Power management for energy harvesting based systems

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(Andrea Castagnetti PhD thesis)

Agenda

1. Introduction and motivations
2. Related works
3. System modeling
4. Power management for energy harvesting WSN nodes
   a) Open-loop energy neutral power manager
   b) Closed-loop: OL plus negative energy power manager
5. A joint Duty-Cycle and Transmission Power Management Approach for EH-WSN
6. Simulation results
7. Conclusion

1. Introduction and Motivations

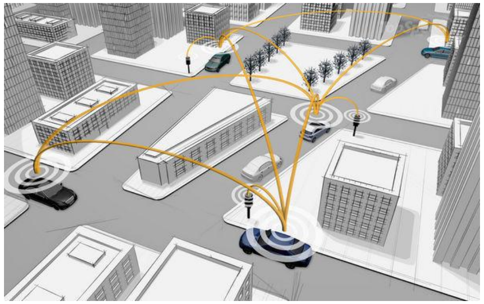
What kinds of issues are addresses?

- Communicating objects able to **collect and process data** (wireless sensor networks)
- **Deployment** of these objects has just started…

Source: SensLab

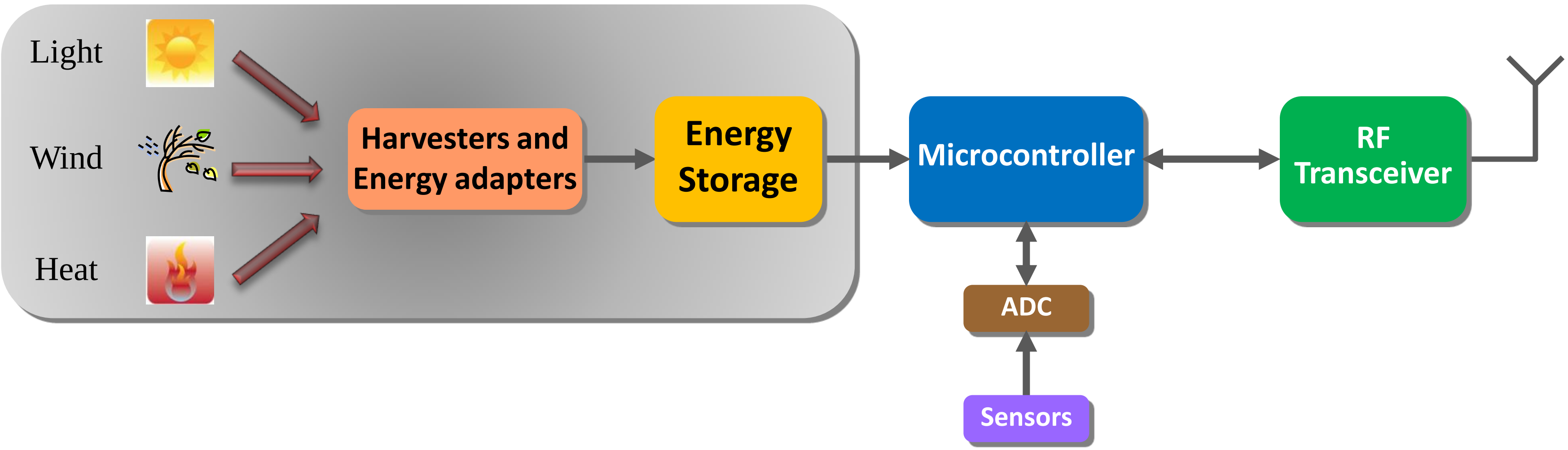
- Power-autonomous objects
  - Harvesting
  - Storage
- An optimized power consumption management (power manager)

- Mobility



Source: Mercedes

Designing Autonomous Communicating Objects



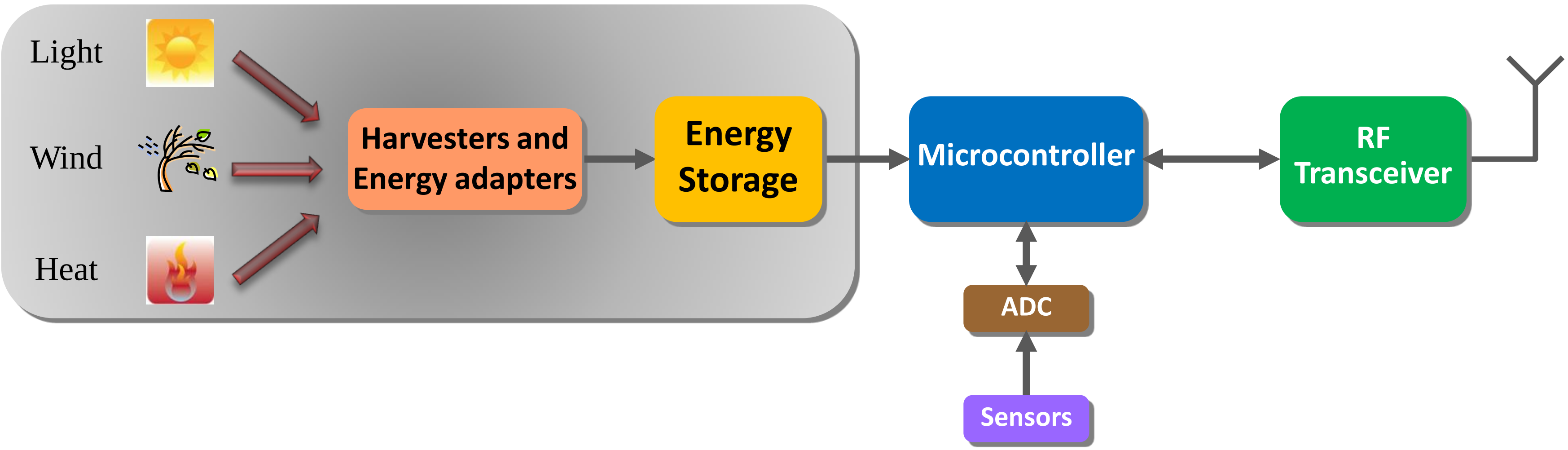
- **Energy Harvesting**: a **new paradigm** for power management
  - The objective is to **balance** (in average) the consumed energy and the harvested energy in order to optimize performance

    ➔ **E**nergy **N**eutral **O**peration (**ENO**)

    Harvested Energy = **Consumed** Energy

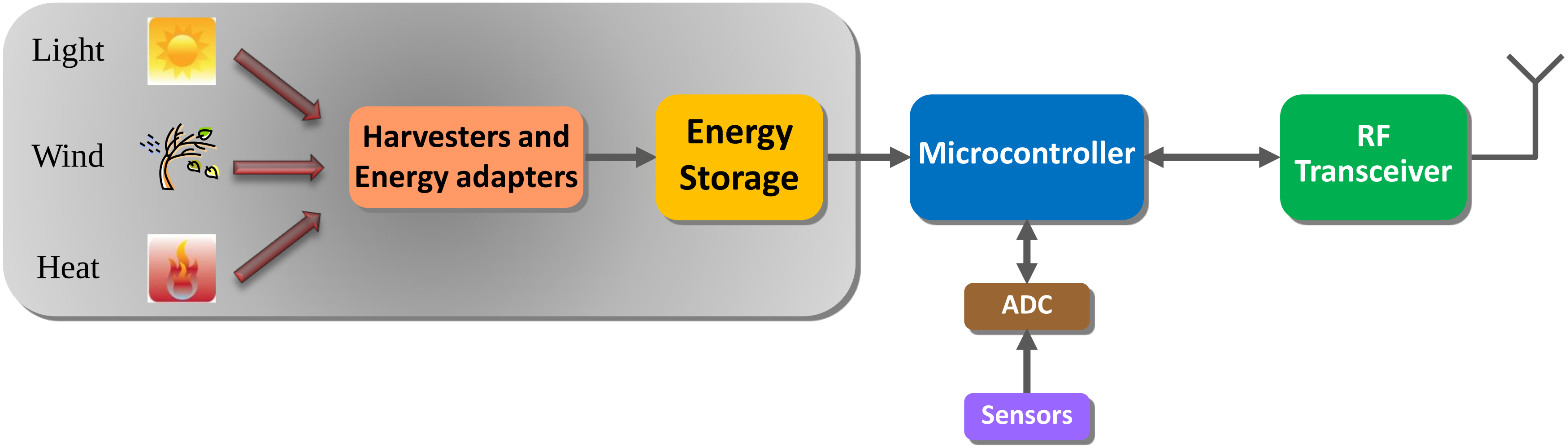
  - The system lifetime can (in theory) lasts forever...

