2nd International Workshop on Energy Neutral Sensing Systems (ENSsys 2014)

A Power Manager with Balanced Quality of Service for Energy-Harvesting Wireless Sensor Nodes

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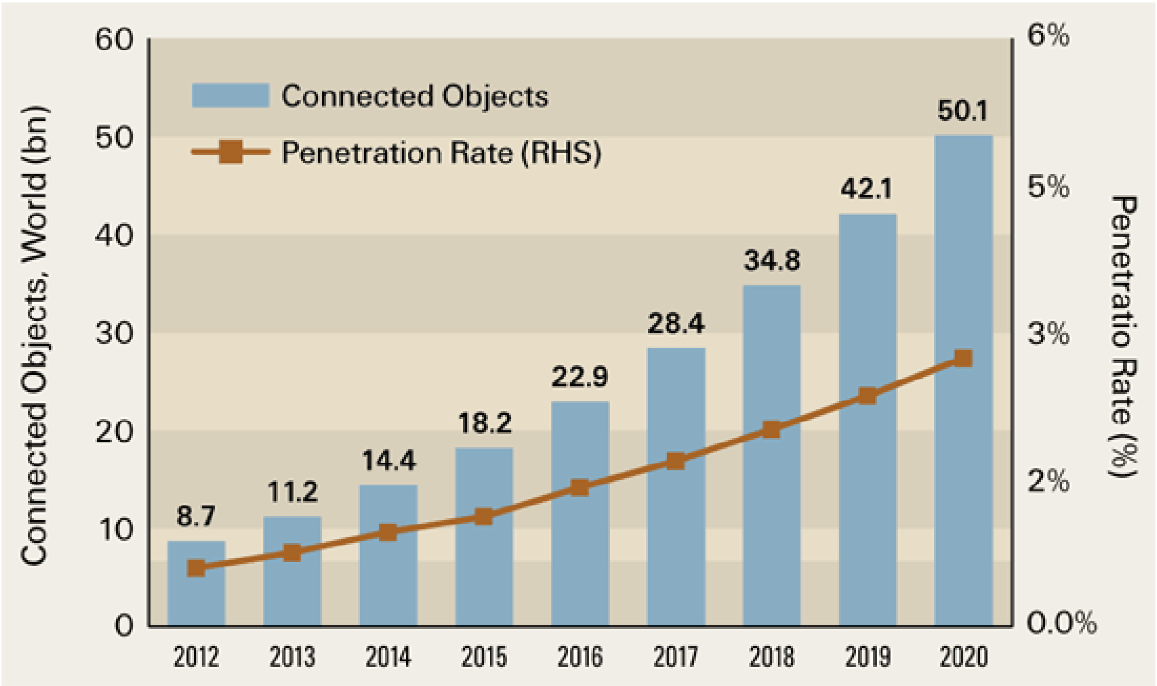
Toward Connected Objects...



Connected objects are expected to 50 billions by 2020
(Cisco Systems 2014)

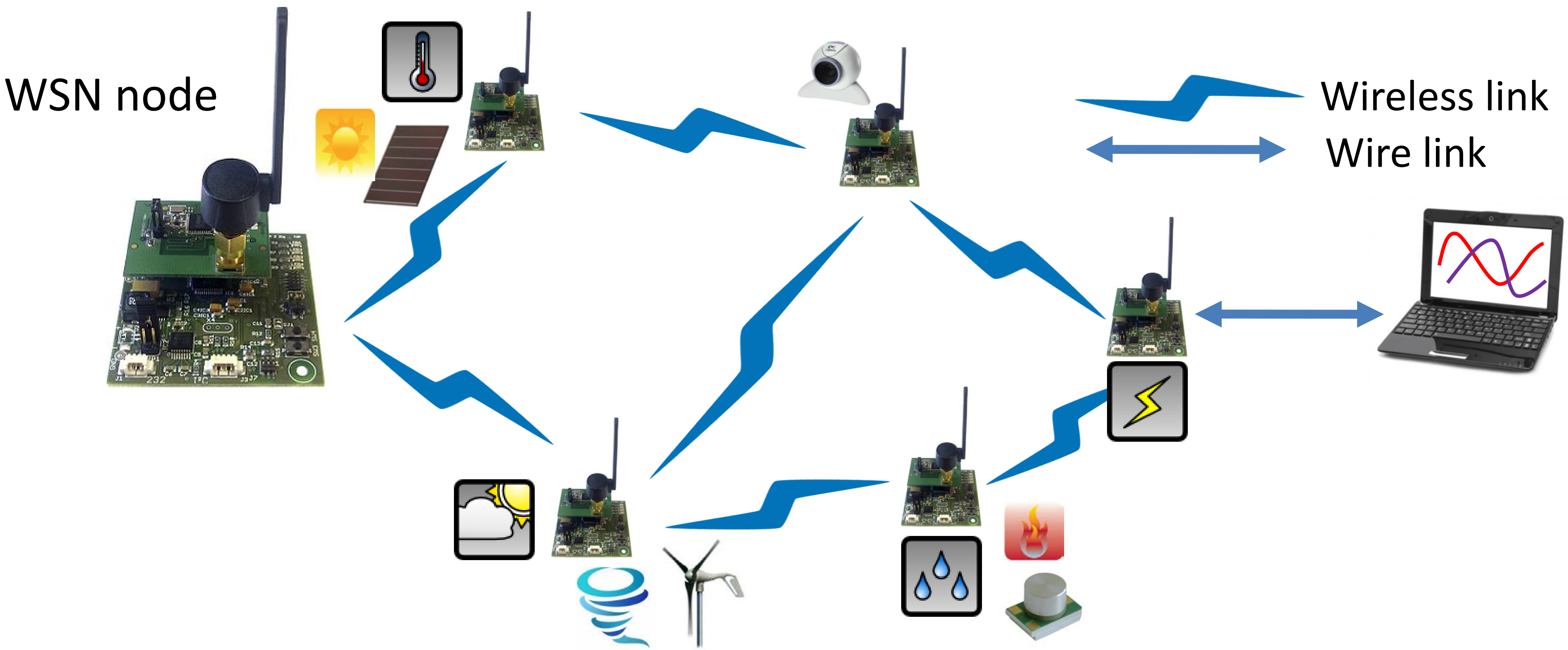
Home automation *(Z-Wave Alliance)*

Smart city *(Santander)*

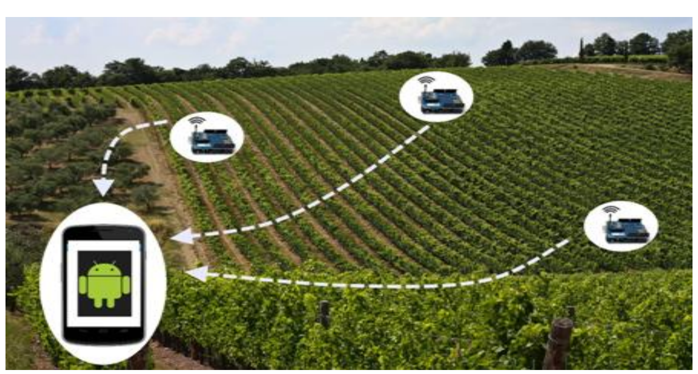
Energy consumption for a huge number of connected objects?

Autonomous designs with battery independency?

