Workshop on Micro and Smart Grids, Champs-sur-Marne, France

Electric vehicle charging games

Samson Lasaulce
Joint work with O. Beaude, M. Hennebel, and I. Mohand-Kaci
L2S & Chaire RTE CentraleSupélec
lasaulce@lss.supelec.fr

October 6, 2017

Introduction

Some results

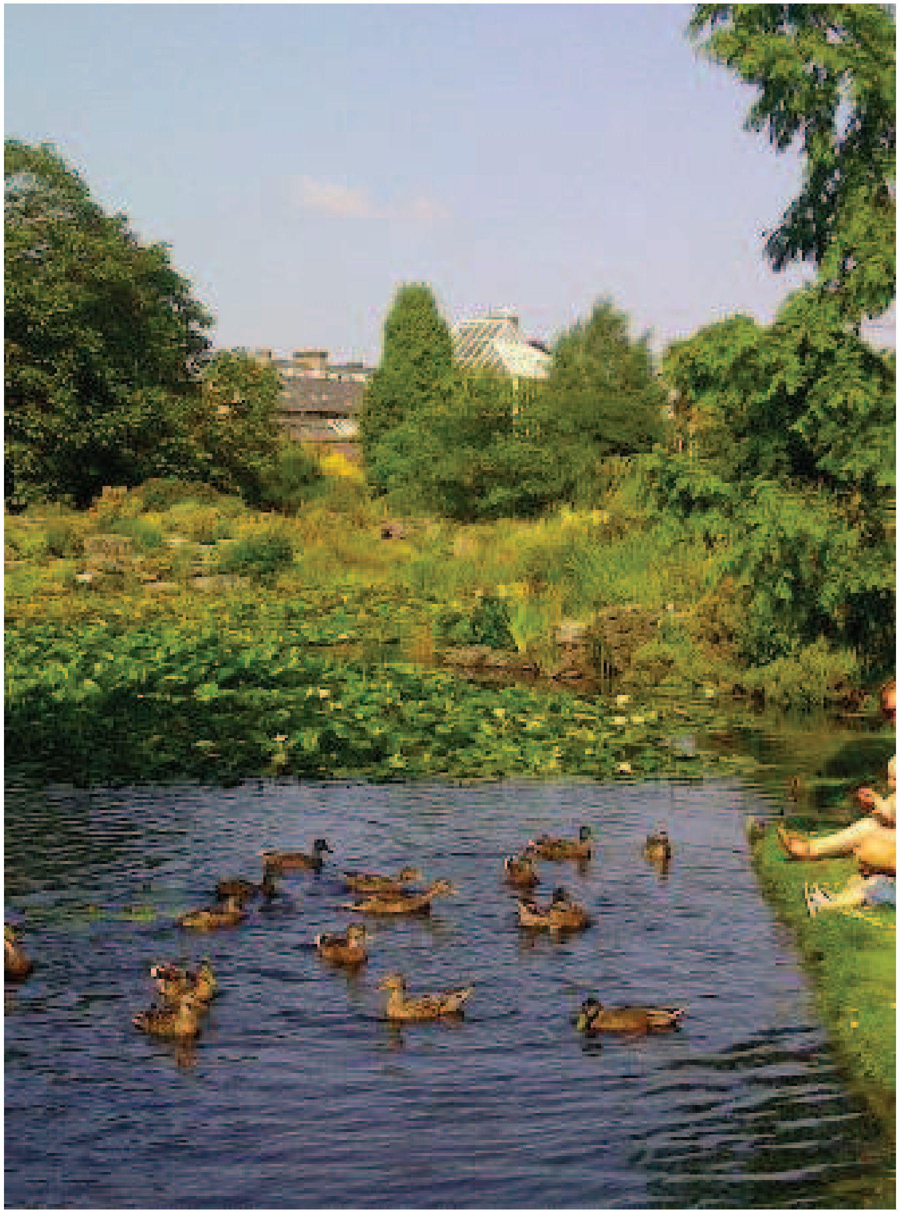
- Charging games $\rightarrow$ congestion games structure

- Equilibrium analysis

- Design of charging algorithms that are distributed, efficient, robust, ...

Main references: [Beaude et al Netgcoop 2012][Beaude et al Netgcoop 2014][Beaude et al ECC 2015][Beaude et al Trans. on Smart Grid 2016]

