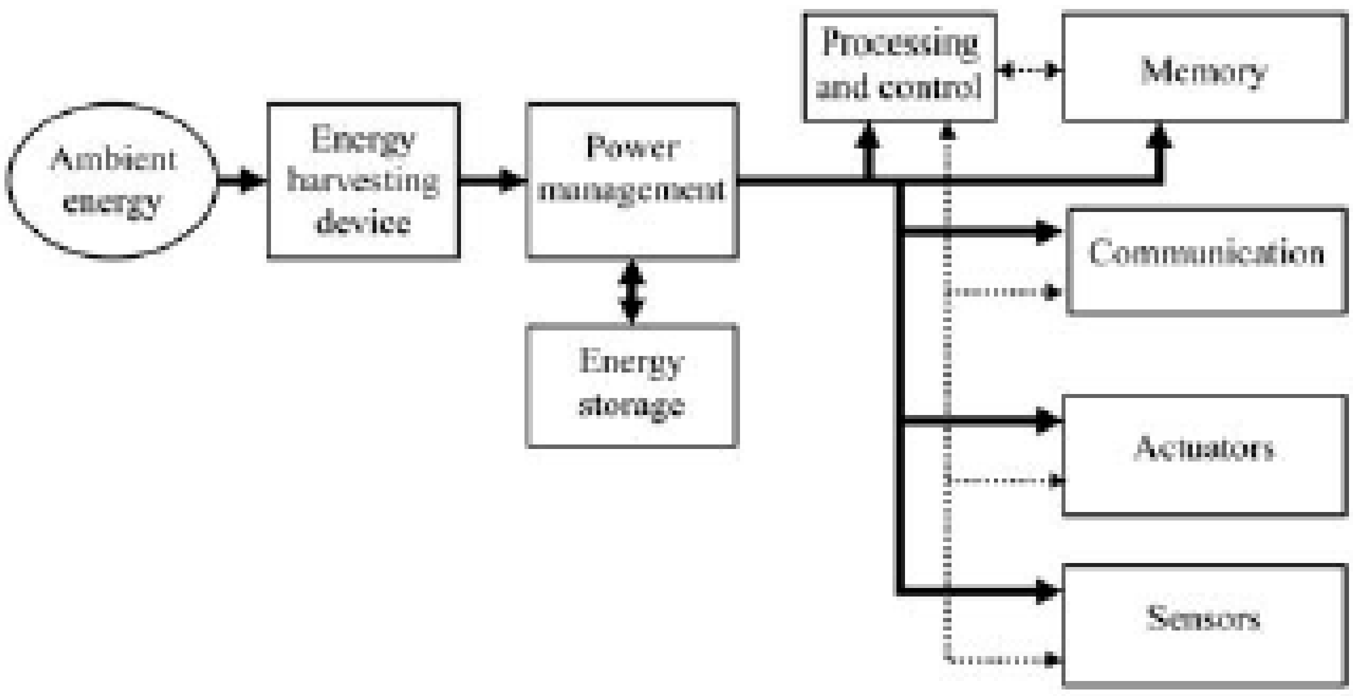


Fig. 1 A generic sensor network node with energy harvesting device

ENERGY MODEL

- Average energy (Eavg) consumed, is

$$E_{avg} = n \cdot t_a \cdot P_a + m \cdot t_{sl} \cdot P_{sl}$$

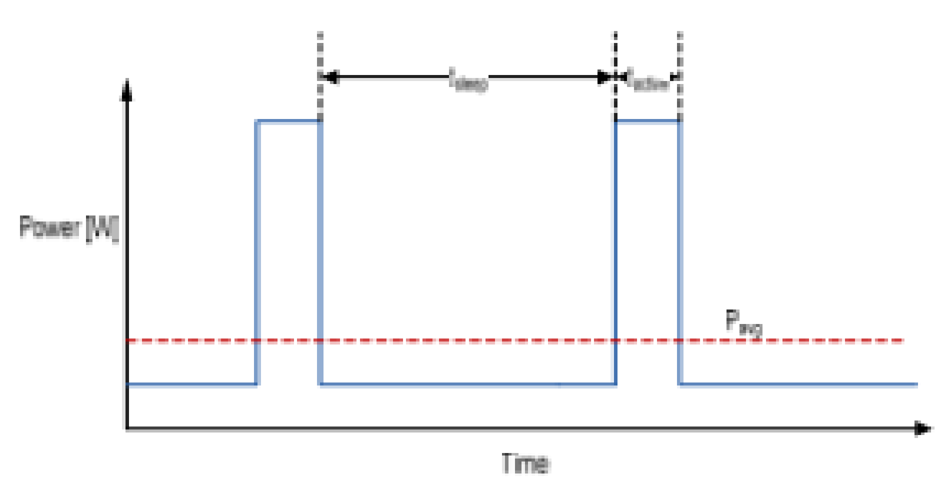
- Where Pa is the power consumed by the node in its active state during ta and n is the rate of occurrence, and Ps that is the power consumed by the node in its inactive state and has the occurrence rate m and lasts for a period equal to ts.

ENERGY MODEL

- energy stored (Est) in the node must be at least equal with the energy used for its operation in the time interval t2-t1.

$$E_{st} \geq \int_{t1}^{t2} (P_{cons} - P_{scav})dt$$

- where Pcons is the power consumed by the sensory node in the time interval t2-t1 and Pscav is the power collected and stored power in the same timeline.



Self Contained Network

- We consider the sensor network to be a closed energy system consisting of producers and consumers. Each node is capable of producing energy with rate Pp(i,t) and consumes energy with rate Pc(i,t). The network longevity depends on Pp−Pc over the entire network
- At any instant of time the amount of energy consumed at node i is:

$$E(i,t) = \int_{t_0}^{t} [P_p(i,t) - P_c(i,t)]dt$$

- The network energy is the summation of the individual node energies across the network:

$$E(t) = \int_{t_0}^{t} (\sum_{i} [P_p(i,t) - P_c(i,t)])dt$$

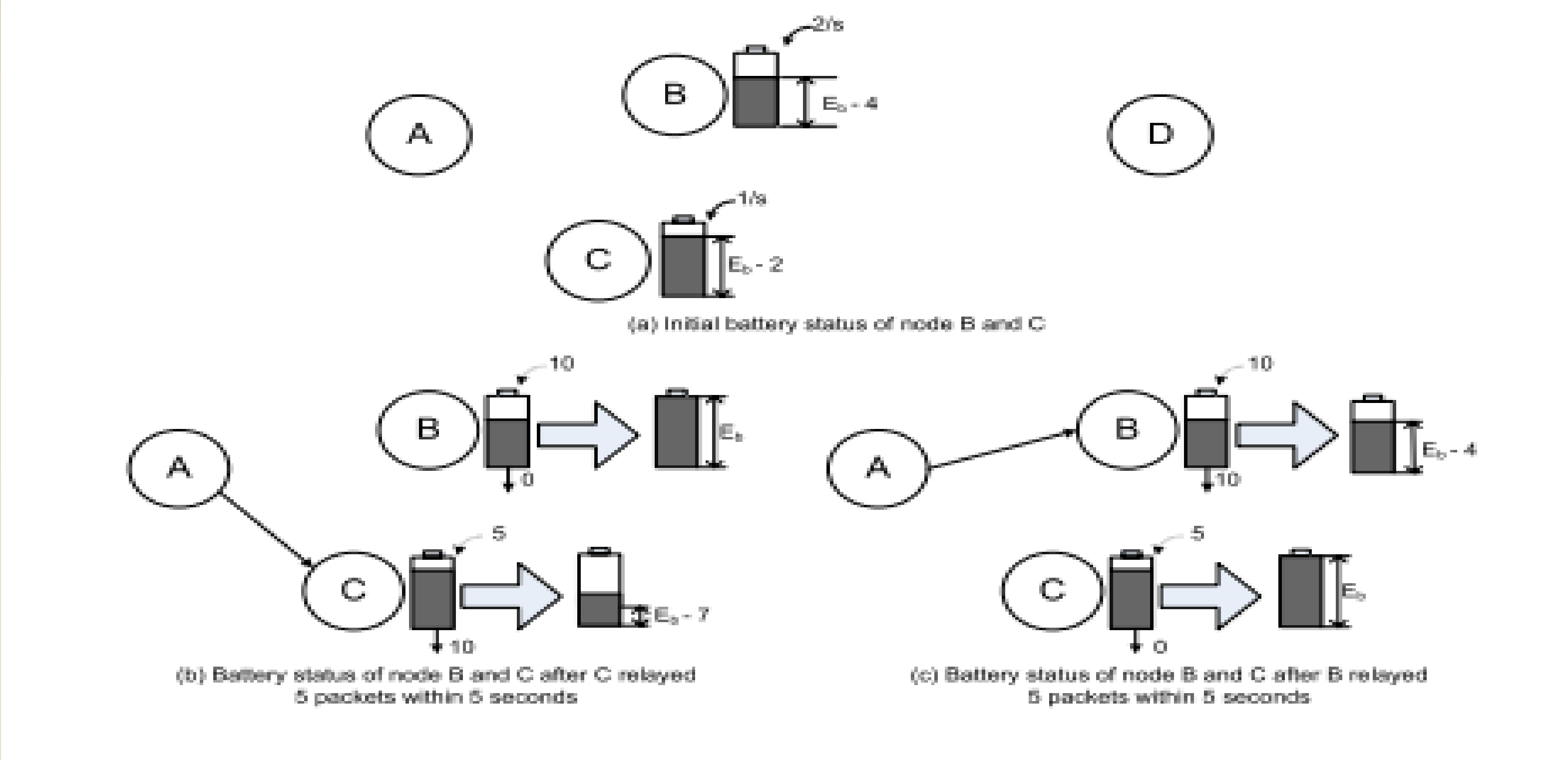
- A node is self contained if:

$$E(t) > 0; \forall t > 0$$

Energy Aware Routing with Energy Harvesting

- node A has two neighbors B and C, and A has five packets to send to a remote destination D with one packet per second. The energy consumption per packet delivery on link AB and AC are the same.
- Assume that B and C have the same battery capacity of Eb units, and Eb − 4 and Eb − 2 units of residual energy respectively; their energy harvesting rates are 2 and 1 units per second respectively; they consume the same energy, say 2 units, to relay (receive and forward) a packet to their next hop.
- For energy aware routing that only considers the residual energy information on nodes, A will send the packets to C because C has more residual energy. As shown in Fig. 1(b), after relaying the five packets, C has residual energy of Eb − 7 units since it consumes 10 units for relaying the packets meanwhile harvesting 5 units, and B is fully recharged since it harvests 4 units of energy.

