How Peer Effects Influence Energy Consumption

D.P. Zhou, M. Roozbehani, M.A. Dahleh, C.J. Tomlin

[datong.zhou, tomlin]@berkeley.edu, [mardavij, dahleh]@mit.edu

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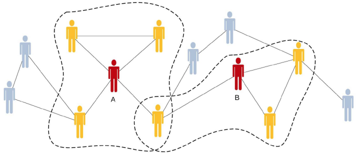
Introduction to Peer Effects

Background

- Social comparisons influence people's behavior:
  - Conform to a standard
  - Receive social acclaim
  - Other people's choices can be informative (recommender systems)



- Network effects in social networks and platforms
  - Positive externalities
- Impact of Peer Effects on energy consumption?[1]
  - Various Randomized Controlled Trials (RCTs) to investigate such effects[2]
  - High consumers reduce most, efficient ones show "boomerang effect"

Question

- How can peer effects in energy networks be exploited for profit-maximization of the load serving entity?

Methodology

- Develop a game between utility and electricity users, introducing peer effects

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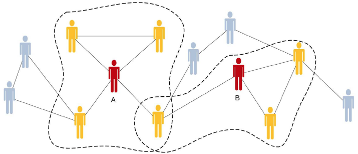

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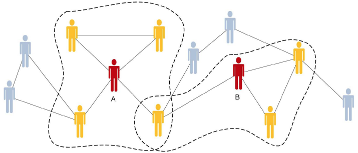

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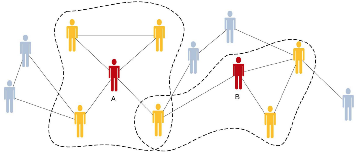

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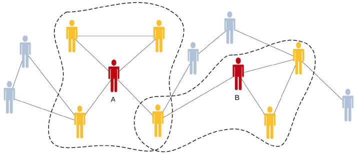

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Two-Stage Game-Theoretic Model

Consumers

- Set of consumers $\mathcal{I} = \{1, \dots, n\}$ with utility function

$$u_i = a_i x_i - b_i x_i^2 - p_i x_i + \gamma_i x_i \left(\sum_{j \in \mathcal{I}} w_{ij} x_j - x_i \right).$$

- Interaction matrix $W \in [0,1]^{n \times n}$
- Each user observes price p_i^* and $\mathbf{x}_{-i}$ and maximizes utility:

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Load-Serving Entity

- Profit: $\Pi = \sum_{i \in \mathcal{I}} p_i x_i - c_i x_i^2$
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Price and Consumption Equilibria

Perfect Price Discrimination

$$\mathbf{p}^* = \frac{\mathbf{a}}{2} + CZ\frac{\mathbf{a}}{2} - W^\top \Gamma Z \frac{\mathbf{a}}{4} + \Gamma W Z \frac{\mathbf{a}}{4},$$

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$$Z = \left[2\Gamma + B + C - \left(\frac{W^\top \Gamma}{2} + \frac{\Gamma W}{2} \right) \right]^{-1}.$$

- Complete knowledge of **a** and **b**
- Incentive for strongly influential users $W^\top \Gamma$
- Additional cost for strongly influenced users ΓW

Single Price, Complete Information

$$p_u^* = \left[1 - \frac{\mathbf{1}^\top A^{-1} \mathbf{1}}{2 \cdot \mathbf{1}^\top \left(A^{-1} + A^{-1} C A^{-1} \right) \mathbf{1}} \right] \bar{a},$$

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$$A = B + 2\Gamma - \Gamma W, \qquad \bar{a} = \sum_{i=1}^{n} a_i / n.$$

- Complete knowledge of **a** and **b**
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Single Price, Incomplete Information

$$\tilde{p}_u^* \geq \frac{\mathbb{E}[a]}{2} \left[1 + \frac{c}{n} \mathbf{1}^\top \left[2\Gamma + (2\mathbb{E}[b] + c) I - \Gamma W \right]^{-1} \mathbf{1} \right],$$

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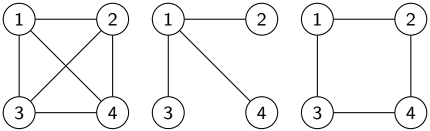

Comparison of Pricing Schemes

Perfect Price Discrimination

$$\mathbf{p}^* = \frac{\mathbf{a}}{2} + CZ\frac{\mathbf{a}}{2} - W^\top \Gamma Z \frac{\mathbf{a}}{4} + \Gamma W Z \frac{\mathbf{a}}{4},$$

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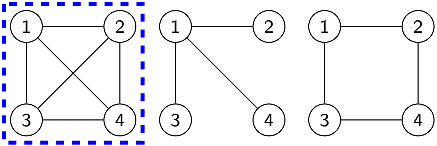

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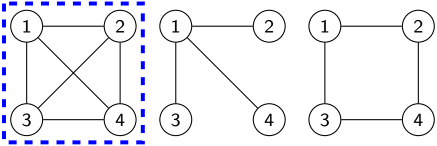

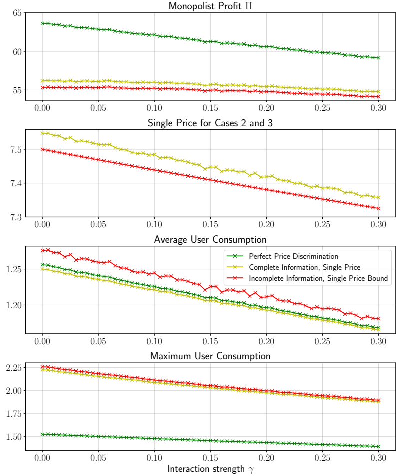

Theoretical Statements

Theorem (Monotonicity of Consumption Equilibrium)

If $a_i = a$, $b_i = b$, and $\gamma_i = \gamma \; \forall \; i \in \mathcal{I}$, then x_i^* is strictly monotonically decreasing in γ independent of the network topology W.

