京都大学
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Coordinated energy management

in prosumer communities

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Traditional Power System

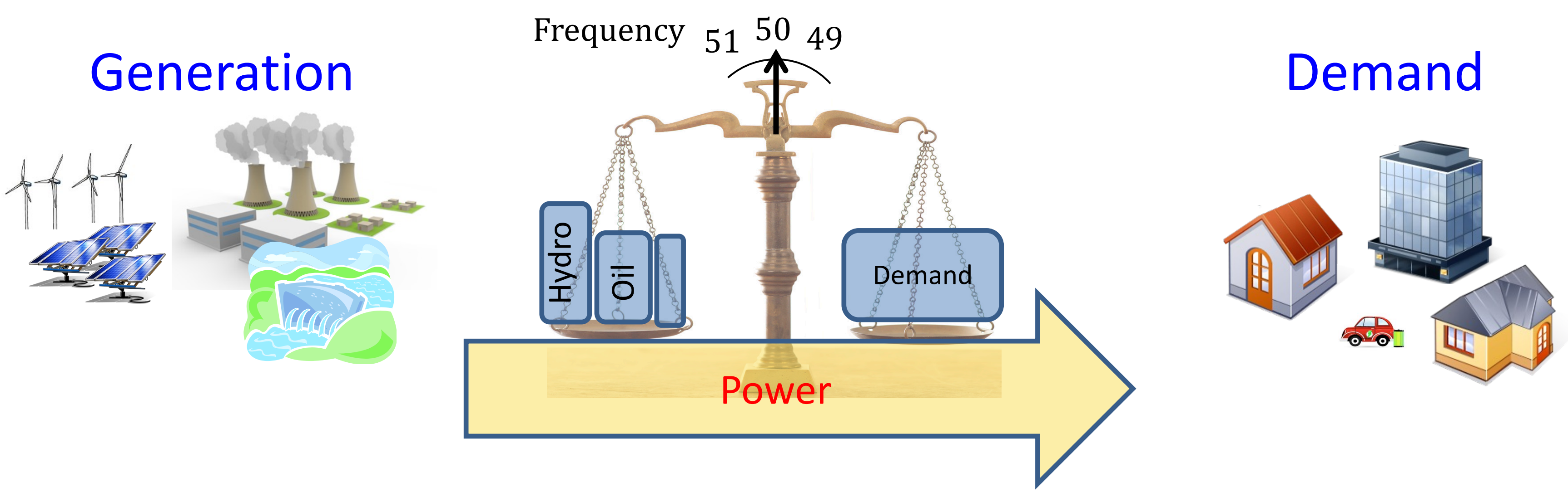
- Centralized Generation
- Uni-directional

- Generation is controlled
- Demand is not controlled

Power Balancing

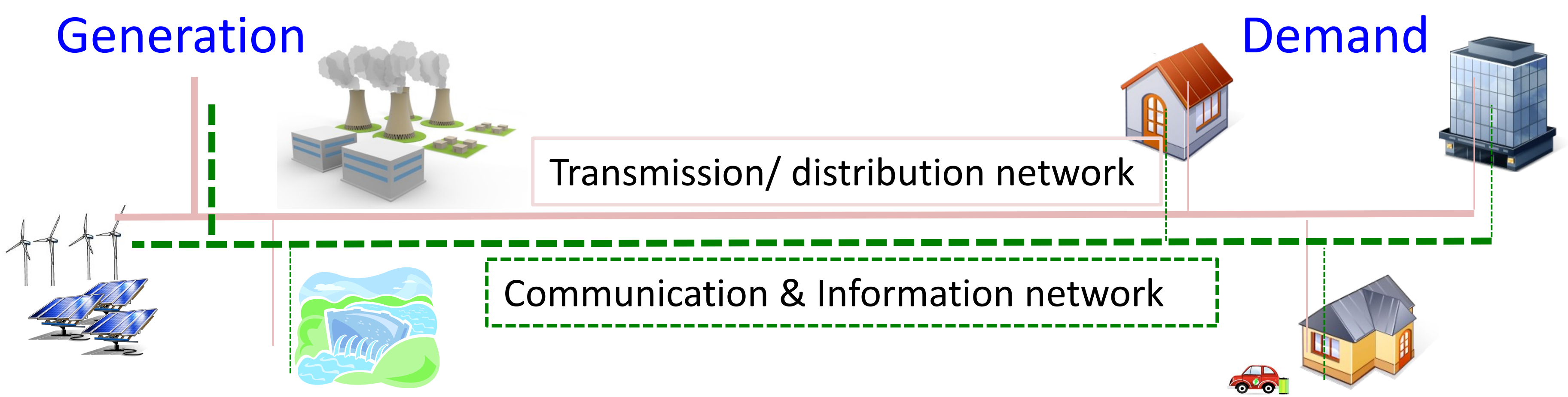
Supply = Demand (+Losses) [W]

Should be satisfied at all times



Grid → Smart-grid

- Smartgrid: Focus on improving the **grid**
- Goals
  - Improve reliability
  - Reduce cost
  - Reduce the need of peaking generation



Priorities in power systems

Developing countries

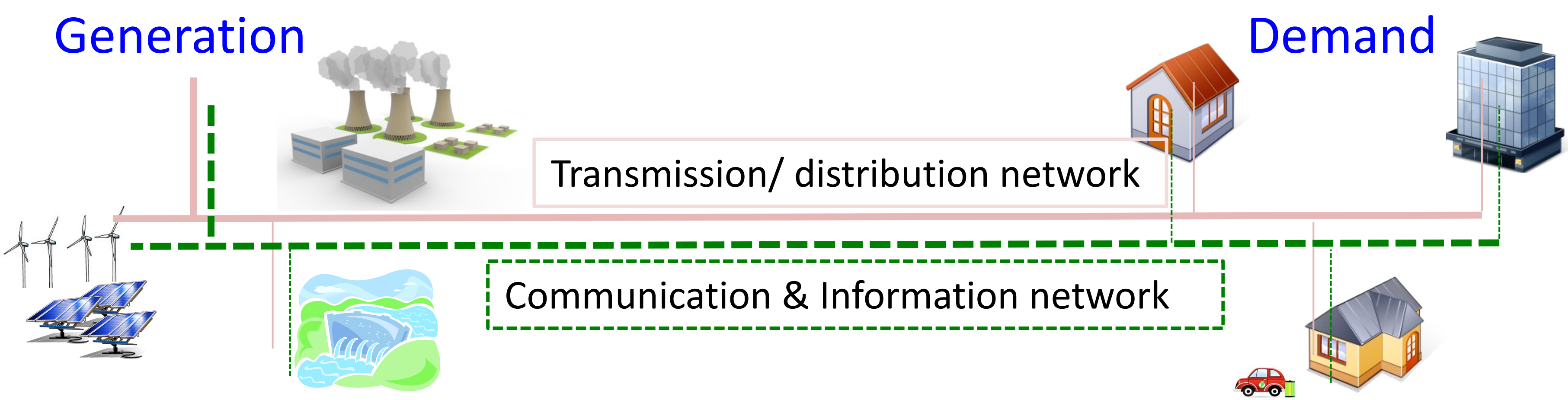
- Manage increasing generation capacity
- Improve system stability

Advanced countries

- Better management of energy consumption
- Demographics changes
- Environmental concerns

Diversify the generation mix

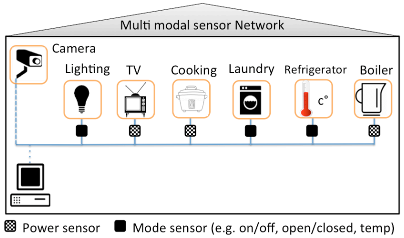
- reduce costs & increase energy security

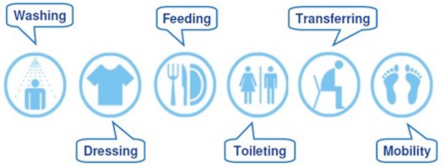


Changes in Technology

- Electrification of loads
  - Heating, transportation

- Sensing & Control
  - Smart-taps
  - Sensor networks
  - Living activity recognition
  - Energy Management Systems (EMS)
    - at home, factories, etc.





- Decrease in cost of
  - Storage (e.g. Batteries)
  - Renewables (e.g. PV and wind)

Changes in Government policies

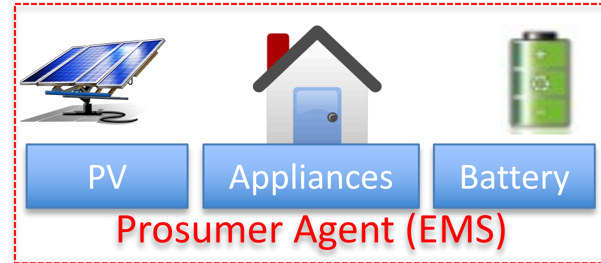
- Increase renewable use (Feed-in tariff (FIT) scheme)
- Deregulation of the power system
  - Elimination of vertical monopolies
  - Liberalization of
    - the generation market
    - the retail market (from April'16, Japan)

As a result:

- Reduced dependency on traditional power sources
- Decentralized & uncontrollable generation
- End-user has sensing, control & generation capabilities

Traditional model of the power system is not sufficient

Consumer → Prosumer

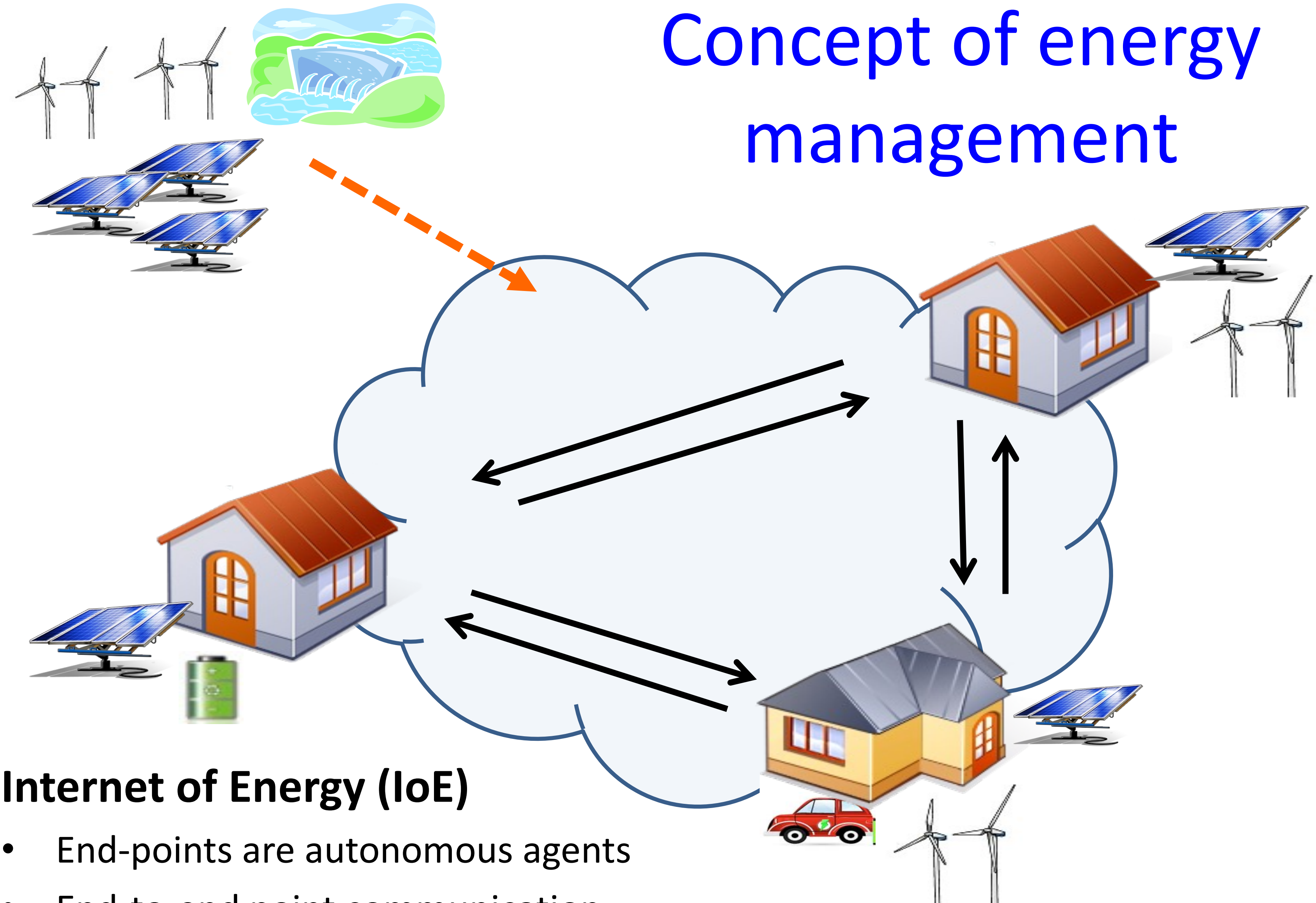


- Prosumer = producer & consumer
  - Sensing, Control, Generation, Storage
- Prosumer can buy & sell power energy
  - Decide which energy they want to buy (origin & type)
- Group of consumers → community of prosumers
- Centralized uni-directional → decentralized bidirectional system