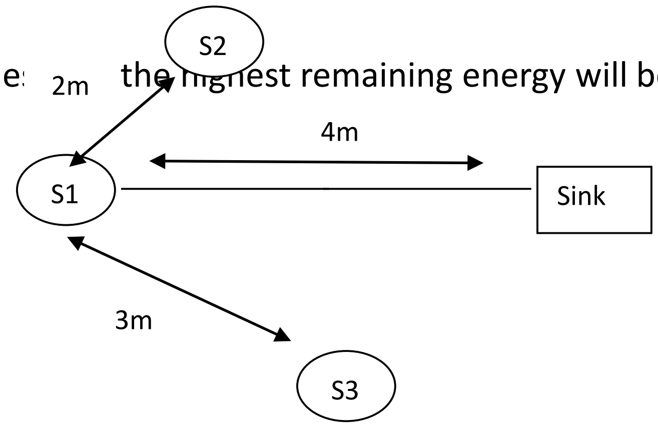
Energy Aware Routing with Energy Harvesting



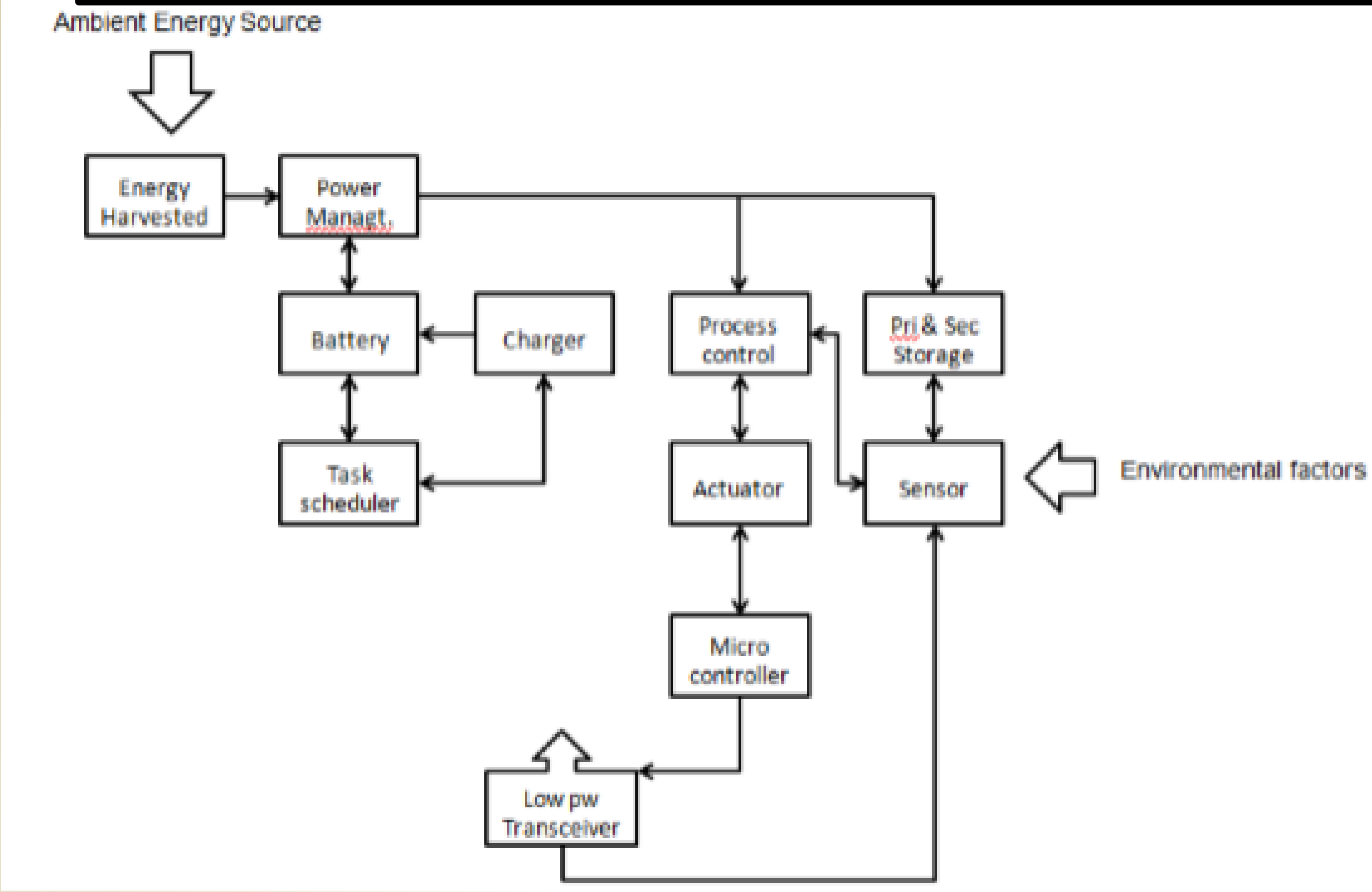
Question ?

Figure 1 shows motion sensor mote deployed in a secluded server room to monitor human movement. Node S1 can either forward the motion data to node S2 or node S3 depending on the residual energy of the nodes or its energy harvesting capability. S1 to S2 and S1 to S3 have the same energy consumption for every packet being delivered and it takes one packet to be delivered in 1 second. Both S2 and S3 have the same battery capacity E_b and residual energy on both nodes is E_b-3 and E_b-5 respectively. And energy harvesting rates at 3 and 2 units per second respectively. S2 and S3 both consume 4 energy units to relay a packet to the A.

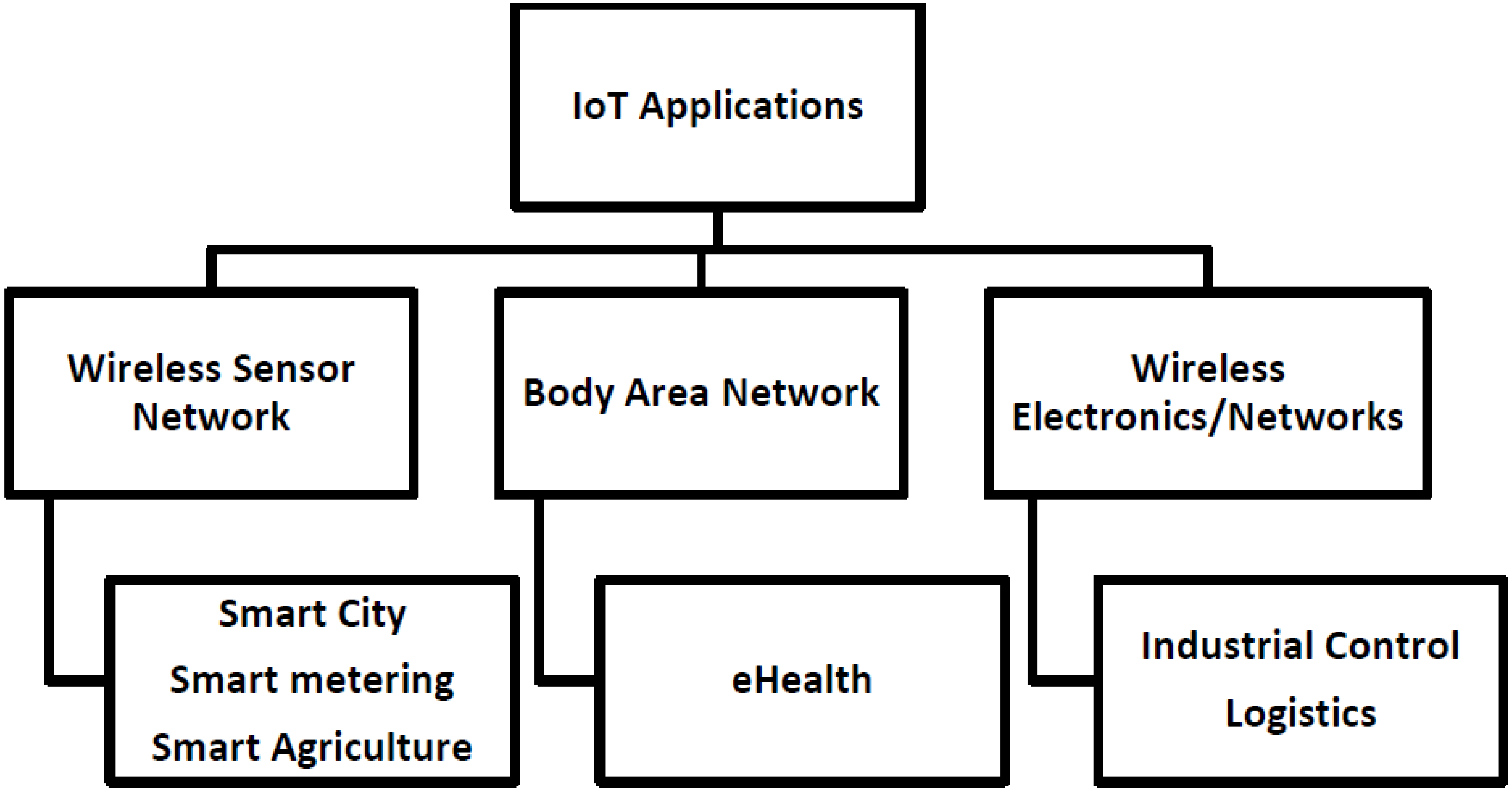
- Calculate the remaining battery of the sensor nodes S1 and S2 after 10 seconds imagining that the same amount of data is sent to both nodes.
- Given a scenario of remaining energy in both nodes when a) S2 is relaying the data to the sink b) S3 is relaying the data to the sink
- Give a scenario for energy aware routing, whereby the nodes the highest remaining energy will be selected as the next hop.



WSAN Energy Harvesting Research

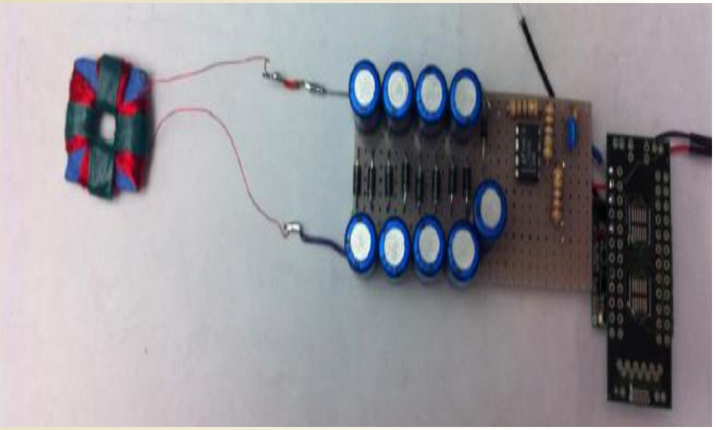


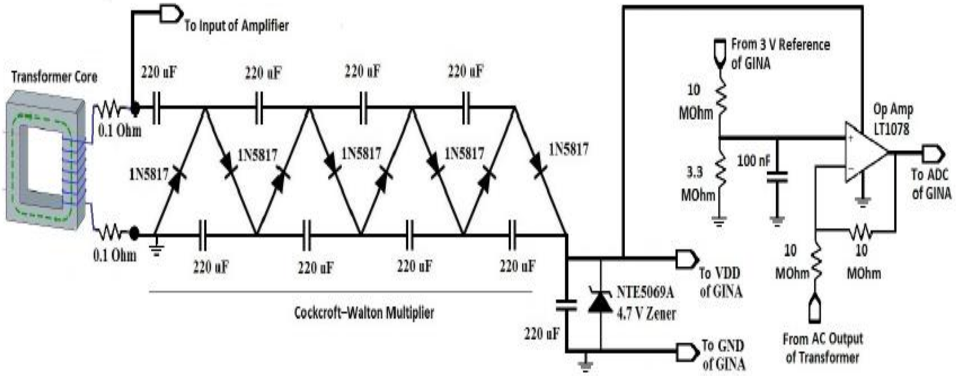
Energy Harvesting Applications



Energy Harvesting in Wireless Sensor Network

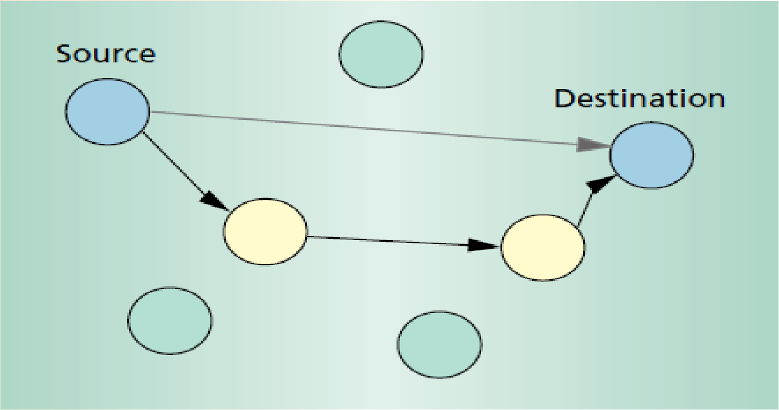
- Lee, (2012) has conducted a research on energy harvesting for wireless sensor network. The author proposed a novel, plug through power monitoring system for commercial use.





