Chapter 14: Energy Harvesting Sensor Nodes: Survey and Implication

Department of CSIE
National Taipei University

Outline

- Introduction
- Energy Harvesting Sensor Nodes
- Energy Harvesting Sensor Nodes And Applications
- Implications On Sensor Network System And Solutions

Introduction: Sensor Network

- Sensor Network
  - A network of collaboration embedded devices (sensor nodes).
  - Used to sense and collect data for application specific analysis.
- Application
  - Sensing modality
  - Sensor node computation
  - Communication
  - Storage capability
  - Cost and size of each node
  - Type of power source
  - Architecture for deployment
  - Protocols for data dissemination
  - To name a few…..

Introduction: Battery-powered sensor nodes

- Application
  - Habitat monitoring
  - Vehicle monitoring
- Restriction
  - Finite battery capacity
- Several solution techniques have been proposed to maximize the lifetime.
  - Optimize and adapt energy usage.
  - But, do not preclude energy-related inhibitions.

Introduction: Energy harvesting

- Harnessing energy from the environment or other energy sources.
- Challenge
  - Estimating the periodicity and magnitude of the harvestable sources.
  - Deciding which parameters to tune.
  - Avoid premature energy depletion before the next recharge cycle.

Introduction: Discussion

- Basic of energy harvesting techniques.
- Details of energy sources used for harvesting and corresponding energy storage technologies.
- Energy harvesting architectures.
- Examples of energy harvesting systems and applications based on these systems
- Implications of energy harvesting on design of sensor network applications and solution.

Energy Harvesting Sensor Nodes

- Typical energy harvesting system
  - Harvesting Architecture
    - Harvest-Use
    - Harvest-Store-Use
  - Energy source
    - Ambient Energy Sources
    - Human Power
  - Energy Conversion Mechanisms
  - Storage Technologies
    - Rechargeable battery

Harvesting Architecture

- Harvesting Architecture
  - Harvest-Use
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- Harvest-Use
  - Energy is harvested just-in-time for use.
- Harvest-Store-Use
  - Energy is harvested whenever possible and stored for future use.

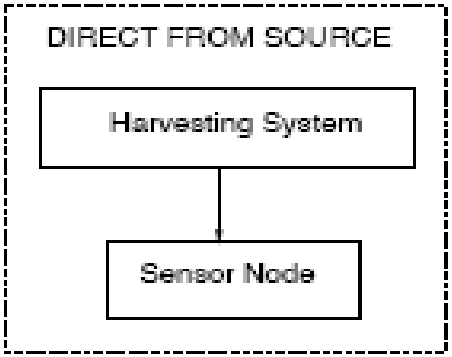

Fig.1(a) Harvest-Use

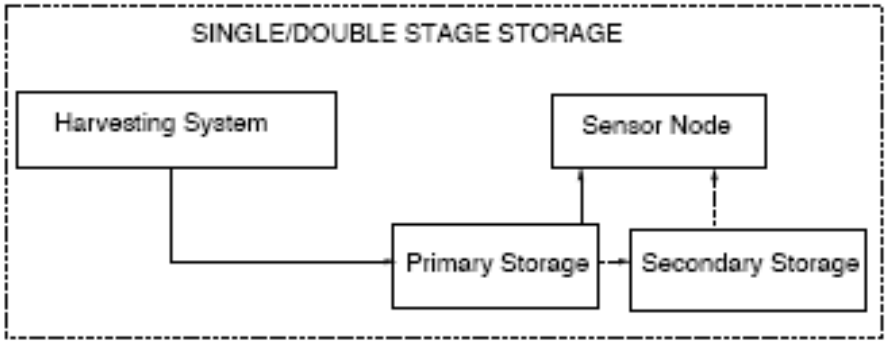

Fig.1 (b) Harvest-Store-Use

Energy Sources

- Solar Energy
  - Uncontrollable
  - Predictable
  - Solar panel
- Mechanical Energy
  - Piezo-electric material
    - PVDF
    - PZT
  - Controllable
- Wind Energy
  - Rotating arm connected

Energy source

Energy Source	Characteristics	Amount of Energy Available	Harvesting Technology	Conversion Efficiency	Amount of Energy Harvested
Solar[25], [26], [27], [28]	Ambient, Uncontrollable, Predictable	$100mW/cm^2$	Solar Cells	15%	$15mW/cm^2$
Wind[28]	Ambient, Uncontrollable, Predictable	-	Anemometer	-	1200mWh/day
Finger motion[22], [24]	Active human power, Fully controllable	19mW	Piezoelectric	11%	2.1mW
Footfalls[22], [24]	Active human power, Fully controllable	67W	Piezoelectric	7.5%	5W
Vibrations in indoor environments[29]	Ambient, Uncontrollable, Unpredictable	-	Electromagnetic Induction	-	$0.2mW/cm^2$
Exhalation[24]	Passive human power, Uncontrollable, Unpredictable	1W	Breath masks	40%	0.4W
Breathing[24]	Passive human power, Uncontrollable, Unpredictable	0.83W	Ratchet-flywheel	50%	0.42W
Blood Pressure[24]	Passive human power, Uncontrollable, Unpredictable	0.93W	Micro-generator	40%	0.37W

