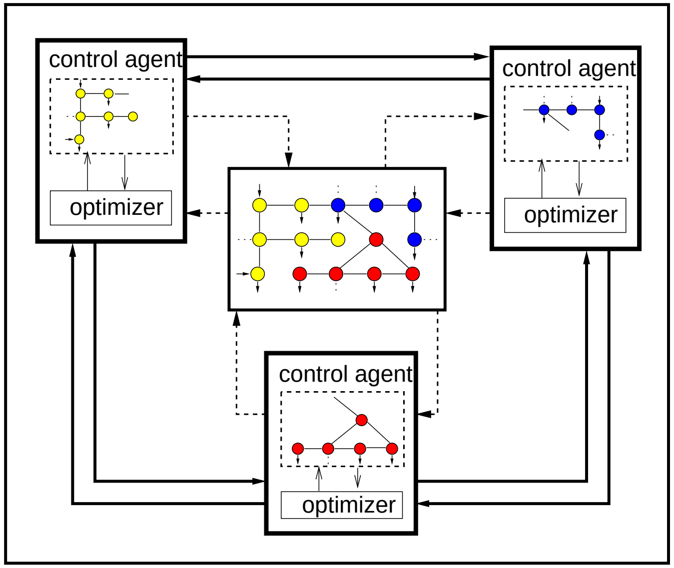
The Netherlands
Research School for
Transport, Infrastructure
and Logistics

TRAIL

Multi-Agent Model Predictive Control

with

Applications to Power Networks



Rudy Negenborn

CABS colloquium – Friday, April 25, 2008

Delft Center for Systems and Control

TUDelft

Delft University of Technology

Overview

1. Power networks

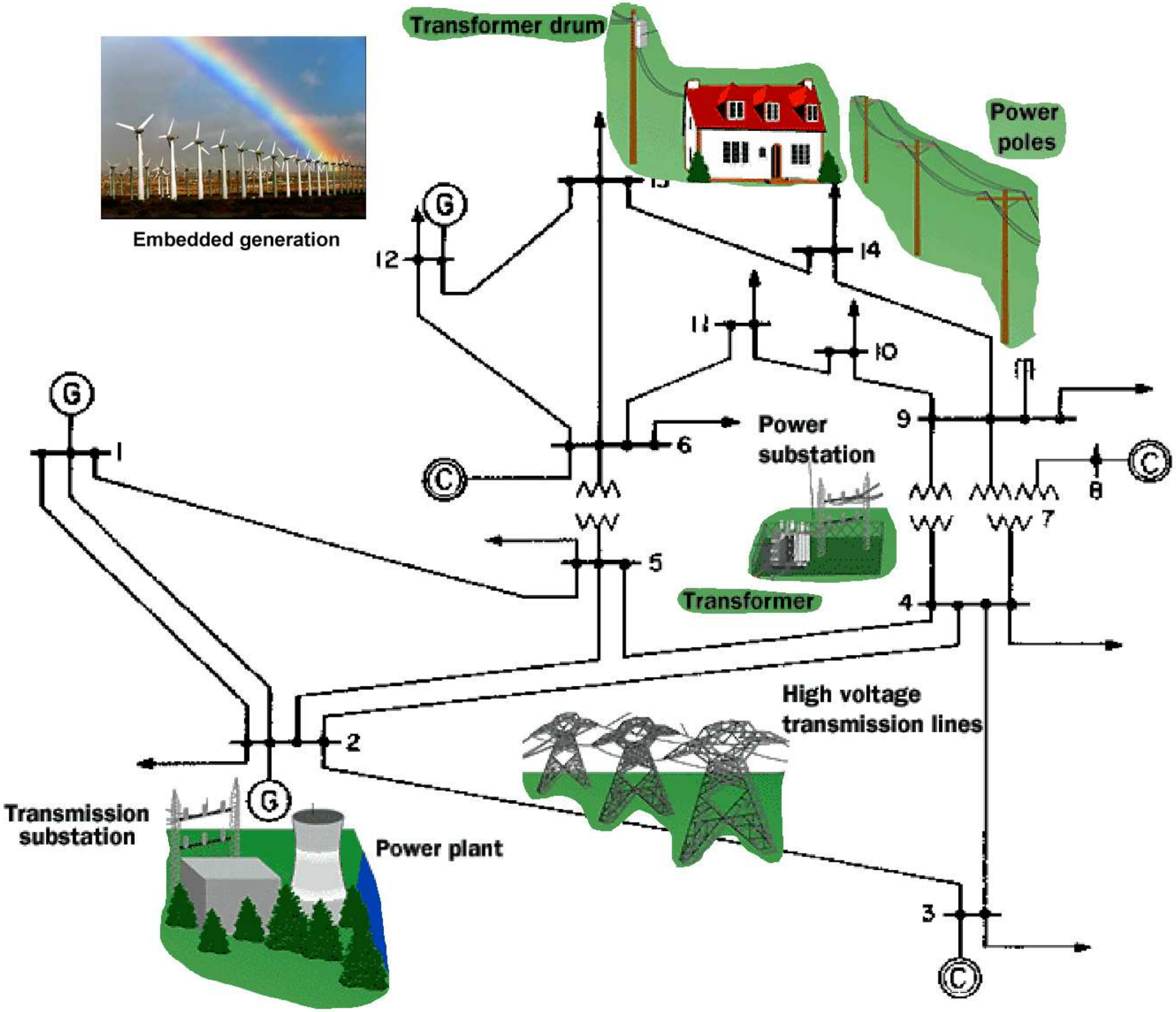
2. Single-agent model predictive control
3. . . . for residential energy control

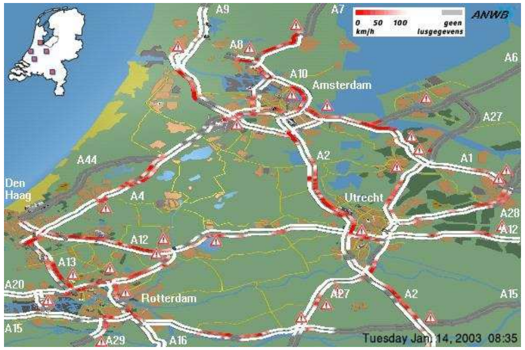
4. Multi-agent model predictive control
5. . . . for load-frequency control

6. What’s more?

7. Concluding remarks

1. Power networks

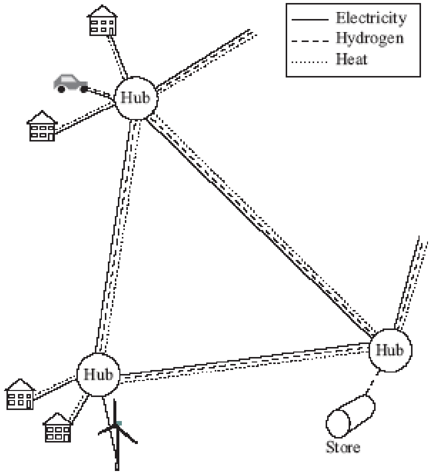


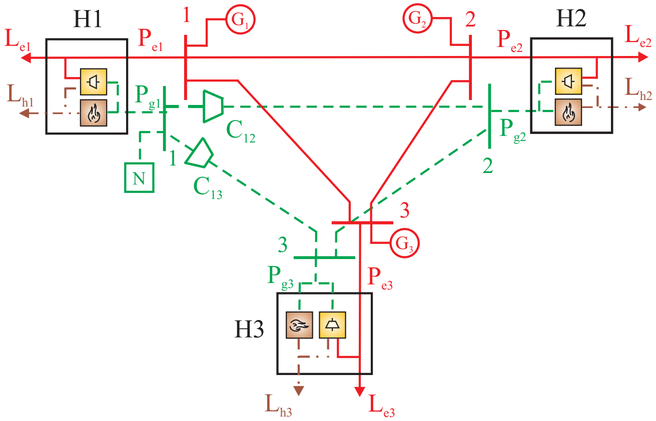


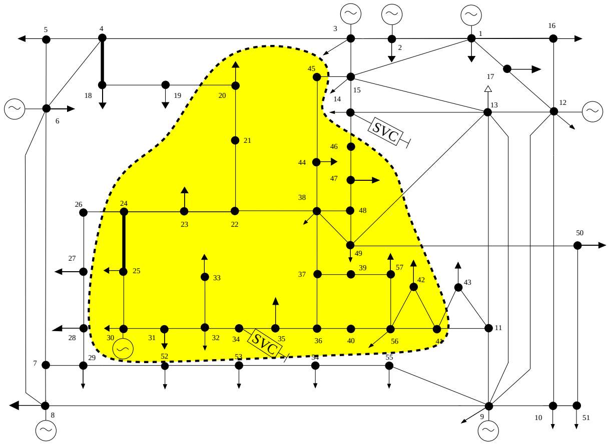
- power networks
- road traffic networks
- water networks
- sewer networks
- gas networks
- railway networks
- ...

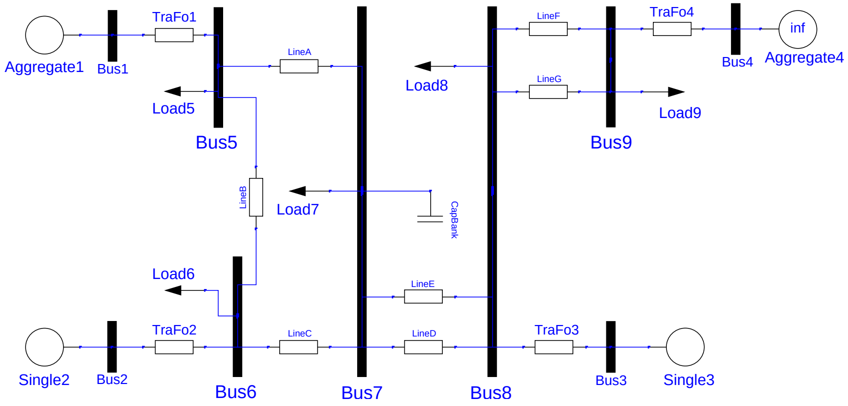
1. Power networks

Nature of power networks is changing









1. Power networks

December 2007 Apache helicopter damaged high-voltage transmission lines

(photos courESTY nu.nl)

Schools and shops closed; problems in milk industry and houses for elderly people; mobile phone network down; traffic jams in river, . . .

1. Power networks

December 2007 Apache helicopter damaged high-voltage transmission lines

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Schools and shops closed; problems in milk industry and houses for elderly people; mobile phone network down; traffic jams in river, . . .

To minimize effects, make more intelligent use of existing infrastructure

1. Power networks

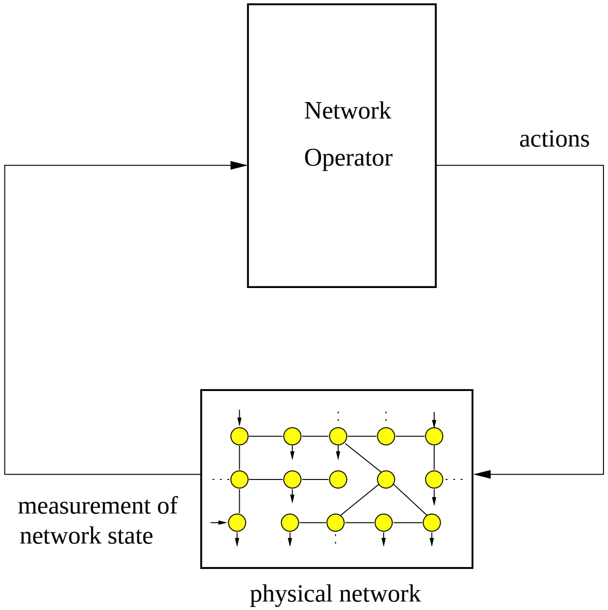
Information available

- measurements of network variables
- models of dynamics of components
- predictions on future demands
- ...

Control goals

- avoiding problems
- minimizing cost of control actions
- satisfying constraints
- ...