Energy Harvesting in Wireless Sensor Network

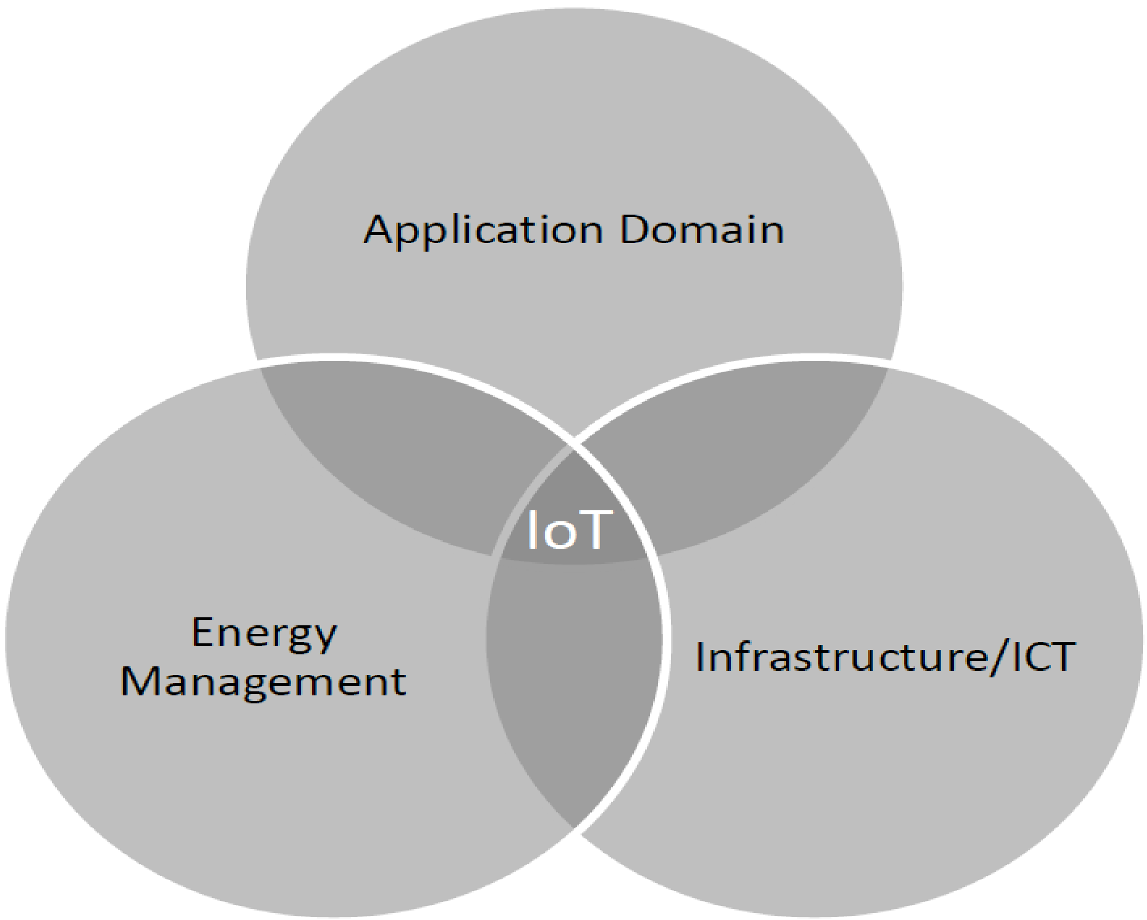
- Rabaey et al. (2000) has worked on PicoRadio Supports Ad Hoc Ultra-Low Power Wireless Networking. PicoNodes were used as self-contained and self-powered by using energy scavenging.



Internet of Things

- Sensors – for tracking and measuring activity
- Connectivity – internet or cloud infrastructure
- Processors – contain some computing power
- **Energy efficiency – difficult for access to charge and replace battery**
- Cost-effectiveness – easily available
- Quality and reliability – need to operate in harsh environments for longer period
- Security – need to relay sensitive information

Network of Things for IoT



Structural and Environmental Health Monitoring

- What is Structural Health Monitoring (SHM)?

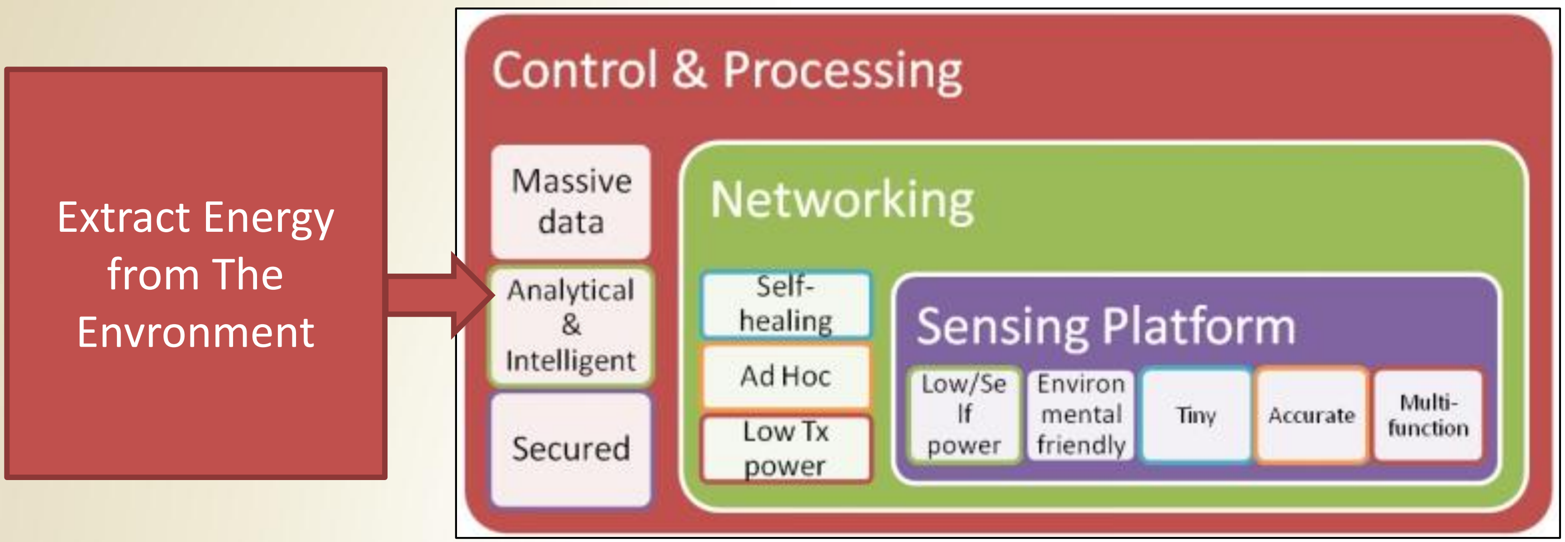
  The process of implementing a damage detection and characterization strategy for engineering structures like machinery,civil

- What is Environmental Health Monitoring (EHM)?

  The process of collection and evaluation of data on environmental pollution and on resulting health outcomes as well.

Motivation of IoT to SHM and EHM

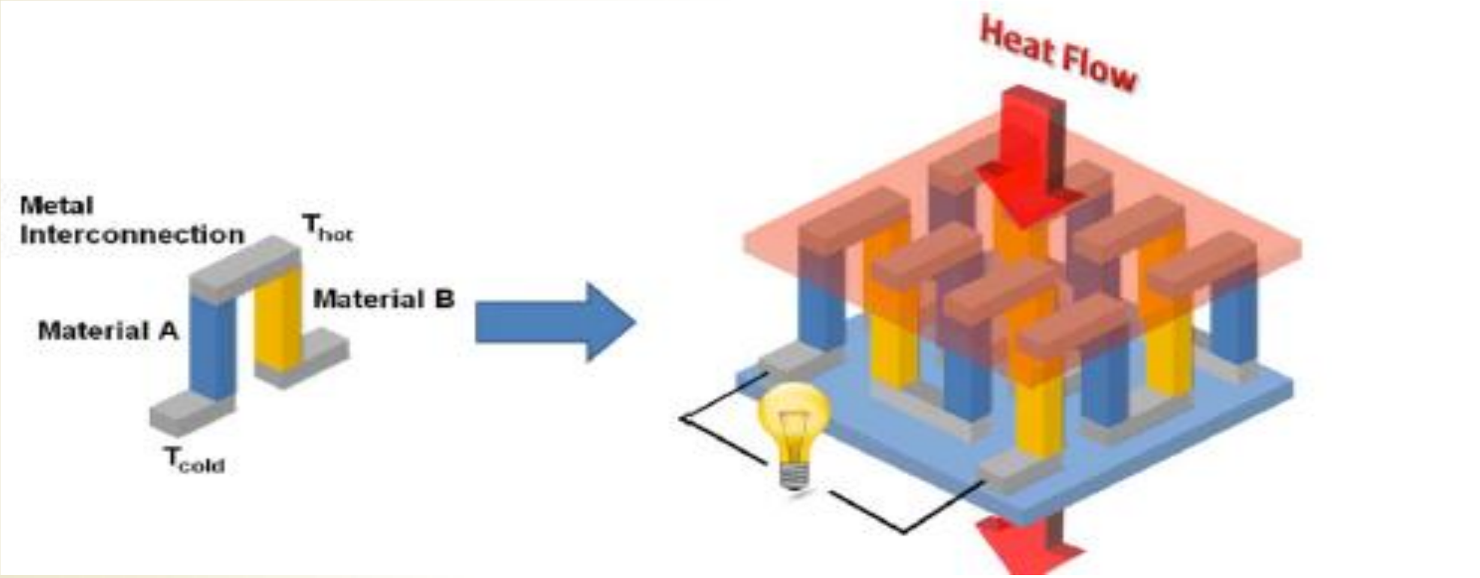
- Autonomous monitoring of machinery, sensors, communication, structures and energy management has been ever-increasing.



.(Image re-drawn from http://www.wsntech.net/kr/index.php?option=com_content&task=view&id=232.
Copyright : MIMOS Sdn. Bhd.)