Table I Listing and characterization of energy sources

Storage Technologies

Battery Type	Nominal Voltage (V)	Capacity (mAh)	Weight Energy Density (Wh/kg)	Power Density (W/kg)	Efficiency (%)	Self Discharge (%/month)	Memory Effect?	Charging Method	Recharge Cycles
SLA	6	1300	26	180	70-92	20	No	Trickle	500-800
NiCd	1.2	1100	42	150	70-90	10	Yes	Trickle	1500
NiMH	1.2	2500	100	250-1000	66	20	No	Trickle	1000
Li-ion	3.7	740	165	1800	99.9	<10	No	Pulse	1200
Li-polymer	3.7	930	156	3000	99.8	<10	No	Pulse	500-1000

Table II Comparison of rechargeable battery technologies

Energy Harvesting Sensor Nodes And Applications

- Solar energy
- Active user power
  - Piezoelectric-based Harvesting
  - Shoe-powered RF Tag System
  - Wireless, Self-Powered Push-Button Controller
- Wind energy
- RF energy

Solar Energy

- Nodes with Battery-based Storage
  - Hydro Watch [26]
  - Heliomote [27]
  - Fleckl [46]
- Nodes with Supercapacitor-based Storage
  - Everlast [34]
  - Sunflower [35]
- Nodes with Tiered Storage
  - Prometheus [25]
  - AmbiMax [28]
- Application
  - ZebraNet [58]

Table III Specifications of Solar Energy Harvesting Sensor Nodes

Node	Solar Panel Power (mW)	Solar Panel Size (inxin)	Energy Availability (mWh /day)	Storage Type (Y/N)	Battery Type	Battery Capacity (mAh)	Sensor Node Used	MPPT Usage
Heliomote[27]	190	3.75 × 2.5	1140	Battery	Ni-MH	1800	Mica2	No
HydroWatch[26]	276	2.3 × 2.3	139	Battery	Ni-MH	2500	TelosB	Yes
Fleck1[46]	-	4.53 × 3.35	2100	Battery	Ni-MH	2500	NA	No
Everlast[34]	450	2.25 × 3.75	2700	Supercap (100F)	NA	NA	NA	Yes
SolarBiscuit[51]	150	2 × 2	900	Supercap (1F)	NA	NA	NA	No
Sunflower[35]	4 PIN photo diodes 20mW	NA	100	Supercap (0.2F)	NA	NA	NA	No
Prometheus[25]	130	3.23 × 1.45	780	Supercap (two 22F) & Battery	Li-poly	200	Telos	No
AmbiMax[28]	400	3.75x2.5	1200	Supercap (two 22F) & Battery	Li-poly	200	Telos	Yes

Hydro Watch [26]