This will require

- advanced communication & information technologies,
- advanced prediction & estimation technologies,
- new economic & social models

Concept of energy management

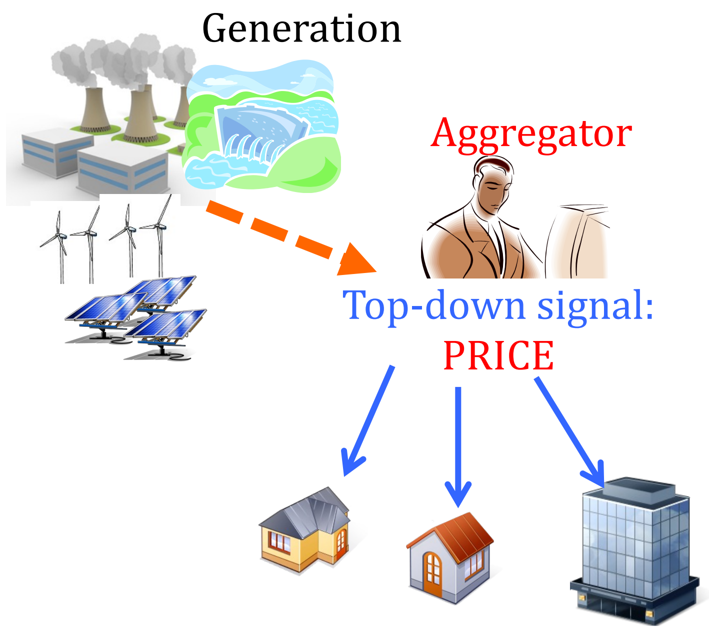


Internet of Energy (IoE)

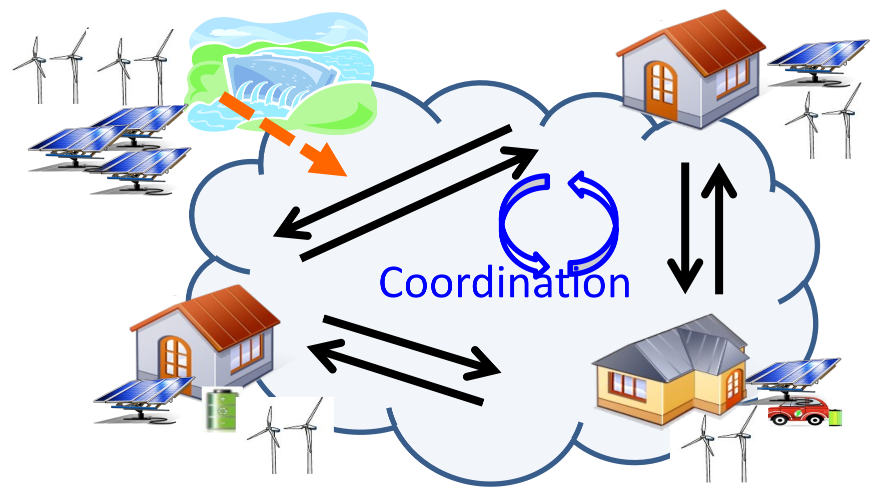
- End-points are autonomous agents
- End-to-end point communication
- Distributed management through collaboration
- IoE: Energy management protocols (vs device control of IoT)

Comparison

➔ Price-based Demand response

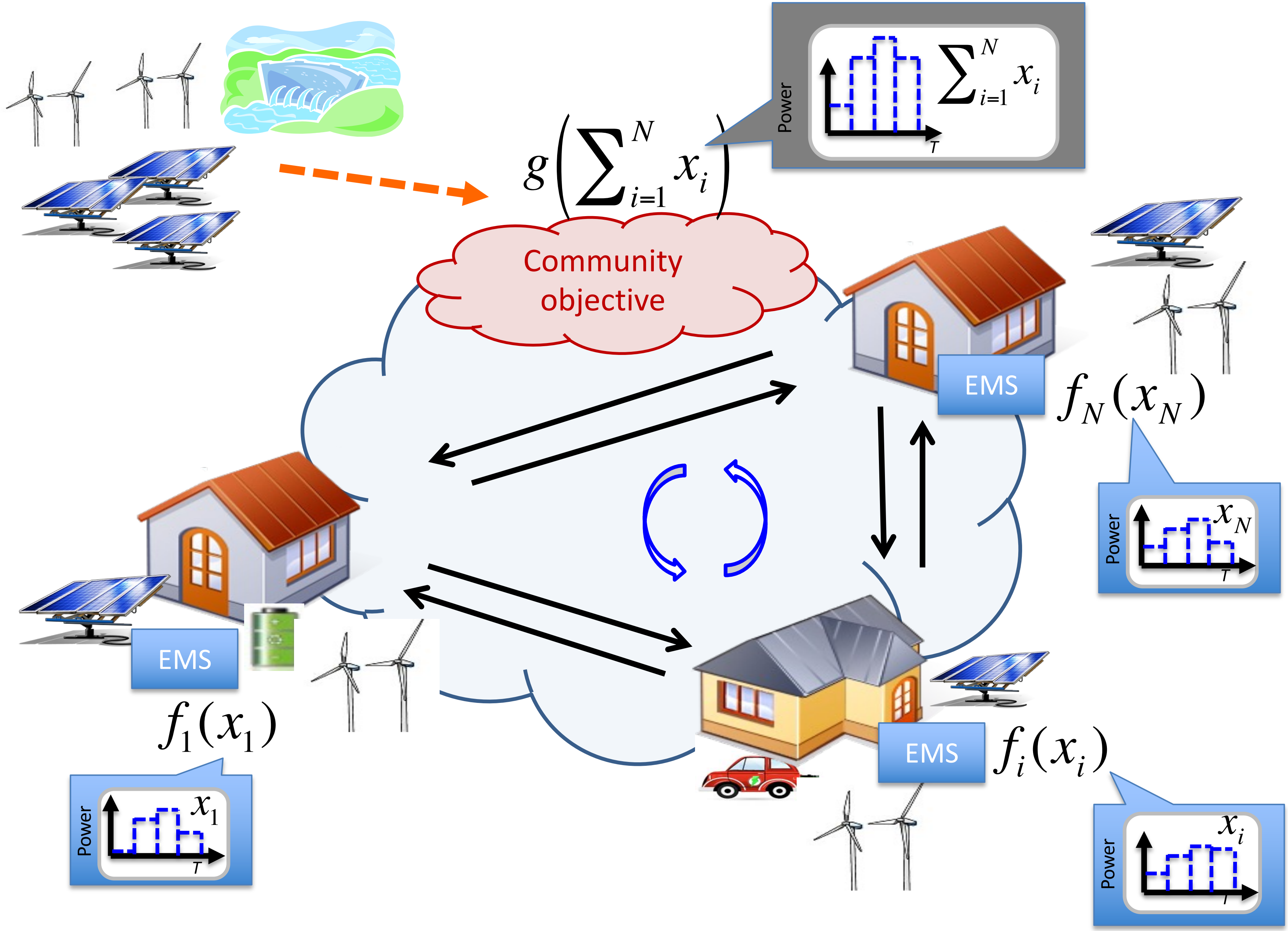


➔ Coordinated energy management



- Agents do not communicate
  - No control feedback
- Cluster of single agent best effort
- Limited control ability

- Agents communicate to coordinate
  - Control feedback
- Community best effort
- Higher control ability



A cost function is associated to each agent and to the community

Formulation (for day-ahead planning)

➔ Price-based Demand response

Price

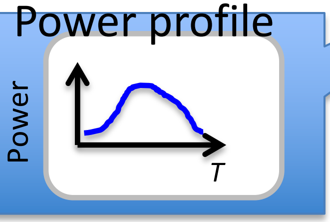
Aggregator Goal

$$\bar{y}, p^* = \underset{\bar{y},p}{\operatorname{argmin}}\ \tilde{g}(N\bar{y}, p),$$

Price

$$x_i^* = \underset{x_i}{\operatorname{argmin}}\ \hat{f}_i(x_i, p^*) \quad \forall i \in \mathcal{N}$$

Consumer Goal



➔ Coordinated energy management

Community Goal

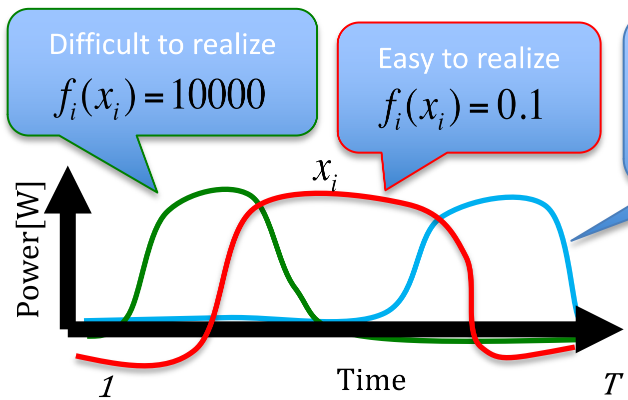
$$\underset{(x_i)_{i\in\mathcal{N}}}{\text{minimize}}\ \sum_{i\in\mathcal{N}} f_i(x_i) + g\Big(\sum_{i\in\mathcal{N}} x_i\Big)$$

Prosumer Goal

Power Profile-based coordination

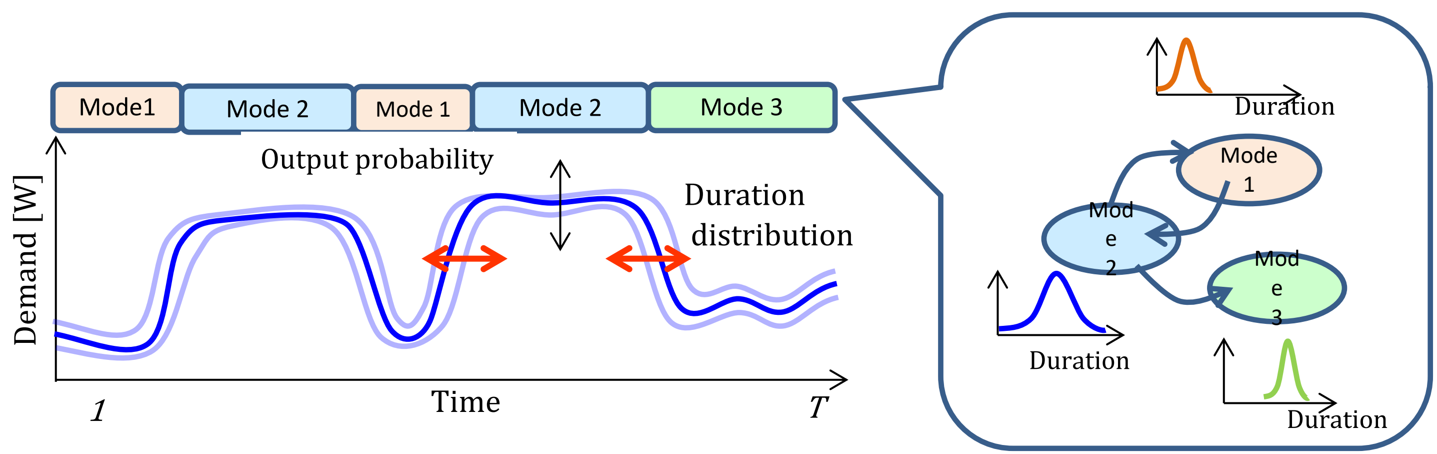
- Objective function $f_i(x_i)$ $x_i \in R^T$
  - Difficulty of realizing profile x_i by Household i