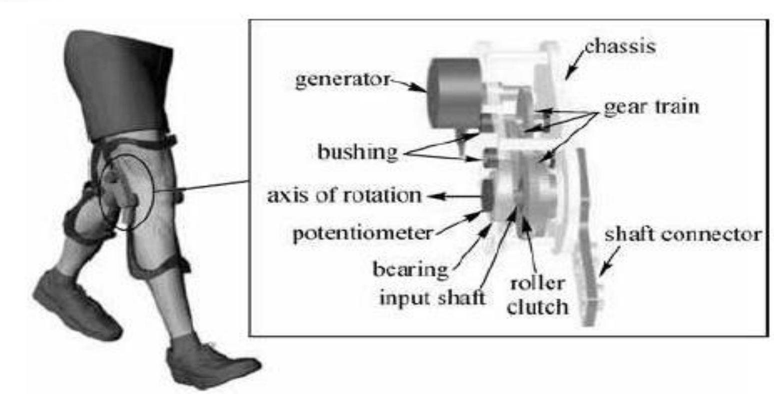
Energy Harvesting in Body Area Networks

- Energy Harvesting and Remote Powering for Implantable Biosensors has been done by Olivio et al. (2011)



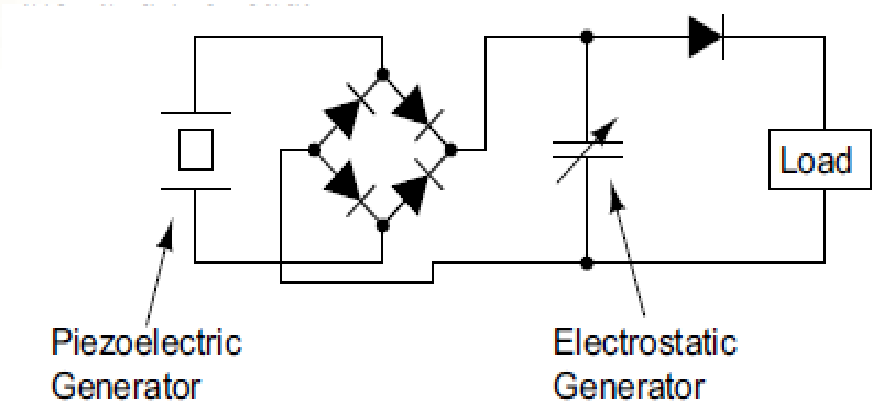
Energy Harvesting in Body Area Networks

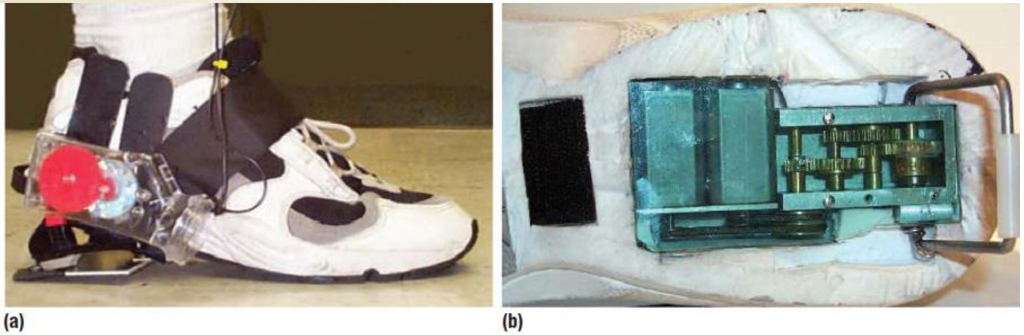
- Jia & Liu (2009) conducted a research on human power-based energy harvesting strategies for mobile electronic devices. The authors proposed energy harvesting through daily activities such as joint rotation and enforcement of body weight for mobile or medical device



Energy Harvesting in Wireless Electronics

- Rocha et al. (2010) has conducted a research on energy harvesting from piezoelectric material that is fully integrated into footwear





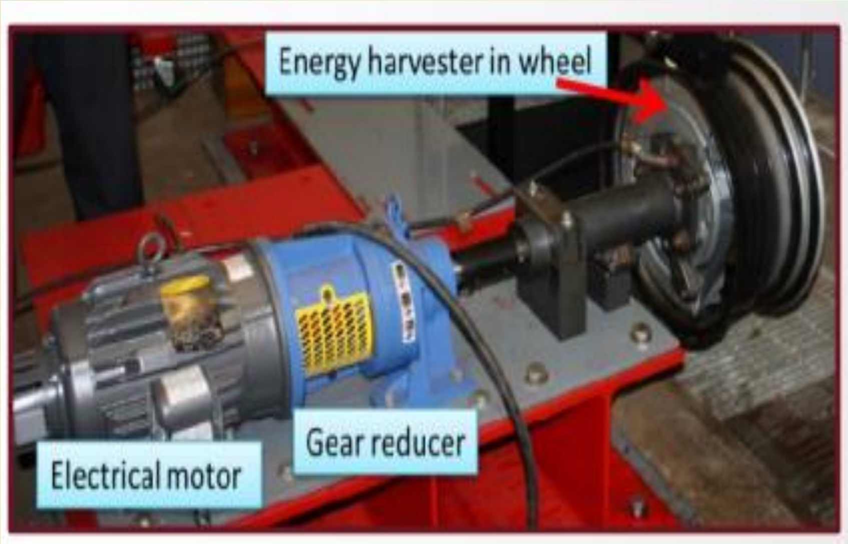
Paradiso & Starner, 2005

Case Studies of Energy Scavenging Technologies Applied to Structural Health Monitoring

Energy Harvesting for Rotating Helocopter
for Components (Arms et al.(2008)

Electromagnetic Energy Harvester on highway bridge (Sazonov et al.(2009)

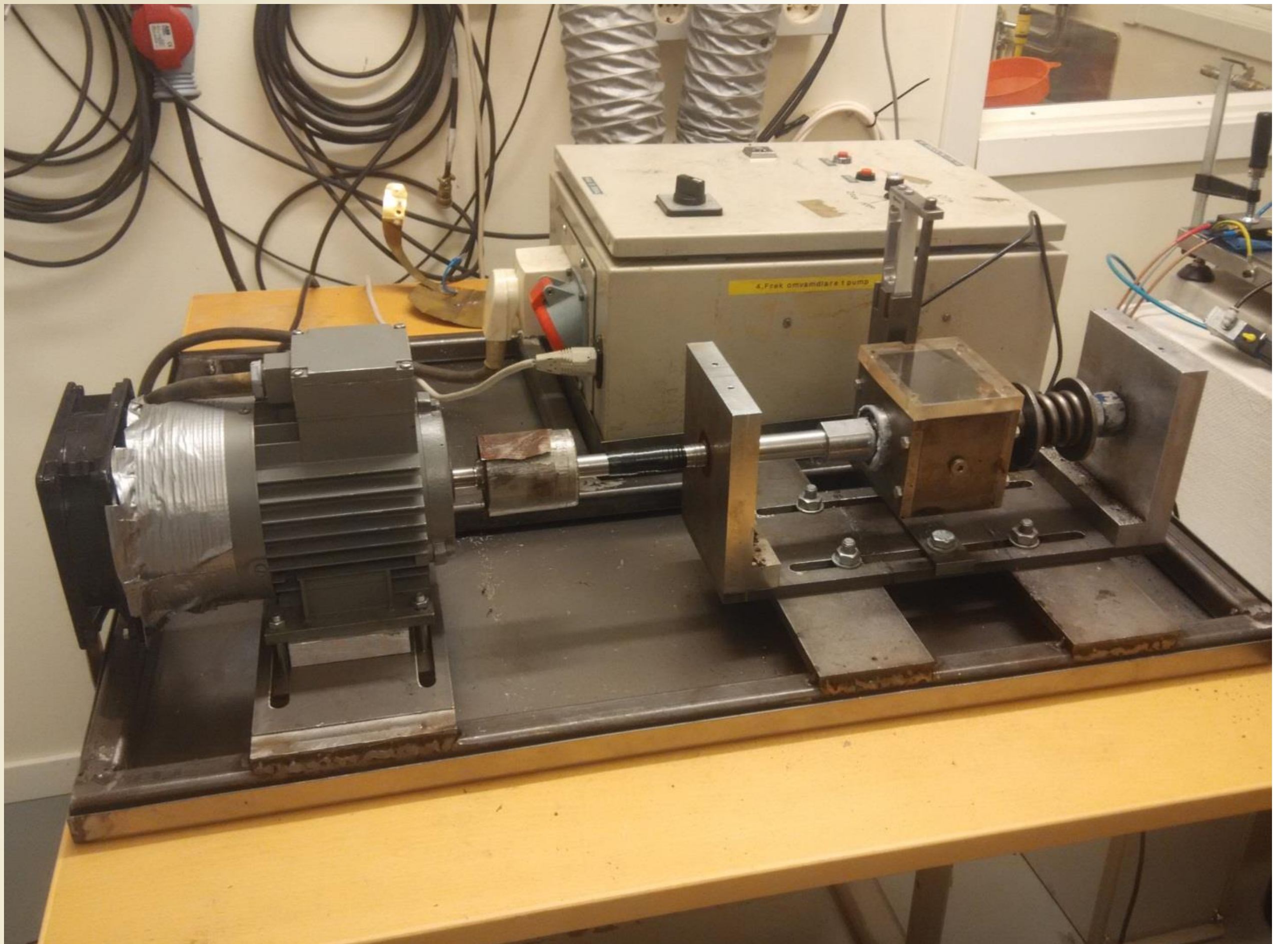
Case Studies of Energy Scavenging Technologies Applied to Structural Health Monitoring



Rotating Energy Harvester for Tire Pressure Monitoring
(Wang et al.(2012)

Solar Energy Harvester for Civil Structural Monitoring
(Arms et al.(2008)

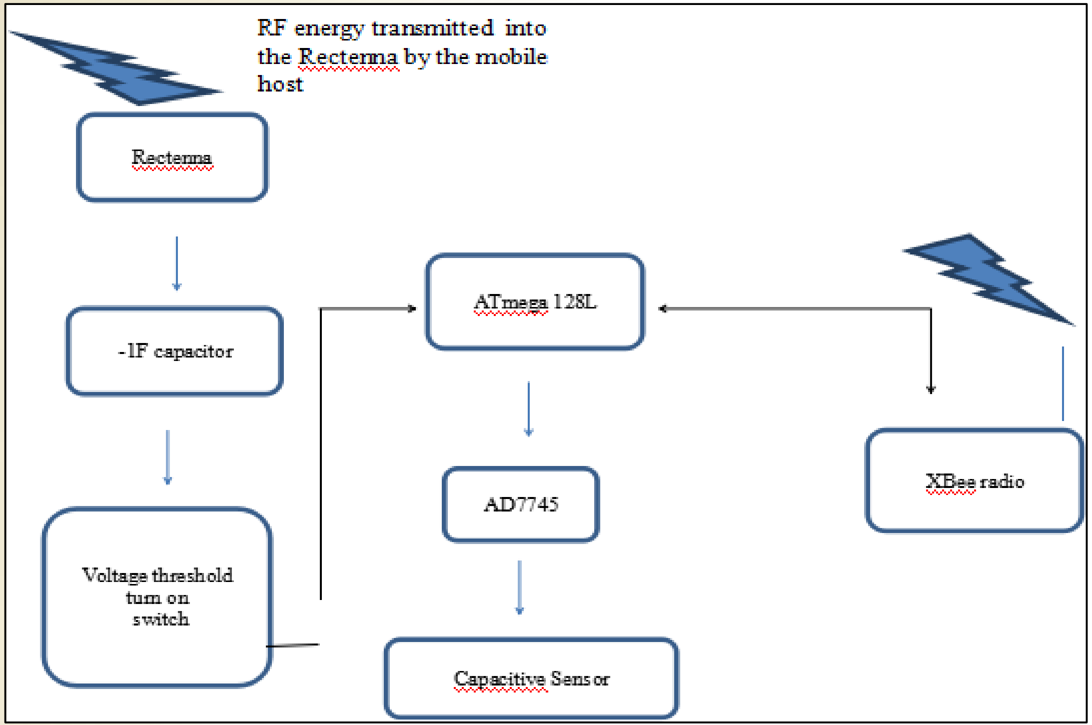
Case Studies of Energy Scavenging Technologies Applied to Structural Health Monitoring



