Models and Control Strategies for Data Center Energy Efficiency

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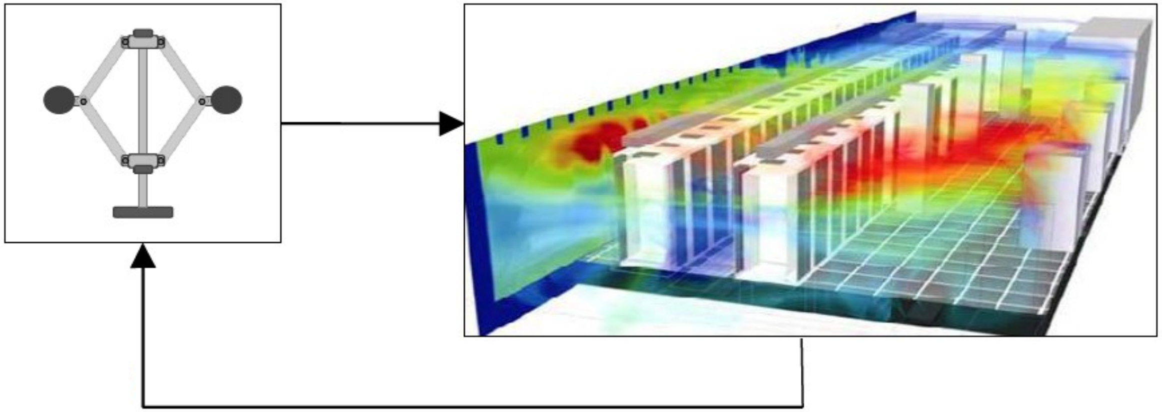
Special Thanks to Zhikui Wang, HP Labs



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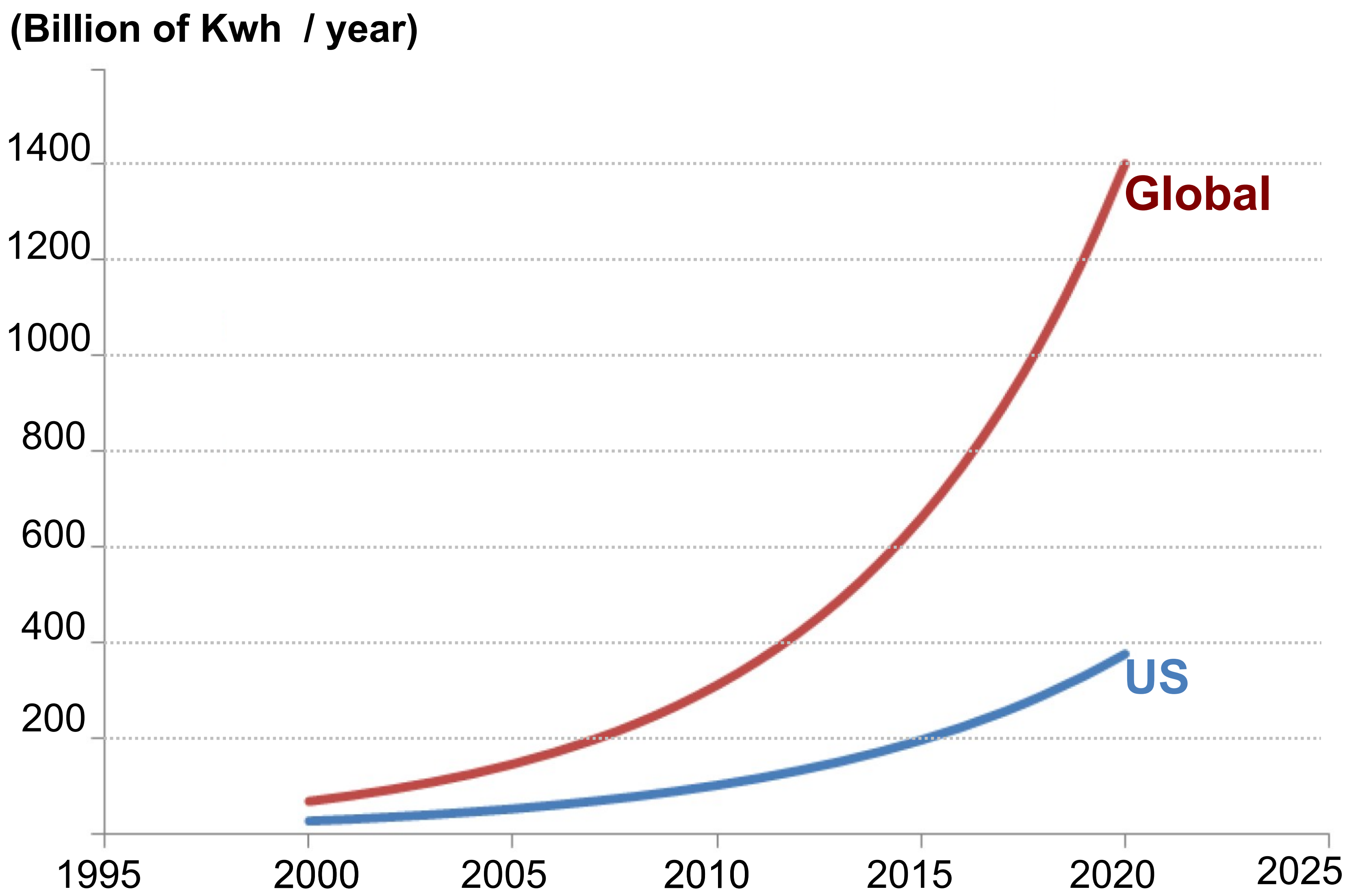
Data center examples

- **Facebook's data center in North Carolina, US**
  - 450$ million project
  - ~28.000 m^2 (300.000 ft^2)
  - Operated by 35 - 45 full-time employees
- **Racks**
  - Contain 42 (1U) servers in a rack
  - 1 server: 480mm x 800mm x 44mm

	Idle power	***Peak power***
Server	200 W	350 W
Rack	8.4 kW	~15 kW

http://blog.cluttr.be/2011/01/26/the-case-for-data-center-power-efficiency/
http://www.datacenterknowledge.com/

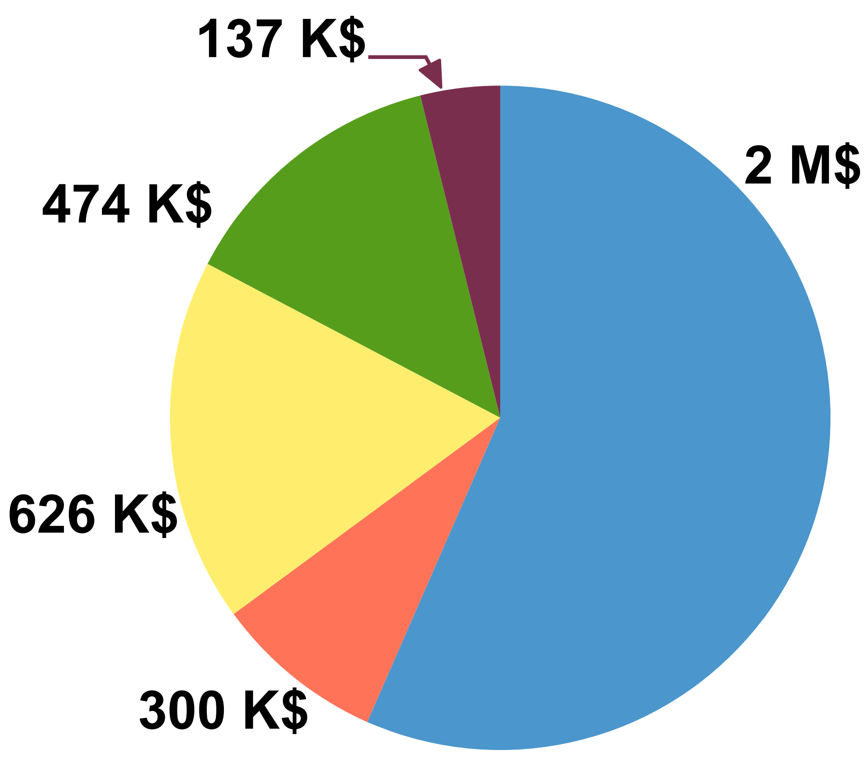
Electricity consumption



C. L. Belady, Projecting annual new datacenter construction market size, Microsoft, 2011

Monthly operating cost

- **Large-scale facility, 50K servers**
  - Facility cost amortized over 10 years
  - Server cost amortized over 3 years
  - Servers account for 70% of total power consumption



Server (hardware cost)	*57%*
Networking equipment	*8%*
Power distribution and cooling	*18%*
Powering cost	*13%*
Other infrastructure	*4%*

- **Total:** ***3.5 M$***

Monthly operating cost

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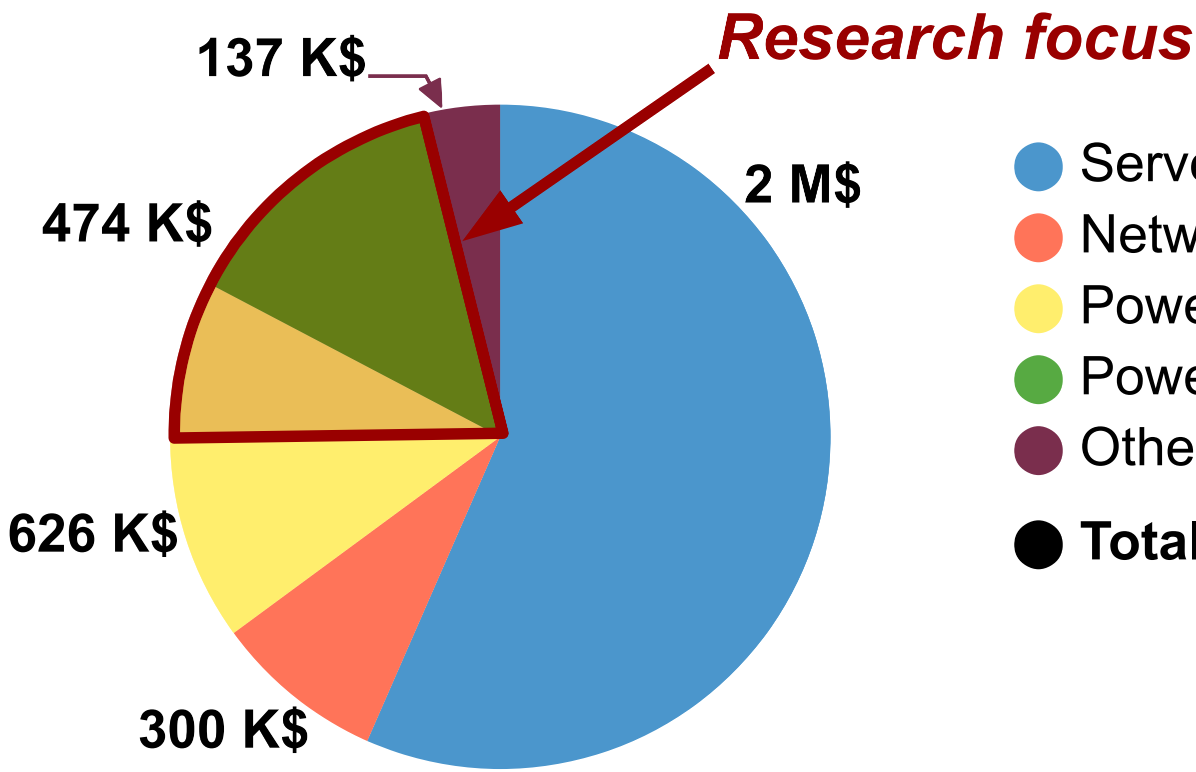

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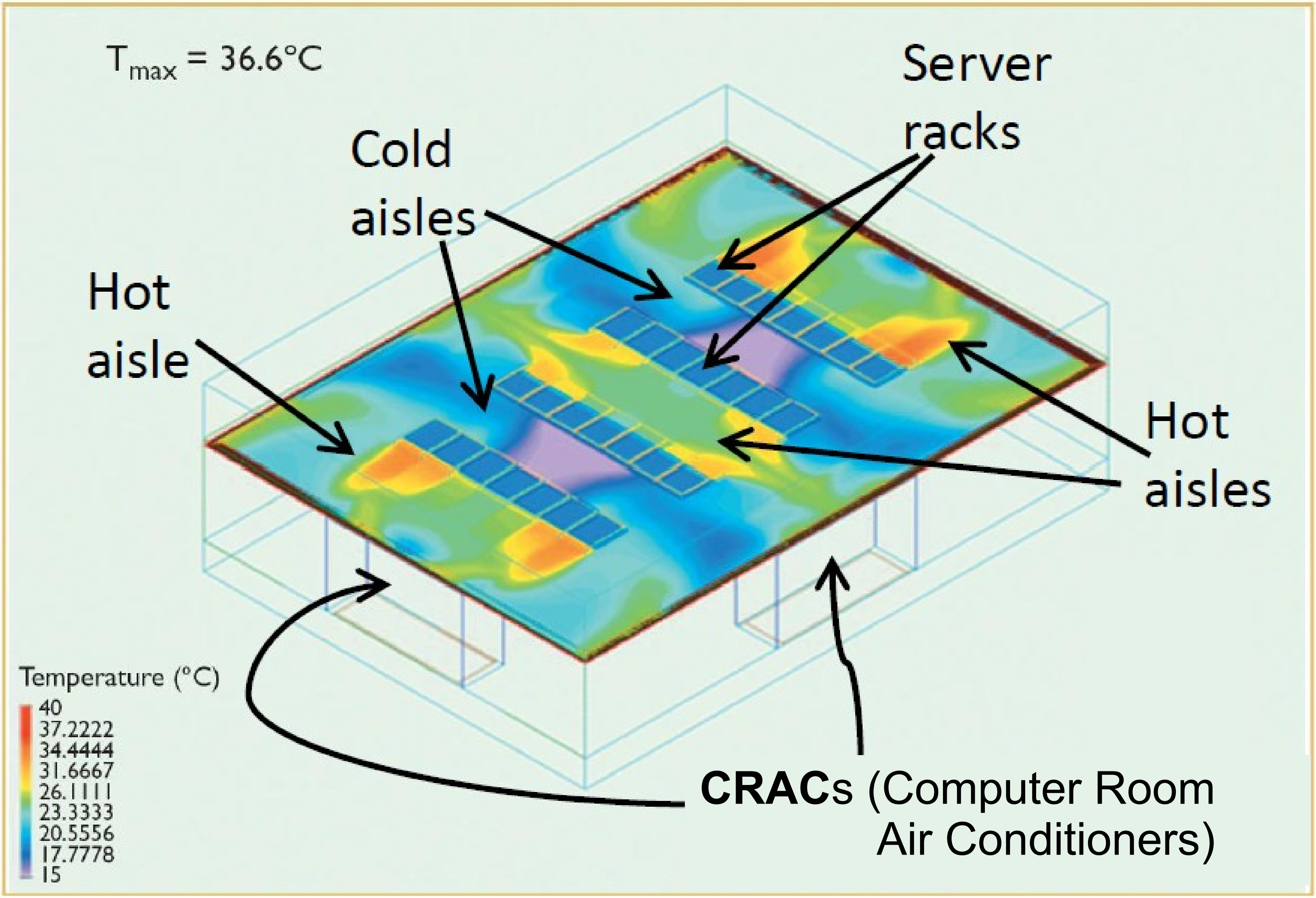
Temperature distribution

