Efficient Coordinated Power Distribution on Private Infrastructure

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Background—Smart Grid

- Smart grid: gathers info about own operation
- Intelligence required to realize potential
- This talk: organizing agent behavior in electrical grids

Background—Microgrids

- Electricity generation + energy storage + loads
- Usually operates connected to a centralized grid
- 685 MW (2013), 4 GW (2020 projection)
  - 4 GW = 2-4 million households
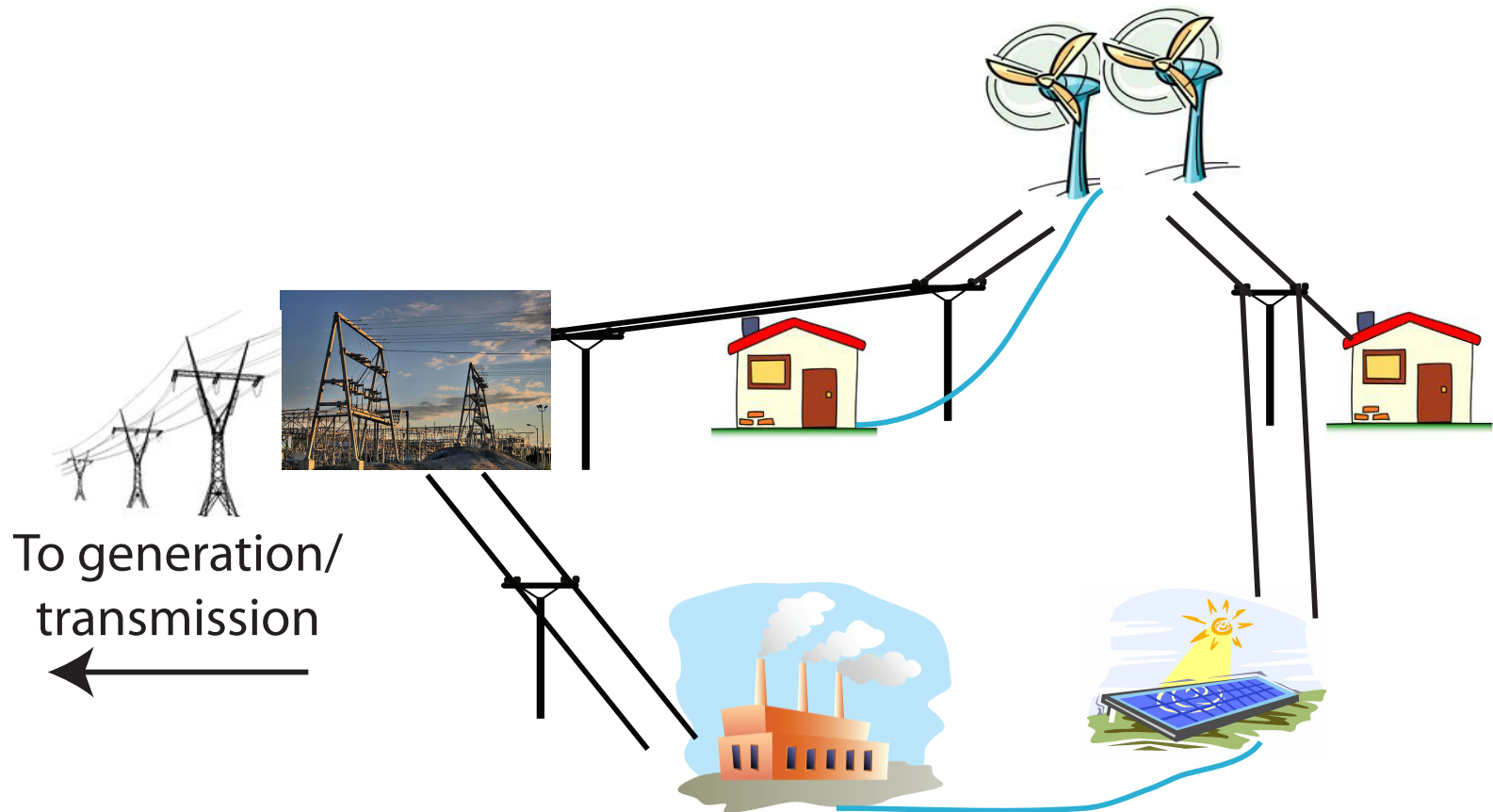
To generation/
transmission
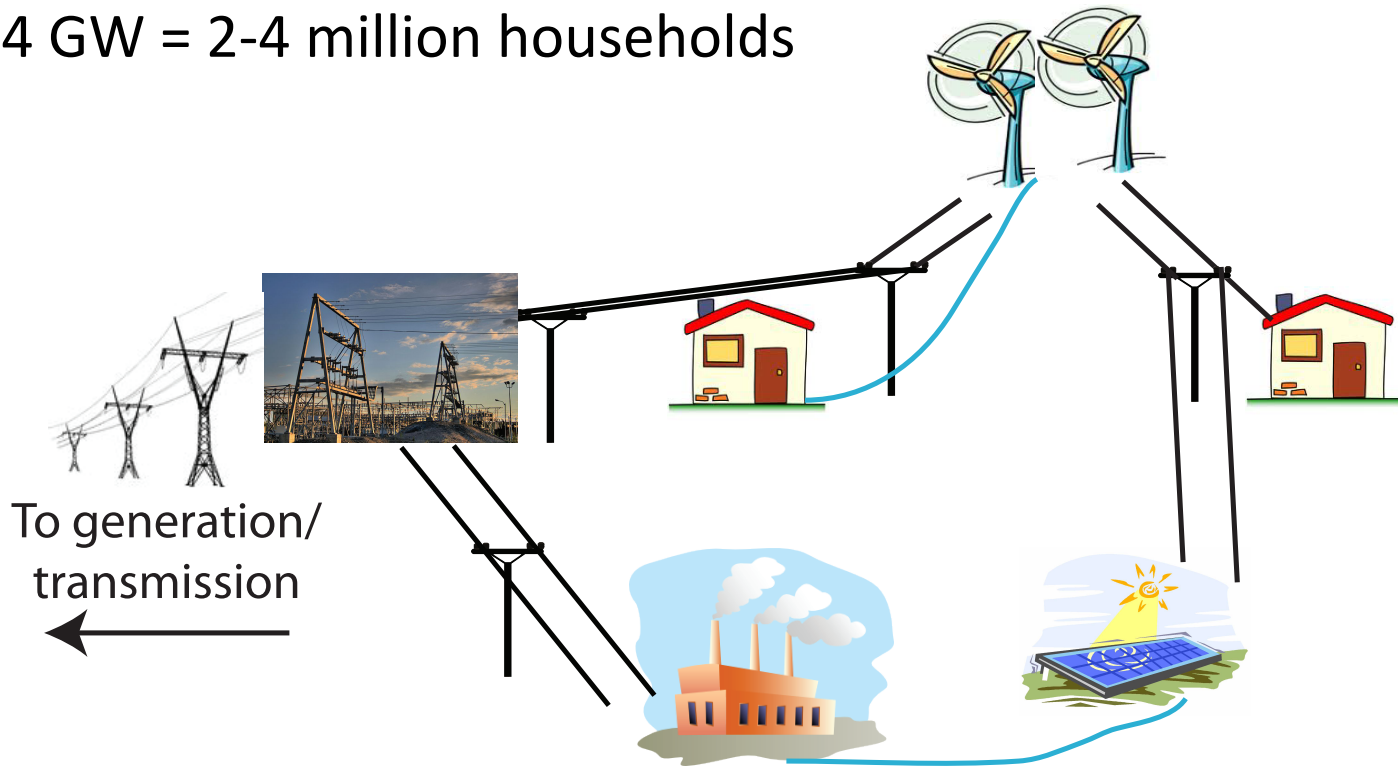
University of California, San Diego Microgrid

