CPS SYNERGY: COLLABORATIVE RESEARCH
BEYOND STABILITY: PERFORMANCE, EFFICIENCY AND DISTURBANCE MANAGEMENT FOR SMART INFRASTRUCTURE SYSTEMS

Dennice Gayme & Enrique Mallada (Johns Hopkins), Vijay Gupta (Notre Dame),
Steven Low & Adam Wierman (Caltech), and Ao Tang (Cornell)

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College of Engineering

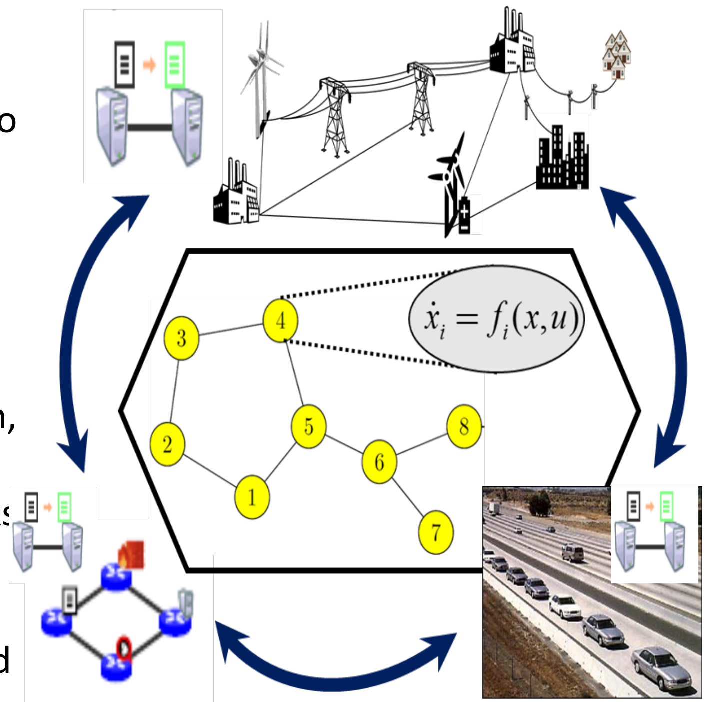
Beyond Stability: Performance, Efficiency and Disturbance Management for Smart Infrastructure Systems

Challenge:

- Theory, algorithms and tools to evaluate and improve efficiency, performance, and disturbance management in next generation infrastructure networks
- Apply results to transportation, communication and power system infrastructure networks

Solution:

- Characterizing weakest links in transportation networks (where disturbances likely lead to collisions)
- Disturbance localization in transportation networks
- Optimizing efficiency in microgrids
- New algorithms for computer clock synchronization
- Multi-time scale architecture for power system optimization



A coupled oscillator serves as the base mathematical abstraction for power, transportation & communication networks

Scientific Impact:

- Use of a common modeling framework and then adapting to each application is generalizable `by design'
- Delay management and interplay between engineered and economic control needed across CPS systems

Broader Impact:

- Focus on efficiency and performance is directly tied to sustainability goals
- K-12 outreach: JHU STEM summer school; Women Serious about Science
- *Rigor & Relevance* blog
- SWE and SHPE mentorship

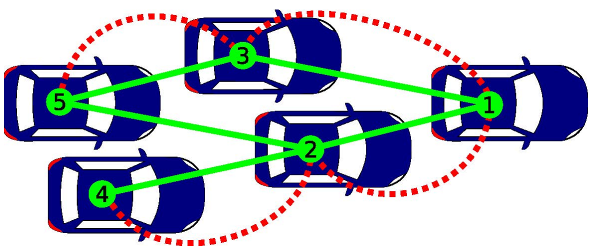
CPS Awards 1544771, 1544724,1544761,1545096
Dennice Gayme & Enrique Mallada (Johns Hopkins), Vijay Gupta (Notre Dame), Ao Tang (Cornell), Steven Low & Adam Wierman (Caltech)

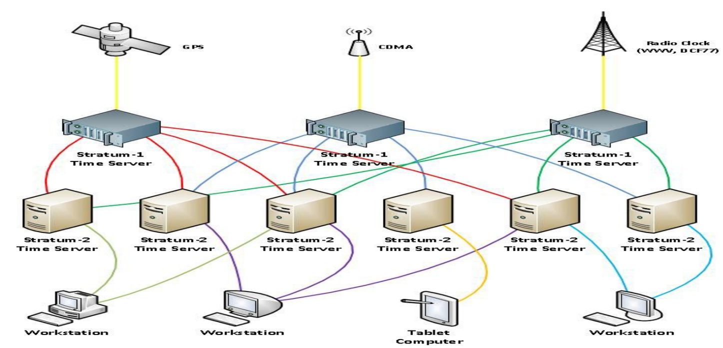
Project Overview

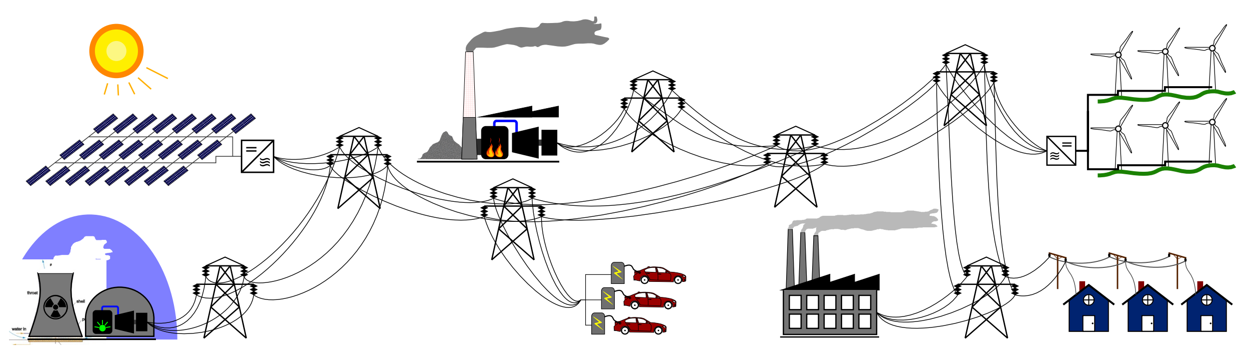
Exploit a common modeling framework to develop new techniques to characterize & control cyber-physical infrastructure networks to not only ensure stability but to also

1. Optimize efficiency and performance.
2. Integrate engineering and economic control mechanisms.

Applications: Transportation Networks, Communication Networks and Power Grids







Broader Impacts

- Future infrastructure networks will have unprecedented complexity
  - Performance criteria such as efficiency are hard to characterize and generally secondary control goals but have big societal impacts (e.g. emissions, traffic congestion)
  - New technologies and greater interest in 'human centered systems' makes design of appropriate interaction of engineered and economic controls a growing challenge for efficient, reliable infrastructure networks

Mentoring examples

- Faculty mentorship for local student chapters
  - Society of Women Engineers (SWE)
  - Society of Hispanic Professional Engineers (SHPE)
  - Institute of Electrical and Electronics Engineers (IEEE)
- Caltech SURF program summer student mentoring