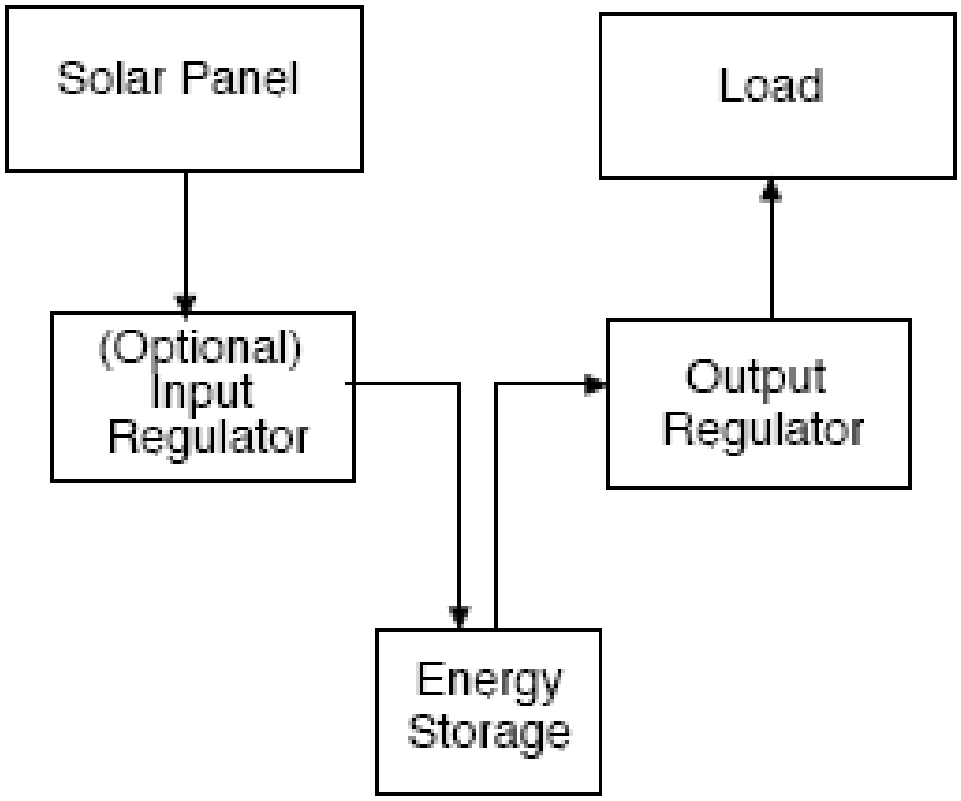

Fig.2 (b) Hydro Watch power subsystem architecture

Everlast [34]

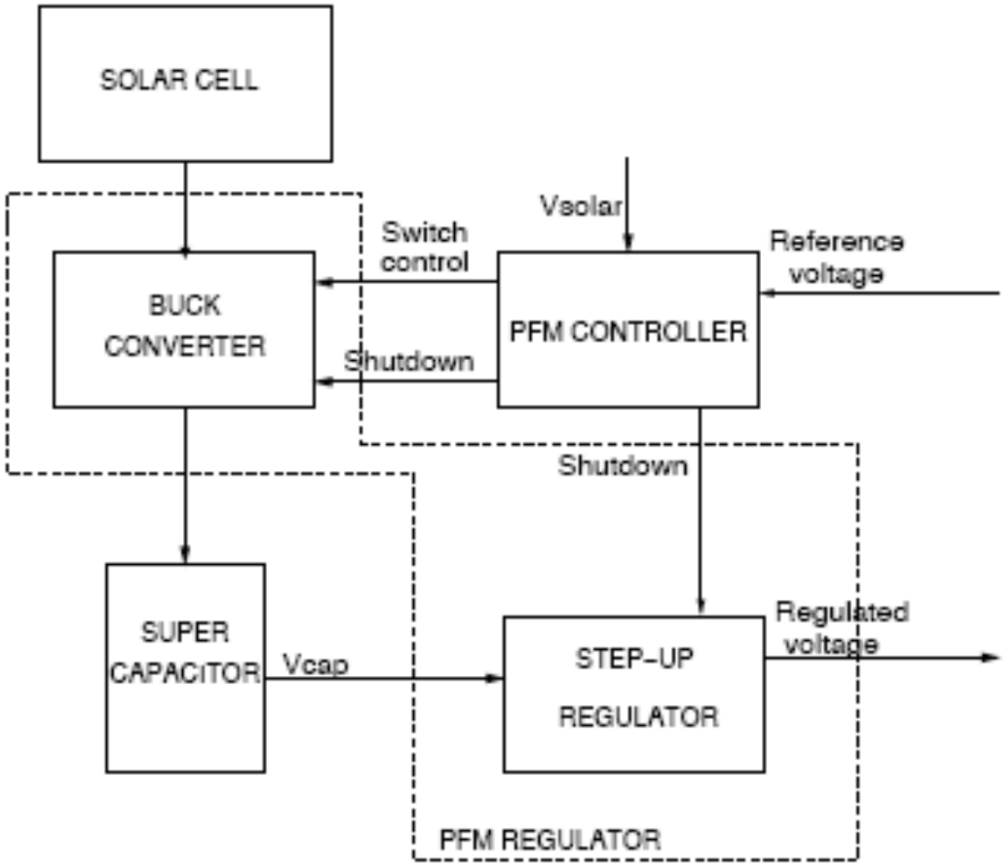

Fig.4 Block diagram of Everlast's energy harvesting sybsystem

Promethus [25]