Designing Autonomous Communicating Objects



- **3 différent modes :**
  - Energy-**neutral** $E_H = E_C$
  - **Negative**-Energy $E_H < E_C$
  - **Positive**-Energy $E_H > E_C$

Designing Autonomous Communicating Objects

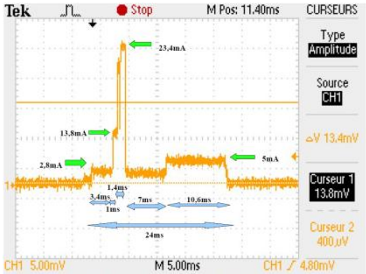


- Harvested Energy (environment) : availability is hard **to control**
- Consumed Energy : **controllable**
  - PHY, MAC, NWK layers
  - RF chip (TX power)
  - Low Power Modes ➔ **Power Manager**

Power Manager

- How to **control the power consumption** of the communicating object?
  - Adapt the wake-up period of the node (**T_{wi}**)
  - Transmit Power (**P_{TX}**)

- **Consumed Energy**
  - Off line characterization of **nodes activities** (**L**ook-**U**p **T**able)
  - Depends on **scenario** or **functional modes**



- **Harvested Energy** models
  - Either **predictions** or **measures** (ex. light sensor)

Power Manager

- Which kind of **energy storage** element?
  - Battery or super capacitor?

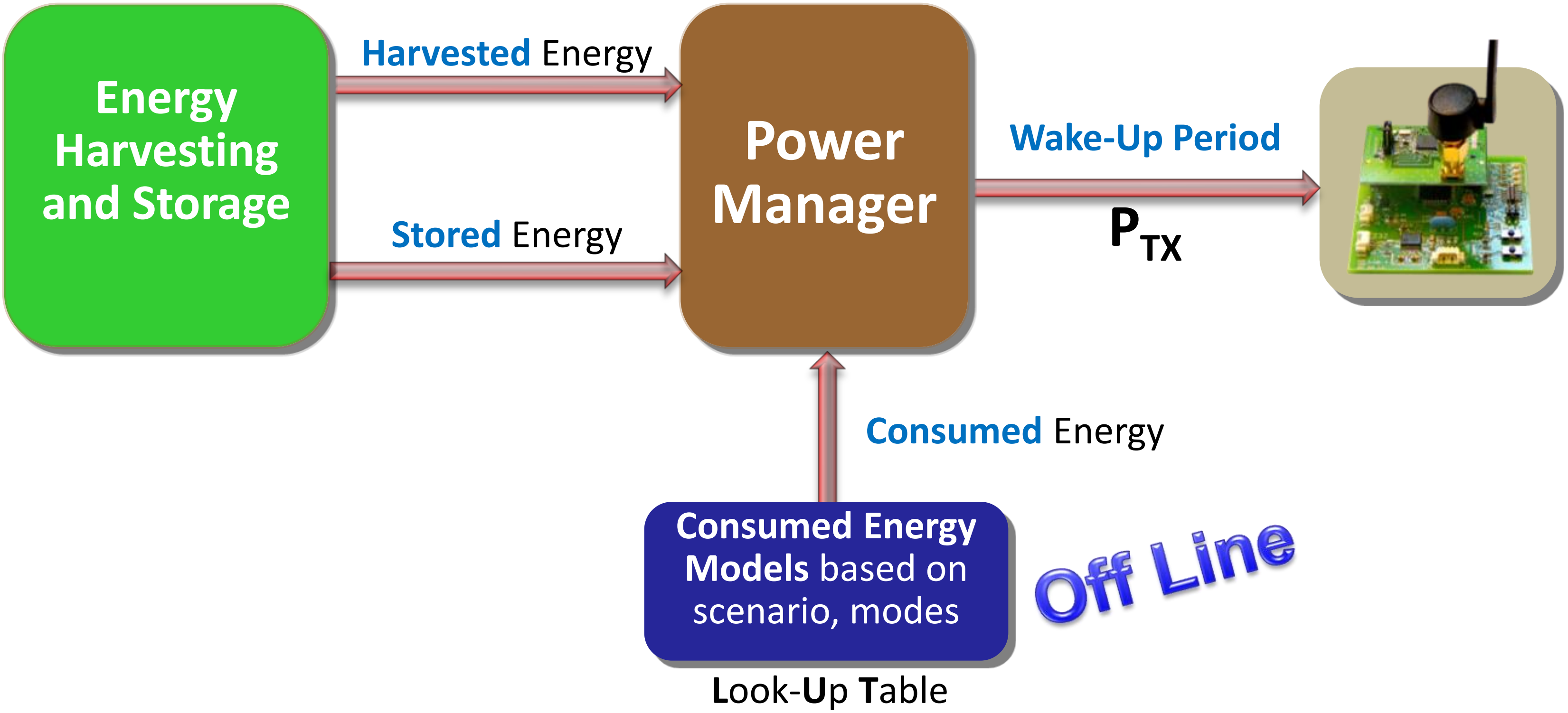
[Cymbet 2011]

- − **500** recharge cycles
- − Difficult to know the state of charge with accuracy
- + **Low leakage current and big capacity**

[HZ202F 2013]

- + **500 000**
- + Easy to know the state of charge
- − High leakage current

Power Manager



- Constraints for power management
  - ➔ **Low complexity**
  - ➔ $T_{PM} = n * T_{WI}$

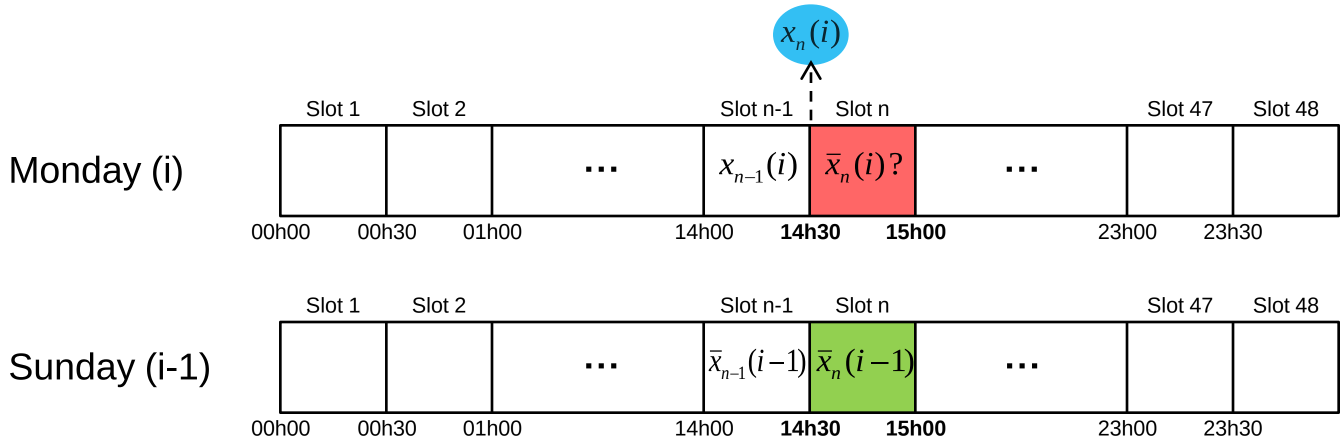
2. Related Works

Kansal et al.

- Kansal et al. were the first to propose **a simple solar energy prediction algorithm** to support their harvested-energy management approach.
- The predictor is based on an **E**xponentially **W**eighted **M**oving **A**verage (**EWMA**) of historical data:

$$\bar{x}(i) = \alpha\bar{x}(i-1) + (1-\alpha)x(i)$$

- The day is divided into **slots**.
- Each slot is **30 minutes long**, as the variation in generated power level is assumed to be small within a 30 minute duration.

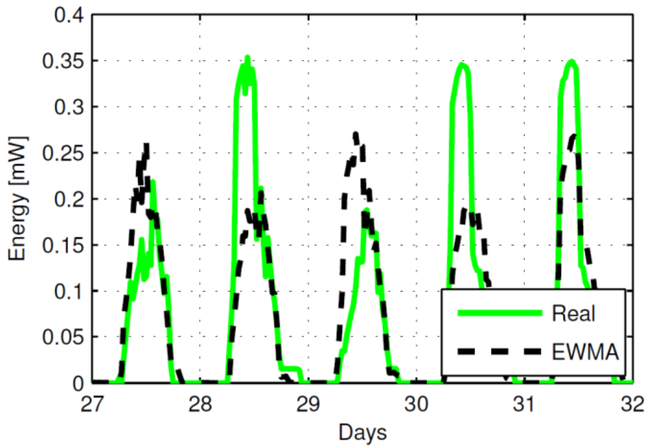


[Kansal 2007]

Recas et al.

- Recas et al. propose a prediction algorithm named **W**eather-**C**onditioned **M**oving **A**verage (**WCMA**) to take into account both the current and past-days weather conditions.