Related to the Quality of Live (QoL) associated to a given profile



Generative Model

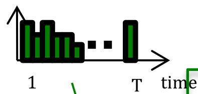
- Sequence of stages
- HSMM-based generative model



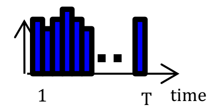
Preliminaries

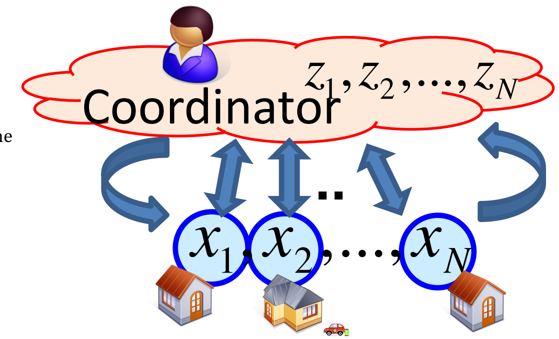
Distributed Optimization via ADMM

Sharing Problem:



Aggregated profile





$$\min_{x_1,\ldots,x_N} \quad L(x) \triangleq \sum_{i\in\mathcal{N}} f_i(x_i) + g\Big(\sum_{i\in\mathcal{N}} x_i\Big) \qquad x_i \in R^T$$

Global cost

Subject to $x_i = z_i$

Dual decomposition with Augmented Lagrangian

$$L_\rho(x,z,\lambda) \triangleq \sum_{i\in\mathcal{N}} f_i(x_i) + g\Big(\sum_{i\in\mathcal{N}} z_i\Big) + \sum_{i\in\mathcal{N}} \lambda_i^\top (x_i - z_i) + \frac{\rho}{2}\sum_{i\in\mathcal{N}} ||x_i - z_i||^2$$

Alternating Direction Method of Multipliers (ADMM):

$$x_i^{(k+1)} := \underset{x_i}{\operatorname{argmin}} \left(f_i(x_i) + \frac{\rho}{2}||x_i - x_i^{(k)} + b^{(k)}||^2 \right) \quad (i = 1, \ldots, N)$$

Prosumer

$x_i^{(k+1)}$

$$\bar{z}^{(k+1)} := \underset{\bar{z}}{\operatorname{argmin}} \left(g(N\bar{z}) + \frac{N\rho}{2}||\bar{z} - (\bar{x}^{(k+1)} + \eta^{(k)})||^2 \right)$$

$$\eta^{(k+1)} := \eta^{(k)} + \bar{x}^{(k+1)} - \bar{z}^{(k+1)}$$

$$b^{(k+1)} := \bar{x}^{(k+1)} - \bar{z}^{(k+1)} + \eta^{(k+1)}$$

$b^{(k)}$

Coordinator

Formulation (for day-ahead planning)

➔ Price-based Demand response

$$\bar{y}, p^* = \underset{\bar{y}, p}{\text{argmin}}\ \tilde{g}(N\bar{y}, p),$$

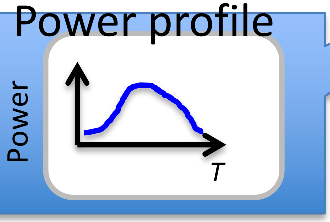
$$x_i^* = \underset{x_i}{\text{argmin}}\ \hat{f}_i(x_i, p^*)\ \forall i \in \mathcal{N}$$

Price

Aggregator Goal

Price

Consumer Goal



➔ Coordinated energy management

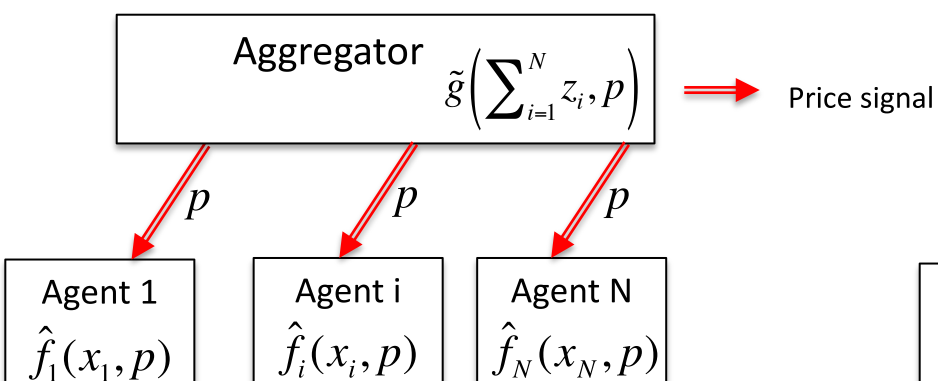
$$\underset{(x_i)_{i\in\mathcal{N}}}{\text{minimize}} \sum_{i\in\mathcal{N}} f_i(x_i) + g\Big(\sum_{i\in\mathcal{N}} x_i\Big)$$

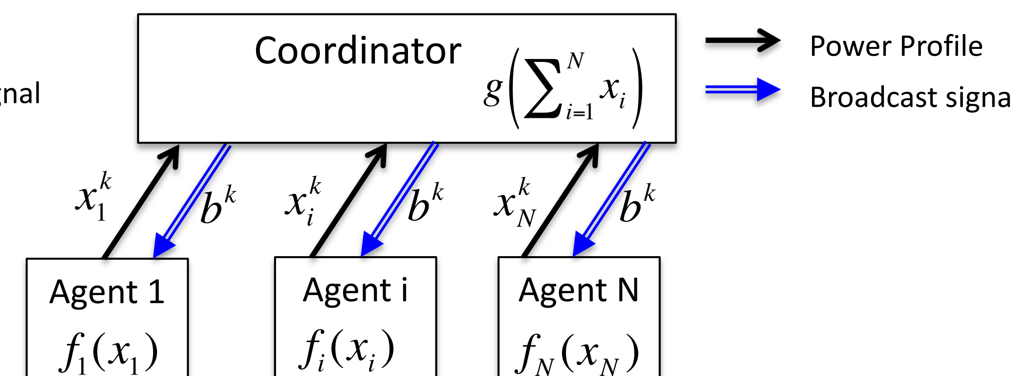
Community Goal

Prosumer Goal

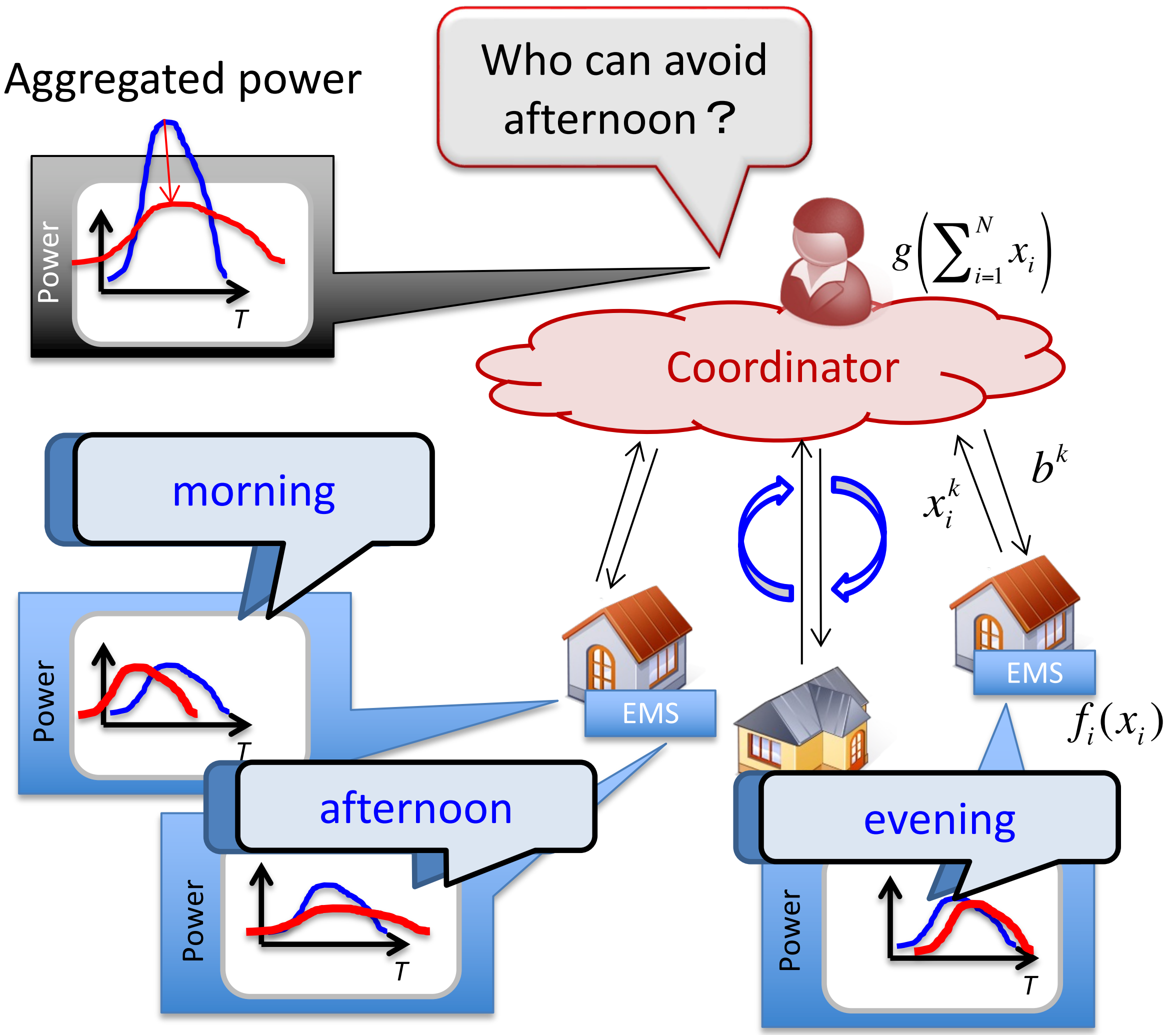
Solved using ADMM
(iterative distributed algorithm)

Architecture





Coordination Framework (ADMM based)



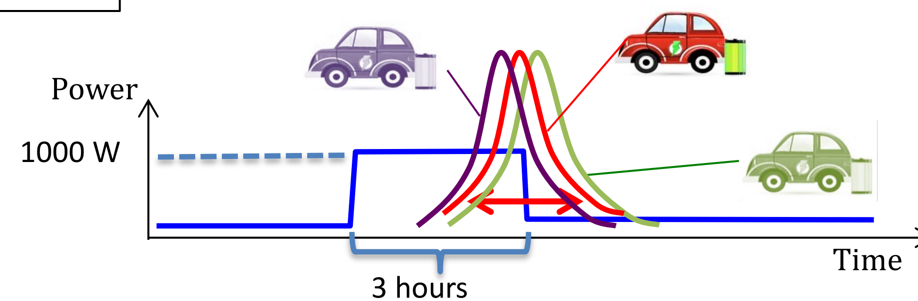
Illustrative Example. Scenario:

- 40 electric vehicles (EV) are charged.
- Charging all EVs at similar time should be avoided.