Broader Impacts: Outreach

Local

- Women Serious about Science
  - Baltimore Polytechnic Institute
- Engineering Innovation
  - A JHU summer course for high school students
- First Lego league Faculty mentor
  - LaSalle Intermediate Academy

International

- *Rigor & Relevance* blog
- State Department program
  - Women's Innovations in Science and Entrepreneurship (Near East and North African delegation)
- IEEE HONET-ICT Int'l Symposium '16

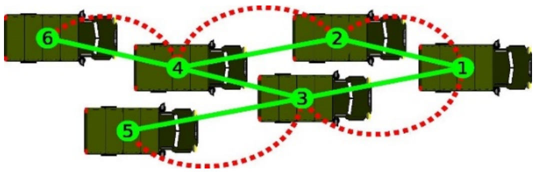
Research Themes

Developing mathematical foundations, theory and algorithms for coupled oscillator systems as a model for smart infrastructures

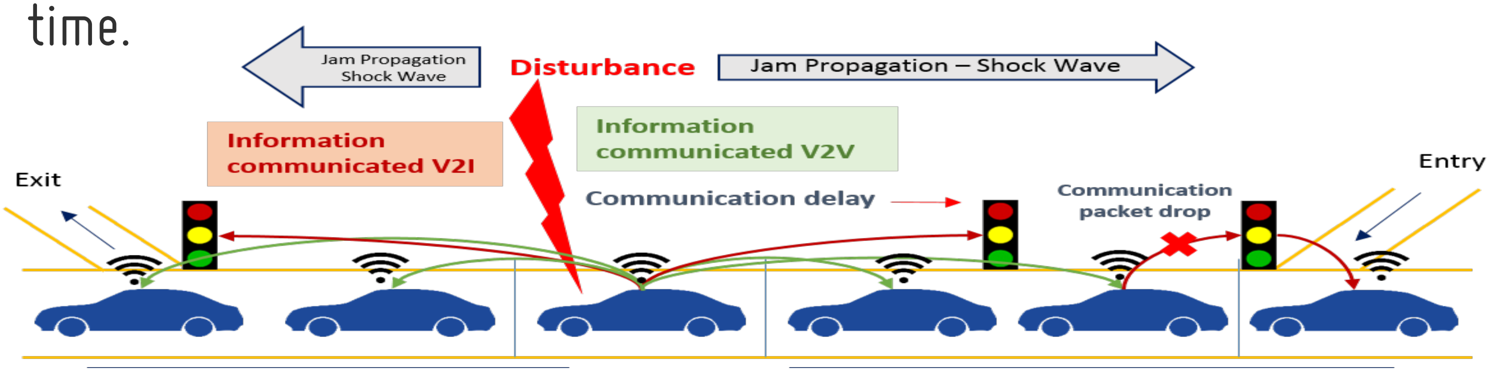
1. Characterizing performance
2. Optimizing performance & robust disturbance management
3. Exploiting interconnection topology & mitigating the impact of communication or control delays
4. The interplay between engineered and economic controls

Sample Results: Transportation Networks

- Performance characterization and control for optimizing performance
- A new robustness measure
  - Norm based characterization of the vehicle most likely to cause a collision and the maximum permissible disturbance to prevent collisions



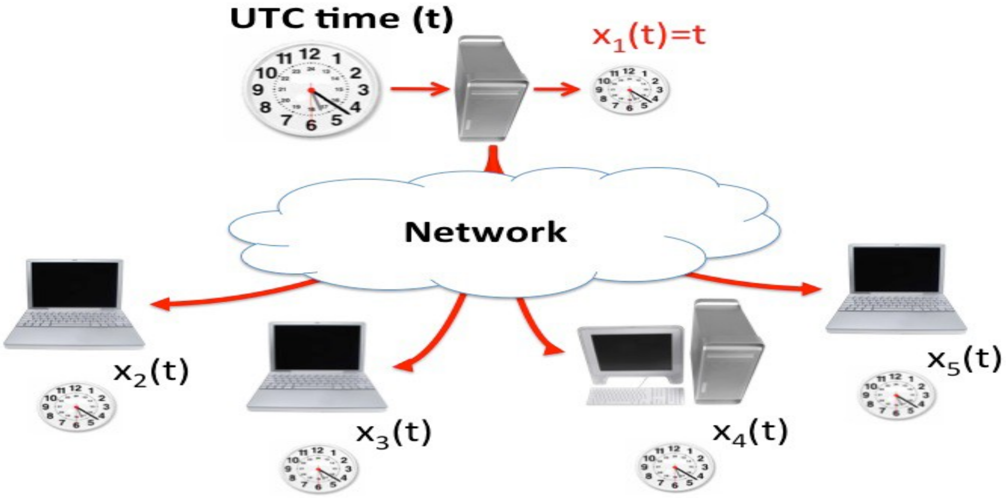
- Isolating shockwaves in traffic (disturbance localization)
  - Distributed control strategies for localization of shock waves (stop-and-go waves) as well as elimination of the waves within a guaranteed period of time.



See poster12 B-R in Studio D

Sample Results: Communication Networks

- Clock Synchronization: Comparing with NTP, our solution achieves μs level accuracy without additional hardware, at least 10X improvement



- Fastest flow reconfiguration without transient congestion

See poster 13 F-L in Studio D

Sample Results: Power Systems

Multi-Timescale Markets for Co-Optimizing Frequency Regulation and Economic Dispatch

- Enrique Mallada (Johns Hopkins), Steven Low (Caltech),
- Adam Wierman (Caltech), Janusz Bialek (Skoltech), Desmond Cai (A-Star), Changhong Zhao (NREL)

