DE LA RECHERCHE À L'INDUSTRIE

Energy management of a Wireless Sensor Network at application level

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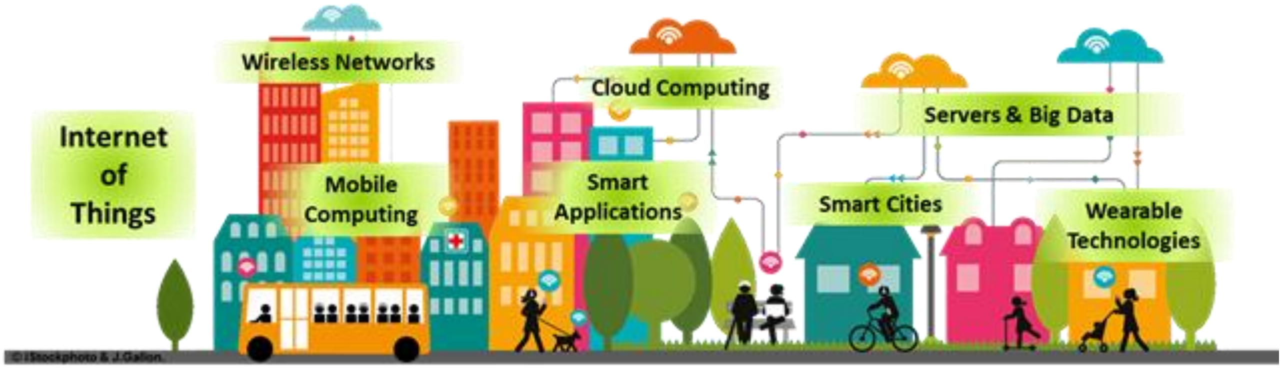
Context 1/2



- Smart environment
  - **Ensure a given service** for a system over a Wireless Sensor Network (WSN)
  - **Maximize** the availability of the application (**WSN lifespan**)

Context 2/2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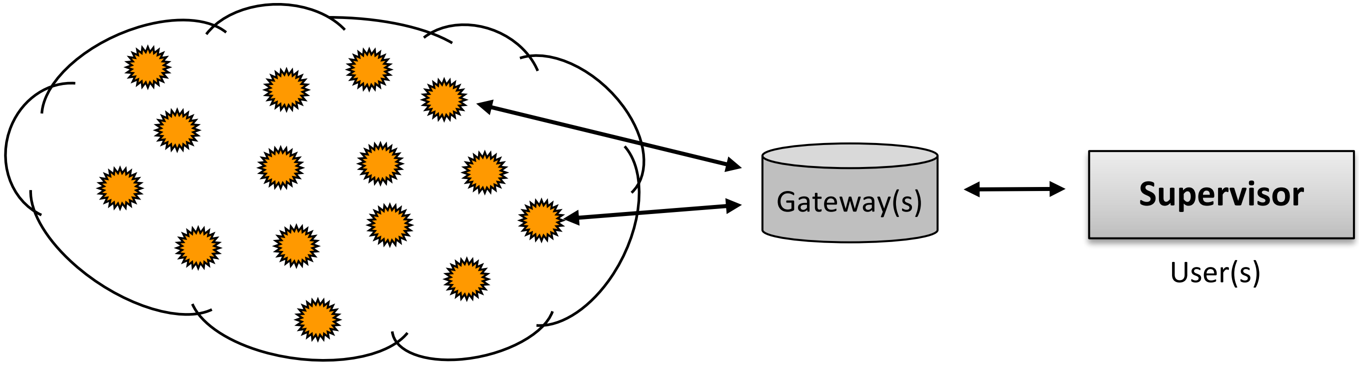
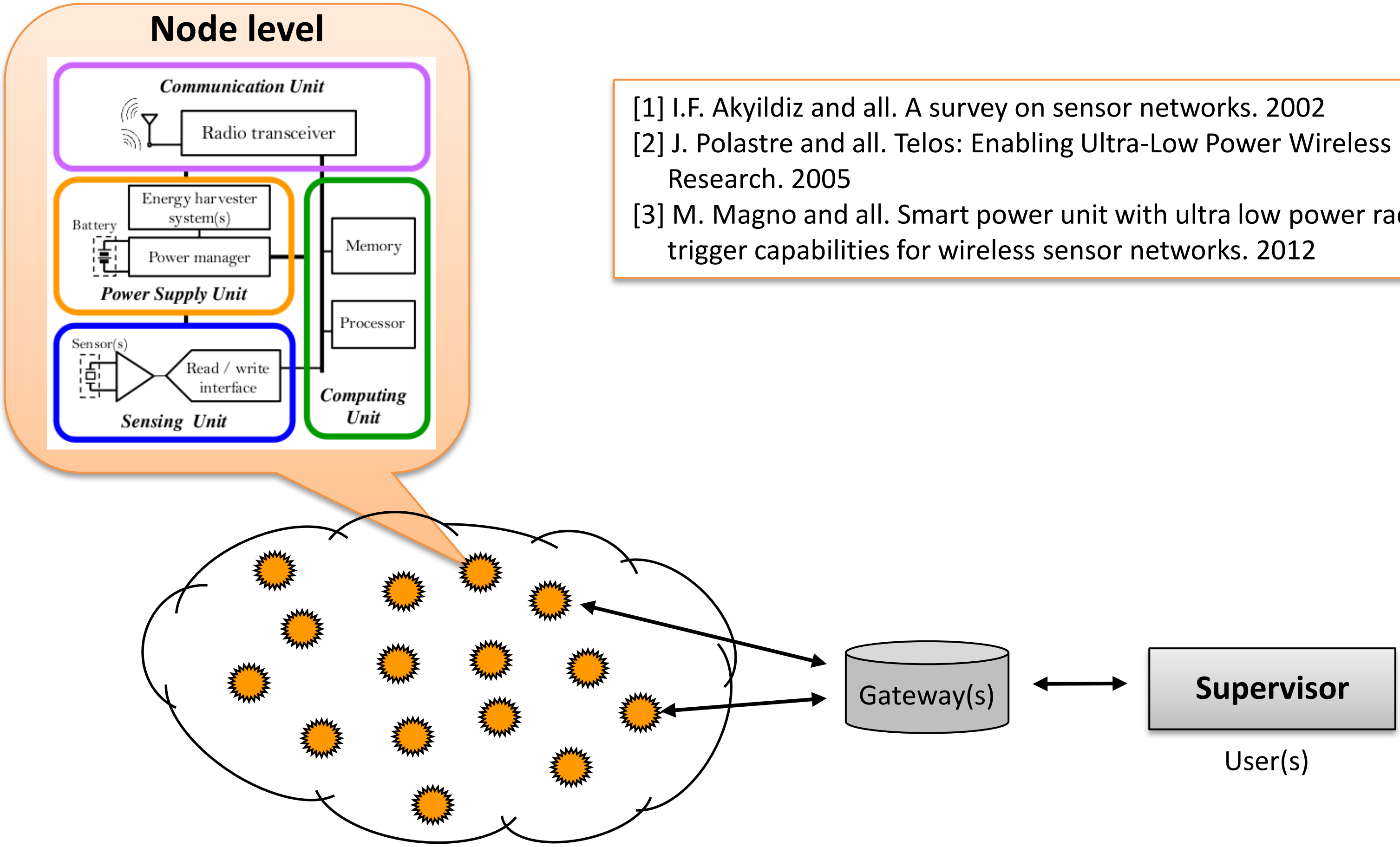