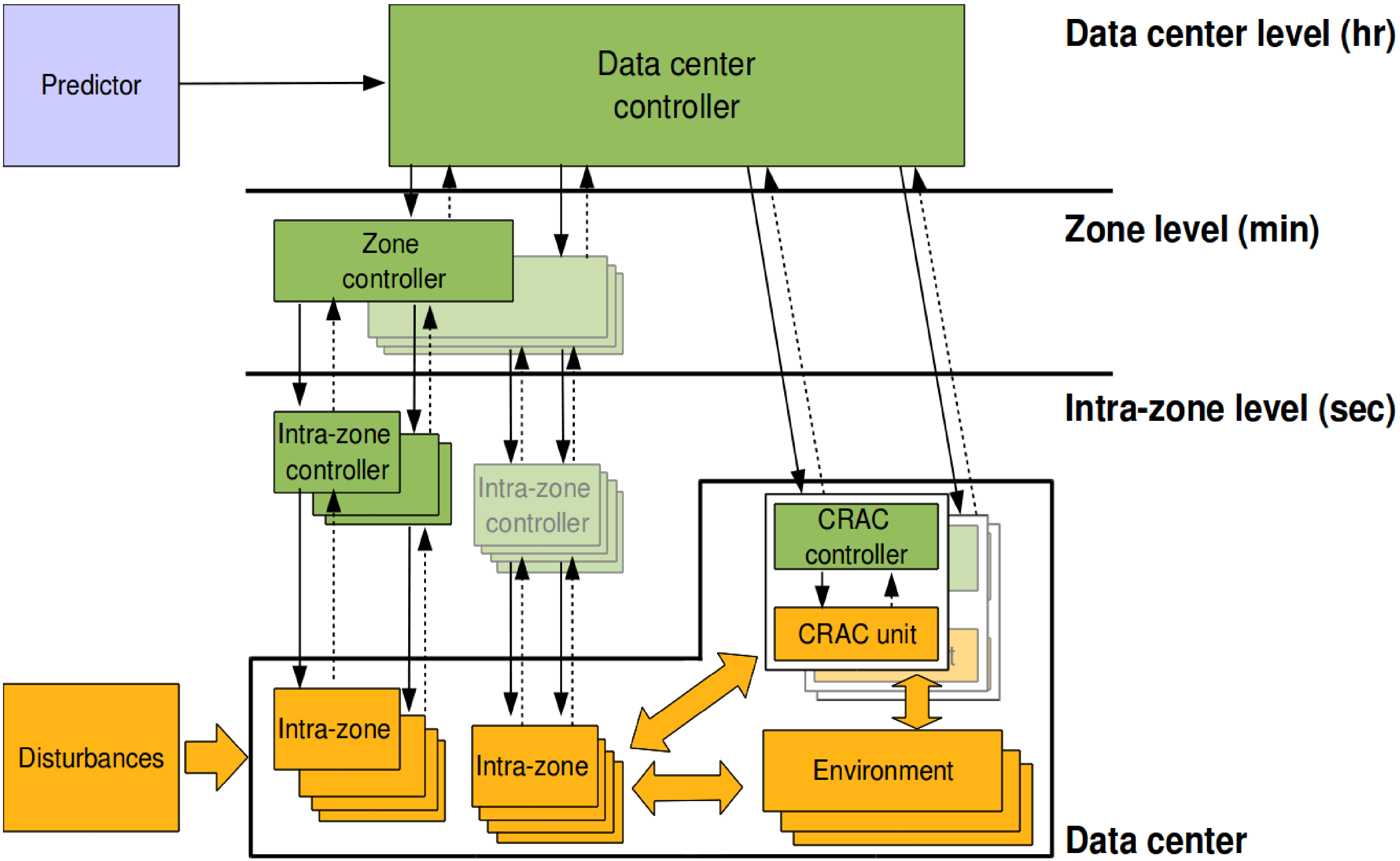


R. K. Sharma *et al.* “Balance of Power: Dynamic Thermal Management for Internet Data Centers”, IEEE Internet Computing 2005

Outline

- Introduction
- **Control-oriented model**
- Control strategies
- Simulation results
- Conclusion and future work

Hierarchical control approach



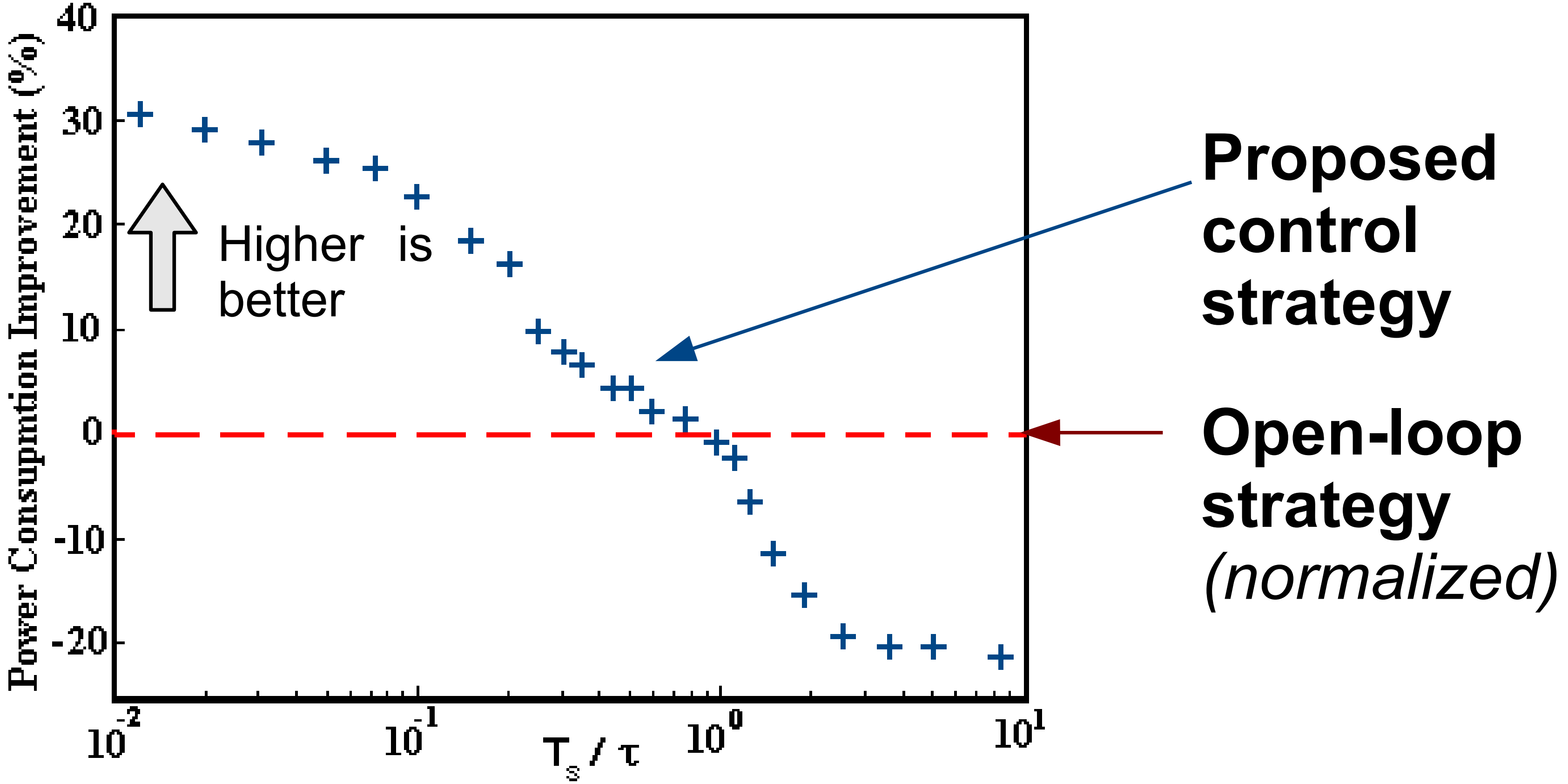
Zone level control

- **Operates at a faster time-scale**
- **Decides how many servers in the zone should be turned on**
- **Control actions based on**
  - Desired workload execution rate (predictive control)
  - Current resource use in the zone (reactive control)
- **Considers**
  - Time to turn servers on: T_S
  - Variability of workload arrival rate

Aghajani, *et al.* "Dynamic Power Allocation in Server Farms: a Real Time Optimization Approach", CDC 2010

Zone level control - simulation results

- **Compare proposed control approach against optimal open-loop strategy**
  - *τ:* expected time interval over which the workload arrival rate is constant



Zone level control - simulation results

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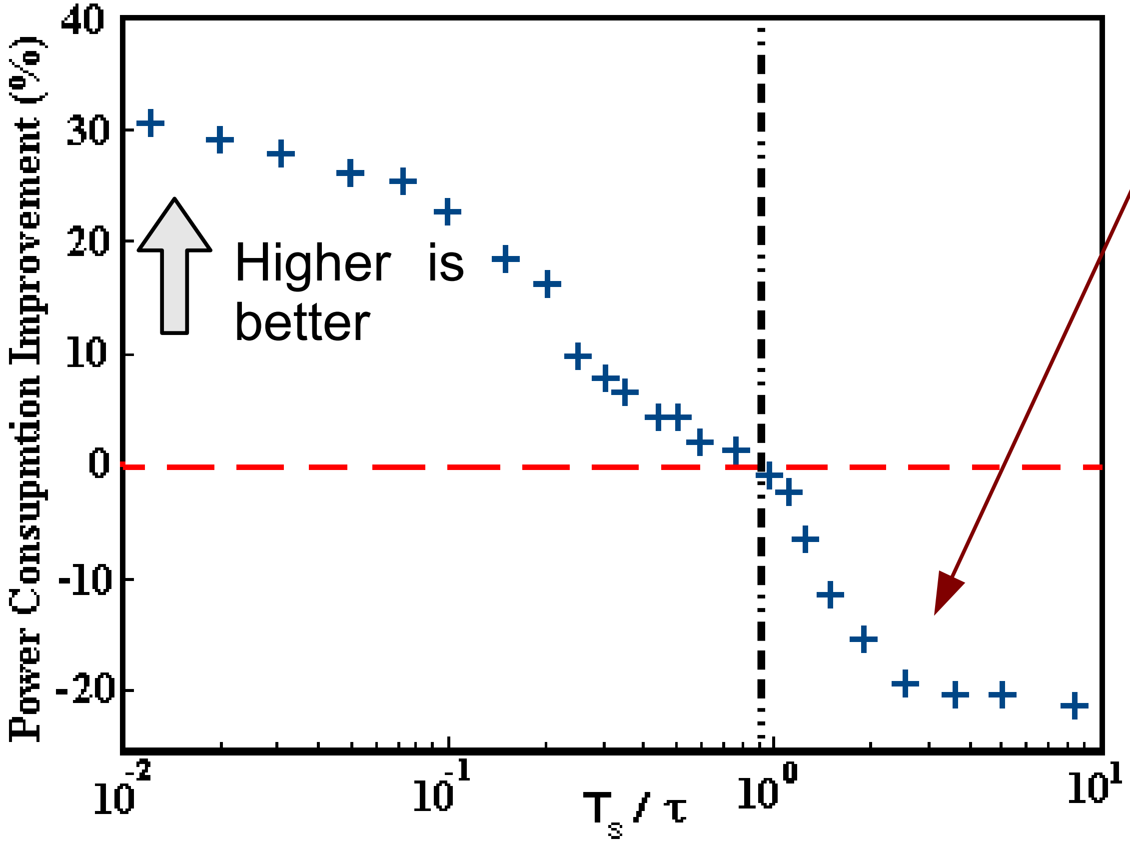


- **Workload arrival rate varies too fast with respect to the time to turn servers on**
- **Best solution is to never turn servers on and off**

Modeling approach: Data Center Level

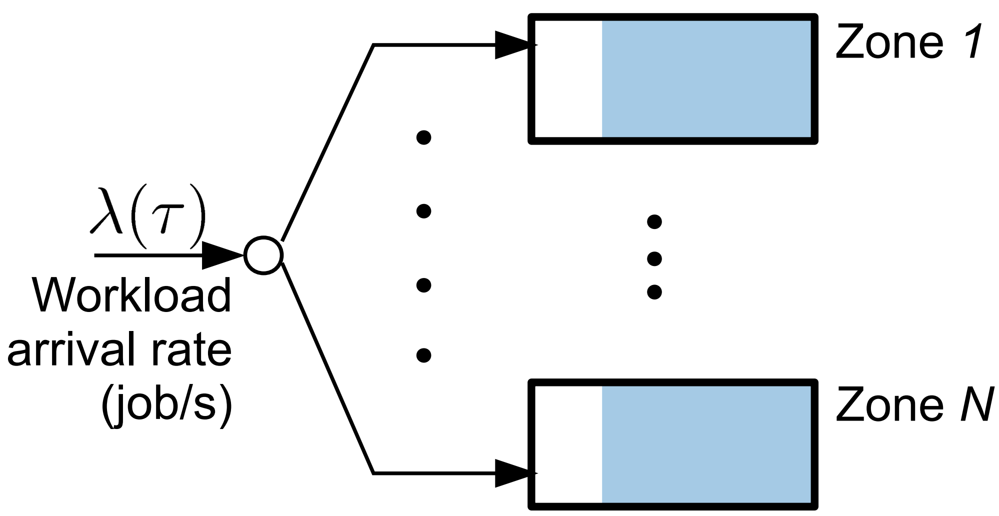
- **Focuses on processes in the hours time scale**

- **Groups servers into zones**
  - Power consumption of a zone is proportional to the amount of workload executed
  - Data are always available
  - Neglect the time to turn servers On and Off
    - Much shorter than the controller sampling-time

- **Considers**
  - Computational and thermal dynamics
  - Nonlinear efficiency of the CRAC units
    - Service level agreements (SLAs) with users and the power-grid

Computational network

- **Describes the evolution of resource usage in the data center**
- **Based on a fluid approximation of the workload execution and arrival processes**
  - First-order approximation of a queuing system



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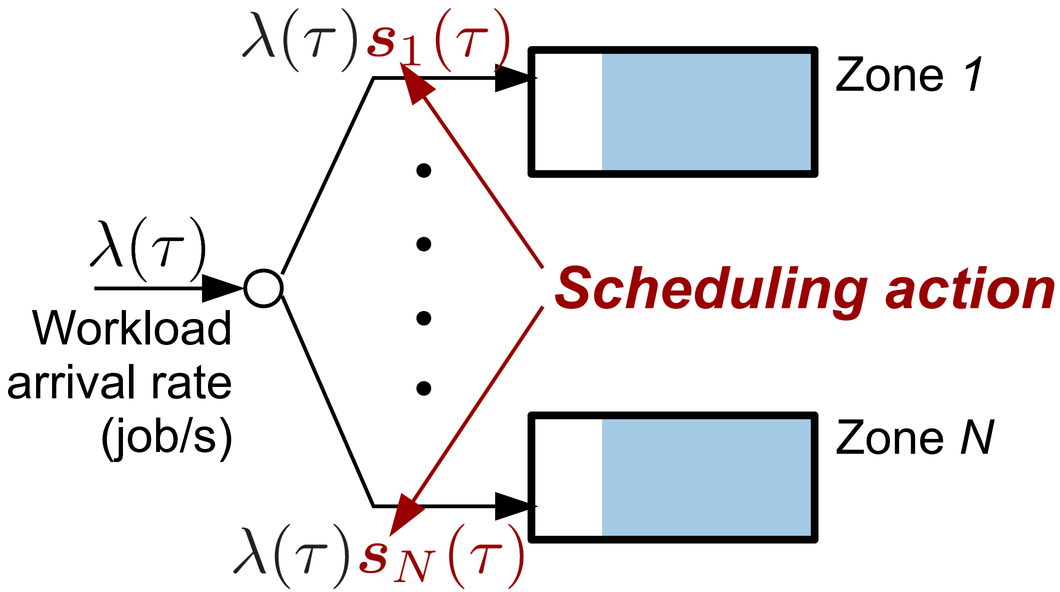

