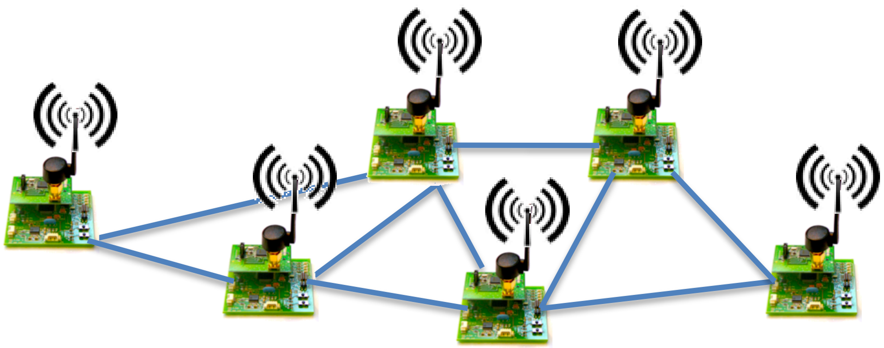
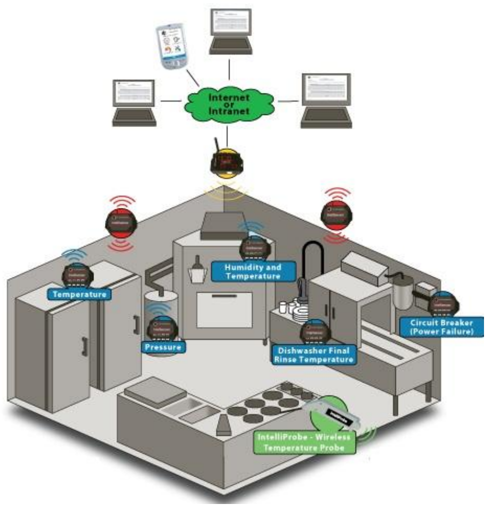
Super Capacitor based Energy Harvesting Wireless Sensor Networks

Trong-Nhan LE (PhD)

Wireless Sensor Networks Applications

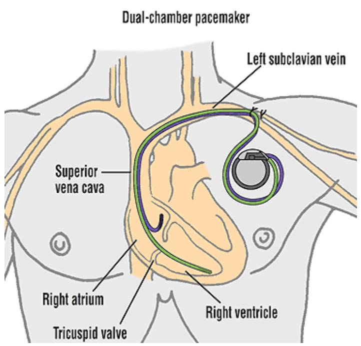
- Wireless Sensor Networks





- Smart building

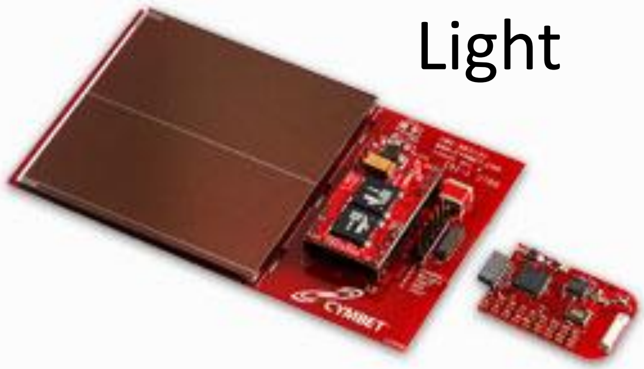
- Medical and Health Monitoring



- Structure Health Monitoring

Energy Harvesting Sources

Light

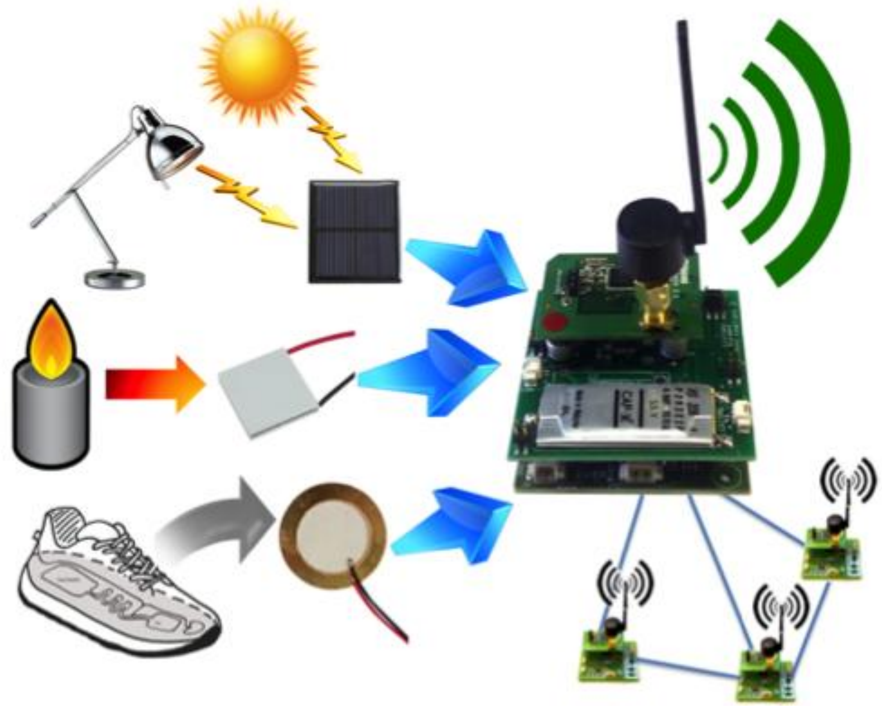


Cymbet [1]

Heat

Micropelt [2]

Multiple-sources



PowWow[3]

Super Capacitor vs Rechargeable Battery[4]

- **500 000** recharge cycles
- **Simple energy monitor** based on its voltage
- High leakage energy