Proof Sketch.

Take derivative $\frac{d\mathbf{x}}{d\gamma} = -\frac{1}{4\gamma(b+\gamma)} K^{-1} F^{-1} (\mathbf{a} - \mathbf{p})$ and exploit diagonal dominance of K and F. Show that all elements $(K^{-1}F^{-1})_{ij}$ are positive. □

Theorem (Influence of High Consumer)

Let $w_{ij} = \left(\sum_{j \in \mathcal{I}} \mathbf{1}_{w_{ij} > 0} \right)^{-1}$, $b_i = b$, $\gamma_i = \gamma$ and $a_i - p_i = \alpha$ for $\mathcal{N} = \{ i \in \mathcal{I} \setminus j \}$. Let j be the "high" consumer. If $a_j - p_j = \bar{\alpha} > n\alpha$, then for each neighbor i of j, x_i^* is initially increasing in γ, whereas x_j^* is strictly monotonically decreasing in γ.

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Evaluate $\frac{dx}{d\gamma}$ at $\gamma = 0$ and use definition of peer effects. □

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Theoretical Statements (cont'd.)

Theorem (Targeted Peer Effects)

For $n = 2$ users, the network effect reduces the sum of their consumptions iff

$$b_1 \leq \frac{(a_1 - p)\,(4b_2 + 3\gamma)}{2(a_2 - p)} \quad \text{and} \quad b_2 \leq \frac{(a_2 - p)\,(4b_1 + 3\gamma)}{2(a_1 - p)}.$$

This can be generalized to $n \geq 3$.

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Utility maximizing response of user i is $x_i^* = \frac{a_i - p_i + \gamma_i \sum_{j \in \mathcal{I}} w_{ij} x_j}{2(b_i + \gamma_i)}$. Result follows. □

Theorem (Efficiency)

The consumption equilibrium $\mathbf{x}^*$ is inefficient as the social welfare $\mathcal{S}$ attained is suboptimal. Specifically, $x_i^* < x_i^o \ \forall \ i \in \mathcal{I}$, where $\mathbf{x}^o$ maximizes social welfare:

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Allocating users per-unit subsidies $s_i = (b_i + \gamma_i) x_i^2 / 2$ can restore the social optimum.

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Unknown Network Structure

- Let $W = W^\top$ and $\Gamma = \gamma I$
- Monopolist only has estimate $\tilde{W}$, where $\tilde{W} = \tilde{W}^\top$
- Lower bound on expected profit $\tilde{\Pi}^*$ under perfect price discrimination:

$$\frac{\tilde{\Pi}^*}{\Pi^*} \geq \frac{\lambda_{\min}(C + B + 2\Gamma - \Gamma W)}{\lambda_{\max}(C + B + 2\Gamma - \Gamma W) + \gamma \|W - \tilde{W}\|_2}$$

- Simulation for $n = 24$ fully connected users:

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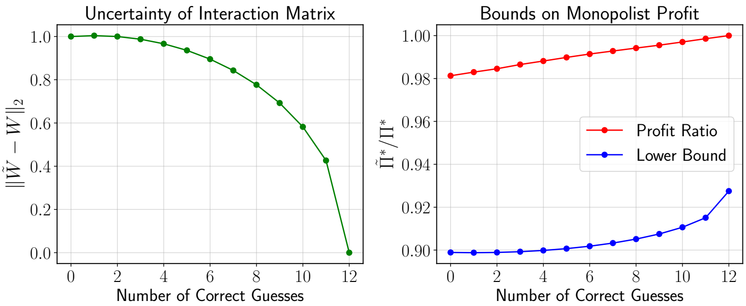

User Selection Problem

Profit Maximization with User Selection

- Which users should be exposed to peer effects to maximize profit?
- Assume p is exogenously set (by the Public Utilities Commission)
- Formulate profit-maximizing problem:

$$\begin{aligned} \underset{\delta_1,\ldots,\delta_n}{\text{maximize}} \quad & \sum_{i=1}^{n} p x_i - c_i x_i^2 \\ \text{subject to} \quad & \mathbf{x} = (B + 2\Delta\Gamma - \Delta\Gamma W)^{-1} (\mathbf{a} - p\mathbf{1}) \\ & \sum_{i=1}^{n} \delta_i = m, \quad \delta_i \in \{0, 1\} \\ & \Delta = \text{diag}(\delta_1, \ldots, \delta_n) \end{aligned}$$

- MIQCP cannot be solved analytically
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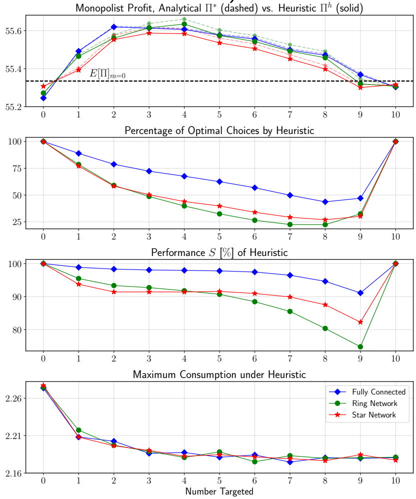

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Summary

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