- Drawback of EWMA (Kansal):



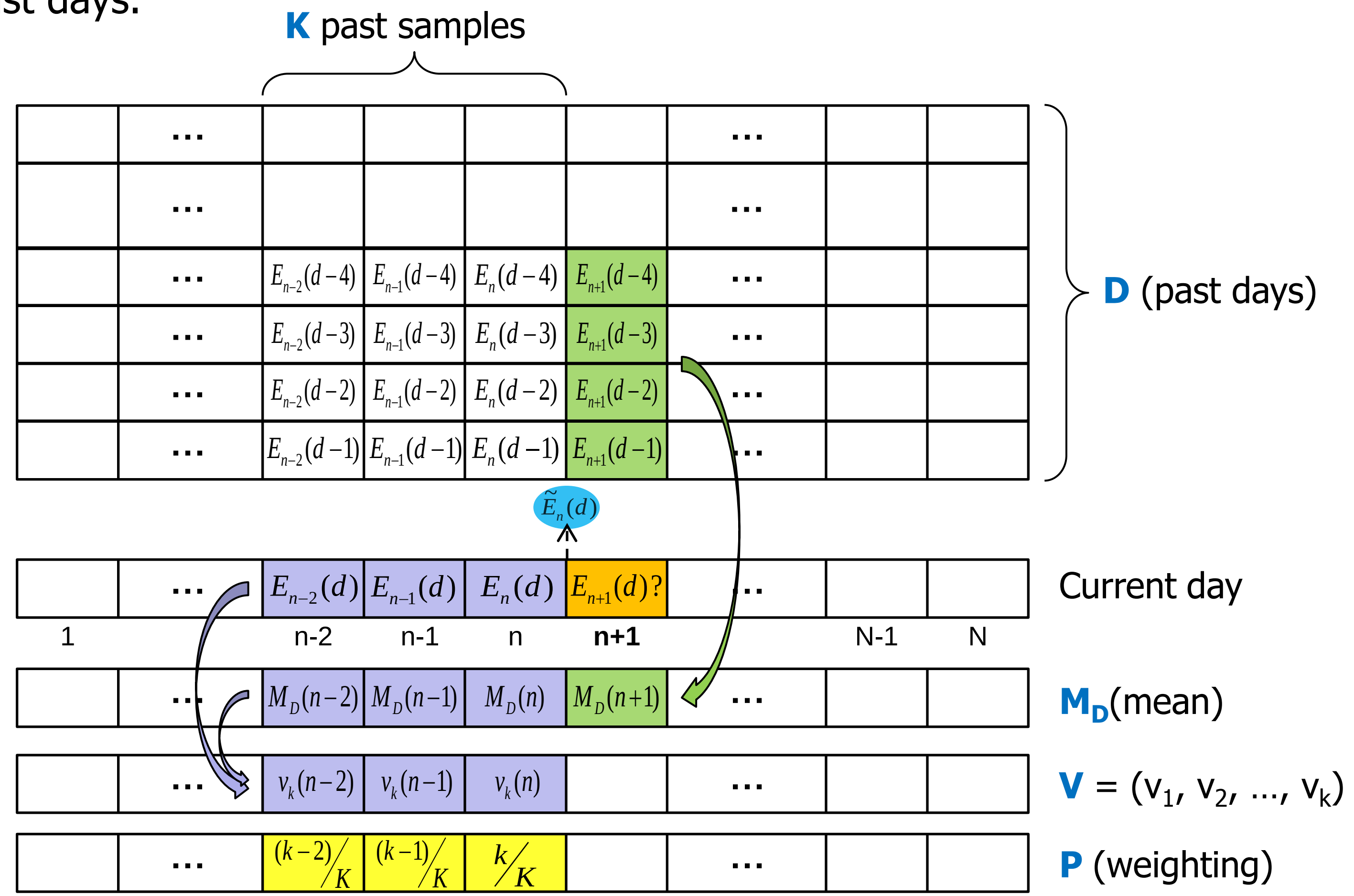
When the sunny and cloudy days alternate, the EWMA produces a significant error in its prediction, **due to the high impact of the solar conditions of previous day** in the predicted value.

- To avoid this effect, Recas et al. propose a prediction algorithm that takes into account not only the solar conditions at a specific time of the day, **but also the weather conditions in the current day**.

[Recas 2009]

$$E(d,n+1) = \alpha \cdot E(d,n) + GAP_k \cdot (1-\alpha) \cdot M_D(d,n+1)$$

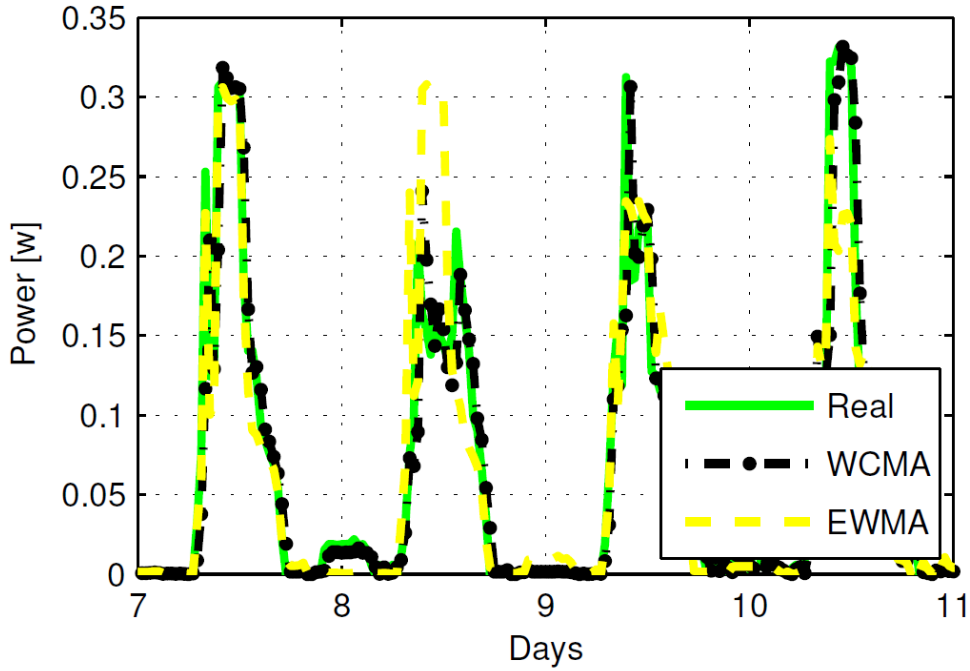
- WCMA algorithm uses an **E matrix of size DxN** that stores N energy values for each D past days.



[Recas 2009]

Recas et al.

- Comparison of WCMA vs. EWMA



Day	E_{real}J	Algorithm	EJ	Err%
7	571.72	WCMA	550.44	3.72
		EWMA	535.50	6.34
8	284.63	WCMA	255.60	10.20
		EWMA	543.60	-90.99
9	400.61	WCMA	360.00	10.14
		EWMA	423.00	-5.59
10	609.50	WCMA	597.60	1.95
		EWMA	406.80	33.26

- Over all 45 days of the collected solar panel data, **EWMA gives an average error of 28.6% compared to 9.8% obtained with WCMA** algorithm.

[Recas 2009]

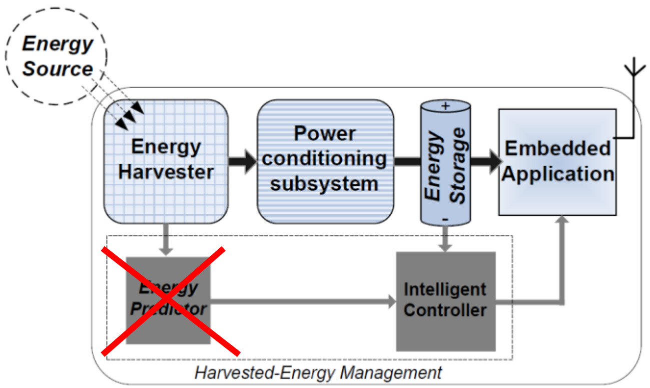
Conclusion

- Kansal approach (EWMA-based algorithm) is accurate for consistent weather conditions, but **when cloudy and sunny days alternate**, recent days energy values introduce **significant prediction errors**.
- In other hand, WCMA based approach (Recas et al.) takes into account weather changes but introduces a **non significant CPU overhead and memory footprint**.
- Moreover, none of these approaches takes into account the **S**tate **o**f **C**harge (**SoC**) of the battery for optimizing the power manager decisions and avoiding a complete discharge of the battery…
- Finally, a wake-up period of 30 minutes for the power manager seems to be too slow for a good system reactivity.