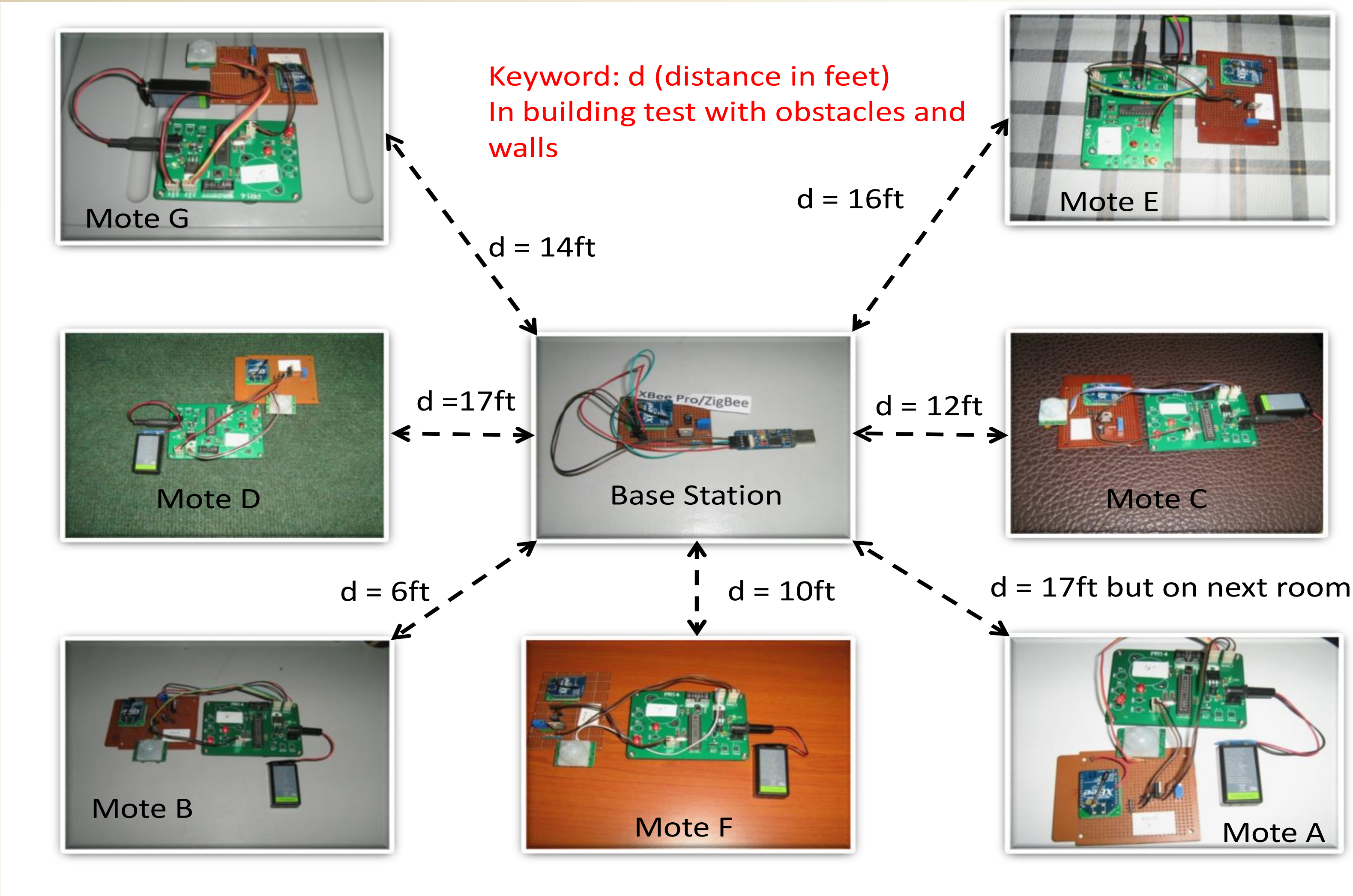
Energy Harvesting for Tunnel Structure Monitoring (Lulea Technological University, EISLAB)

Wireless Energy Transmission for Bridge SHM

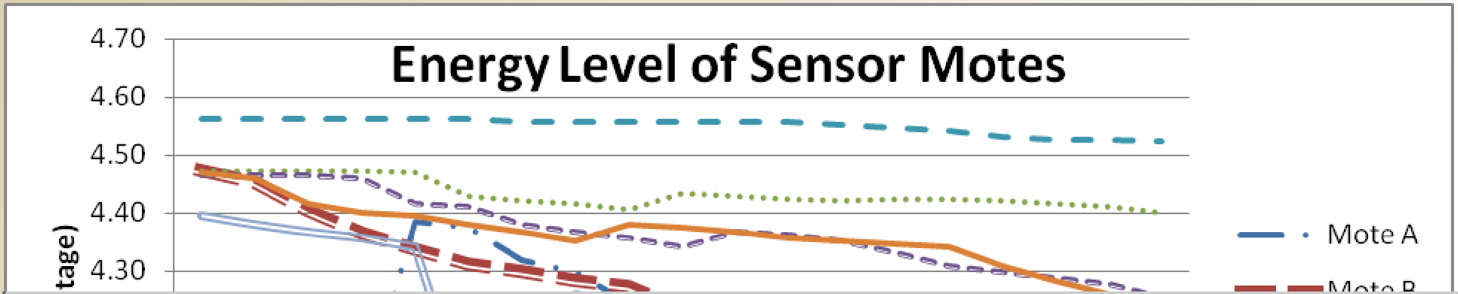
Mascareñas. D. et. al. (2006) explore a new alternative to the conventional battery resource constrained sensor nodes by exploiting mobile host.