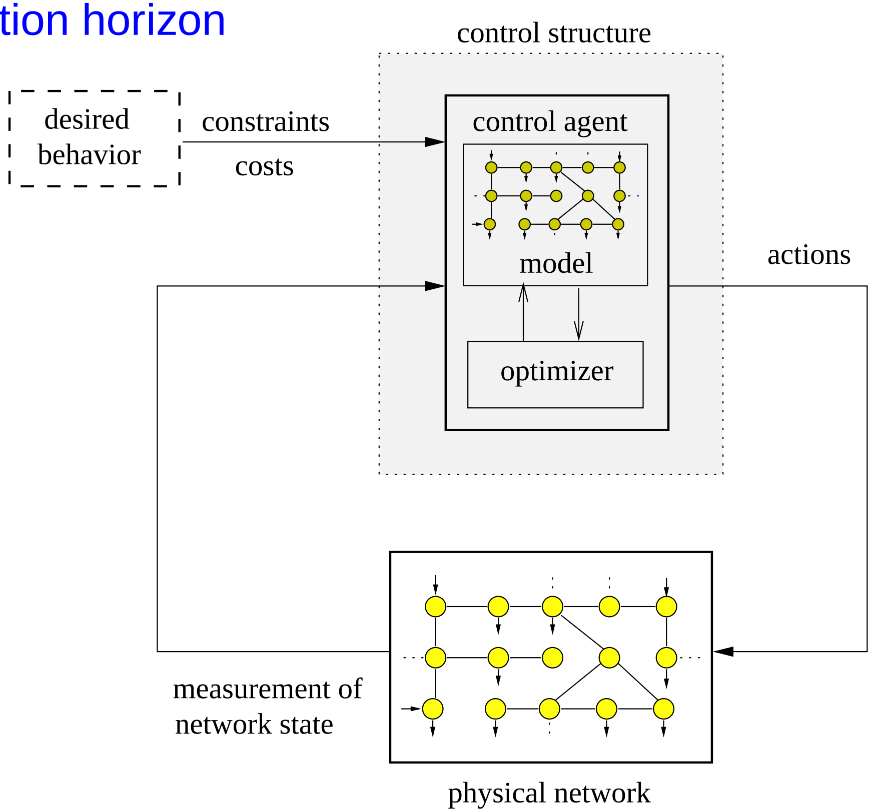
At each decision step,
use available information to
determine actions that
achieve the control goals



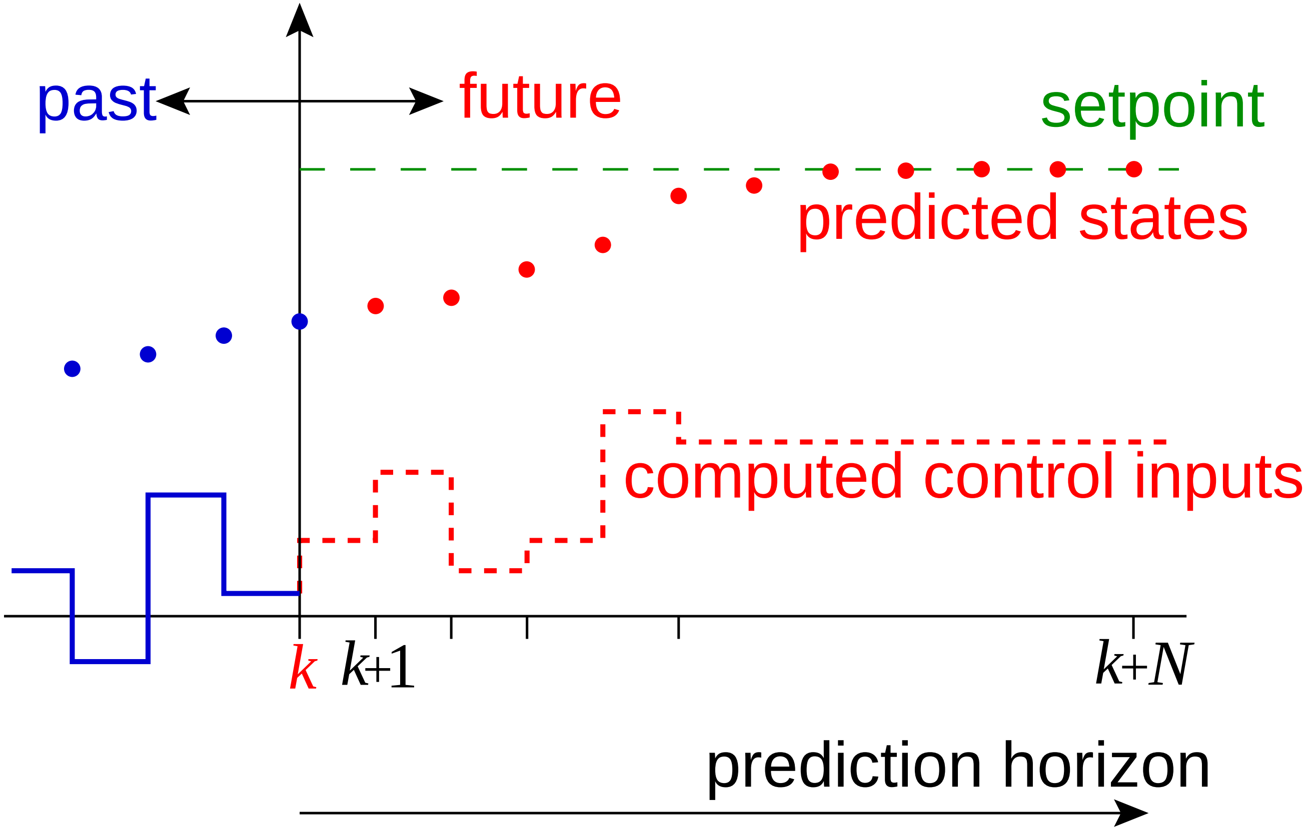
2. Model predictive control

Use a model to make predictions and find actions that give the best performance

- Measure current state of the network
- Find the actions with the best predicted performance over a prediction horizon
- Implement the actions found for the coming time step
- Network transitions to next time step
- Repeat



2. Model predictive control



2. Model predictive control

MPC control problem at decision step k

$$\min_{\tilde{u}(k),\tilde{\mathbf{x}}(k+1)} J(\tilde{\mathbf{u}}(k),\tilde{\mathbf{x}}(k+1))$$

subject to

- predition model of network dynamics

$$\mathbf{x}(k+1) = f(\mathbf{x}(k),\mathbf{u}(k),\mathbf{d}(k))$$

$$\vdots$$

$$\mathbf{x}(k+N) = f(\mathbf{x}(k+N-1),\mathbf{u}(k+N-1),\mathbf{d}(k+N-1))$$

- initial state $\mathbf{x}(k) = \mathbf{x}_{\text{measured}}$
- disturbances $\mathbf{d}(k+i)$, for $i = 0,\ldots,N-1$
- additional constraints

where

J	objective function
$\mathbf{x}(k)$	states
$\mathbf{u}(k)$	actions
$\mathbf{d}(k)$	disturbances
f	transition function
N	horizon length
$\tilde{\cdot}(k)$	variables over horizon from k to $k+N-1$

2. Model predictive control

Standard classes of optimization problems

- linear programming problem
- quadratic programming problem
- linear mixed-integer programming problem
- nonlinear programming problem
- . . .

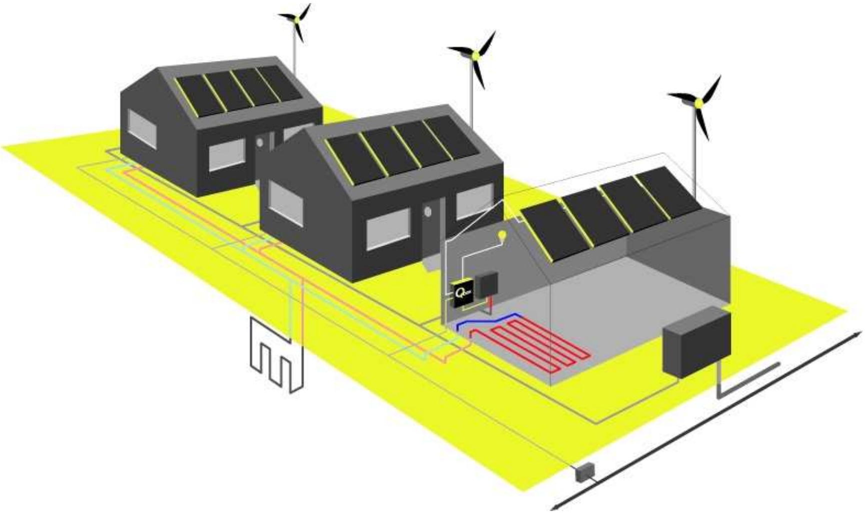
Depending on characteristics, different types of optimization problems have to be solved

Free and commercial solvers are available for solving standard problems (e.g., CPLEX, SNOPT, KNITO, MINOS, Xpress, . . .)

Reformulation or approximation often used to obtain standard form

Next: Application of model predictive control for residential energy control

3. Residential energy control



http://qmunity.qurrent.com/opwekking.aspx

Opwekking voor 23 Sept 2007 t/m 23 Sept 2007

Energie (kWh)

6,35 kWh

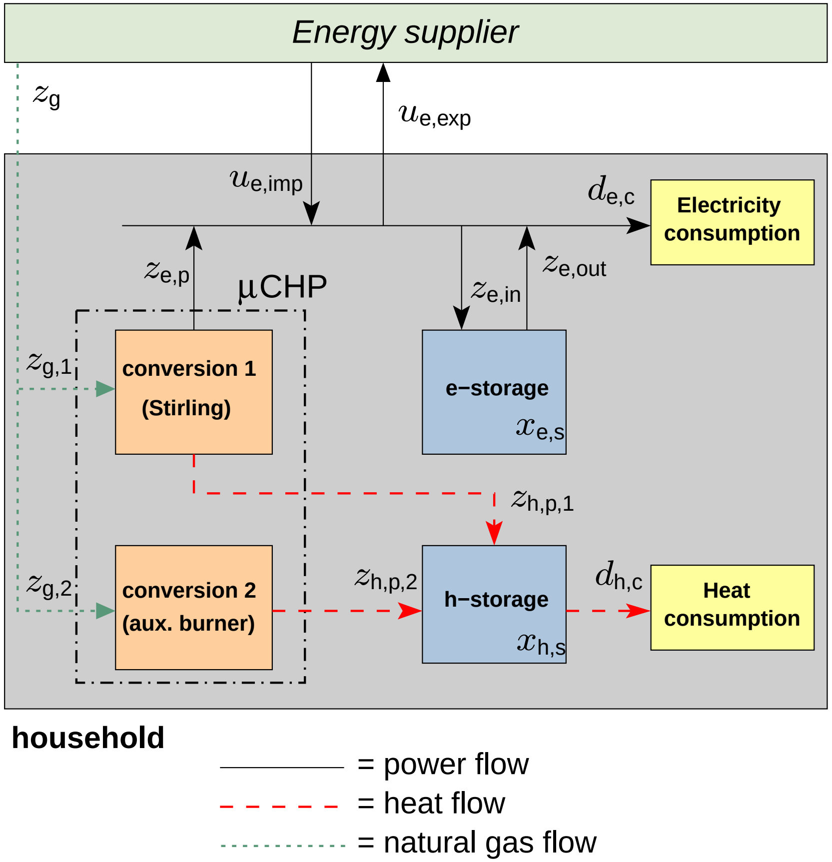
Qbox Woonhuis
☑ Windturbine
☑ Zonnepanelen

Qbox Garage
☑ Windturbine
☐ Biodiesel WKK

Ter vergelijking
☑ Vorig jaar
☑ Gemiddeld

3. Residential energy control

A household system



3. Residential energy control

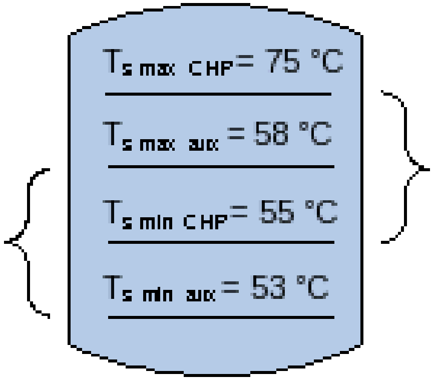
System characteristics

Hybrid dynamics: combination of continuous evolution

- energy flows
- dynamics of electricity and heat storage (with saturation)
- power balance

with discrete logic and constraints, such as

- conversion unit 1 operation *off*, *partial* or *full*
- *full* only after *partial* generation
- conversion unit 1 priority over 2
- minimum activation constraint
- internal temperature-based controller logic (determines when to switch to partial mode)
- capacity constraints



3. Residential energy control

Why MPC for household control?