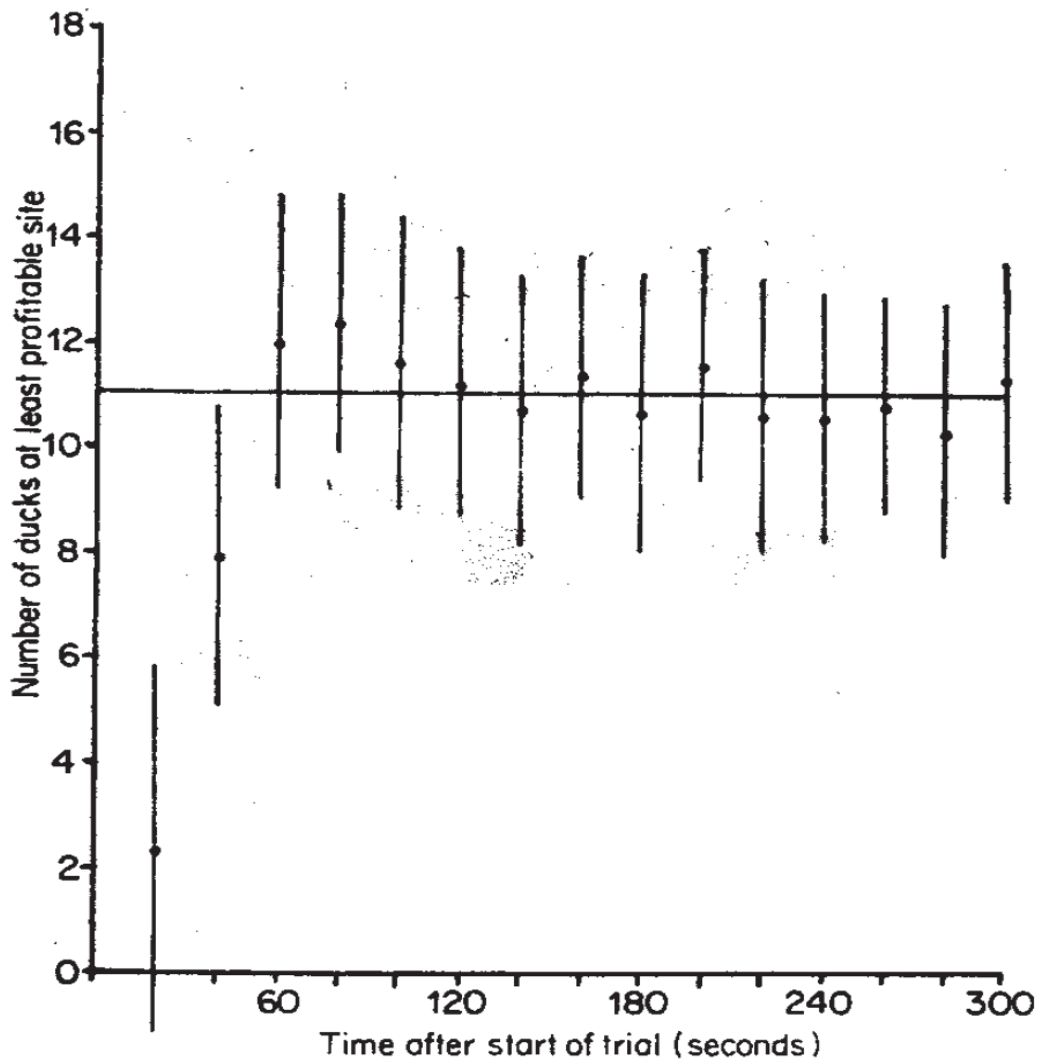
Cambridge University, UK, winter 1979



Data

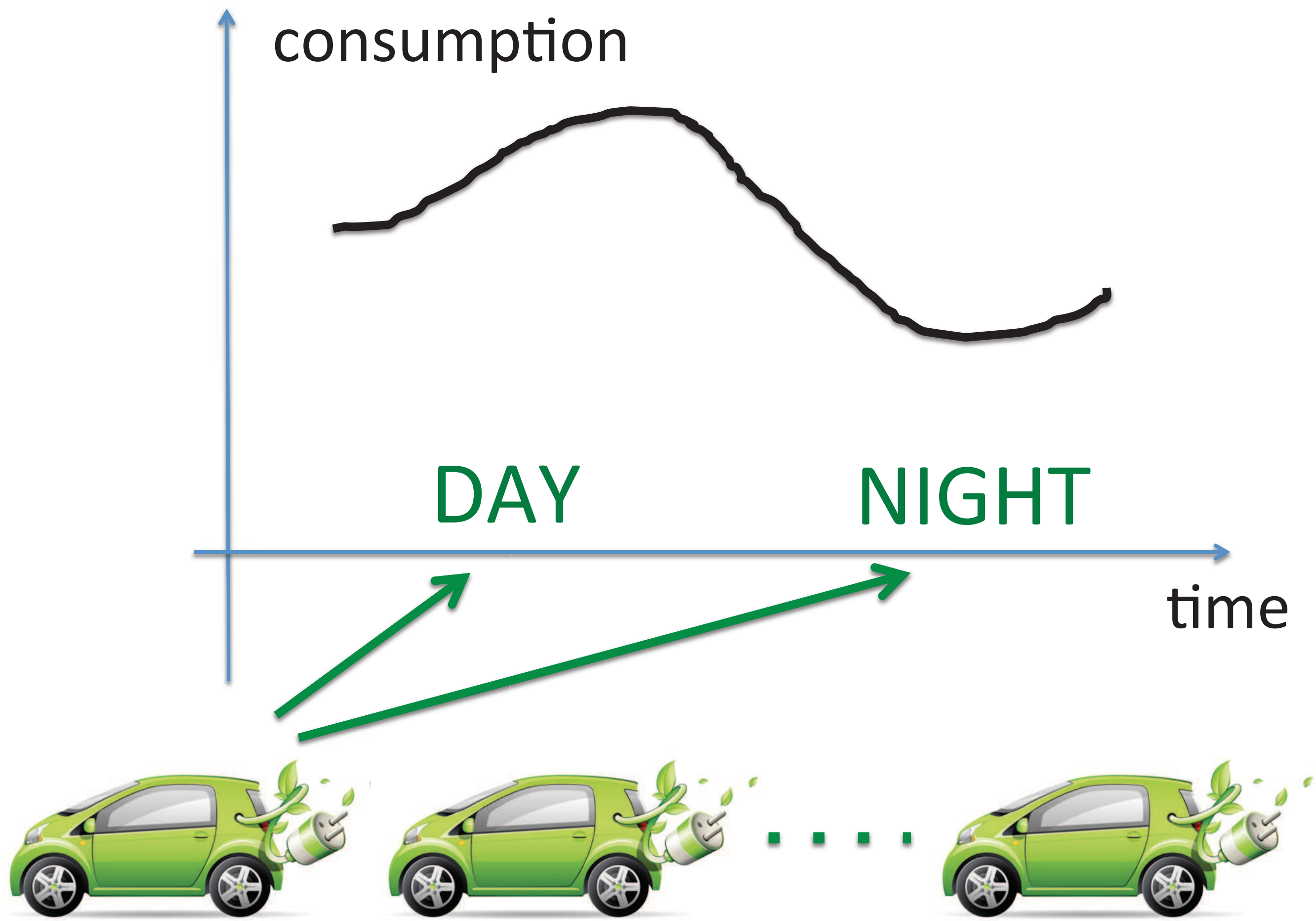
- 33 ducks
- Two observers/sites 20 m apart
- Site 1: 12 items/min
- Site 2: 24 items/min