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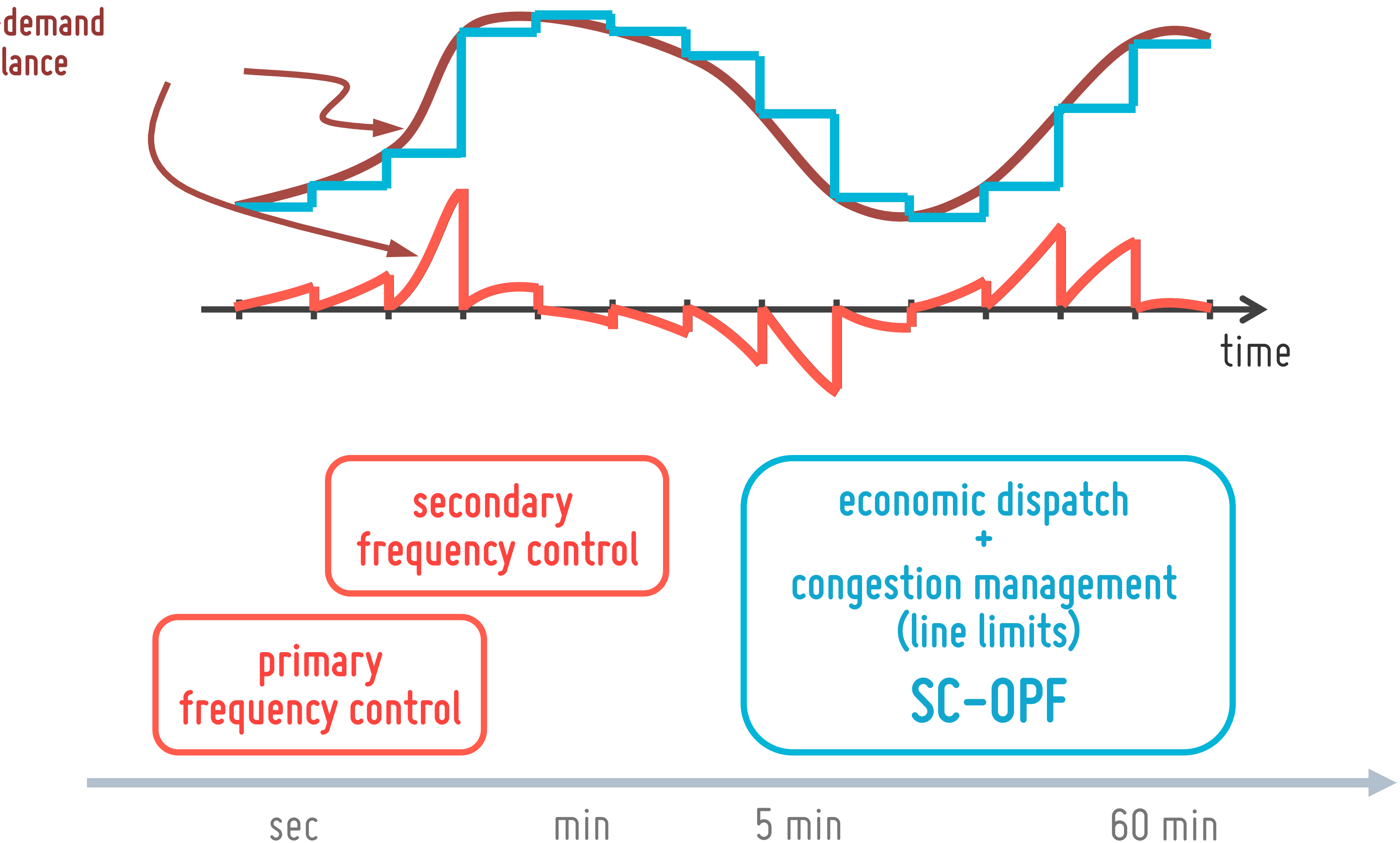
Skoltech