Maximize WSN lifespan ⇨

- Node level
- Network level
- Application level

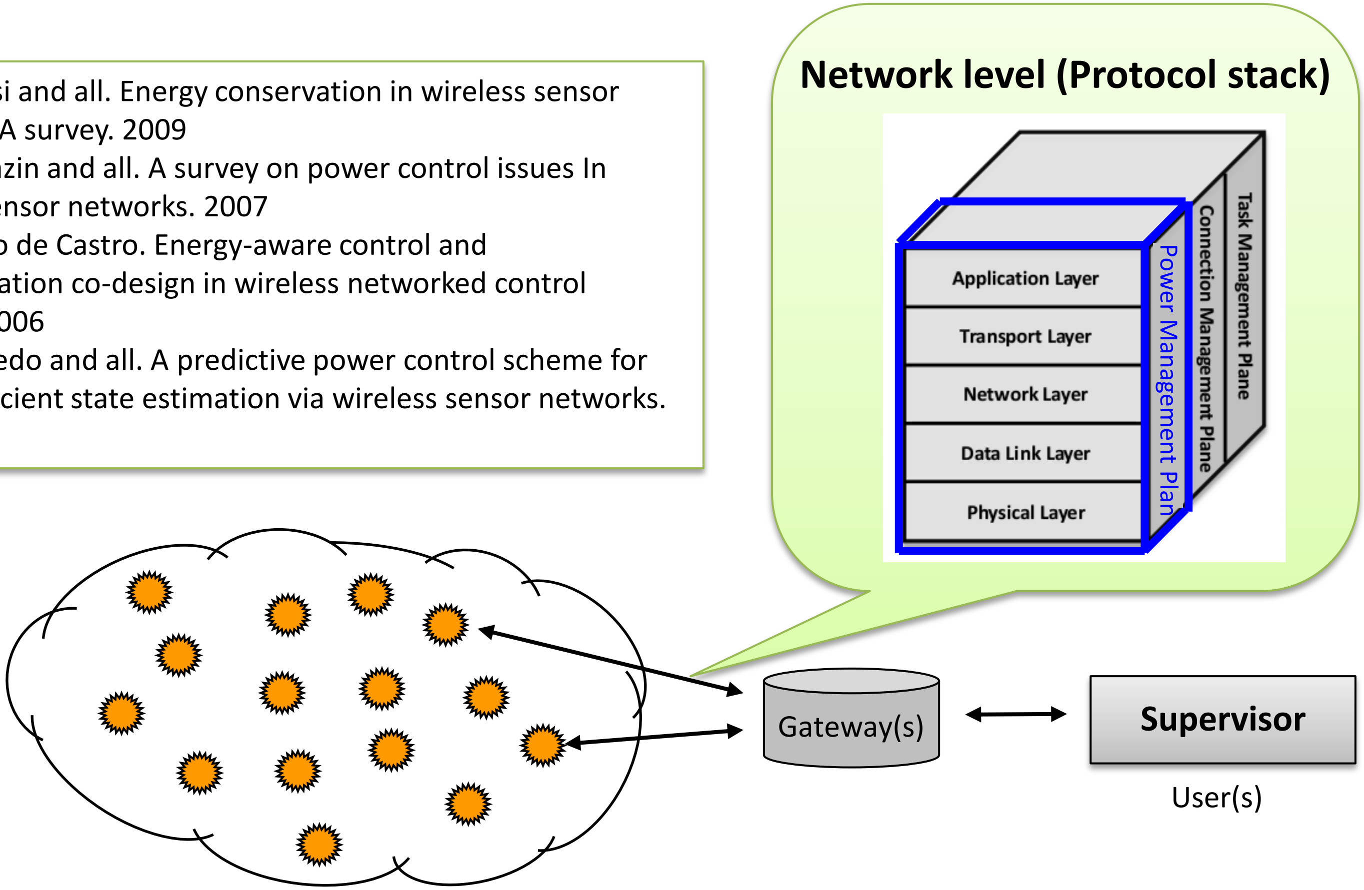
Context 2/2



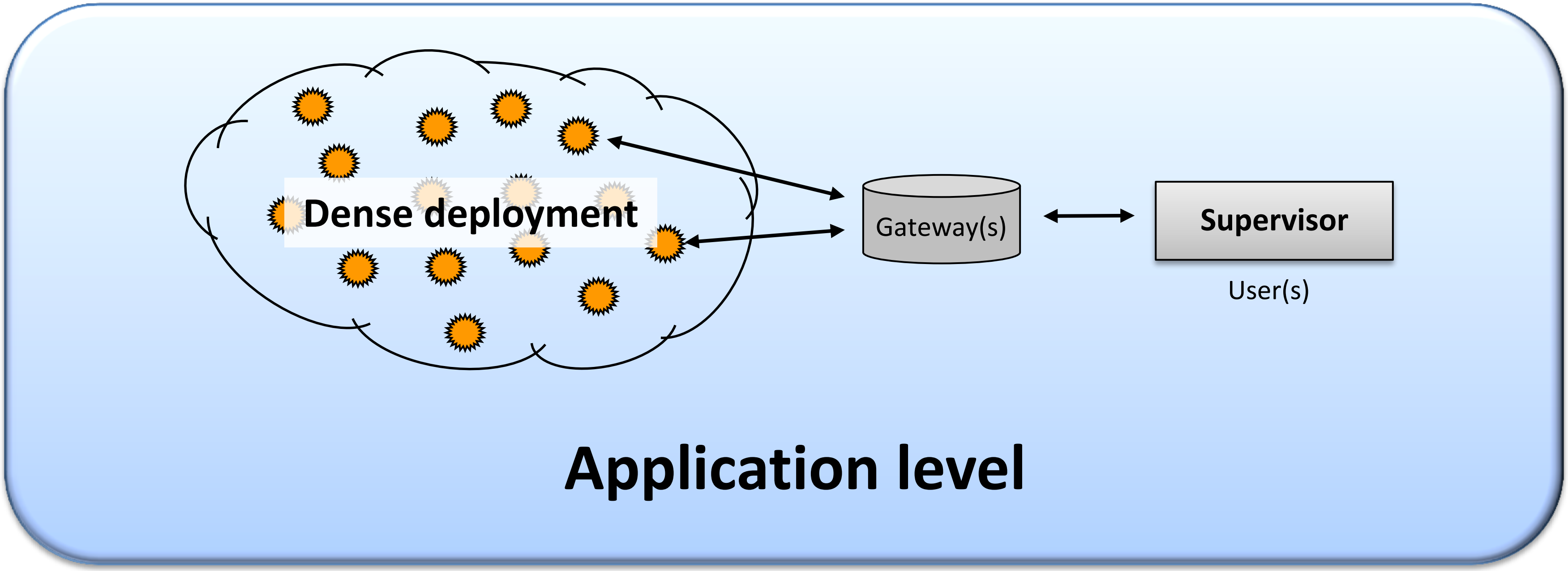
[1] I.F. Akyildiz and all. A survey on sensor networks. 2002
[2] J. Polastre and all. Telos: Enabling Ultra-Low Power Wireless Research. 2005
[3] M. Magno and all. Smart power unit with ultra low power radio trigger capabilities for wireless sensor networks. 2012

Context 2/2

[1] G. Anastasi and all. Energy conservation in wireless sensor networks: A survey. 2009
[2] N.A. Pantazin and all. A survey on power control issues In wireless sensor networks. 2007
[3] N. Cardoso de Castro. Energy-aware control and communication co-design in wireless networked control systems. 2006
[4] D.E. Quevedo and all. A predictive power control scheme for energy efficient state estimation via wireless sensor networks. 2008



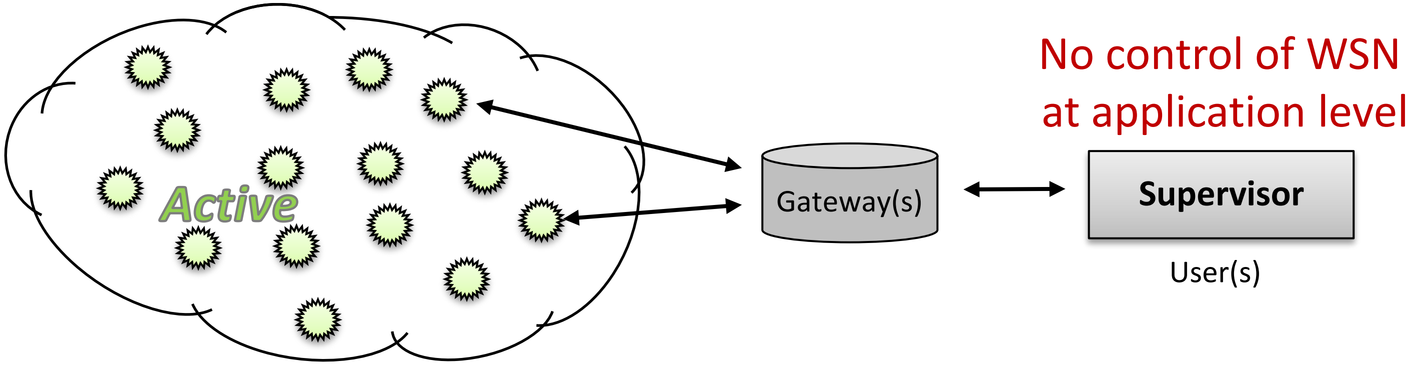
Context 2/2



Application level

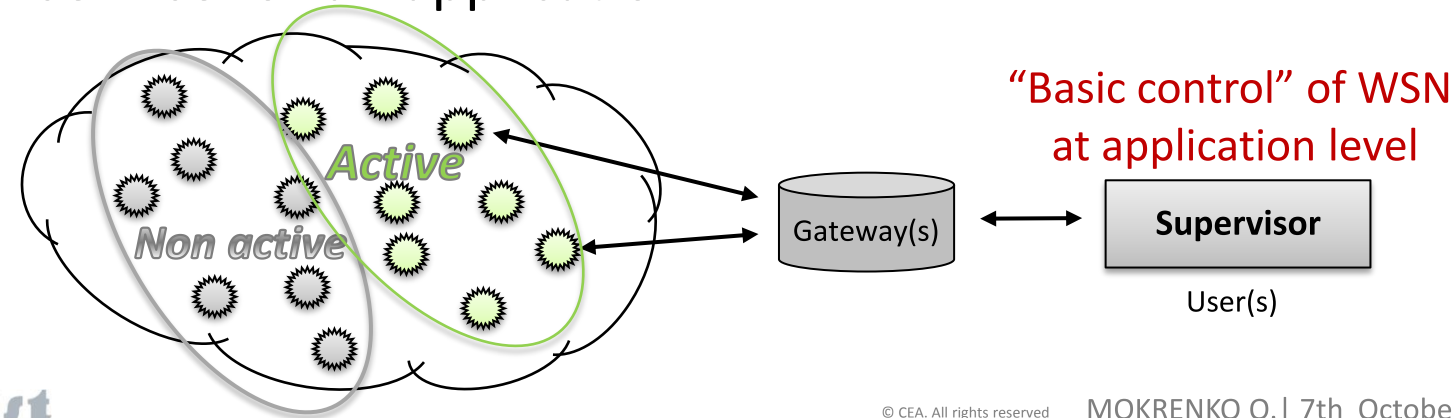
Dummy & Basic schemes

- Dummy scheme
  - **All nodes** are active to ensure a given service for an application



No control of WSN at application level

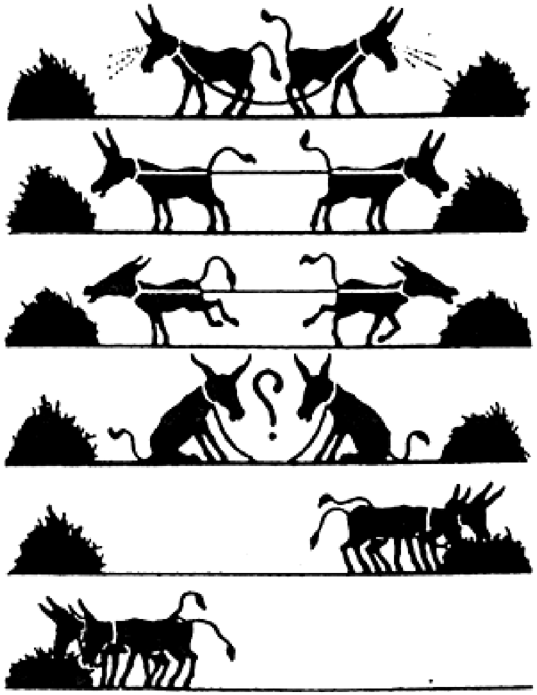
- Basic scheme
  - A **given number of nodes** are active to ensure a given service for an application

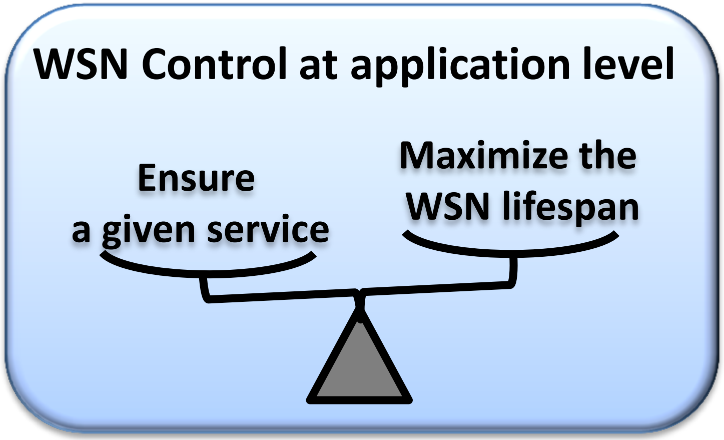


"Basic control" of WSN at application level

Objectives

- **Exploit trade-offs:** find a **balance** between different **contradictory objectives** that occur at the same **time**
- Example:
  - Maximize the performance (Ensure a given service)
  - Maximize the WSN lifespan





WSN Control at application level

Ensure a given service

Maximize the WSN lifespan

Outline

- Context
- Model Predictive Control Approach
- Hybrid Dynamic System Approach
- Implementation on a Test-Bench and Results
- Comparisons of Both Control Strategies
- Conclusions

Outline

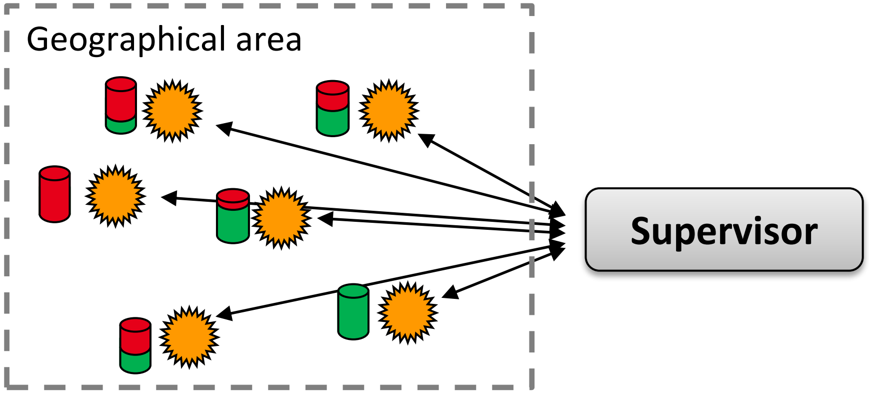
Context

Model Predictive Control (MPC) Approach

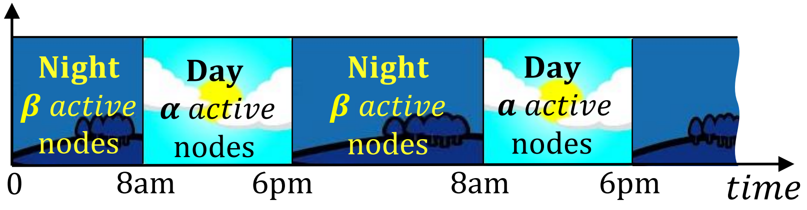
- Problem statement
- WSN: system modeling
- MPC design
  - Control design
  - Benchmark description
  - Simulation results
- Conclusion on the MPC approach