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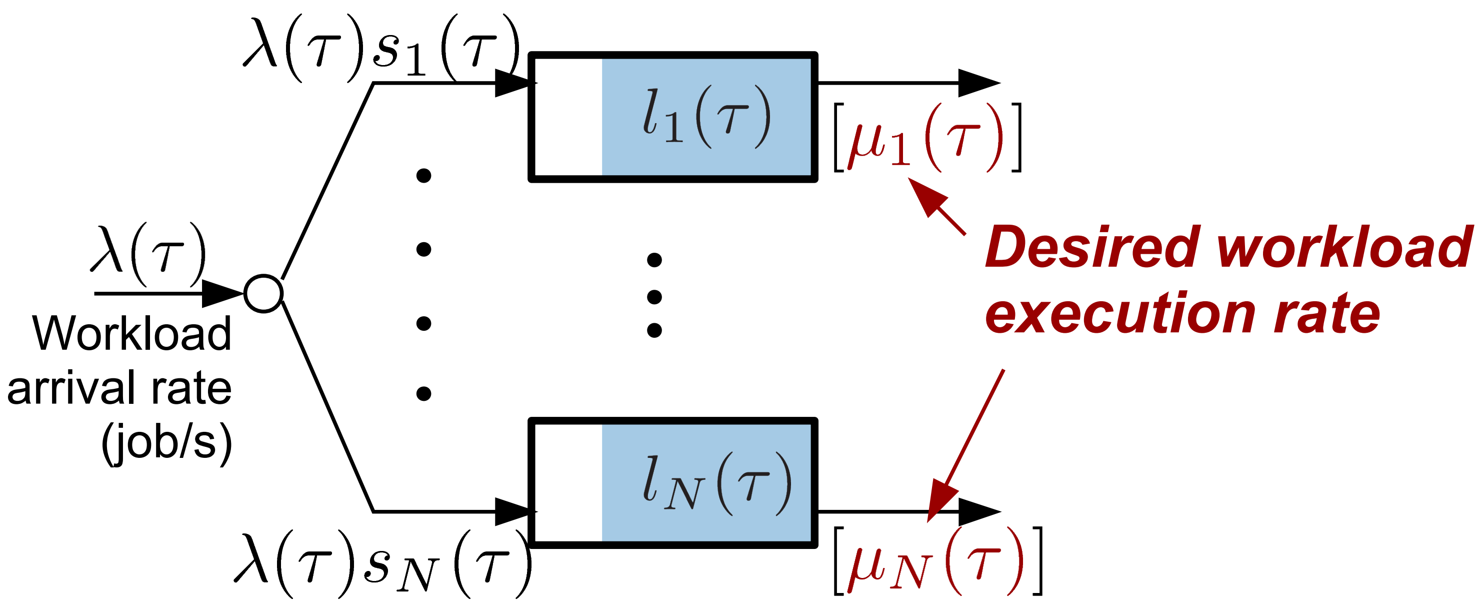

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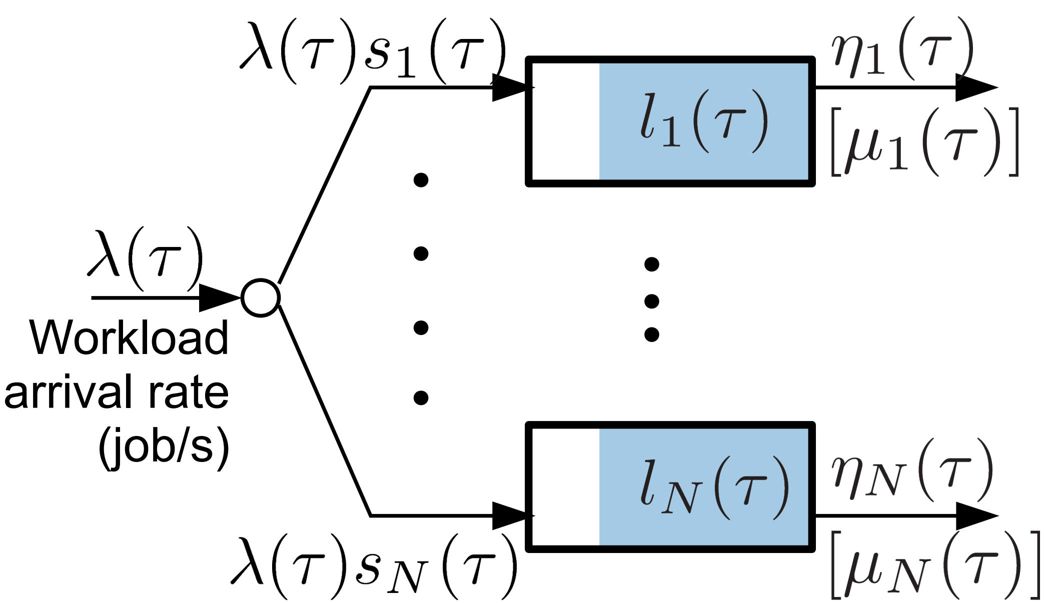

$$a_1(\tau) = \lambda(\tau)s_1(\tau)$$
$$d_1(\tau) = \eta_1(\tau)$$
$$\dot{l}_1(\tau) = a_1(\tau) - d_1(\tau)$$
$$\eta_1(\tau) = \begin{cases} \mu_1(\tau) & \text{if } l_1(\tau) > 0 \\ & \text{or } a_1(\tau) > \mu_1(\tau) \\ a_1(\tau) & \text{otherwise} \end{cases}$$

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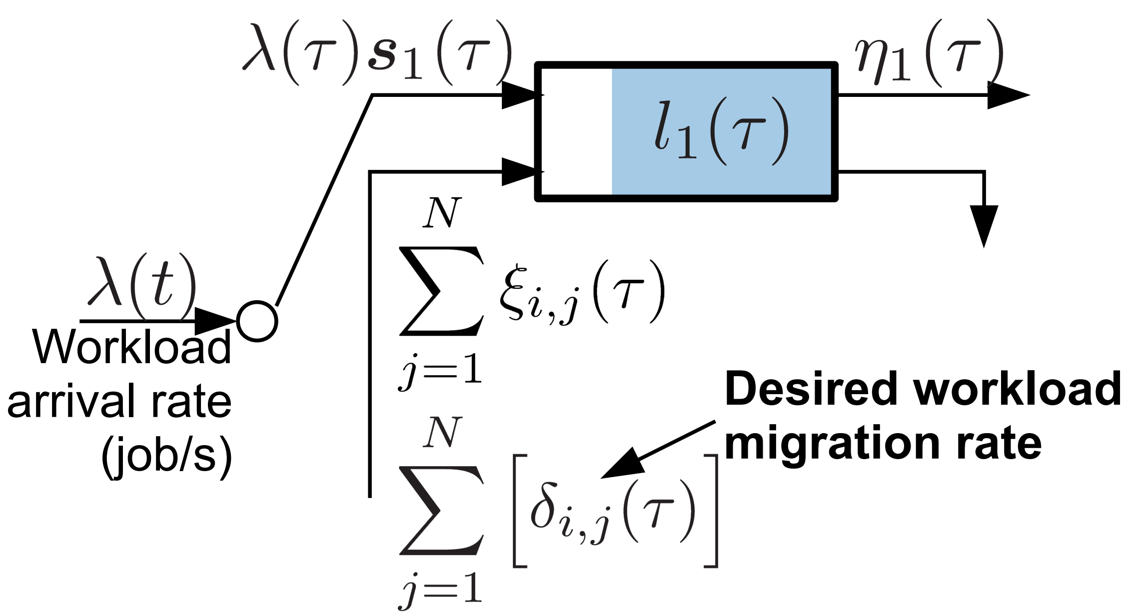

$$a_1(\tau) = \lambda(\tau)\boldsymbol{s}_1(\tau) + \sum_{j=1}^{N} \xi_{1,j}(\tau)$$

$$d_1(\tau) = \eta_1(\tau) + \sum_{j=1}^{N} \xi_{j,1}(\tau)$$

$$\dot{l}_1(\tau) = a_1(\tau) - d_1(\tau)$$

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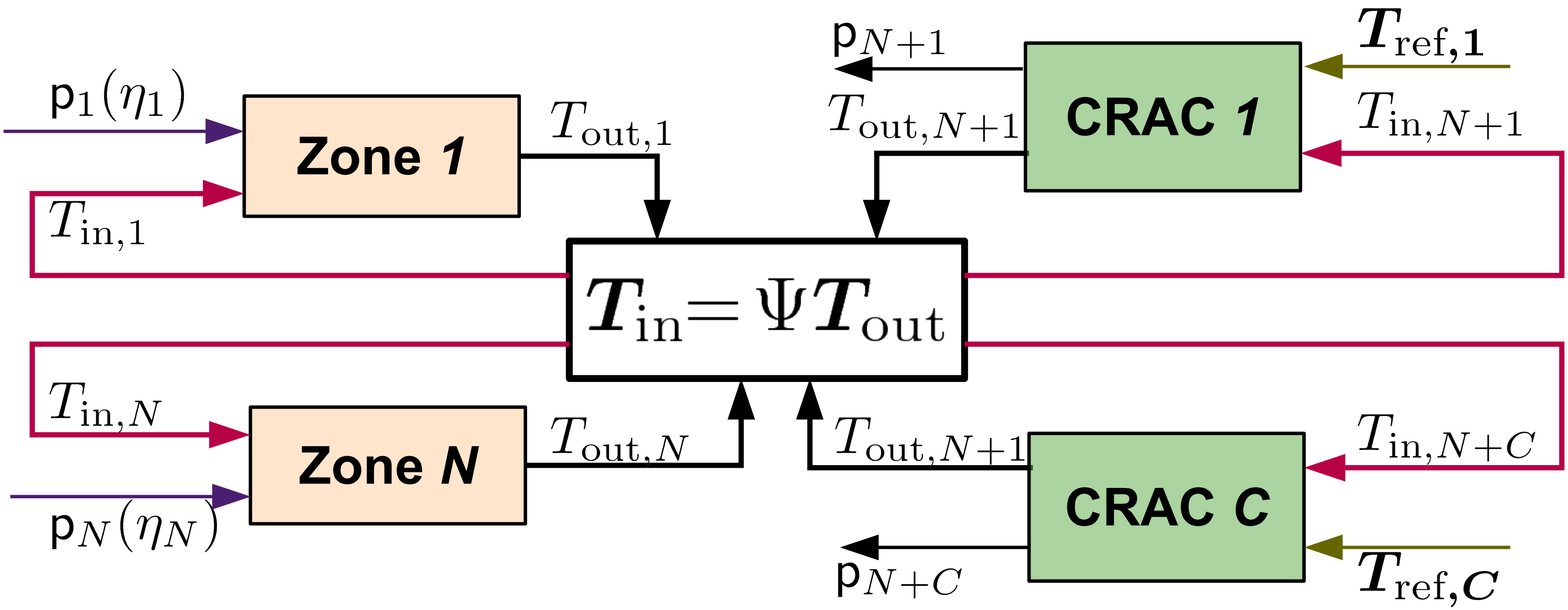
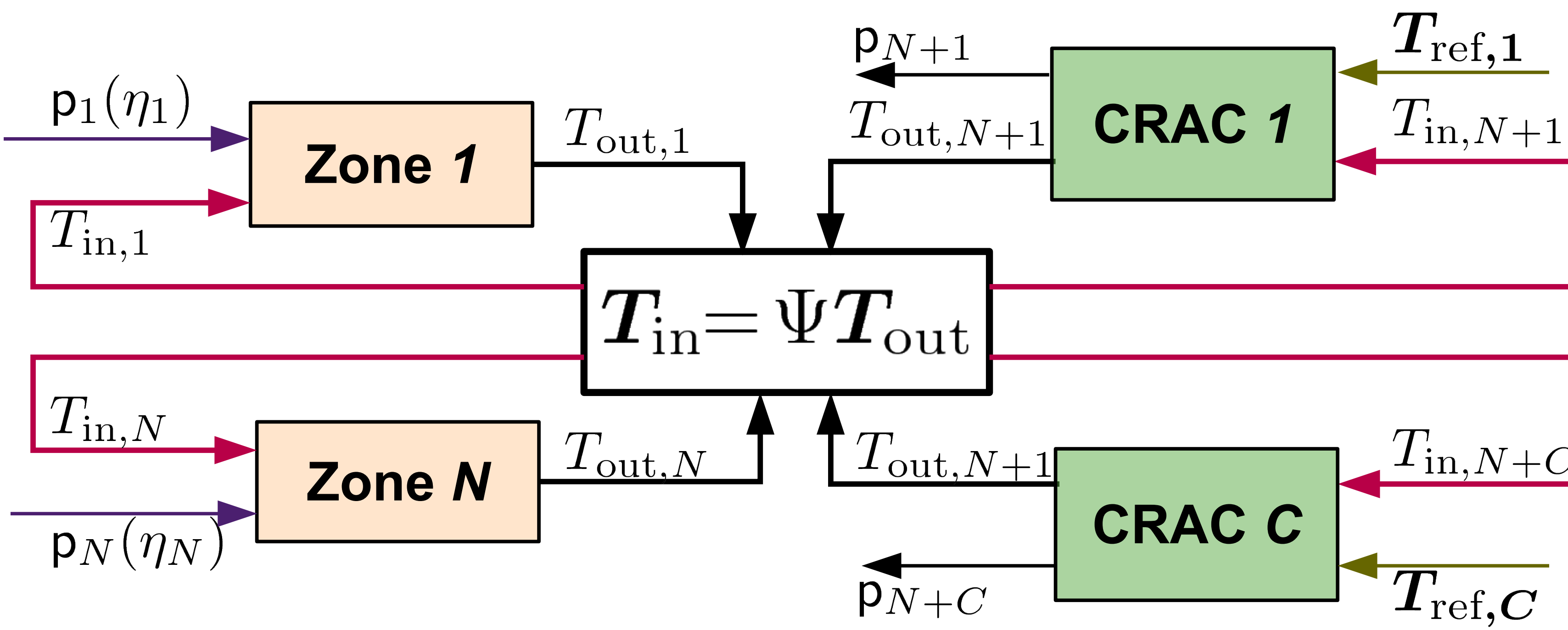
Thermal network



Q. Tang *et al.* "Sensor-based fast thermal evaluation model for energy efficient high-performance data centers", 2006

Thermal network



- **Inlet temperature constraint** $\boldsymbol{T}_{\mathrm{in}}(\tau) = \Psi \boldsymbol{T}_{\mathrm{out}}(\tau) \leq \overline{\boldsymbol{T}_{\mathrm{in}}}$

Heat removed rate (W)

- **CRAC power consumption** $p_i(t) = \dfrac{\dot{Q}_i(t)}{COP_i(T_{\mathrm{out},i}(t))}$

Q. Tang *et al.* "Sensor-based fast thermal evaluation model for energy efficient high-performance data centers", 2006

Variables at step *k*

			Variables
Input	Controllable	Job scheduling	$\boldsymbol{s}(k)$
		Resource allocation	$\boldsymbol{\mu}(k)$
		Job migration	$\boldsymbol{\delta}(k)$
		CRAC unit reference temperature	$\boldsymbol{T}_{\mathrm{ref}}(k)$
	Uncontrollable	Job arrival	$\boldsymbol{\lambda}(k)$
Output	Zone power consumption		$\boldsymbol{p}_N(k)$
	Power consumption of CRAC nodes		$\boldsymbol{p}_C(k)$
	Input temperatures of zones		$\boldsymbol{T}_{\boldsymbol{in}}(k)$
State	Number of jobs in every zones		$\boldsymbol{l}(k)$
	Output temperatures of CRACs and zones		$\boldsymbol{T}_{out}(k)$