3. System Modeling

Global View of the System

- Generic Solar Harvesting Systems

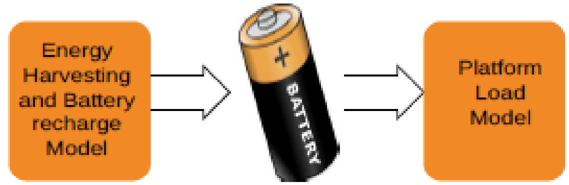


[Ali 2010]

- Battery Centric Modeling

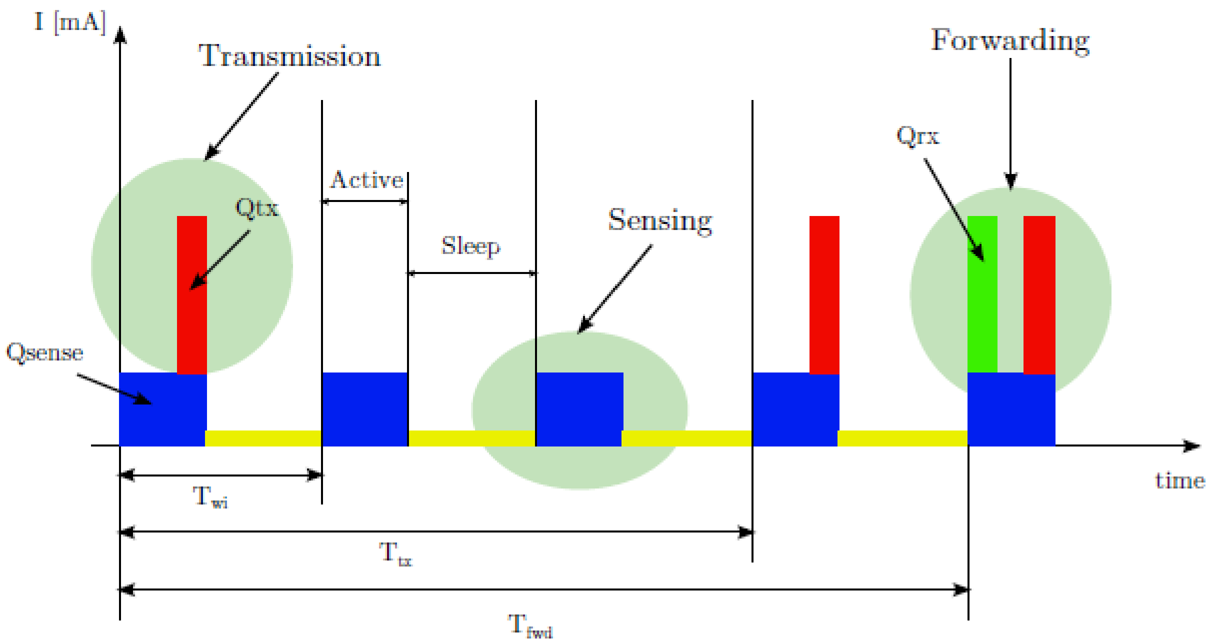
$SoC(\alpha, \beta, t)$

SoC_{max} SoC_{min}



β α

A Periodic Task-level Platform Load Model



- **Q_{sense}** : charge consumed for a sensing operation [Coulomb].
- **Q_{tx}** : charge consumed for a RF transmission [Coulomb].
- **Q_{rx}** : charge consumed for a RF transmission [Coulomb].
- **T_{wi}** : wake-up period for sensing [seconds].
- **T_{tx}** : RF transmission period (multiple of Twi) [seconds].
- **T_{fwd}** : Forwarding transmission period (multiple of Twi) [seconds].

- Rate of discharge of the battery (**α**)

$$\alpha = \frac{Q_i}{T_i} [C/s] \text{ or } [A]$$

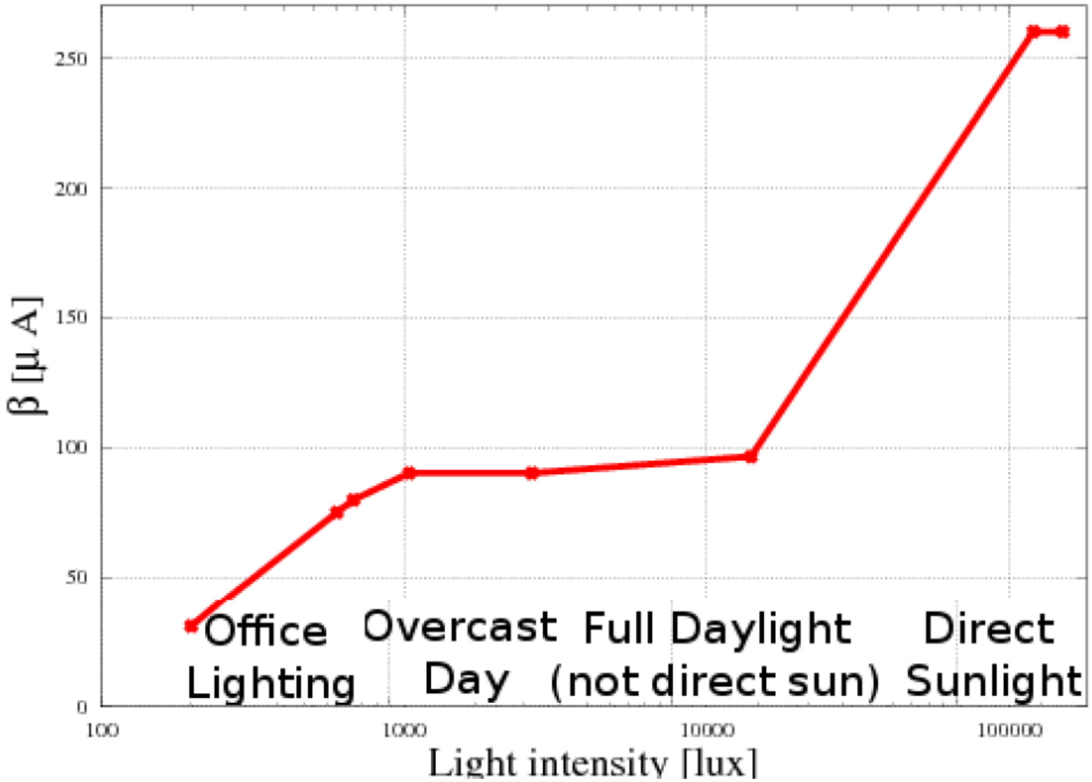
[Castagnetti 04-2012]

A Battery and Energy Harvesting Integrated Model

- Rate of recharge of the battery (**β)**
  - **β** is expressed in Ampere and **indicates the rate at which the energy harvester can recharge the battery** under a fixed amount of energy available from the environment.
  - The **β** parameter models both the **efficiency of the energy harvester** and the **efficiency of the voltage regulator** and **the charge circui**t that are used to recharge the battery.

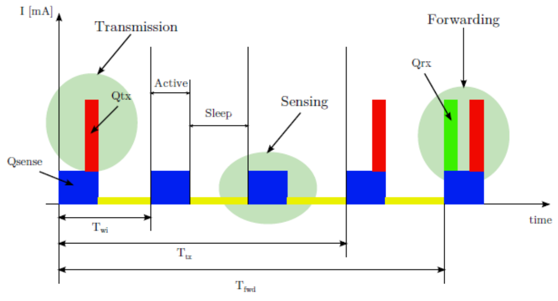
A Battery and Energy Harvesting Integrated Model

- Rate of recharge (β) for different light conditions



A Battery State of Charge Model for Periodic Workload

State of Charge (SoC) Estimation



- The SoC depends upon:
  - The **harvested** energy (**β**).
  - The **platform load** current consumption ($\alpha = \dfrac{Q_i}{T_{Wi}}$)
  - The **leakage** current (battery self discharge and low-power mode current consumption).

The State of Charge (SoC) of a battery for n wake-up periods (T_{wi})

$$SoC(t+nT_{Wi}) = SoC(t) + [\beta - (\alpha_s + \alpha_{Tx}\frac{T_{Wi}}{T_{Tx}} + \alpha_{fwd}\frac{T_{Wi}}{T_{fwd}})] \times nT_{Wi} - K_{leak} \times nT_{Wi}$$

Conditions

$$SoC(t=0) = SoC_{max}.$$

$$SoC_{min} \leq SoC(t + n\,T_{wi}) \leq SoC_{max}.$$

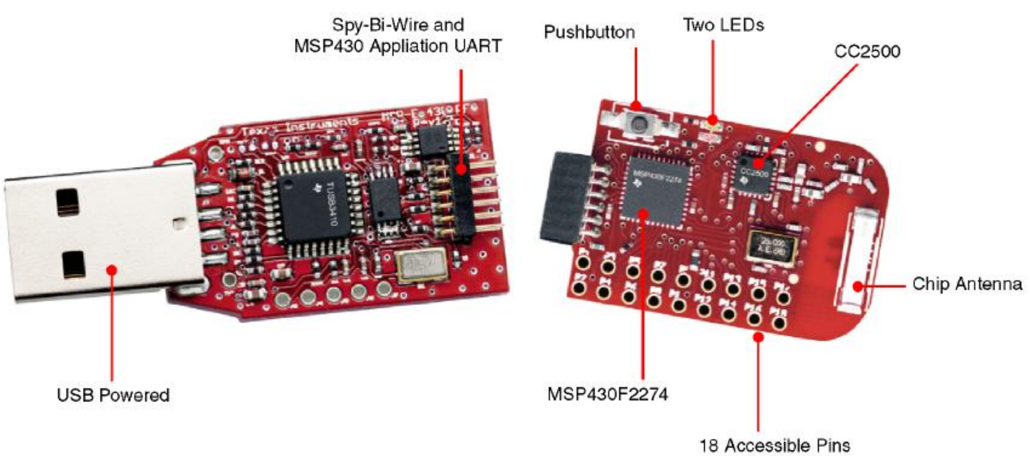
β, α_s and α_{Tx} are constants on $[t, t + n\,T_{wi}]$.