Problem statement, control objectives

- Wireless sensor network
  - **Nodes** deployed in a geographical area
  - To **ensure** a given **service**
  - **Same functionality** → Redundant information



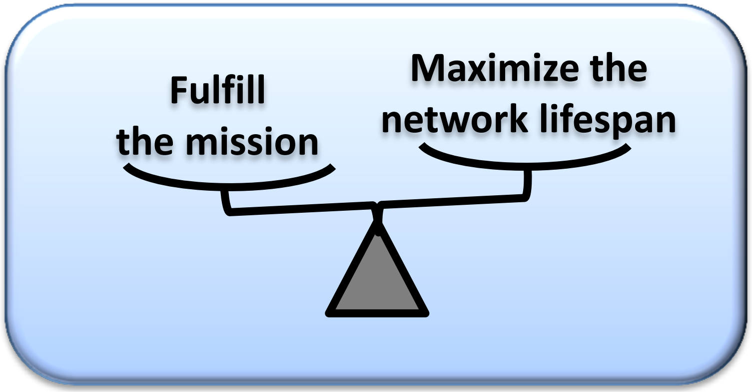
- Service = **mission**
  - Minimum number of *active* nodes during a given time period



- Energy consumption
  - Average energy consumption for node i in mode j for a given time period

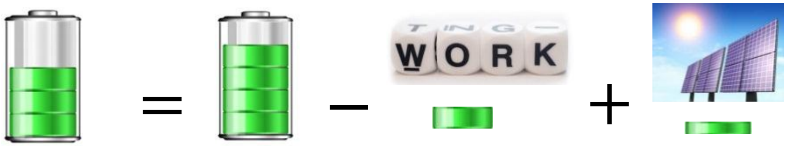
Node	Mode M_1	Mode M_2	$\cdots$	Mode M_m
1	b_{11}	b_{12}	$\cdots$	b_{1m}
2	b_{21}	b_{22}	$\cdots$	b_{2m}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
n	b_{n1}	b_{n2}	$\cdots$	b_{nm}

- **Control objectives**



System modeling

Node i: energy consumption model

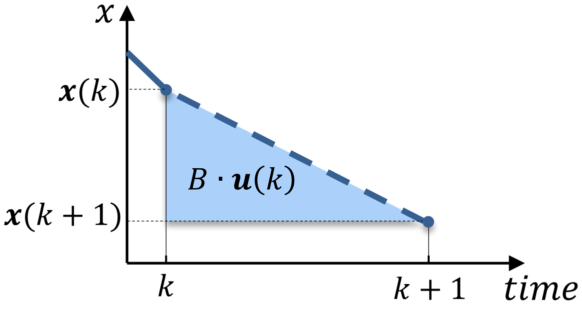


$$x_i(k+1) = x_i(k) - B_i \cdot u_i(k) + E_i \cdot w_i(k)$$

$y_i(k) = x_i(k)$ (measurement)

Maximize lifespan → $\mathbf{max} \sum_{all\ nodes} x_i(k+1)$ ⇨

Whole system model



Compute $\boldsymbol{u}(k)$ s.t. $\mathbf{min} \sum_{all\ nodes} B_i \cdot u_i(k)$

Under constraints

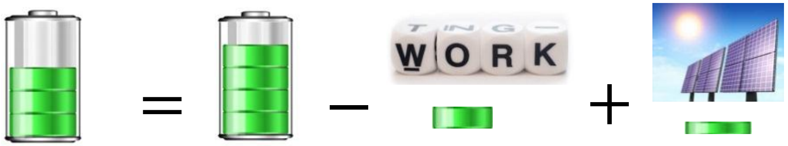
1. Binary control (at time k)

Mode M_1 ON
Mode M_2 OFF
⋮
Mode M_m OFF

$$\begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = u_i(k)$$

System modeling

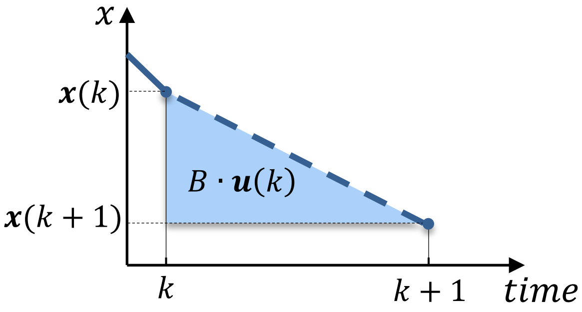
- Node i: energy consumption model



$$x_i(k+1) = x_i(k) - B_i \cdot u_i(k) + E_i \cdot w_i(k)$$

$y_i(k) = x_i(k)$ (measurement)

- Whole system model



Maximize lifespan → $\max \sum_{all\ nodes} x_i(k+1)$ ⇒ **Compute $\boldsymbol{u}(k)$** s.t. $\min \sum_{all\ nodes} B_i \cdot u_i(k)$

- Under constraints

1. **Binary control** (at time k)

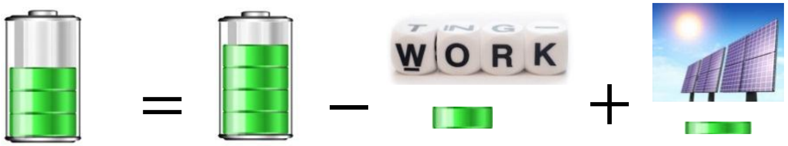
Mode M_1 ON
Mode M_2 OFF
⋮ ⋮
Mode M_m OFF

2. **Node** works **in a unique mode** at time k

$$\sum_{h=1}^{m} u_{ih} = 1$$

System modeling

- Node i: energy consumption model



$$x_i(k+1) = x_i(k) - B_i \cdot u_i(k) + E_i \cdot w_i(k)$$

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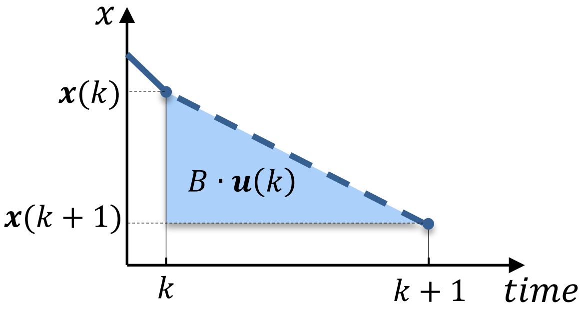
- Whole system model



Maximize lifespan → $\mathbf{max} \sum_{all\ nodes} x_i(k+1)$ ⇨ Compute $\boldsymbol{u}(k)$ s.t. $\mathbf{min} \sum_{all\ nodes} B_i \cdot u_i(k)$

- Under constraints

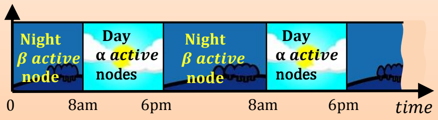
1. Binary control (at time k)

Mode M_1
Mode M_2
⋮
Mode M_m

2. Node works **in a unique mo**

$$\sum_{h=1}^{m} u_{ih}$$

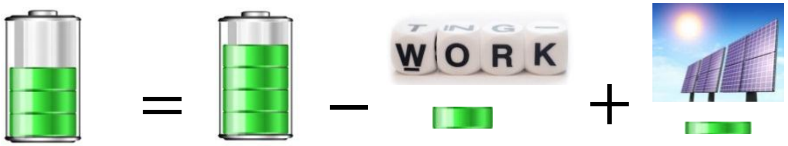
3. Mission definition



$$\text{For mode } M_h\text{:} \sum_{i=1}^{n} u_{ih} = d_h$$

System modeling

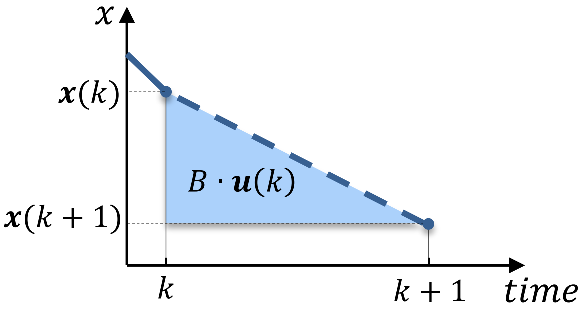
- Node i: energy consumption model



$$x_i(k+1) = x_i(k) - B_i \cdot u_i(k) + E_i \cdot w_i(k)$$

$$y_i(k) = x_i(k) \text{ (measurement)}$$

- Whole system model



Maximize lifespan → $\max \sum_{all\ nodes} x_i(k+1)$ ⇒ **Compute $\boldsymbol{u}(k)$** s.t. $\min \sum_{all\ nodes} B_i \cdot u_i(k)$

- Under constraints

1. Binary control (at time k)

Mode M_1 ON

Mode M_2 OFF

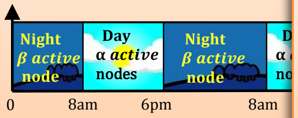
⋮ ⋮

Mode M_m OFF

2. Node works in a unique mo

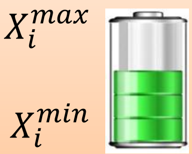
$$\sum_{h=1}^{m} u_{ih}$$

3. Mission definition



For mode M_h: $\sum_{i=1}^{n}$

4. Bounded capacity of the battery



$$0 < X_i^{min} \le x_i \le X_i^{max}$$

Control design

- Model Predictive Control

$$\boldsymbol{u}^* = \arg\min_{\boldsymbol{u}} \left(\sum_{j=0}^{N_p} \left(\boldsymbol{X}^{max} - \boldsymbol{x}_{k+j|k}\right)^T Q \left(\boldsymbol{X}^{max} - \boldsymbol{x}_{k+j|k}\right) + \sum_{j=0}^{N_u-1} \boldsymbol{u}_{k+j|k}{}^T R \boldsymbol{u}_{k+j|k} \right)$$

Subject to:

$$\begin{cases} \boldsymbol{x}_{k+1+j|k} = A\boldsymbol{x}_{k+j|k} + B\boldsymbol{u}_{k+j|k} + E\boldsymbol{w}_{k+j|k}, \qquad j = 0,1,\dots,N_p \\ \boldsymbol{X}^{min} \leq \boldsymbol{x}_{k+j|k} \leq \boldsymbol{X}^{max}, \qquad j = 0,1,\dots,N_p \\ \displaystyle\sum_{i=1}^{n} u_{ih} = d_h \text{ for each } (k+j|k) \\ \displaystyle\sum_{h=1}^{m} u_{ih} = 1 \text{ for each } (k+j|k) \\ \boldsymbol{u}_{k+j|k} \in \{0,1\}^{mn}, j = 0,1,\dots,N_u - 1 \end{cases}$$

Weighting matrices chosen depending on the application:

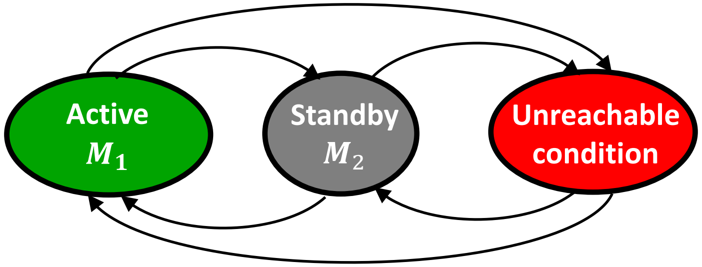
$$\begin{cases} Q \in \mathbb{R}_{\geq 0}^{n\times n} \\ R \in \mathbb{R}_{>0}^{mn\times mn} \end{cases}$$

→ Mixed Integer Quadratic Programming (MIQP)

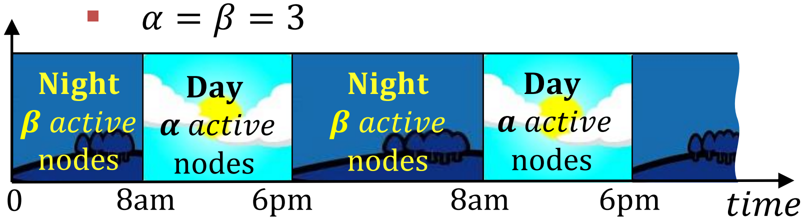
Benchmark description

Benchmark

- 6 sensor nodes
- 3 states:
  - 2 functioning modes
  - Unreachable condition



- **Mission** : 3 *active* nodes (mode M_1)
  - $\alpha = \beta = 3$

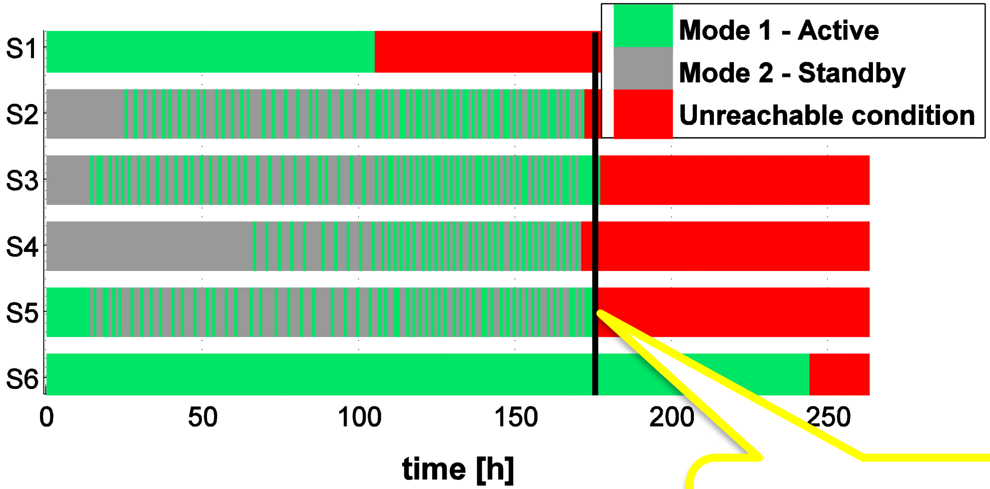


- Weighting matrices
  - $Q = \left(\mathrm{diag}\left(\frac{1}{X_1^{max}}, \dots, \frac{1}{X_6^{max}}\right)\right)^2$
  - $R = B'_{cons} * B_{cons}$, where $B_{cons} = \mathrm{diag}(b_{11}, b_{12}, \dots, b_{62})$

- Nodes characteristics (including harvesting availability) (values from datasheets)

Node	Consum. in mode M_1, $[mWh]$	Consum. in mode M_2, $[mWh]$	Nom. bat. capacity, X_i^{max}, $[mWh]$	Harvesting availability E_i, $[mWh]$	Energy coef. [1]	Harvesting period, per 24 hours
1	36,593	5,846	3885 (type 1)	missing	1	--
2	36,482	6,031	3885 (type 1)	missing	0,8	--
3	34,854	6,105	3885 (type 1)	77,7	0,9	7h-12h
4	36,482	6,301	3515 (type 2)	missing	0,7	--
5	36,556	6,105	3515 (type 2)	99,9	1	13h-18h
6	33,041	5,735	8510 (type 3)	missing	1	--

Simulation results without harvesting



No-de	Consum. in mode M_1, $[mWh]$	Consum. in mode M_2, $[mWh]$	Nom. bat. capacity, X_i^{max}, $[mWh]$	Energy coef. [1]
1	36,593	5,846	3885 (type 1)	1
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3	34,854	6,105	3885 (type 1)	0,9
4	36,482	6,301	3515 (type 2)	0,7
5	36,556	6,105	3515 (type 2)	1
6	33,041	5,735	8510 (type 3)	1

Large number of switches

WSN lifespan = 175 hours

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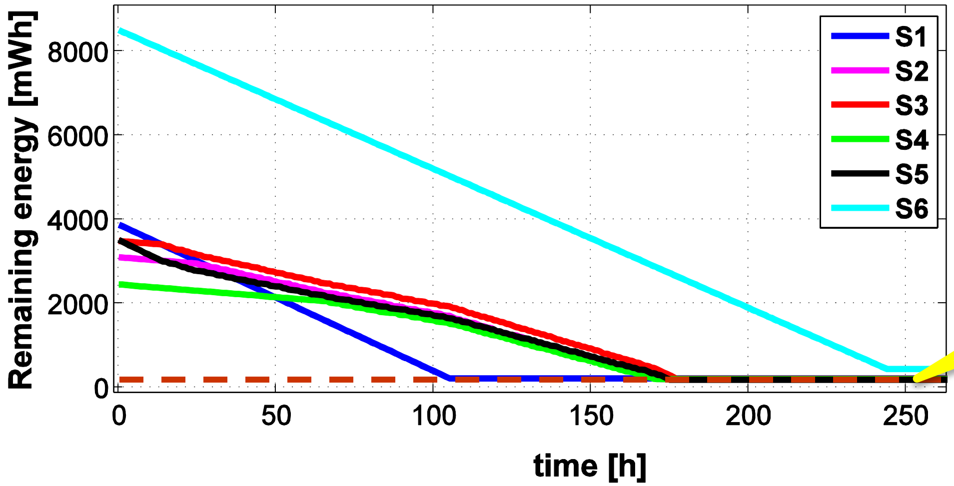
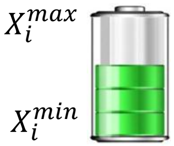
WSN lifespan with basic scheme = 128 hours

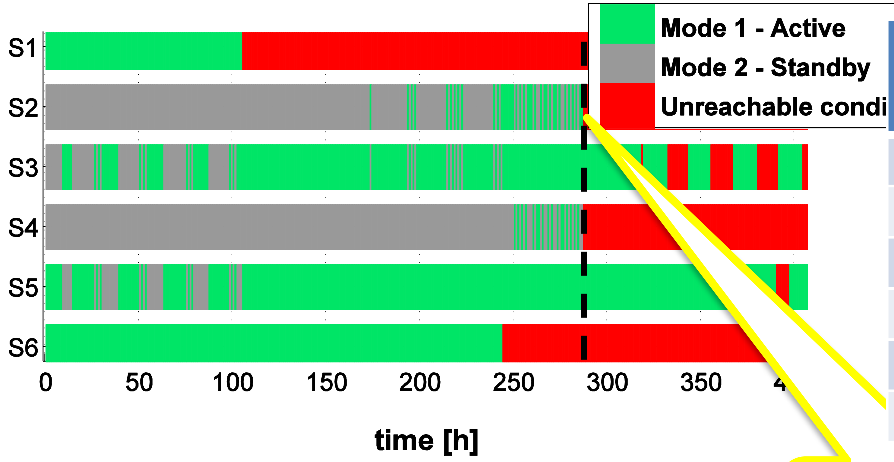


Constraint is fulfilled



$$0 < X_i^{min} \leq x_i \leq X_i^{max}$$

Simulation results with harvesting



No-de	Consum in M_1, $[mWh]$	Consum. in M_2, $[mWh]$	Nom. bat. cap., X_i^{max}, $[mWh]$	Harv. avail. E_i, $[mWh]$	En. coef. [1]	Harv. per., per 24 hours
1	36,593	5,846	3885 (type 1)	missing	1	--
2	36,482	6,031	3885 (type 1)	missing	0,8	--
3	34,854	6,105	3885 (type 1)	77,7	0,9	7h-12h
4	36,482	6,301	3515 (type 2)	missing	0,7	--
5	36,556	6,105	3515 (type 2)	99,9	1	13h-18h
6	33,041	5,735	8510 (type 3)	missing	1	--

Large number of switches

WSN lifespan = 287 hours

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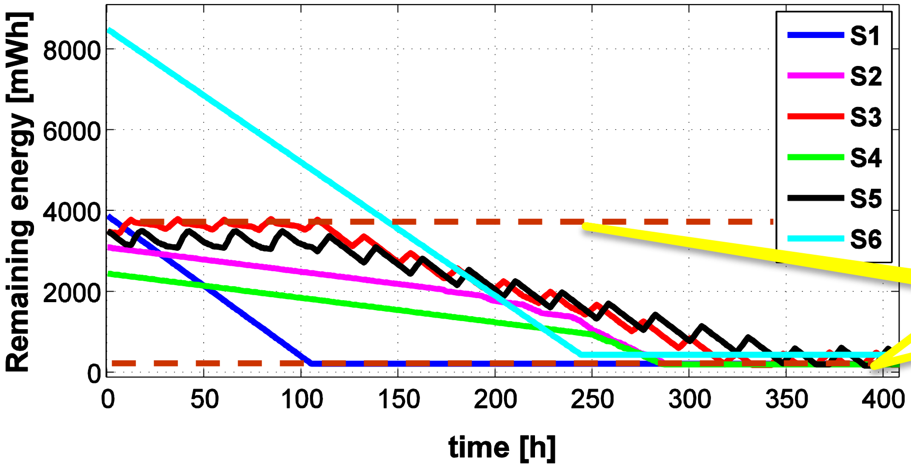
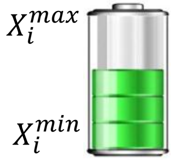
WSN lifespan with basic scheme = 192 hours



Constraint is fulfilled



$$0 < X_i^{min} \le x_i \le X_i^{max}$$

Conclusion on the MPC Approach

☺ **Lifespan increase** up to 27% (without harvesting) and 33% (with harvesting) when **compared to basic scheme**

☺ Constraints respected

☹ Large number of switches

=> Properly take into account the cost of the switches

☹ Problem solved with MIQP

=> Complexity (extra energy consumption)

☺ MILP problem formulation

Hybrid Dynamic System (HDS) approach

=> Naturally introduces jumps between systems of different structures

=> Cost of switches naturally taken into account

Outline

- ○ Context
- ○ Model Predictive Control Approach
- ● Hybrid Dynamic System Approach
- ● Implementation on a Test-Bench and Results
- ● Comparisons of Both Control Strategies
- ● Conclusions