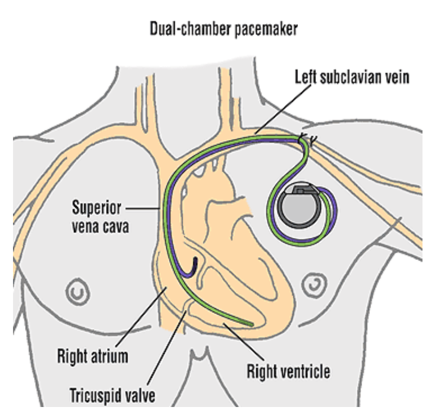
Wireless Sensor Networks (WSNs)



Environment Monitoring



Health Monitoring

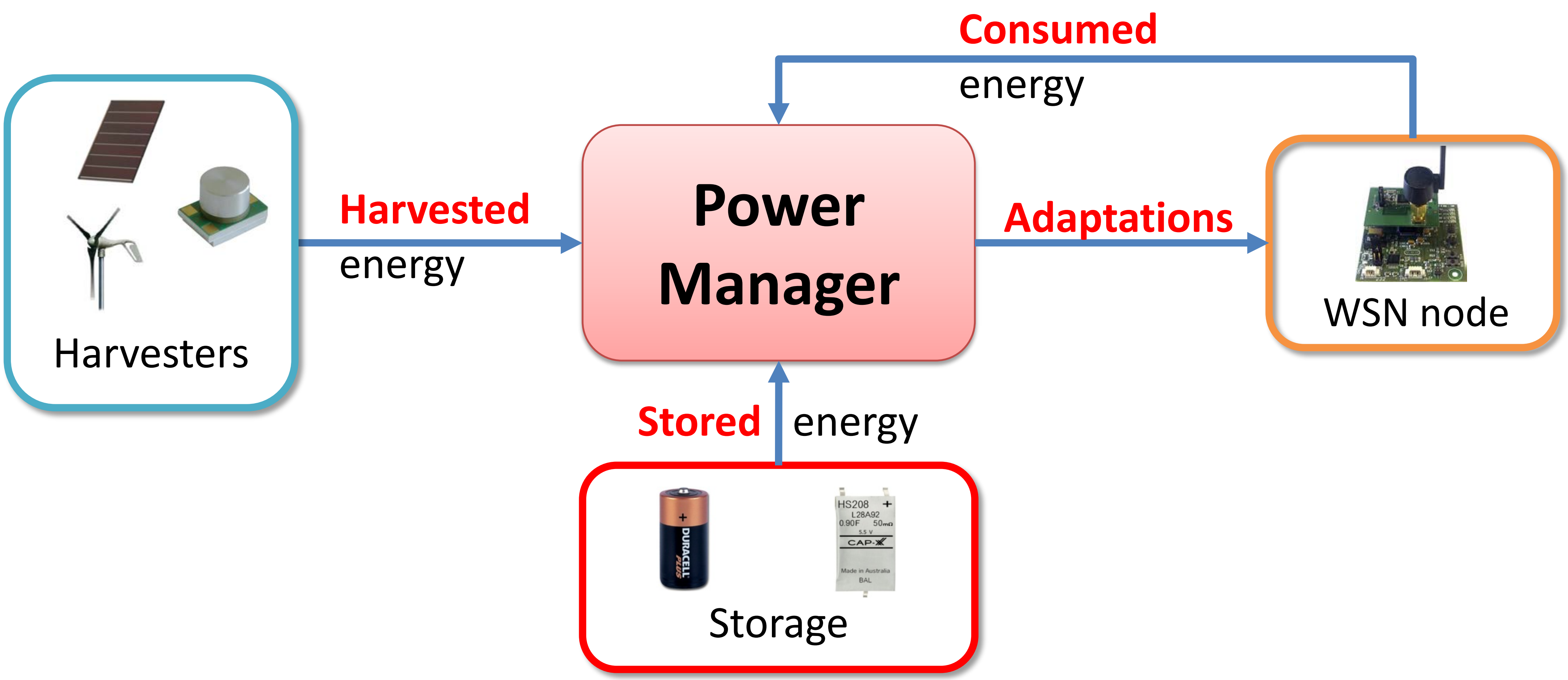


Structure Monitoring

Generic Power Manager Architecture

- Energy Harvesting (EH): a new paradigm for Power Manager (PM):
  - The objective is **no more to minimize** the consumed energy as battery-powered WSN
  - But rather to satisfy **E**nergy **N**eutral **O**peration (ENO) condition [KAN2007]

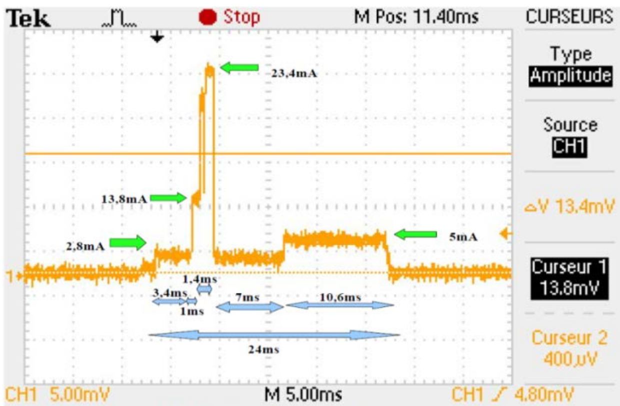
consumed energy = **harvested** energy

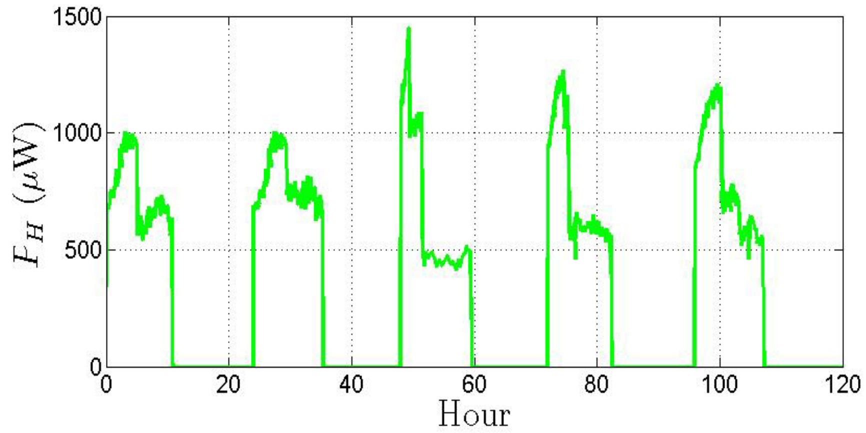


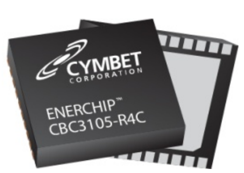
[KAN2007] A. Kansal, J. Hsu, S. Zahedi and M.B. Srivastava, “Power management in energy harvesting sensor networks,” *ACM Transactions in Embedded Computing Systems (TECS)*, 2007.

Power Manager Challenges

- How to **control energy consumption**?
  - **Adapt the wake-up interval (T_{WI})**
  - Adapt transmit power
  - Dynamic Voltage and Frequency Scaling (DVFS)
- **Consumed energy** model:
  - Depend on **scenarios** or **functional modes**
- **Harvested energy** model:
  - Different energy sources: solar, wind, thermal…
  - Real-time monitoring
- Which kind of **energy storage**?