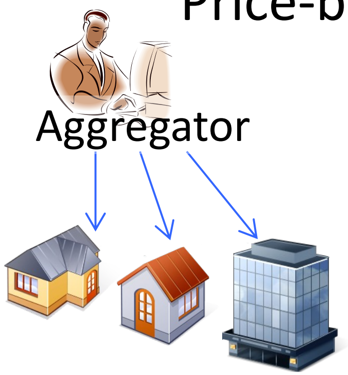
Electric vehicle charging

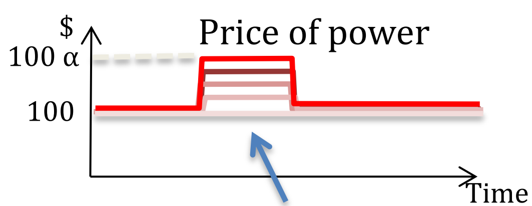
- Takes about 3 hours (uninterruptible)
- Requires 1000 Watts

The scheduling is done by taking into account each agent's preferences

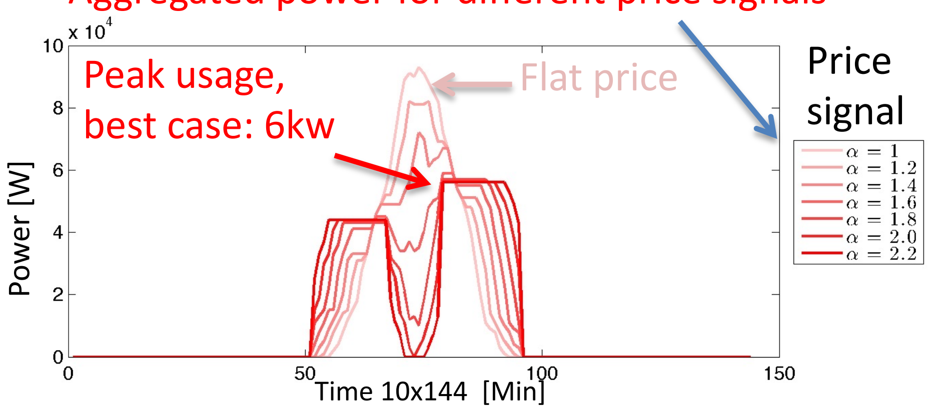


Price-based demand response

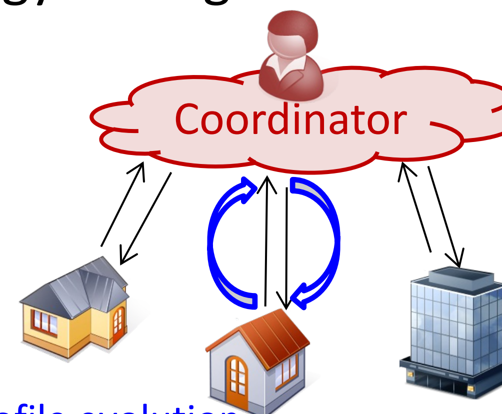




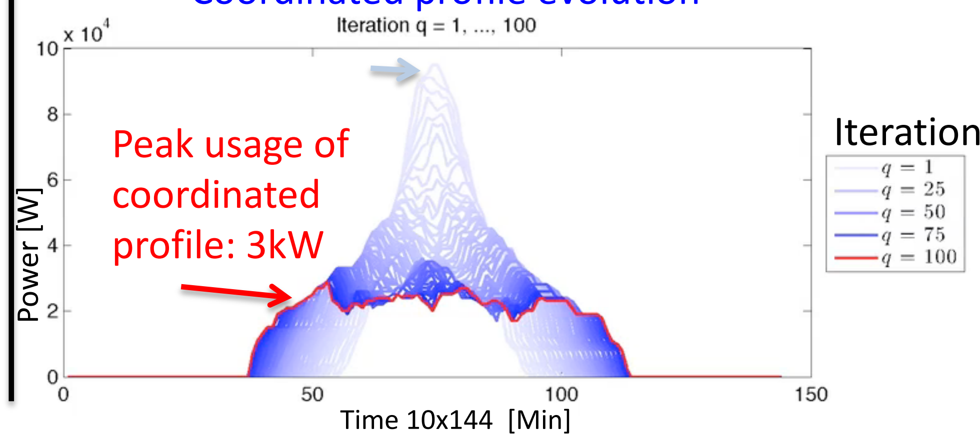
Aggregated power for different price signals

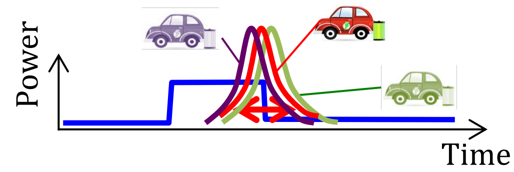


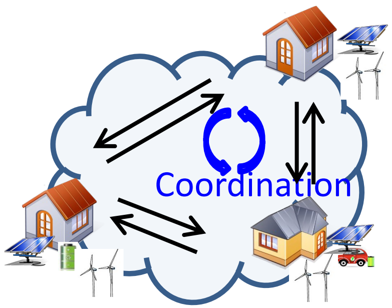
Coordinated energy management



Coordinated profile evolution

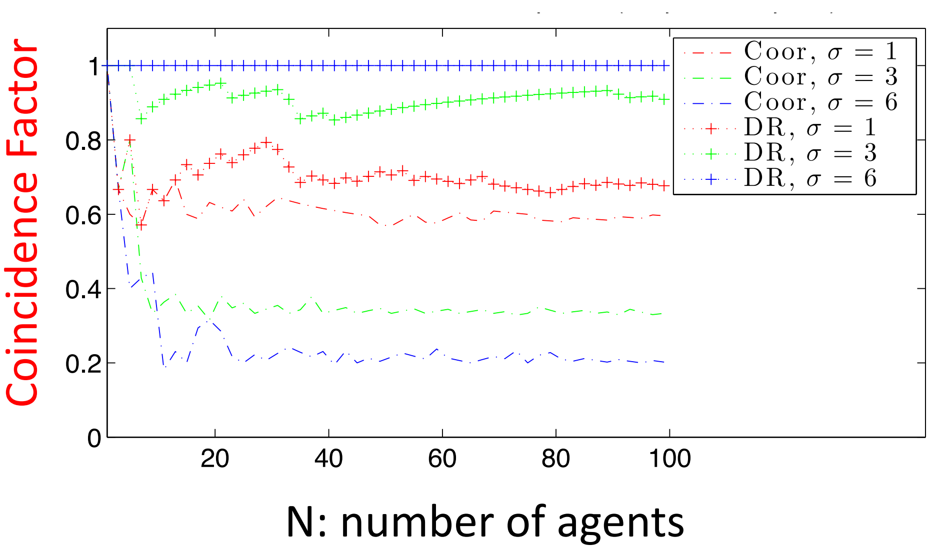




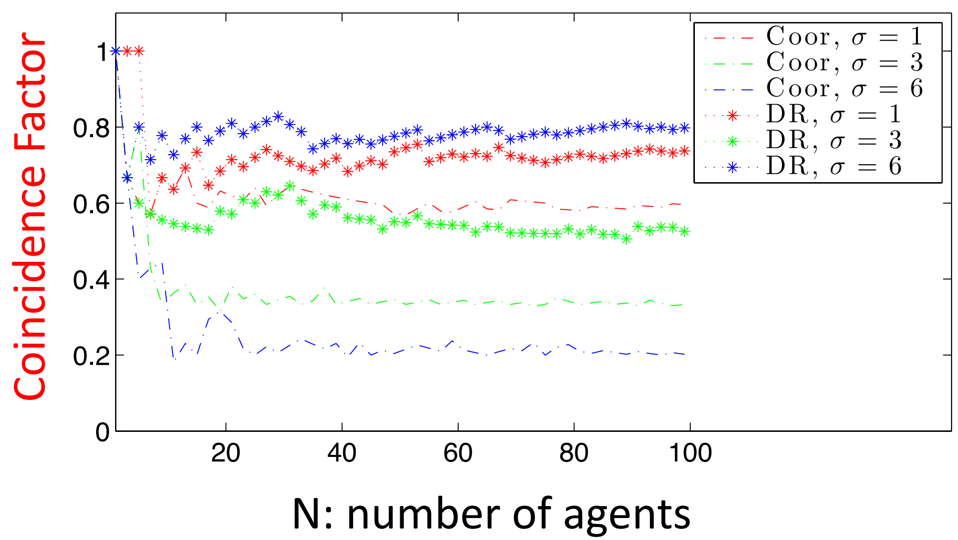


Scalability

Coordination versus critical-peak-pricing DR



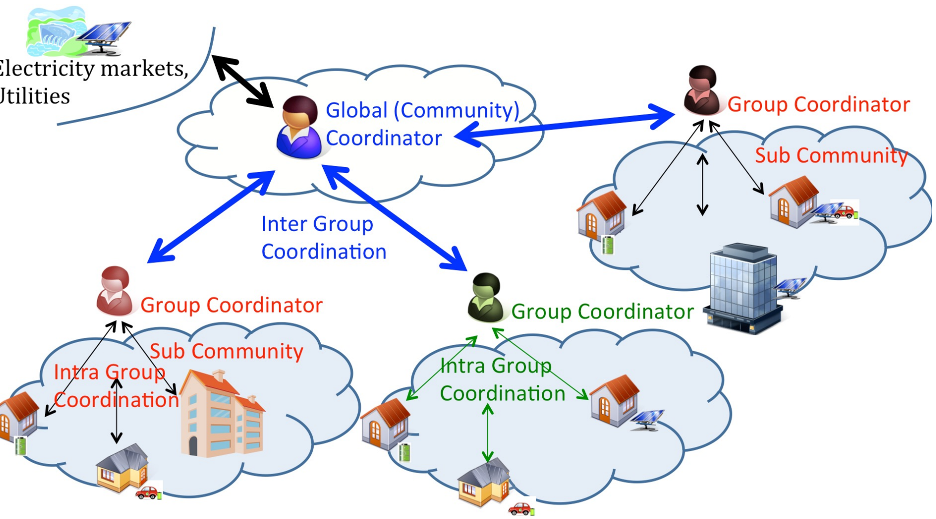
Coordination versus proportional price DR

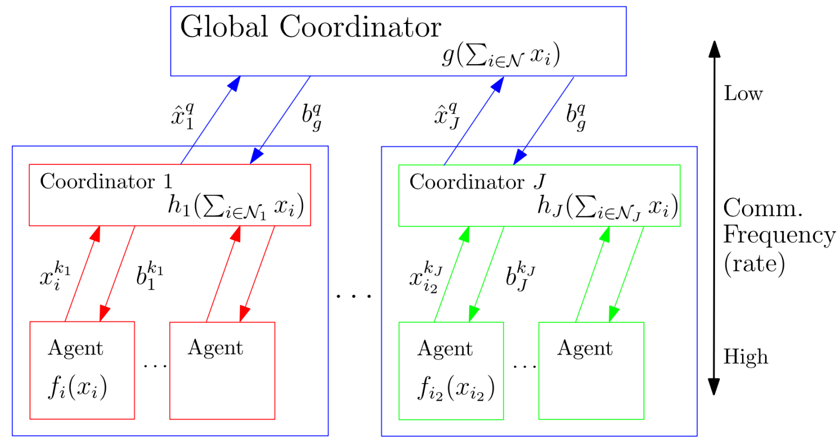


Coincidence Factor: peak consumption relative to peak consumption of worst case (no energy management)