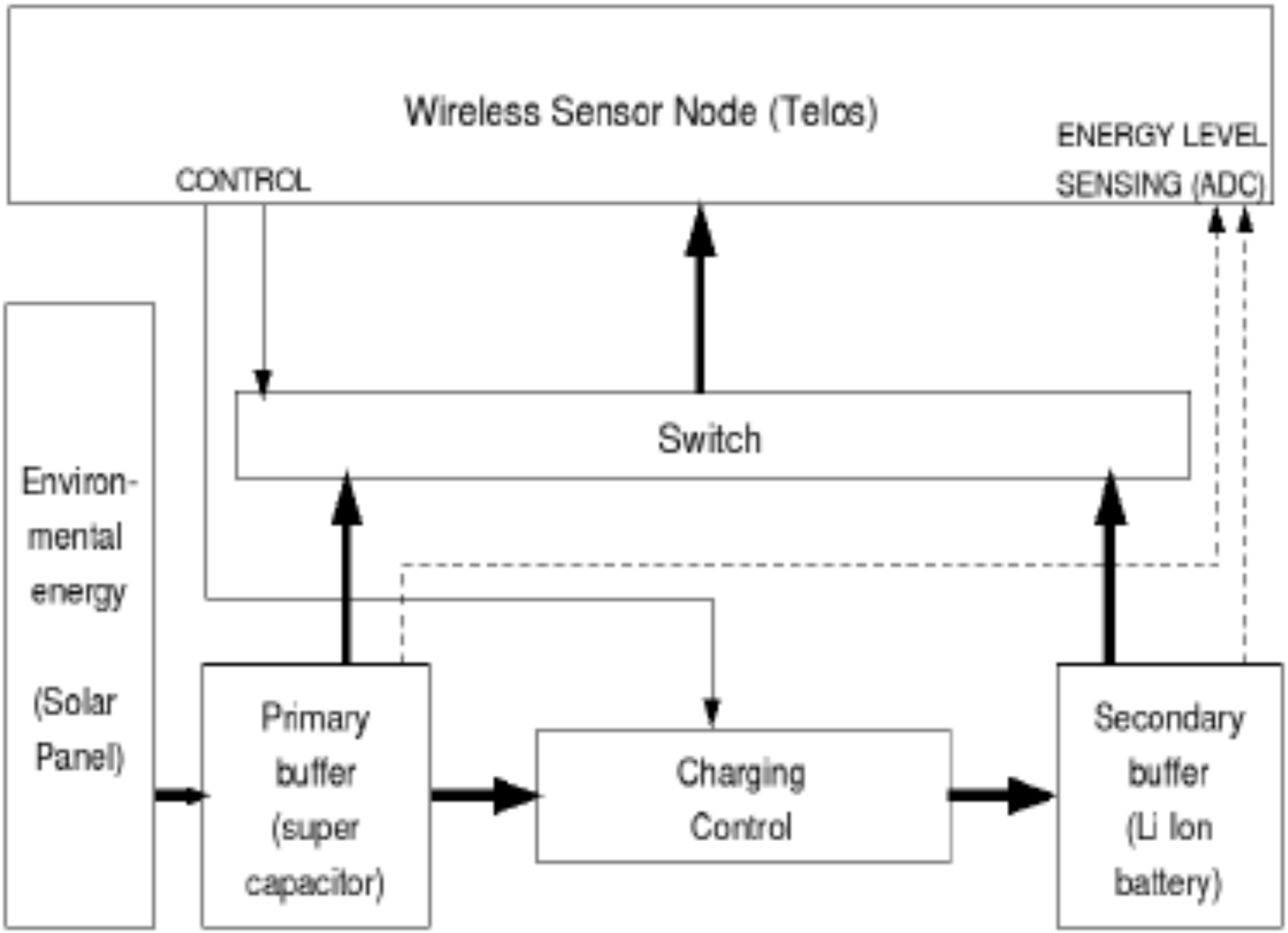

Fig.5 Promethus energy harvesting architecture

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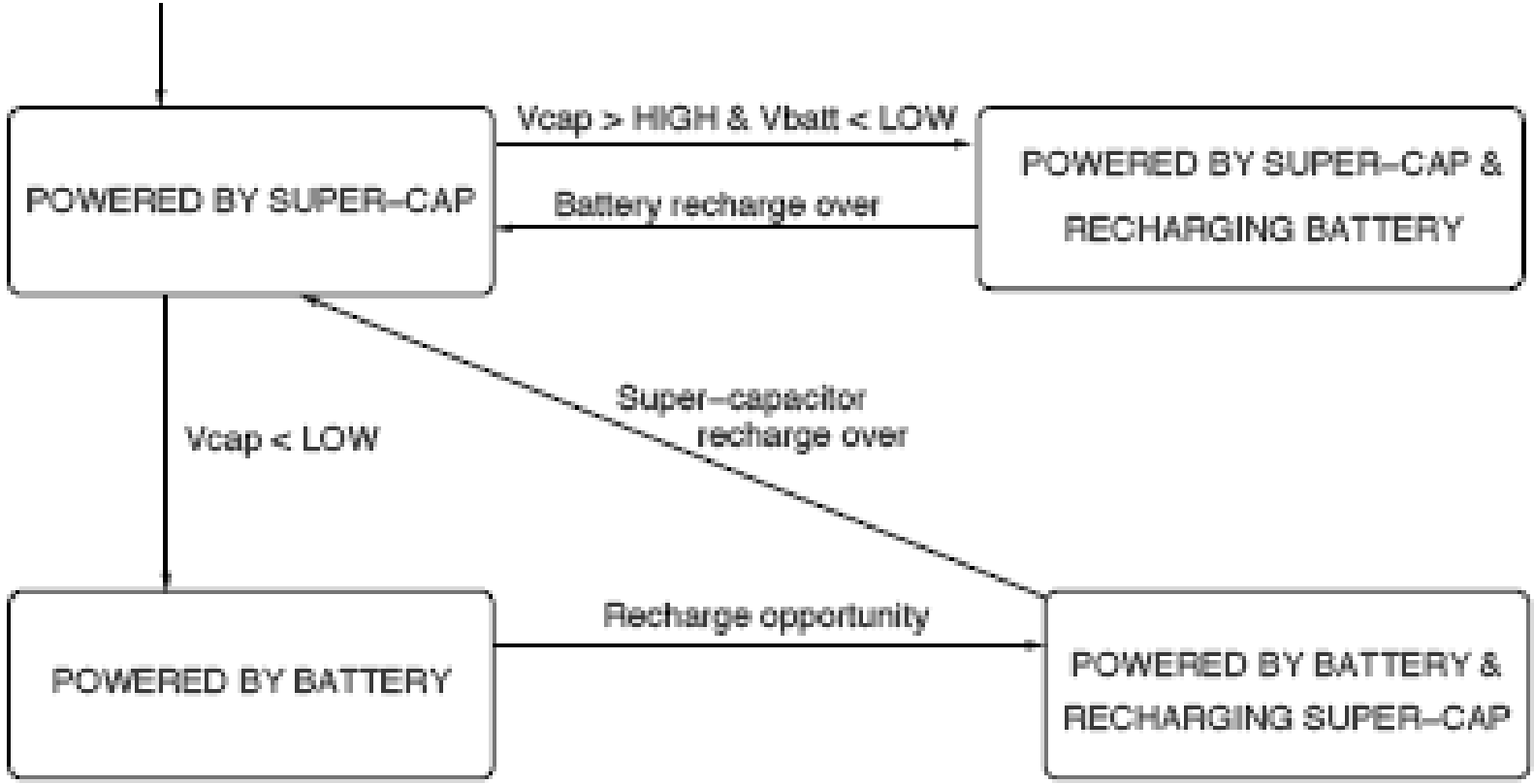