Observations ⋆⋆⋆



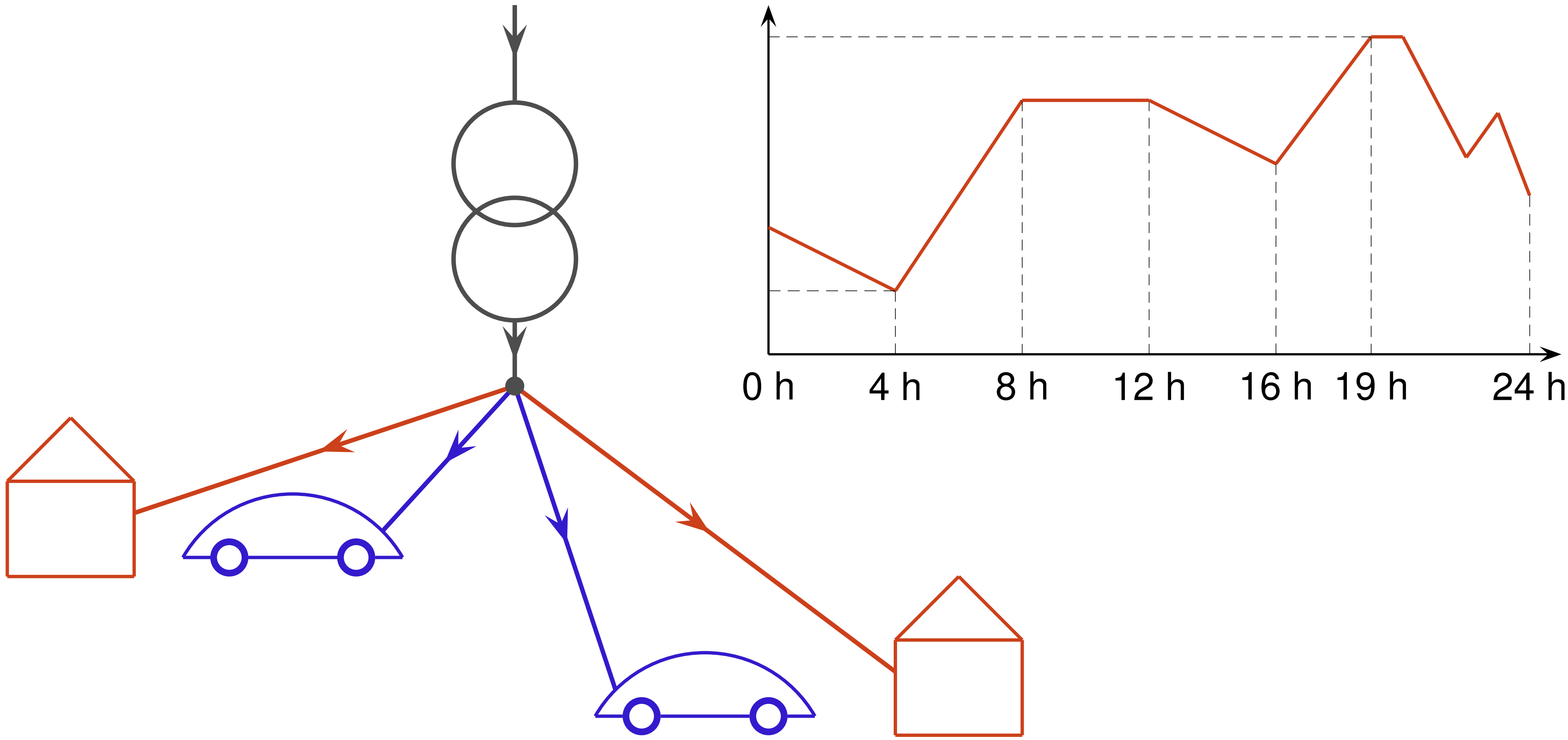
D. G. Harper, "Competitive foraging in mallards: Ideal free ducks", *Anim. Behav.*, 1982, 30, 575-585.