[Cymbet]

500 recharge cycles

Difficult to estimate the state of charge

Low leakage current

http://www.cymbet.com

[CapXX]

500 000 recharge cycles

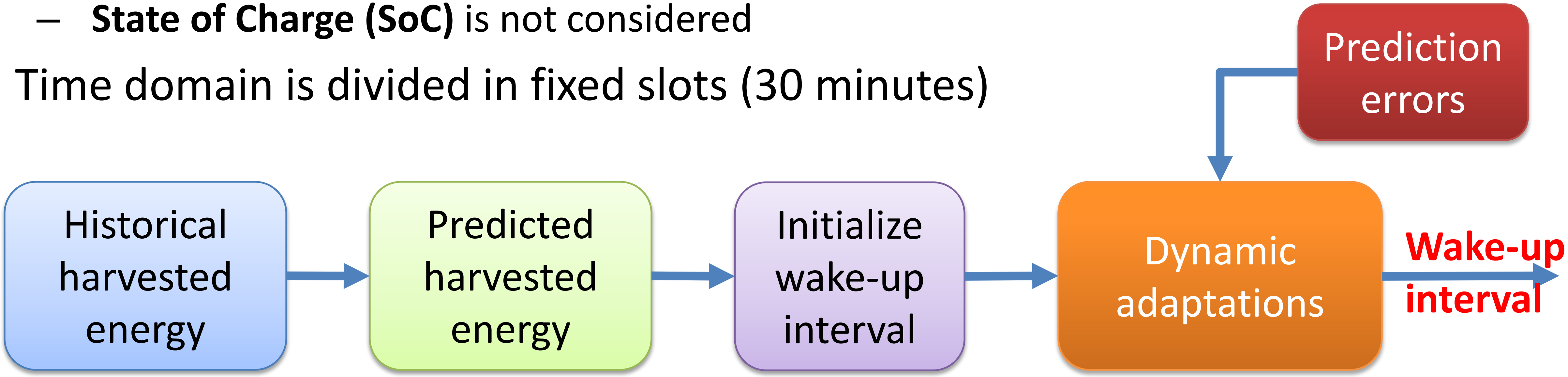
Easy to estimate the state of charge

High leakage current

http://cap-xx.com

Related Work: KAN-PM [KAN2007]

- Designed for **solar-powered** WSN with **rechargeable batteries**
- Adaptations are based on **prediction of harvested energy:**
  - **Energy consumption is a constant**
  - **State of Charge (SoC)** is not considered
- Time domain is divided in fixed slots (30 minutes)

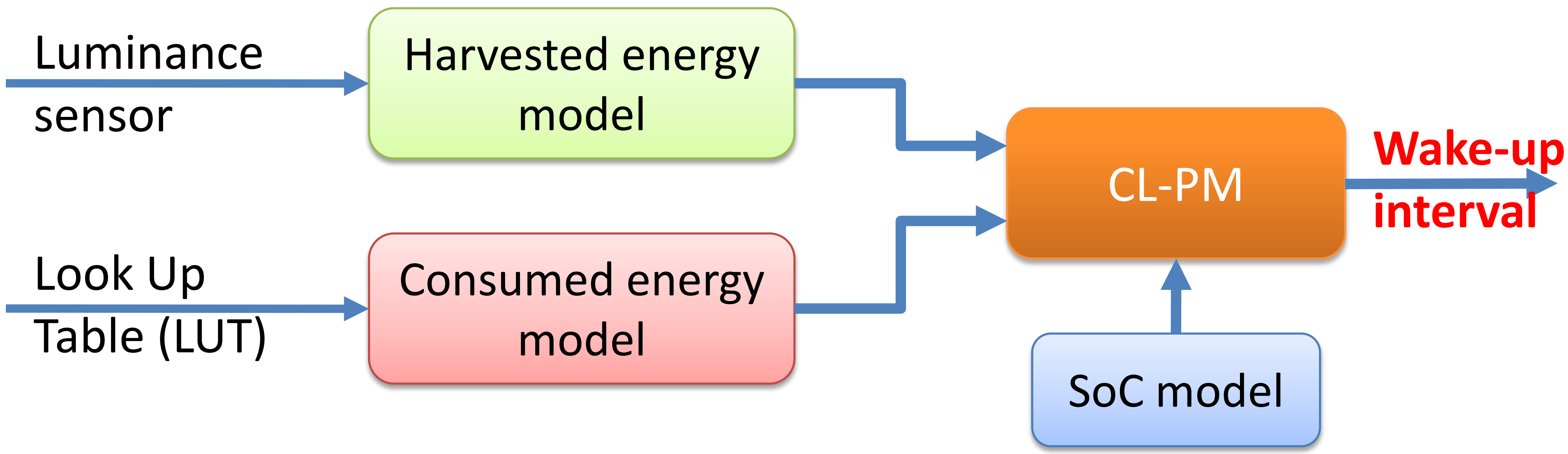


- **Low response** to the change of harvested energy
- **Battery failure can occur** (WSN is shutdown!!!)
- **High performance** when harvested energy is available
- **Low performance** when there is no harvested energy

[KAN2007] Kansal et al., "Power management in energy harvesting sensor networks," *ACM Transactions in Embedded Computing Systems (TECS)*, 2007.

Related Work: CL-PM [CAS2012]

- Adaptations are based on **current harvested energy** and **State of Charge (SoC)** of the battery:
  - Harvested energy model is based on a luminance sensor
  - Consumed energy model is based on a Look Up Table (LUT)
- Dynamic adaptation periods



- **Fast response** to the change of harvested energy
- **Battery failure** is avoided in CL-PM
- **High performance** when harvested energy is available
- **Low perfomance** when there is no harvested energy

[CAS2012] Castagnetti et al., "A framework for modeling and simulating energy harvesting wsn nodes with efficient power management policies," EURASIP, 2012.

Contributions

- Global power manager for **supercapacitor-based** energy harvesting WSN node:
  - **Balance performance** while satisfying ENO
  - **Energy sources independence**: solar, wind, thermal…
  - **Precise energy model**: consumed, harvested and SoC models
  - Low complexity, memory footprint
- **Periodic energy sources**:
  - Light energy in an office
  - Energy Interval (T_{EI})
  - Non-Energy Interval (T_{NEI})