- 500 recharge cycles
- Complex energy monitor
- **Low leakage energy**

Content

- **Generic Architecture of Energy Harvesting WSN**
  - Energy Adapter
  - Energy Flow Controller
- **Energy Monitor for Super Capacitor based WSN**
  - Store Energy Model
  - Consumed Energy Model
  - Harvested Energy Model
- **Duty-cycled Power Manager**
  - Energy Prediction
  - Budget Energy
  - Adapt Next Wake-up Time
  - Power Manager with Wake Up Variation Reduction
- **Demo**
  - PowWow platform

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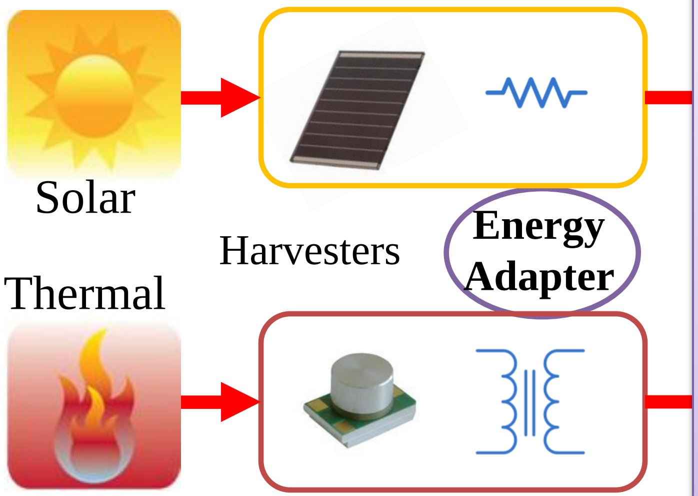
Generic Energy Harvesting WSN

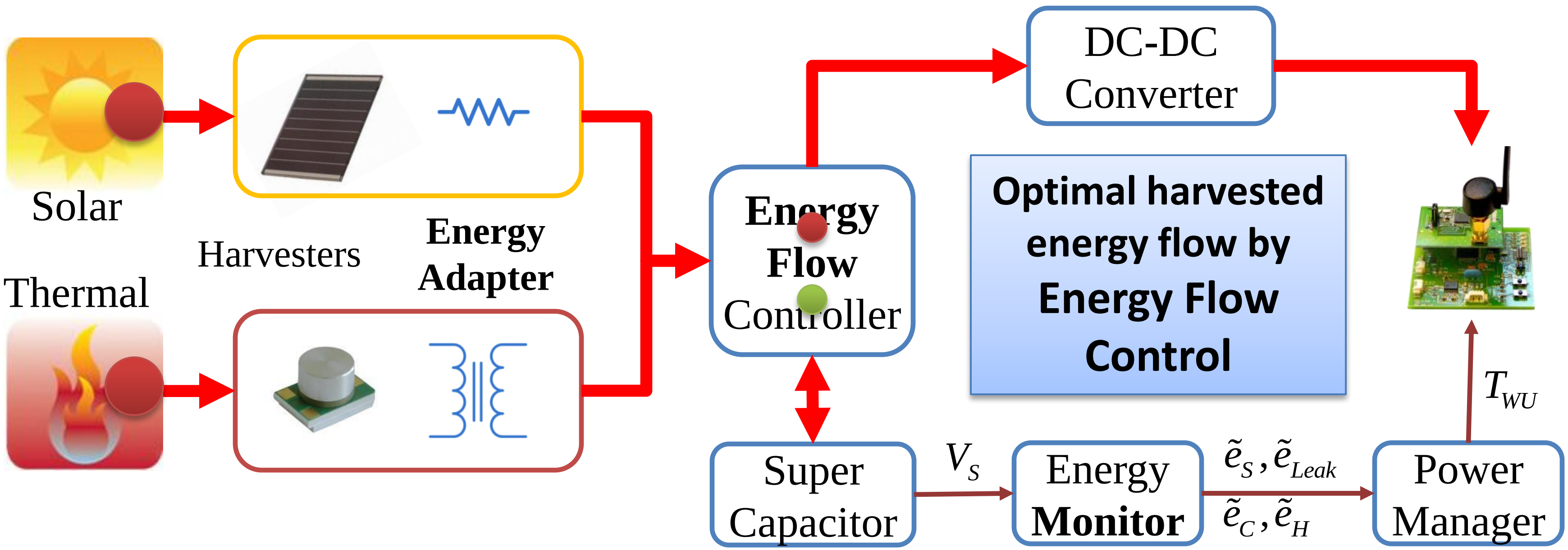


Multi-sources energy harvesting

Energy Adapter is designed **to normalize** the output energy shape from different harvesters:

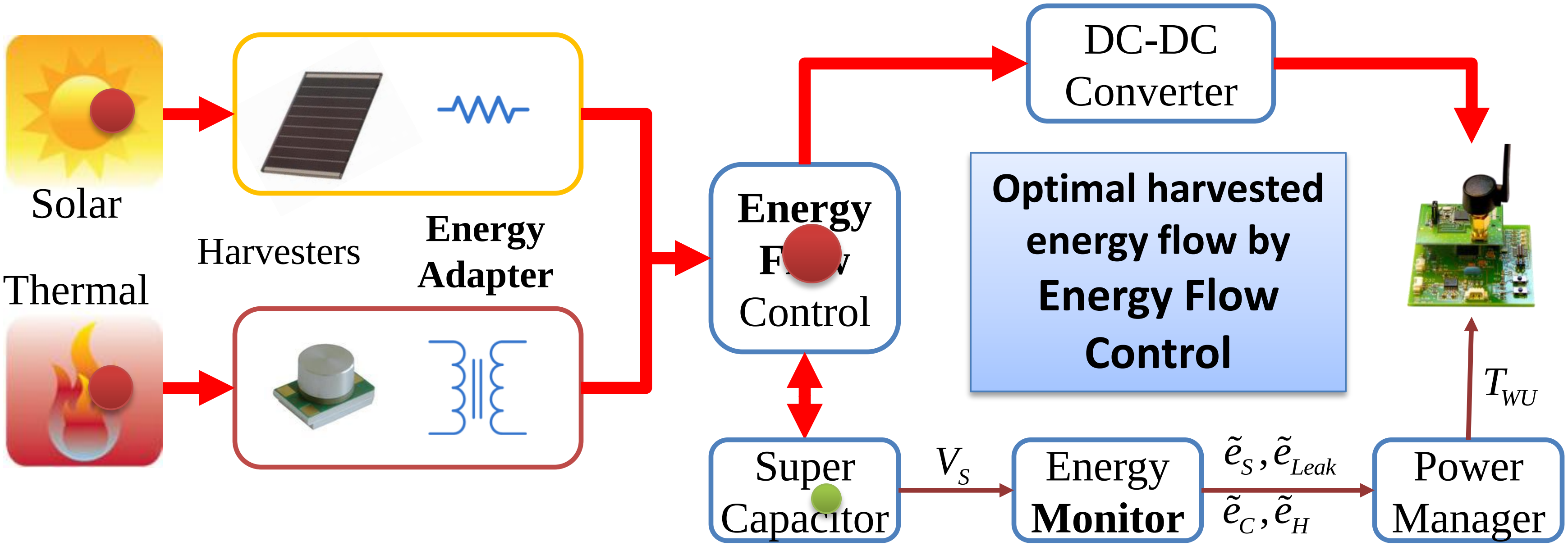
- **Photovoltaic** (PV) : High voltage (e.g. 5V), low current (µA) → ***Resistor***
- **Thermal generator** (TEG) : Low voltage (e.g. 20mV), high current (mA) → ***Step up transformer***
- **Vibration scavenger** : AC current → ***Diode bridge***