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Control strategies

- **Baseline**
  - Open-loop strategy
  - Sets control variables for the worst-case scenario
- **Uncoordinated**
  - Manages the computational and the thermal resources independently
  - Neglects the thermal-computational coupling in the data center
- **Coordinated**
  - Manages the computational and the thermal resources in a single optimization problem

Baseline & uncoordinated approaches

- **Baseline**

$$\boldsymbol{\mu}(\tau) = \overline{\boldsymbol{\mu}} \qquad \boldsymbol{\delta}(\tau) = \mathbf{0} \qquad \boldsymbol{s}(\tau) = \mathbf{1}\frac{1}{N} \qquad \boldsymbol{T}_{\text{ref}}(\tau) = \underline{\boldsymbol{T}}_{\text{ref}}$$

- **Uncoordinated controller**

$$\begin{aligned}
\min_{\mathcal{M},\mathcal{S},\mathcal{D}} \quad & \sum_{h=k}^{k+\mathcal{T}-1} \mathbf{1}^T \hat{\mathbf{p}}_{\mathcal{N}}(h|k) \\
\textbf{s.t.} \quad & \hat{\boldsymbol{l}}(k|k) = \boldsymbol{l}(k) \\
& \text{for all } h = k, \ldots, k+\mathcal{T}-1 \\
& \text{computational dynamics} \\
& \text{QoS constraints} \\
& \mathbf{0} \leq \hat{\boldsymbol{\mu}}(h|k) \leq \overline{\boldsymbol{\mu}}, \quad \hat{\boldsymbol{\delta}}(h|k) = \mathbf{0} \\
& \mathbf{0} \leq \hat{\boldsymbol{s}}(h|k) \leq \mathbf{1}, \quad \mathbf{1}^T \hat{\boldsymbol{s}}(h|k) \leq 1
\end{aligned}$$

Minimize expected zone power consumption

- Computational dynamics
- Quality of service (QoS) constraints
- Control constraints

$$\mathcal{D} = \left\{ \hat{\boldsymbol{\delta}}(k|k), \ldots, \hat{\boldsymbol{\delta}}(k+\mathcal{T}-1|k) \right\} \qquad \mathcal{T}_{ref} = \left\{ \hat{\boldsymbol{T}}_{\text{ref}}(k|k), \ldots, \hat{\boldsymbol{T}}_{\text{ref}}(k+\mathcal{T}-1|k) \right\}$$

$$\mathcal{M} = \left\{ \hat{\boldsymbol{\mu}}(k|k), \ldots, \hat{\boldsymbol{\mu}}(k+\mathcal{T}-1|k) \right\} \quad \mathcal{S} = \left\{ \hat{\boldsymbol{s}}(k|k), \ldots, \hat{\boldsymbol{s}}(k+\mathcal{T}-1|k) \right\}$$

Baseline & uncoordinated approaches

- **Baseline**

$$\boldsymbol{\mu}(\tau) = \overline{\boldsymbol{\mu}} \qquad \boldsymbol{\delta}(\tau) = \mathbf{0} \qquad \boldsymbol{s}(\tau) = \mathbf{1}\frac{1}{N} \qquad \boldsymbol{T}_{\text{ref}}(\tau) = \underline{\boldsymbol{T}}_{\text{ref}}$$

- **Uncoordinated controller**

$$\begin{aligned} \min_{\mathcal{M},\mathcal{S},\mathcal{D}} \quad & \sum_{h=k}^{k+\mathcal{T}-1} \mathbf{1}^T \hat{\mathbf{p}}_{\mathcal{N}}(h|k) \\ \textbf{s.t.} \quad & \hat{\boldsymbol{l}}(k|k) = \boldsymbol{l}(k) \\ & \text{for all } h = k, \ldots, k+\mathcal{T}-1 \\ & \text{computational dynamics} \\ & \text{QoS constraints} \\ & \mathbf{0} \leq \hat{\boldsymbol{\mu}}(h|k) \leq \overline{\boldsymbol{\mu}}, \quad \hat{\boldsymbol{\delta}}(h|k) = \mathbf{0} \\ & \mathbf{0} \leq \hat{\boldsymbol{s}}(h|k) \leq \mathbf{1}, \quad \mathbf{1}^T \hat{\boldsymbol{s}}(h|k) \leq 1 \end{aligned}$$

$$\xrightarrow{\{\hat{\mathbf{p}}_{\mathcal{N}}(h|k)\}}$$

$$\begin{aligned} \min_{\mathcal{T}_{ref}} \quad & \sum_{h=k}^{k+\mathcal{T}-1} \mathbf{1}^T \hat{\mathbf{p}}_{\mathcal{C}}(h|k) \\ \textbf{s.t.} \quad & \hat{\boldsymbol{T}}_{\text{out}}(k|k) = \boldsymbol{T}_{\text{out}}(k) \\ & \text{for all } h = k, \ldots, k+\mathcal{T}-1 \\ & \text{thermal dynamics} \\ & \underline{\boldsymbol{T}}_{\text{ref}} \leq \hat{\boldsymbol{T}}_{\text{ref}}(h|k) \leq \overline{\boldsymbol{T}}_{\text{ref}} \\ & \hat{\boldsymbol{T}}_{\text{in}}(h+1|k) \leq \overline{\boldsymbol{T}}_{\text{in}} \end{aligned}$$

$$\mathcal{D} = \left\{ \hat{\boldsymbol{\delta}}(k|k), \ldots, \hat{\boldsymbol{\delta}}(k+\mathcal{T}-1|k) \right\} \qquad \mathcal{T}_{ref} = \left\{ \hat{\boldsymbol{T}}_{\text{ref}}(k|k), \ldots, \hat{\boldsymbol{T}}_{\text{ref}}(k+\mathcal{T}-1|k) \right\}$$

$$\mathcal{M} = \left\{ \hat{\boldsymbol{\mu}}(k|k), \ldots, \hat{\boldsymbol{\mu}}(k+\mathcal{T}-1|k) \right\} \qquad \mathcal{S} = \left\{ \hat{\boldsymbol{s}}(k|k), \ldots, \hat{\boldsymbol{s}}(k+\mathcal{T}-1|k) \right\}$$

Coordinated approach

- **Considers the computational and the thermal dynamics in the same optimization problem**

$$\min_{\mathcal{M},\mathcal{S},\mathcal{D},\mathcal{T}_{ref}} \left(\sum_{h=k}^{k+\mathcal{T}-1} \mathbf{1}^T \hat{\mathbf{p}}_{\mathcal{N}}(h|k) + \mathbf{1}^T \hat{\mathbf{p}}_{\mathcal{C}}(h|k) \right)$$

Minimize expected zone and CRAC power consumption

$$\begin{aligned}
\textbf{s.t.}\quad & \hat{\boldsymbol{l}}(k|k) = \boldsymbol{l}(k), \quad \hat{\boldsymbol{T}}_{\text{out}}(k|k) = \boldsymbol{T}_{\text{out}}(k) \\
& \text{for all } h = k, \ldots, k + \mathcal{T} - 1 \\
& \text{computational dynamics,} \\
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& \text{QoS constraints,} \\
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& \underline{\boldsymbol{T}_{\text{ref}}} \le \hat{\boldsymbol{T}}_{\text{ref}}(h|k) \le \overline{\boldsymbol{T}_{\text{ref}}}, \quad \hat{\boldsymbol{T}}_{\text{in}}(h+1|k) \le \overline{\boldsymbol{T}_{\text{in}}}, \\
& \hat{\mathbf{p}}(h|k) = \mathsf{B}_{\eta} \hat{\boldsymbol{\eta}}(h|k)
\end{aligned}$$

Considers both thermal and computational dynamics

Thermal-computational coupling

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- **Simulation results**
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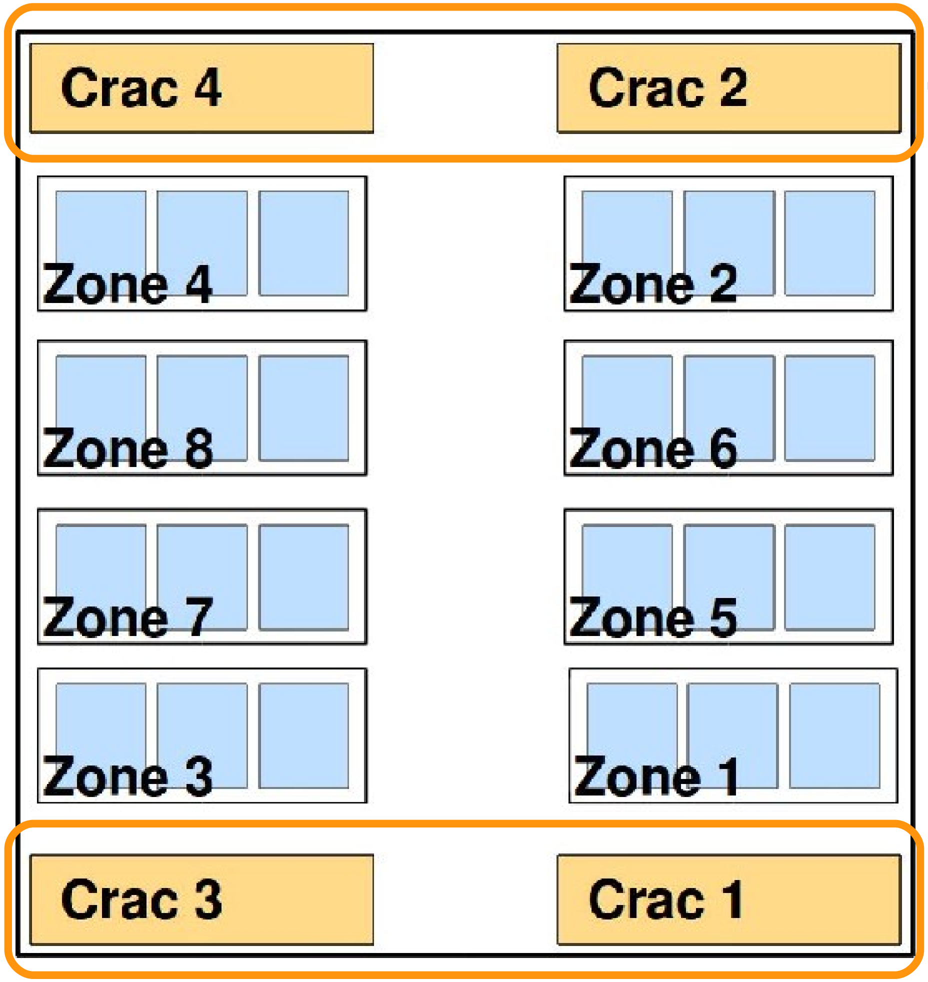
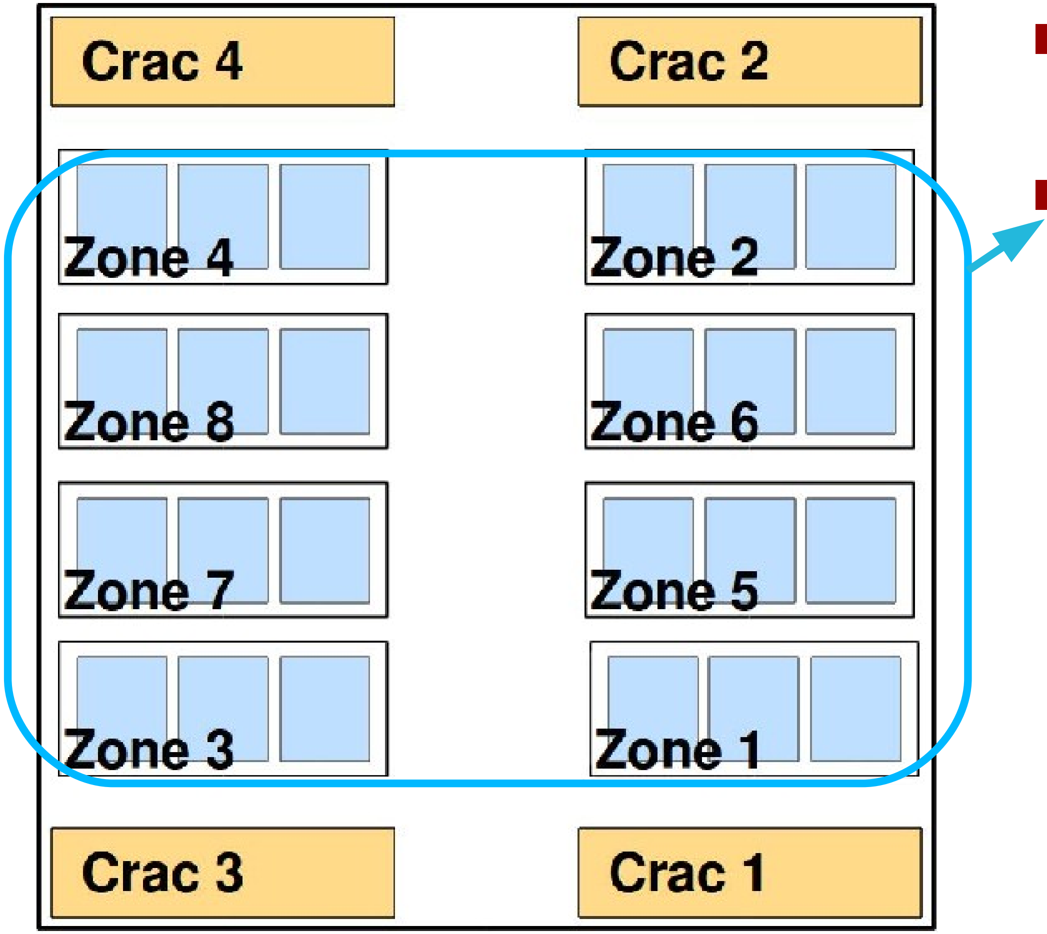
Simulation parameters



- **4 CRAC units**
  - Identical to each other

Simulation parameters



- **4 CRAC units**
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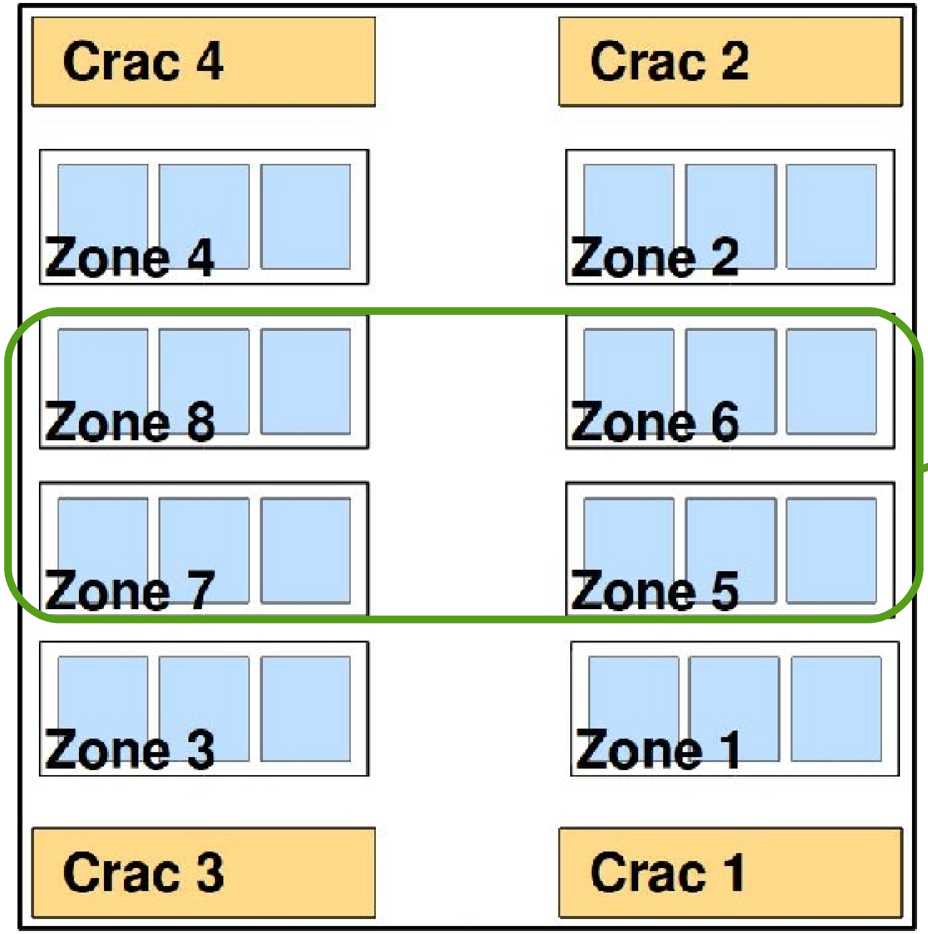
- **8 Zones**
  - 3 Racks each (126 servers per zone)