[Castagnetti 04-2012]

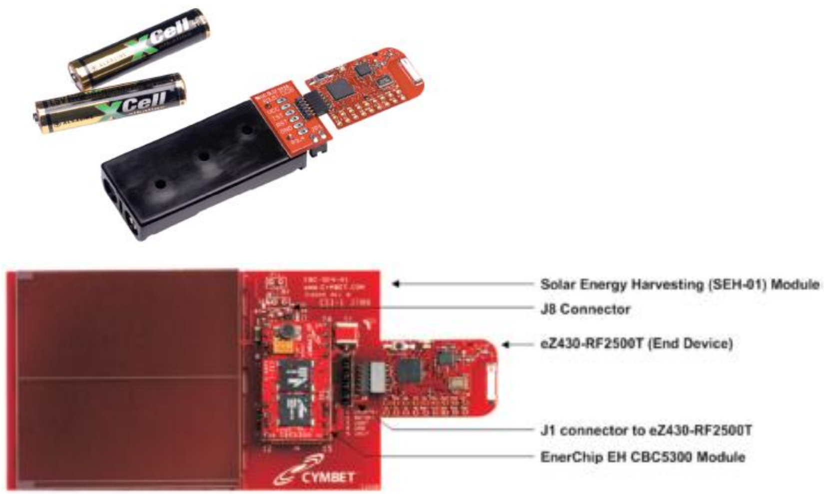
Model Validation

Case Study: Model Validation Using the EZ430 platform

- Texas Instruments EZ430 solar energy harvesting platform
  - MSP430 microcontroller (cadenced at 16MHz) and a CC2500 RF transceiver.
  - 2.25in x 2.25in solar panel.
  - Two lithium thin-film 50 µAh rechargeable batteries.



Access Point

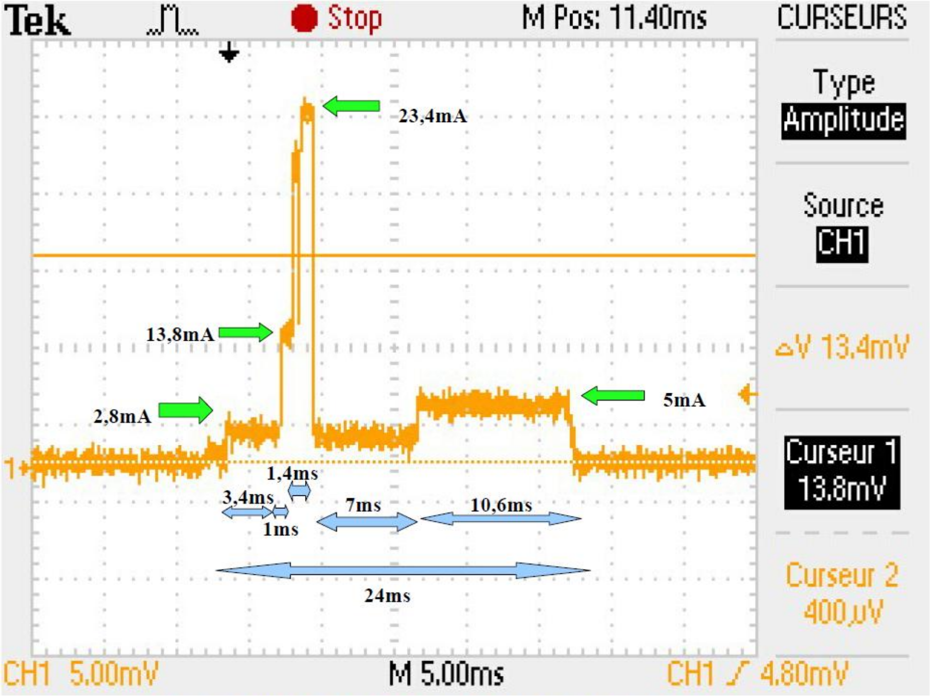


End Devices

Model Validation

Case Study: Model Validation Using the TI EZ430 platform

- Platform load characterization (Q_i)



Q = [(2,8mA*3,4ms)+(13,8mA*1ms)+
(23,4mA*1,4ms)+(2,8mA*7ms)+
(5mA*10,6ms)]
= 9,52µAs+13,8µAs+32,76µAs+19,6µAs+53µAs
= 128,68µAs
= **0,0357µAh**

SoC_{min}	SoC_{max}	C_d
[μAh]	[μAh]	[μAh]
37	100	63

- The platform load characterization is performed by measuring the current consumed for the different tasks (TX, RX, CPU…) of an end-device.

Model Validation

Case Study: SOC Model Validation Using the EZ430 platform

- Experimental results: **lifespan prediction** (in minutes)

		0 lux		$\simeq$ 200 lux	
T_{wi} [sec]	α [μA]	LT (exp)	LT (model)	LT (exp)	LT (model)
1	128.52	28	29	50	38
2	64.26	54	59	140	112
3	42.84	83	88	312	332
4	32.13	107	117	/	$+\infty$
6	21.42	162	176	/	$+\infty$
10	12.85	290	294	/	$+\infty$
20	6.43	585	587	/	$+\infty$

16,8% error margin when β = ~200lux

β ≥ α

5,5% error margin when β =0

4. Power Management for Energy Harvesting WSN Nodes

Balancing the Harvested and Consumed Energy

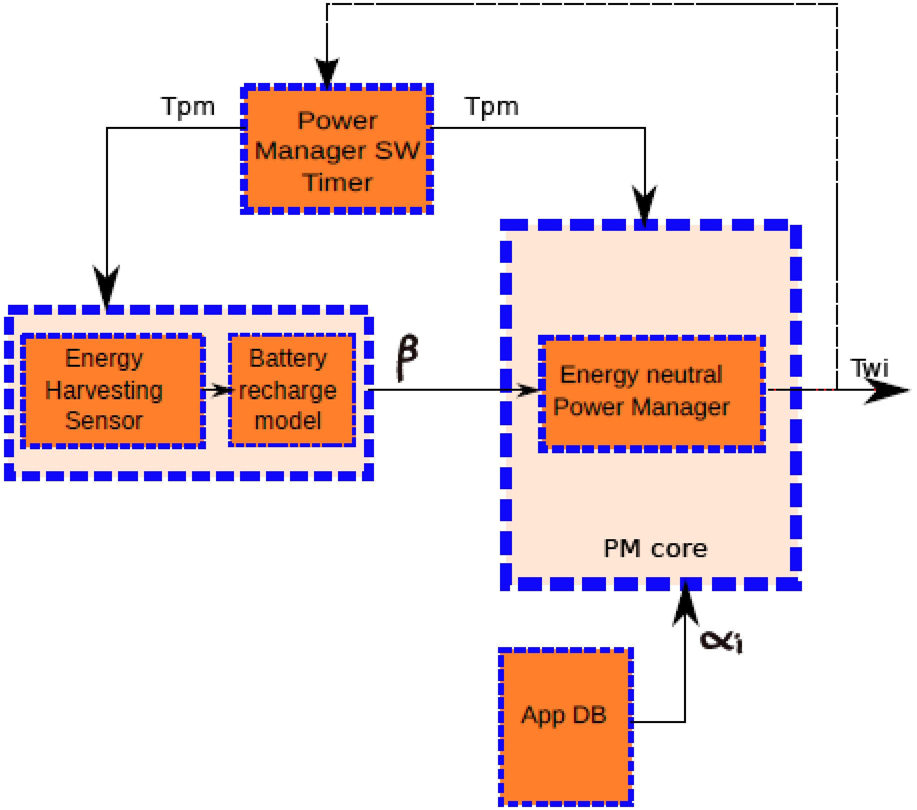
- Adapting the performance and the power consumption of the system to the available energy (i.e. **β**).
- Performance scaling is achieved by varying the wake-up period (T_{wi}) of the sensor node (i.e. **α**).
- The objective is to operate in **Energy Neutrality** (ENO)

  → balancing the **α** and **β** parameters.

- Hypothesis:
  - The power manager must measure/estimate **β**.
  - The values of **α** are known (Q_i off-line profiling).
- Consequence:
  - In energy neutrality, SoC(t) is constant over time: SoC(t) = SoC(t + n Twi)

An Open-Loop Energy Neutral Power Manager (OL-PM)