Generic Energy Harvesting WSN



- Case 1 : Harvested energy > Consumed energy
  - Surplus energy charges the Super Capacitor (SuperCap)

Generic Energy Harvesting WSN



- Case 2: Harvested energy < Consumed energy
  - Remaining energy is served by the SuperCap

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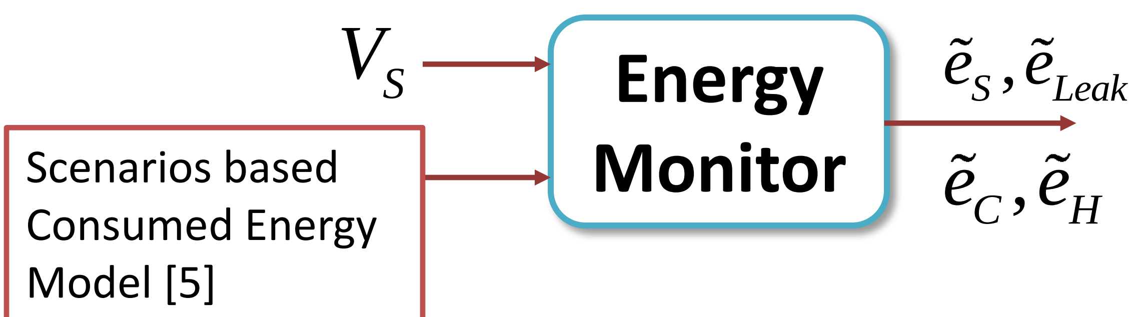
Energy Monitor

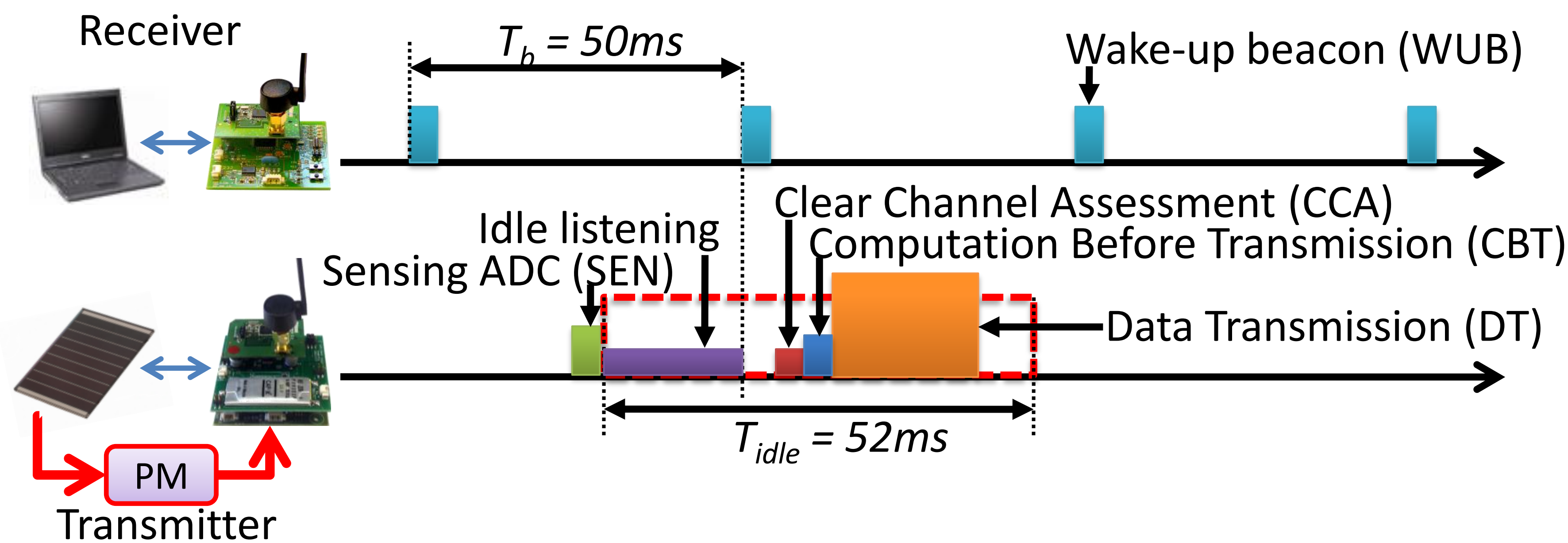
- Provide **energy profiles** to the Power Manager
  - Current energy in the SuperCap (or SoC) ($\tilde{e}_S$)
  - Leakage energy ($\tilde{e}_{Leak}$)
  - Consumed energy of the WSN node ($\tilde{e}_C$)
  - Harvested energy from harvesters ($\tilde{e}_H$)
- **Independent** of harvester, **low complexity** and **real-time** monitoring