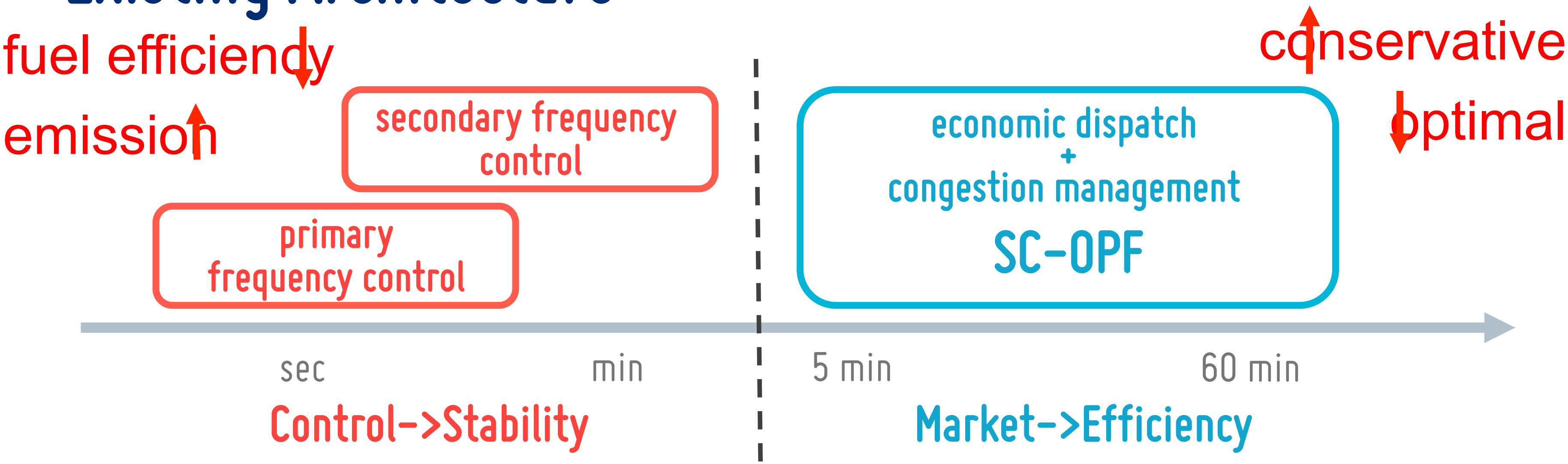
See poster 13 F-R in Studio D

Supply-demand Balance: Multi Timescale Approach

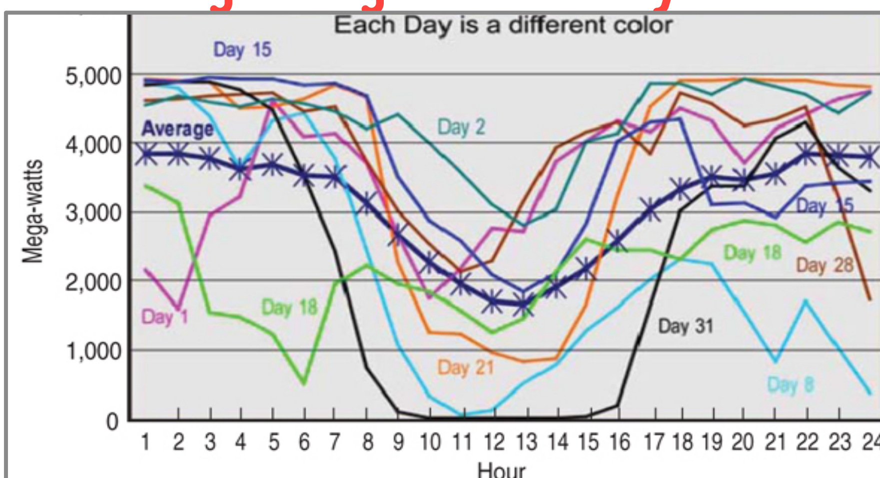


SC-OPF: Chance constrained; N-1 secure

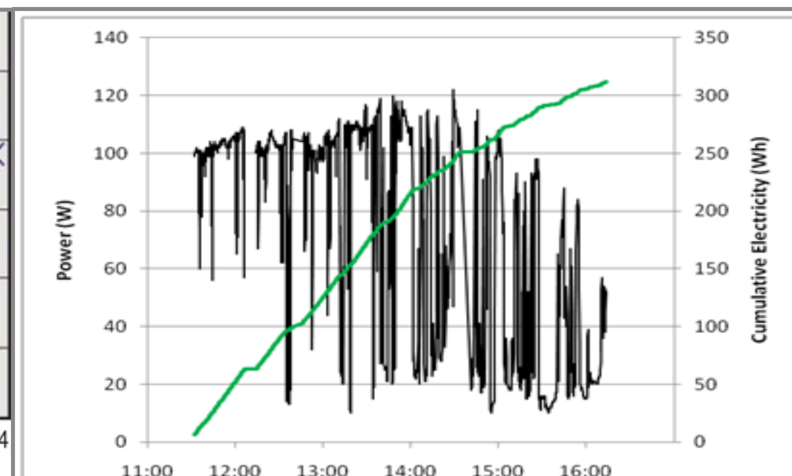
Existing Architecture



Challenge: High Volatility

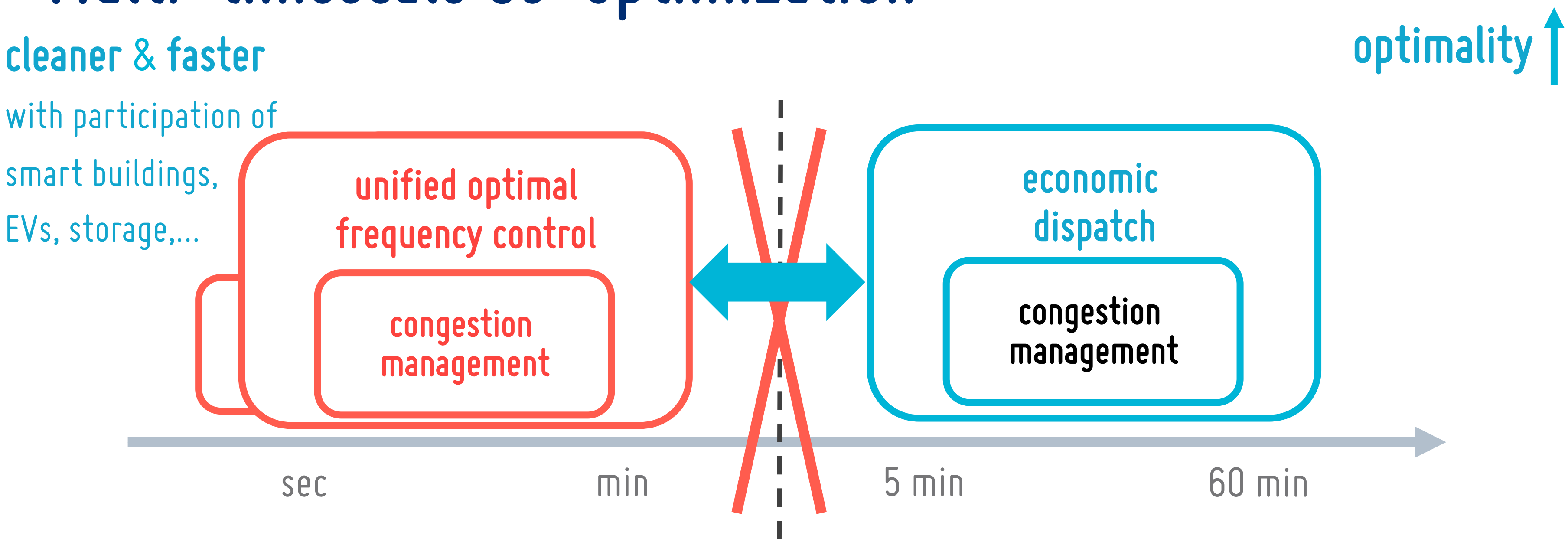


Daily **wind** generation [Tehachapi, CA]



5-hour **solar** generation [Columbia Univ.]

Multi-timescale Co-optimization



1)Unified Optimal Freq. Control

- Generator + **load** control
- **Fully distributed**
- Stability + **efficiency**
- **Congestion management**

2) Joint Ec. Dispatch and Freq. Reg.

- **Co-optimized** multiple time-scales
- **Increased** efficiency
- **Market-based** Implementation

Unified Controller Design

control objectives

$$\min_{p,P,\omega} \quad \sum_i c_i(p_i)$$
$$\text{s.t.} \quad r_i + p_i - D_i\omega_i = \sum_{j:i\sim j} P_{ij} \quad \text{bus } i$$
$$\omega_i = 0 \quad \text{bus } i$$
$$\underline{P}_{ij} \le P_{ij} \le \bar{P}_{ij} \quad \text{line } ij$$