- Architecture



Equations

- Power Management software timer

$$T_{pm} = n\,Twi$$

- Energy Neutral wake-up period

$$SoC(t) = SoC(t + n\,Twi) - Q_{pm}$$

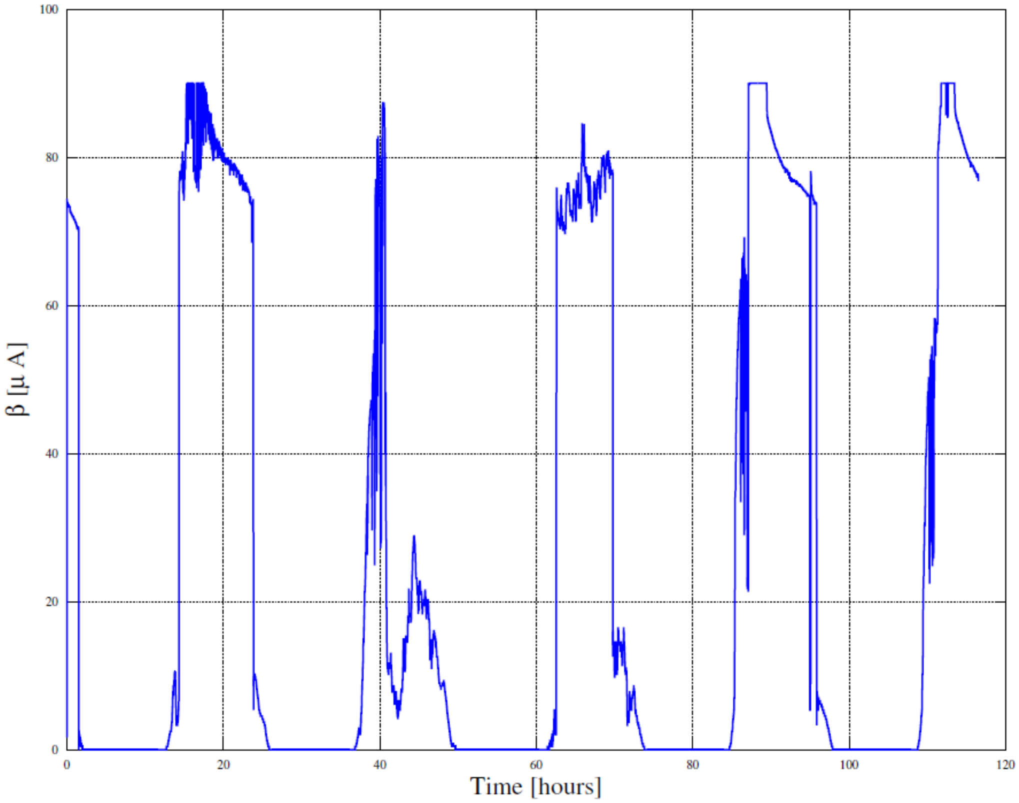
$$T_{wi} = \left\lceil \frac{Q + Q_{pm}/n}{\beta - K_{leak}} \right\rceil$$

Ceil function returns the smallest following integer

5. Simulation Results

Simulation setup

- The values of Q_{sense} and Q_{Tx} have been measured with the TI EZ430 platform.
- **β** is estimated from light intensity measurements taken in an office (indoor conditions) at 5-second intervals during 5 days using a lux-meter.



Harvested energy over 5 days

Evaluation Metrics

- **Average data-Rate** (**<Rd>**): the average throughput is computed over the five days, including the periods of time where the battery is fully discharged.

$$\langle Rd \rangle = \frac{Packet_{payload}}{\overline{T}_{wi}}$$

$Packet_{payload} = 33$ bytes

- **Maximum and minimum data-rate** (**Rd_{max}, Rd_{min}**): peak and minimal achievable performance of a node using a given power manager.
- **Average SoC** (**<SoC>**): to assess if the power management algorithm drifts in energy-neutral condition.
- **Battery failures** (**B_f**): a value of 0 means that the battery is never fully discharged and the node is always operational. Otherwise, it exists at least a $t^* \mid SoC(t^*) < SoC_{min}$

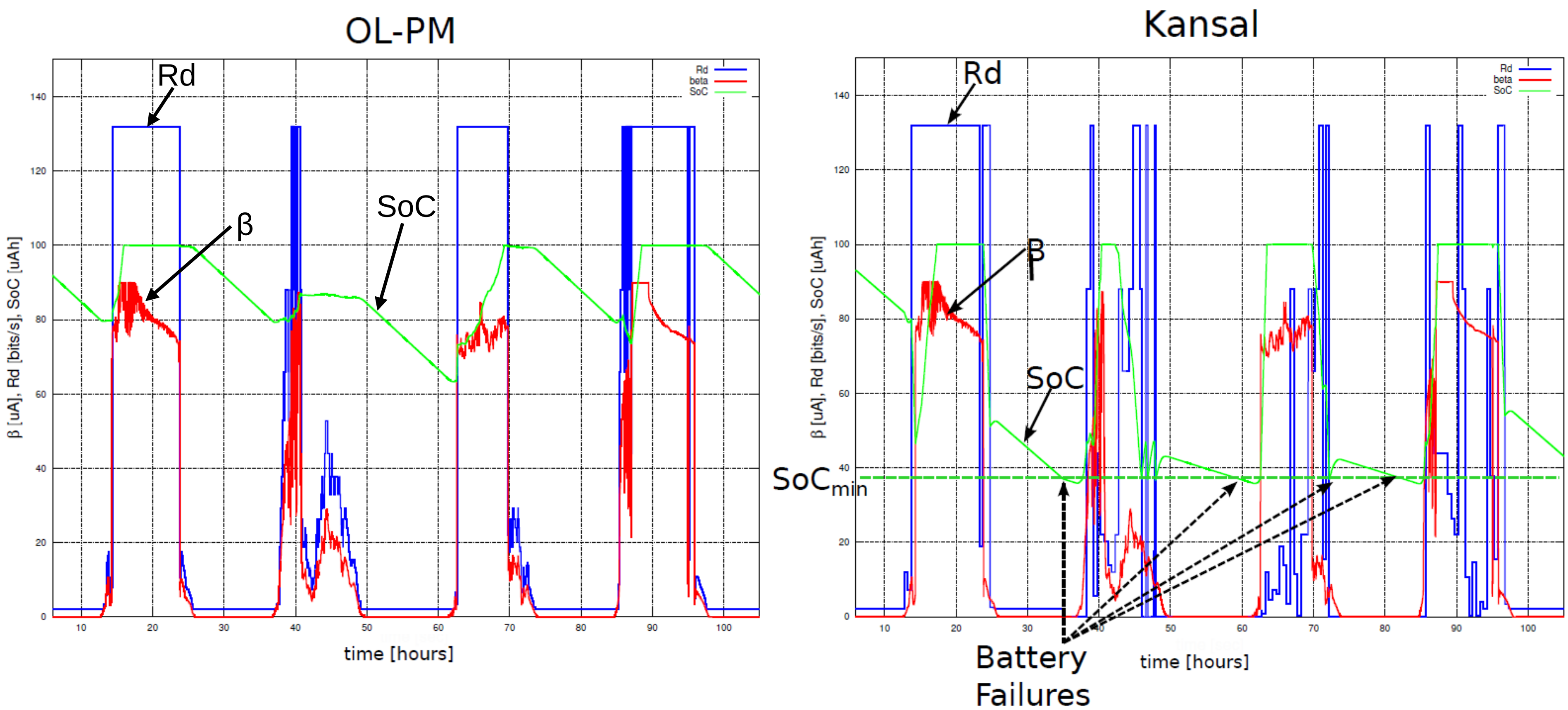
Performance Analysis and Comparison

- The OL-PM has been simulated over the five-day data-set.
- A state of the art power manager ([Kansal 2007]) for solar energy harvesting WSN has been implemented and simulated over the same data-set.
- Power Managers comparison:

	$\langle Rd \rangle$	Rd_{max}	Rd_{min}	$\langle SoC \rangle$	B_f
	[bits/s]	[bits/s]	[bits/s]	[μAh]	
Kansal	29.55	132	0	65.81	9
OL-PM	44.61	132	2.2	88.8	0

- The average **data-rate is improved by 51%** using the OL-PM.
- The OL-PM always provide **a minimum QoS** ($Rd_{min} \neq 0$).
- Remark: Simulating the five-day data-set **takes about 2 minutes** using a laptop PC equipped with an Intel Core-i5 CPU cadenced at 2.5 GHz and 3.8 GB of RAM.

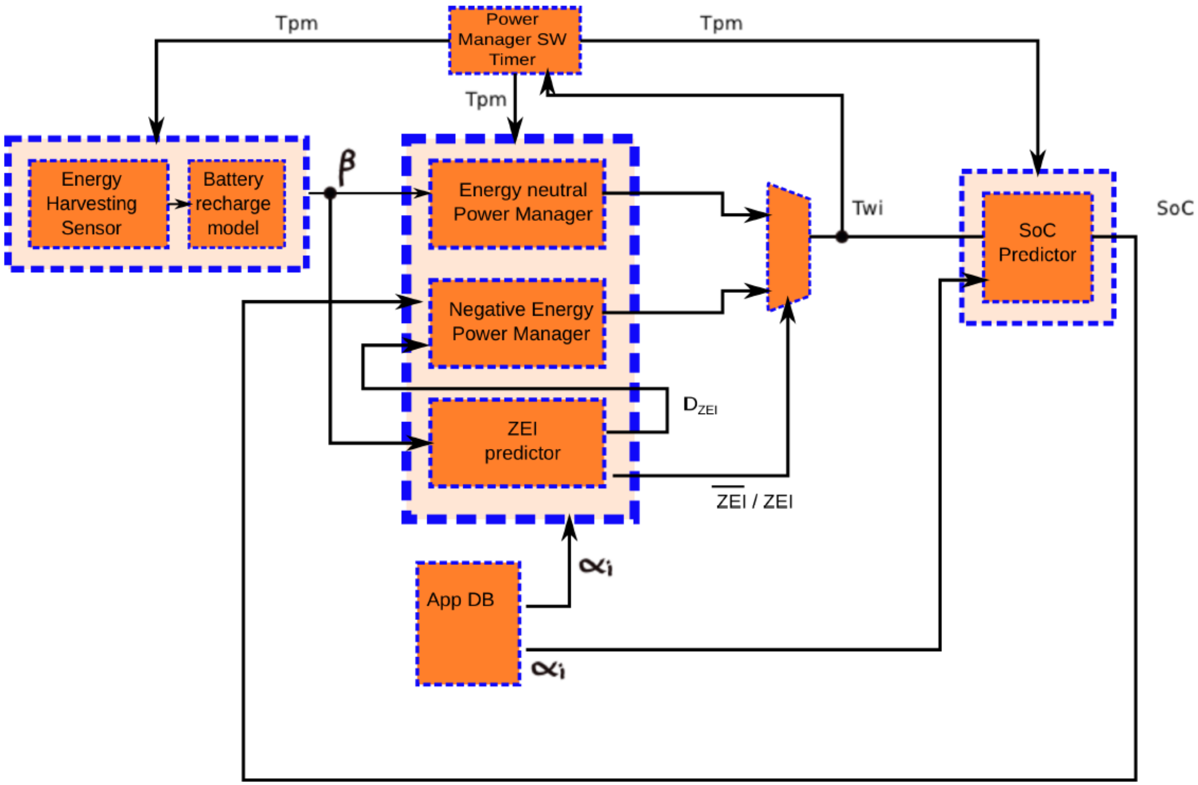
Execution Traces



- The Open-Loop power manager avoids battery failures but does partially exploits the battery capacity…