Simulation parameters



- **4 CRAC units**
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  - Energy efficient servers

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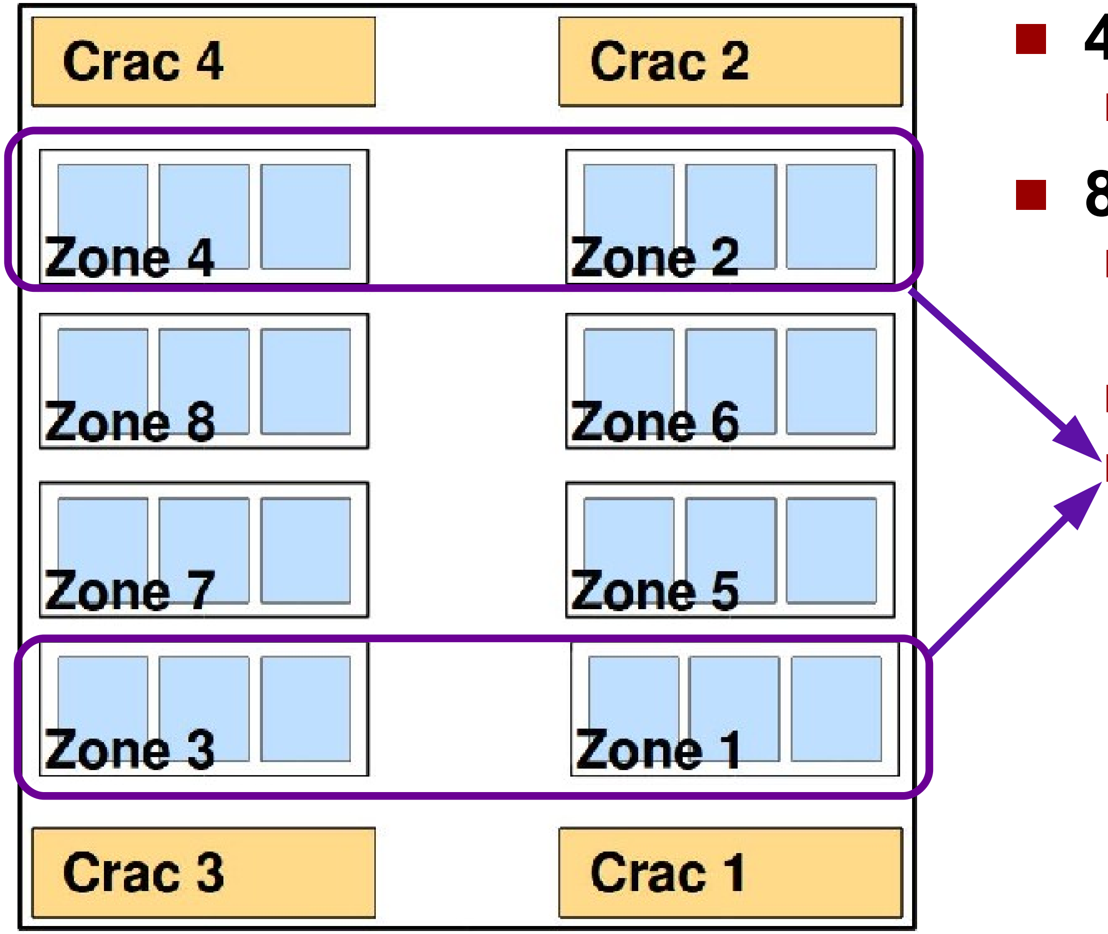

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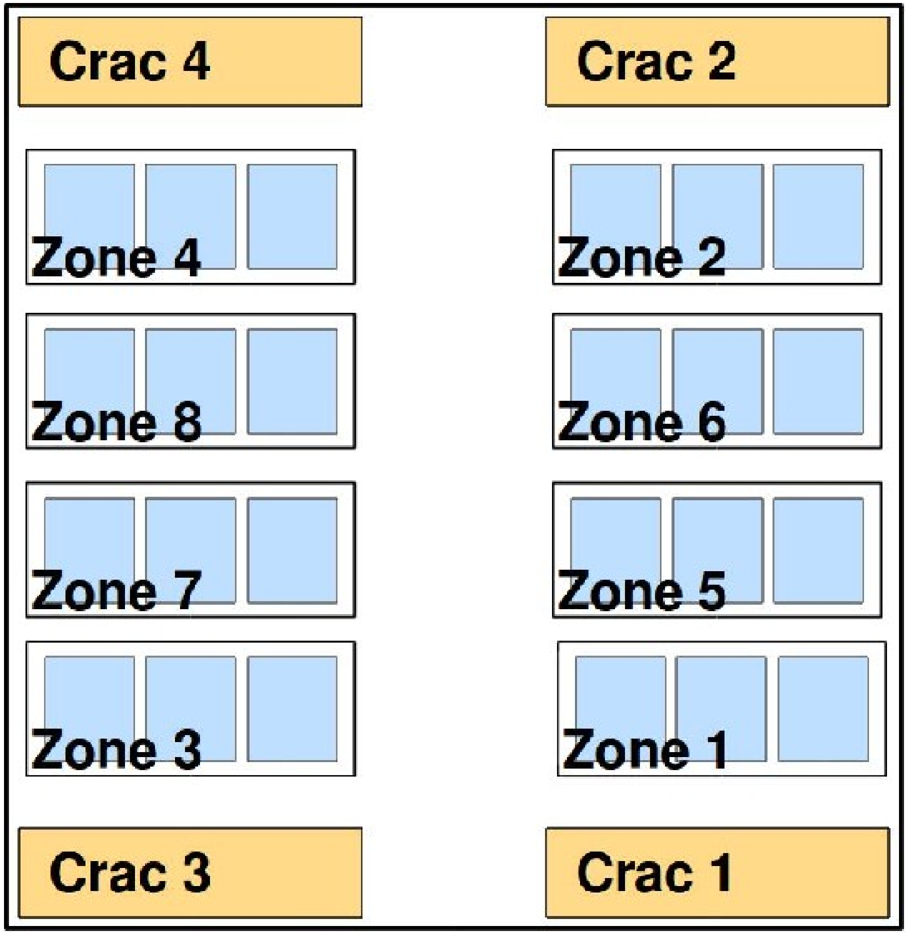
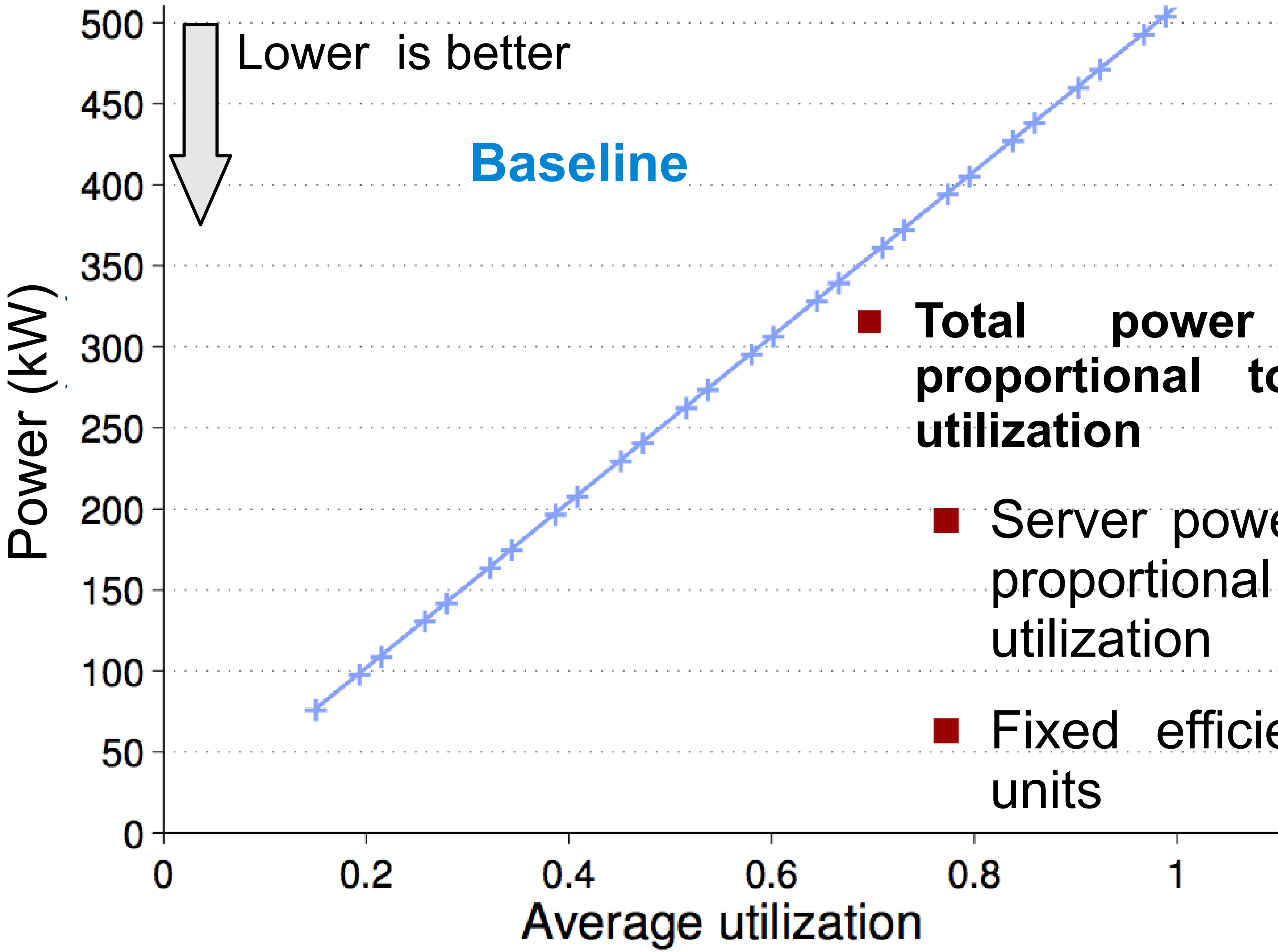


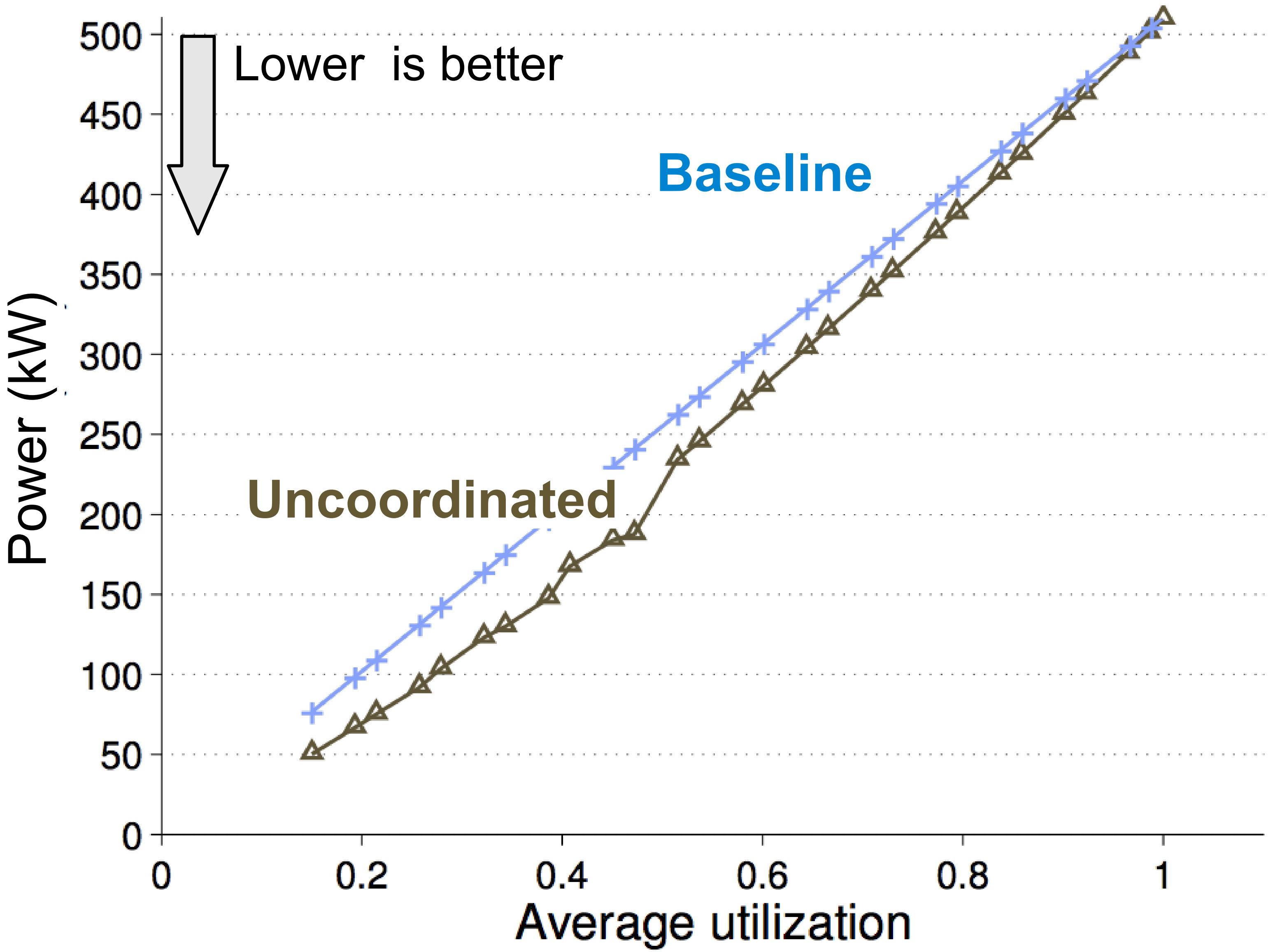
- **4 CRAC units**
  - Identical to each other
- **8 Zones**
  - 3 Racks each (126 servers per zone)
  - Energy efficient servers
  - Efficiently cooled servers
- **Analyze the average power consumption for different workload arrival rates**
- **Modeling language: TomSym**
- **Solver: KNITRO 7.0**

Total power consumption



- **Total power consumption proportional to the average utilization**
  - Server power consumption proportional to the average utilization
  - Fixed efficiency of CRAC units