Outline

Context

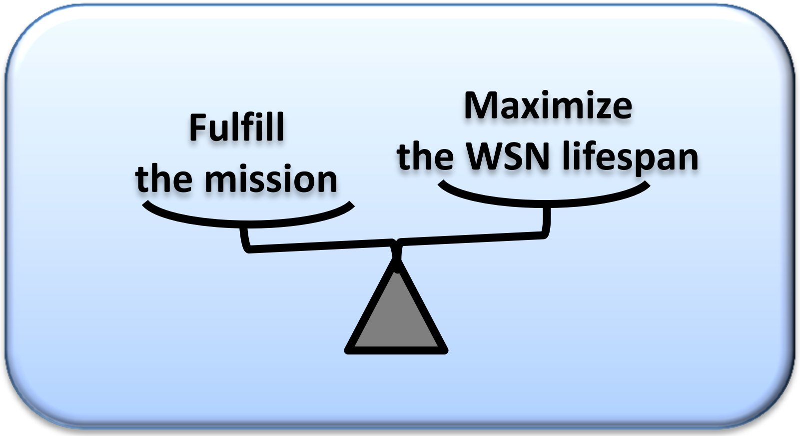
Model Predictive Control Approach

Hybrid Dynamic System Approach

- Control objectives
- WSN: system modeling
- Hybrid Dynamic System (HDS)
  - Control design , scheduling law
  - Benchmark description
  - Simulation results
- Conclusions on the HDS approach

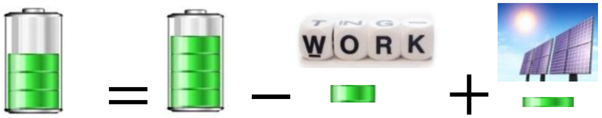
Control objectives

- Same as for the MPC strategy



System modeling (1/2)

- MPC (**discrete time** model)
  - B_i and E_i are the energy (J, Wh)



$$x_i(k+1) = x_i(k) - B_i \cdot u_i(k) + E_i \cdot w_i(k)$$

$y_i(k) = x_i(k)$ (measure)

System modeling (1/2)

- Node i: energy consumption model
  - HDS (**hybrid** model)
    - *Flow* (continuous time) dynamics
    - B_i and E_i : power (W)

$$\begin{cases} \dot{x}_i(t) = -B_i \cdot u_i(t) + E_i \cdot w_i(t) \\ y_i = \alpha_i(t) \cdot x_i(t) \\ \dot{u}_i(t) = \mathbf{0}^m \end{cases}$$

- - - *Jump* dynamics (**2 nodes swap their role**)

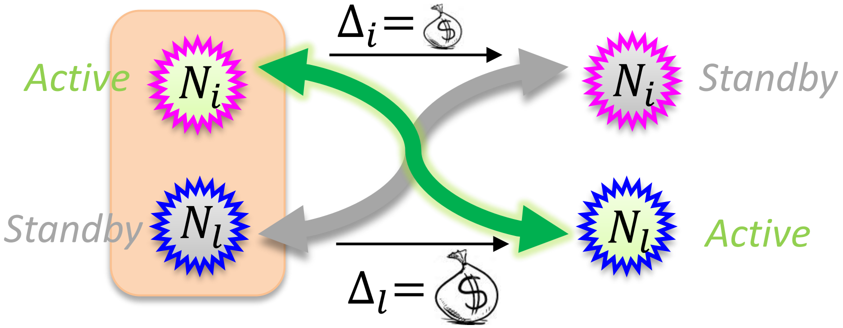
Pairwise jump rule for two nodes i and l

$$\begin{bmatrix} x_i^+ \\ x_l^+ \end{bmatrix} = \begin{bmatrix} x_i - (u_i^+)^T \Delta_i u_i \\ x_l - (u_l^+)^T \Delta_l u_l \end{bmatrix} = g_x^{il}(x,u)$$

$$\begin{bmatrix} u_i^+ \\ u_l^+ \end{bmatrix} = \begin{bmatrix} u_l \\ u_i \end{bmatrix} = g_u^{il}(x,u)$$

With the **switching consumption matrix** Δ_i

$$\Delta_i = \begin{bmatrix} 0 & \cdots & \delta_i^{m\to 1} \\ \vdots & \ddots & \vdots \\ \delta_i^{1\to m} & \cdots & 0 \end{bmatrix}$$



System modeling (2/2)

- HDS
  - *Flow* dynamics

$$\begin{cases} \dot{x}_i(t) = -B_i \cdot u_i(t) + E_i \cdot w_i(t) \\ y_i = \alpha_i(t) \cdot x_i(t) \qquad \text{- measure} \\ \dot{u}_i(t) = \mathbf{0}^m \end{cases}$$

  - *Jump* dynamics

$$\begin{bmatrix} x_i^+ \\ x_l^+ \end{bmatrix} = \begin{bmatrix} x_i - (u_i^+)^T \Delta_i u_i \\ x_l - (u_l^+)^T \Delta_l u_l \end{bmatrix} = g_x^{il}(x,u)$$

$$\begin{bmatrix} u_i^+ \\ u_l^+ \end{bmatrix} = \begin{bmatrix} u_l \\ u_i \end{bmatrix} = g_u^{il}(x,u)$$

- Constraints

1. **Binary control** (at time t) $u_i \in \{0,1\}^m$
2. **Node** work in a **unique mode** at time t
3. **Mission** definition for mode M_h $\sum_{i=1}^{n} u_i^T e_h = d_h$
4. **Bounded capacity** of the battery $0 < X_i^{min} \leq x_i \leq X_i^{max}$

Compute $u_i(t)$ such that lifespan maximized

Lifespan: $\max \sum_{all\ nodes} \frac{x_i + \enclose{circle}{E_i w_i} - X_i^{min}}{B_i u_i}$

System modeling (2/2)

- HDS
  - *Flow* dynamics

$$\begin{cases} \dot{x}_i(t) = -B_i \cdot u_i(t) + E_i \cdot w_i(t) \\ y_i = \alpha_i(t) \cdot x_i(t) \qquad \text{- measure} \\ \dot{u}_i(t) = \mathbf{0}^m \end{cases}$$

  - *Jump* dynamics

$$\begin{bmatrix} x_i^+ \\ x_l^+ \end{bmatrix} = \begin{bmatrix} x_i - (u_i^+)^T \Delta_i u_i \\ x_l - (u_l^+)^T \Delta_l u_l \end{bmatrix} = g_x^{il}(x,u)$$

$$\begin{bmatrix} u_i^+ \\ u_l^+ \end{bmatrix} = \begin{bmatrix} u_l \\ u_i \end{bmatrix} = g_u^{il}(x,u)$$

- Constraints

1. **Binary control** (at time t) $u_i \in \{0,1\}^m$
2. **Node** work in a **unique mode** at time t
3. **Mission** definition for mode M_h $\sum_{i=1}^{n} u_i^T e_h = d_h$
4. **Bounded capacity** of the battery $0 < X_i^{min} \leq x_i \leq X_i^{max}$

Compute $u_i(t)$ such that lifespan maximized

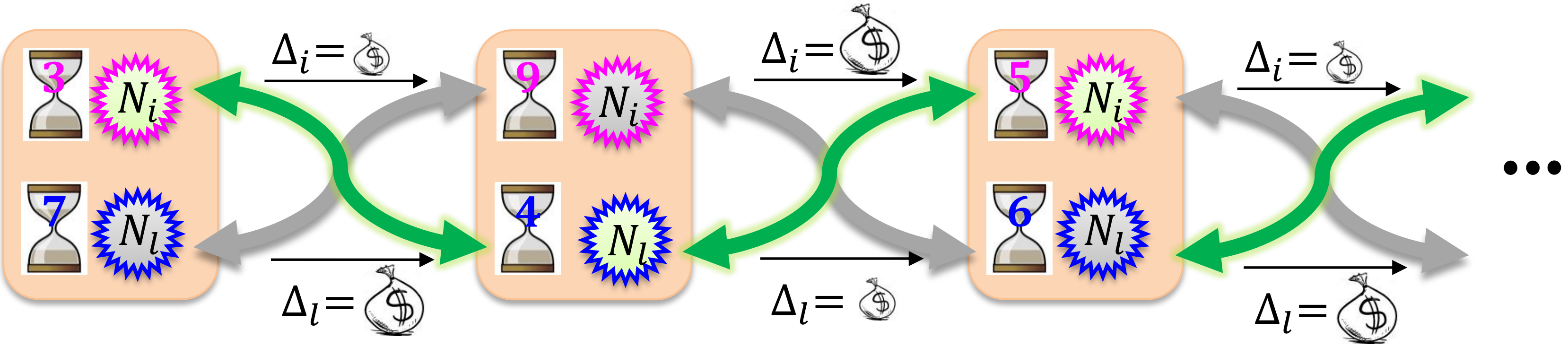
Lifespan: $$\max \sum_{all\ nodes} \frac{y_i - X_i^{min}}{B_i u_i}$$

Design of the scheduling law

- Compute $u_i(k)$ => when do nodes i and l need to swap their role?
  - Lifespan of the solution (WSN lifespan) expressed by a cost function

$$J_{il}(\boldsymbol{x},\boldsymbol{u}) \coloneqq \min_{k=i,l;k:u_k\neq\mathbf{0}^m} \frac{y_k - X_k^{min}}{B_k u_k}$$

  - First condition to jump (or swap role)
    - Lifespan of the solution is larger after the swap



Design of the scheduling law

- Compute $u_i(k)$ => when do nodes i and l need to swap their role?
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$$J_{il}(\boldsymbol{x},\boldsymbol{u}) := \min_{k=i,l;k:u_k\neq \mathbf{0}^m} \frac{y_k - X_k^{min}}{B_k u_k}$$

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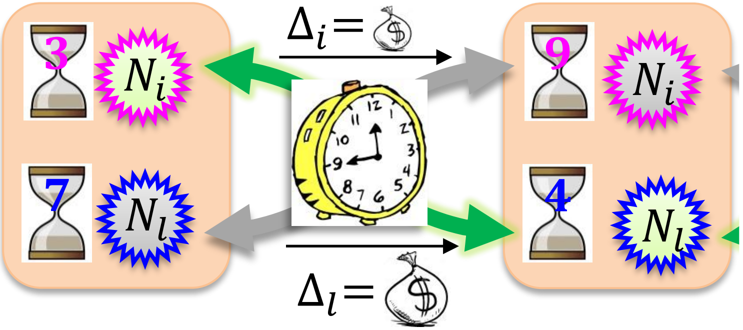

  - Second condition to jump
    - Time of the switch

Design of the scheduling law

- Compute $u_i(k)$ => when do nodes i and l need to swap their role?
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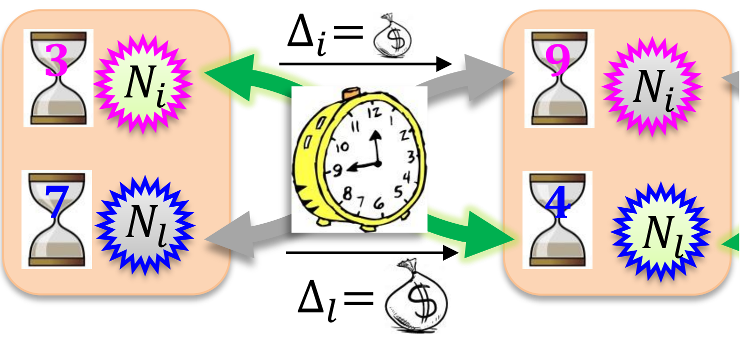
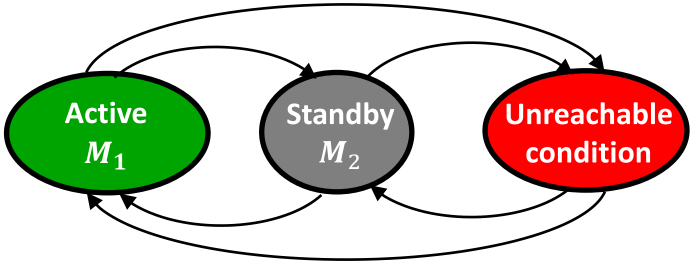