Extension 1: Inter-community coordination

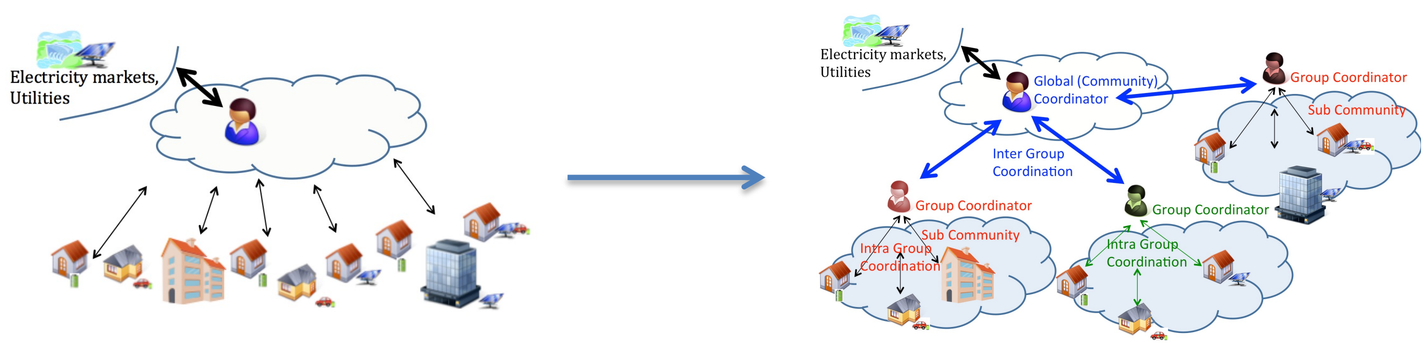
Hierarchical architecture & coordination algorithms





Extension 2: Group formation

Grouping of agents: assignment algorithm & criteria



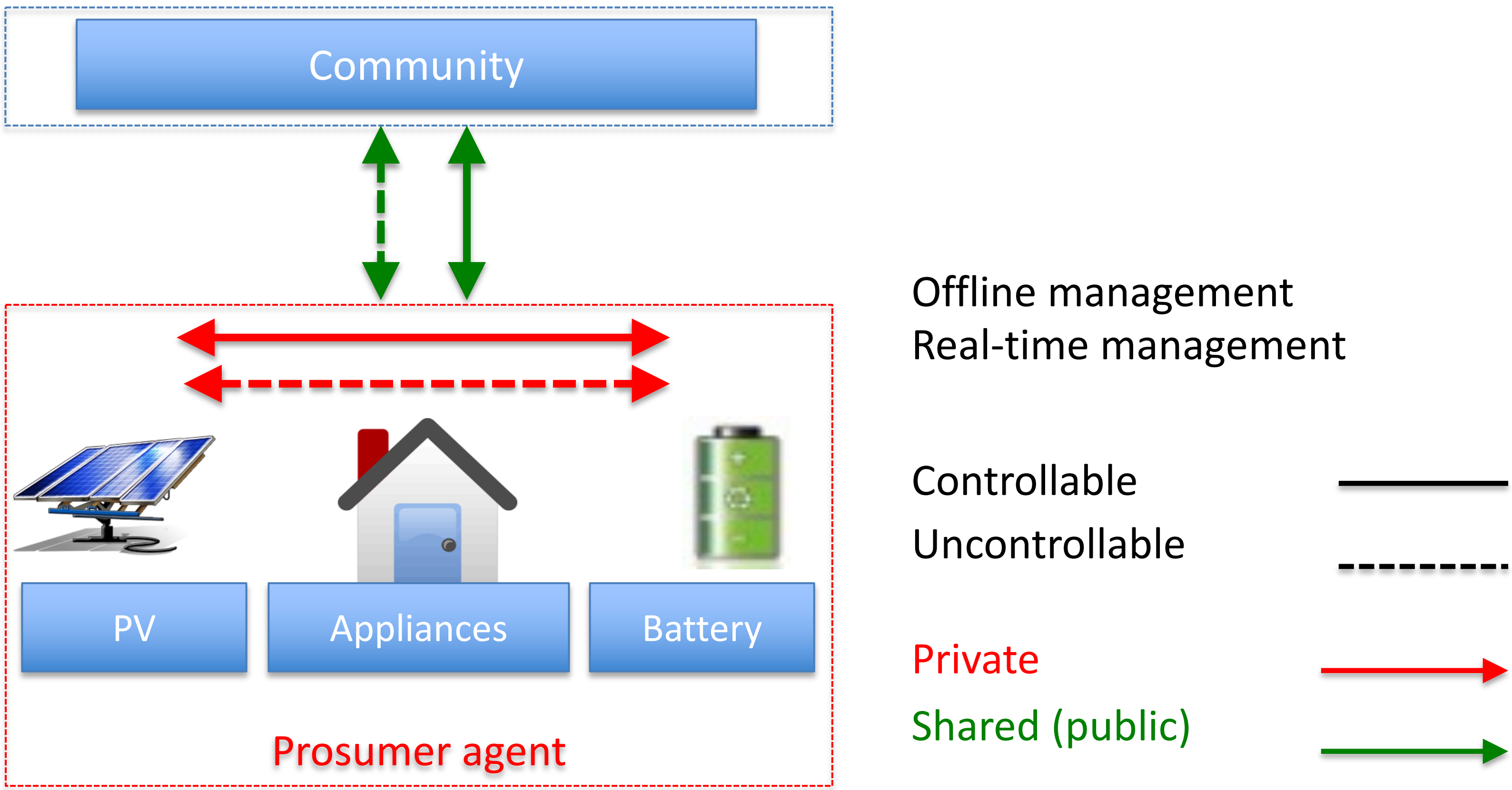
Extension 3: Plan update

AUGMENTED PROSUMER MODEL

Consumer → Prosumer

- Prosumer = producer & consumer
  - Sensing, Control, Generation, Storage
- Prosumer could buy & sell power energy
  - Decide which energy they want to buy (origin & type)
- Group of consumers → community of prosumers
- Centralized uni-directional → decentralized bidirectional

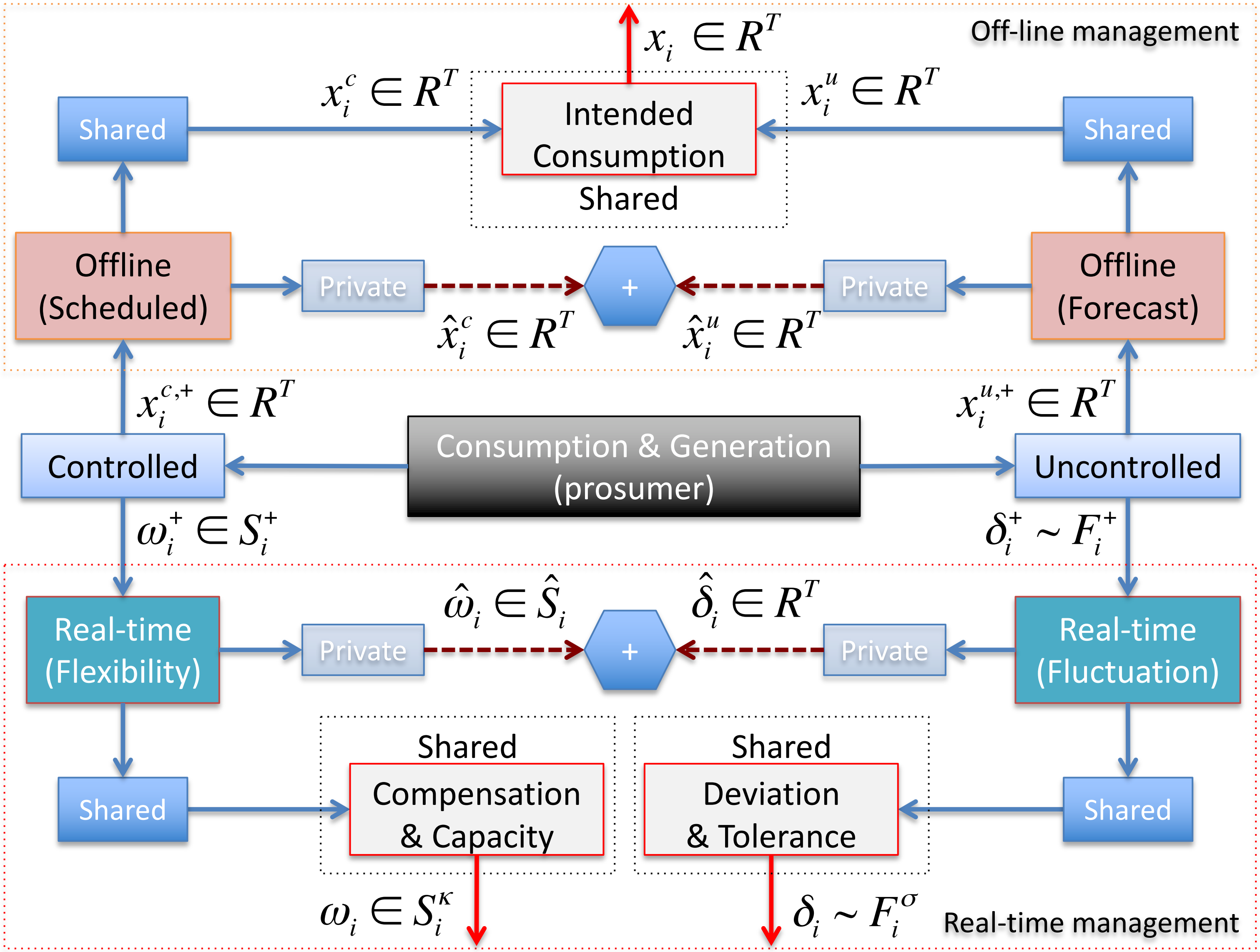
Consumer → Prosumer



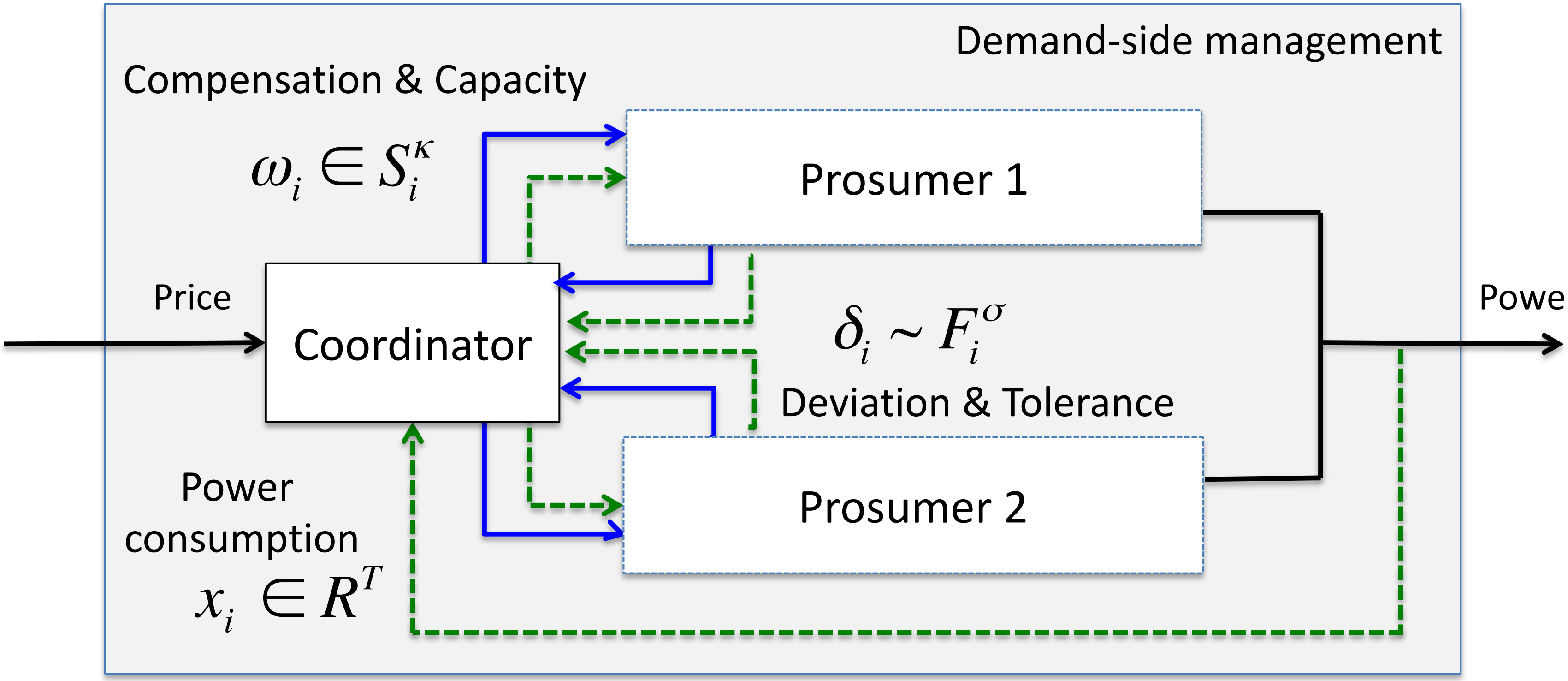
Augmented prosumer model

Power profile is decomposed in 8 components:

- Controlled / uncontrolled
- Offline / real-time
- Shared / private

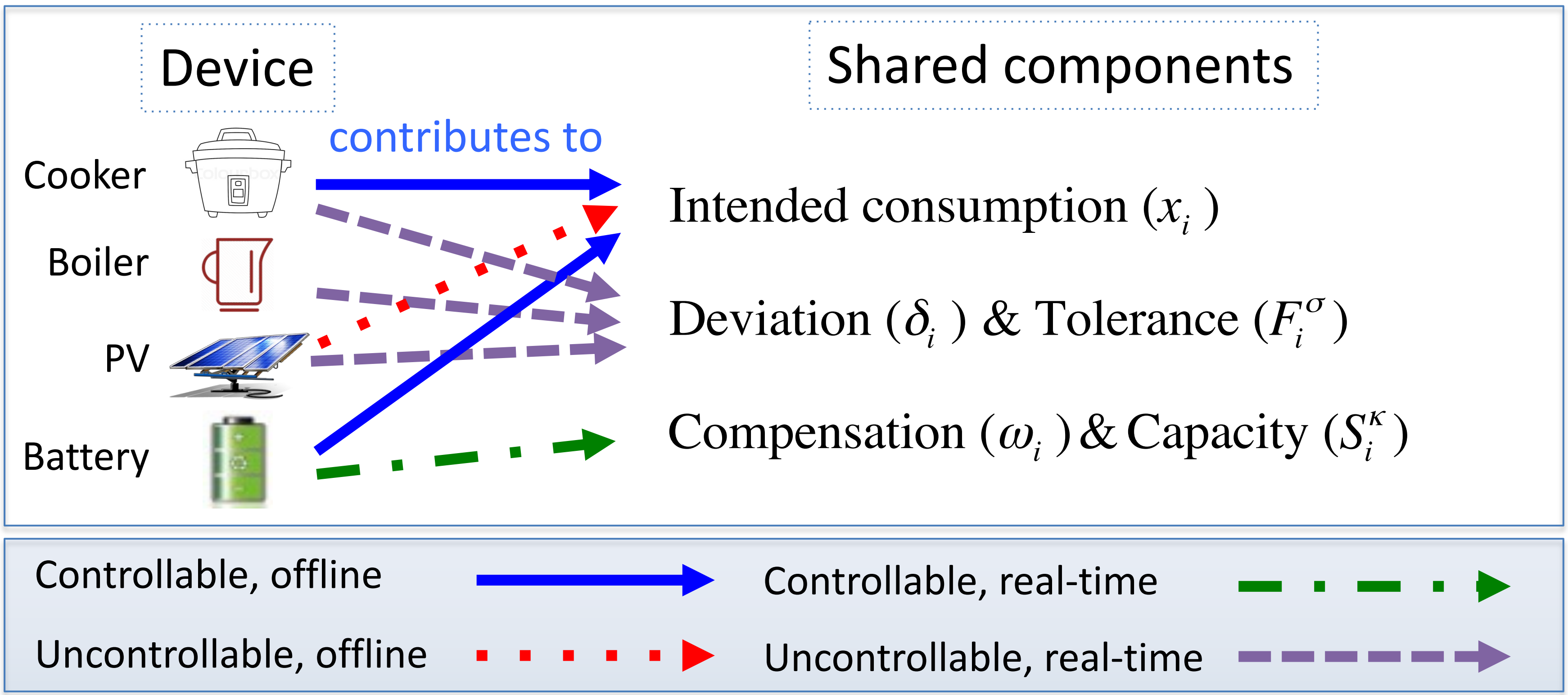


Augmented Control model



Prosumer model and devices

Intended consumption: $\sum_{p=1}^{P} x_i^p$, with $x_i^p \in \mathbb{R}^T$ the intended consumption of device p.
Compensation (shared and private) $\omega_i = \sum_{p=1}^{P} \omega_i^p$ and $\hat{\omega}_i = \sum_{p=1}^{P} \hat{\omega}_i^p$, and *capacity* (shared and private) $S_i = S_i^1 \oplus \ldots \oplus S_i^P$ and $\hat{S}_i = \hat{S}_i^1 \oplus \ldots \oplus \hat{S}_i^P$.
Deviation (shared and private) $\delta_i = \sum_{p=1}^{P} \delta_i^p$ and $\hat{\delta}_i = \sum_{p=1}^{P} \hat{\delta}_i^p$, and *tolerance* (shared and private) $F_i = F_i^1 * \ldots * S_i^P$ and $\hat{F}_i = \hat{F}_i^1 * \ldots * \hat{F}_i^P$.



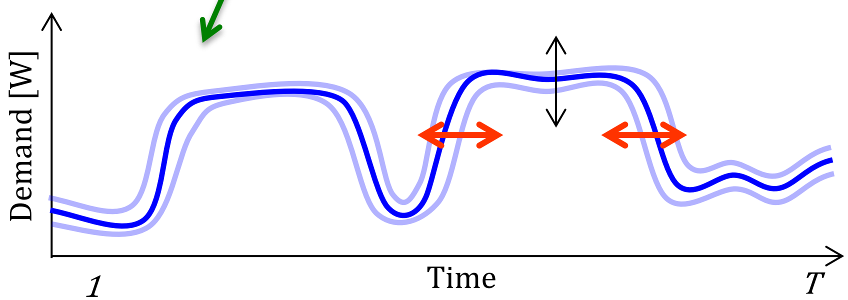
Decomposition of the ability to control the power profile

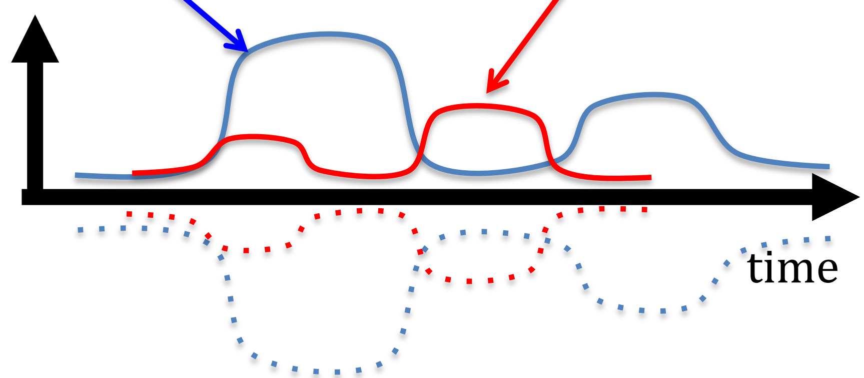
$x_i \in R^T$: Consumption plan profile

$\kappa_i \in R_+^T$: Control capacity profile [Wh]

$\sigma_i \in R_+^T$: Tolerance profile [W]

Represent PDF





These can be aggregated at the community level

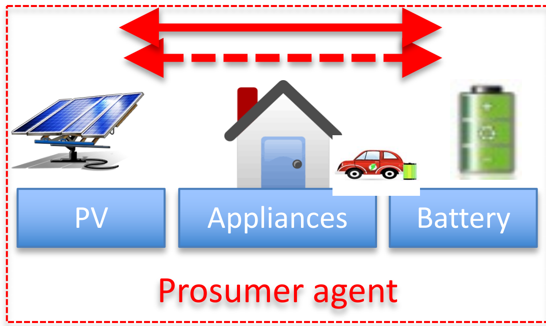
Augmented day-ahead coordination

Optimization problem (sharing problem)

$$\text{Minimize} \sum_{i \in \mathcal{N}} f_i(x_i, \sigma_i, \kappa_i,) + g(\sum_{i \in \mathcal{N}} x_i, \sum_{i \in \mathcal{N}} \sigma_i, \sum_{i \in \mathcal{N}} \kappa_i) \quad (1)$$

with i an agent $\in \mathcal{N}$.

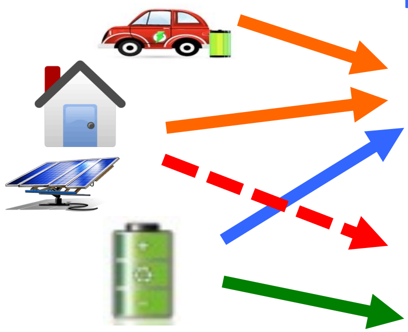
Basic Agent Model



Each agent has three devices:

- EV: controllable
- Battery: controllable
- PV: uncontrollable

The agents coordinate:



x_i : Power profile (generation + controllable appliance + base consumption + battery (dis)charge plan)

σ_i : Deviation profile

κ_i : Capacity profile

Optimization problem to be solved by the community

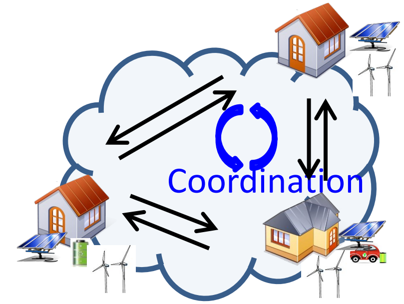
$$\underset{(x_i,\sigma_i,\kappa_i)_i}{\text{minimize}} \underbrace{\sum_{i=1}^{N} f_i(x_i,\sigma_i,\kappa_i)}_{\text{Agent cost}} + \underbrace{g^{x}\left(\sum_{i=1}^{N} x_i\right)}_{\text{Community cost (power)}} + \underbrace{g^{\sigma,\kappa}\left(\sum_{i=1}^{N} \sigma_i, \sum_{i=1}^{N} \kappa_i\right)}_{\text{Community cost (encapsulation of deviation by capacity)}}$$

Agent cost

Community cost (power)

Community cost (encapsulation of deviation by capacity)

Coordinator Model



Community objective function:

$$g(x,\sigma,\kappa) = g^{x}(x) + g^{\sigma,\kappa}(\sigma,\kappa)$$

Power Cost:

$$g^{x}(x) = \beta_2 \|x\|^2$$

Flatten power

Encapsulation of deviation by capacity:

Shared capacity larger than aggregated shared deviation (at each time slot)

$$g^{\sigma,\kappa}(\sigma,\kappa) = \Pi\left[\Delta d\sigma_t < \kappa_t - C_\kappa, \forall t\right], \text{ with } C_\kappa = 50[Wh]$$

Gap

$$\sigma = (\sigma_1,\ldots,\sigma_T) \in R_+^T$$

$$\kappa = (\kappa_1,\ldots,\kappa_T) \in R_+^T$$

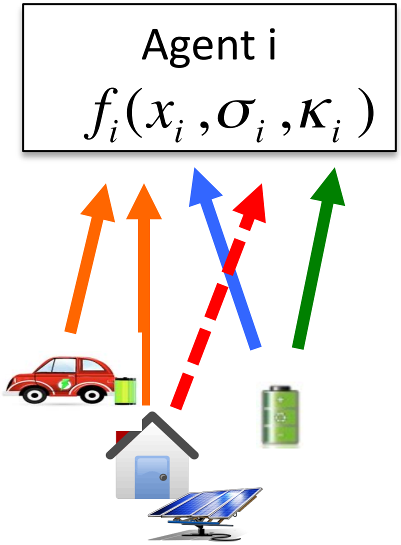
Δd with is the time-slot duration

e.g. $\Delta d x T = 24\text{hrs}$

Indicator function:

$$\Pi[v] = \begin{cases} 0, & \text{if } v \text{ is true} \\ +\infty, & \text{otherwise} \end{cases}$$

["Energy Management in Prosumer Communities: A Coordinated Approach", Energies (under review).]