A Closed-Loop Energy Power Manager (CL-PM)

- Architecture
  - The CL-PM is composed of same building blocks as the OL-PM, plus the negative-energy power manager, the **Z**ero-**E**nergy-**I**nterval (**ZEI**) predictor and the SoC predictor.

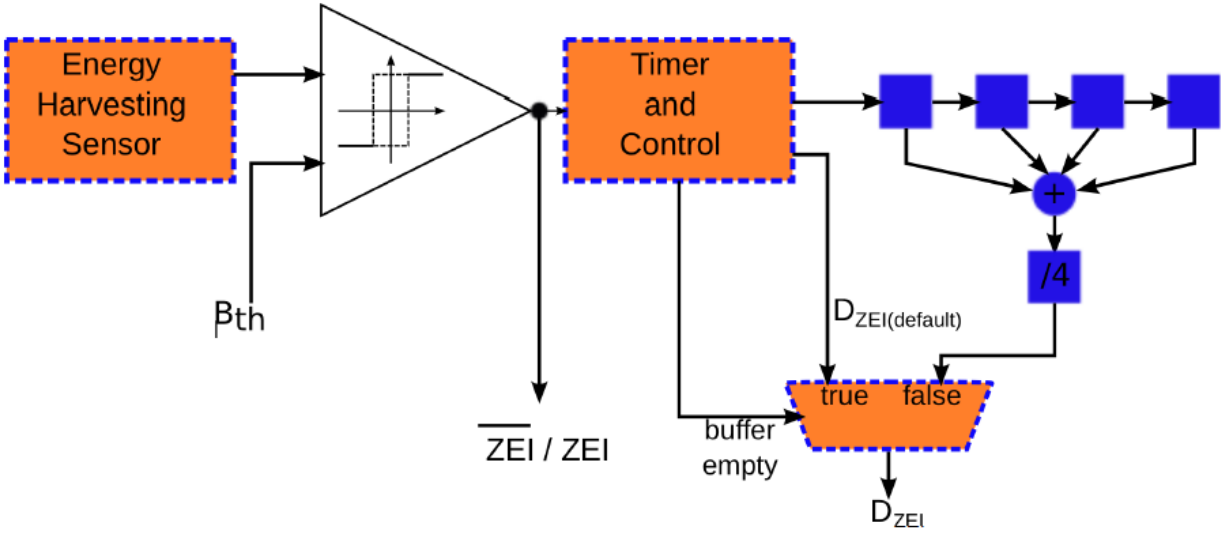


- Two power management strategies are available: the **energy-neutral** and the **negative-energy**.
- **Closed-loop** is used as the output signal (SoC(t)) is fed back into the input of the negative-energy power manager block.

[Castagnetti 05-2012]

The Zero-Energy Interval (ZEI) Predictor

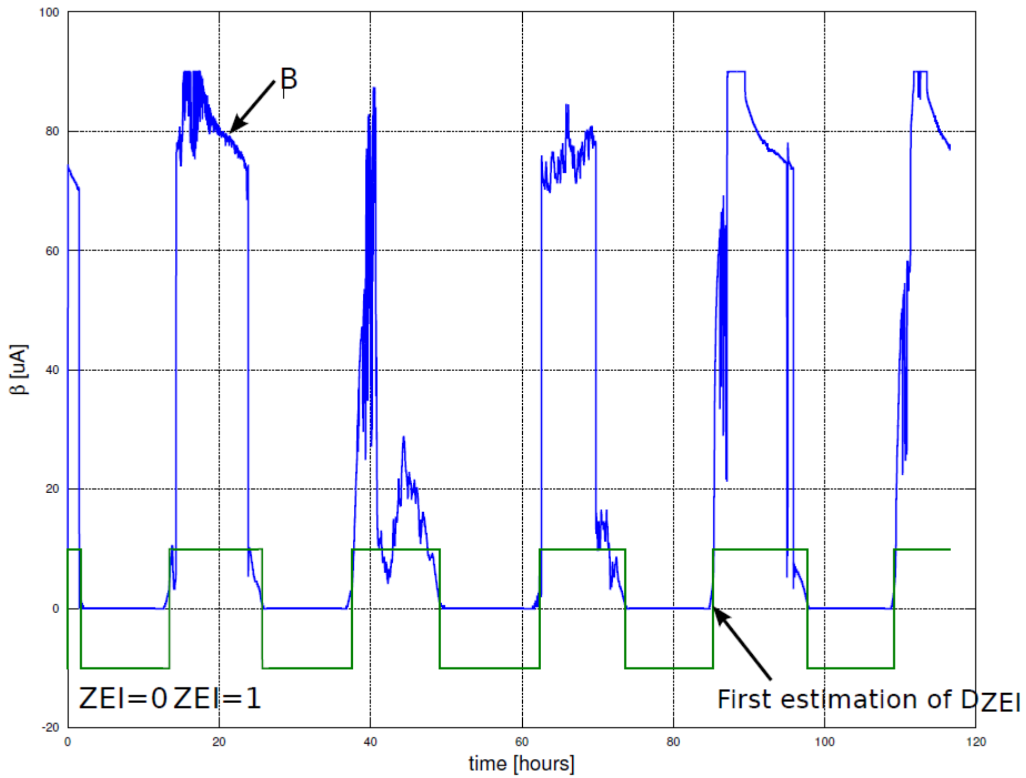
- Block Diagram



- **ZEI**: a **Boolean that indicates if the incoming $\beta \leq \beta_{th}$**. An hysteresis comparator is used to prevent oscillations.
- **D_{ZEI}** : an integer value expressed in seconds used to **estimate the ZEI duration**. This value is computed as the average of the last four measured D_{ZEI}. If less than four measures are available, a default value of 14 hours (50400 seconds) is used.

Estimation of the Zero-Energy Intervals

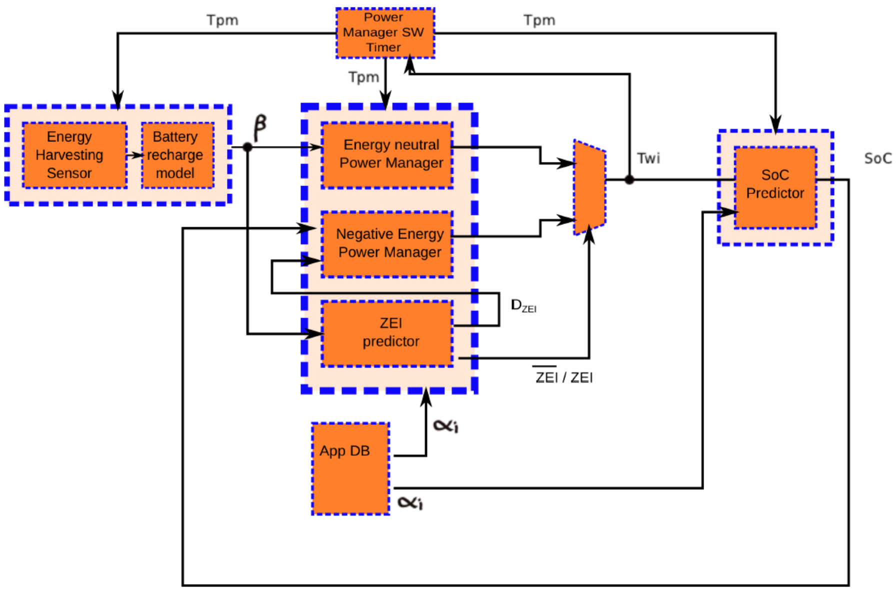
- Behavior of the ZEI predictor during the 5-day data-set



The hysteresis of the comparator prevents undesired oscillation of the ZEI signal and thus provides an accurate estimation of the ZEI duration.

A Closed-Loop Energy Power Manager (CL-PM)

- Problem: finding the next wake-up period T_{wi} that prevents a complete discharge of the battery.