- optimize usage of heat and electricity storage units
- take into account decision freedom due to electricity import and export, and due to own generation of energy
- incorporate forecasts on residential electricity and heat demands
- incorporate models of the dynamics and constraints of installed generators and storage units
- minimize daily operational costs and maintain level of heat storage unit between desired upper and lower limit

Actions to be determined

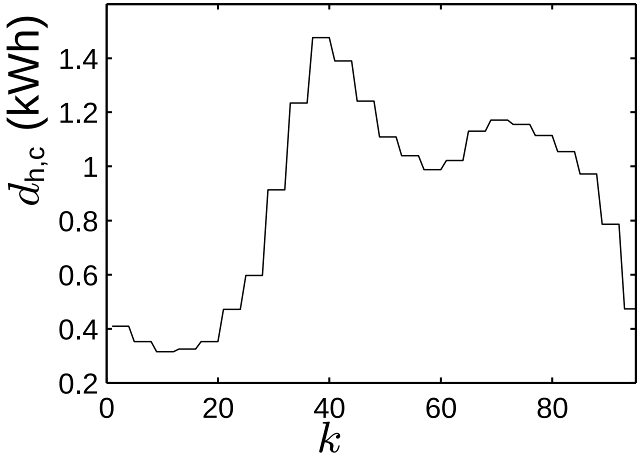
- *full* activation of unit 1
- electricity export/import/storage
- gas import

MPC problem cast as mixed-integer linear programming problem

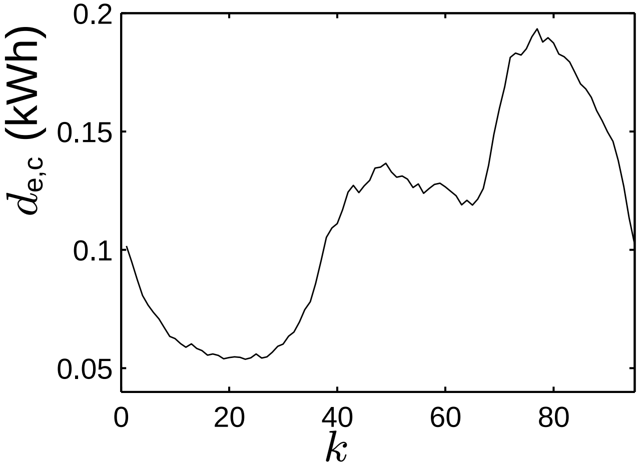
3. Residential energy control

A winter day (January 29, 2006)

- Average residential electricity and aggregated heat demand profiles created from EnergieNed data
- Prices for gas and electricity export fixed
- Prices for electricity import variable
- Control sample step size of 15 minutes



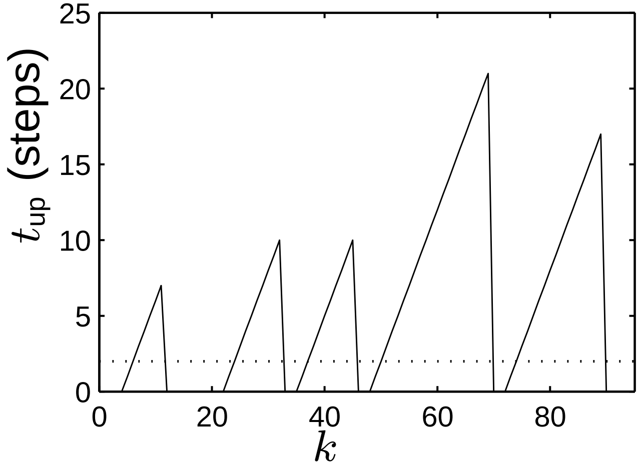
Heat demand data

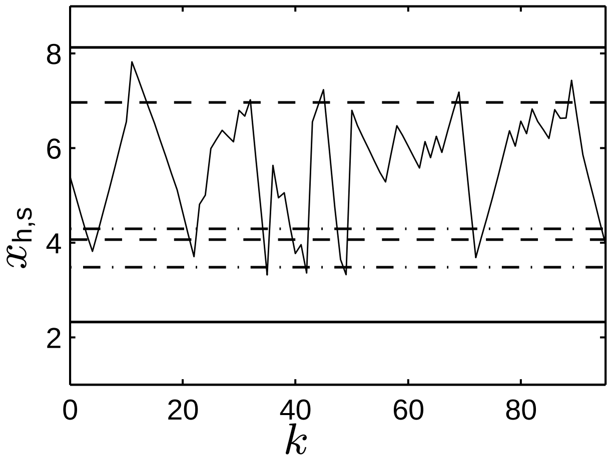


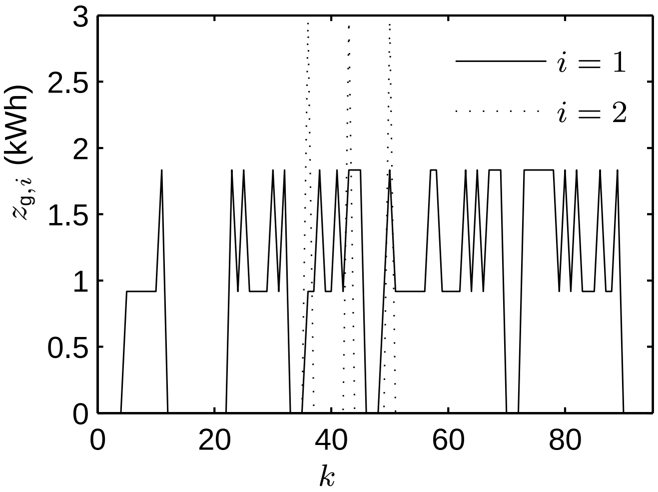
Electricity demand data

3. Residential energy control

Result for a particular simulation (with $N = 16$)







Activation constraint satisfied

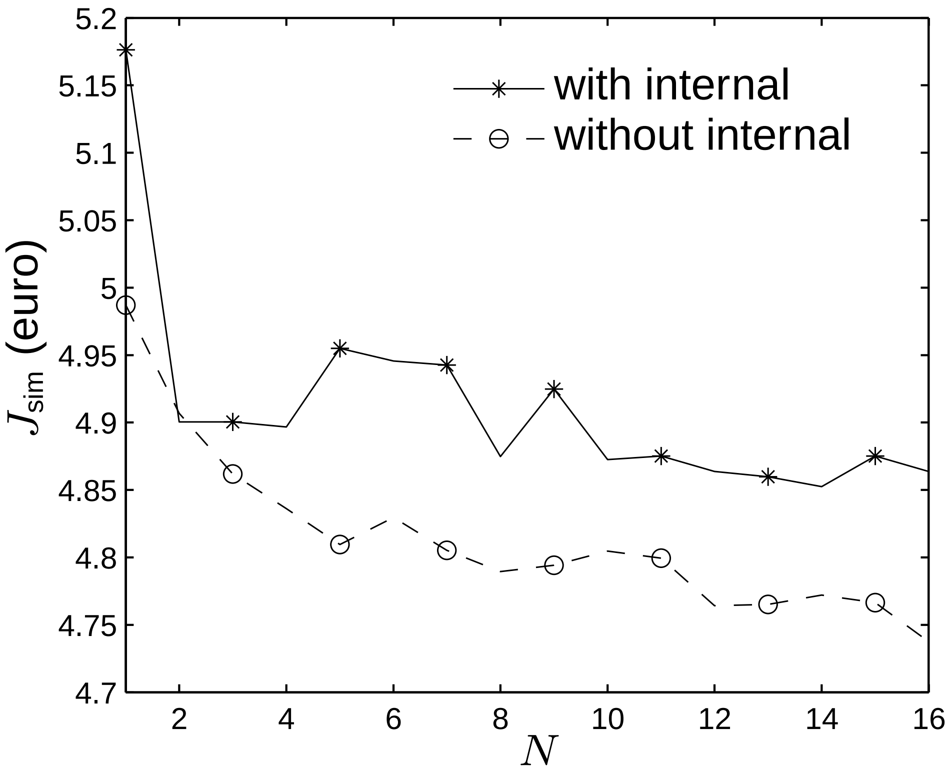
Heat storage constraint satisfied

Priority constraint satisfied

Full after partial constraint satisfied

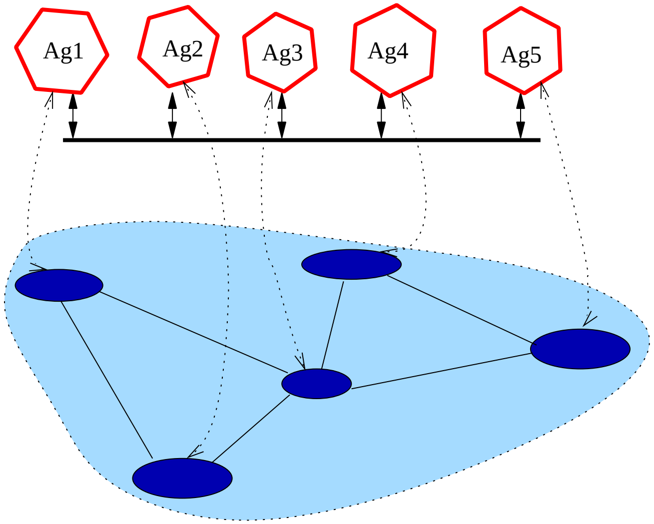
3. Residential energy control

Results for varying N



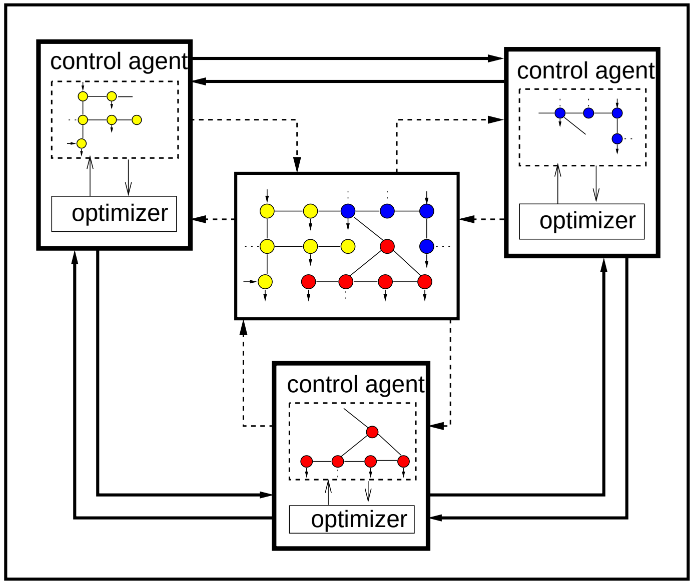
- Varying prediction horizon length N
- With and without internal controllers

4. Multi-agent MPC



Multi-agent control: more than 1 decision maker

- subnetworks instead of overall network
- single agent for each subnetwork
    - limited action capabilities
    - limited information gathering



Challenge

agents should choose local inputs that are globally optimal using communication, coordination, cooperation, and negotiation

4. Multi-agent MPC

Local control problem of agent i at decision step k

$$\min_{\tilde{u}_k^i, \tilde{x}_{k+1}^i} J_{\text{local}}^i(\tilde{u}_k^i, \tilde{x}_{k+1}^i)$$

subject to

- subnetwork dynamics

$$x_{k+1}^i = f^i(x_k^i, u_k^i, d_k^i, \ldots)$$

$$\vdots$$

$$x_{k+N}^i = f^i(x_{k+N-1}^i, u_{k+N-1}^i, d_{k+N-1}^i, \ldots)$$

- initial local state and additional constraints

where

J_{local}^i	local objective function
x_k^i	local states
u_k^i	local actions
d_k^i	local disturbances
f^i	local transition function