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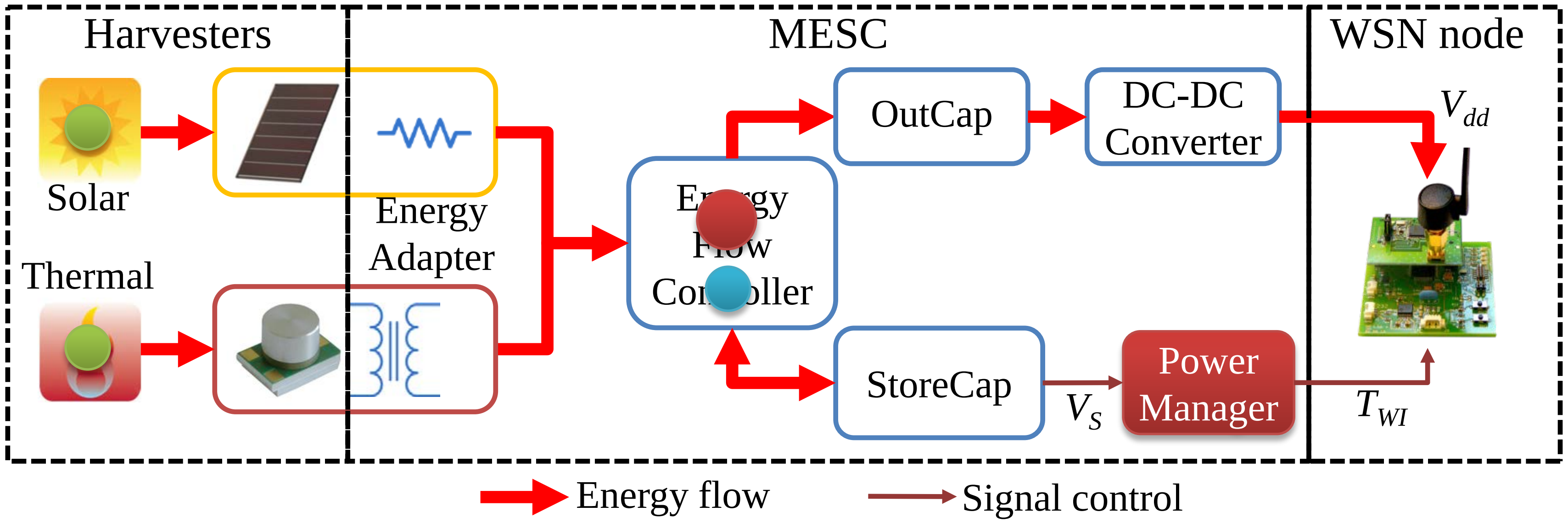
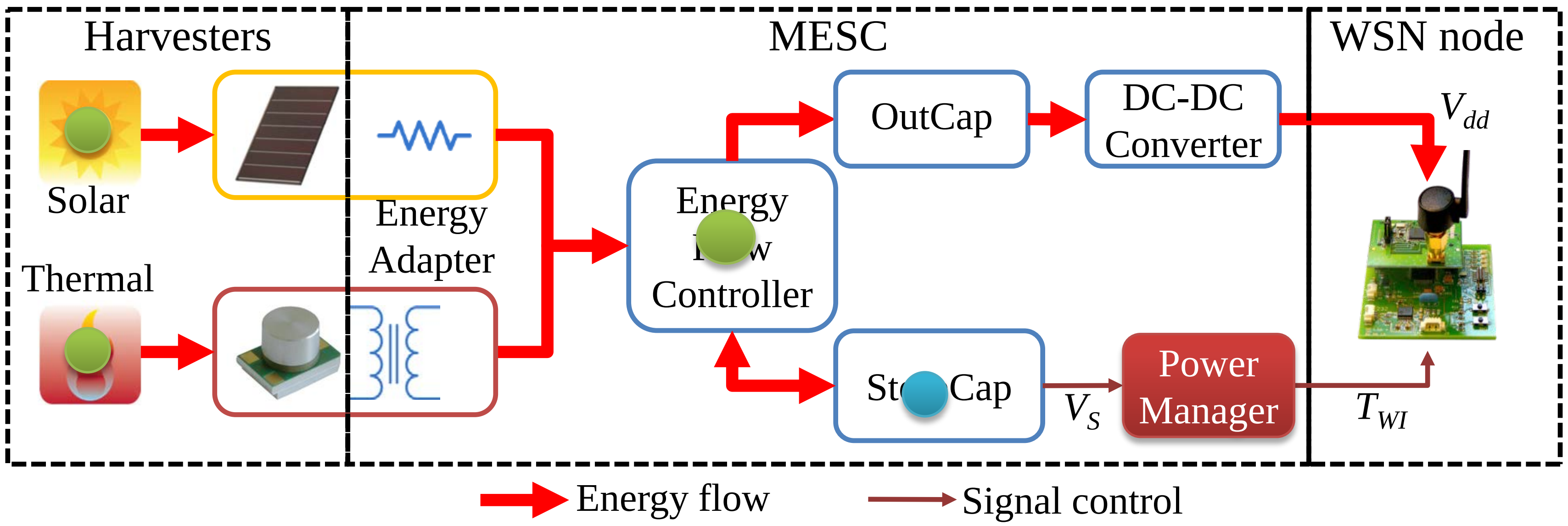
    1. Hardware Architecture
    2. Energy Monitor
    3. Energy Predictor
2. Power Manager with Balanced Quality of Service (BQS-PM)
    1. Positive Energy Power Manager (PE-PM)
    2. Negative Energy Power Manager (NE-PM)
3. Simulations and Comparisons
4. Conclusions

Multiple Energy Sources Converter (MESC)



- Support different sources: solar, thermal, wind
- Supercapacitor-based energy storage
- Optimized energy flow
- DC/DC converter efficiency: η **= 0.85**
- Optimized sizing **OutCap** and **StoreCap**

Multiple Energy Sources Converter (MESC)



- Support different sources: solar, thermal, wind
- Supercapacitor-based energy storage
- Optimized energy flow
- DC/DC converter efficiency: **η = 0.85**
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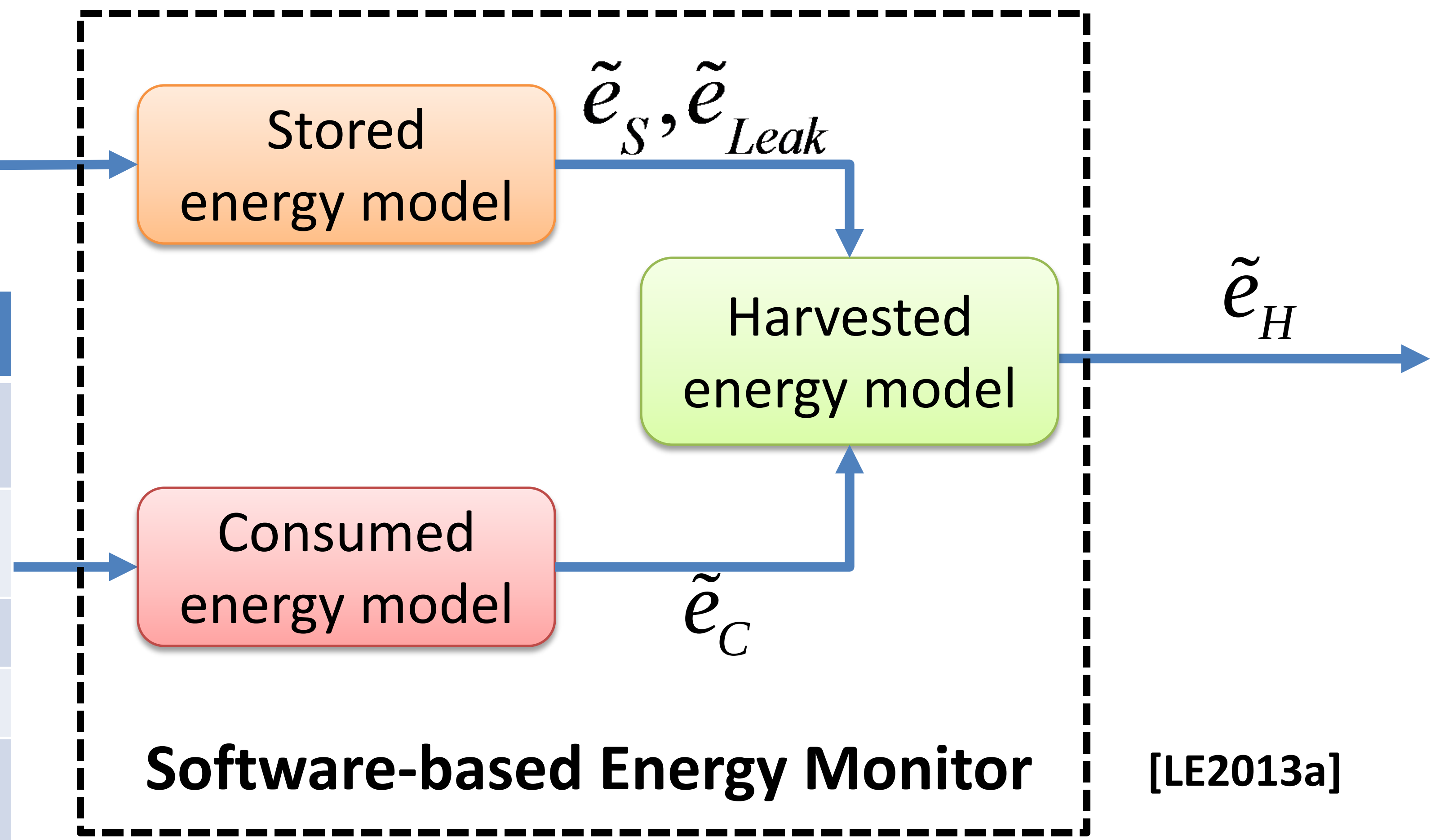
[LE2014] LE et al. , “Energy Neutral Design Framework for Supercapacitor-based Autonomous Wireless Sensor Networks” *ACM Journal of Emerging Technology (JETC)*, 2014.