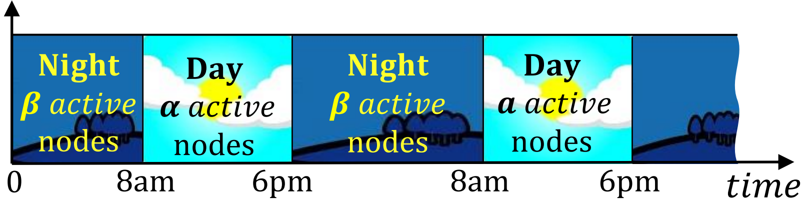
  - Second condition to jump
    - Time of the switch

Benchmark description

- Same benchmark as for MPC
  - 6 sensor nodes
  - 3 states:
    - 2 functioning modes
    - Unreachable condition



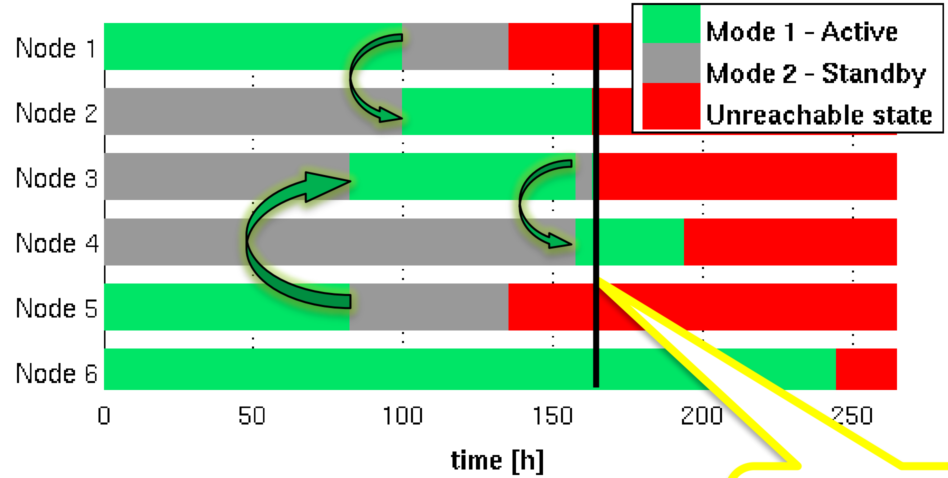
- **Mission** : 3 *active* nodes (in mode M_1)
  - $\alpha = \beta = 3$



- Nodes characteristics (including harvesting availability)

Node	Consum. in mode M_1, $[mW]$	Consum. in mode M_2, $[mW]$	Nom. bat. capacity, X_i^{max}, $[mWh]$	Harvesting availability E_i , $[mW]$	Energy coef. [1]	Harvesting period, per 24 hours
1	36,593	5,846	3885 (type 1)	missing	1	--
2	36,482	6,031	3885 (type 1)	missing	0,8	--
3	34,854	6,105	3885 (type 1)	77,7	0,9	7h-12h
4	36,482	6,301	3515 (type 2)	missing	0,7	--
5	36,556	6,105	3515 (type 2)	99,9	1	13h-18h
6	33,041	5,735	8510 (type 3)	missing	1	--

Simulation results without harvesting



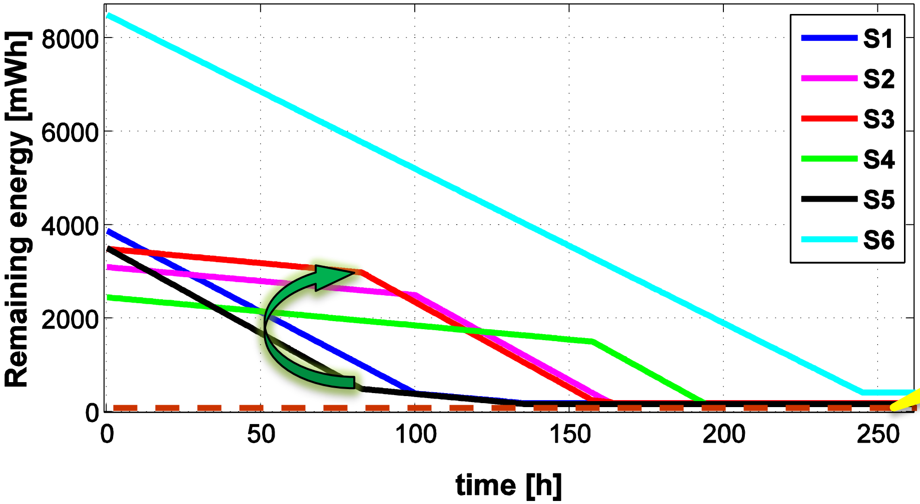
No-de	Consum. in mode M_1, $[mW]$	Consum. in mode M_2, $[mW]$	Nom. bat. capacity, X_i^{max}, $[mW]$	Energy coef. [1]
1	36,593	5,846	3885 (type 1)	1
2	36,482	6,031	3885 (type 1)	0,8
3	34,854	6,105	3885 (type 1)	0,9
4	36,482	6,301	3515 (type 2)	0,7
5	36,556	6,105	3515 (type 2)	1
6	33,041	5,735	8510 (type 3)	1

Number of switches is very small

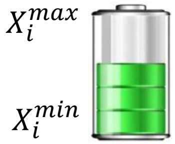
WSN lifespan = 164 hours

\>

WSN lifespan with basic scheme = 128 hours

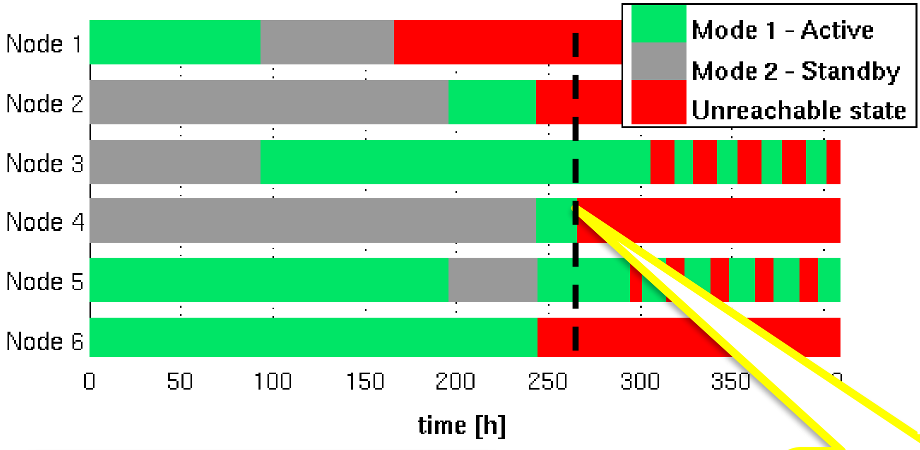


Constraint is respected



$$0 < X_i^{min} \le x_i \le X_i^{max}$$

Simulation results with harvesting



No -de	Consum. in M_1, $[mW]$	Consum. in M_2, $[mW]$	Nom. bat. cap., X_i^{max}, $[mWh]$	Harv. avail. E_i, $[mW]$	En. coef. [1]	Harv. per., per 24 hours
1	36,593	5,846	3885 (type 1)	missing	1	--
2	36,482	6,031	3885 (type 1)	missing	0,8	--
3	34,854	6,105	3885 (type 1)	77,7	0,9	7h-12h
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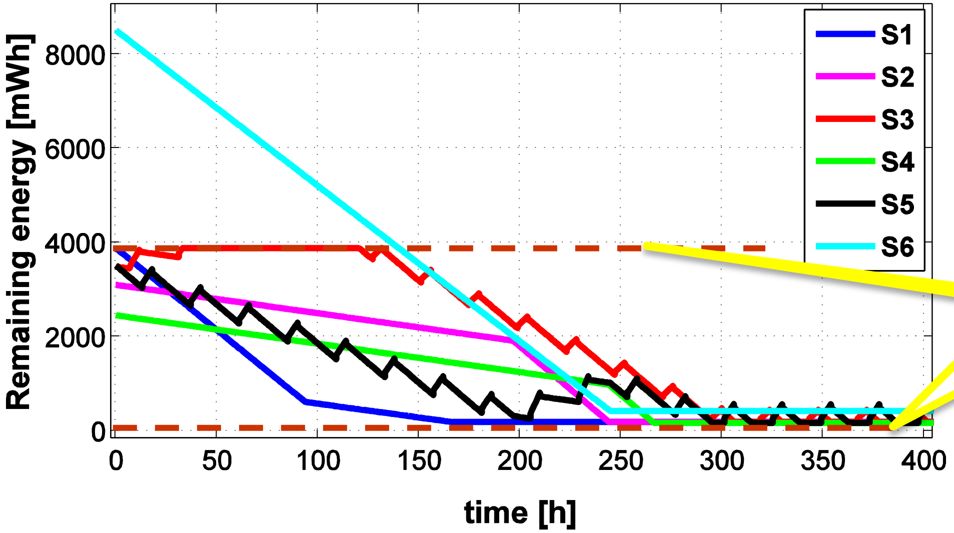
5	36,556	6,105	3515 (type 2)	99,9	1	13h-18h
6	33,041	5,735	8510 (type 3)	missing	1	--

Number of switches is very small

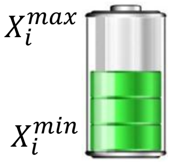
WSN lifespan = 266 hours

\>

WSN lifespan with basic scheme = 192 hours



Constraint is respected



$$0 < X_i^{min} \le x_i \le X_i^{max}$$

Conclusion on the HDS approach

- ☺ **Lifespan increase** up to 22% (without harvesting) and 28% (with harvesting) when **compared to basic scheme**
- ☺ **Constraints** respected
- ☺ Very small number of switches
- ☺ Take into account the **cost of the switches**
  - => Promising solution

- 😐 Lifespan decrease up to 7% when compared to MPC strategy
  - => Switching cost

Outline

- Context
- Model Predictive Control Approach
- Hybrid Dynamic System Approach
- Implementation on a Test-Bench and Results
- Comparisons of Both Control Strategies
- Conclusions

Outline

Context

Model Predictive Control Approach

Hybrid Dynamic System Approach

Implementation on a Test-Bench and Results

- ○ Test-bench description
- ○ Experimental results for the MPC strategy
- ○ Experimental results for the HDS strategy
- ○ Conclusion of the section

Test-bench description (1/3)

- Benchmark
  - Platform **OpenPicus** (FLYPORT Wi-Fi 802.11G with 16 Bit Processor PIC24FJ256) [1]
  - Temperature & humidity sensors (Aosong DHT11) [2]
  - Li-polymer rechargeable batteries [3]
  - Router Wi-Fi
  - Without harvesting systems
- Deployed in an “open-space” office
  - More information than required at the application level of the WSN

[1] http://www.openpicus.com/
[2] http://www.aosong.com/en/products/details.asp?id=109
[3] www.farnell.com/datasheets/1666650.pdf and 1666648.pdf

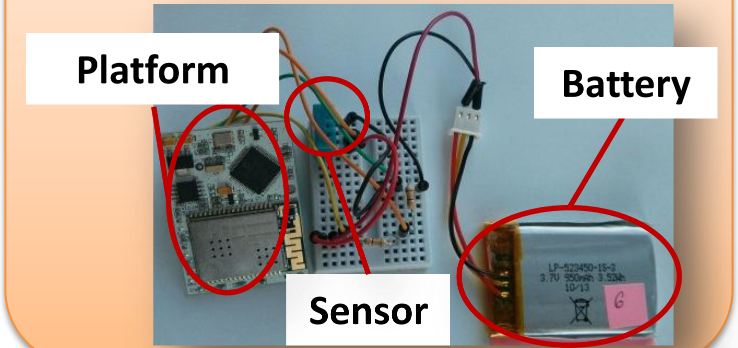
Test-bench description (2/3)

- Deployed in the open-space office

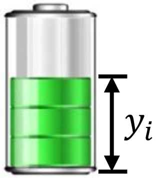
Control algorithm written in Python

Middleware LINC:
- Node synchronization
- Data management

Sensor node



Measurement of
the remaining energy y_i ?
Estimation !

