Model Predictive Control of Data Centers in the Smart Grid Scenario

Luca Parolini, Bruno Sinopoli, Bruce H. Krogh

Electrical and Computer Engineering
Carnegie Mellon University

IFAC – 1st Sep. 2011
Electricity consumption

Historical energy use vs. Future energy use projections

- Historical trends scenario
- Current efficiency trends scenario
- Improved operation scenario
- Best practice scenario
- State of the art scenario

Electricity consumption

Historical energy use vs. Future energy use projections

- Historical trends scenario
- Current efficiency trends scenario
- Improved operation scenario
- Best practice scenario
- State of the art scenario

55% decrease

Examples of data centers

- Racks
  - 42 (1U) servers are stacked in a rack
  - 1U server
    - 480mm x 800mm x 44m
    - Peak power ~380W
  - Rack peak power ~16KW
  - Large density of power consumption
    - 800W/m² – 1.6KW/m²

- Facebook's data center in North Carolina, US
  - 450$ million project
  - ~28,000 m² (300,000 ft²)

- One of the data center in San Jose
  - 2,300 m² (25,000 ft²), 5 MW load

http://www.datacenterknowledge.com/
Thermal constraints

- Without proper cooling, chip temperatures would exceed safe operation limits
  - *Almost complete transformation of electrical energy into heat*

- Chip temperature generally unobservable

- Industrial approach
  - Bound server *inlet air temperature*
Temperature distribution

\[ T_{\text{max}} = 36.6^\circ \text{C} \]

- Cold aisles
- Hot aisle
- CRACs
- Server racks

Temperature (\(^{\circ}\text{C}\)):
- 40
- 37.2222
- 34.4444
- 31.6667
- 26.1111
- 23.3333
- 20.5556
- 17.7778
- 15

Plane location \( Y = 1.84785 \text{ m} \)

R. K. Sharma et al. IEEE Internet Computing 2005
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)
  - $\text{SLA}_U$: sets the income based on the quality of service (QoS)
    - Approximated by the ratio between required and assigned hardware resources
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.
Interaction with the smart grid

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

\[ p(k) - \alpha_e(k) \leq \beta_e(k) \]

Cost

\[ \alpha_e(k) \]

\[ \beta_e(k) \]

Average power

\[ p(k) \]
Outline

- Introduction
- Control-oriented model
- Simulation results
- Conclusion and future work
Control approach

- Hierarchical-distributed control approach
  - Takes advantage of the modularity found in data centers

- We focus on the highest level of the hierarchy
  - Based on a model predictive control (MPC) approach
  - Simplified modeling approach
    - Single servers are grouped into zones
    - Power consumption of a zone is proportional to the amount of workload executed in the zone
  - Considers computational and thermal dynamics
  - Considers the nonlinear efficiency of the CRAC units
Computational model

- **Computational resources modeled via a network of queues**
  
  \[ \hat{l}(\nu + 1|k) = \hat{l}(\nu|k) + \hat{A}(\nu|k)\hat{s}(\nu|k) - \hat{d}(\nu|k) \]
  
  \[ \hat{d}(\nu|k) = \min \left\{ \hat{l}(\nu|k) + \hat{A}(\nu|k)\hat{s}(\nu|k), M\hat{\rho}(\nu|k) \right\} \]

- **Power consumption proportional to the amount of jobs processed**
  
  \[ \hat{p}_N(\nu|k) = B_d \hat{d}(\nu|k) \]
Thermal network

- **Linear model**

\[
\hat{T}_{\text{out}}(\nu + 1|k) = A_{T,D} \hat{T}_{\text{out}}(\nu|k) + B_{T,D} \left[ p_N(\nu|k)^T \hat{T}_{\text{ref}}(\nu|k)^T \right]^T
\]

Output temperature of zones and CRAC units

Power consumption of zones

Reference temperature of CRAC units

\[
\hat{T}_{\text{in}}(\nu|k) = \Psi \hat{T}_{\text{out}}(\nu|k) \leq \overline{T}_{\text{in}}
\]

- **CRAC power consumption depends on the coefficient of performance (COP)**

\[
p_i(t) = \frac{\dot{Q}_i(t)}{COP_i(T_{\text{out},i}(t))}
\]

Heat removed rate (W)
Computational variables at time $k$

<table>
<thead>
<tr>
<th>Input</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controllable</td>
<td>Job scheduling $s(k)$</td>
</tr>
<tr>
<td></td>
<td>Resource allocation $\rho(k)$</td>
</tr>
<tr>
<td>Uncontrollable</td>
<td>Job arrival $a(k)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone power consumption $p_N(k)$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of jobs in zones $l(k)$</td>
<td></td>
</tr>
</tbody>
</table>
Thermal network variables at time $k$

