Greening Multi-Tenant Data Center Demand Response

Niangjun Chen

Joint work with Xiaoqi Ren, Shaolei Ren, and Adam Wierman
2 stories about energy and data centers

Typical story: data centers are energy hogs

Emerging story: data centers are valuable resources

Idea: use data centers for demand response (DR)
DR is crucial for renewable integration
Finding DR resources is challenging

GTM research, “U.S. Demand Response Outlook 2014”
Data centers have great potential for DR

20 MW Data Center with 20% flexibility = 700 kWh fast charging, optimally placed storage [Liu et al 2014]

~$5 million cost!

However, current participation is still inefficient

This talk: Efficient DR in Multi-tenant Data Centers
Multi-tenant (colocation) data centers

Multiple tenants house and manage their own servers independently in **shared** space
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Data center operator is mainly responsible for facility support (e.g., power supply, cooling).
Multi-tenant (colocation) data centers

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Data center operator is mainly responsible for facility support (e.g., power supply, cooling).

...of total data center industry electricity usage

CoreSite’s “One Wilshire” (Photo: CoreSite)
Why target **multi-tenant** data center for DR?

Most multi-tenant data centers are in metropolitan areas
– Downtown Los Angeles, New York, Silicon Valley, etc.
This is where demand response is **most** needed!

**Example:** On July 22, 2011, hundreds of multi-tenant colocation data centers participated in emergency demand response and contributed by cutting their electricity usage before a nation-wide blackout occurred in the U.S. and Canada.

--- A. Misra, “Responding Before Electric Emergencies.”
How do multi-tenant data center provide DR?

- Turn on **diesel generator** upon utility’s request
  - Costly and environmentally unfriendly

**Opportunity:**

Tenants typically have great flexibility in energy usage

[LBNL, HP] workload management can save 10-30+% in server energy 10-60min

We should **buy energy reduction from tenants!**
Our contribution: a **simple and provably efficient mechanism to incentivize tenants’ reduction**

Goal: \[ \min \alpha \cdot y + \sum_i c_i(s_i) \]

\[ \text{s.t. } y + \sum_i s_i = \delta \]

**Operator’s challenge:**
1. No direct control of tenants’ reduction \( s_i \)
2. Tenants’ private cost \( c_i \) unknown

- \( y \): amount of local generation
- \( s_i \): load reduction of tenant \( i \)
- \( \alpha \): price for diesel
- \( c_i \): cost of reduction of tenant \( i \)
**ColoDR:** a supply function mechanism for DR

1. Operator announces supply function $s(b, p) = \delta - b/p$
2. Tenant $i$ submits bid $b_i$
3. Operator sets market price $p$ to minimize its own cost (payment to tenants plus diesel cost)
4. DR is exercised

**Cut energy** $\delta$

Diesel energy $y = \delta - \sum_i s_i$

**Utility**

**Supply bid** $b_i$

**Price** $p$

Tenants

Cut energy by $s_i = \delta - b_i / p$
**ColoDR**: a supply function mechanism for DR

Cut energy $\delta$

Diesel energy

$y = \delta - \Sigma_i s_i$

Supply bid $b_i$

Price $p$

Cut energy by $s_i = \delta - b_i / p$

**Simple**: tenant only need to communicate one parameter

**Fair**: no price differentiation

**Cost saving for operator**: cost of dispatch decrease compared to diesel only

**Equilibrium**: always exists and unique (more on this later)
Why supply function bidding?

1. VCG type mechanisms are problematic
   [Zhang et al 2015] [Rothkopf 2007]

2. Supply function bidding is widely used in electricity market
   [Baldick et al 2004] [Day et al 2002] [David and Wen 2000]

3. Prior work on supply function bidding
   [Klemperer and Meyer 1989] [Niu et al 2005] [Johari and Tsitsiklis 2011] [Xu et al 2015]
How well does ColoDR work?

1. What is the social cost?
2. What are tenants’ costs?
3. What is operator’s cost?
4. What is the reduction in diesel usage?

We answer these questions with both theoretical guarantees and trace-based simulations.
What should we compare to?