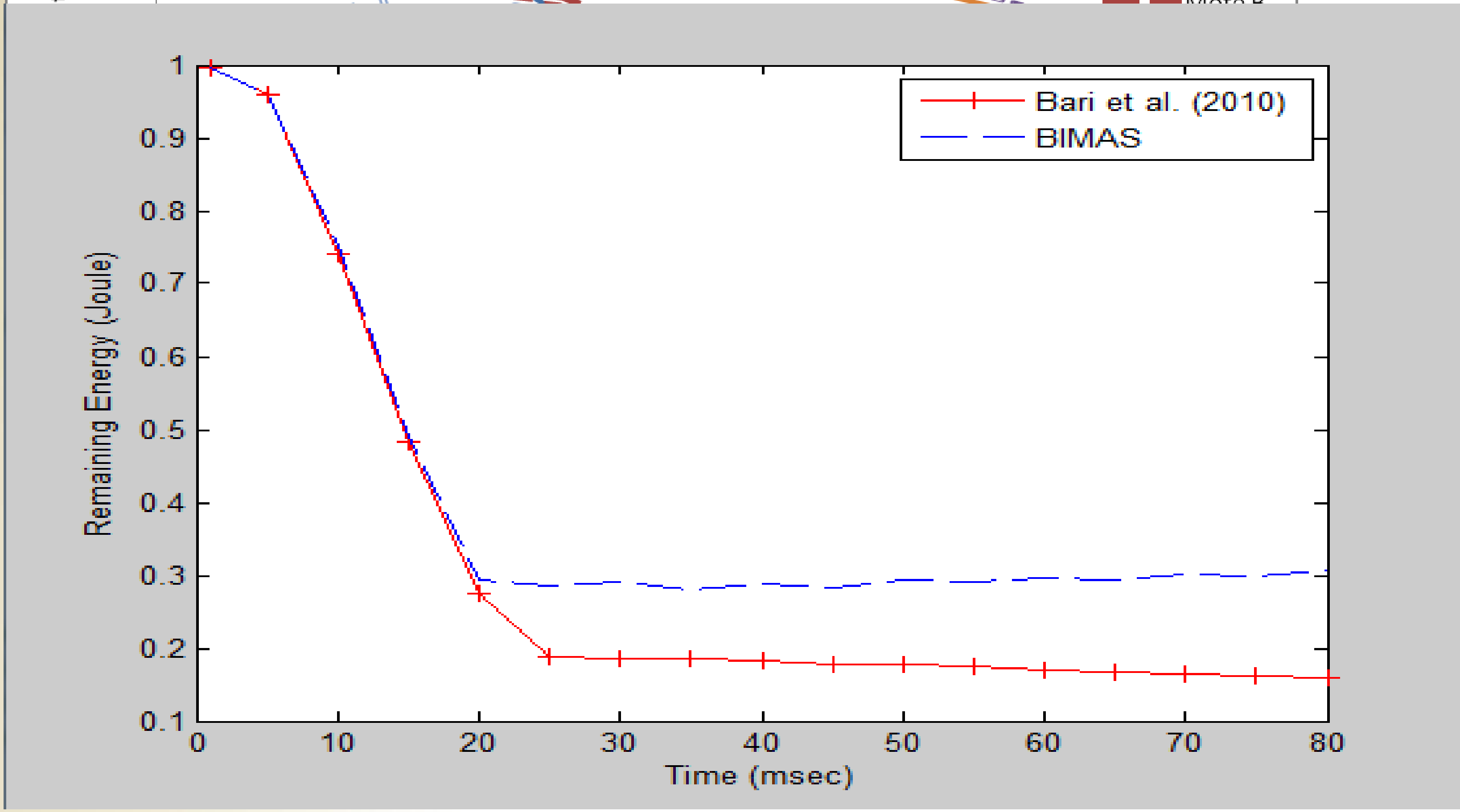


Sensor Topology



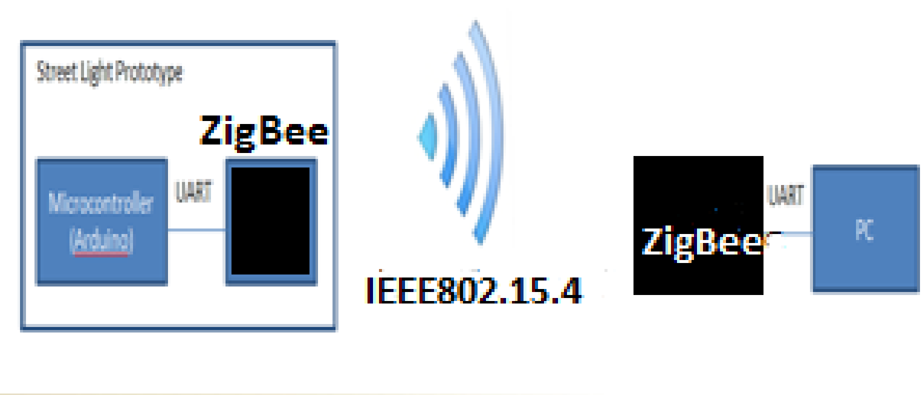
Prototype Results





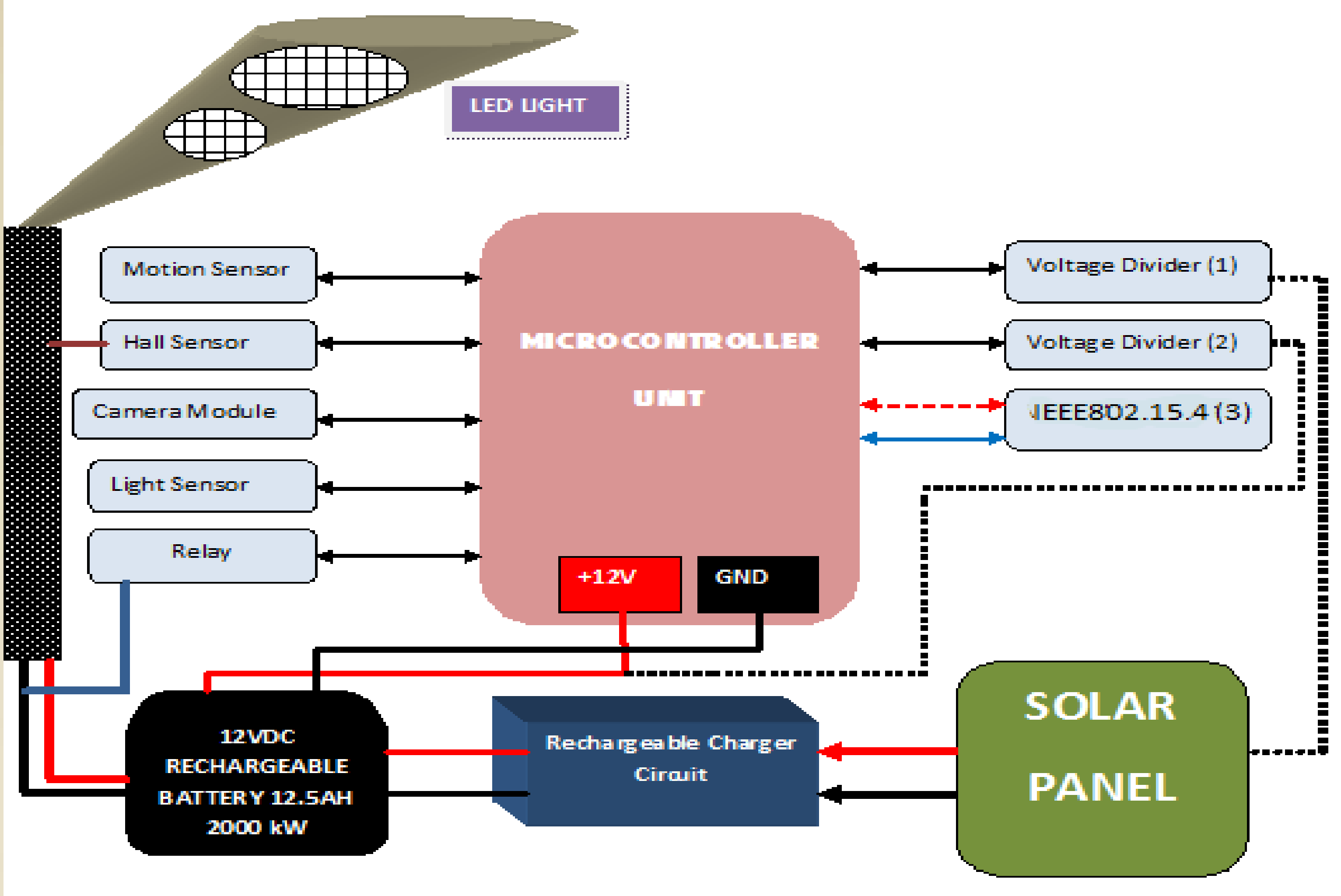
Smart Street Light

- ZigBee technology will be implemented in the solar based smart street light design with remote service management system.



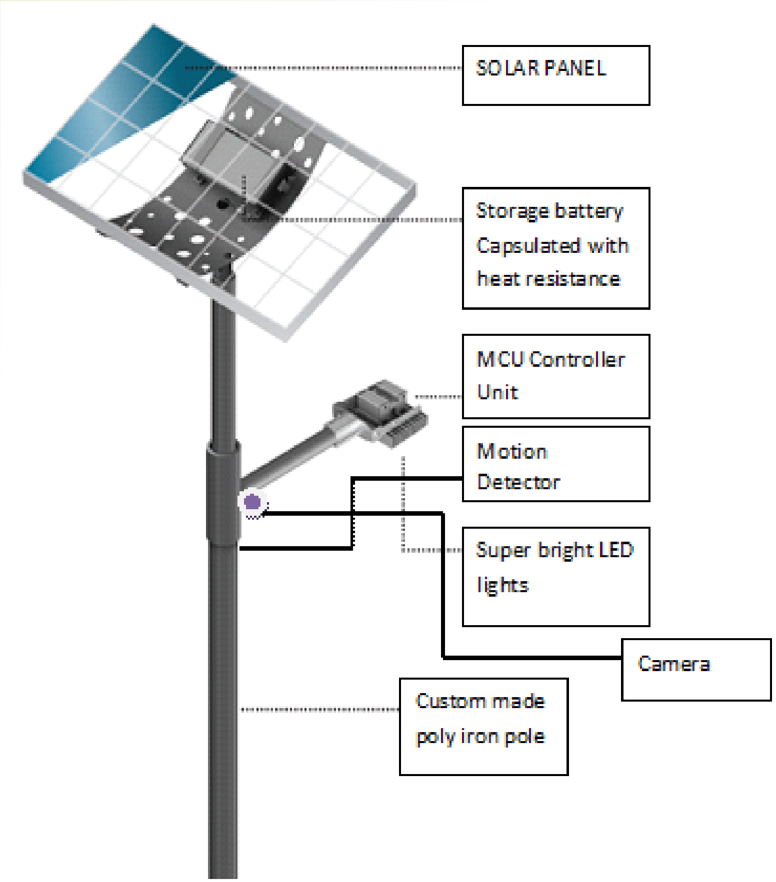
- The design of the smart street light system comprises of three major aspects which is the implementation of smart street light control system, the use of an environment friendly energy resource and to provide a surveillance security system.

Smart Street Light Management System



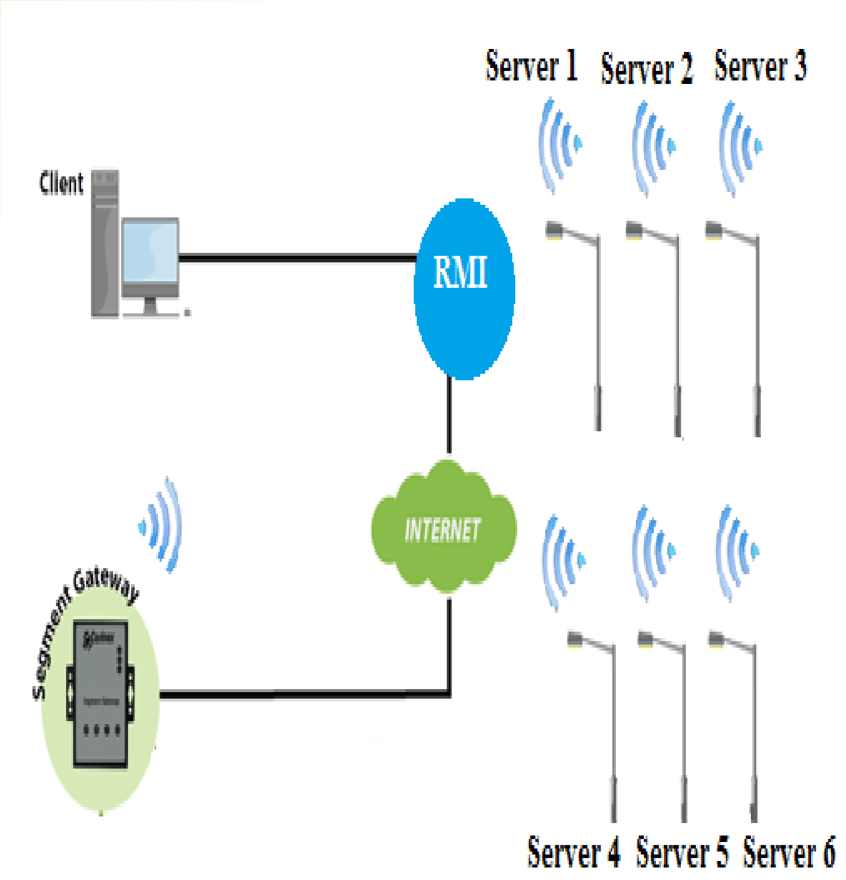
Physical Outlook of Smart Street Light Design

- The solar panel fixed to the street lamp supplies DC voltage to the storage battery to recharge
- Weather proof casing will be used for the controller, motion detector and the camera module.



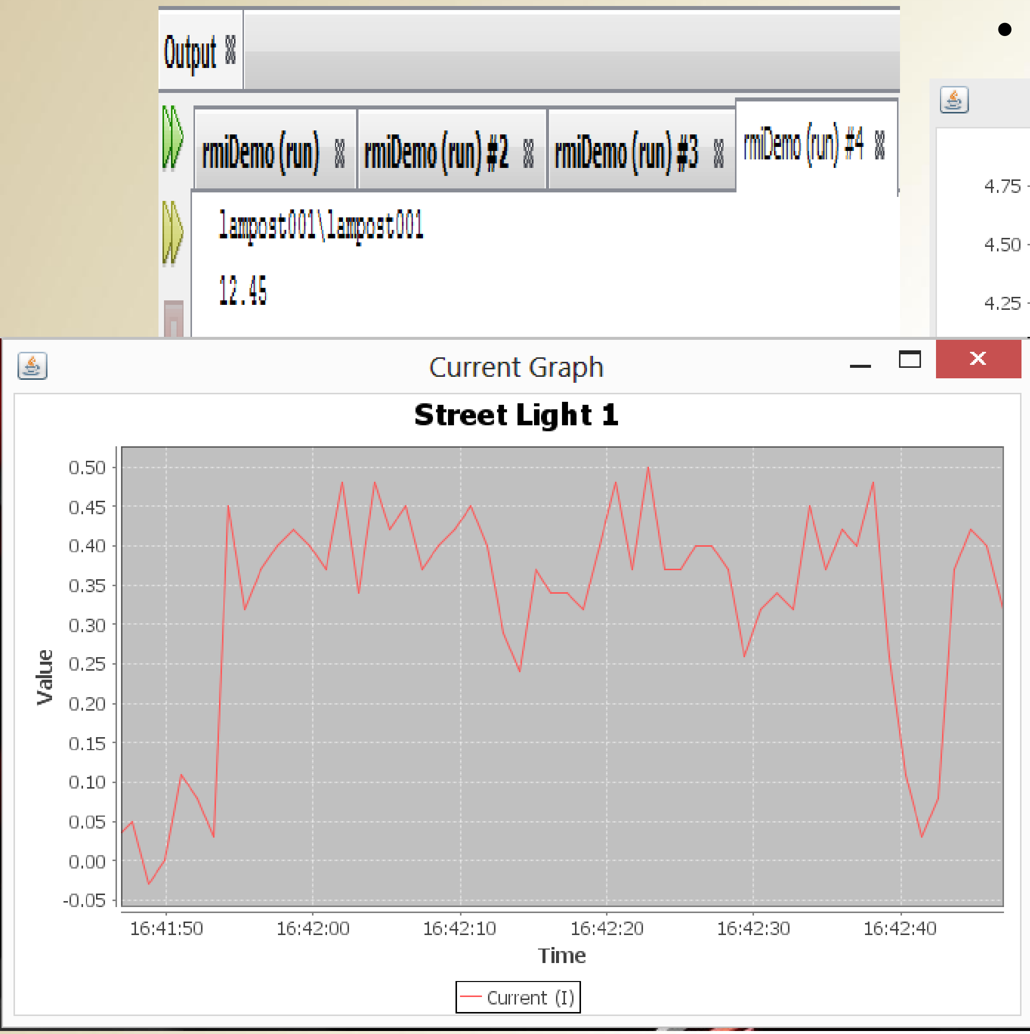
Client-Server Connection

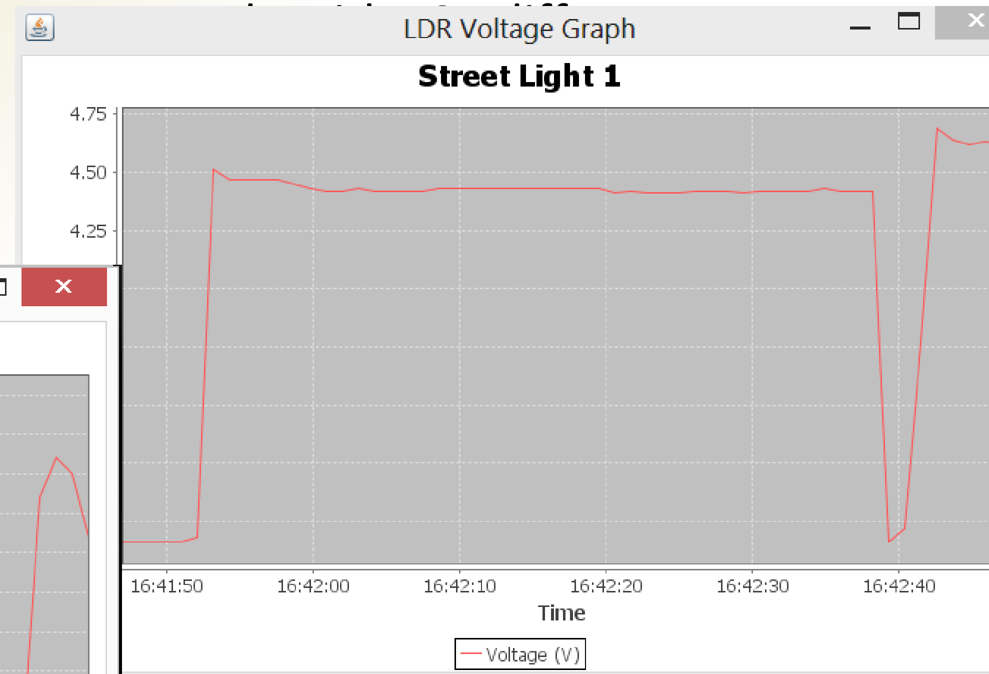
- Client server connection to monitor the health status of each lamp post in a residential area. A Remote Method Invocation (RMI) register register's all the unique street lights that is connected in the network structure.