Power Manager

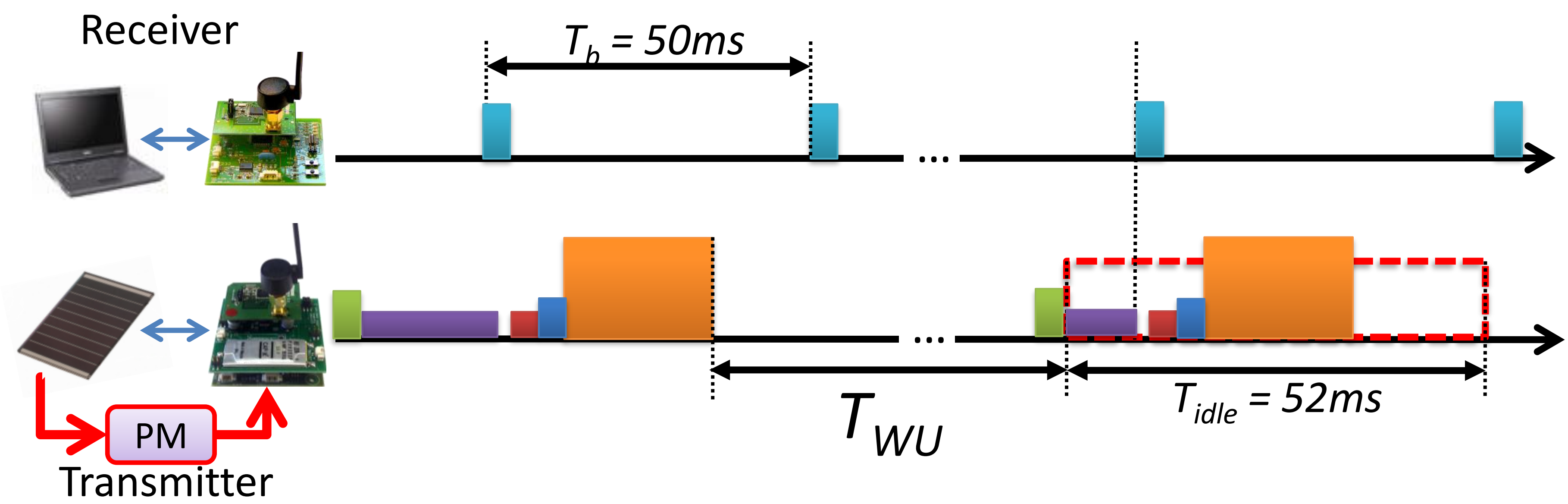
- Power Manager (PM) is the heart of the energy harvesting WSN.
- Adapt power consumption and computation loads according to harvested energy to achieve **Energy Neutral Operation** (ENO).
- **Dynamic duty cycle** by **changing the wake up interval (T_{WU})** is the most popular approach.

WSN Nodes and Protocols



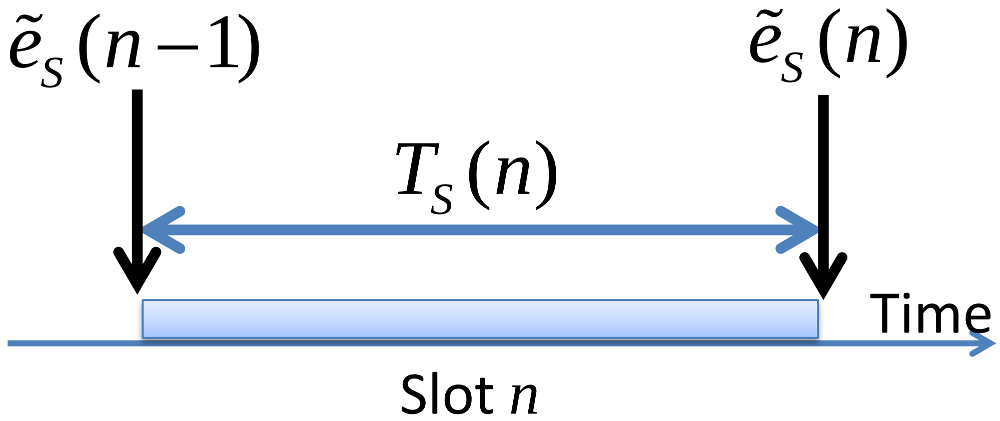
- Receiver Initiated Protocol (RICER) [7]
  - After receiving a beacon packet (WUB), the transmitter forwards data package (DT) after Clear Channel Assessment (CCA)

WSN Nodes and Protocols



- After finishing DT, the transmitter runs into sleep mode for T_{WU}, which is adapted by the PM at the end of each slot
- $T_S(n)$ is slot duration
- $T_S(n) = k * T_{WU}(n)$

Energy Monitor – **Stored** Energy Model



$$\tilde{e}_S(n) = \frac{1}{2} C V_S^2(n)$$

$$\tilde{e}_{Leak}(n) = P_{Leak} T_S(n)$$

- n : slot index
- C : storage capacitance
- P_{Leak} : leakage power
- $T_S(n)$: slot duration

Energy Monitor – **Consumed** Energy Model

Consumed Energy in PowWow [5]

Description	Symbol	Energy
Calculation Before Transmission	E_{CBT}	9.7μJ
Transmit/Receive wake-up Beacon	E_{WUB}	51μJ
Data Transmission	E_{DT}	80μJ
Data Reception	E_{DR}	100μJ
Clear Channel Assessment	E_{CCA}	18μJ
Sensing ADC	E_{SEN}	27μJ
Transmission power	P_{Tx}	66.33mW
Reception power	P_{Rx}	76.89mW
Sleep power	P_{Sleep}	85.8mW