Software-based Energy Monitor

- Provide energy profiles
  - Current energy in the StoreCap ($\tilde{e}_S$)
  - Leakage energy of the whole system ($\tilde{e}_{Leak}$)
  - Consumed energy of the WSN node ($\tilde{e}_C$)
  - Harvested energy from harvesters ($\tilde{e}_H$)

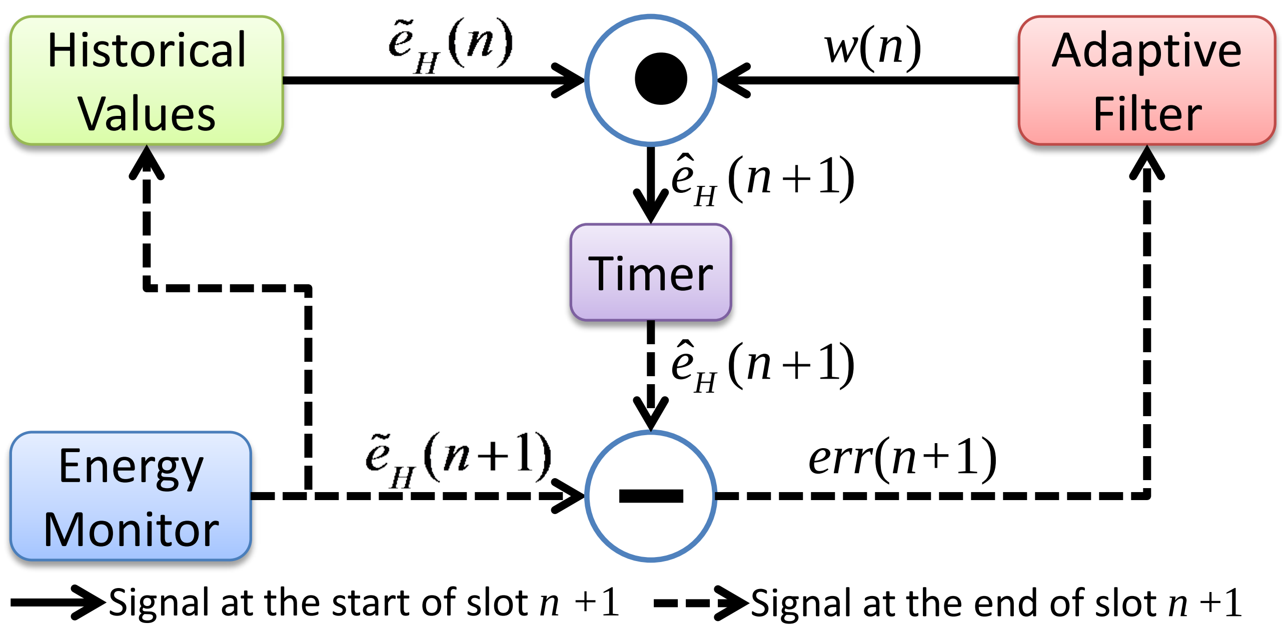


[LE2013a]

Look Up Table		
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

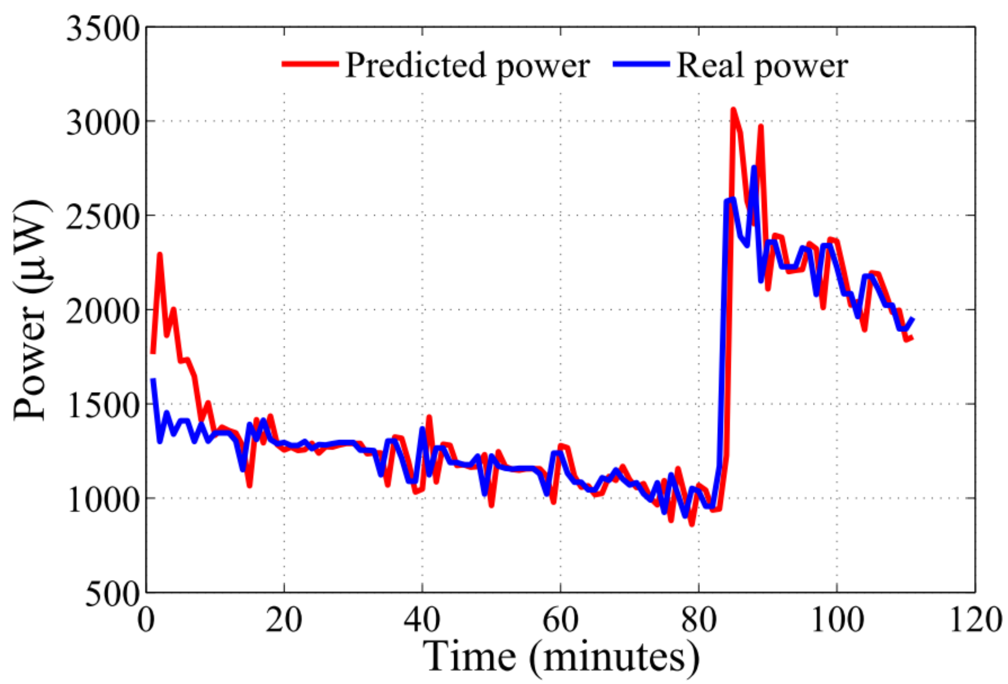
[LE2013a] Le et al. "Duty-Cycle Power Manager for Thermal-Powered Wireless Sensor Networks." *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. 2013.

Adaptive Filter-based Energy Predictor



- $\hat{e}_H(n+1)$: Predicted harvested energy in slot n+1
- $err(n+1)$: Prediction error
- $w(n)$: Filter coefficients
- **Low-complexity filter order p = 1**

- Low complexity and memory footprint
- Acceptable average error (less than 15%)
- Independent of energy sources: outdoor solar, indoor light, wind



[LE2013b]

[LE2013b] T.N. Le, O. Sentieys, O. Berder, A. Pegatoquet, C. Belleudy, "Adaptive Filter for Energy Predictor in Energy Harvesting Wireless Sensor Networks," *Architecture of Computing Systems (ARCS)*, 2013