Ducks → vehicles

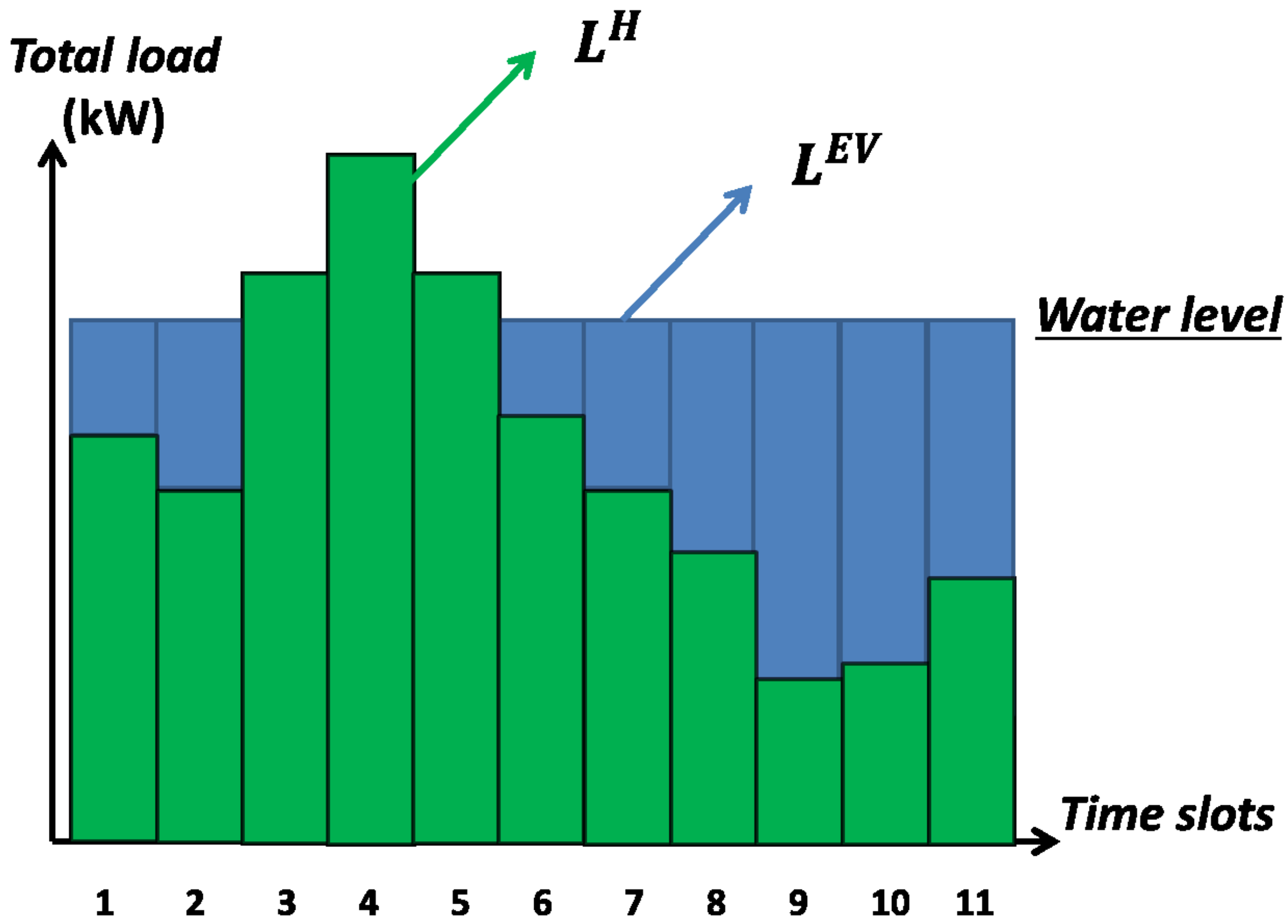


Problem statement

The charging problem in a nutshell



A well-known state-of-the art scheme: water-filling



[Shinwari et al Trans. on SG 2012][Gan et al Trans. on PS 2013]