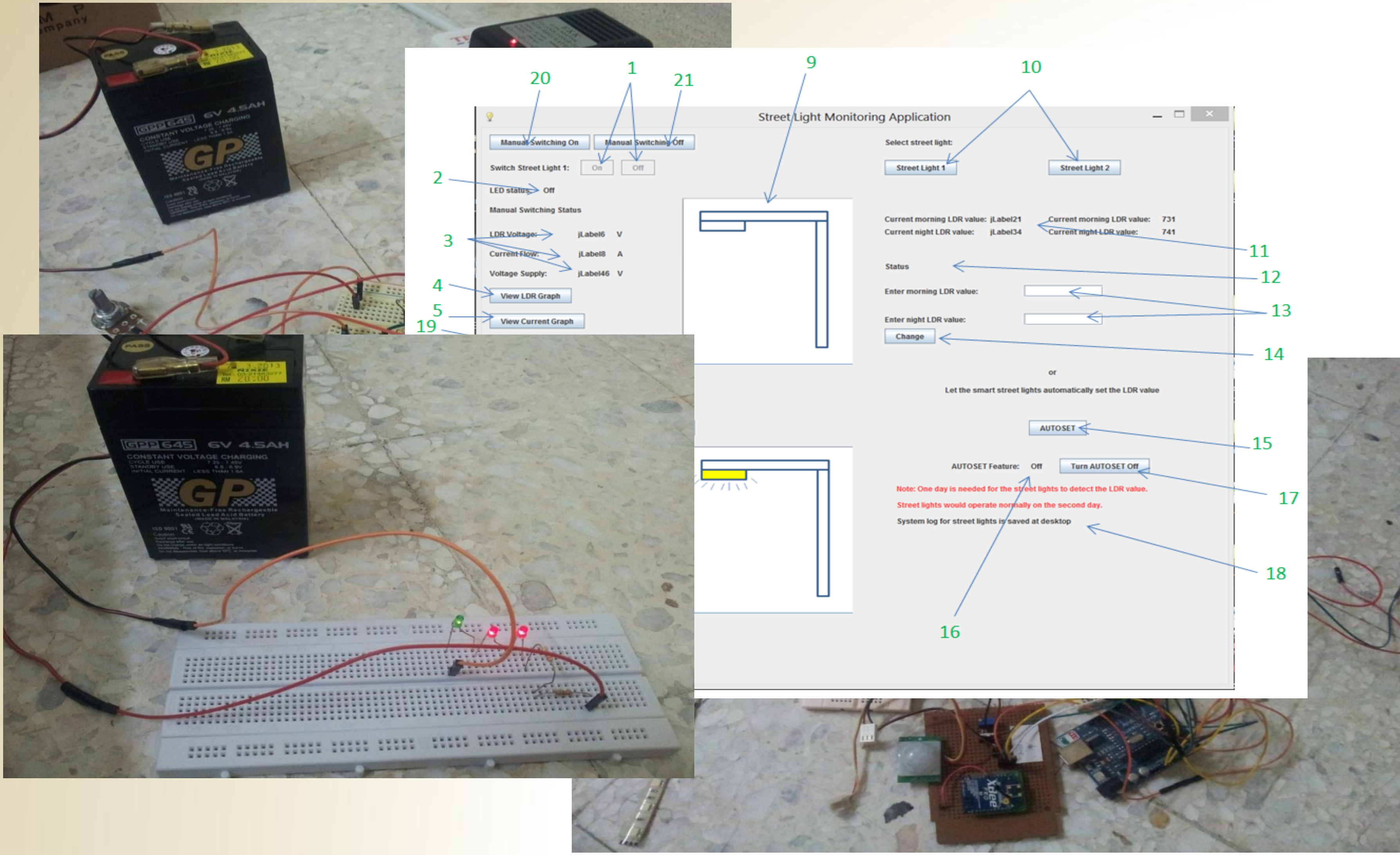
Records

- 3 different smart street lights are





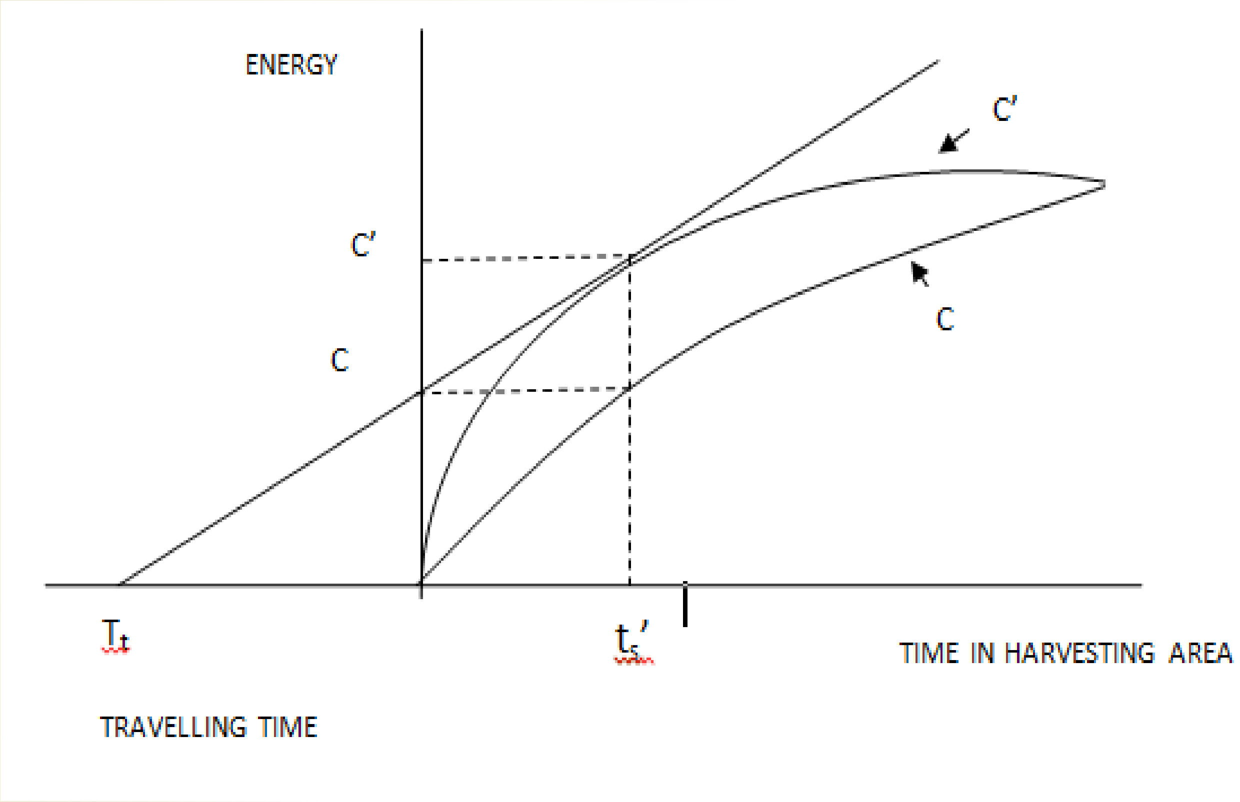
Prototype



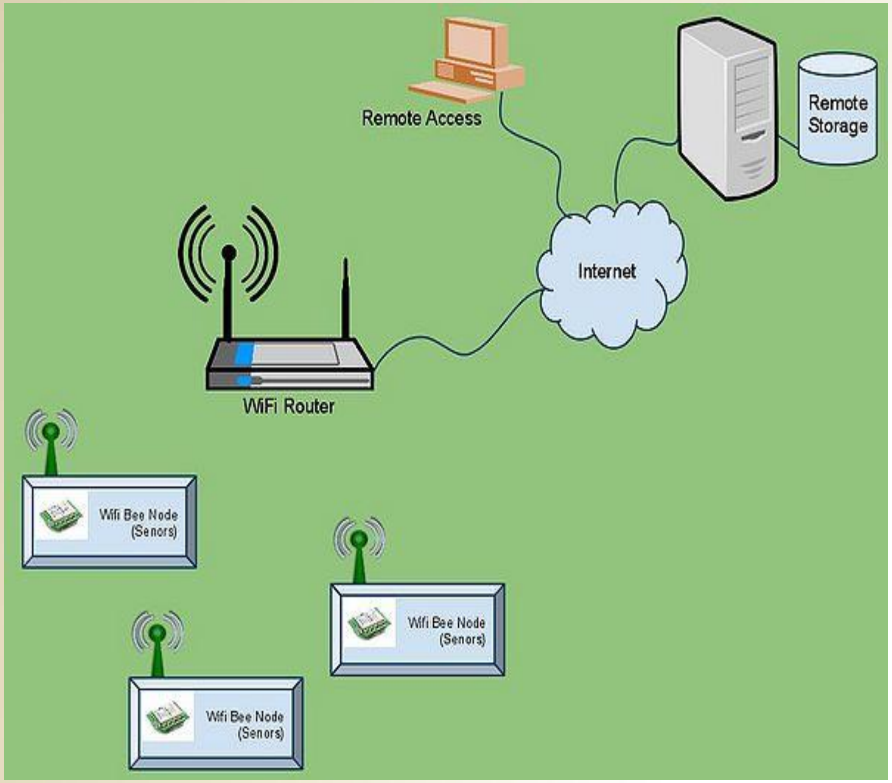
Street Light Monitoring Application
Manual Switching On
Manual Switching Off
Switch Street Light 1:
On
Off
LED status: Off
Manual Switching Status
LDR Voltage: jLabel6 V
Current Flow: jLabel8 A
Voltage Supply: jLabel46 V
View LDR Graph
View Current Graph
Select street light:
Street Light 1
Street Light 2
Current morning LDR value: jLabel21
Current night LDR value: jLabel34
Current morning LDR value: 731
Current night LDR value: 741
Status
Enter morning LDR value:
Enter night LDR value:
Change
or
Let the smart street lights automatically set the LDR value
AUTOSET
AUTOSET Feature: Off
Turn AUTOSET Off
Note: One day is needed for the street lights to detect the LDR value.
Street lights would operate normally on the second day.
System log for street lights is saved at desktop
1
2
3
4
5
9
10
11
12
13
14
15
16
17
18
19
20
21
GPP645 6V 4.5AH
CONSTANT VOLTAGE CHARGING
GP
Maintenance-Free Rechargeable Sealed Lead Acid Battery