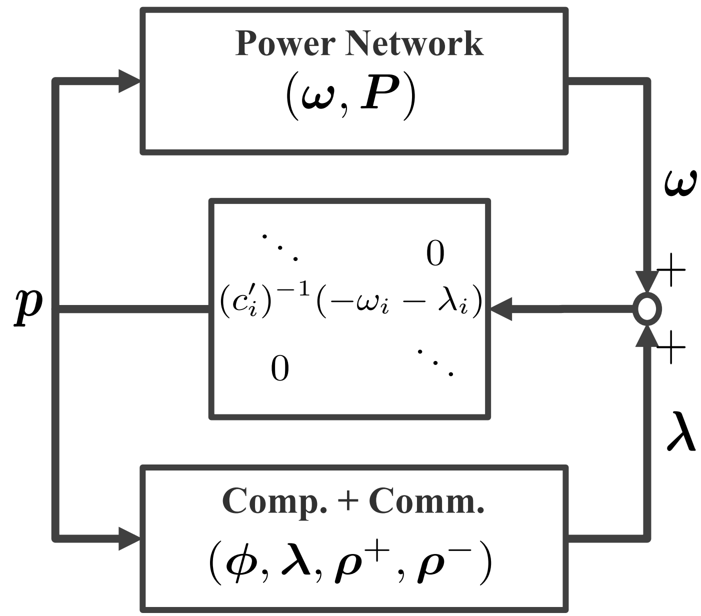
gen. cost

power balance

freq. nominal

thermal limits

unified controller



physics

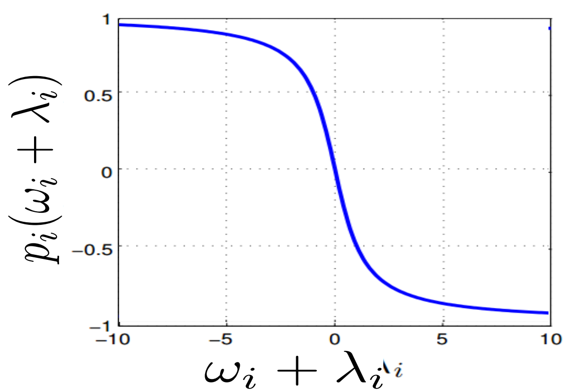
+

controllers

+

cyber:
computation & communication

controller



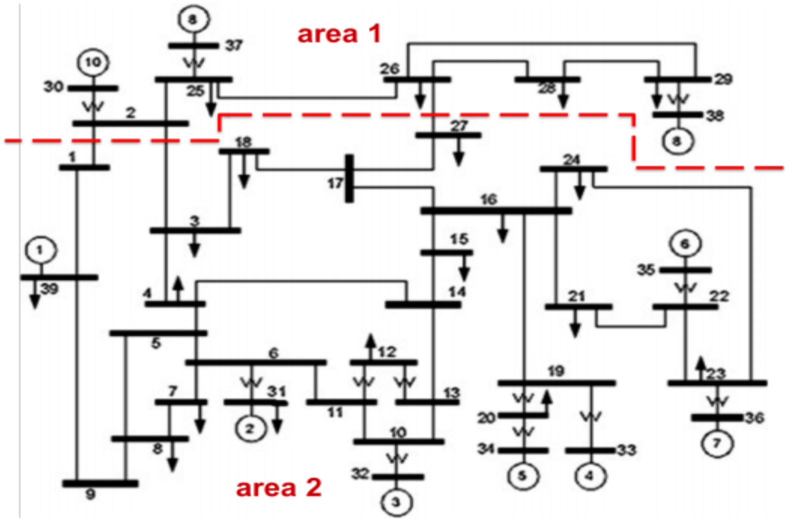
freq

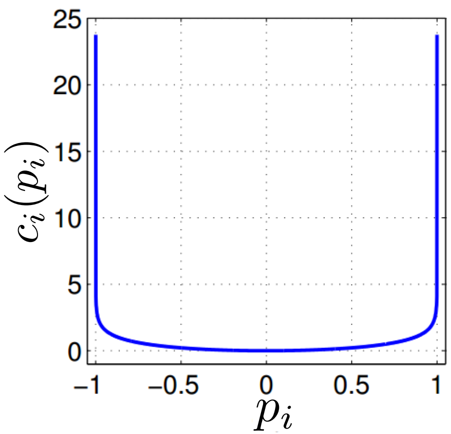
multi-bus AGC

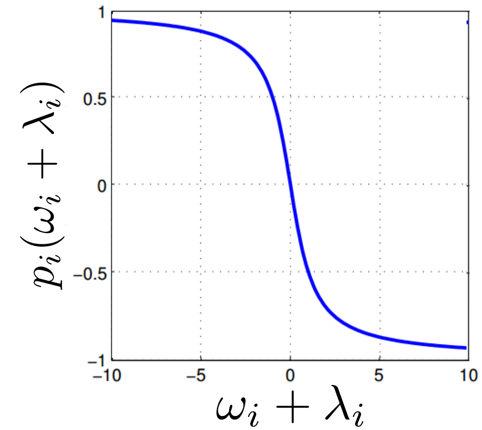
power = $p_i = c_i'^{-1}(\omega_i + \lambda_i)$

using generation or demand

Simulation setup: IEEE 39-bus system

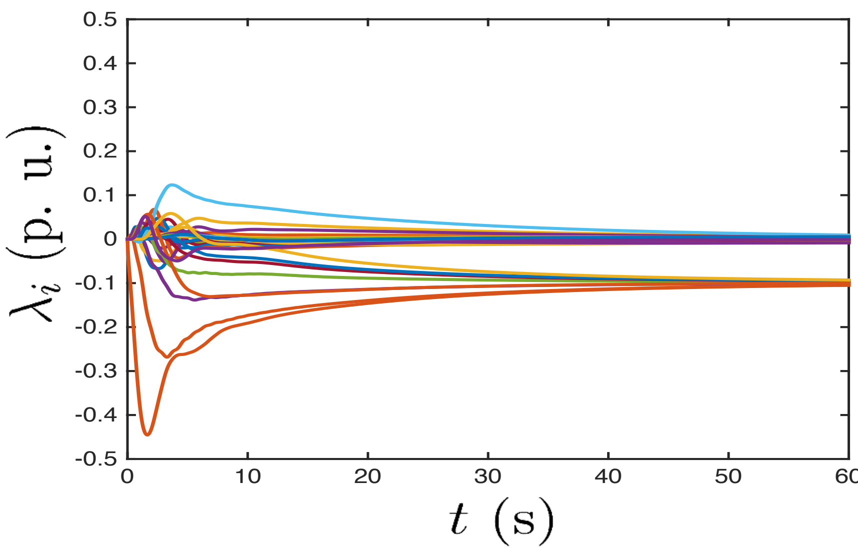


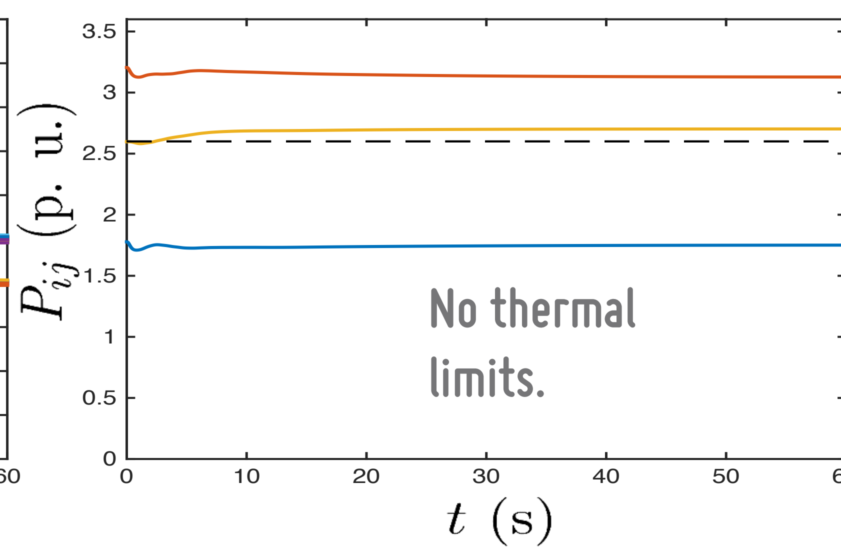




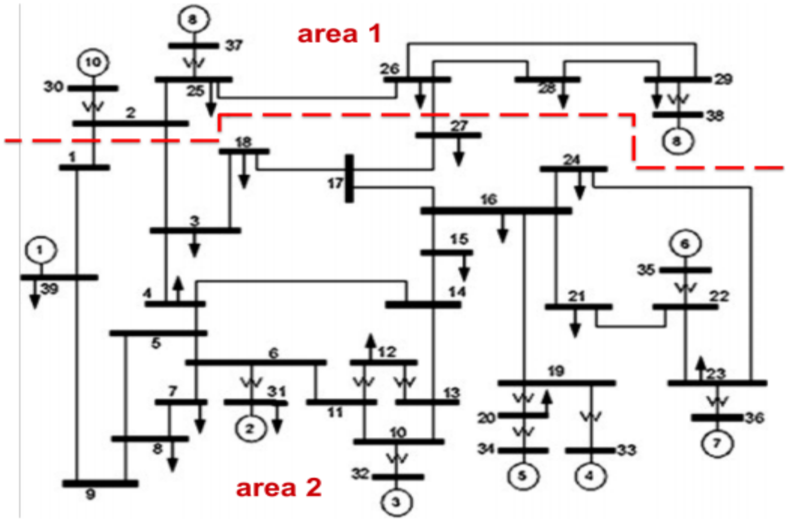
Exogenous input: $\Delta P_i^{net} = -0.5$ p.u.