Fig.6 State diagram of Prometheus driver.

Implications On Sensor Network System And Solutions

- Energy Neutral Operation
  - Node-level energy neutrality
  - Application-level energy neutrality
- Performance Adaptation
  - Energy Prediction Methods
  - Node-level Adaptations
    - Duty-Cycling
    - Transmit Power
    - Sensing Reliability
    - Transmission Scheduling
  - Network-level Design
    - Routing
    - Clustering
    - Data Collection
    - Miscellaneous

Application-level energy neutrality

- Meeting application requirements at all.
  - Providing continuous sensing coverage to a region.
- Co-ordination and cooperation amongst nodes to tune system parameters.
- Consider two closely placed nodes.
  - Adjust their parameters such that one is ON and the other OFF.
  - The OFF-node becomes operational only when the ON-node fail to meet application requirements.

Energy Prediction Methods

- Energy harvesting framework (EEHF) [62]
  - Predict a node's effective energy.
- Enhanced-EEHF [63]
  - Extends EEHF.
- Exponentially Weighted Moving-Average (EWMA)
  - Divided into 48 half hour slots.

Energy harvesting framework (EEHF) [62]

- Predict a node's effective energy.
- A day as a single epoch.
- Energy consumption and energy availability over finite number of previous epochs, to predict the energy available in the next epoch.
- Effective energy is formulated as a weighted function.
  - Predicted expected energy
  - Energy consumption
  - Battery level

Enhanced-EEHF [63]

- Extends EEHF.
- Uses the concept of rounds within each cycle/epoch.
- Obtains a first estimate of the expected energy for a round of a particular cycle.
- Using the estimated and generated energy of the same round of the previous cycle.

Exponentially Weighted Moving-Average (EWMA)

- A day divided into 48 half hour slots.
- $$\overline{x}(i) = \alpha\overline{x}(i-1) + (1-\alpha)x(i)$$
  - $\overline{x}(i)$: Average energy availability of a slot.
  - x(i) : Actual generated energy in slot i.
  - α : Weighting factor.
- α of 0.5 was empirically found to be an optimal value for minimum prediction error.

Node-level Adaptations

- Duty-Cycling
  - The fraction of time a node is ON in a cycle of ON and OFF durations.
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Network-level Design

- Routing
  - Depend on gradients from the data source to sink for route setup.
  - Active energy saving protocols
  - Passive energy saving protocols
  - Topology control protocols
- Clustering
  - To route packets in sensor networks through formation of clusters.

Conclusions

- In this paper, they discussed various aspects of energy harvesting systems.
  - Presented basic concepts of harvesting systems—architectures, types of harvestable energy sources, and storage technologies.
- Described details of existing energy harvesting sensor nodes and applications
  - Solar energy
- Presented insights into implications of recharge opportunities on node-level operations and design of sensor network applications and solutions.

Question

- How's the Prometheus energy harvesting system work?

- What's the different between EEHF, E-EEHF and EWMA?