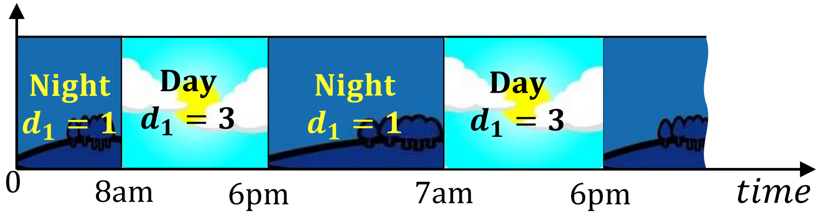


Test-bench description (3/3)

- Characteristics of nodes (from datasheet and lab. measurements)

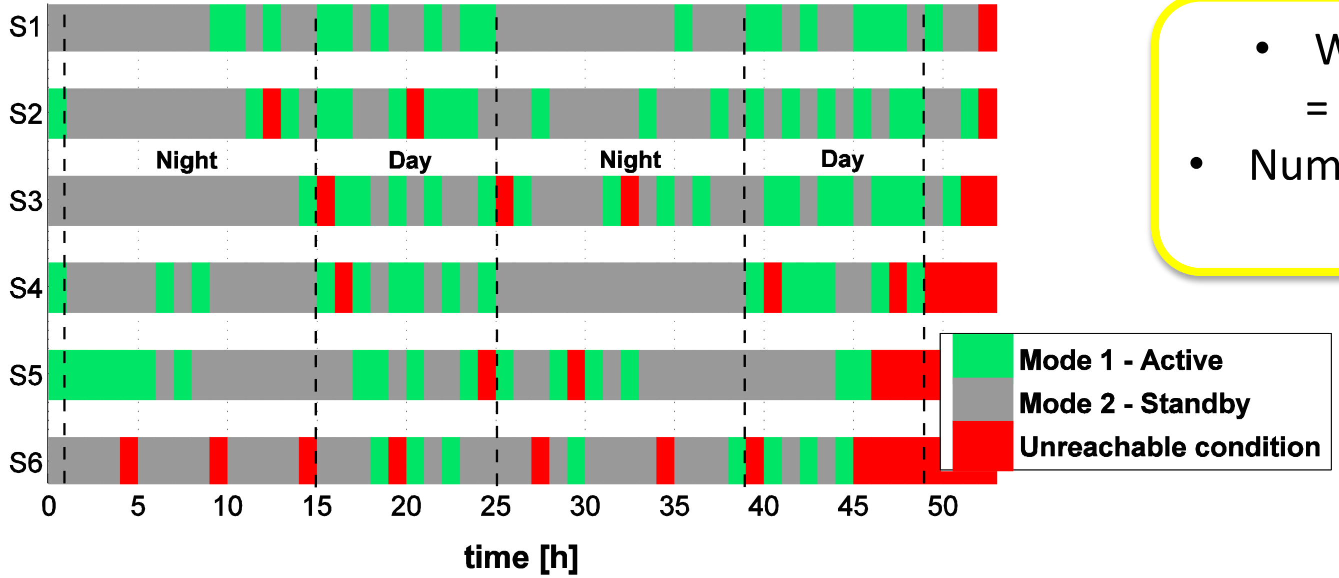
No-de	Consum. in mode M_1, $[mWh]$	Consum. in mode M_2, $[mWh]$	Nom. bat. capacity, X_i^{max}, $[mWh]$
1	36,593	5,846	3885 (type 1)
2	36,482	6,031	3885 (type 1)
3	34,854	6,105	3885 (type 1)
4	36,482	6,301	3515 (type 2)
5	36,556	6,105	3515 (type 2)
6	33,041	5,735	3515 (type 2)

- **Dynamic Mission** : 3 (or 1) *active* nodes (in mode M_1)

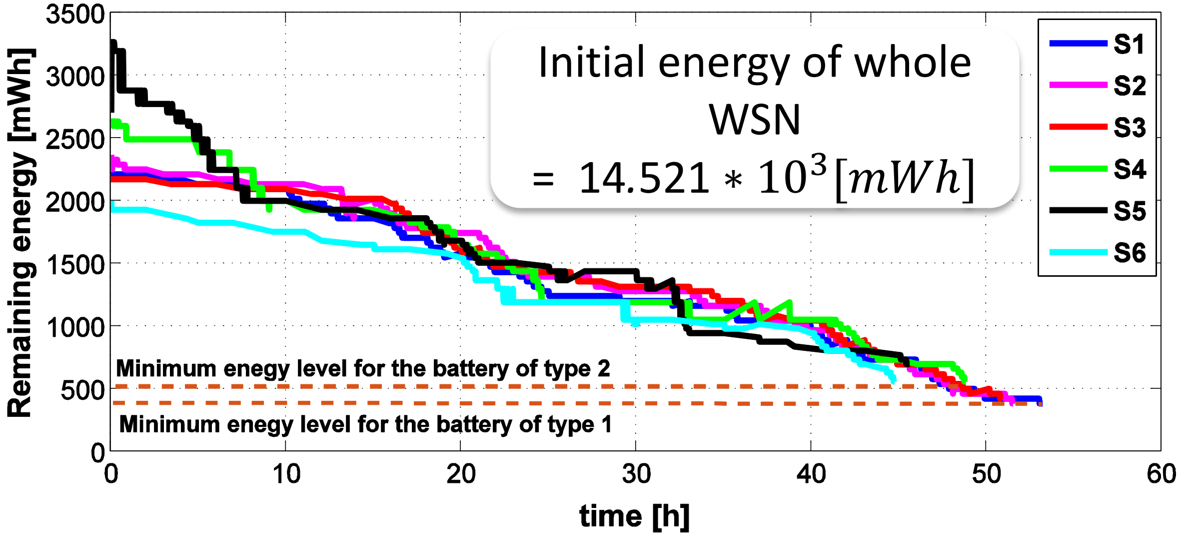


- Experiments start 5 p.m.
- Radio environment not under control

Experimental results for the MPC strategy

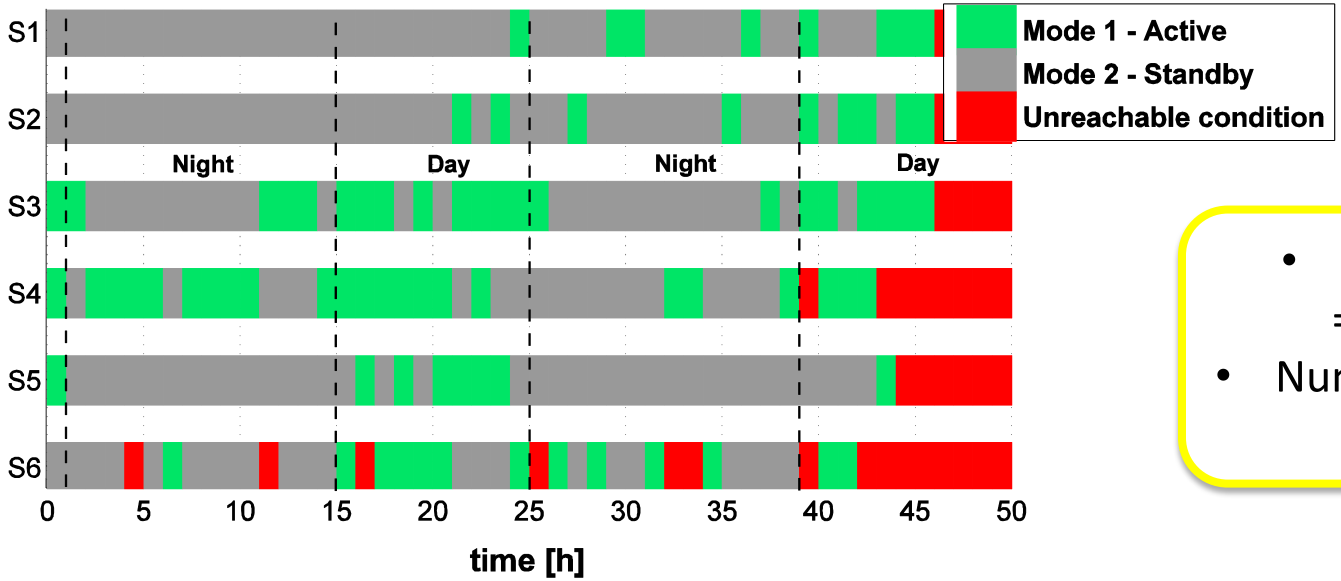


- WSN lifespan = 53 hours
- Number of switches ≈ 100

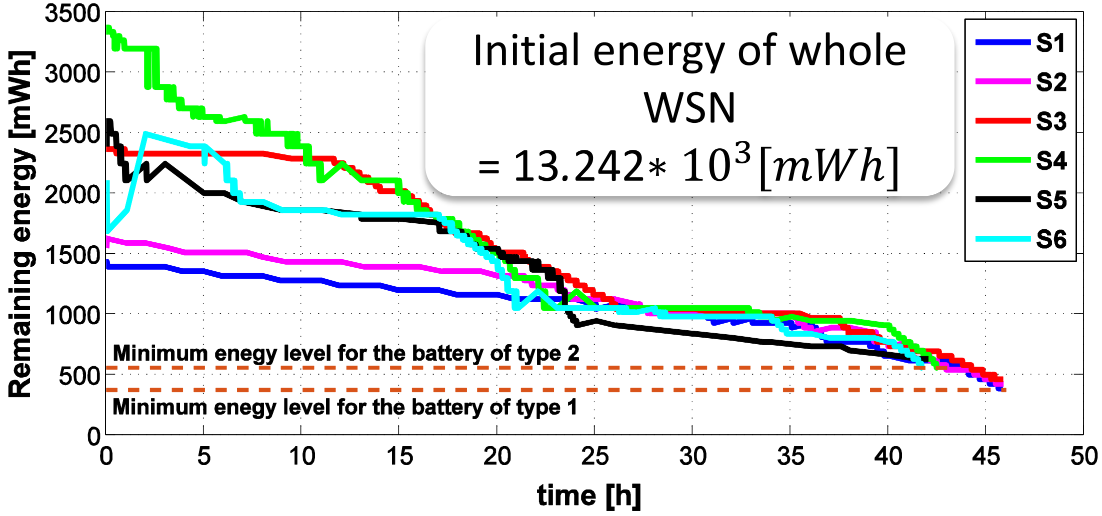


Initial energy of whole WSN = $14.521 * 10^3 [mWh]$

Experimental results for the HDS strategy



- WSN lifespan = 46 hours
- Number of switches ≈ 60



Initial energy of whole WSN $= 13.242 * 10^3 [mWh]$

Conclusion of the section

☺ Control strategies are validated on a real-life test-bench
=> Mission is fulfilled