Main drawbacks of state-of-the art charging schemes

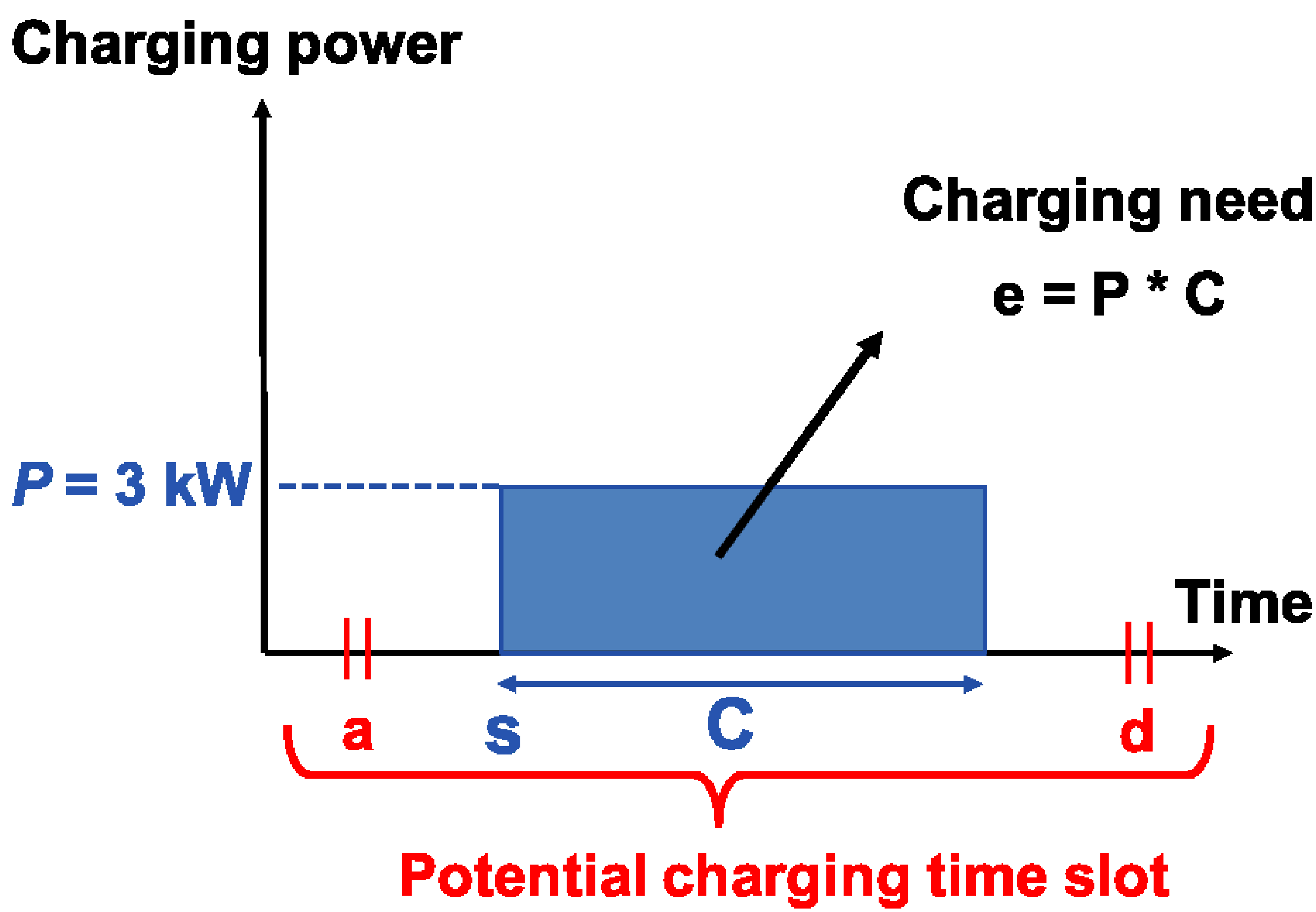
- ► Not tailored to a given utility/payoff or cost function (transformer lifetime, Joule losses, recharging monetary cost, ...)

- ► Typically not globally efficient

- ► Lack of robustness to imperfect forecast

Static game formulation of the problem

Rectangular charging profiles are assumed



[Beaude et al Trans. on SG 2016]

Motivations for rectangular profiles

- Used in reality (e.g., by Renault)
- Delay is minimized
- EV battery aging is managed

About finding the start time instants jointly and exhaustively

- Charging start instants (actions) for EV $i \in \{1, ..., I\}$ (players): $s_i \in \mathcal{S}_i = \{1, ..., T\}$

- Vector of charging start instants: $s = (s_1, ..., s_I)$

Example. $T = 48, I = 10 \to T^I \sim 10^{18}$

Motivations for distributed optimization

- **Complexity.** Single decision-making entity: $O(T^I) \to O(I \times T)$

- **Partial control.** Decision-makers = EVs: only s_i is controlled by EV i

Payoff functions

$$u_i(s_1, ..., s_I) = f_i \left[g_i^{\mathrm{DN}}(s) + g_i^{\mathrm{EV}}(s_i) \right]$$

NB: DN (distribution network); EV (electric vehicle)

About the payoff functions

- Distribution network component = transformer aging + distribution Joule losses

- EV component = charging monetary cost

Solving the problem

Proposed distributed charging algorithm [Beaude et al Trans. on SG 2016]

Algorithm 1: The proposed distributed EV charging algorithm.

Initialize the round index as $m = 0$. *Initialize the vector of charging start times as* $\mathbf{s}^{(0)}$.

while $\|\mathbf{s}^{(m)} - \mathbf{s}^{(m-1)}\| > \delta$ *or* $m \leq M$ **do**

__Outer loop__. Iterate on the round robin phase index: $m = m + 1$. *Set* $i = 0$.

__Inner loop__. Iterate on the DM index: $i = i + 1$. *Do:*

$$s_i^{(m)} \in \arg\max_{s_i \in \mathcal{S}_i} u_i(s_1^{(m)}, s_2^{(m)}, ..., s_i, s_{i+1}^{(m-1)}, ..., s_I^{(m-1)}) \qquad (11)$$

where $s_i^{(m)}(i)$ stands for action of DM i in the round robin phase m. Stop when $i = I$ and go to **Outer loop**.

end

Main issues and solutions

- ○ Does it converge?
- ○ What are the convergence point(s)?
- ► Congestion game structure
- ► Nash points (existence, uniqueness, efficiency)

Sufficient conditions for convergence

Exact potentiality [Monderer Shapley 1996]
$\exists \Phi, \forall i, \forall s, \forall s'_i :$

$$u_i(s) - u_i(s'_i, s_{-i}) = \Phi(s) - \Phi(s'_i, s_{-i})$$

Ordinal potentiality

$$u_i(s) - u_i(s'_i, s_{-i}) \geq 0 \Leftrightarrow \Phi(s) - \Phi(s'_i, s_{-i}) \geq 0$$

Potentiality $\leftrightarrow$ payoff structure

Total load at time $t \in \{1, ..., T\}$:

$$\ell_t(s) = \ell_t^{\mathrm{exo}} + \ell_t^{\mathrm{EV}}(s)$$

- Distribution network component:

$$g_i^{\mathrm{DN}}(s) = \sum_{t \in \{s_i, ..., s_i + C_i - 1\}} A_t\left(\ell_1(s), ..., \ell_t(s)\right) + J\left(\ell_t(s)\right)$$