Bio-Inspired Energy Scavenging for SHM

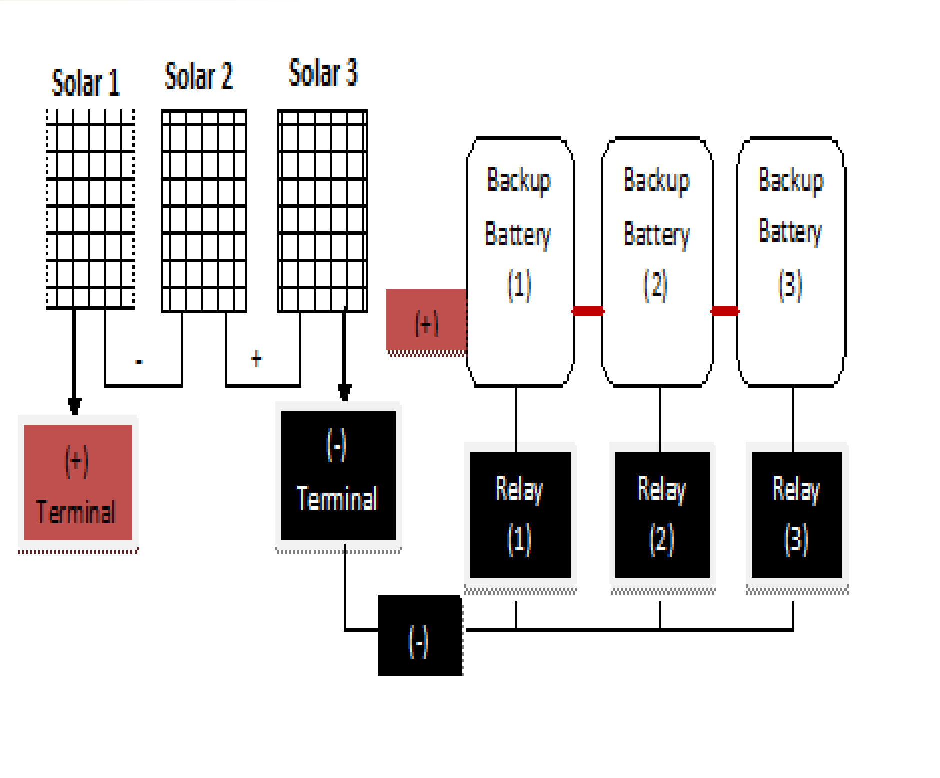
- The Orians-Pearson Model of Prey Selection



Autonomous Solar Energy Management



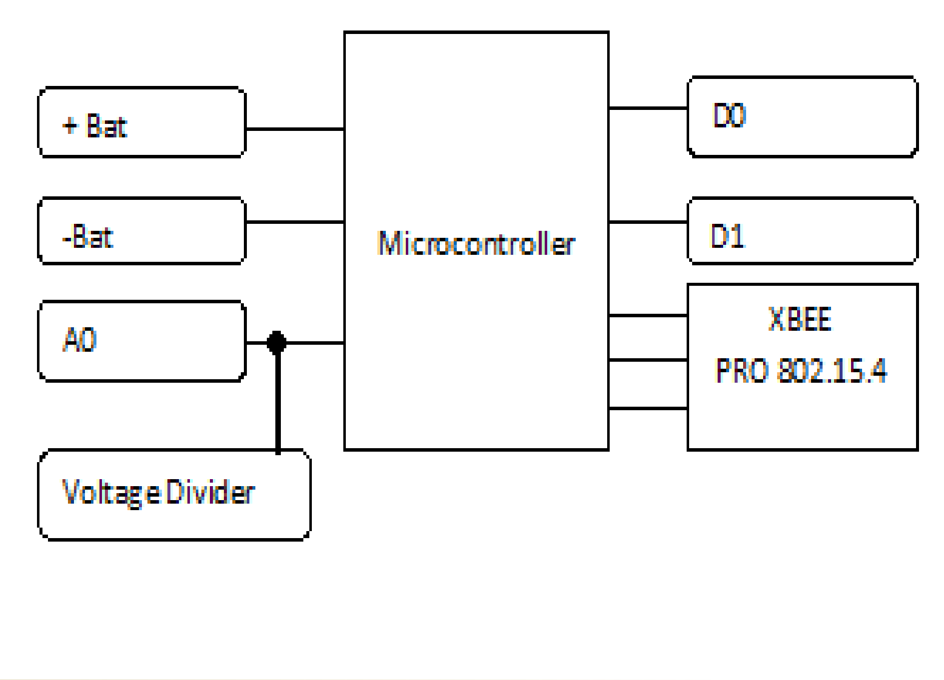
The architecture of Solar Powered Wireless Sensor Network.



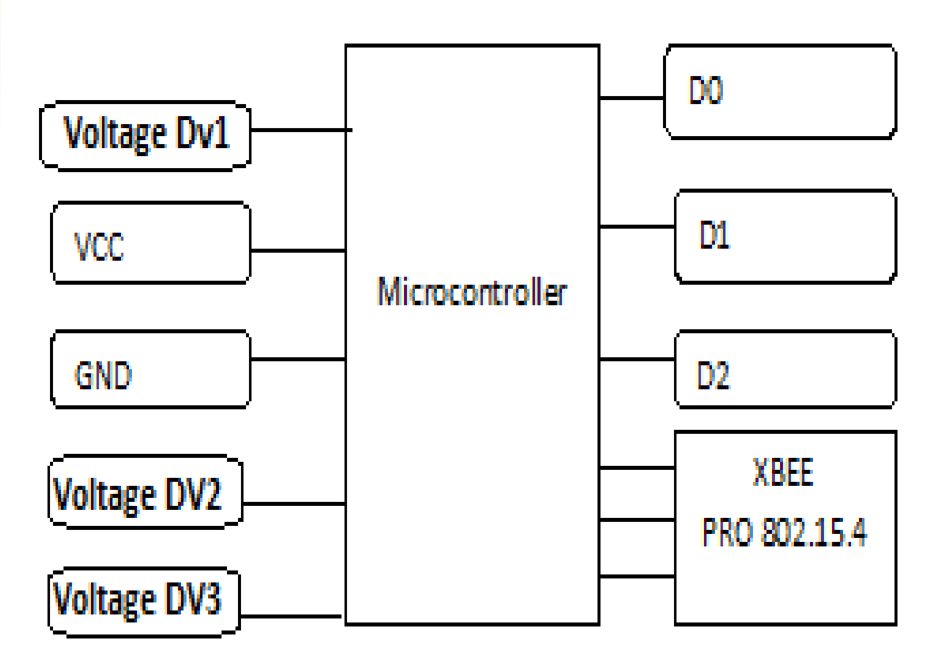
Solar Charging LiPO Batteries

Autonomous Solar Energy Management

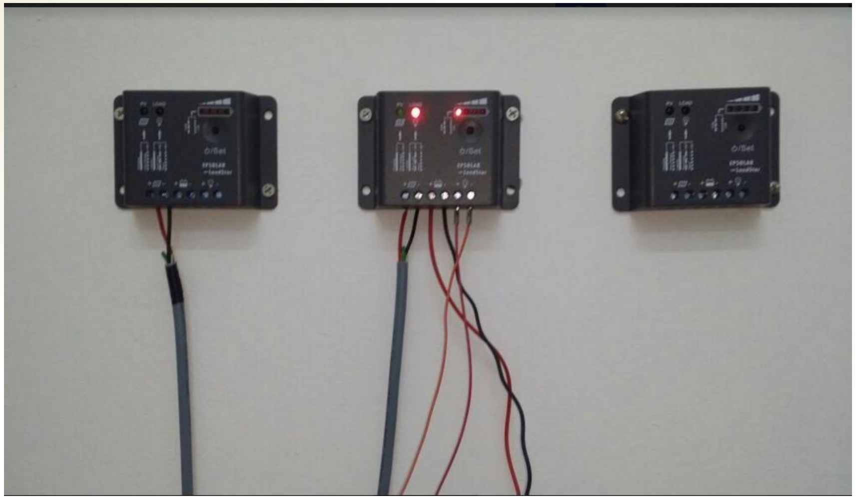
- Child Mote

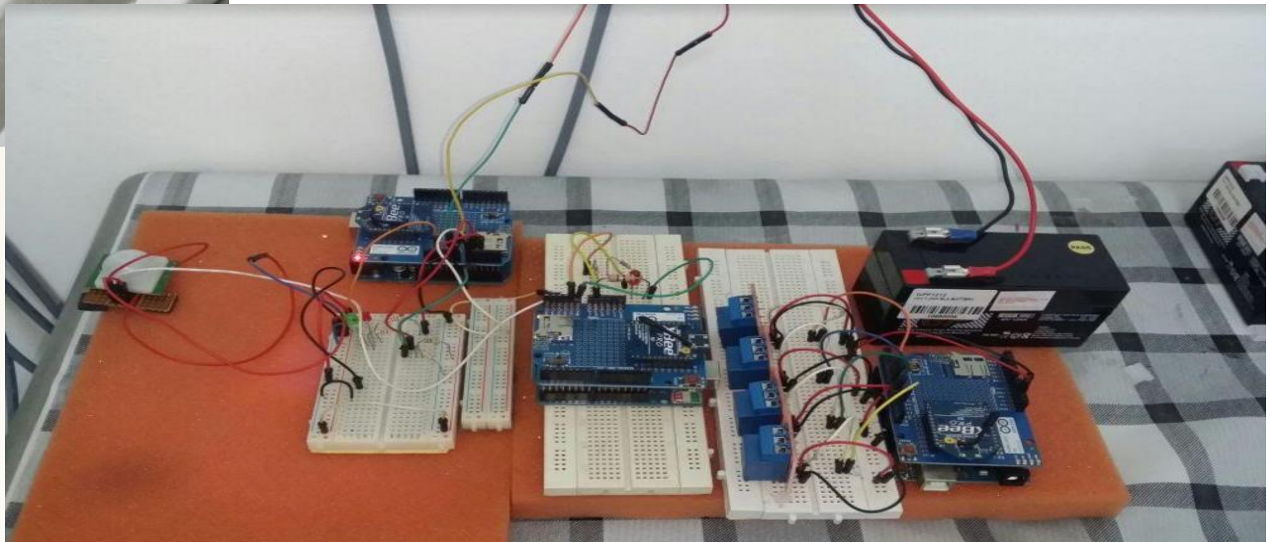


- Parent Mote



Autonomous Energy Management Prototype





Autonous Sensor Design for Structural Health Monitoring of Bridges

- The sensor nodes are autonomous in terms of energy management and these nodes can transfer material strength between the gap of a structural bridge design.
- A bridge can collapse overtime due to the expansion between the connection of a bridge design, therefore it is important to monitor the split between the connector.

Design Challenges And Guidelines

- Wireless power transmission technology has been there for some time, but it is still at its premature stage due to the challenges and limitations of such technology. Wireless power transmission is highly restricted by the distance between the antennas.
- Based on Choi et al. (2011), the transmission efficiency of wireless energy transmission resonators decreases proportionally over distance irrespective of the receiving coil size.

References/Sources

- M. Rahimi, H. Shah, G. S. Sukhatme, J. Heidemann and D. Estrin, “Studying the feasibility of energy harvesting in a mobile sensor network”, in Proc. IEEE Int. Conf. on Robotics and Automation, 2003.
- F. K. Shaikh and S. Zeadally, “Energy harvesting in wireless sensor networks: A comprehensive review,” Renewable and Sustainable Energy Reviews, vol. 55, pp. 1041–1054, 2016.
- L. Xiao, P. Wang, D. Niyato, D. Kim, and Z. Han, “Wireless networks with RF energy harvesting: A contemporary survey,” IEEE Communications Surveys & Tutorials, 2014.
- D. Lozneanu, L. Miron, G. Pana, "Energy model of sensor nodes in WSN", Review of the Air Force Academy, 2011, ISSN 1842-9238
- K. Zeng, K. Ren, W. Lou, P. J. Moran, Energy aware efficient geographic routing in lossy wireless sensor networks with environmental energy supply, Wireless Networks 15 (1) (2009) 39–51.
- S. S. Kumar and D. K. Kashwan, “Research study of energy harvesting in wireless sensor networks,” International Journal of Renewable Energy Research (IJRER), vol. 3, no. 3, pp. 745–753, 2013.