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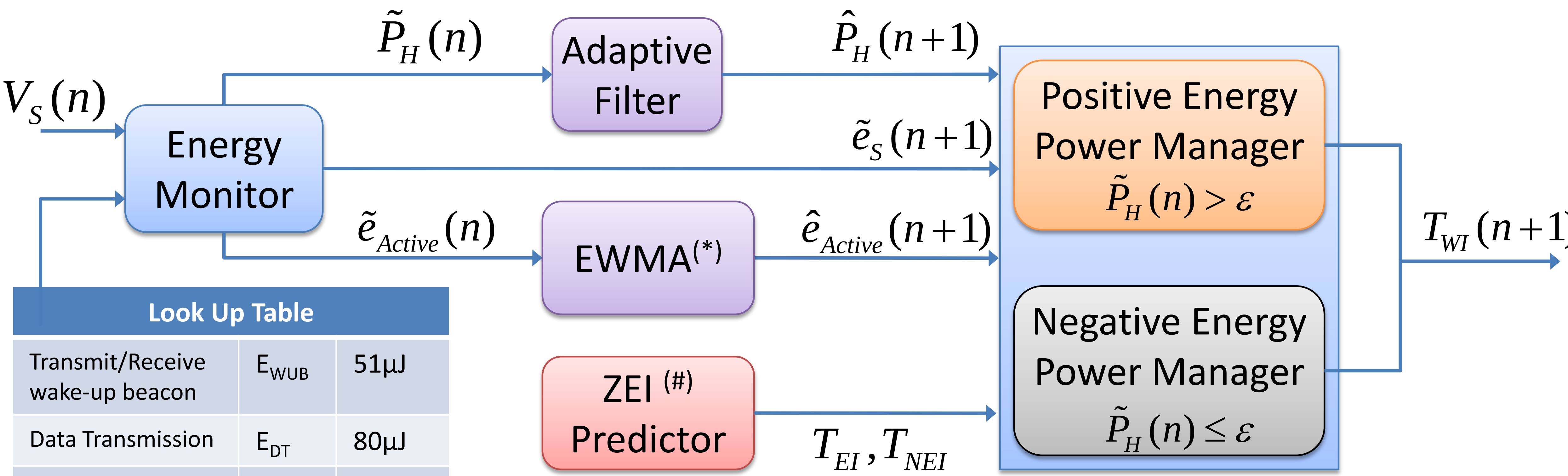
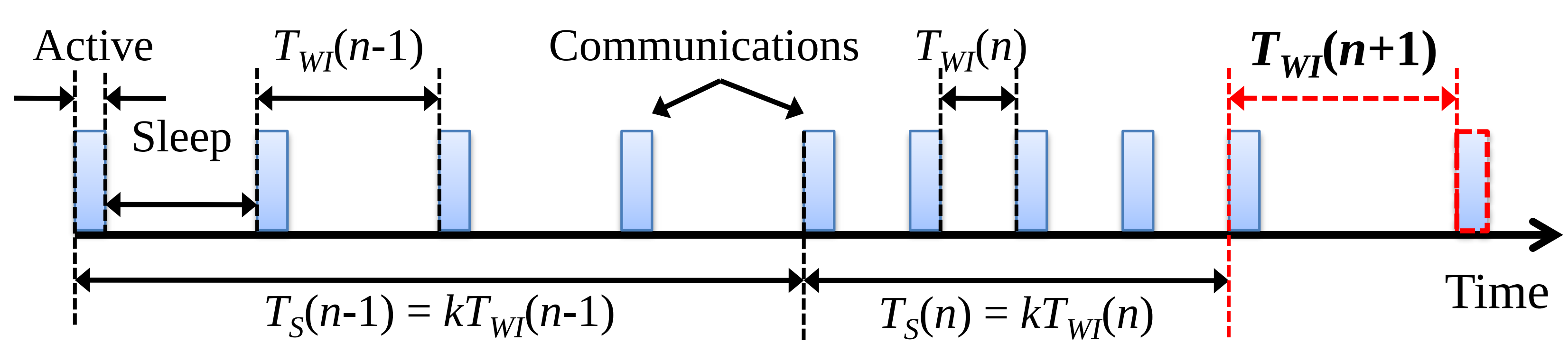
Power Manager with Balanced Quality of Service (BQS-PM)



Look Up Table		
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	E_{SEN}	27µJ
Transmit/Receive Acknowledgment	E_{ACK}	51µJ

(*)**EWMA**: **E**xponentially **W**eighted **M**oving **A**verage
(#)**ZEI**: **Z**ero **E**nergy **I**nterval [CAS2012]



Positive Energy Power Manager (PE-PM)

- Energy constraint to respect ENO:

$$\frac{\hat{e}_H(n+1)}{1+\varphi} = \frac{1}{\eta}\hat{e}_C(n+1) + P_{Leak}T_S(n+1) \qquad \varphi = \frac{T_{NEI}}{T_{EI}}$$

$$\frac{\hat{e}_H(n+1)}{1+\varphi} = \frac{1}{\eta}[\hat{e}_{Active}(n+1) + P_{Sleep}T_S(n+1)] + P_{Leak}T_S(n+1)$$

- Next wake-up interval:

$$T_{WI}(n+1) = \frac{(1+\varphi)\hat{e}_{Active}(n+1)/k}{\eta\hat{P}_H(n+1) - (1+\varphi)(\eta P_{Leak} + P_{Sleep})}$$

Negative Energy Power Manager (NE-PM)

- Remaining time of non-energy interval:

$$R(n+1) = R(n) - T_S(n) = R(n) - kT_{WI}(n)$$

- Available energy for waking-up:

$$E_R(n+1) = \frac{1}{2}C_S\left[V_S^2(n) - V_0^2\right] - (P_{Sleep} + \eta P_{Leak})R(n+1)$$

- Next wake-up interval:

$$T_{WI}(n+1) = \frac{R(n+1)\hat{e}_{Active}(n+1)}{kE_R(n+1)}$$

Contents

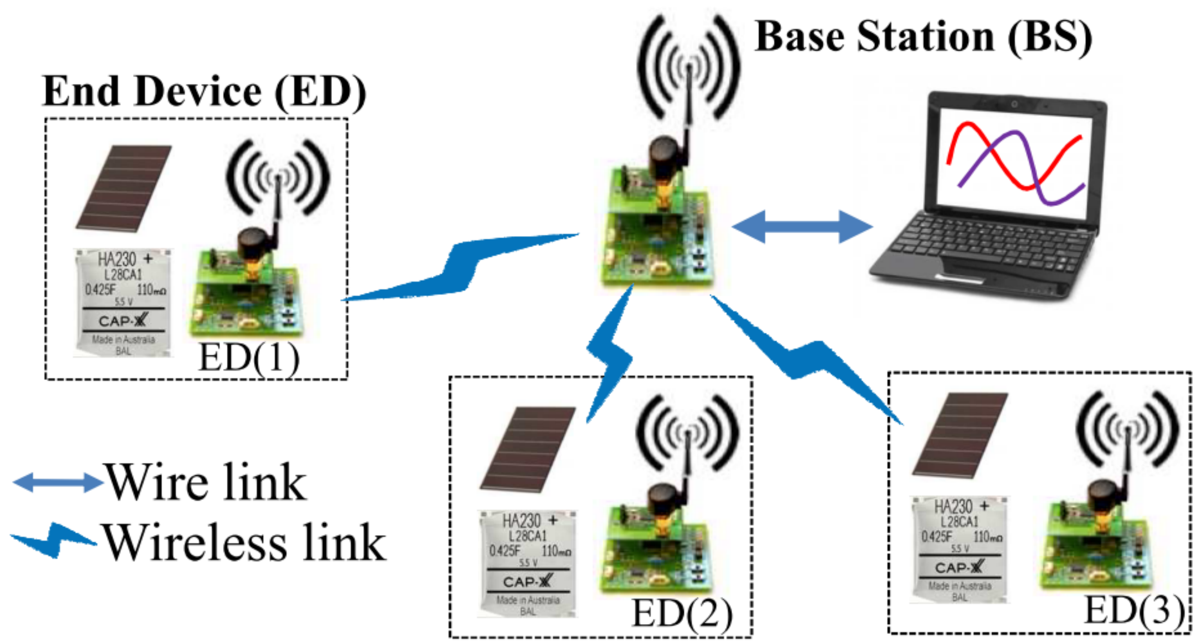
BQS-PM Simulation Setup

Evaluation metrics

- $W_{EI}(s)$: Average wake-up interval during T_{EI}
- $W_{NEI}(s)$: Average wake-up interval during T_{NEI}
- $W_C(s)$: Average wake-up interval during T_C
- Mem(words): Memory footprint
- Mul: Number of multiplications
- B_f(minute): Battery failure duration
- Gap: the difference of W_{EI} and W_{NEI}