😐 Number of switches is similar

😐 Different radio environment for both experiments

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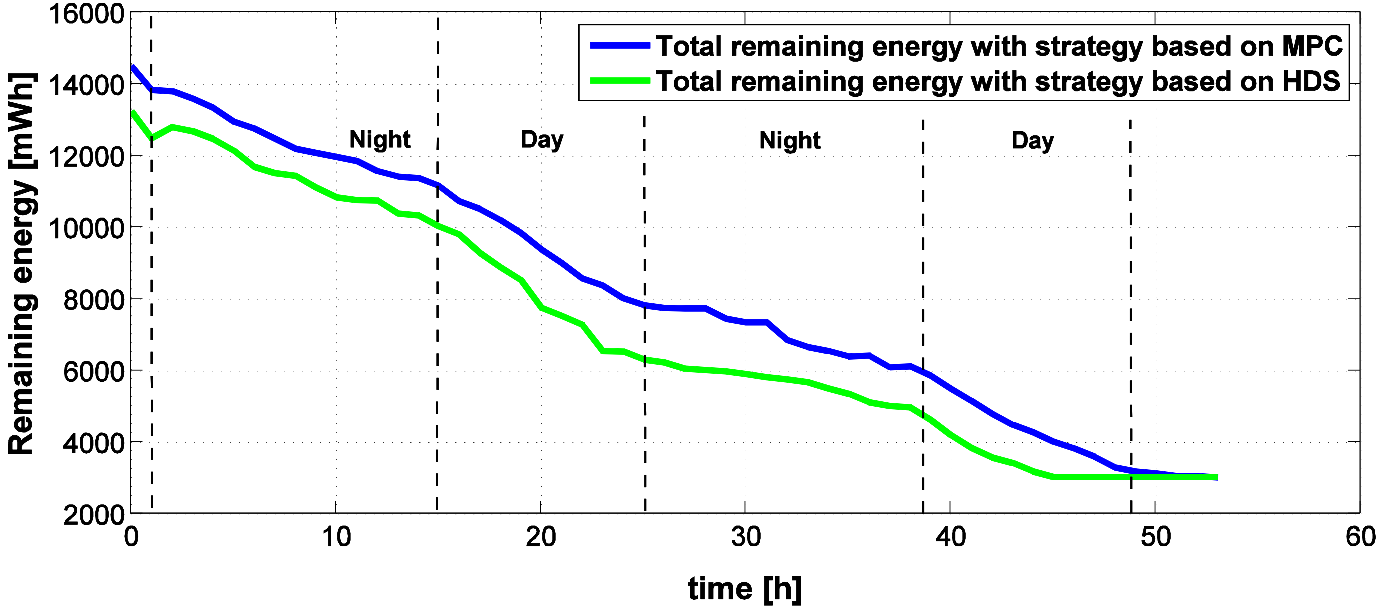
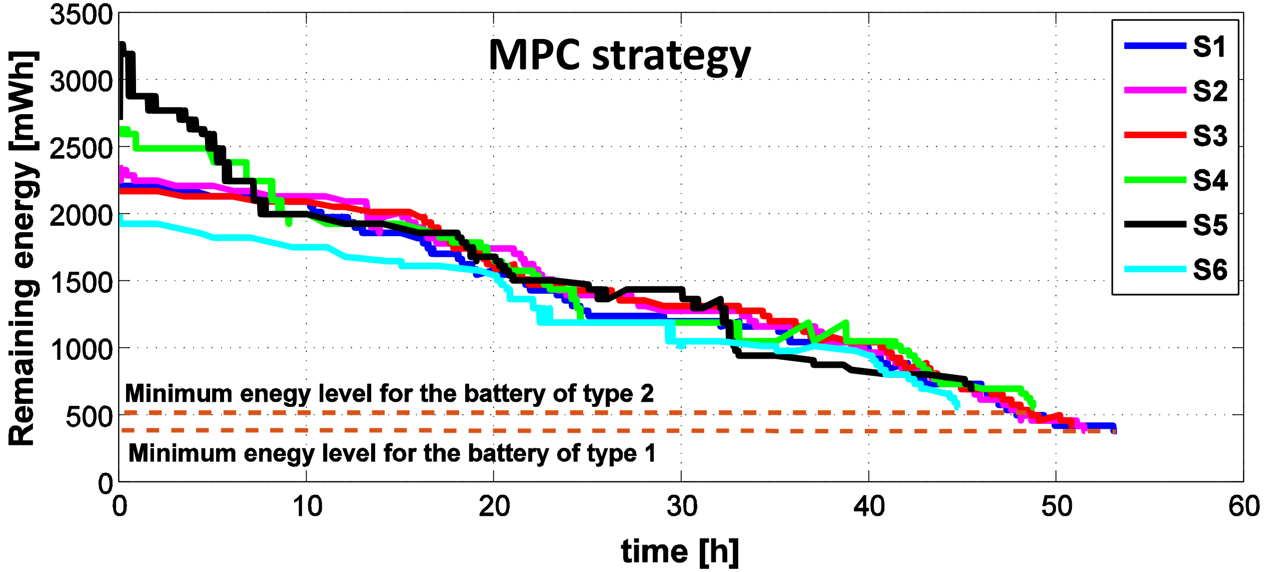
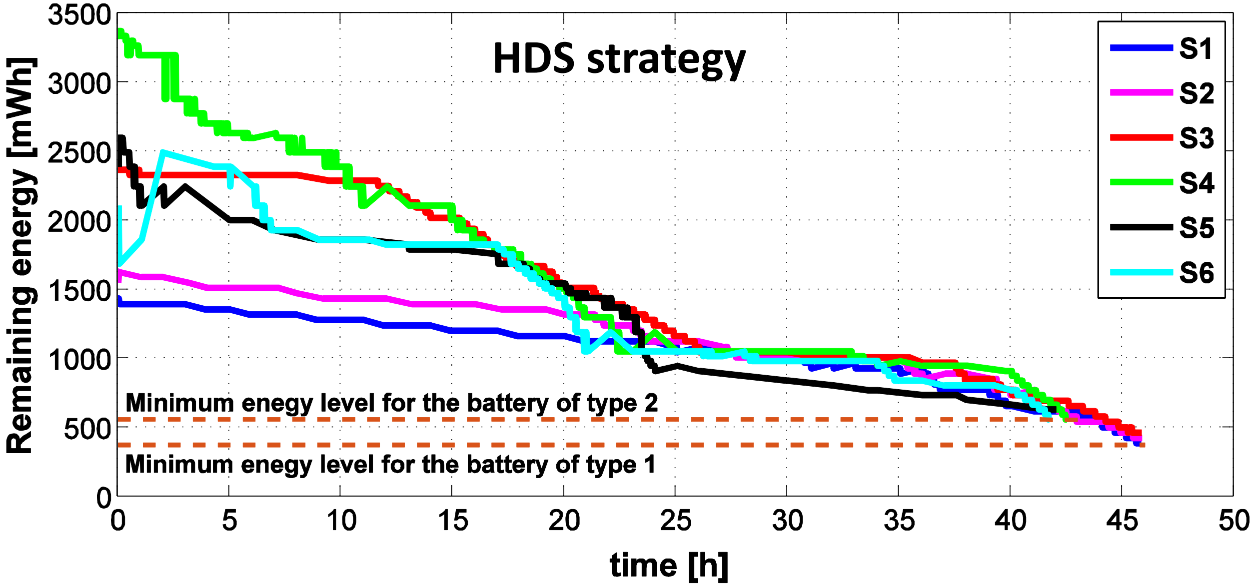
Comparisons of Both Control Strategies

Strategy	WSN lifespan, [hours]	Initial energy in the whole WSN, [mWh]	Final energy in the whole WSN, [mWh]
MPC	**53** (100%)	$14.521 * 10^3$ (100%)	$3.032 * 10^3$
HDS	**46** (86,8%)	$13.242 * 10^3$ (91,2%)	$3.039 * 10^3$



Remaining energy evolution





Outline

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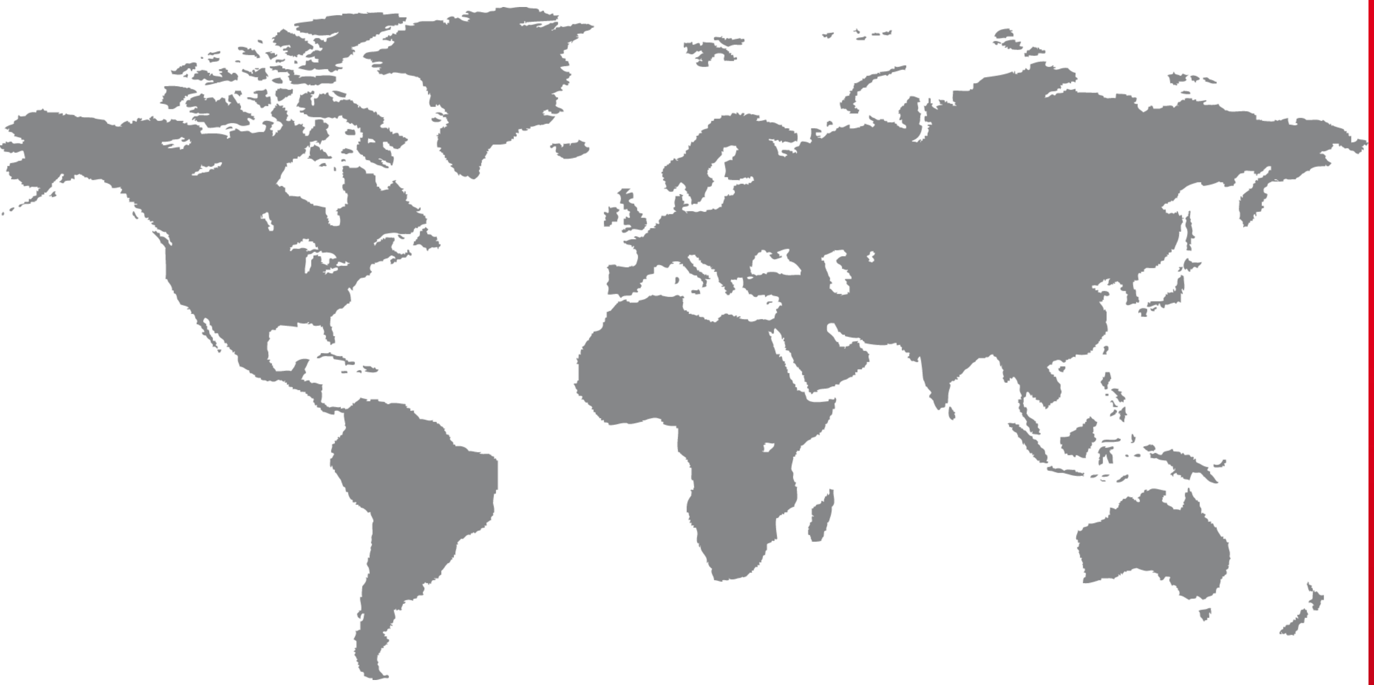
Conclusions

- Control strategies for WSN energy management are proposed (via MPC and HDS)
  - WSN lifespan **extended by >20%** when compared to basic scheme

- Implementation on a real test-bench is performed
  - Validation of the control strategies
  - More experiments to be done



Thank you

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