4. Multi-agent MPC

Local control problem of agent i at decision step k

$$\min_{\tilde{u}_k^i, \tilde{x}_{k+1}^i} J_{\text{local}}^i(\tilde{u}_k^i, \tilde{x}_{k+1}^i)$$

subject to

- subnetwork dynamics

$$\begin{aligned}
x_{k+1}^i &= f^i(x_k^i, u_k^i, d_k^i, w_{\text{in},k}^{j_1 i}, \ldots, w_{\text{in},k}^{j_{m_i} i}) \\
w_{\text{out},k+1}^{ji} &= h_{\text{out}}^{ji}(u_k^i, d_k^i, x_{k+1}^i) && \text{for all neighbors } j \\
&\vdots \\
x_{k+N}^i &= f^i(x_{k+N-1}^i, u_{k+N-1}^i, d_{k+N-1}^i, \\
&\qquad w_{\text{in},k+N-1}^{j_1 i}, \ldots, w_{\text{in},k+N-1}^{j_{m_i} i}) \\
w_{\text{out},k+N}^{ji} &= h_{\text{out}}^{ji}(u_{k+N-1}^i, d_{k+N-1}^i, x_{k+N}^i) && \text{for all neighbors } j
\end{aligned}$$

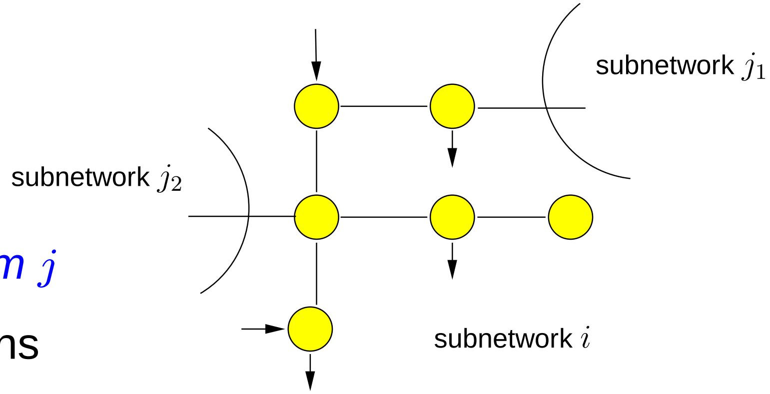
- initial local state and additional constraints

where

J_{local}^i	local objective function
x_k^i	local states
u_k^i	local actions
d_k^i	local disturbances
f^i	local transition function
w_{in}^{ji}	local internetwork inputs
w_{out}^{ji}	local internetwork outputs
h_{out}^{ji}	local int.net. output function

4. Multi-agent MPC

Interconnecting constraints



- constraints on internetwork variables
- imposed by dynamics of overall network
- *what goes in into i equals what goes out from j*
- satisfaction necessary for accurate predictions

$$\boxed{\begin{aligned} w_{\text{in},k}^{ji} &= w_{\text{out},k}^{ij} \\ w_{\text{out},k}^{ji} &= w_{\text{in},k}^{ij} \\ \vdots\quad &\quad\vdots \\ w_{\text{in},k+N-1}^{ji} &= w_{\text{out},k+N-1}^{ij} \\ w_{\text{out},k+N-1}^{ji} &= w_{\text{in},k+N-1}^{ij} \end{aligned}}$$

4. Multi-agent MPC

Interconnecting constraints

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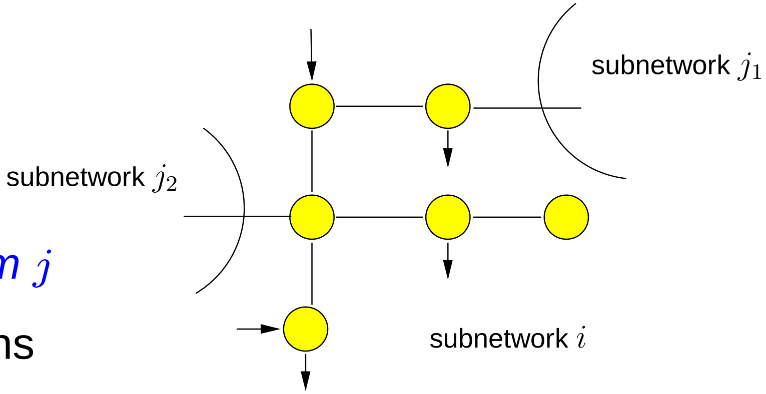


$$\boxed{\begin{aligned} w^{ji}_{\text{in},k} &= w^{ij}_{\text{out},k} \\ w^{ji}_{\text{out},k} &= w^{ij}_{\text{in},k} \\ &\vdots \\ w^{ji}_{\text{in},k+N-1} &= w^{ij}_{\text{out},k+N-1} \\ w^{ji}_{\text{out},k+N-1} &= w^{ij}_{\text{in},k+N-1} \end{aligned}}$$

For agent controlling subnetwork i

- w^{ij}_{in} and w^{ij}_{out} of neighbor j unknown
- how make accurate predictions?
  → ignore, assume constant,
  predict, negotiate, ...

4. Multi-agent MPC

A negotiation approach

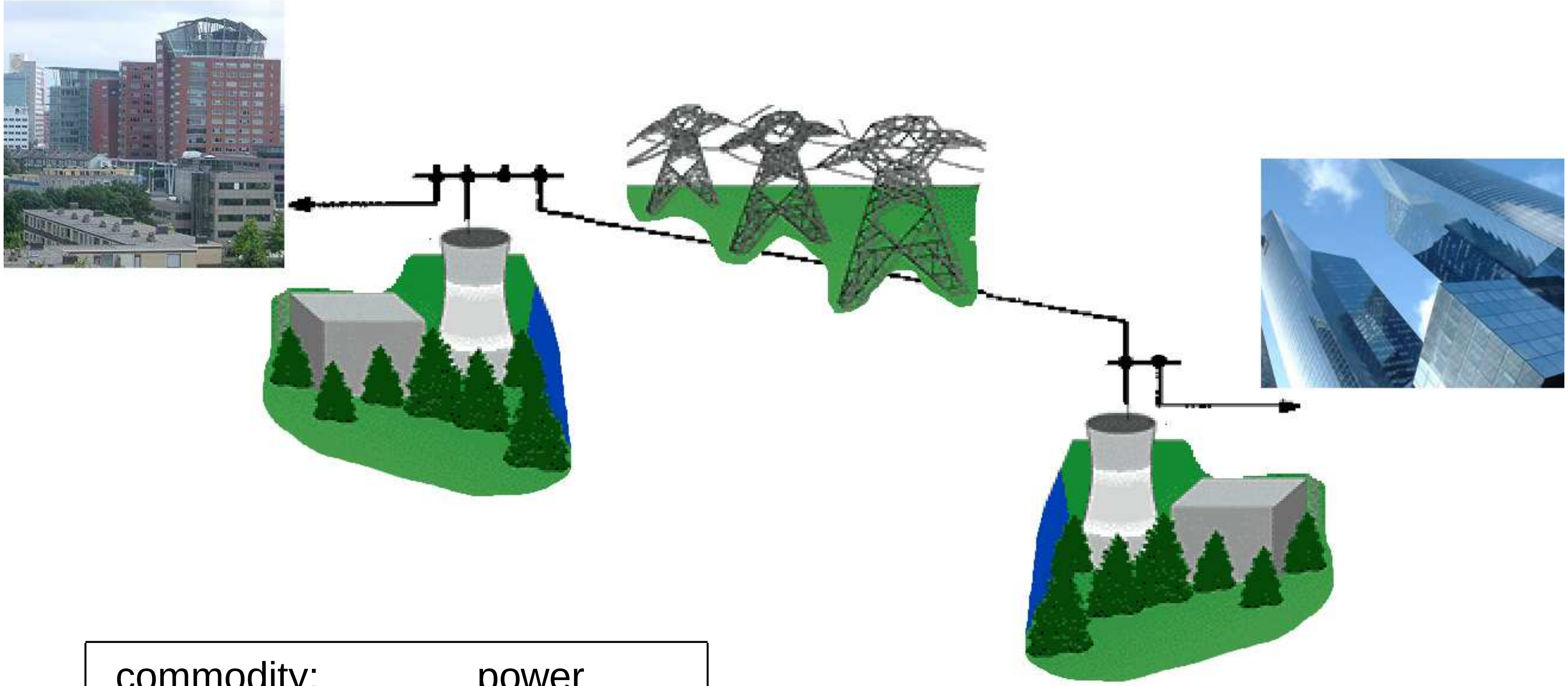
- accurate predictions by agreeing on values of internetwork variables
- each agent
  - computes optimal local *and* internetwork variables
  - communicates internetwork variables to neighbors
  - updates parameters $\tilde{\lambda}_{\text{in}}^{ji}, \tilde{\lambda}_{\text{out}}^{ji}$ of additional cost term J_{inter}^{i}
- iterations until stopping criterion satisfied

$$\min_{\tilde{u}_k^i, \tilde{x}_{k+1}^i, \tilde{w}_{\text{in},k}^{li}, \tilde{w}_{\text{out},k}^{li}} J_{\text{local}}^{i}(\tilde{u}_k^i, \tilde{x}_{k+1}^i) + \sum_{j \in \text{neighbors}^i} J_{\text{inter}}^{i}(\tilde{w}_{\text{in},k}^{ji}, \tilde{w}_{\text{out},k}^{ji}, \tilde{\lambda}_{\text{in}}^{ji}, \tilde{\lambda}_{\text{out}}^{ji})$$

subject to

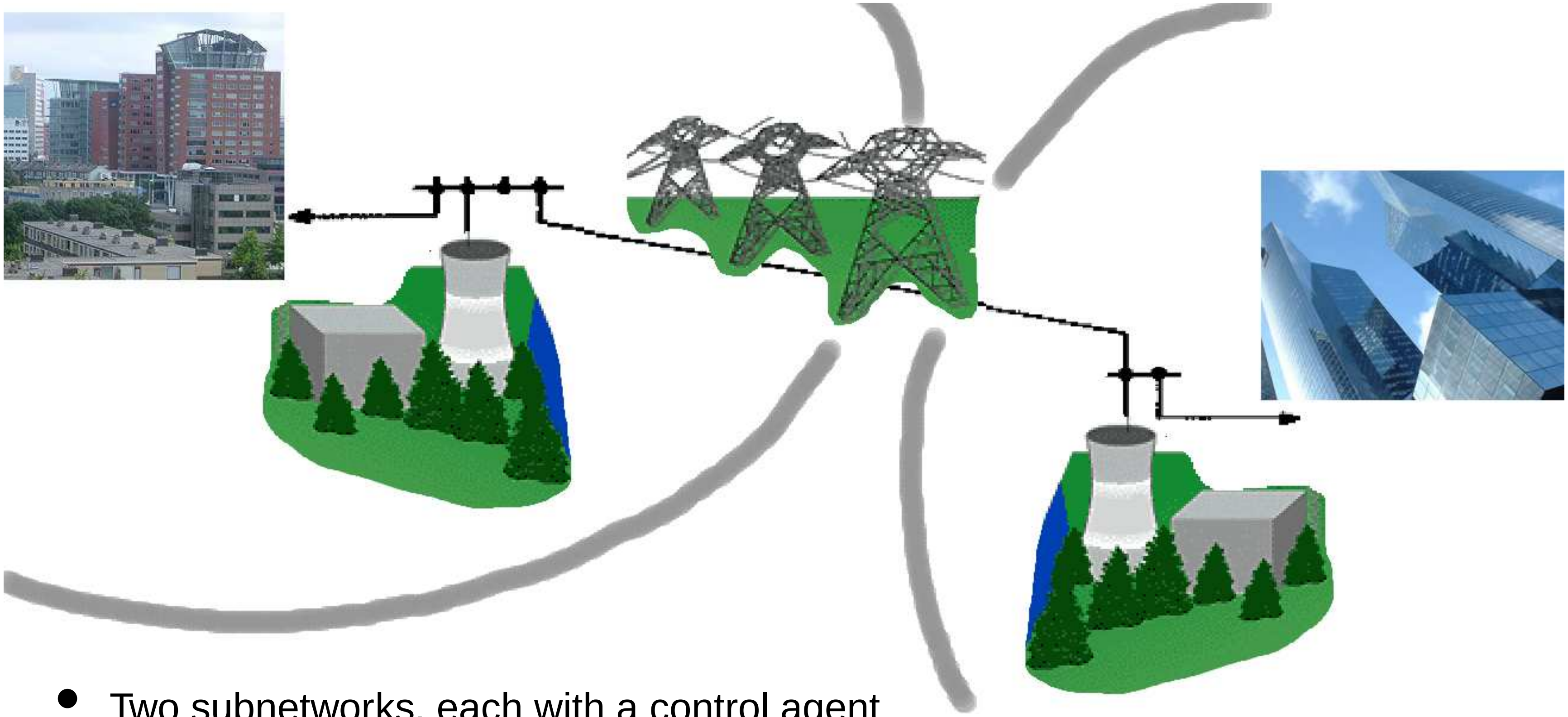
- dynamics of subnetwork i over the horizon
- initial local state and additional constraints