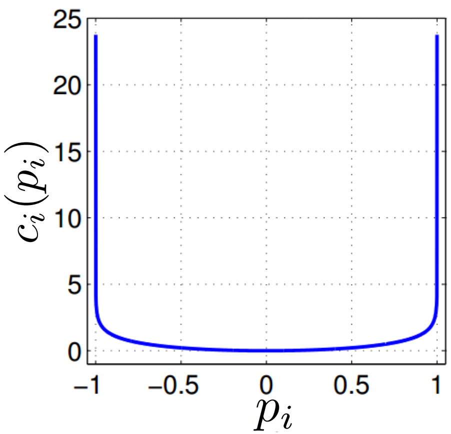
Without respecting thermal limits

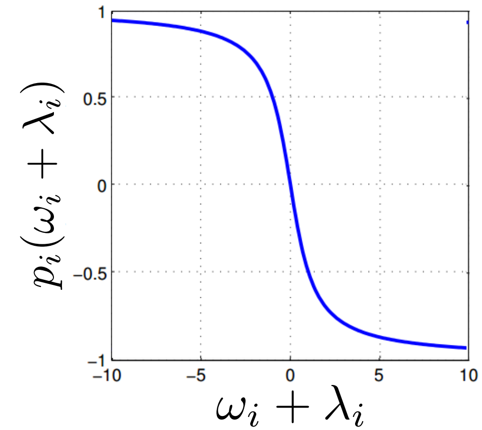




Simulation setup: IEEE 39-bus system







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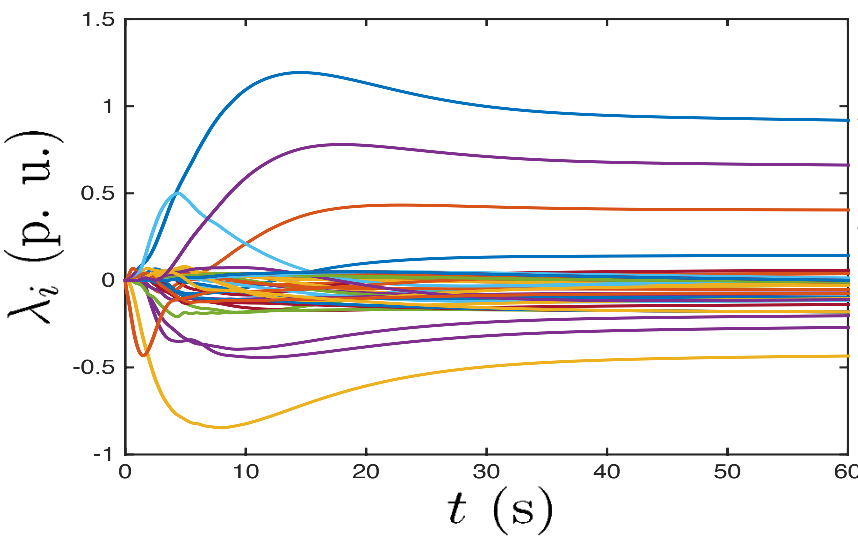
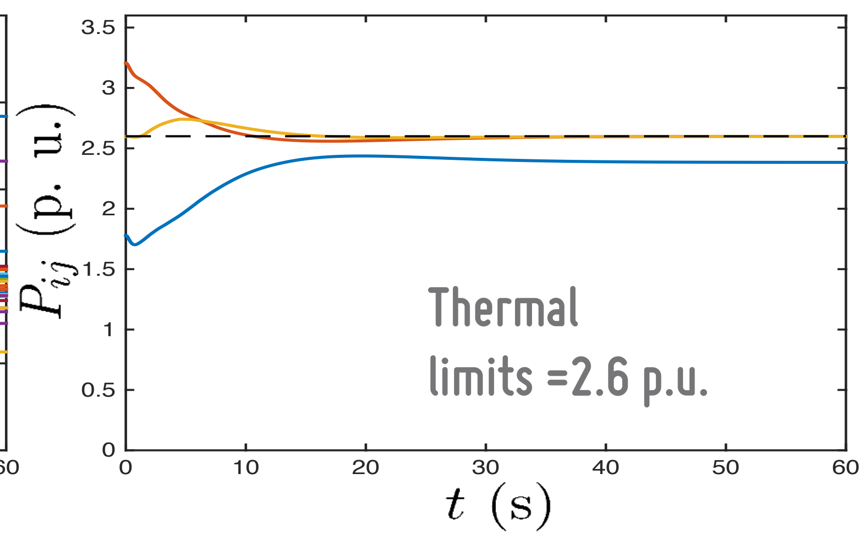
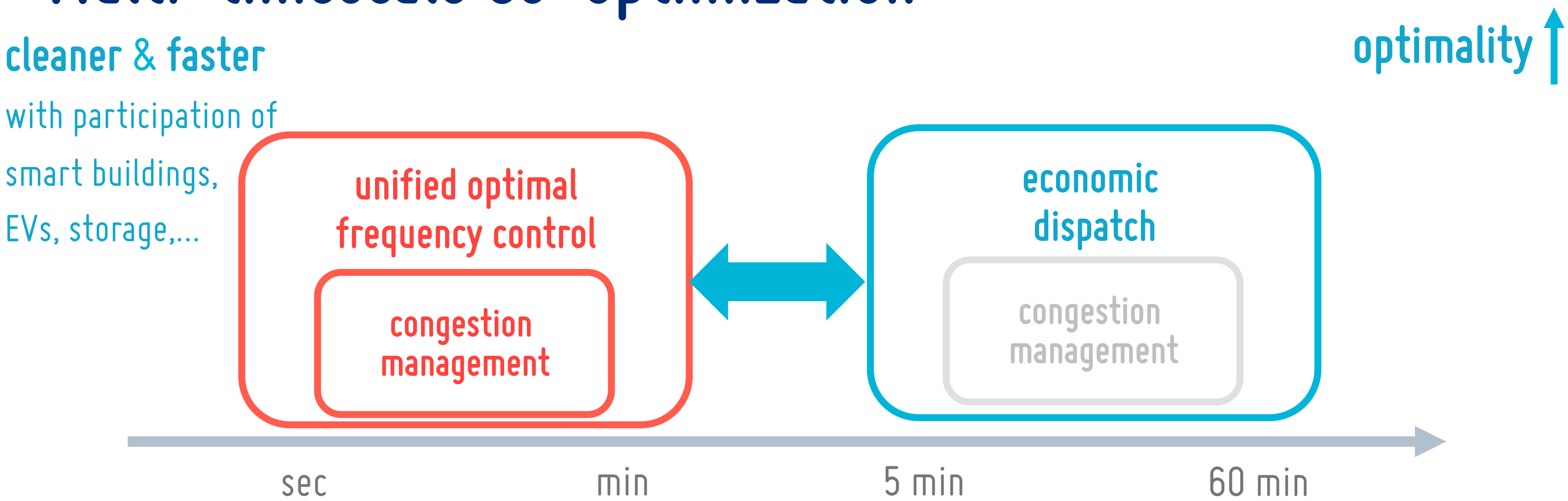
Real-time congestion management