- Consumed energy in **active period**

$$\tilde{e}_{Active}(n) = \sum_{i=1}^{k} t_{idle}(i) P_{Rx} + k\left(E_{WUB} + E_{SEN} + E_{CCA} + E_{CBT} + E_{DT}\right)$$

  - k : number of wake-up times
  - $t_{idle}(i)$: i^{th} idle listening time

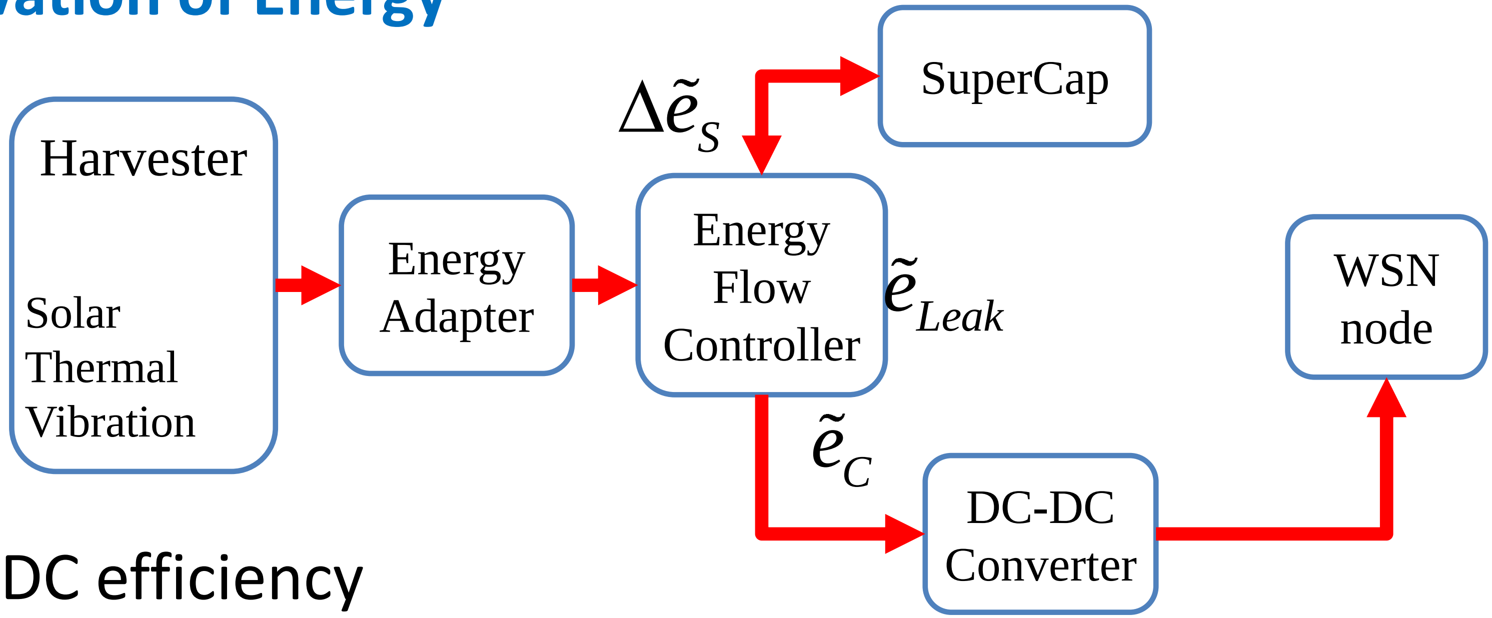
- Consumed energy in **sleep period**

$$\tilde{e}_{Sleep}(n) = P_{Sleep} T_S(n)$$

$$\tilde{e}_C(n) = \tilde{e}_{Active}(n) + \tilde{e}_{Sleep}(n)$$

Energy Monitor – **Harvested** Energy Model

Conservation of Energy



η : DC-DC efficiency

$$\tilde{e}_H(n) = \tilde{e}_S(n) - \tilde{e}_S(n-1) + \tilde{e}_{Leak}(n) + \frac{1}{\eta}\tilde{e}_C(n)$$

$$\tilde{P}_H(n) = \frac{\eta\left[\tilde{e}_S(n) - \tilde{e}_S(n-1)\right] + \tilde{e}_{Active}(n)}{\eta T_S(n)} + P_{Leak} + \frac{1}{\eta}P_{Sleep}$$

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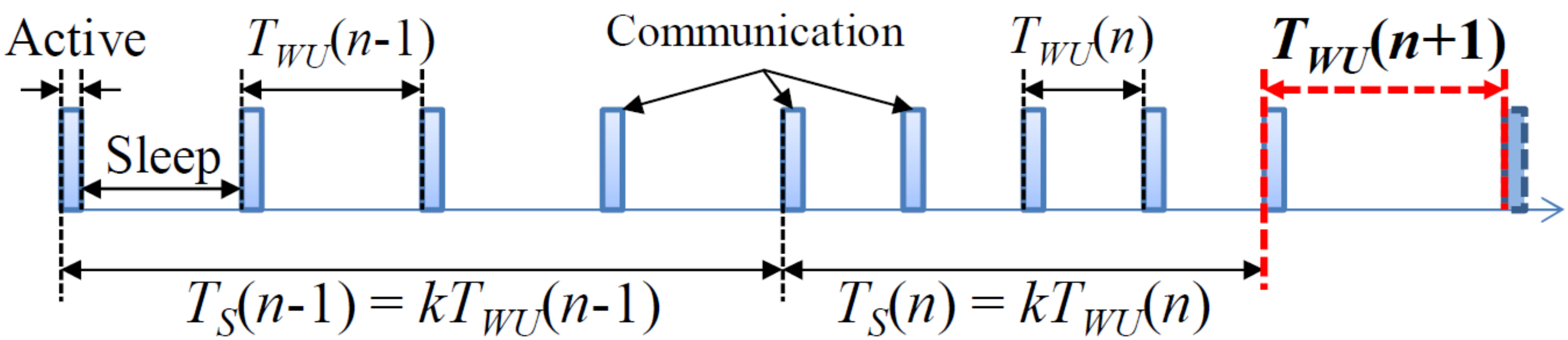
Duty-cycled Power Manager