5. Load frequency control



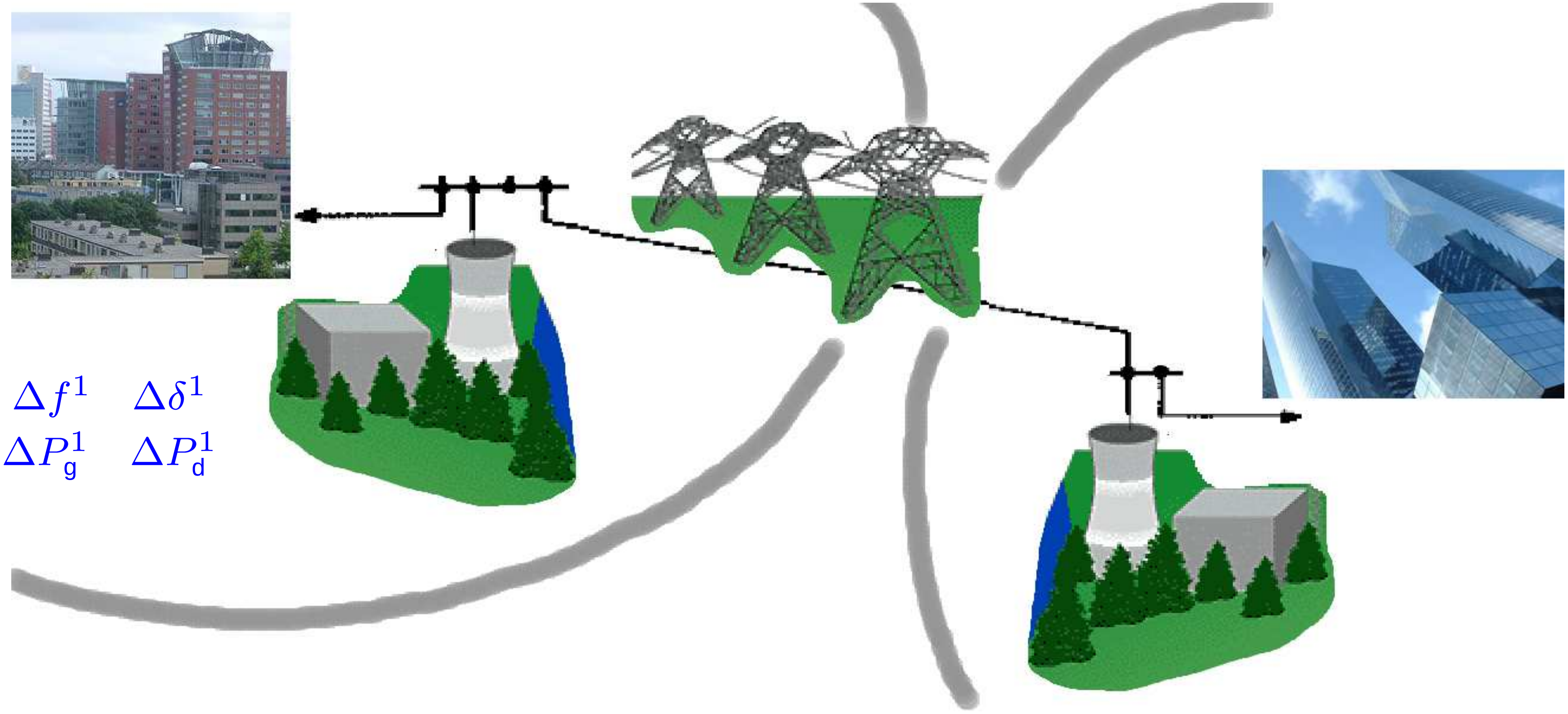
commodity:	power
sources:	generators
sinks:	loads
interconnections:	power lines

5. Load frequency control



- Two subnetworks, each with a control agent
- *Frequency deviations* due to imbalance generation and consumption
- Main goal: maintain frequency deviation in each subnetwork close to zero
- How? by controlling generation

5. Load frequency control



Δf^1 $\Delta \delta^1$

ΔP_{g}^1 ΔP_{d}^1

Δf^2 $\Delta \delta^2$

ΔP_{g}^2 ΔP_{d}^2

Δf	frequency deviation	$\Delta \delta$	angle deviation
ΔP_{d}	load deviation	ΔP_{g}	generation deviation

5. Load frequency control

Objective agent i: minimize frequency deviation Δf^i and generation change ΔP_{g}^i

$$J_{\mathrm{local}}^i(\tilde{u}_k^i, \tilde{x}_{k+1}^i) = \sum_{p=0}^{N-1} q_{\Delta f}^i (\Delta f_{k+p+1}^i)^2 + q_{\Delta P_g}^i (\Delta P_{\mathrm{g},k+p}^i)^2$$

where $q_{\Delta f}^i$ and $q_{\Delta P_{\mathrm{g}}}^i$ are cost coefficients

Subnetwork i model

$$\Delta \dot{\delta}^i = 2\pi \Delta f^i$$

$$\Delta \dot{f}^i = -\frac{1}{T_{P^i}} \Delta f^i + \frac{K_{P^i}}{T_{P^i}} \Delta P_{\mathrm{g}}^i - \frac{K_{P^i}}{T_{P^i}} \Delta P_{\mathrm{d}}^i + \frac{K_{P^i} K_{S_{ij}}}{2\pi T_{P^i}} (\Delta \delta^j - \Delta \delta^i).$$

- Δf^i depends on variable of both subnetworks, $\Delta \delta^j$ and $\Delta \delta^i$
- Agent i does not know $\Delta \delta^j$, agent j does not know $\Delta \delta^i$

5. Load frequency control

Continuous-time subnetwork model discretized

$$
\begin{aligned}
x^i_{k+1} &= A^i x^i_k + B^i_1 u^i_k + B^i_2 d^i_k + B^i_3 w^{ji}_{\text{in},k} \\
w^{ji}_{\text{out},k+1} &= C^{ji}_{\text{out}} x^i_{k+1}
\end{aligned}
$$

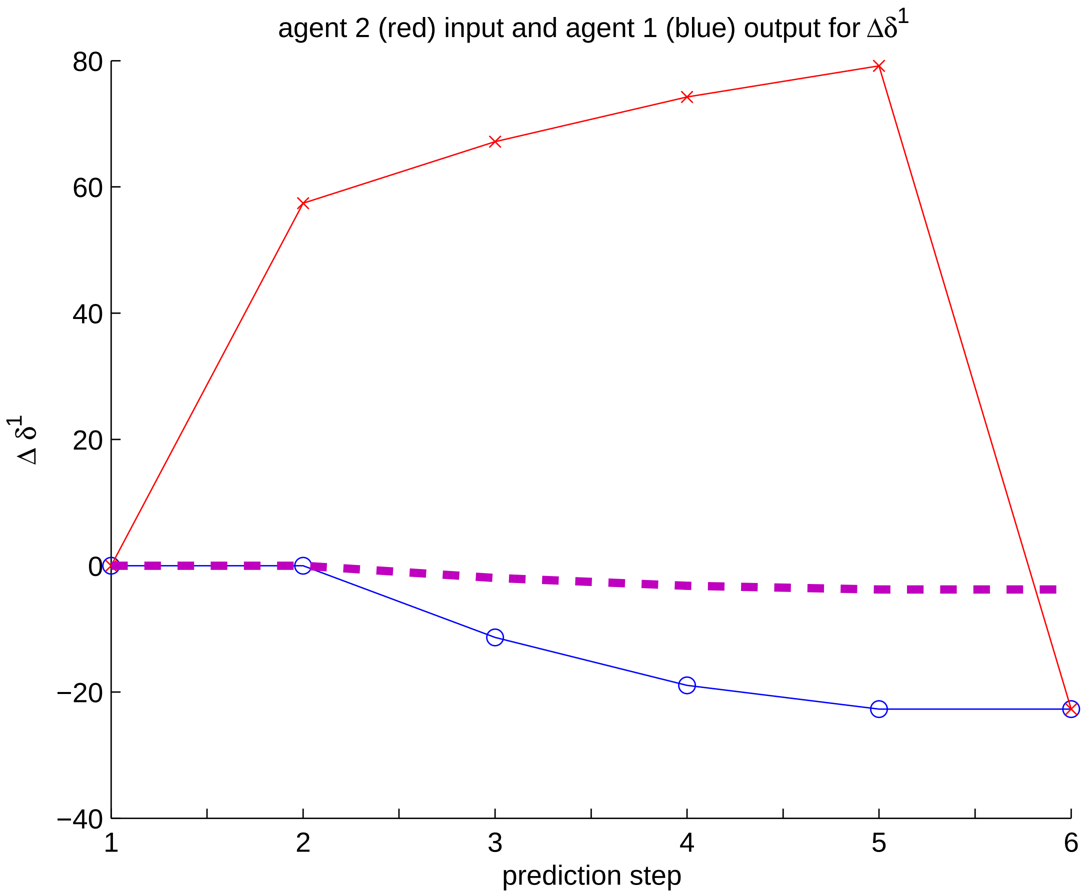
where for subnetwork i

- w^{ji}_{in} is internetwork input $\Delta\delta^j$ from subnetwork j
- w^{ji}_{out} is internetwork output $\Delta\delta^i$ to subnetwork j