Total power consumption



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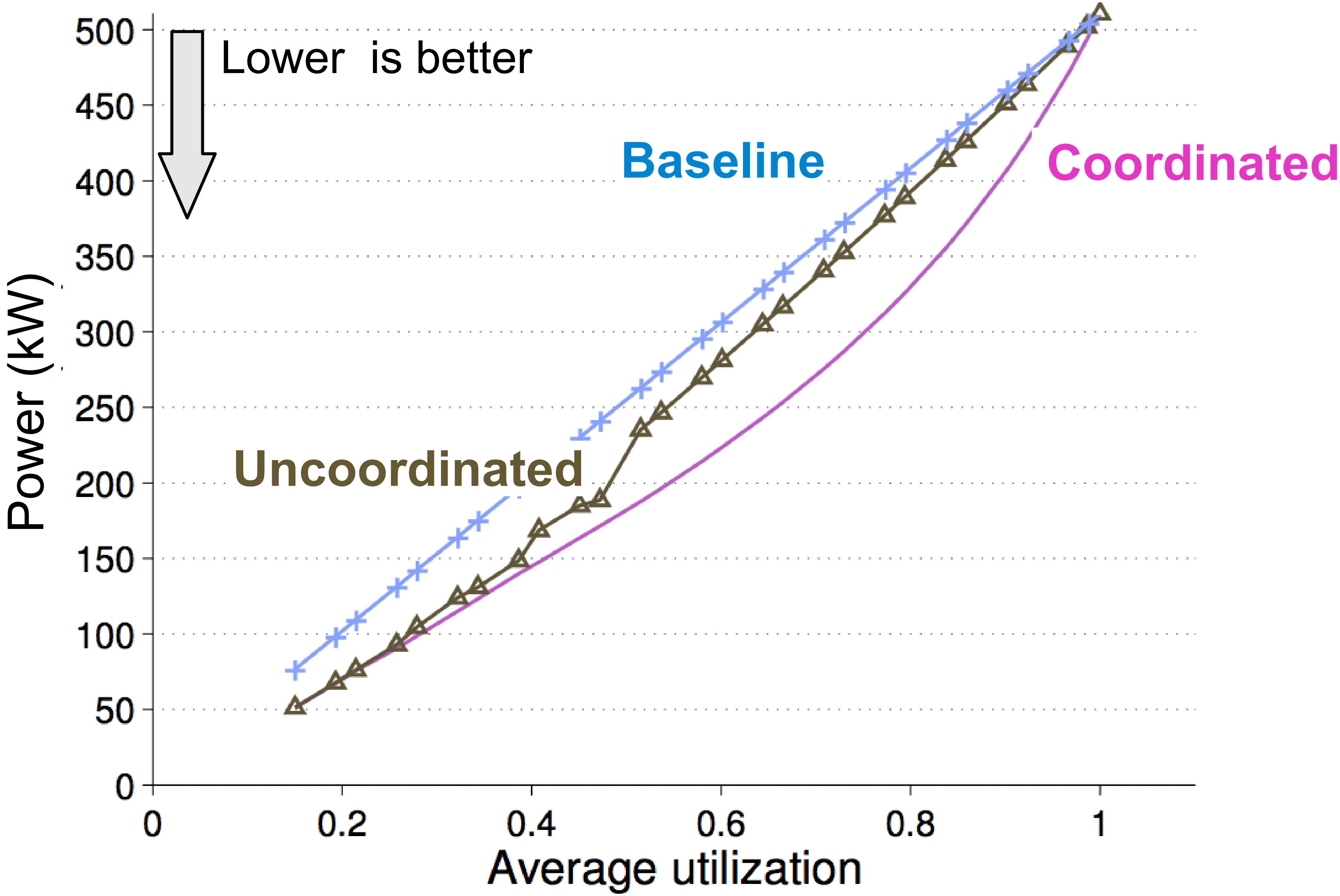

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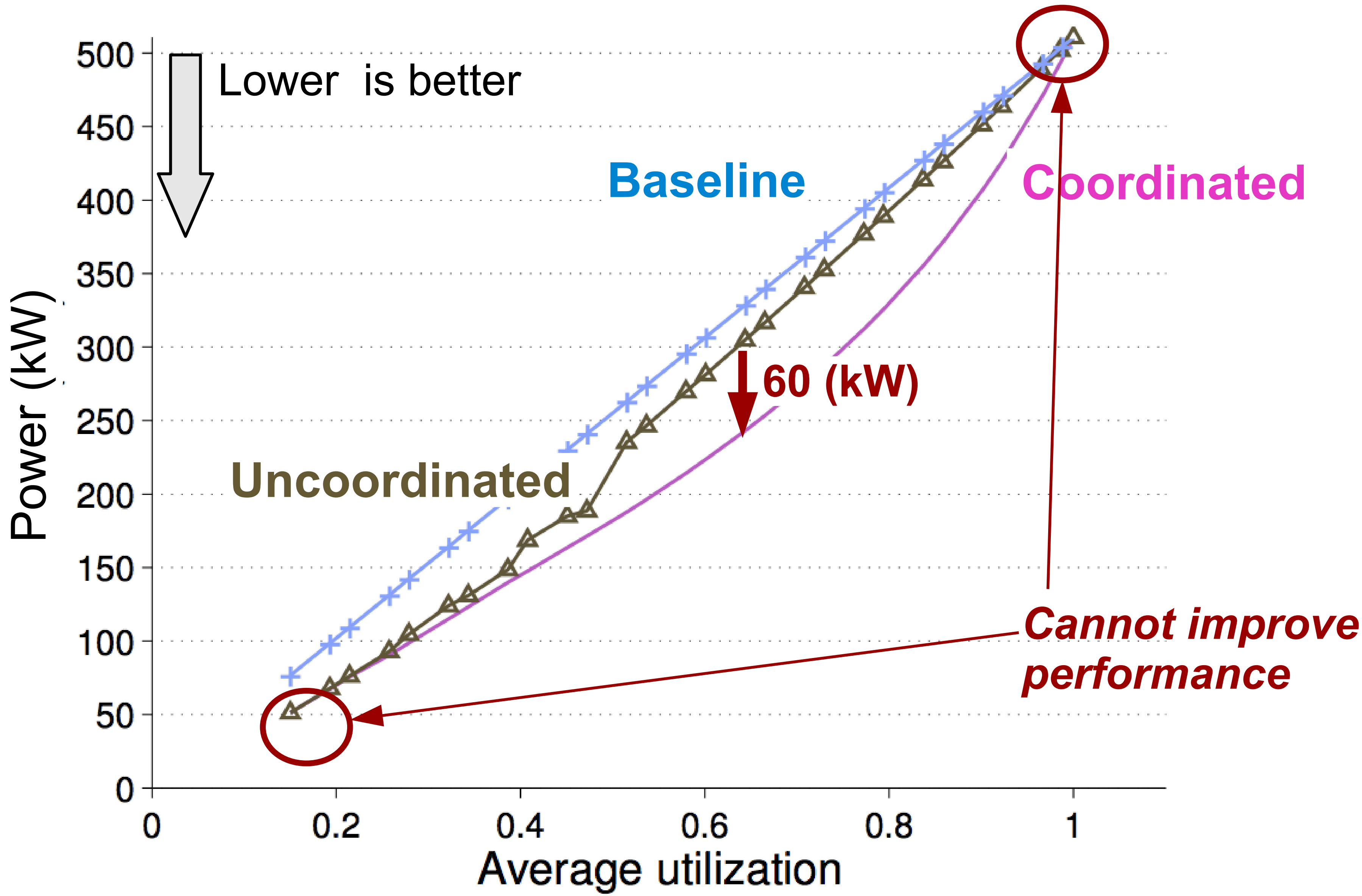
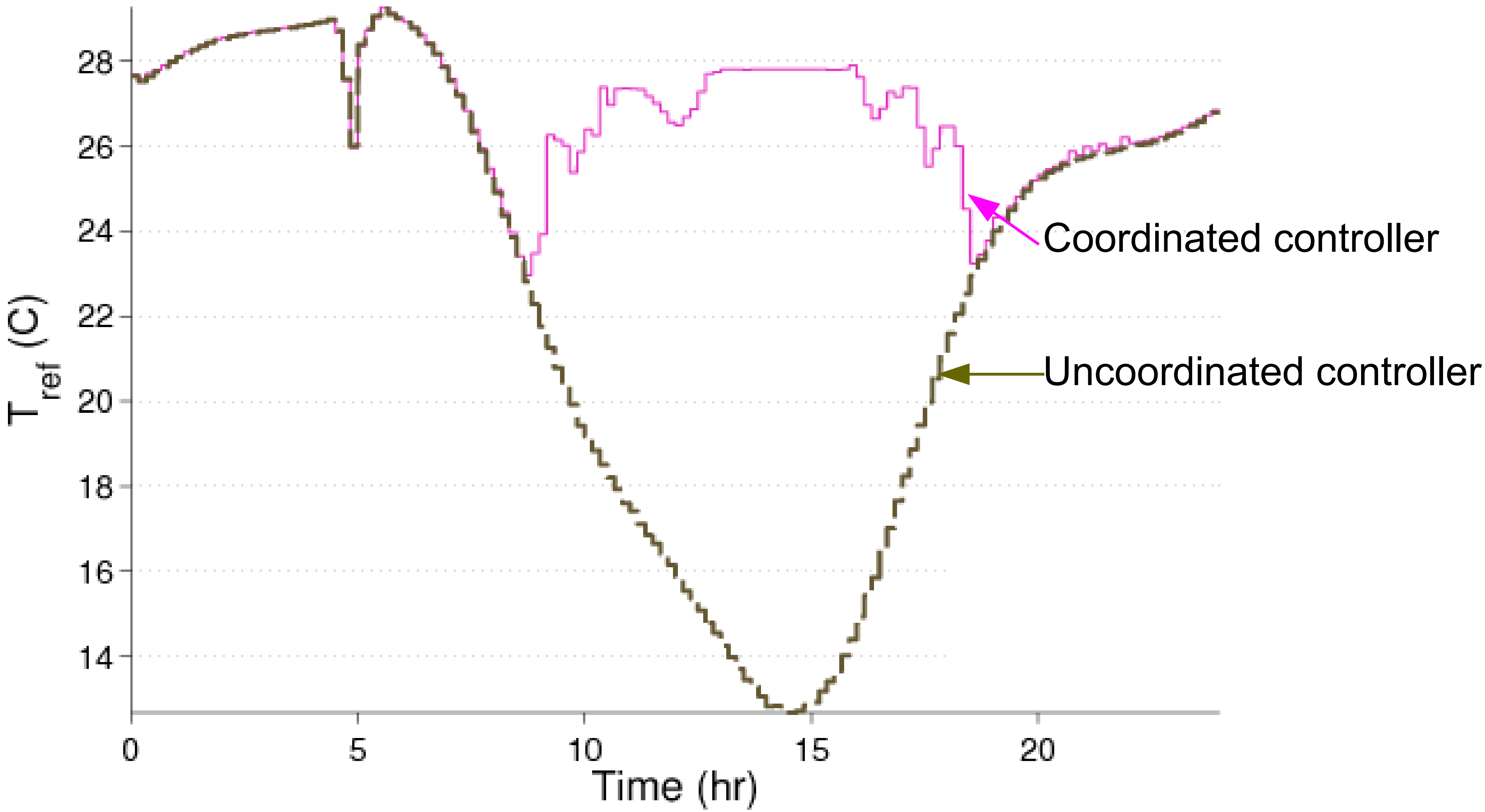
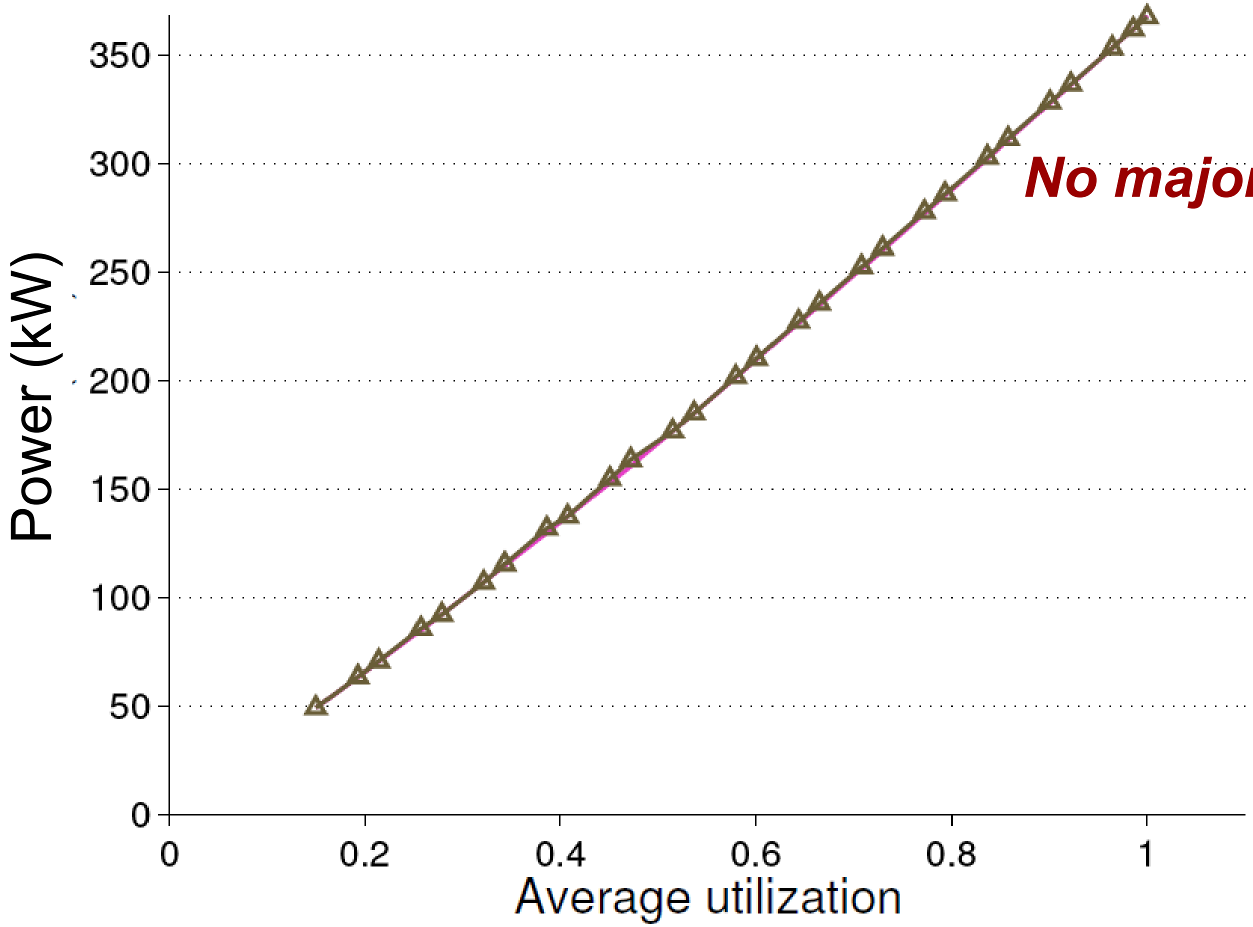