- EV component: $g_i^{\mathrm{EV}}(s_i) = \sum_{t=s_i}^{s_i + C_i - 1} \pi_{i,t}$

Nash point definition

- For $I = 2$

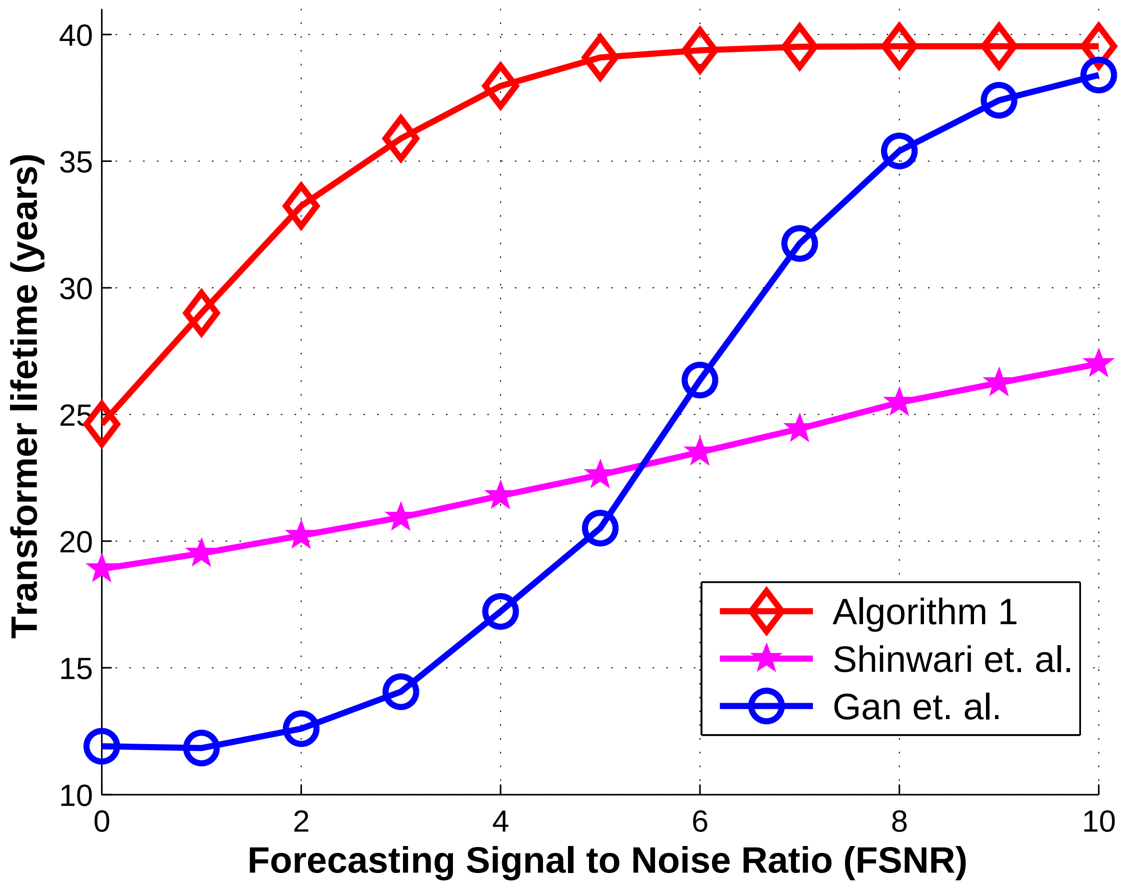
$$\begin{cases} u_1(s_1^\star, s_2^\star) \geq u_1(s_1, s_2^\star) \\ u_2(s_1^\star, s_2^\star) \geq u_2(s_1^\star, s_2) \end{cases}$$