Overall control problem convex

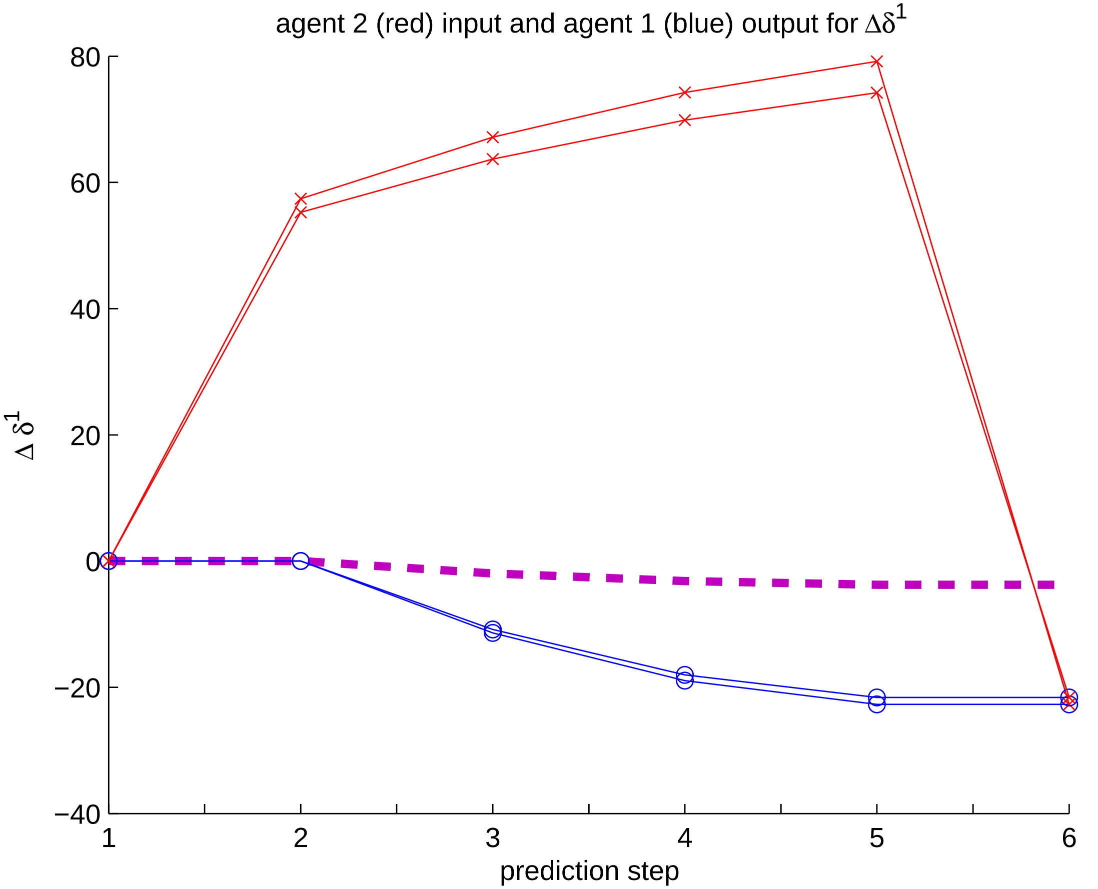
- all variables bounded and real valued
- convex objective function
- convex constraint set