Agent model

x_i : Power profile (base consumption +battery)

σ_i : Deviation profile

κ_i : Capacity profile

$$f_i(x_i, \sigma_i, \kappa_i) = \min_{\tau_i, y_i \in \mathcal{U}_i} f_i^{\tau}(\tau_i) + f_i^{x|\tau,y}(x_i, \tau_i, y_i) + f_i^{\sigma,\kappa|y}(\sigma_i, \kappa_i, y_i)$$

Control Variables:

- Battery Charge/discharge plan
- EV starting time

EV scheduling

Constraint

Capacity, deviation, & battery

Battery charge/discharge

EV charging profile

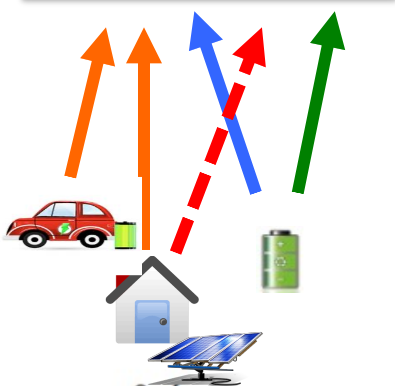
Base consumption

Constraint: $f_i^{x|\tau,y}(x_i, \tau_i, y_i) = \Pi[x_i = \psi_i(\tau_i) + y_i + \bar{x}_i^g]$

$$\Pi[v] = \begin{cases} 0, & \text{if } v \text{ is true} \\ +\infty, & \text{otherwise} \end{cases}$$

Agent i

$f_i(x_i, \sigma_i, \kappa_i)$



Agent model

$$\Pi[v] = \begin{cases} 0, & \text{if } v \text{ is true} \\ +\infty, & \text{otherwise} \end{cases} \quad \mathbf{1}_T = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \\ 1 \end{pmatrix}, \quad \mathbf{L} = \begin{pmatrix} \Delta d & 0 & 0 & \cdots & 0 \\ \Delta d & \Delta d & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 & \vdots \\ \Delta d & \Delta d & \cdots & \Delta d & 0 \\ \Delta d & \Delta d & \cdots & \Delta d & \Delta d \end{pmatrix}$$

x_i : Power profile (base consumption +battery)

σ_i : Deviation profile

κ_i : Capacity profile

$$f_i(x_i, \sigma_i, \kappa_i) = \min_{\tau_i, y_i \in \mathcal{U}_i} f_i^{\tau}(\tau_i) + f_i^{x|\tau,y}(x_i, \tau_i, y_i) + f_i^{\sigma,\kappa|y}(\sigma_i, \kappa_i, y_i)$$

Control Variables: | EV | Constraint | Capacity, deviation, & battery

Battery:

SoC | Capacity | Private capacity = priv deviation

$$f_i^{\sigma,\kappa|y}(\sigma_i, \kappa_i, y_i) = \beta_2 \|\sigma_i\|^2 + \beta_3 \|\kappa_i\|^2$$
$$+\Pi\left[C_{\min} 1_T \le L y_i + c_0 + \kappa_i + \Delta d(\sigma_i^{\max} - \sigma_i) \le C_{\max} 1_T\right]$$
$$+\Pi\left[C_{\min} 1_T \le L y_i + c_0 - \kappa_i - \Delta d(\sigma_i^{\max} - \sigma_i) \le C_{\max} 1_T\right]$$
$$+\Pi\left[C_{\min} 1_T \le L y_i + c_0 \le C_{\max} 1_T\right]$$
$$+\Pi\left[y_i^{\min} \le y_i \le y_i^{\max}\right] + \Pi\left[\kappa_i^{\min} \le \kappa_i \le \kappa_i^{\max}\right] + \Pi\left[\sigma_i^{\min} \le \sigma_i \le \sigma_i^{\max}\right]$$

allow negative shared deviation & negative shared capacity

Encapsulation (symmetric deviation and capacity)

Constraints (allowed ranges)

RESULTS

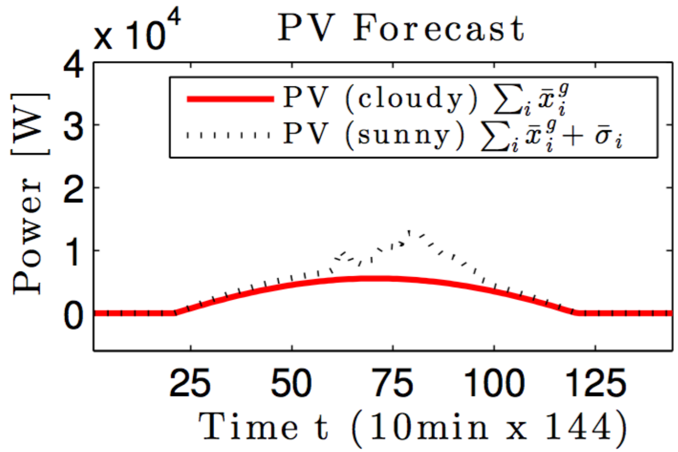
Example 1

- PV (deviation)

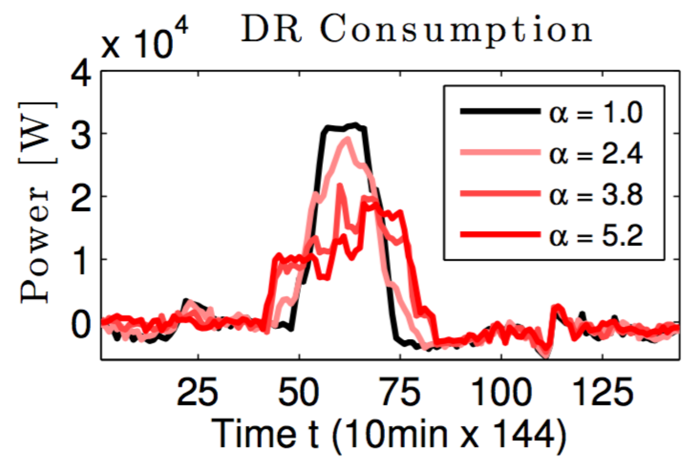
- EV (off line control)
- Battery (online & off line control)

Generation

Demand response:
intended power consumption

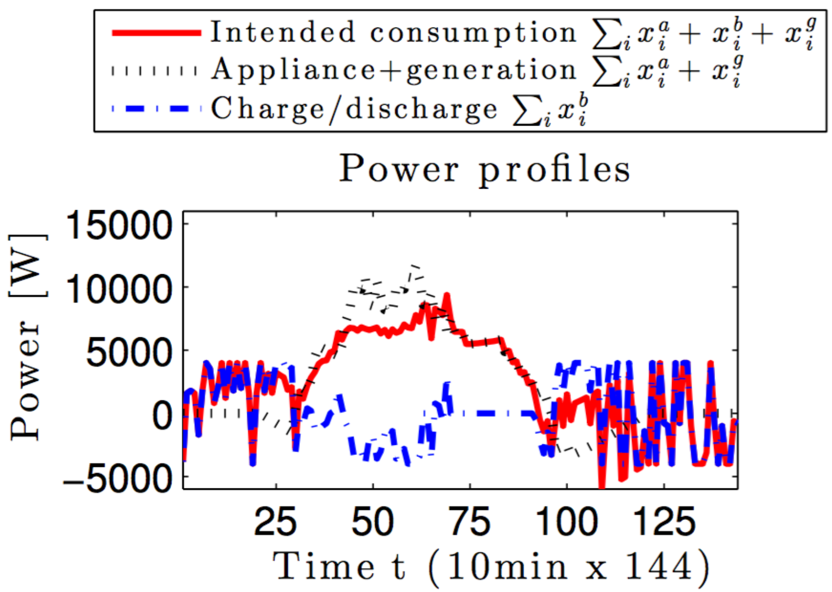


(a)

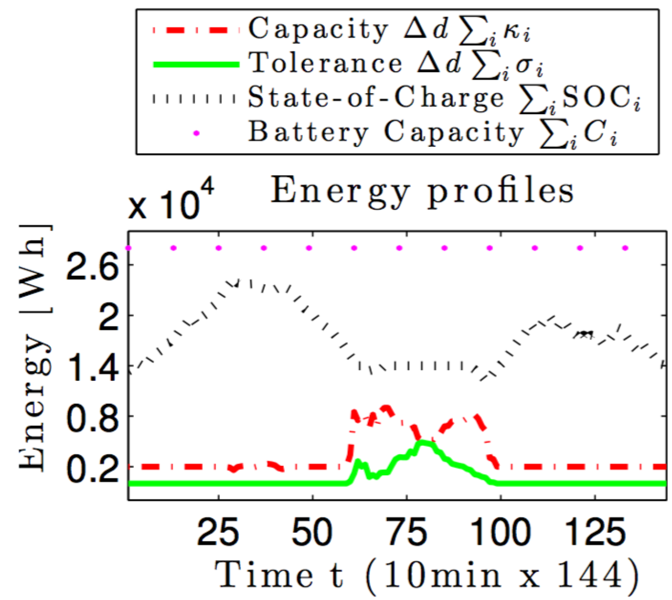


(b)