Multi-timescale Co-optimization



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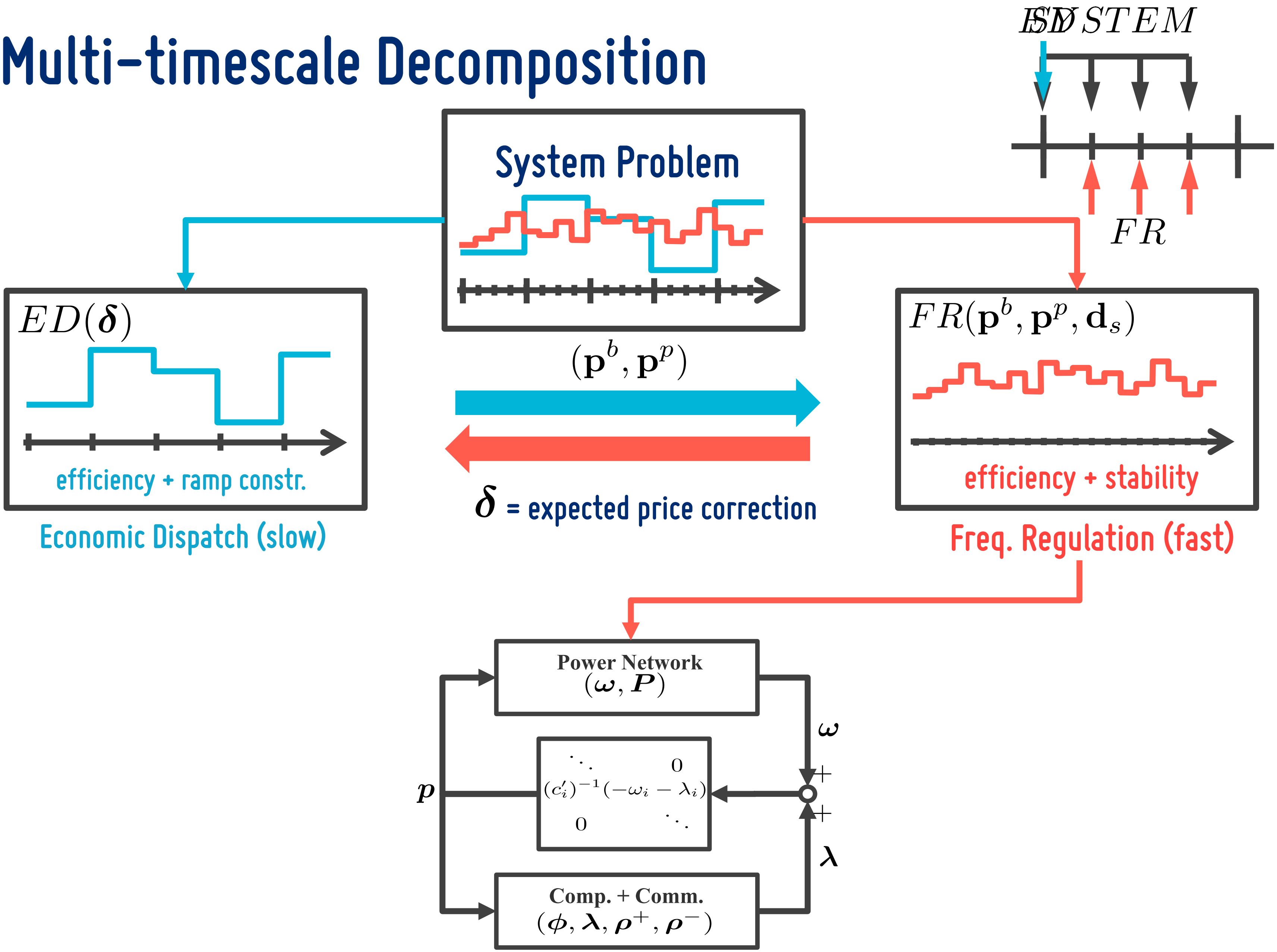
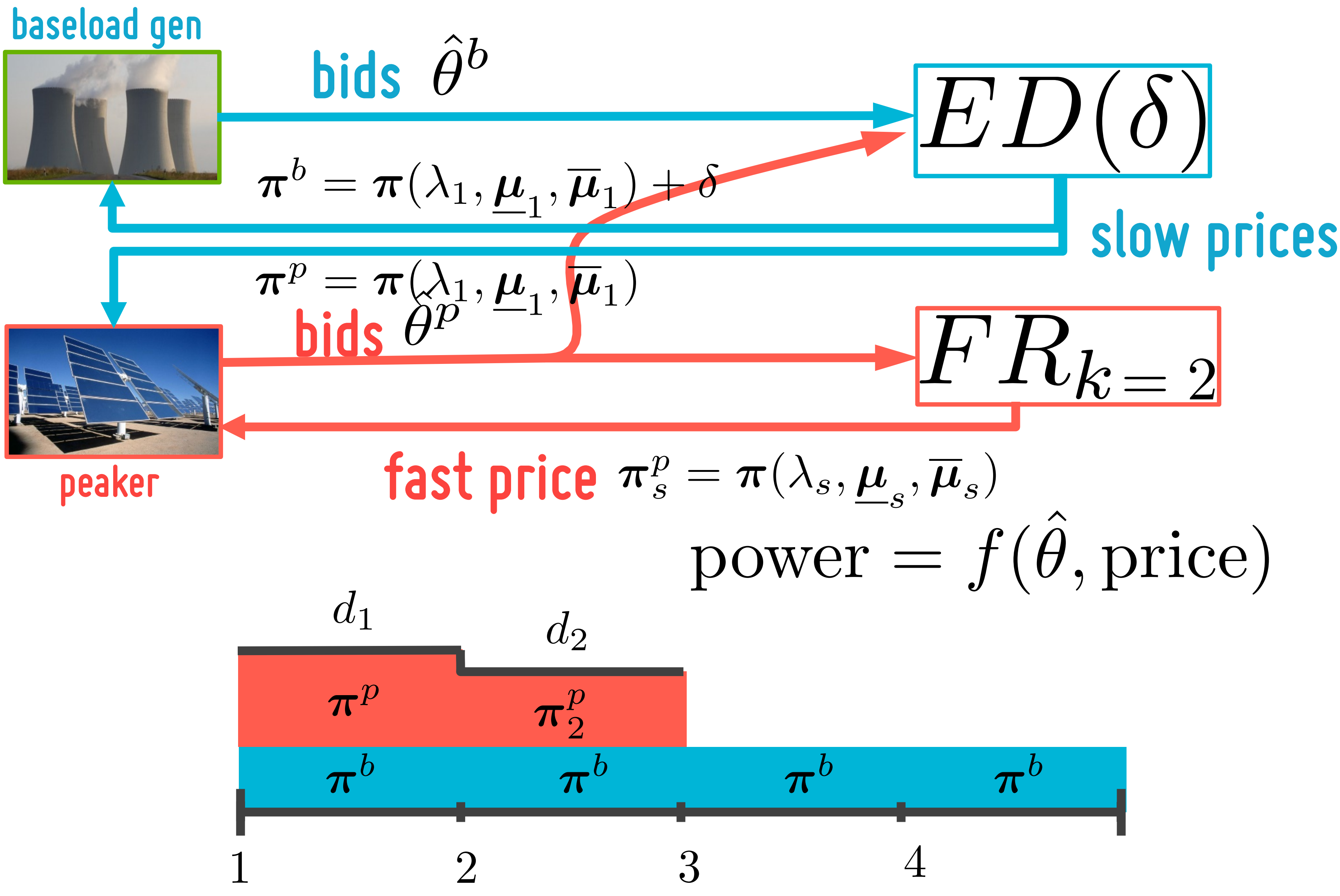
Multi-timescale Decomposition