<table>
<thead>
<tr>
<th>Input</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controllable</td>
<td>CRAC unit reference temperature</td>
</tr>
<tr>
<td>Uncontrollable</td>
<td>Zone power consumption</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption of CRAC nodes</td>
<td>$p_c(k)$</td>
</tr>
<tr>
<td>Input temperatures of zones</td>
<td>$T_{\text{in}}(k)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output temperatures of CRACs and zones</td>
<td>$T_{\text{out}}(k)$</td>
</tr>
</tbody>
</table>
Outline

- Introduction
- Control-oriented model
- Simulation results
- Conclusion and future work
Simulation parameters

- 4 CRAC units
- Identical each other
Simulation parameters

- 4 CRAC units
  - Identical each other
- 8 Zones
  - 3 Racks each (126 servers per zone)
Simulation parameters

- **4 CRAC units**
  - Identical each other
- **8 Zones**
  - 3 Racks each (126 servers per zone)
  - Energy efficient servers
Simulation parameters

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

- **8 Zones**
  - 3 Racks each (126 servers per zone)
  - Energy efficient servers
  - Efficiently cooled servers
Simulation parameters

- 4 CRAC units
  - Identical each other
- 8 Zones
  - 3 Racks each (126 servers per zone)
  - Energy efficient servers
  - Efficiently cooled servers
- Simulate data center over 24hr time
  - Two control approaches
  - Controllers' time step: 10 min
  - Horizon: 6 steps (1hr)
Uncoordinated & Coordinated strategies

- Uncoordinated strategy
  - Two-step control approach

\[ 1. \min_{\mathcal{R}, \mathcal{S}} F_1(\mathcal{R}, \mathcal{S}; \mathbf{l}(k)) \]

subject to
  
  computational dynamics

\[ 2. \min_{\mathcal{T}_{\text{ref}}} F_2(\mathcal{T}_{\text{ref}}; \mathbf{l}(k), \mathbf{T}_{\text{out}}(k)) \]

subject to
  
  thermal dynamics

\[ \hat{T}_{\text{in}}(\nu|k) \leq \overline{T}_{\text{in}} \]

- Coordinated strategy

\[ \min_{\mathcal{R}, \mathcal{S}, \mathcal{T}_{\text{ref}}} F(\mathcal{R}, \mathcal{S}, \mathcal{T}_{\text{ref}}; \mathbf{l}(k), \mathbf{T}_{\text{out}}(k)) \]

subject to
  
  computational dynamics

thermal dynamics

\[ \hat{p}_N(\nu|k) = B_d \hat{d}(\nu|k) \]

\[ \hat{T}_{\text{in}}(\nu|k) \leq \overline{T}_{\text{in}} \]

\[ \mathcal{R} = \{ \hat{\rho}(k|k), \ldots, \hat{\rho}(k+T-1|k) \} \]

\[ \mathcal{S} = \{ \hat{s}(k|k), \ldots, \hat{s}(k+T-1|k) \} \]

\[ \mathcal{T}_{\text{ref}} = \{ \hat{T}_{\text{ref}}(k|k), \ldots, \hat{T}_{\text{ref}}(k+T-1|k) \} \]
Job arrival rate and electricity costs

- **Real data**
  - Job arrival rate

- **Day-ahead electricity cost**

- **Parameters in the simulation**
  - Job arrival rate, 2 classes of jobs

- **Electricity costs**
  - High cost
  - Low cost

The Internet traffic archive, http://ita.ee.lbl.gov/

PJM, http://www.pjm.com/
Total data center power consumption
Total data center power consumption

Power (KW)

Time (hr)

Uncoordinated controller

Coordinated controller

Time-varying power threshold

23%

Different scheduling strategies
Average reference temperatures

![Graph showing temperature reference over time for coordinated and uncoordinated controllers. The graph indicates a decrease and then an increase in temperature over time, with different markers for coordinated and uncoordinated controllers.]
Average reference temperatures

- Higher efficiency of CRAC units
- Coordinated controller
- Uncoordinated controller
Average reference temperatures

Over-cool servers to take advantage of reduced electricity price

Variation of electricity cost
Simulation parameters

- **4 CRAC units**
  - Identical each other
- **8 Zones**
  - 3 Racks each (126 servers per zone)
  - Energy efficient servers
  - Efficiently cooled servers
- **Simulate data center over 24hr time**
  - *Compare two coordinated control strategies*
Total data center power consumption

- High cost of dropping jobs
- Low cost of dropping jobs
Total data center power consumption

Power cap also depends on the job arrival rate

\[ \beta_e(k) = 1.6 \alpha_e(k) \]
Conclusion and future work

- Discussed a control-oriented model which considers both the computational and the thermal characteristics of a data center.

- Proposed two control strategies which take advantage of SLA with both the users and the power grid.
  - Uncoordinated control approach can be as optimal as the coordinated approach.
  - Depends on the thermal-computational characteristics of the data center.
Thank you!