- Largest in US
- 100 buildings, 42 MW peak load, >50k people
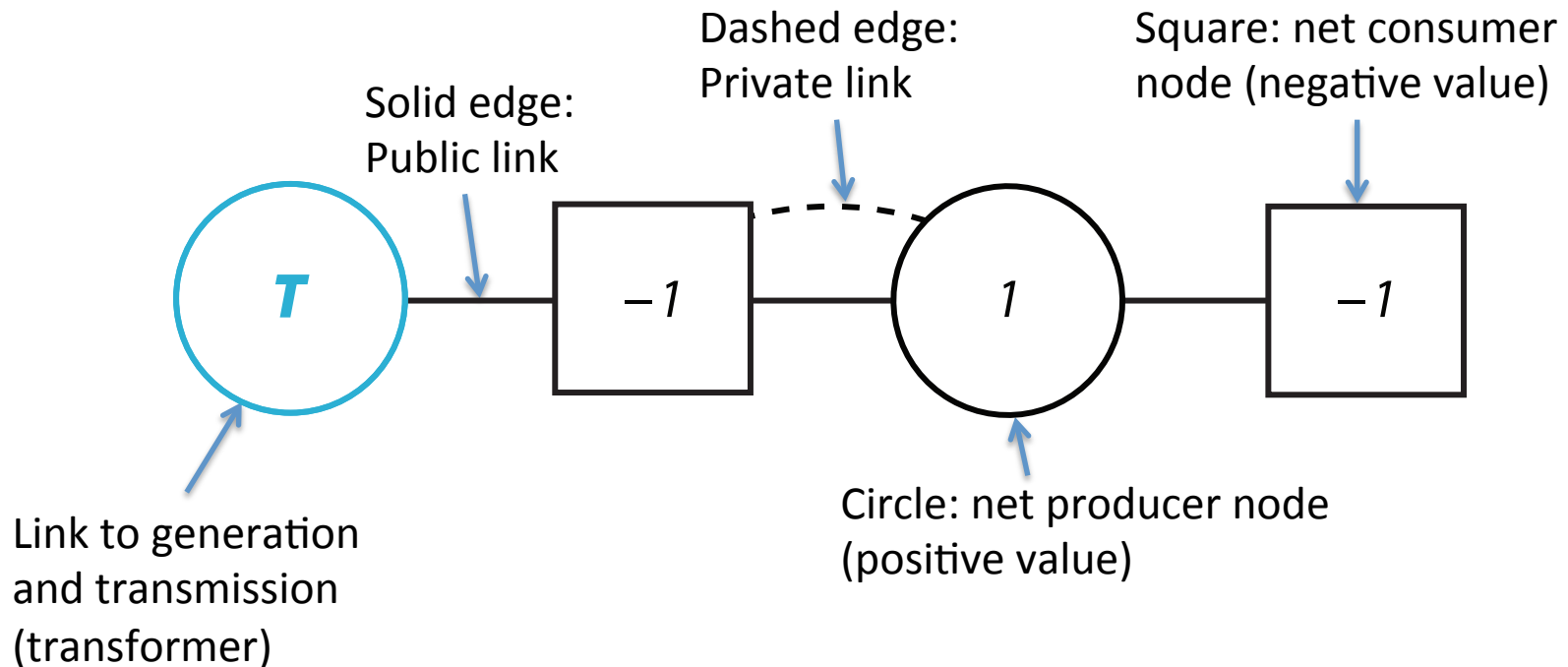- >92% annual electricity self-generation