Equations

- If we call **t*** the start of a ZEI, the condition that must be respected is:

$$SoC(t^*) - (\alpha + K_{leak})D_{ZEI} \geq SoC_{\min} + M$$

$$T_{wi} \geq \frac{Q D_{ZEI}}{SoC(t^*) - K_{leak} D_{ZEI} - (SoC_{min} + M)}$$

where

- SoC(t*) is the state of charge of the battery at the beginning of the ZEI,
- D_{ZEI} is an estimation of the duration of the ZEI,
- M is the battery discharge margin

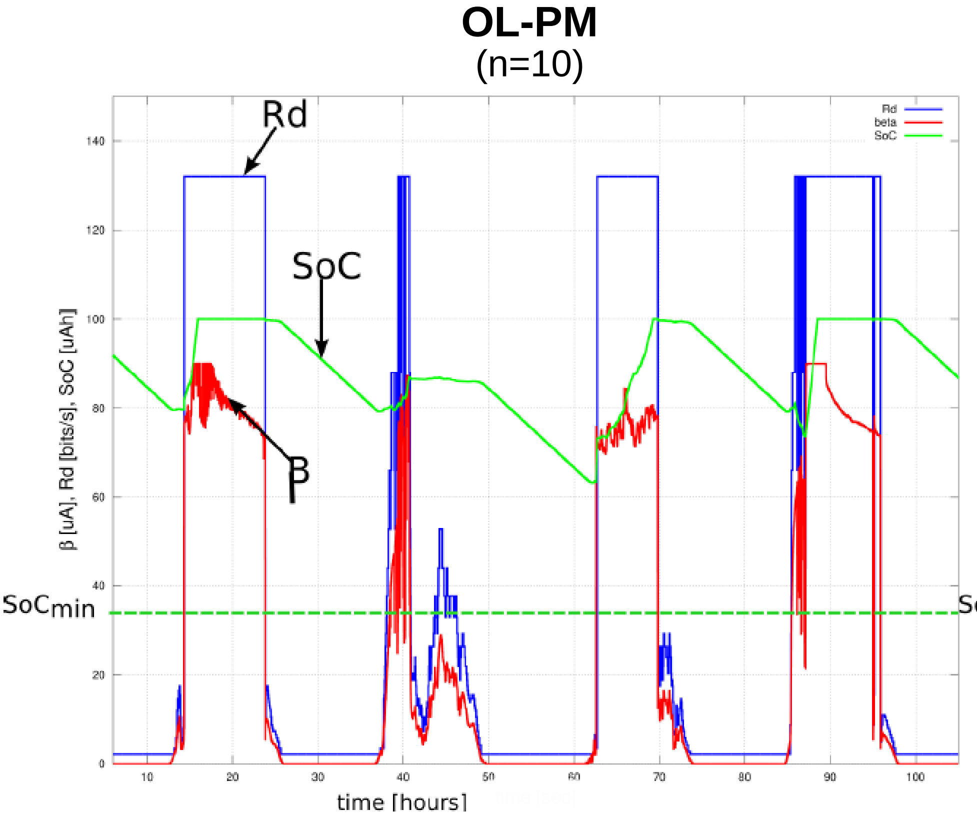
Performance Analysis and Comparison

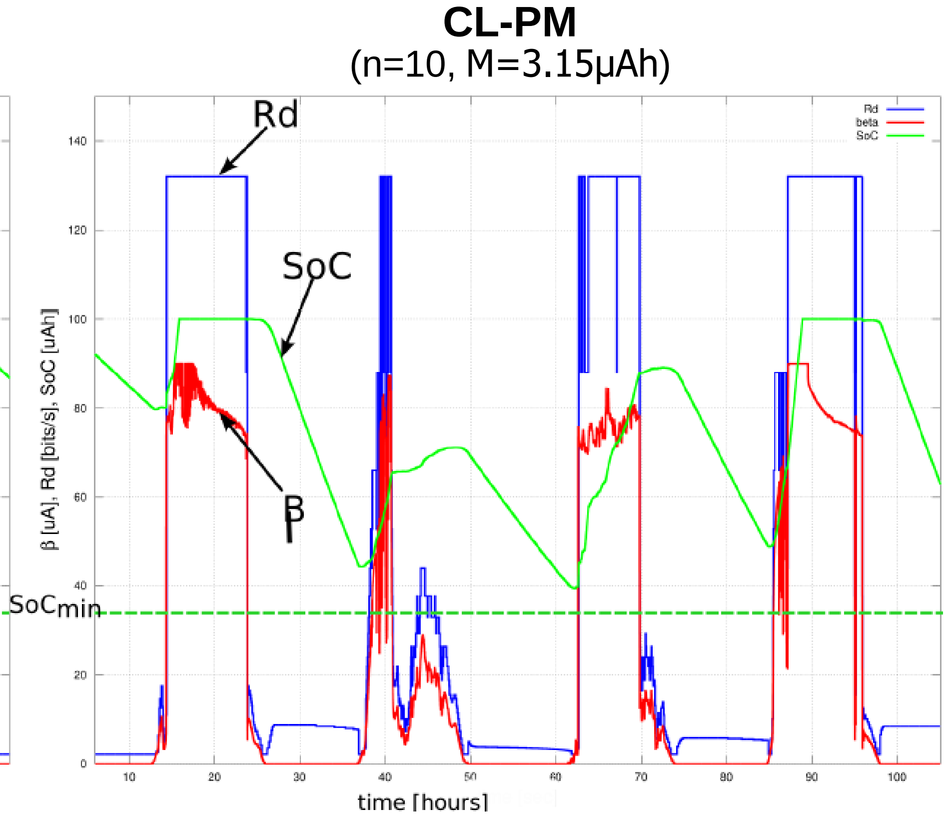
- The CL-PM has been simulated over the five-day data-set.
- Power Managers comparison:

	$\langle Rd \rangle$	Rd_{max}	Rd_{min}	$\langle SoC \rangle$	B_f
	[bits/s]	[bits/s]	[bits/s]	[μAh]	
Kansal [8]	29.55	132	0	65.81	9
OL-PM	44.61	132	2.2	88.8	0
CL-PM	45.87	132	0.37	69.27	0

- The Closed-Loop Power Manager:
  - slightly (globally) improves the average data-rate
  - Does not lead to battery failures
  - Decreases the <SoC>…

Execution Traces

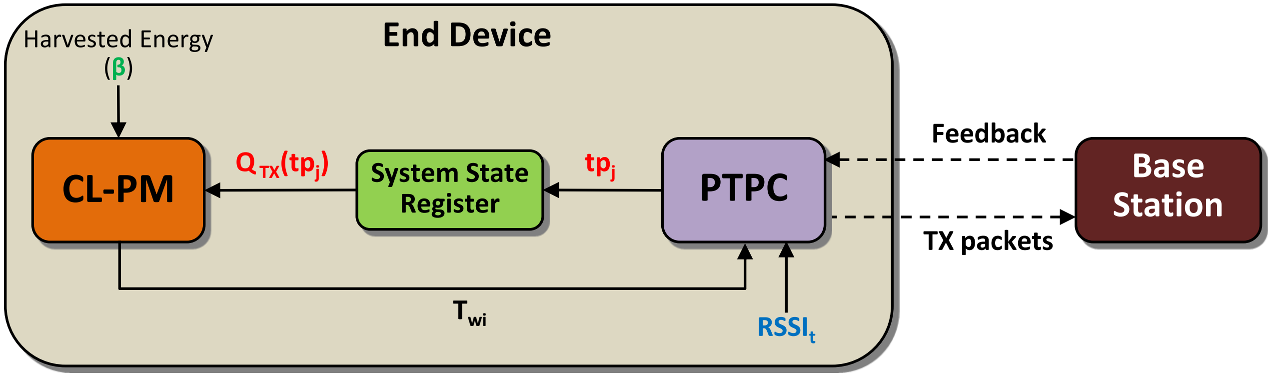




- The Closed-Loop power manager better exploits the battery capacity
- It provides better QoS during the night…

6. A joint Duty-Cycle and Transmission Power Management Approach for EH-WSN

Overview and Results



- According to the **received signal strength** (RSSI), the PM will adapt the transmit power of the node, thus its power consumption…
- CL-PM determine the next wake-up period (**T_{wi}**) according to the new transmission power (**$Q_{TX}(tp_j)$**)
- This approach provides up to **26% energy saving**

PowWow

	Speed [m/s]	**PRR** (%)	E_u [µJ]	**Energy Gain** (%)
CLPM-Fixed	0.2	97	210	
	0.4	95	196	
CLPM-PTPC	0.2	93	155	26.2
	0.4	89	160	23.6

7. Conclusions

Conclusions

Modeling

- A high-level modeling approach for energy harvesting WSN nodes.
- Using **α** and **β** models, the system can be described in a compact form.

Power Management

- Up to 50% data-rate improvement compared to a state of the art power manager.
- System robustness is improved by avoiding the battery to discharge too deeply.
- A global approach is needed for an efficient wake-up period adaptation (channel conditions, TX power, etc.)

References

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GRECO

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Thank you !

Any questions?