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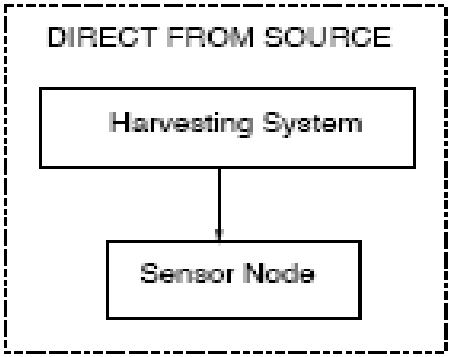

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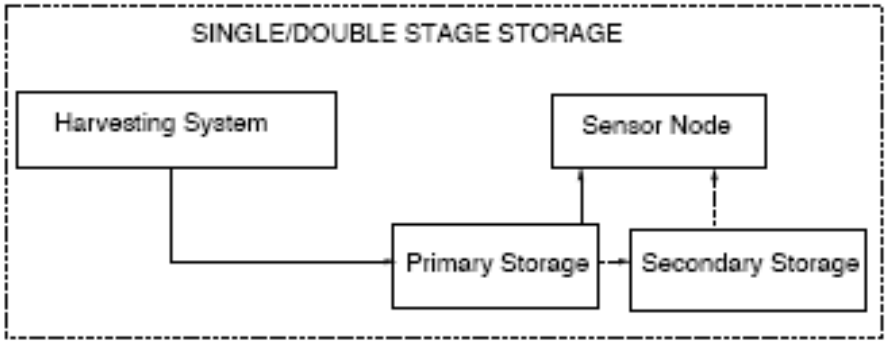

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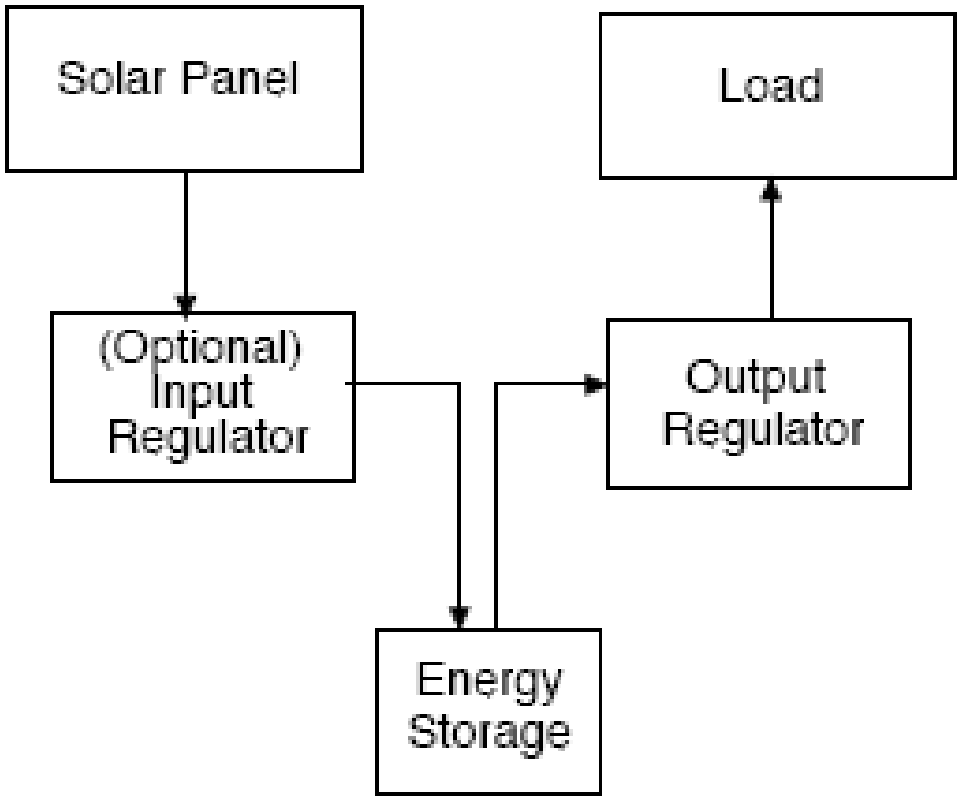