**Benchmark:** Centrally controlled social cost minimization (SCM)

\[
\min \alpha \cdot y + \sum_i c_i(s_i)
\]

s.t. \( y + \sum_i s_i = \delta \)

**Tenant behavior for ColoDR**

**Price-taking:** Consider the price as is:

\[
\max_{b_i} p \cdot S_i(b_i, p) - c_i(S_i(b_i, p))
\]

**Price-anticipating:** Consider the impact of bidding decisions on the market price:

\[
\max_{b_i} p(b) \cdot S_i(b_i, p(b)) - c_i(S_i(b_i, p(b)))
\]
What should we compare to?

Case study

DR signals issued by PJM on January 7, 2014, due to cold weather.

Three different types of workload with different tolerance to delay.
1. What is the social cost?

**Theorem:** For both price-taking and price-anticipating tenants, \( \text{cost}(\text{ColoDR}) \leq \text{cost}(\text{SCM}) + \frac{\alpha \delta}{N} \)

Near optimal when \( N \) is small.

Vanishing when \( N \) is large, what if \( N \) is small?
2&3. What are tenants’ and operator’s costs?

**Theorem:** For both price-taking and price-anticipating tenants,

\[
\begin{align*}
\text{cost}_t(\text{ColoDR}) & \leq \text{cost}_t(\text{SCM}) + \frac{2\alpha \delta}{N} \\
\text{cost}_o(\text{ColoDR}) & \geq \text{cost}_o(\text{SCM}) - \frac{\alpha \delta}{N}
\end{align*}
\]

Higher utility for tenants with larger flexibility
4. What is the reduction in diesel usage?

**Theorem:** For both price-taking tenants, \( y^t < y^* + \delta/2 \)
for price-anticipating tenants, \( y^a \leq y^* + \delta \)

In worst case, ColoDR may use a lot more diesel than optimal

<table>
<thead>
<tr>
<th>Diesel price ($/kWh)</th>
<th>Energy reduction (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>T1, T2, T3, Diesel</td>
</tr>
<tr>
<td>0.2</td>
<td>T1, T2, T3, Diesel</td>
</tr>
<tr>
<td>0.3</td>
<td>T1, T2, T3, Diesel</td>
</tr>
<tr>
<td>0.4</td>
<td>T1, T2, T3, Diesel</td>
</tr>
<tr>
<td>0.5</td>
<td>T1, T2, T3, Diesel</td>
</tr>
<tr>
<td>0.6</td>
<td>T1, T2, T3, Diesel</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \] ColoDR(price-taking)  ColoDR(price-anticipating)  SCM
How well does ColoDR work?

1. What is the social cost?
   \[ \text{cost}(\text{ColoDR}) \leq \text{cost}(\text{SCM}) + \alpha\delta/N \]
2. What is tenants’ cost?
   \[ \text{cost}_t(\text{ColoDR}) \leq \text{cost}_t(\text{SCM}) + 2\alpha\delta/N \]
3. What is operator’s profit?
   \[ \text{cost}_o(\text{ColoDR}) \geq \text{cost}_o(\text{SCM}) - \alpha\delta/N \]
4. What is the reduction in diesel usage?
   \[ y^t \leq y^* + \delta/2 \quad y^a \leq y^* + \delta \]

All these follow from one key characterization lemma
Characterize **equilibrium** as the outcome of an optimization problem

**Lemma:** When tenants are **price-taking**, the market equilibrium is unique and characterized by

\[
\begin{align*}
\min_{s,y} & \quad \sum_i c_i(s_i) + \frac{\alpha}{2N\delta} (y + (N - 1)\delta)^2 \\
\text{s.t.} & \quad \sum_i s_i + y = \delta
\end{align*}
\]

Due to strategic behavior of operator
A characterization lemma

Characterize equilibrium as the outcome of an optimization problem

**Lemma:** When tenants are price-anticipating, the market equilibrium is unique and characterized by

\[
\min_{s,y} \sum_i \hat{c}_i(s_i) + \frac{\alpha}{2N\delta} (y + (N - 1)\delta)^2
\]

subject to

\[
\sum_i s_i + y = \delta
\]

where

- Strategic behavior of tenants
  \[c_i(s_i) \leq \hat{c}_i(s_i) \leq c_i(s_i) + s_i\alpha/2N\]
- Strategic behavior of operator
Two messages

#1: Multi-tenant data center DR is a billion dollar market
   - Turning an energy hog into a social asset!

#2: Multi-tenant data center demand response can be “green” by incentivizing tenants’ cooperation
   - Our proposed mechanism based on supply function bidding incentivizes and coordinates tenants’ energy shedding, with a provably-efficient outcome.