Average reference temperatures



Total power consumption

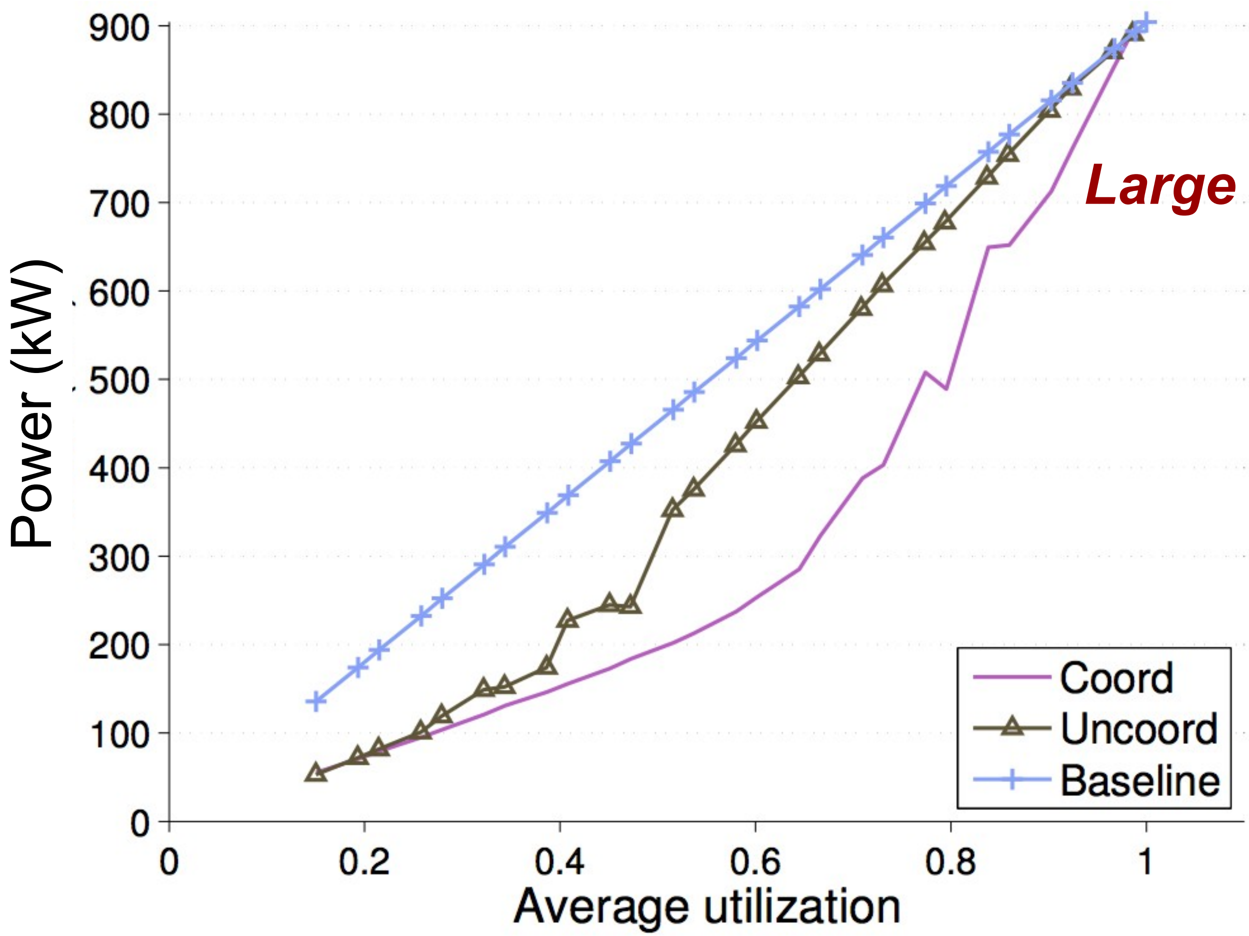
- **How do the controllers perform when all of the zones are efficiently cooled?**



No major improvements

Total power consumption

- **How do the controllers perform when large variability exists among the zone efficiency cooling?**



Large improvements

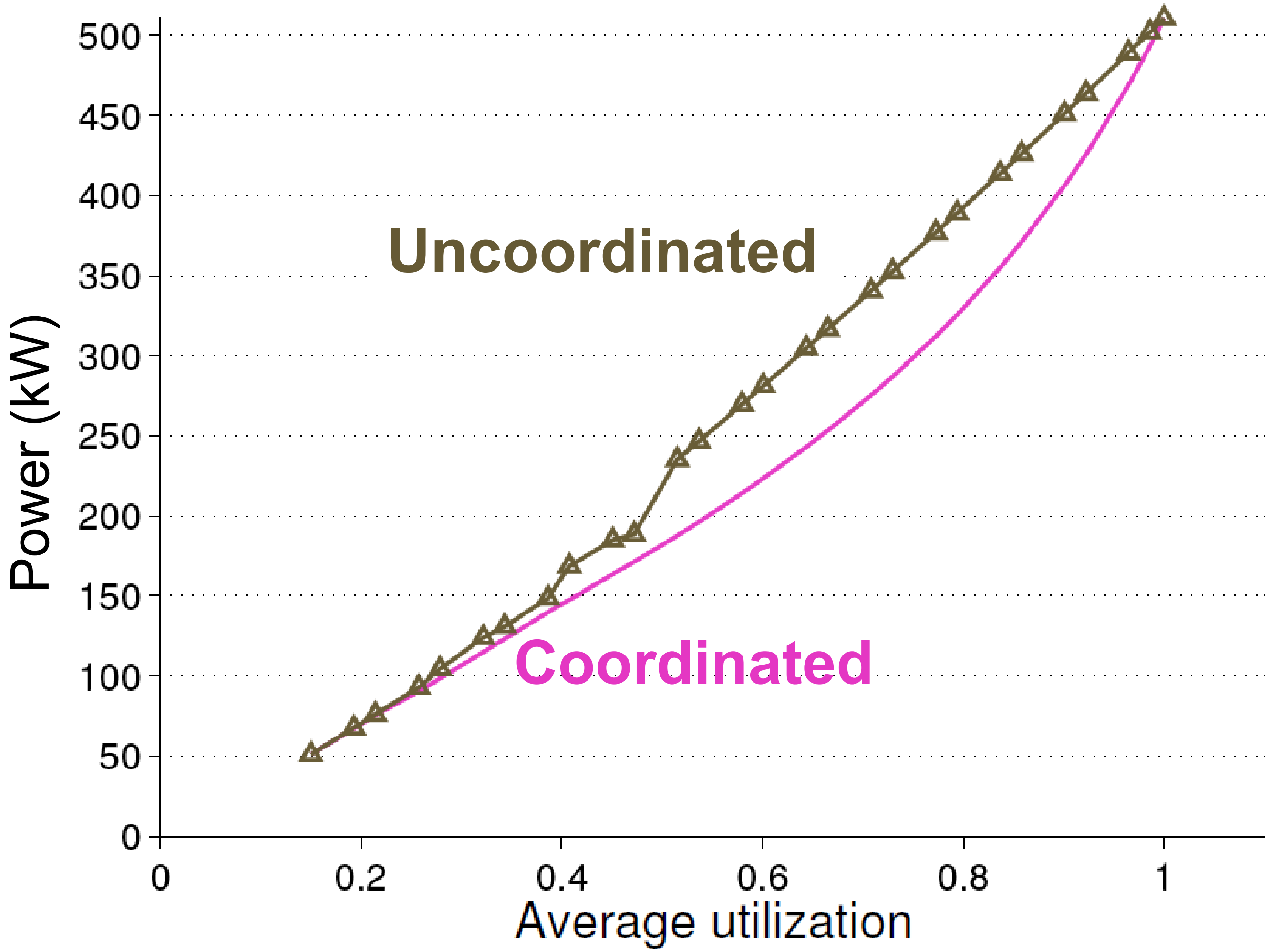
Cyber-Physical index

- **Given a data center**
  - How much energy can be saved by a coordinated controller, with respect to an uncoordinated controller?

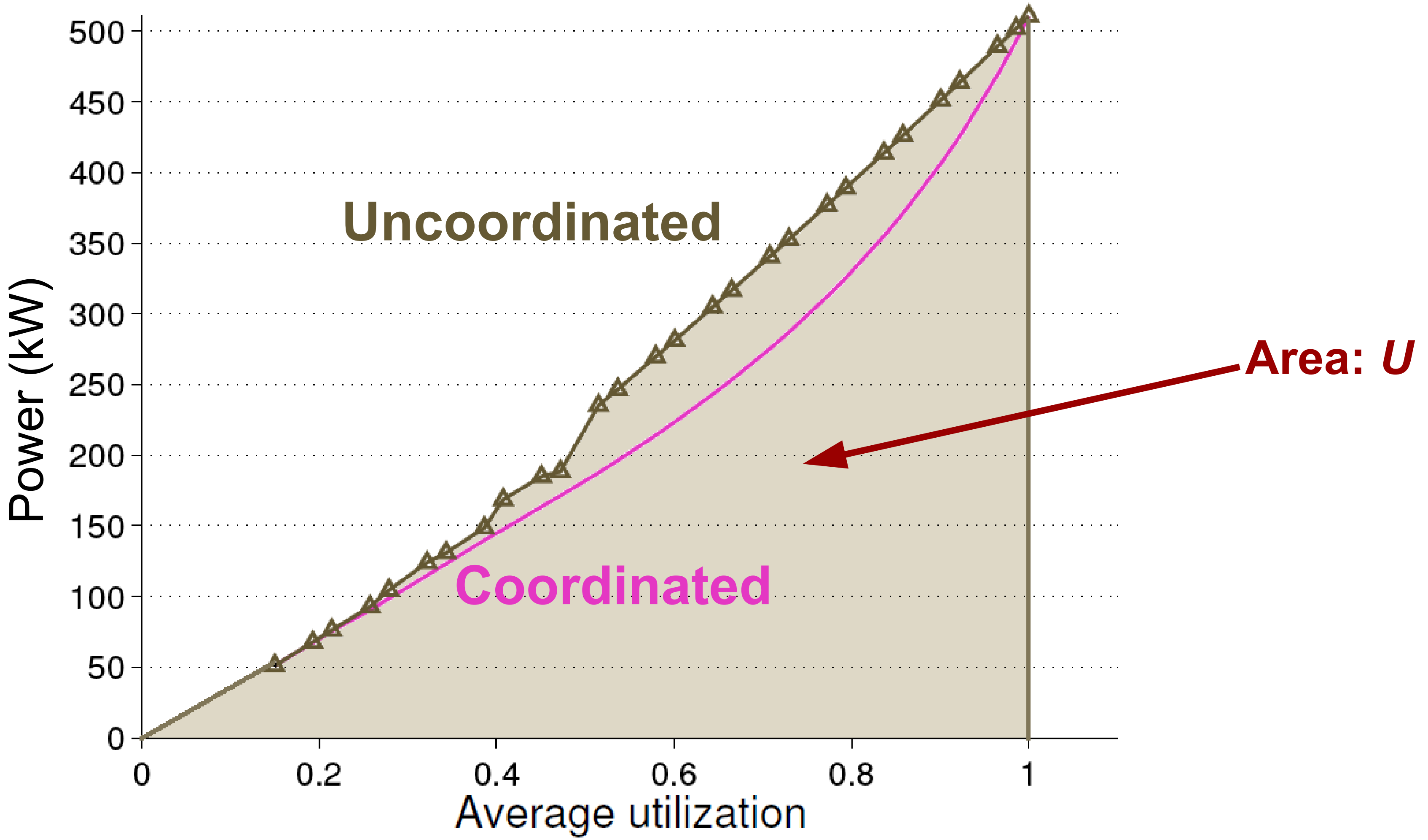
Cyber-Physical index

- **Given a data center**
  - How much energy can be saved by a coordinated controller, with respect to an uncoordinated controller?
- **Cyber-Physical index (CPI), values in [0,1]**
  - When CPI is close to 1, then a coordinated approach is advisable
  - When CPI is close to 0, then an uncoordinated approach tends to be as efficient as a coordinated approach
- **CPI is function of the sensitivity of the zones with respect to variations of the workload departure rate and of reference temperatures**