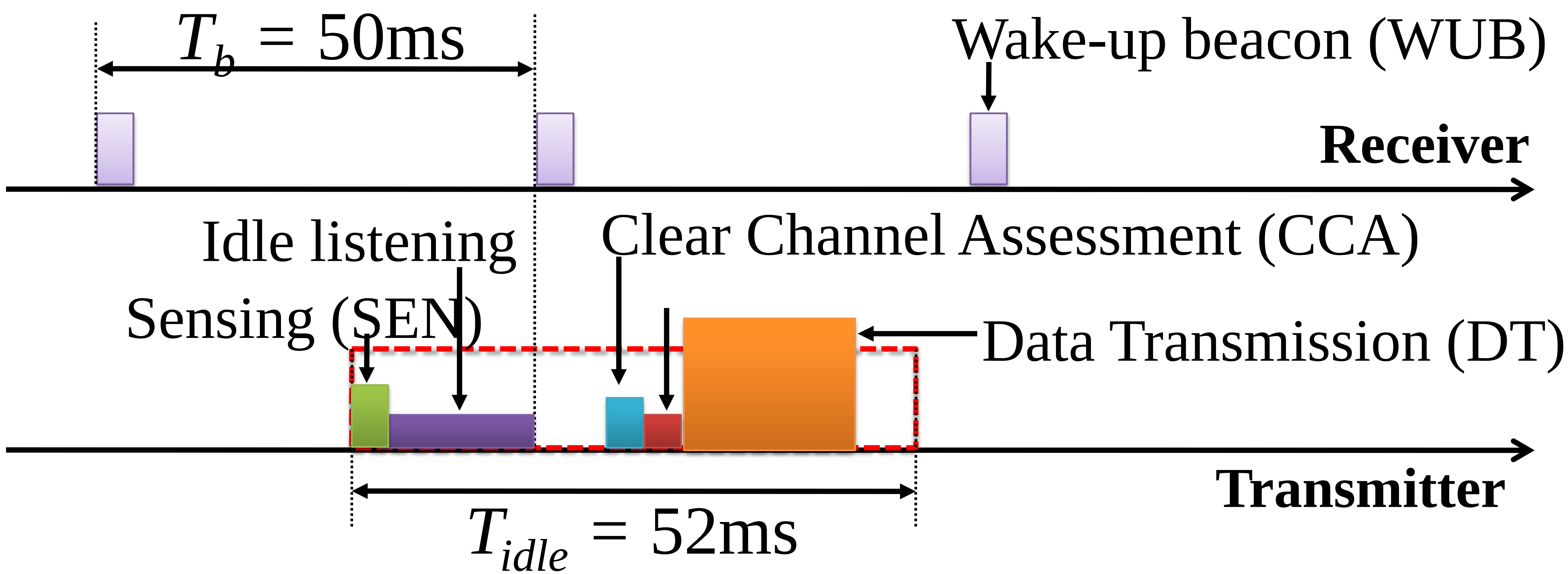
$$Gap = \frac{|W_{EI} - W_C| + |W_{NEI} - W_C|}{W_C}$$

Single-hop EH-WSN



$$C_S = 1.8F, V_{Min} = 1.8V, V_{Max} = 5.2V$$

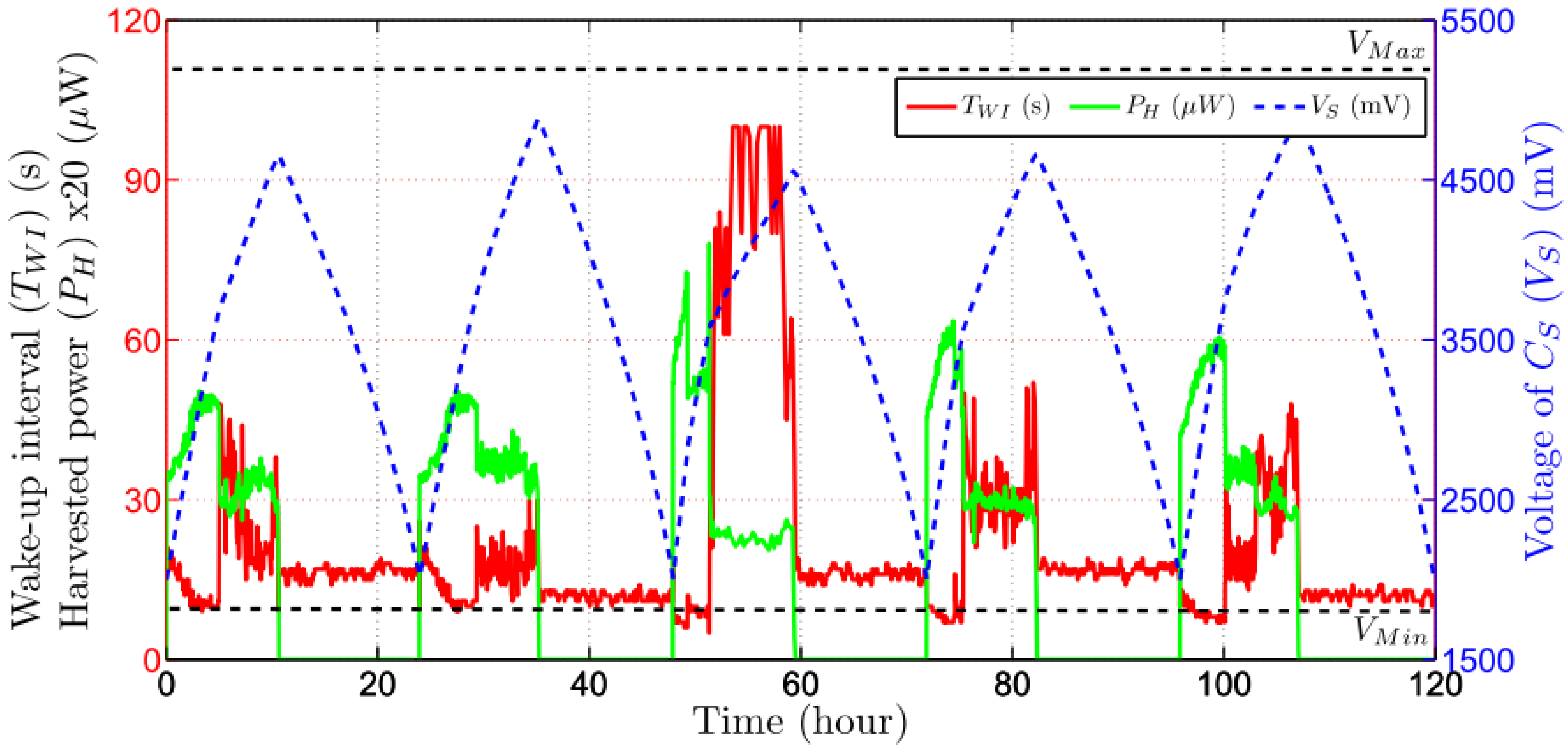
Receiver Initiated Protocol (RICER) [EYL2004]



– After receiving a beacon packet (WUB), the transmitter forwards data package (DT) after Clear Channel Assessment (CCA)