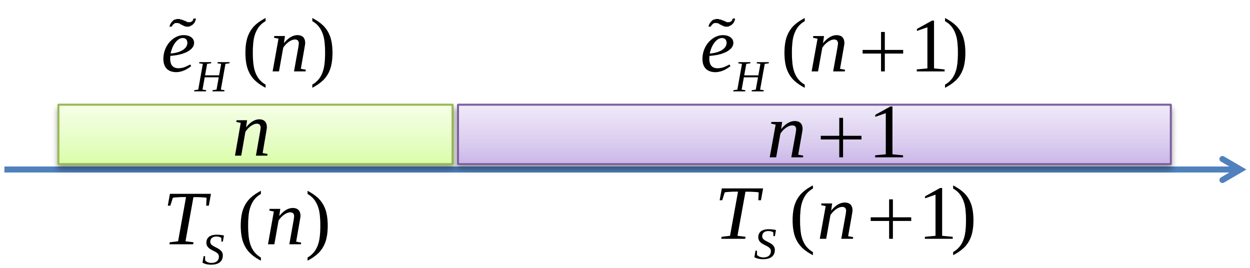
- Dynamic adaptation period
- Respect ENO [8] in the **next slot**
  → determines $T_{WU}(n+1)$
- Proposed monitoring applications:
  - Hospitals with light energy
  - Industrial machines with heat and vibration energy

Energy Predictions

- **Consumed energy** prediction:

$$\hat{e}_C(n+1) = \tilde{e}_{Active}(n) + P_{Sleep} k T_{WU}(n+1)$$

- **Harvested energy** prediction:



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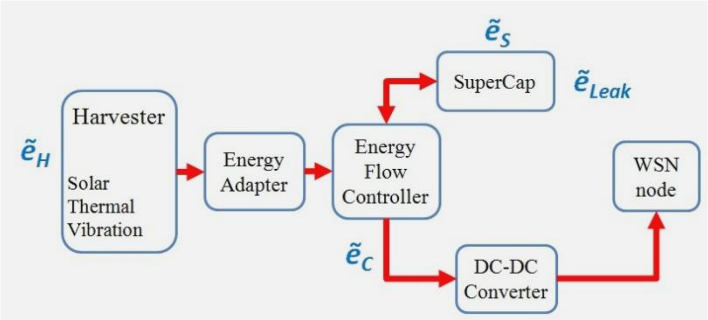
$$\hat{e}_H(n+1) = \tilde{P}_H(n) k T_{WU}(n+1)$$

Energy Budget



- **Residual energy** of slot n :

$$\tilde{e}_{Bud}(n) = \tilde{e}_H(n) - \tilde{e}_{Leak}(n) - \frac{1}{\eta}\tilde{e}_C(n)$$

$\tilde{e}_{Bud(n)}$ is the ≠ between harvested and total consumed energy

$\tilde{e}_{Bud(n)}$ can be either **positive or negative** and is used in the next slot

- **Conservation Energy** Equation :

$$\tilde{e}_H(n) = \tilde{e}_S(n) - \tilde{e}_S(n-1) + \tilde{e}_{Leak}(n) + \frac{1}{\eta}\tilde{e}_C(n)$$

$$\tilde{e}_{Bud}(n) = \tilde{e}_S(n) - \tilde{e}_S(n-1) = \Delta\tilde{e}_S$$

Adapt Next Wake-up Time

- **ENO condition** in next slot $(n+1)$:

$$\hat{e}_H(n+1)+\tilde{e}_{Bud}(n)=\tilde{e}_{Leak}(n+1)+\frac{1}{\eta}\hat{e}_C(n+1)$$

- **Next wake-up** period:

$$T_{WU}(n+1)=\frac{\left[\tilde{e}_{Active}(n)-\eta\tilde{e}_{Bud}(n)\right]/k}{\eta\left[\tilde{P}_H(n)-P_{Leak}\right]-P_{Sleep}}$$

Monitoring in an office ??

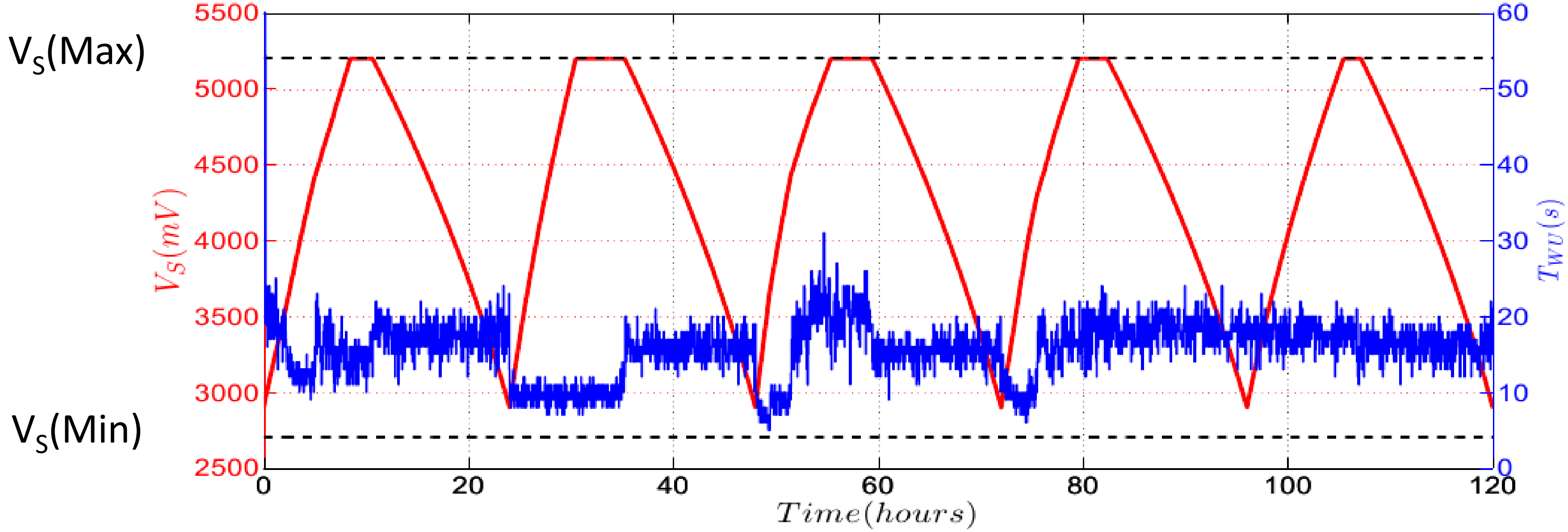
- Light energy is **only available a certain period** of the day (e.g. working hours)
- ENO condition is considered after **a day**:
  - The PM **saves harvested energy** during working hours.
  - Harvested energy is used for **continuous operations** during the night.