Relative efficiency

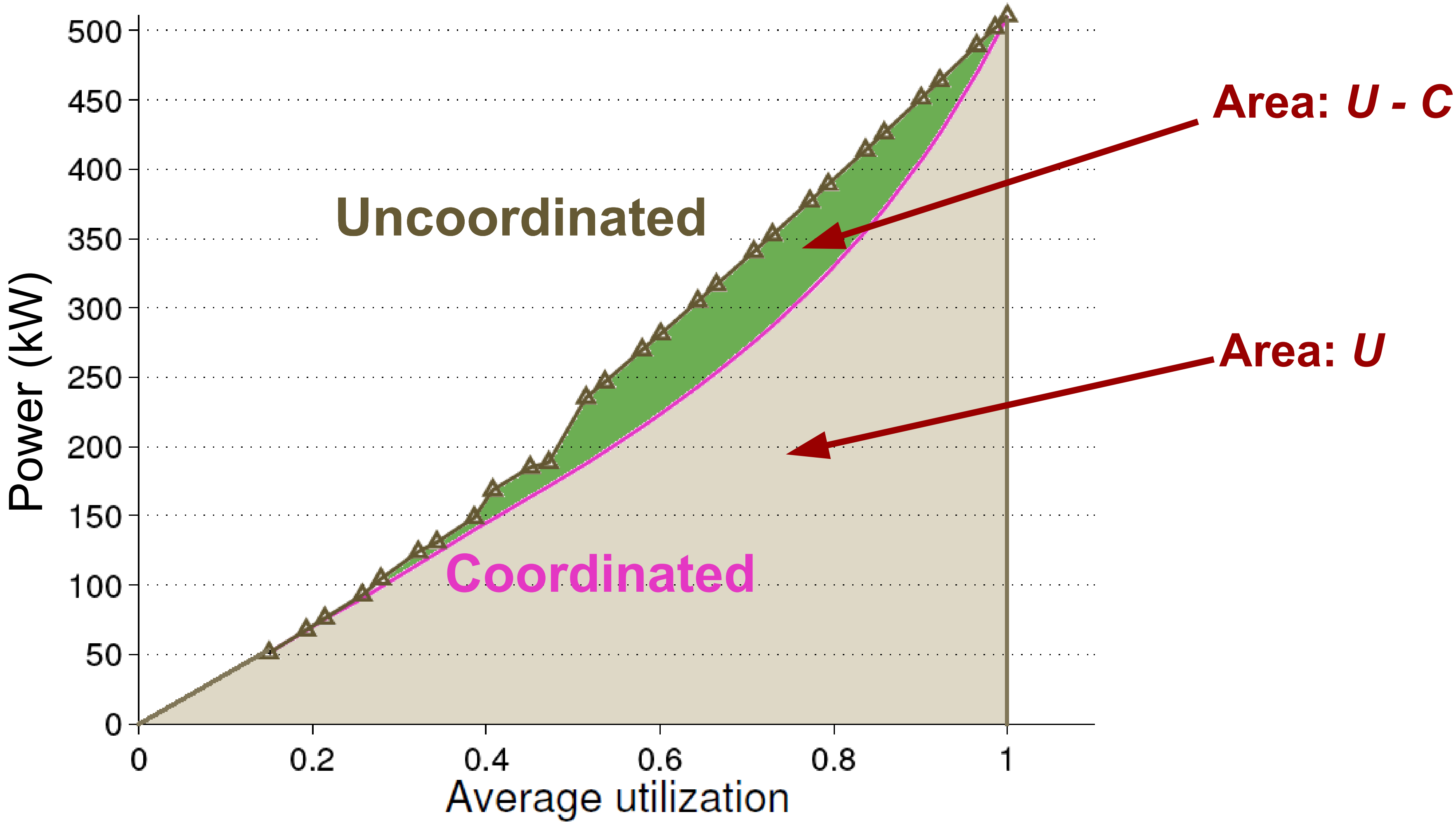


Relative efficiency



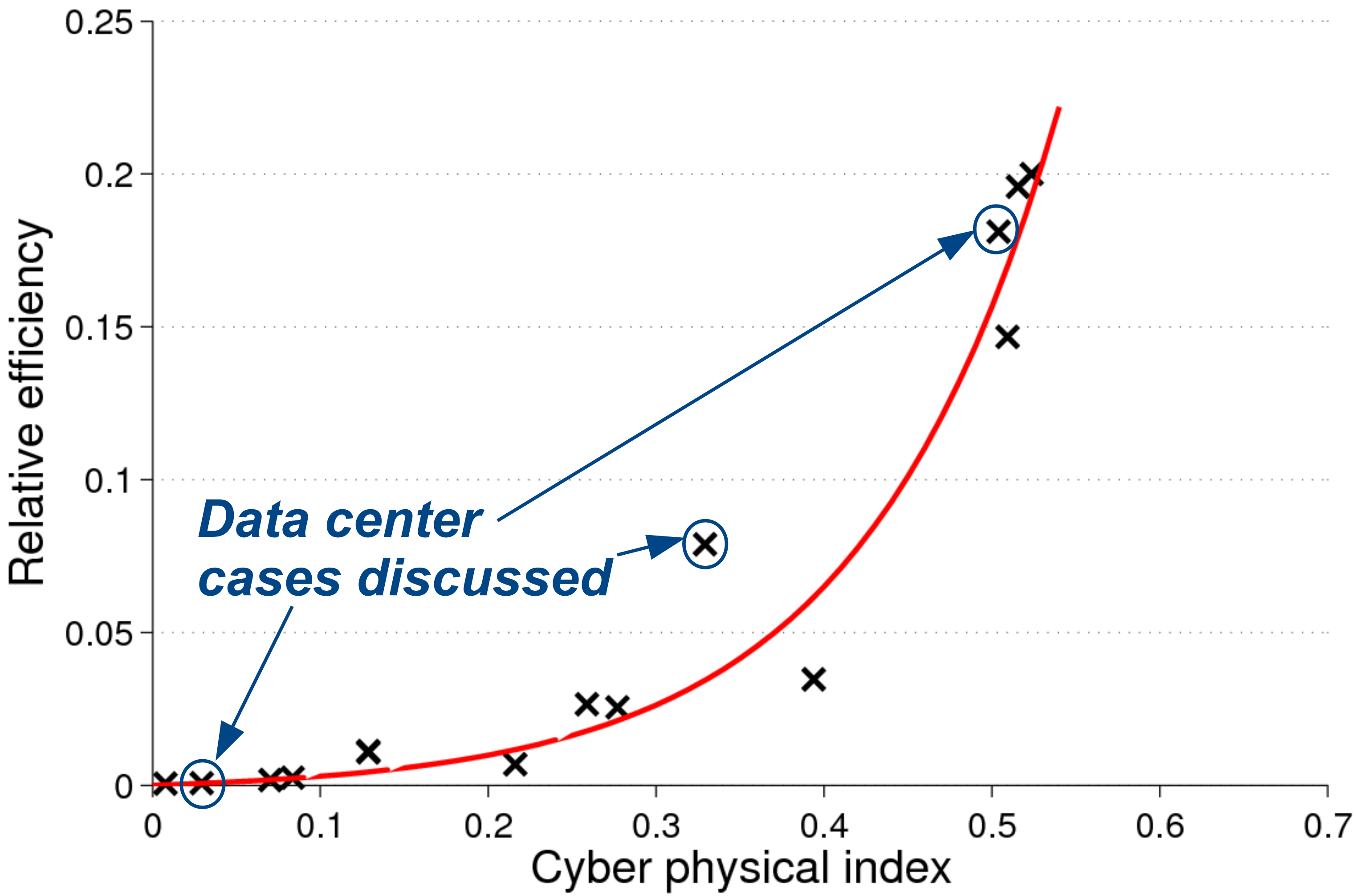
Relative efficiency

- **Relative efficiency =** $\dfrac{U - C}{U}$



Relative savings

- Every point represents a different data center



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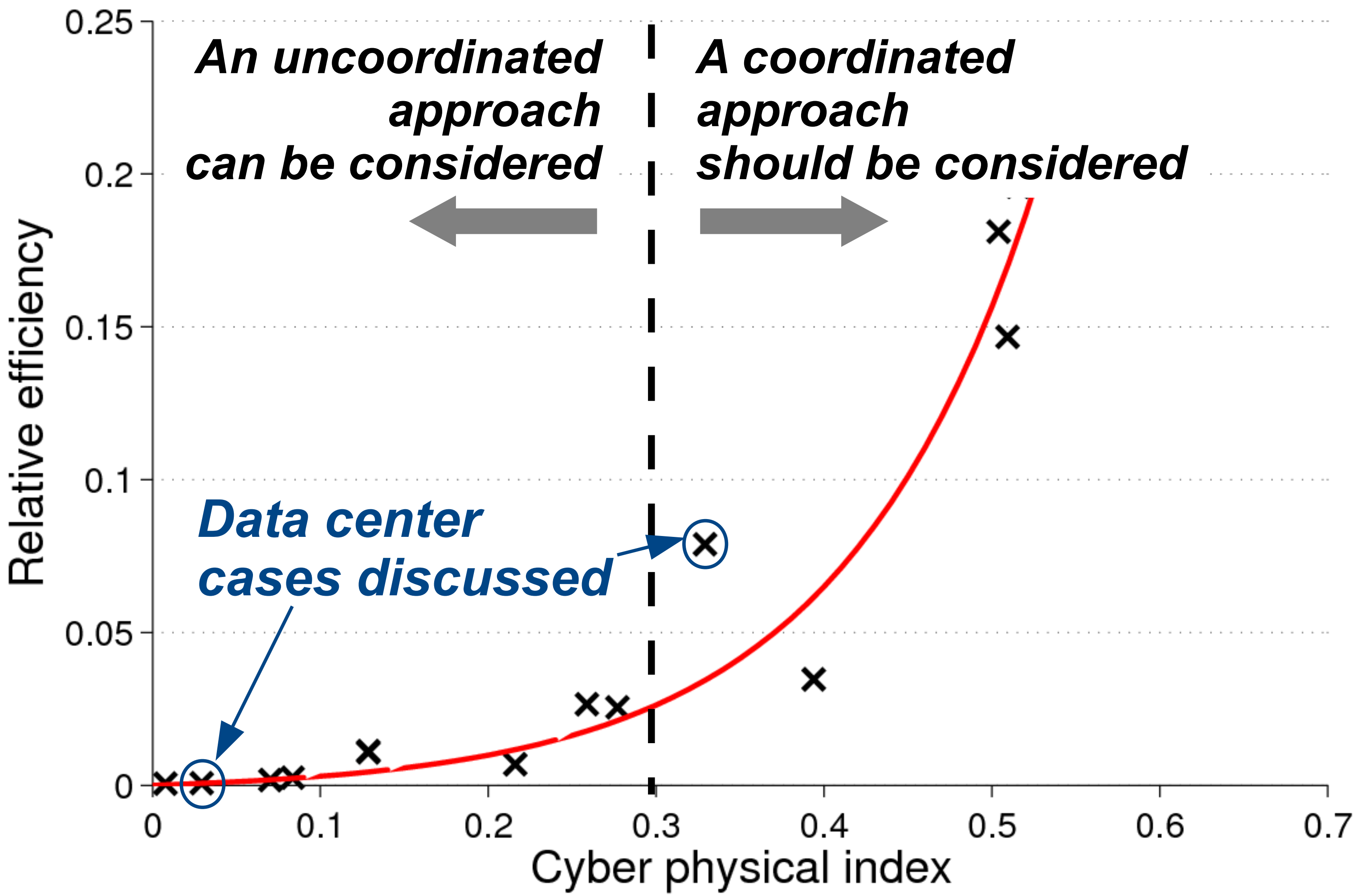
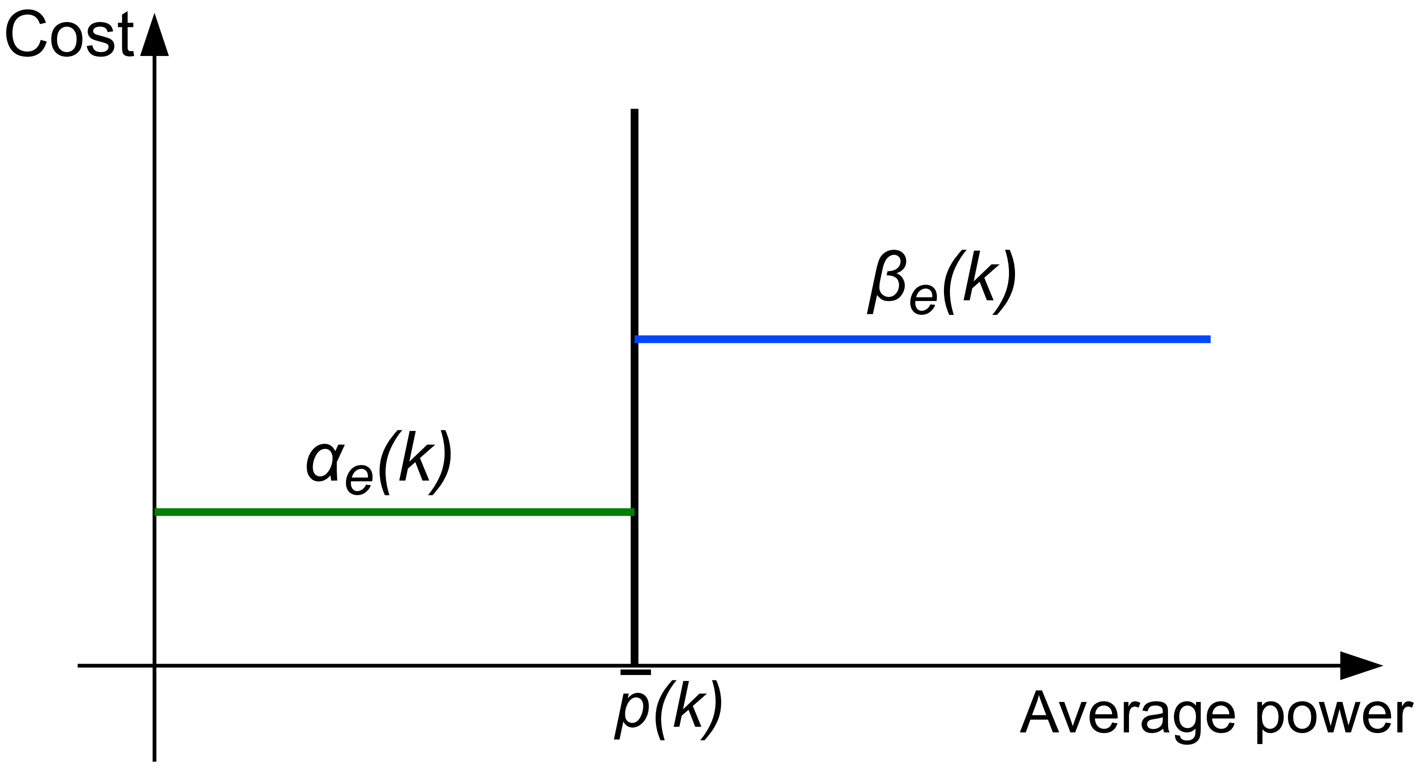


Interaction with the smart grid

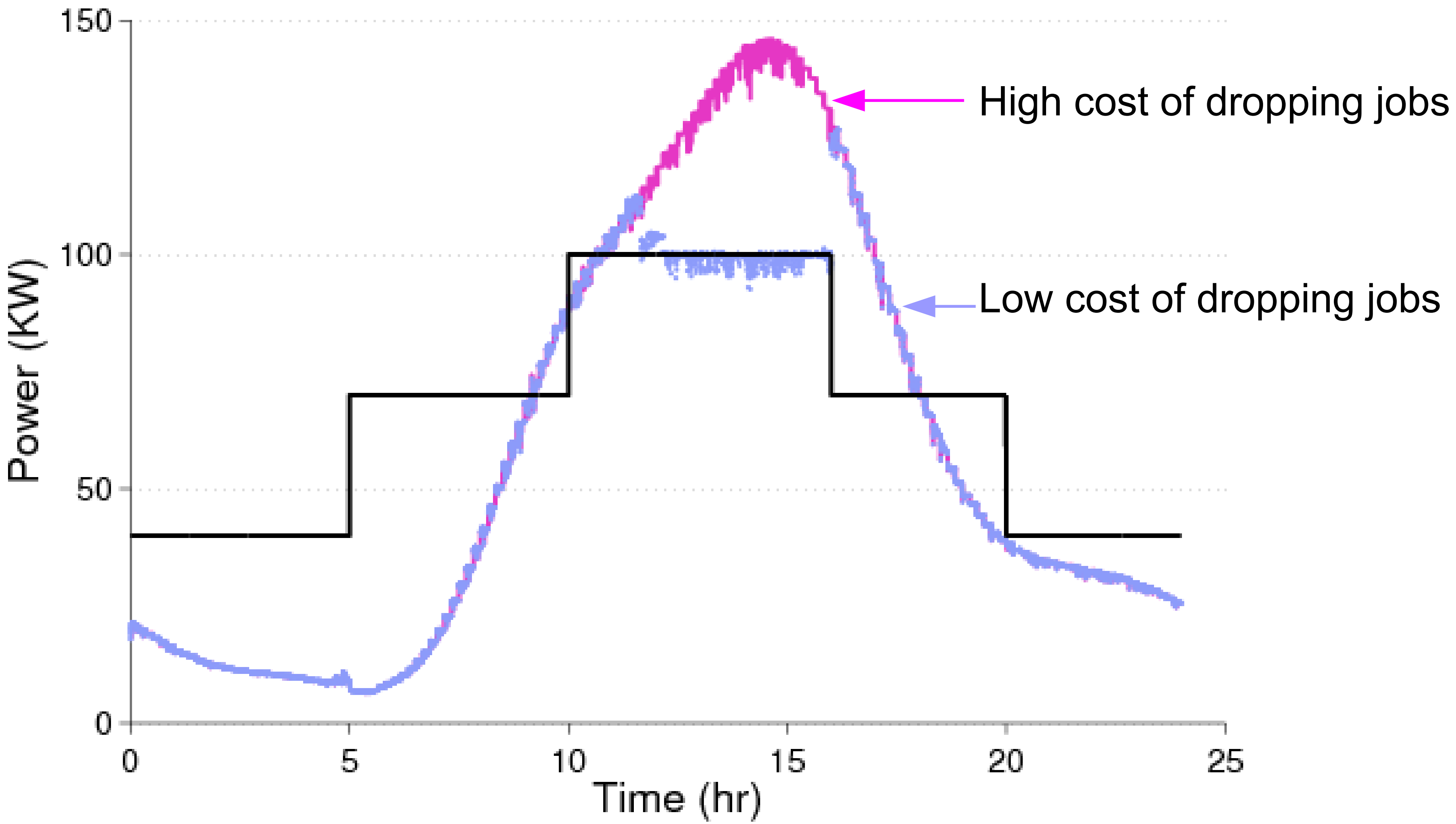
- **Time-varying electricity price**
  - Used by the smart-grid to cap the average power consumption of the data center



Run-time cost

- **Difference between income due to the workload processing and the cost of powering the data center**
- **Depends on two service level agreements (SLAs)**
  - SLA_U: sets the income based on the quality of service (QoS)
    - Approximated by the ratio between required and assigned hardware resources
  - SLA_G: sets the data center's powering cost
    - The energy cost is time-varying and power consumption dependent

Total data center power consumption



Conclusion

- **Discussed a control-oriented data center model**
  - Considers both the computational and the physical characteristics of a data center
  - The model can be extended to consider electricity cost (interaction with the smart-grid) and other data center equipment
- **Introduced two control strategies**
  - Representative of different approaches to data center control
- **Compared the performance of the control strategies under the same scenario**
- **Proposed a cyber-physical index**
  - First attempt to characterize the thermal and computational characteristics of the data center within a single index
- **Analyzed the impact of time-varying electricity prices**

Future work

- **Controllers can take advantage of service level agreements (SLAs) with both the users and the power grid**
  - Uncoordinated control approach can be as optimal as the coordinated approach
  - Depending on the SLA with the grid, the data center may induce large variations on the real-time electricity price
- **Given a data center, where should we locate its server so as to reduce its CPI?**
- **Feasibility and stability of coordinated and uncoordinated controller**
  - The coordinated controller is always feasible, but does not lead to a stable equilibrium point
  - How should the cost function be formulated so that the closed-loop system has a stable, economically optimal, equilibrium point?