implemented by controllers

Multi-timescale Market Design

$k = 2$



Multi-timescale Market Design

$k = 3$

baseload gen

$ED(\delta)$

$\boldsymbol{\pi}^b = \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1) + \delta$

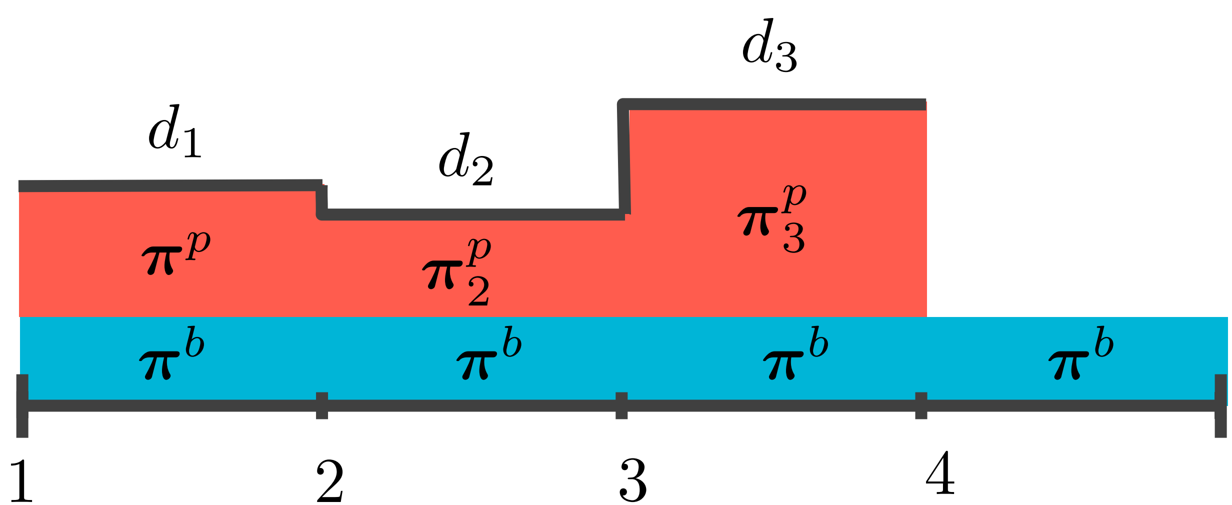
slow prices

$\boldsymbol{\pi}^p = \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1)$

$FR_{k=3}$

peaker

fast price $\boldsymbol{\pi}_s^p = \boldsymbol{\pi}(\lambda_s, \underline{\boldsymbol{\mu}}_s, \overline{\boldsymbol{\mu}}_s)$



Multi-timescale Market Design

$k = 4$

baseload gen

$ED(\delta)$

$\boldsymbol{\pi}^b = \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1) + \delta$

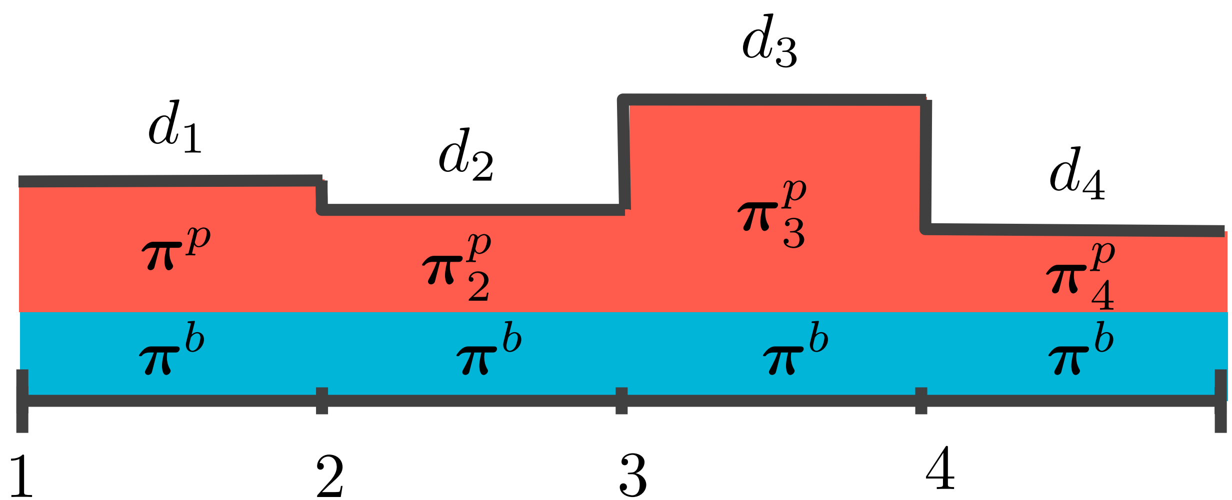
slow prices

$\boldsymbol{\pi}^p = \boldsymbol{\pi}(\lambda_1, \underline{\boldsymbol{\mu}}_1, \overline{\boldsymbol{\mu}}_1)$

$FR_{k=4}$

peaker

fast price $\boldsymbol{\pi}^p_s = \boldsymbol{\pi}(\lambda_s, \underline{\boldsymbol{\mu}}_s, \overline{\boldsymbol{\mu}}_s)$



Thank you

NSF

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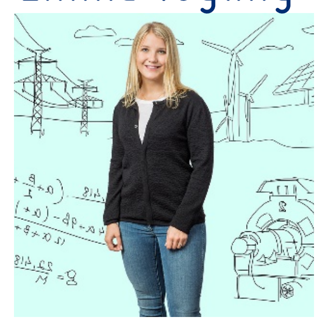
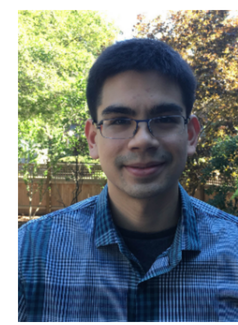


Ted Grunberg



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