- For $I \geq 2$

$$\forall i, \;\; u_i(s_i^\star, s_{-i}^\star) \geq u_i(s_i, s_{-i}^\star)$$

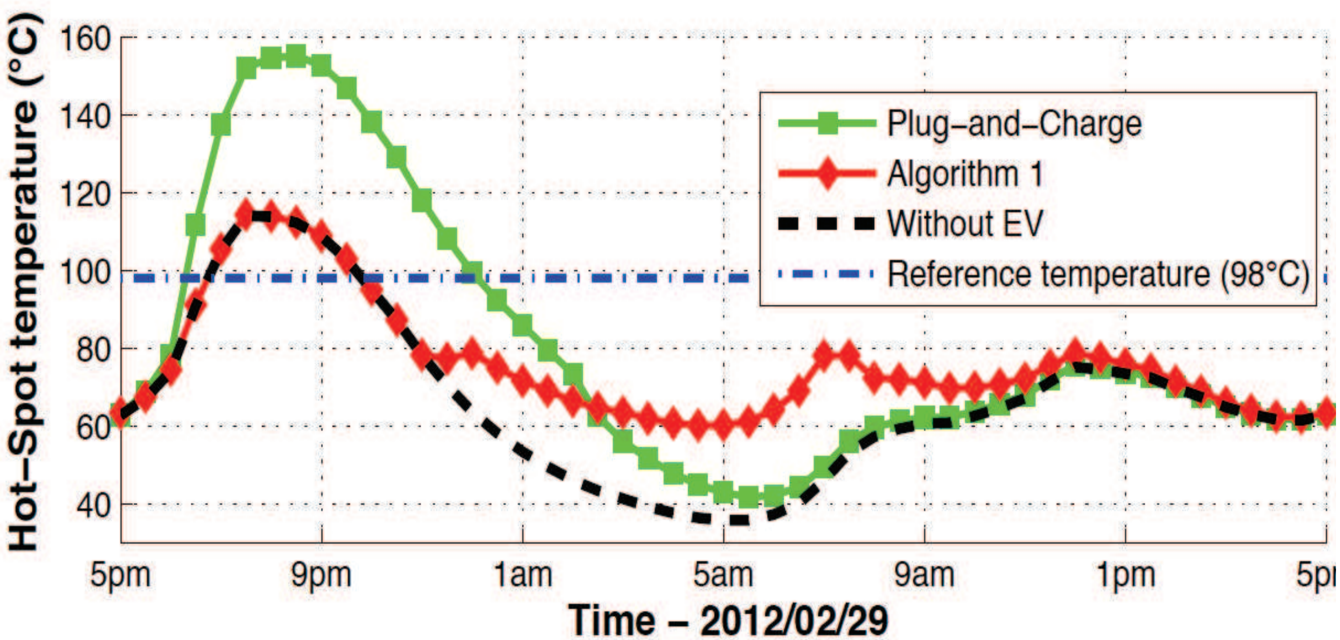
Numerical results

Influence of forecasting errors



[Beaude et al TSG 2015] ⋆

Observing the hot-spot temperature



Fireworks

At least two motivations for moving to a dynamical game formulation

- Maximal temperature

- More efficiency: binary charging power $\rightarrow$ continuous charging power

Dynamical game formulation of the problem

Optimal control formulation

$$\forall t, \qquad x_t \leq x_{\max}$$

Optimal control formulation

$$\forall t \qquad x_t = a x_{t-1} + b_1 \times \left(\ell_t^{\text{exo}} + \sum_{i=1}^{I} v_{i,t} \right)^2$$

$$+ b_2 \times \left(\ell_{t-1}^{\text{exo}} + \sum_{i=1}^{I} v_{i,t-1} \right)^2 + c_t$$

$$\forall t, \qquad x_t \leq x_{\max} \,,$$

Optimal control formulation

$$\forall (i,t), \qquad 0 \leq v_{i,t} \leq V_{\max}$$

$$\forall t \qquad x_t = a x_{t-1} + b_1 \times \left(\ell_t^{\text{exo}} + \sum_{i=1}^{I} v_{i,t} \right)^2 + b_2 \times \left(\ell_{t-1}^{\text{exo}} + \sum_{i=1}^{I} v_{i,t-1} \right)^2 + c_t$$

$$\forall t, \qquad x_t \leq x_{\max} \ ,$$

Optimal control formulation

$$
\begin{aligned}
&\forall i, && \sum_{t=1}^{T} v_{i,t} \geq C_i \\
&\forall (i,t), && 0 \leq v_{i,t} \leq V_{\max} \\
&\forall t && x_t = a x_{t-1} + b_1 \times \left(\ell_t^{\text{exo}} + \sum_{i=1}^{I} v_{i,t} \right)^2 \\
& && \qquad + b_2 \times \left(\ell_{t-1}^{\text{exo}} + \sum_{i=1}^{I} v_{i,t-1} \right)^2 + c_t \\
&\forall t, && x_t \leq x_{\max} \ ,
\end{aligned}
$$

Optimal control formulation

minimize $g(v,x) = \sum_{t=1}^{T} e^{\alpha x_t} + J\left(\ell_t^{\text{exo}} + \sum_{i=1}^{I} v_{i,t}\right)$ s.t. :

$\forall i,$ $\sum_{t=1}^{T} v_{i,t} \geq C_i$

$\forall (i,t),$ $0 \leq v_{i,t} \leq V_{\max}$

$$\forall t \quad x_t = a x_{t-1} + b_1 \times \left(\ell_t^{\text{exo}} + \sum_{i=1}^{I} v_{i,t}\right)^2 + b_2 \times \left(\ell_{t-1}^{\text{exo}} + \sum_{i=1}^{I} v_{i,t-1}\right)^2 + c_t$$