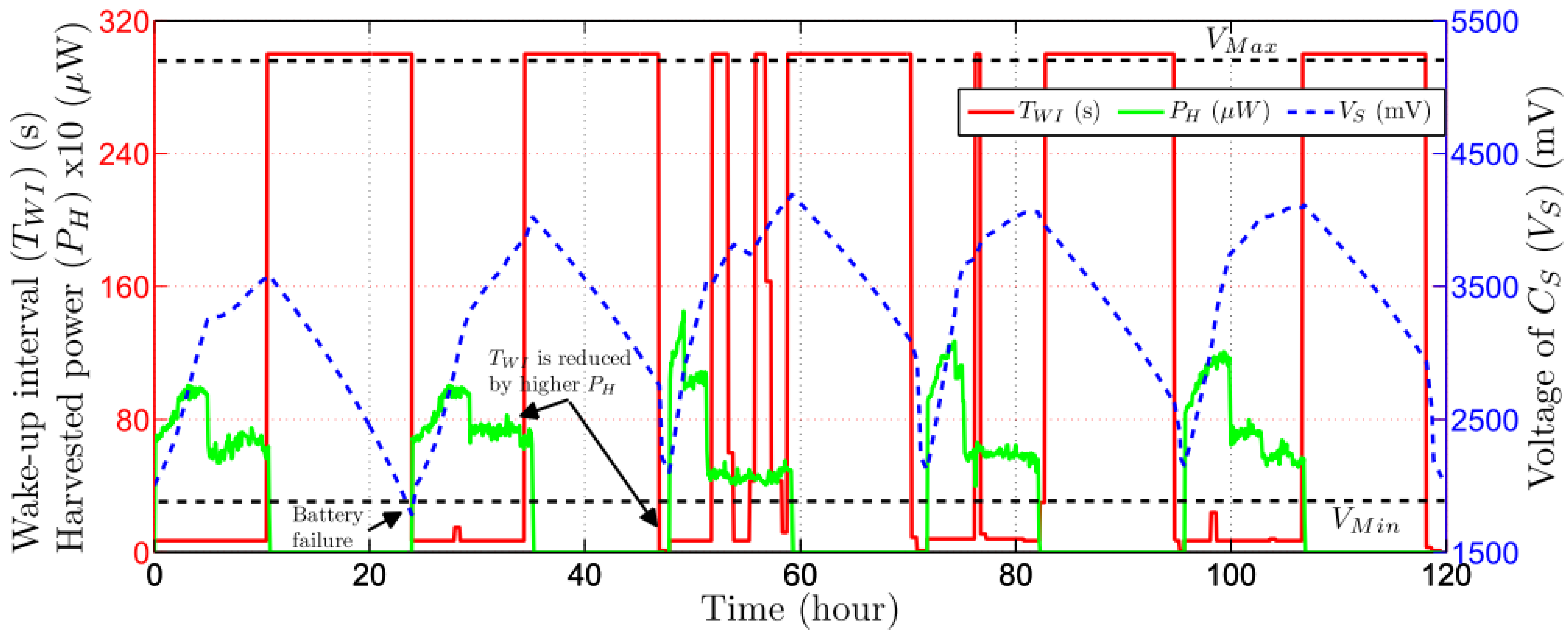
[LIN2004] Lin et al. "Power-efficient rendez-vous schemes for dense wireless sensor networks", In *IEEE International Conference on Communications*, 2004.

BQS-PM Simulation Results



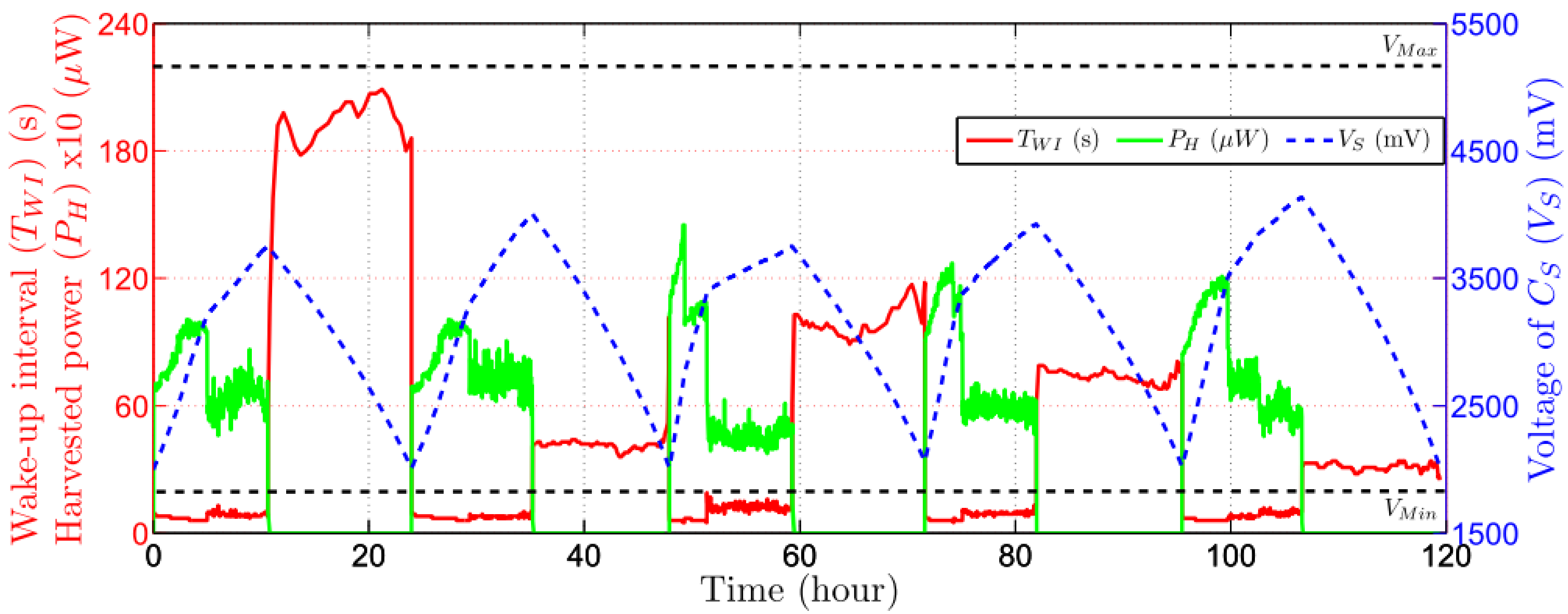
- Wake-up interval presents an inverse shape according to the harvested power
- ENO condition is satisfied after a day (24hours)
- There is no battery failure or overflow

KAN-PM Simulation Results



- Low response to the change of harvested energy
- Does not well satisfy ENO condition
- Low T_{WI} during T_{EI} but very high T_{WI} during T_{NEI}

CL-PM Simulation Results



- Fast response to the change of harvested energy
- Satisfies ENO condition, without battery failure
- Low T_{WI} during T_{EI} but very high T_{WI} during T_{NEI}

PEO-PM, KAN-PM and CL-PM Comparisons

	BQS-PM	KAN-PM	Gain (%)	CL-PM	Gain(%)
W_{EI} (s)	21.1	11.1	-47.4	10.4	-50.7
W_{NEI} (s)	18.9	125.2	84.9	111.6	83.1
W_C (s)	19.9	111.6	3.13	19.6	-0.26
Gap	0.2	5.6	98.0	5.13	97.9
Mem (words)	11	48	77.08	10	-10.00
Mul	16	28	42.86	9	-77.78
B_f (min)	0	18	-	0	-

- While balancing wake-up interval, W_{NEI} is significantly improved
- Difference of wake-up interval between T_{EI} and T_{NEI} is removed
- Low complexity, low memory footprint and no battery failure

Conclusions

- Power manager with Balanced Quality of Service (BQS-PM):
  - Adapt the node to **ENO, without battery failure**
  - **Improve 85%** the QoS when there is no more harvested energy
- Independence of periodic energy sources
- Low memory footprint, low complexity

Thank You !

A Power Manager with Balanced Quality of Service for Energy-Harvesting Wireless Sensor Nodes

Q&A!