5. Load frequency control



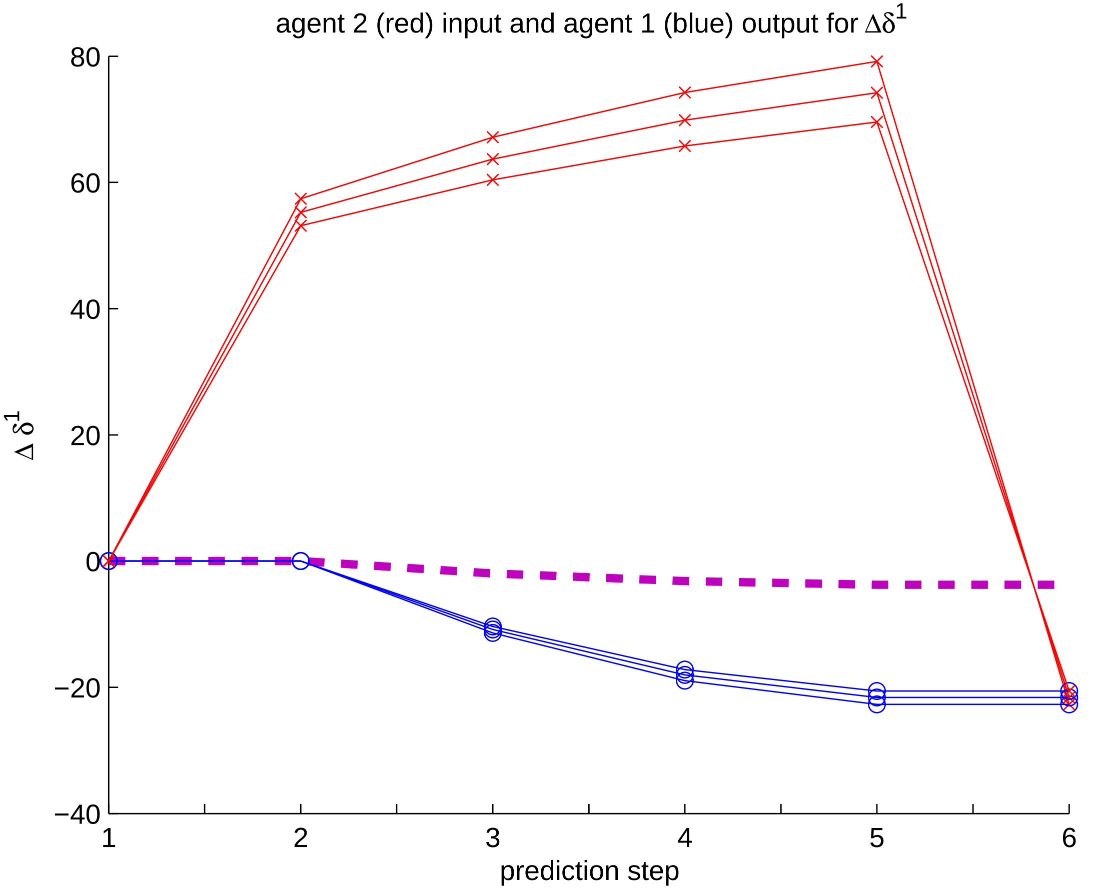
Iteration 1

5. Load frequency control



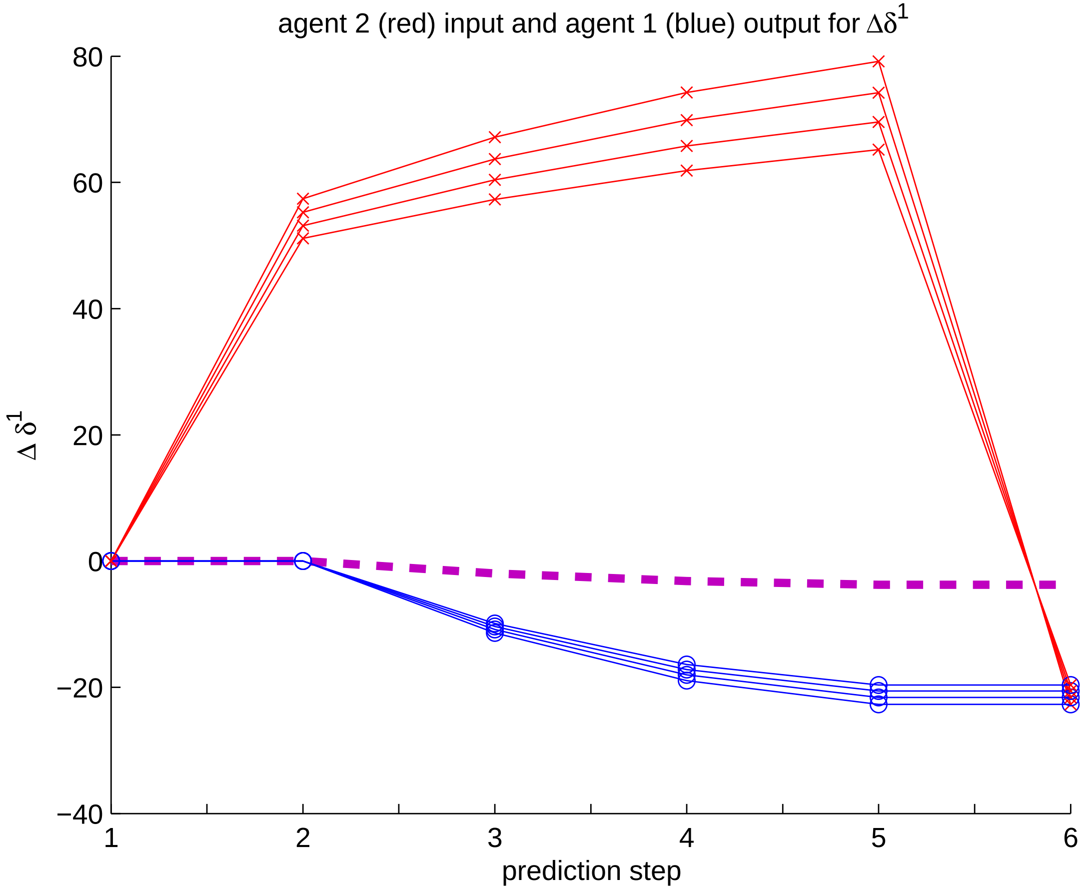
Iteration 2

5. Load frequency control



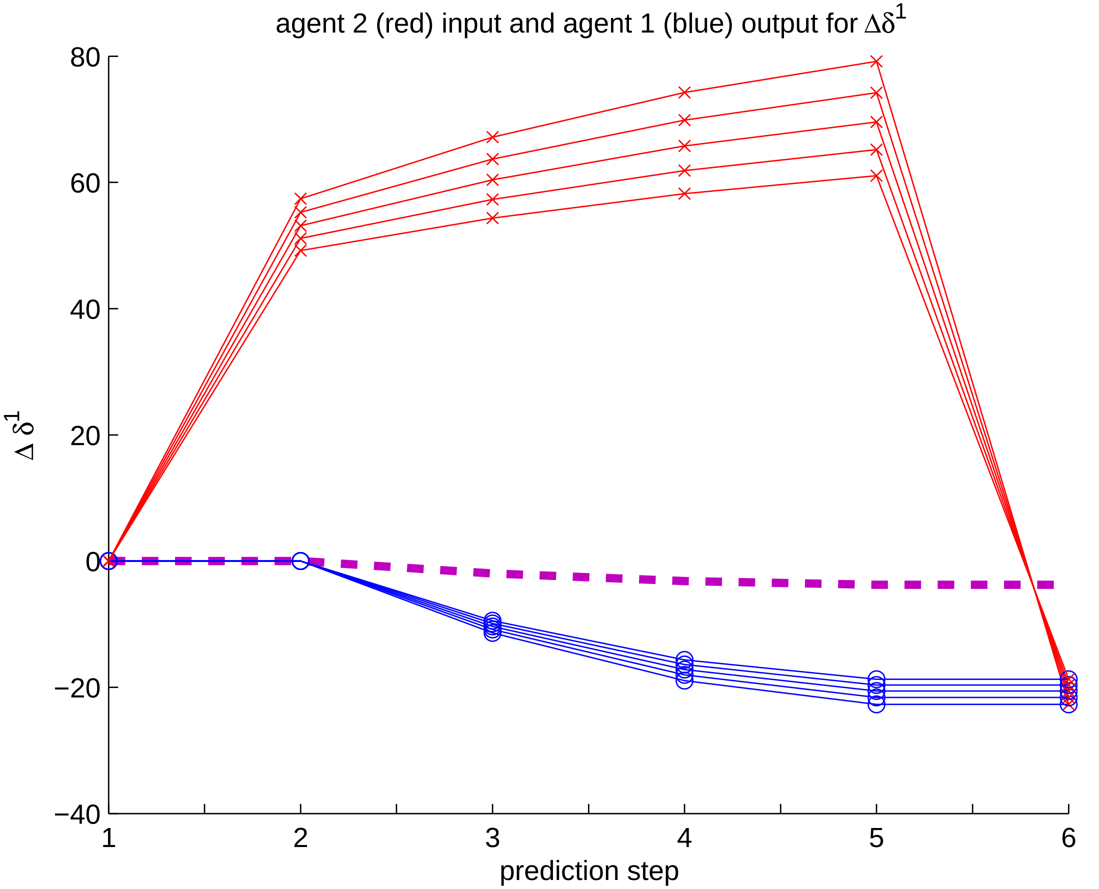
Iteration 3

5. Load frequency control



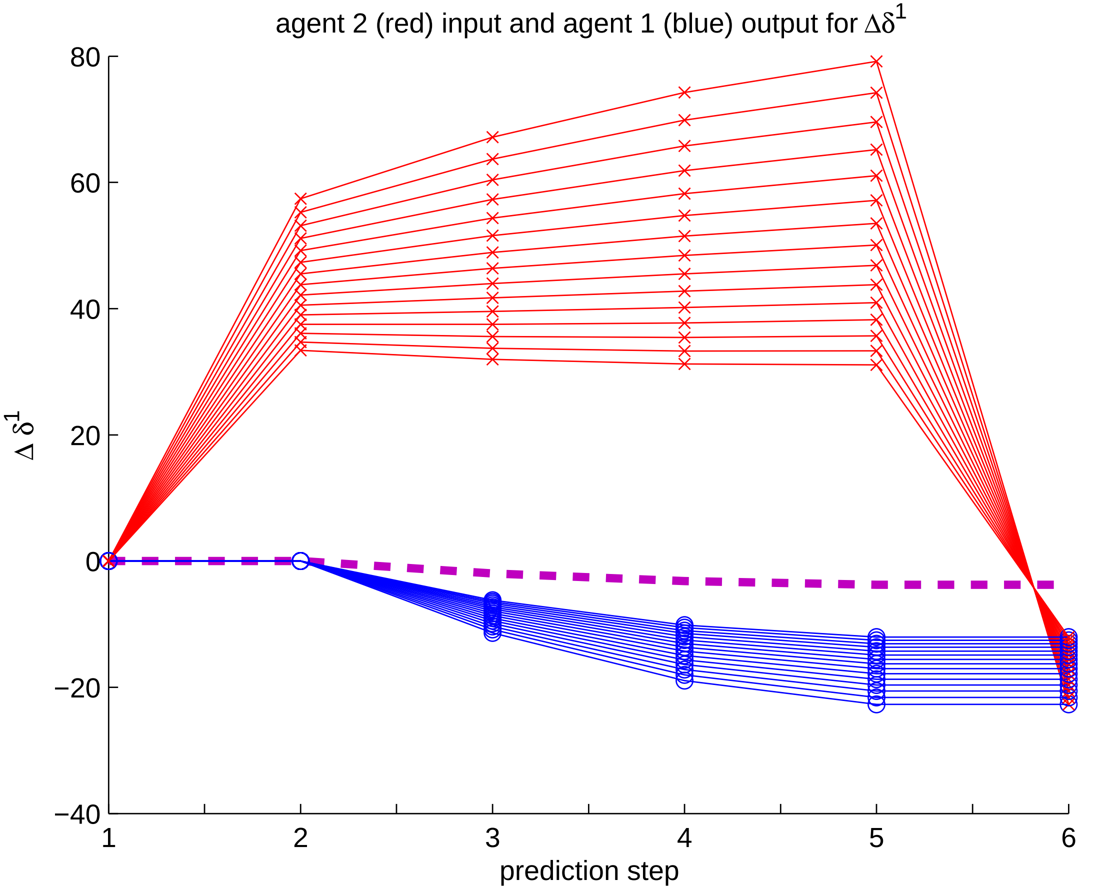
Iteration 4

5. Load frequency control



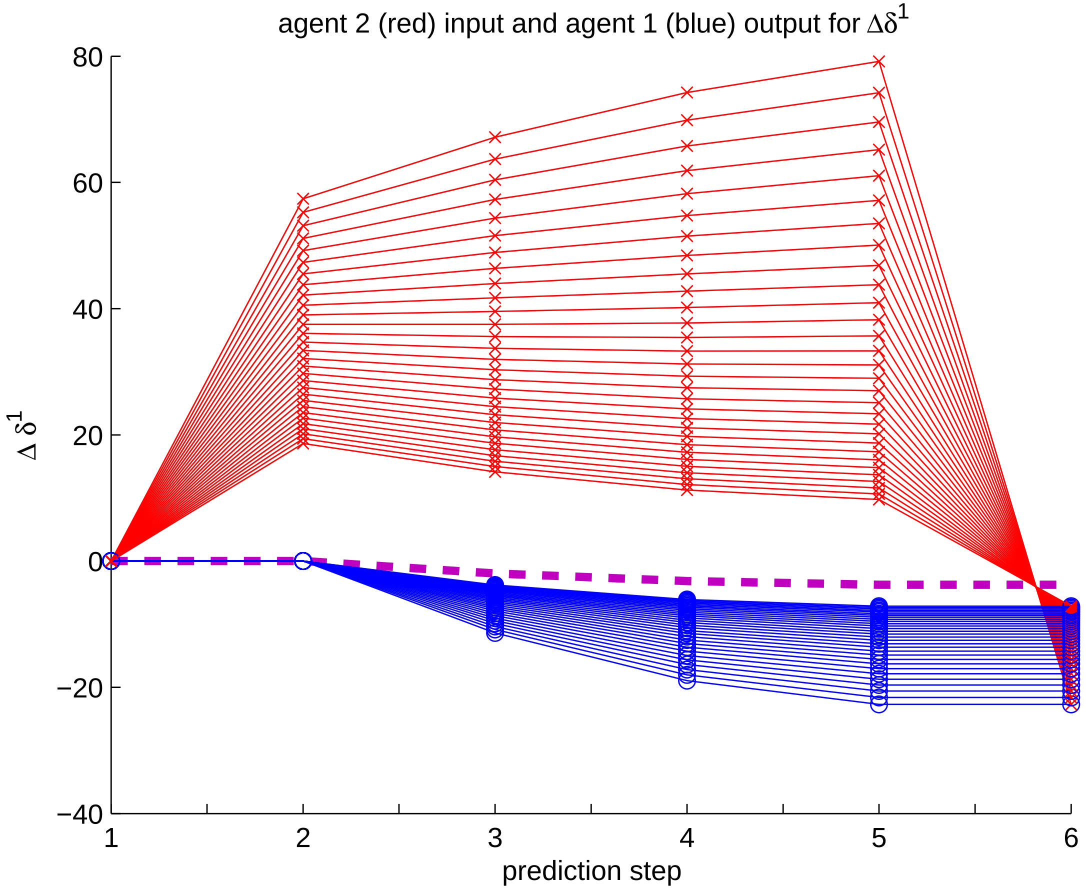
Iteration 5

5. Load frequency control



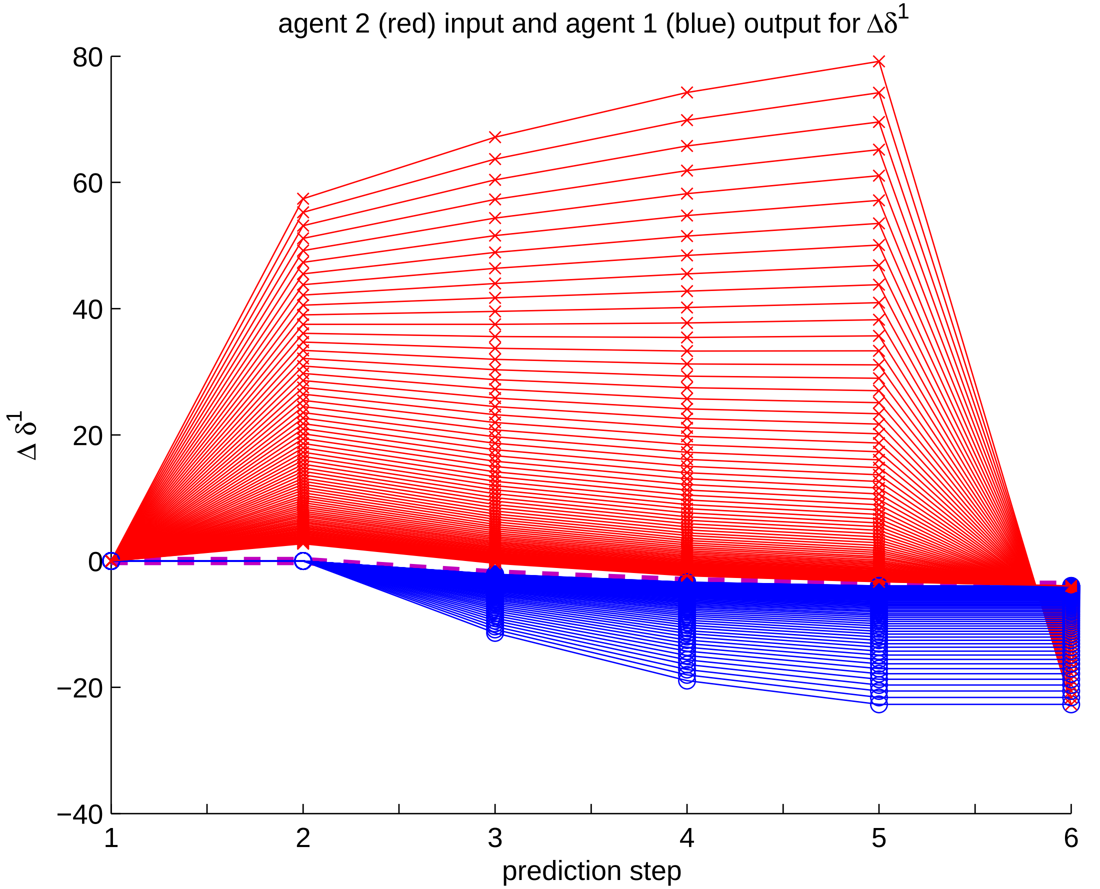
Iteration 15

5. Load frequency control



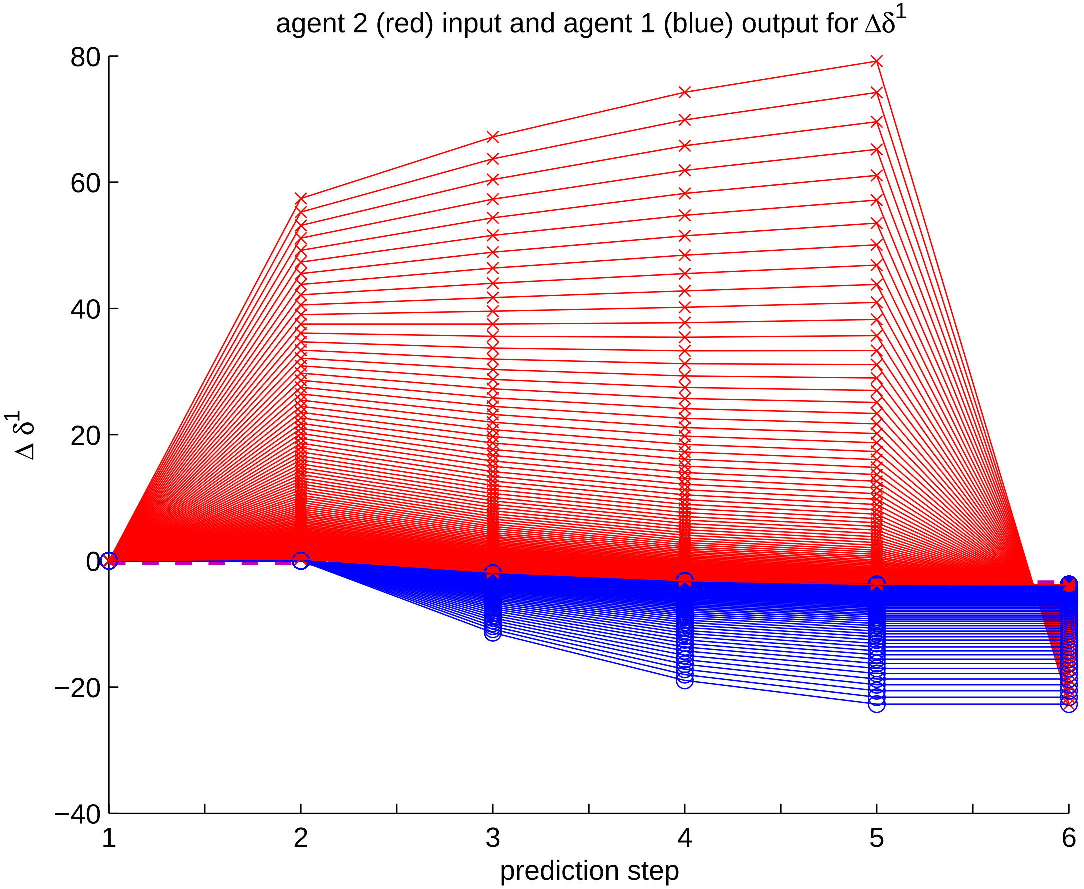
Iteration 30

5. Load frequency control



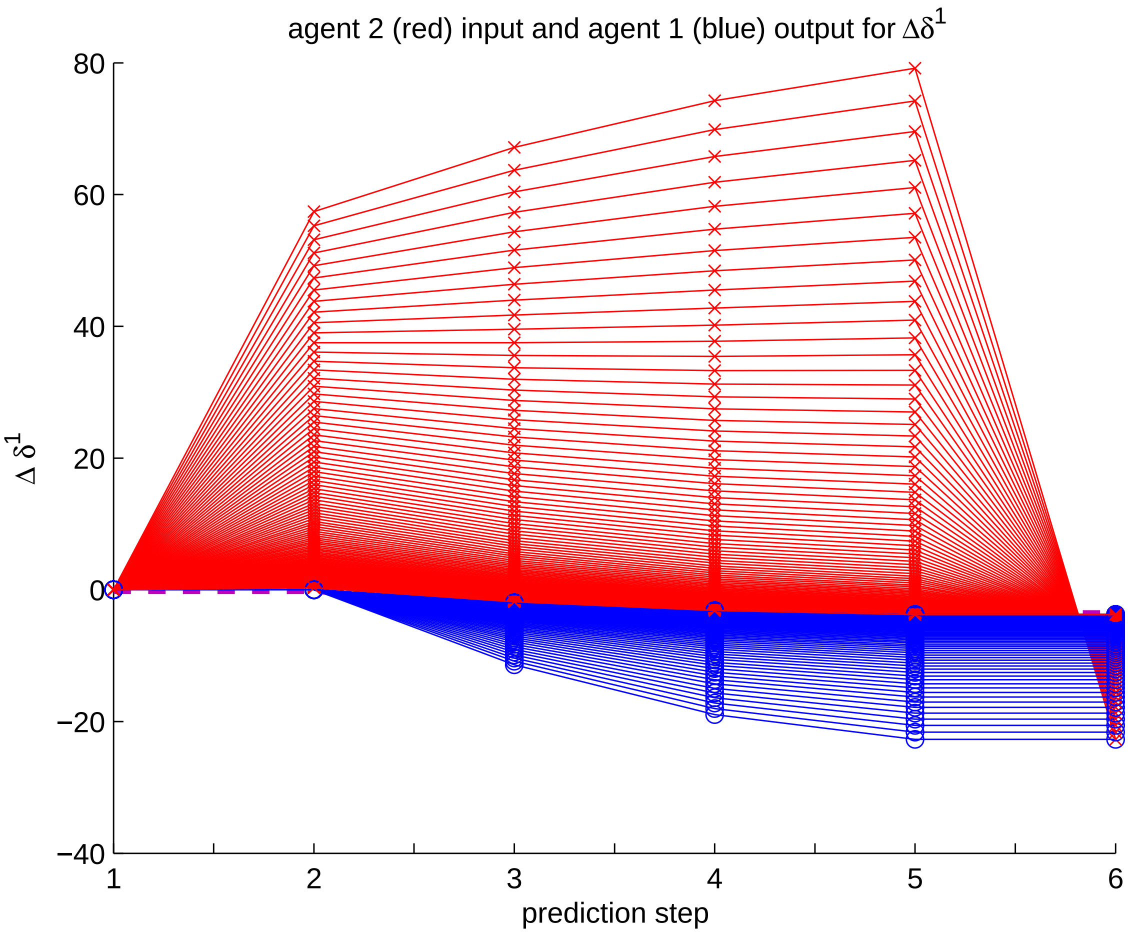
Iteration 80

5. Load frequency control



Final

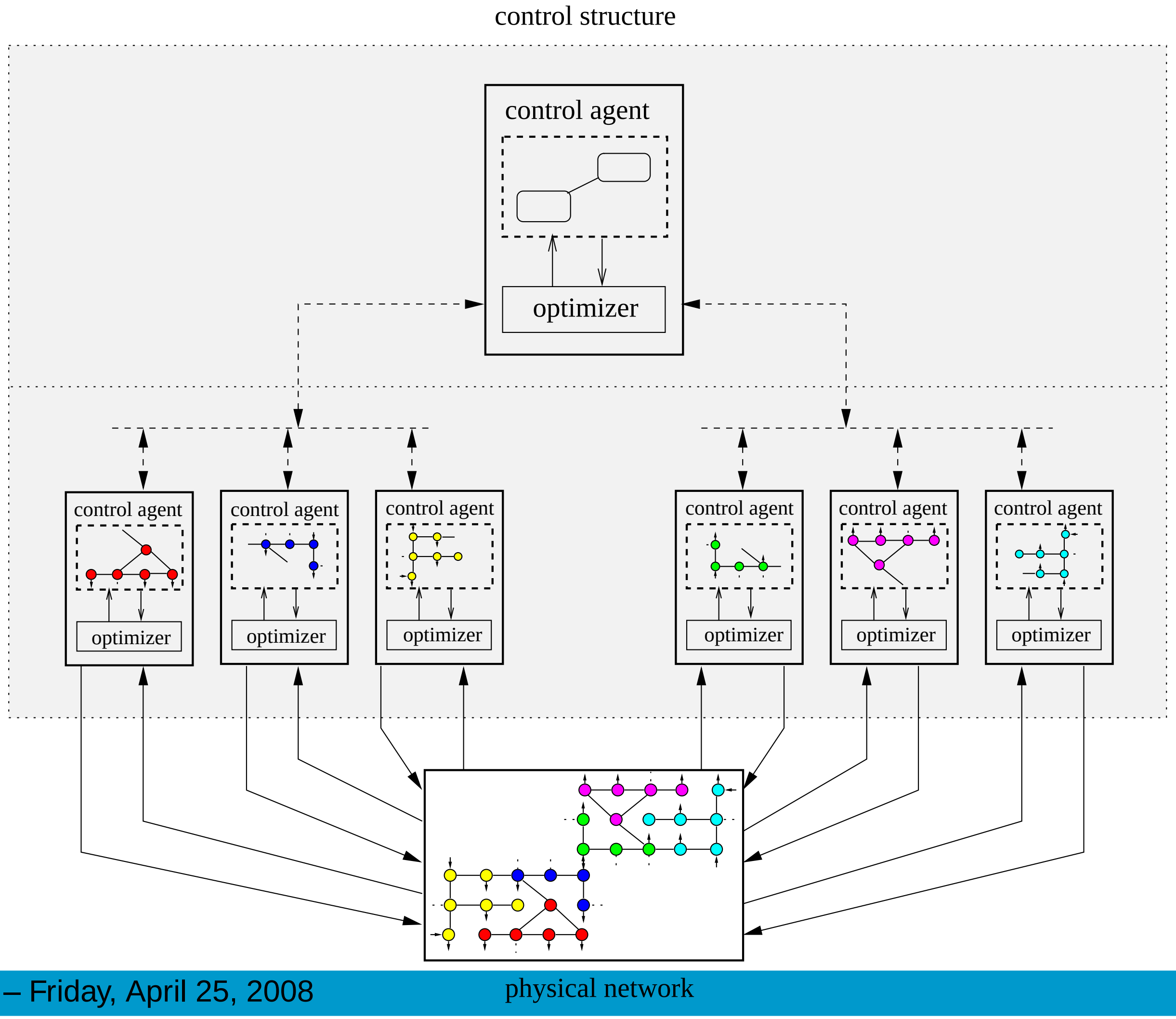
5. Load frequency control



- Convergence to satisfying interconnecting constraints
- Convergence to overall optimal solution under convexity assumption
  (e.g. linear models, continuous inputs, convex objective function)

6. What’s more?

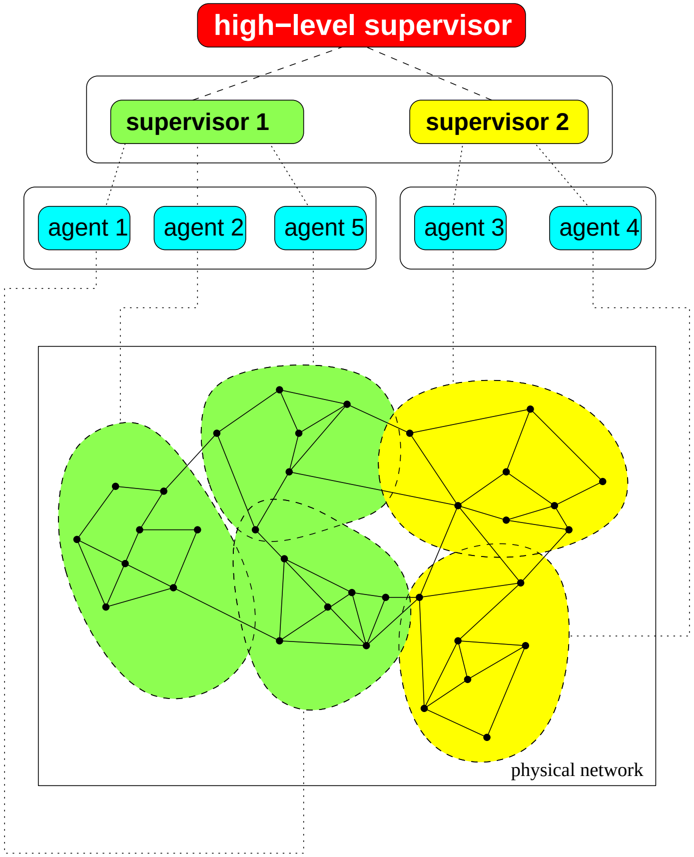
Hierarchical multi-agent MPC

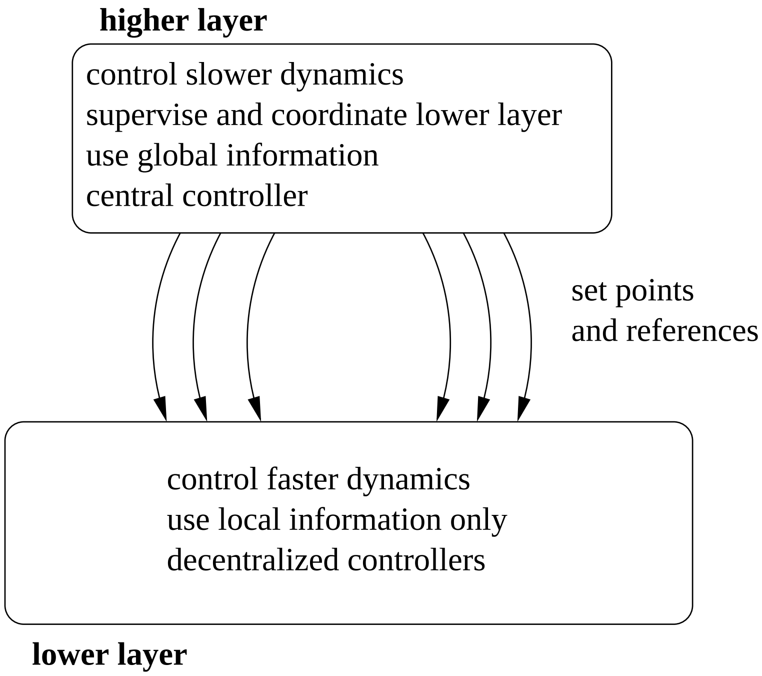


6. What's more?

Hierarchical multi-agent MPC

Time-based separation into layers





higher layer

control slower dynamics
supervise and coordinate lower layer
use global information
central controller

set points
and references

control faster dynamics
use local information only
decentralized controllers

lower layer

7. Concluding remarks

- Applications differ in control goals, available sensors and actuators, models used to make predictions, technique to solve the optimization problems
- Depending on structure of objective function, prediction model, and additional constraints a different type of optimization problem has to be solved
- Sometimes adequate solvers already exist, sometimes they have to be developed first
- Various contexts for MPC: Supervisory, distributed, decentralized
- Applications:
    - Emergency voltage control
    - Load frequency control
    - FACTS-based optimal flow
    - Household energy optimization

7. Concluding remarks

- Future application in control of open water systems (canals, rivers, . . .)
- Distributed control of hybrid systems, i.e., systems with both continuous and discrete dynamics
- Combining control engineering with computer science
  (e.g., single/multi-agent reasoning, planning, cognitive models, teamwork, coalition formation, distributed problem solving, modeling other agents and self, auction and mechanism design, . . .)

Further reading

`http://www.negenborn.net/mampc/`