Simulation Set Up

- Two **PowWow** nodes perform communications using RICER protocol (WUB every 50ms)
- Harvested energy extracted is used as the input.
- C_S = **2.7F** (C_{STORE})
- k = 10
- 2 power managers:
  - **Positive-energy** during the day (consume less than harvested)
  - **Negative-energy** during the night (harvested energy = 0)

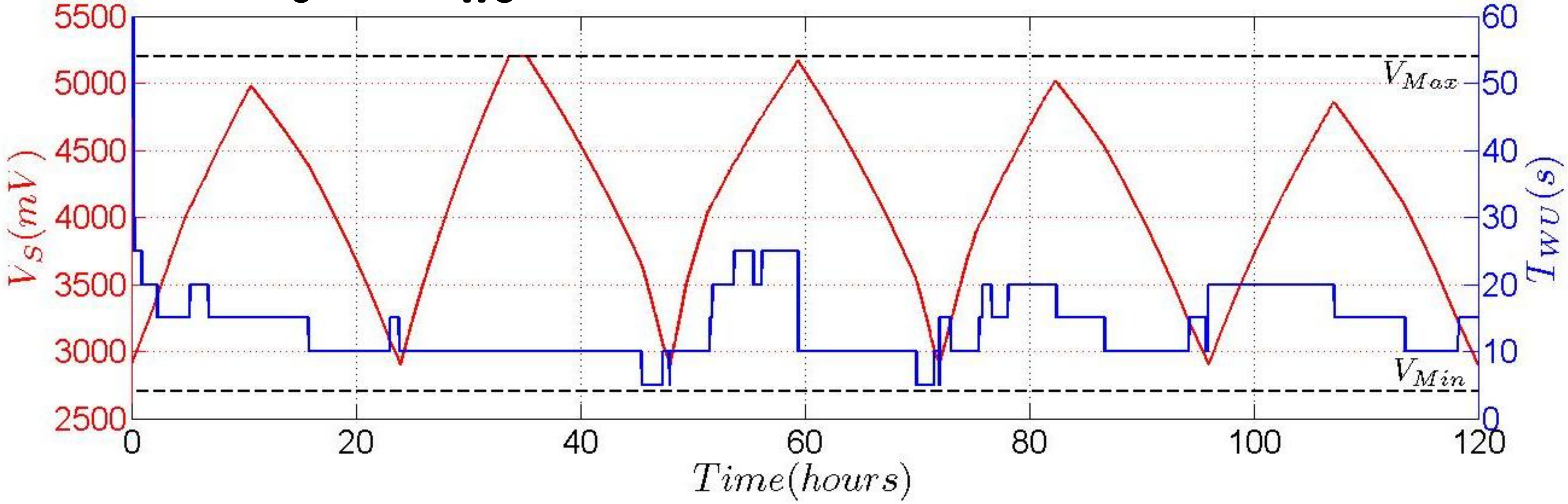
The fluctuation of the harvested power leads to many variations of the wake up period. The **W**ake **U**p **V**ariation **R**eduction (**WUVR**) using EWMA is applied to reduce these variations

Voltage of the SuperCap (V_S) and wake up period of the node (T_{WU})



Power Manager with Wake Up Variation Reduction (WUVR)

V_S and T_{WU} over 5 days when WUVR is applied



- Number of variations is 43 (instead of 2403)

Benefits when WUVR is applied

- The Receiver sent a WUB every 5 seconds

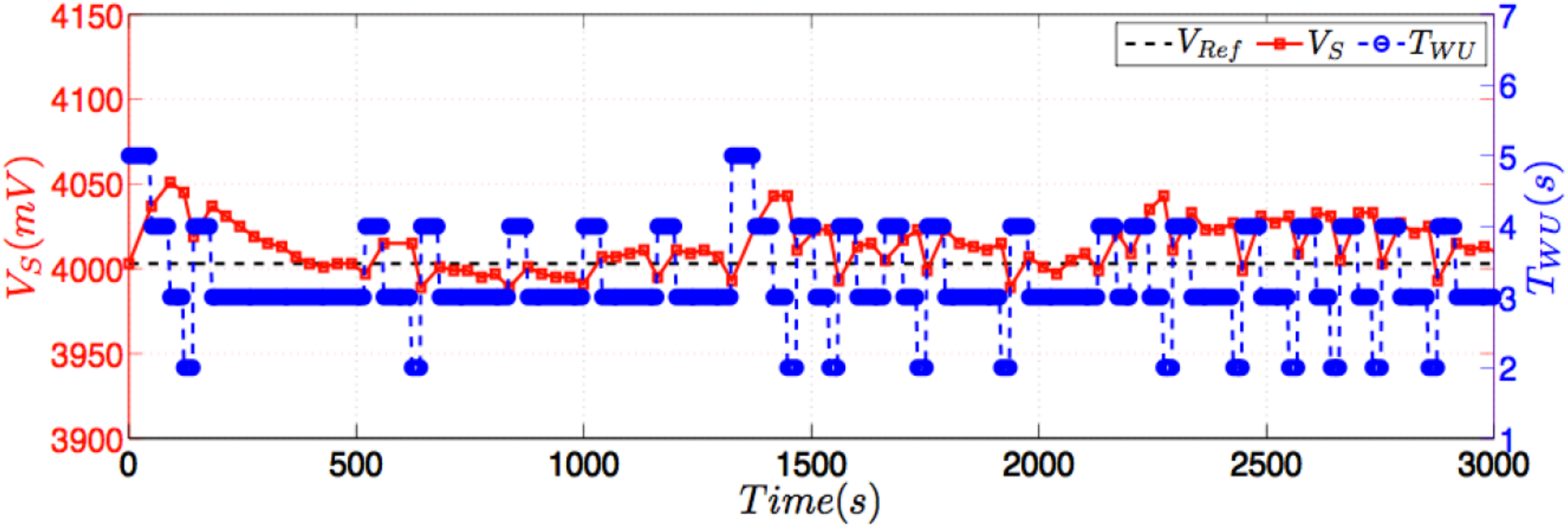
	Non_WUVR	WUVR	Kansal [8]
Idle listening	147 (ms)	**30(ms)**	228(ms)
Consumed TX	11547 (μJ)	2531(μJ)	17765(μJ)
Consumed RX	522 (μJ)	223(μJ)	865(μJ)
Average Energy	12071(μJ)	**2755(μJ)**	18631(μJ)