Coordination: intended power consumption



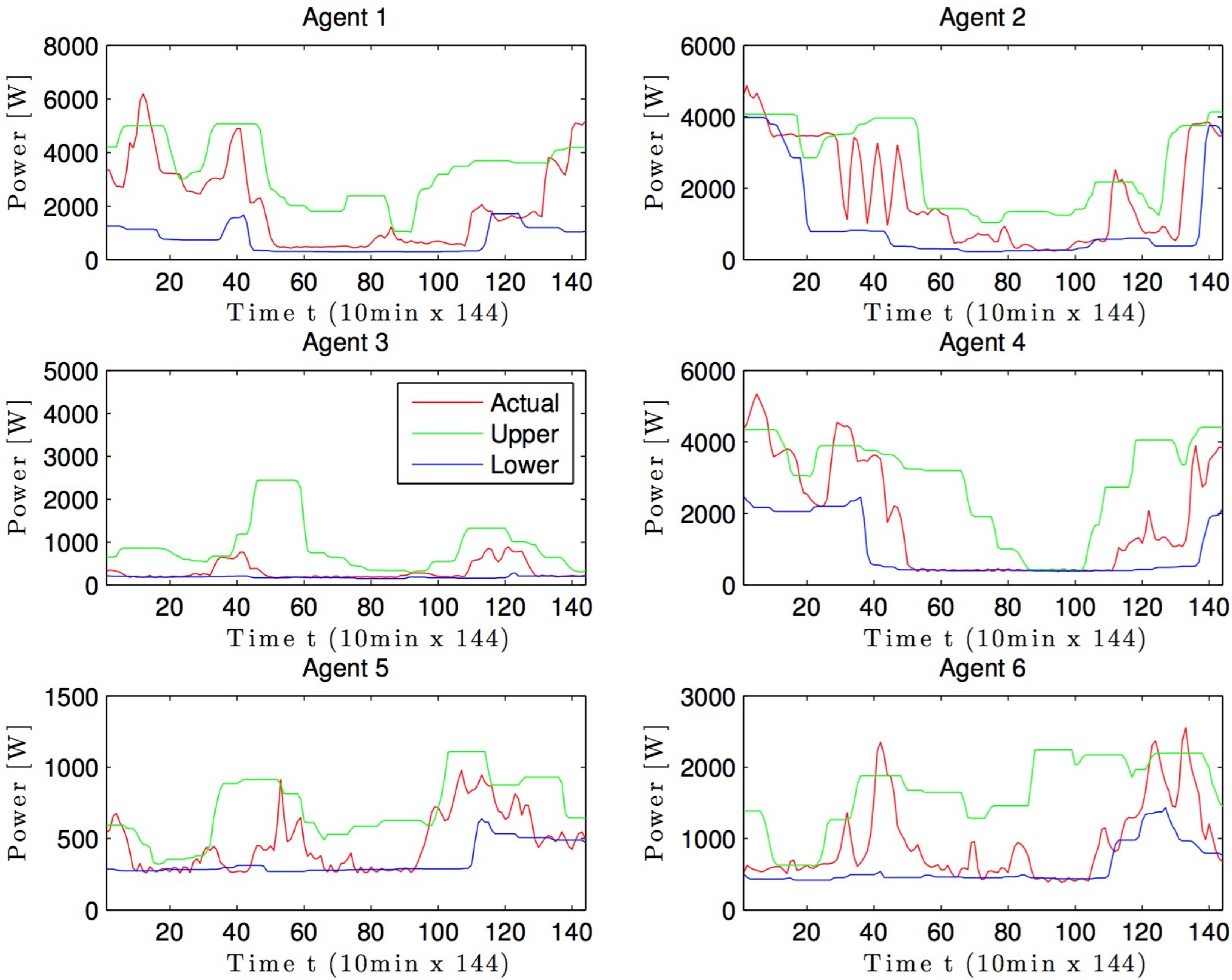
Coordination: Tolerance & capacity



Example 2

- Household (deviation): real data
- Battery (online & off line control)

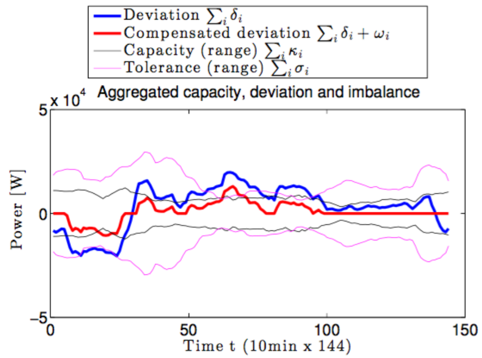
Consumption data



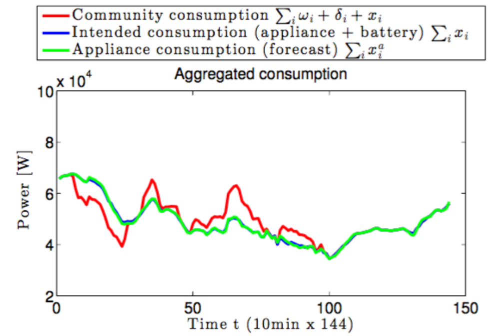
Day ahead-planning

Deviation / compensation | Power Consumption | Imbalance

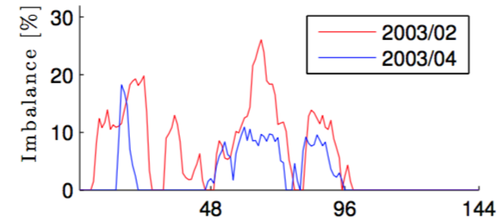
Tiny



(a) $\bar{C} = 0.3 \times 700[Wh]$.

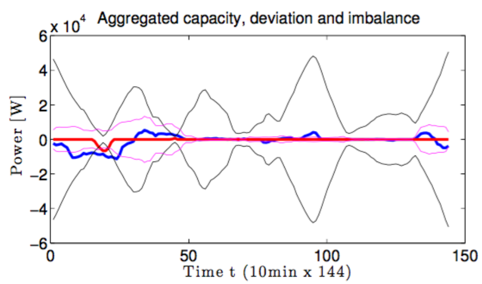


(b) $\bar{C} = 0.3 \times 700[Wh]$.

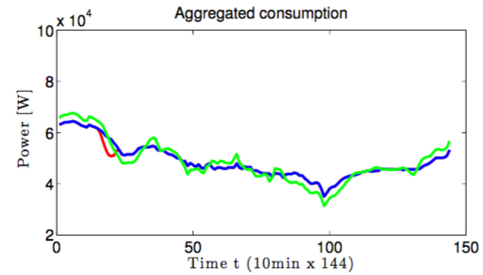


(c) $\bar{C} = 0.3 \times 700[Wh]$.

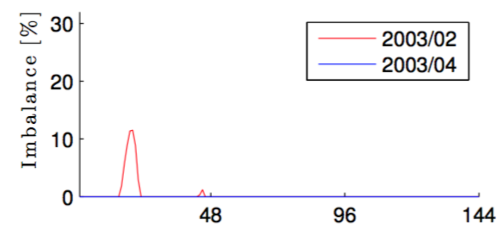
Small



(d) $\bar{C} = 700[Wh]$.

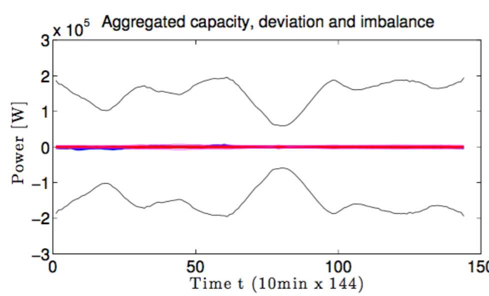


(e) $\bar{C} = 700[Wh]$.

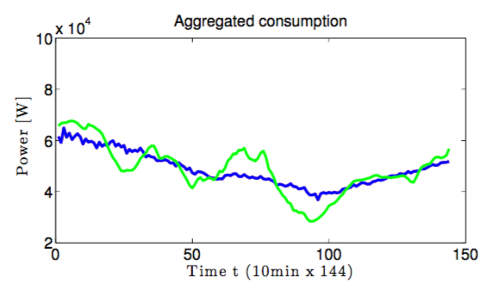


(f) $\bar{C} = 700[Wh]$.

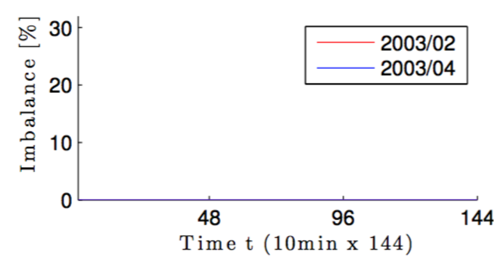
Medium



(g) $\bar{C} = 3 \times 700[Wh]$.

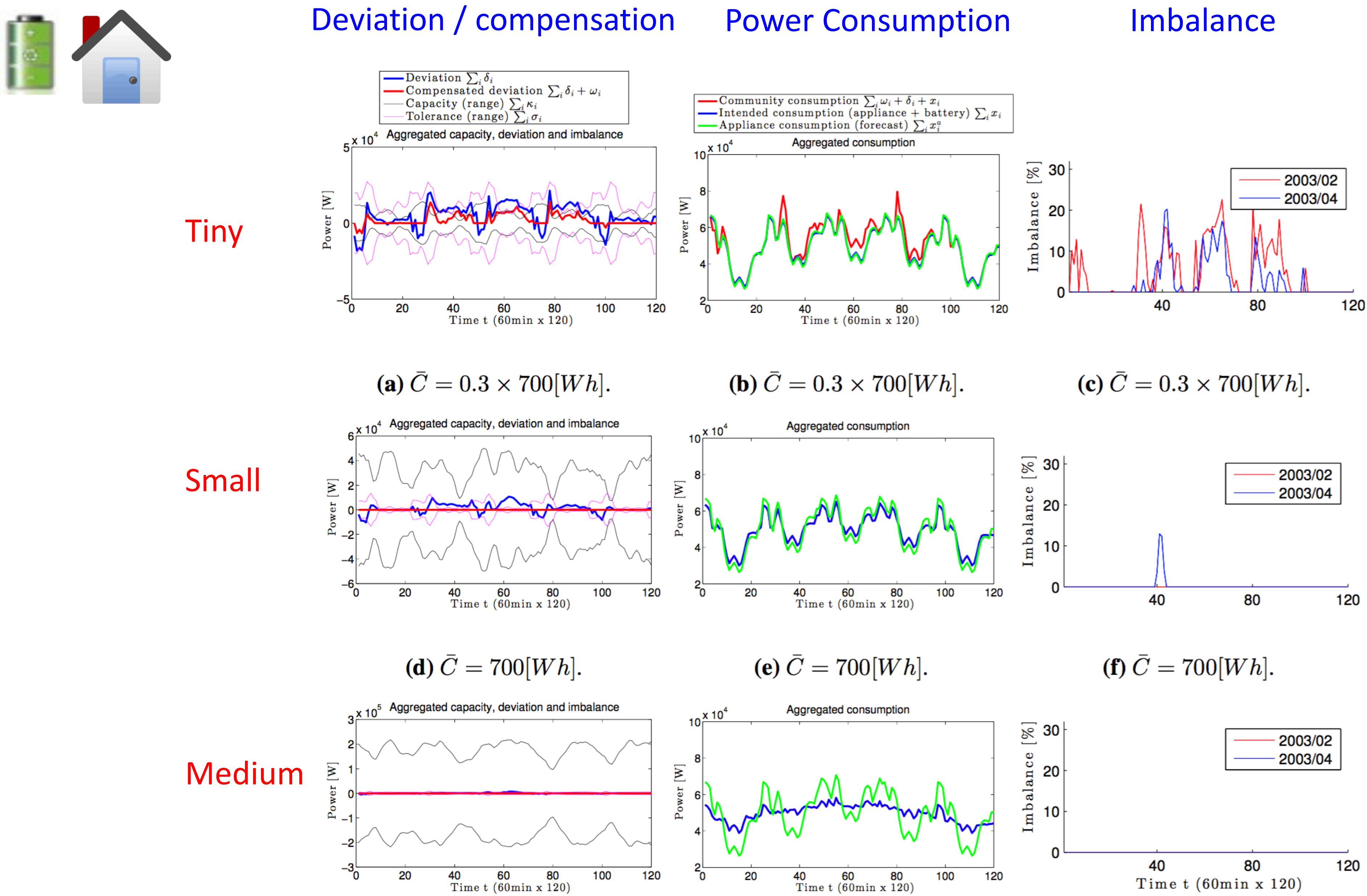


(h) $\bar{C} = 3 \times 700[Wh]$.



(i) $\bar{C} = 3 \times 700[Wh]$.

Week ahead-planning



(a) $\bar{C} = 0.3 \times 700[Wh]$. (b) $\bar{C} = 0.3 \times 700[Wh]$. (c) $\bar{C} = 0.3 \times 700[Wh]$.

(d) $\bar{C} = 700[Wh]$. (e) $\bar{C} = 700[Wh]$. (f) $\bar{C} = 700[Wh]$.

(g) $\bar{C} = 3 \times 700[Wh]$. (h) $\bar{C} = 3 \times 700[Wh]$. (i) $\bar{C} = 3 \times 700[Wh]$.

Discussion

Coordination requires new technologies

- Prediction & estimation technologies
  - Living activity recognition
  - Living activity prediction
  - Local weather forecast
  - PV, wind generation forecast

Current and future directions

- Day-ahead, hour-ahead, *real-time* coordination
- Social issues
  - User incentives, Exchange Market
  - User acceptance: Fairness, Transparency, & QoL
- Evaluate Benefits for the environment & society

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THANK YOU FOR YOUR ATTENTION