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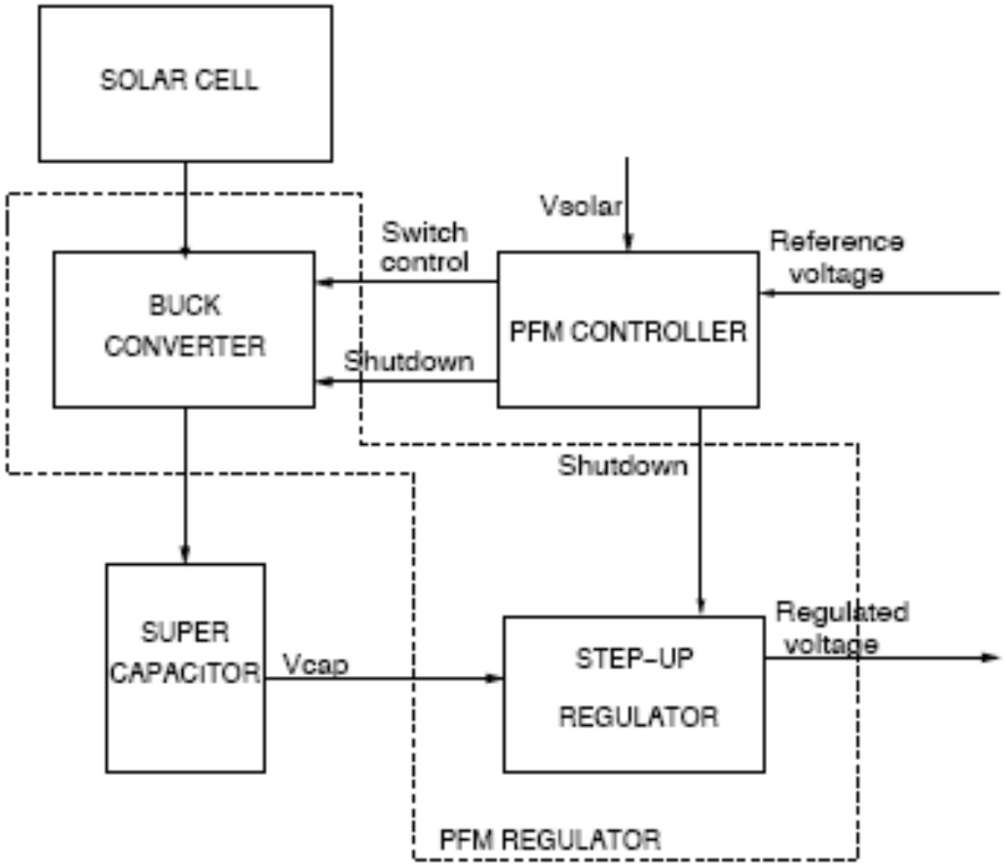

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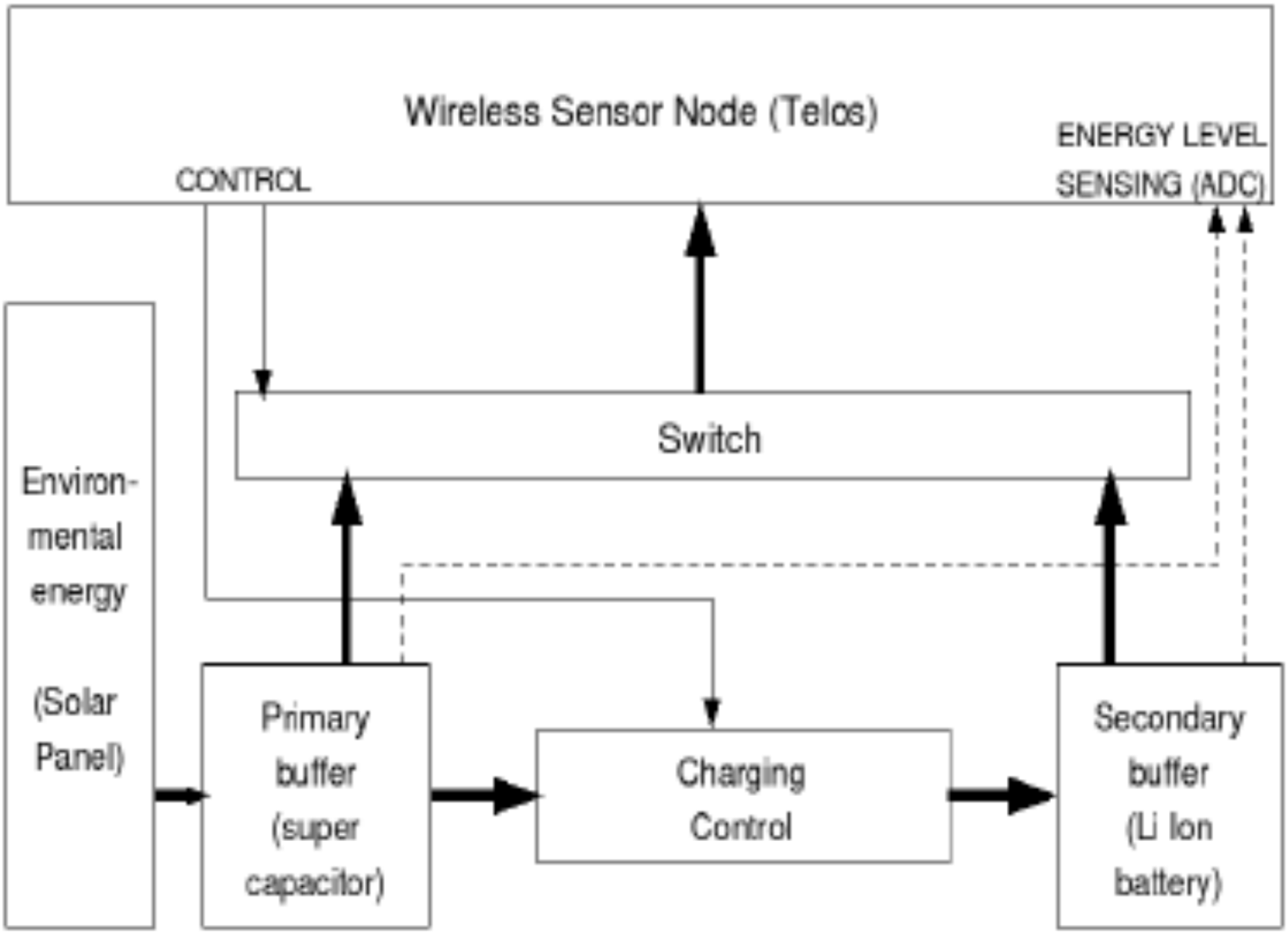