- WUVR significantly reduces the idle listening at the transmitter (**80%**)
- Average energy for a successful communication is reduced by **77%**

Experimental Results for Thermal Harvester

- The Power Manager performs adaptations on a wireless sensor network hardware **platform**
- **Thermal energy** is harvested (heat from a laptop power adapter)

$\mathbf{k} = 10$, $\mathbf{C_S} = 0.09$F, $\boldsymbol{\alpha} = 0.6$, $\mathbf{V_{Ref}} = 4$V



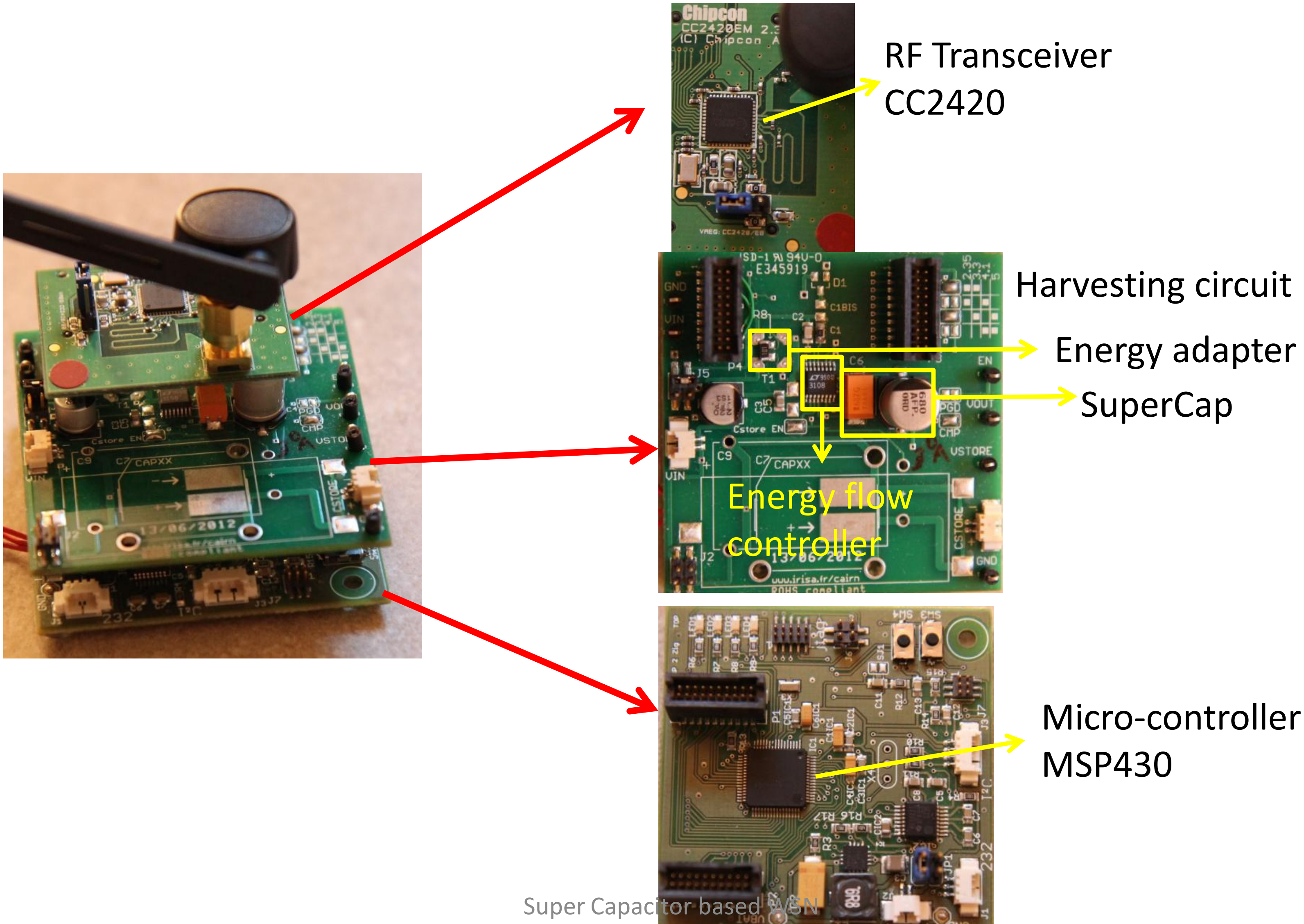
[Trong-Nhan Le 2013c]

Conclusions

- Generic architecture for **super capacitor based** energy harvesting WSN.
- Low complexity, **independent of harvesters** and real-time energy monitor.
- Practical **duty-cycled power manager** on a real platform.

Demo – Solar Energy

PowWow platform



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