$\forall t,$ $x_t \leq x_{\max}$,

Proposed methodology to solve the problem

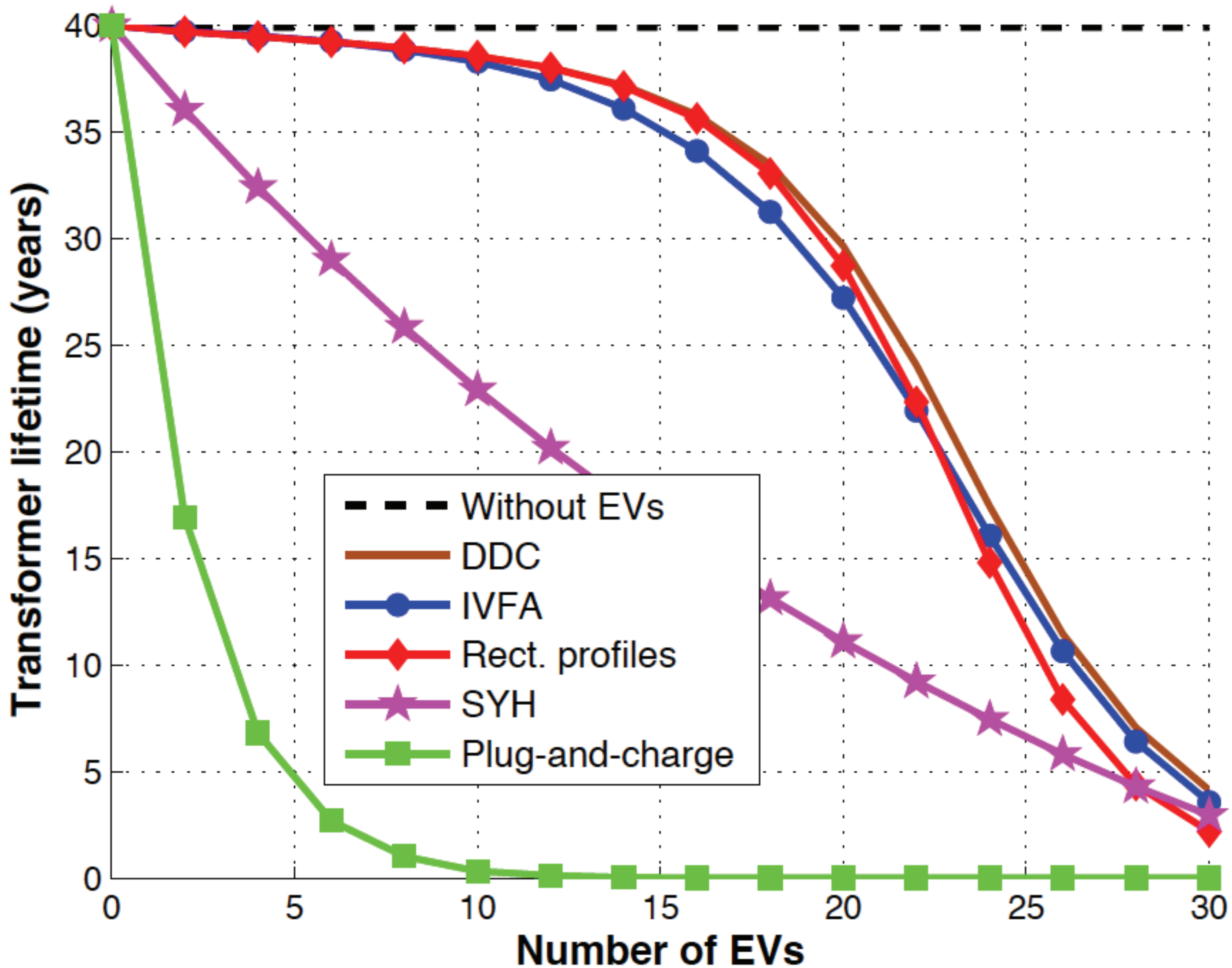
- Substitution technique

- Operate in a convex regime (e.g., $ab_1 + b_2 \geq 0$)

- Distributed approach: Apply the best response dynamics with $v_i = (v_{i,1}, ..., v_{i,T})$

[Beaude et al ECC 2015]

Numerical results (perfect forecast)



Ongoing research

☐ Algorithmic aspect: dynamical formulation + uncertainty (MDP) [Gonzalez et al Gretsi 2017]

☐ Strategic aspect: stochastic difference games, mean-field games

☐ Limiting performance characterization [Beaude et al Smart Grid Comm 2015]

Thank you!

Main publications (1/2)

[Gonzalez et al Gretsi 2017] M. Gonzalez, O. Beaude, P. Bouyer, S. Lasaulce, and N. Markey, ”Stratégies d’ordonnancement de consommation d?’énergie en présence d’information imparfaite de prévision”, Gretsi conference, Juan-les-Pins, France, Sep. 2017.

[Beaude et al TSG 2016] O. Beaude, S. Lasaulce, M. Hennebel, and I. Mohand-Kaci, ”Reducing the impact of distributed EV charging on distribution network operating costs”, IEEE Transactions on Smart Grid, Vol. 7, No.6, pp. 2666–2679, 2016.

[Beaude et al Smart Grid Comm 2015] O. Beaude, A. Agrawal, and S. Lasaulce, ”A framework for computing power consumption scheduling functions under uncertainty”, 6th IEEE International Conference on Smart Grid Communications (SmartGridComm 2015), Miami, Florida, USA, Nov. 2015.

[Beaude et al ECC 2015] O. Beaude, S. Lasaulce, M. Hennebel, and J. Daafouz, ”Minimizing the impact of EV charging on the distribution network”, European Conference on Control (ECC), Linz, Austria, July 2015.

Main publications (2/2)

[Beaude et al Netgcoop 2014] O. Beaude, C. Wan, and S. Lasaulce, ”Composite charging games in networks of electrical vehicles”, IEEE Proc. of the 8th International Conference on NETwork Games, COntrol and OPtimization (NETGCOOP), Trento, Italy, Oct. 2014.

[Beaude et al Netgcoop 2012] O. Beaude, S. Lasaulce, and M. Hennebel, ”Charging Games in Networks of Electric Vehicles”, IEEE Proc. of the 6th International Conference on NETwork Games, COntrol and OPtimization (NETGCOOP), Avignon, France, Nov. 2012.

Other references

[Gan et al Trans. on PS 2013] L. Gan, U. Topcu, and S. H. Low, ”Optimal decentralized protocol for electric vehicle charging,” Power Systems, IEEE Trans. on, Vol. 28, No. 2, pp. 940–951, 2013.

[Shinwari et al Trans. on SG 2012] M. Shinwari, A. Youssef, and W. Hamouda, ”A water-filling based scheduling algorithm for the smart grid,” Smart Grid, IEEE Trans. on, Vol. 3, No. 2, pp. 710–719, 2012.

[Monderer Shapley 1996] D. Monderer and L. S. Shapley, ”Potential games,” Games and Economic Behavior, vol. 14, no. 1, pp. 124–143, 1996.