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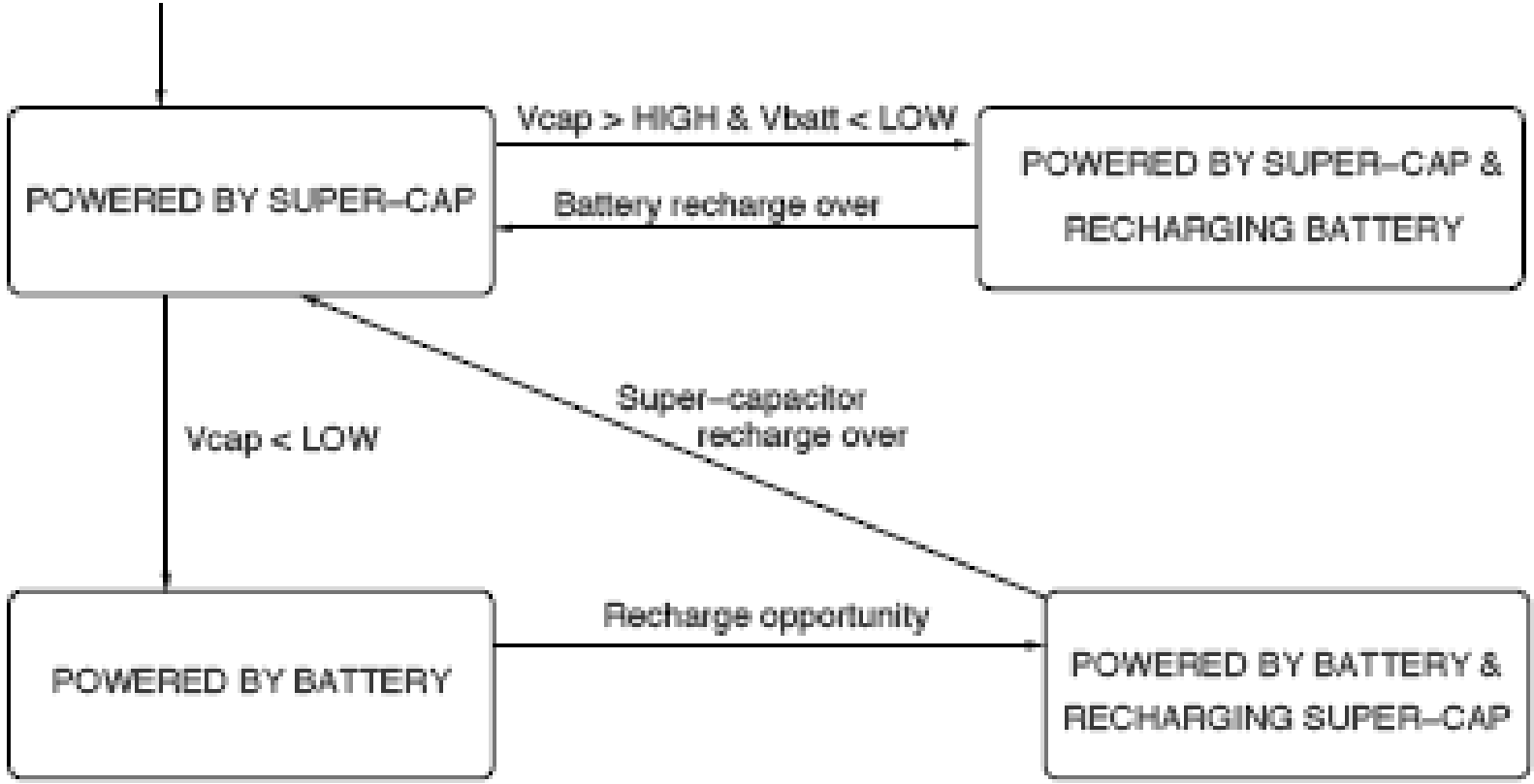

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Question

1. What is detailed operations of the Prometheus energy harvesting system ?

2. What's the difference between EEHF, E-EEHF and EWMA protocols ?