Geisel Library, UCSD

Problem

To generation/
transmission

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Problem

- Efficiently coordinate:
    - Locally-generated and main-grid power
    - Use of private and public infrastructure
    - ….while satisfying incentives
- Major effects on realistic grids

Modeling Hybrid Public-Private Networks

Dashed edge:
Private link

Square: net consumer
node (negative value)

Solid edge:
Public link

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Link to generation
and transmission
(transformer)

Circle: net producer node
(positive value)

Objective: Minimize Physical Losses

- Resistive losses (DC approximation)
  - Resistance (R), voltage (U): properties of infrastructure
  - Current (I) proportional to power but current^2 proportional to resistive losses
- Linear losses at transformer
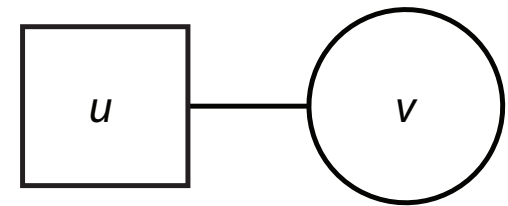
$$\underbrace{U'_{u,v} I_{u,v}}_{\text{Power to } v} = \underbrace{U_{u,v} I_{u,v}}_{\text{Power from } u} - \underbrace{I^2_{u,v} R_{u,v}}_{\text{Resistive loss across } (u,v)}$$

Current (I): focus of optimization
I^2: source of difficulties

Basic Optimization Problem

- External power req'd = net demand + losses
- Minimize external power = minimize losses
- Control priv. infrastructure to minimize amount of external power req'd
  - Assumption: local generation from renewables
- Intuition: minimize amount of flow and distribute flow evenly across lines
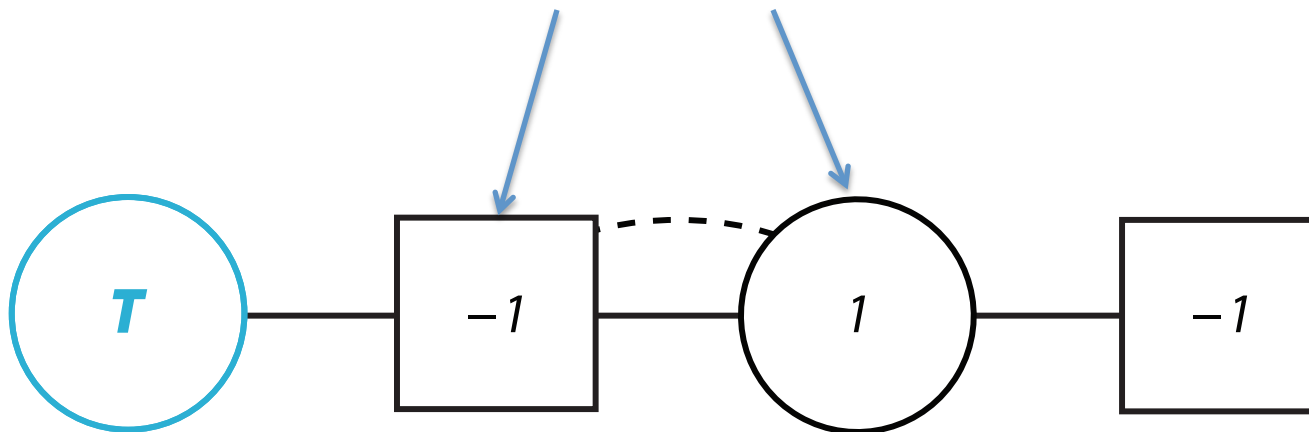
Side Deals

- Grid prices do not reflect true value
- Private infrastructure allows agents to trade outside of the main grid
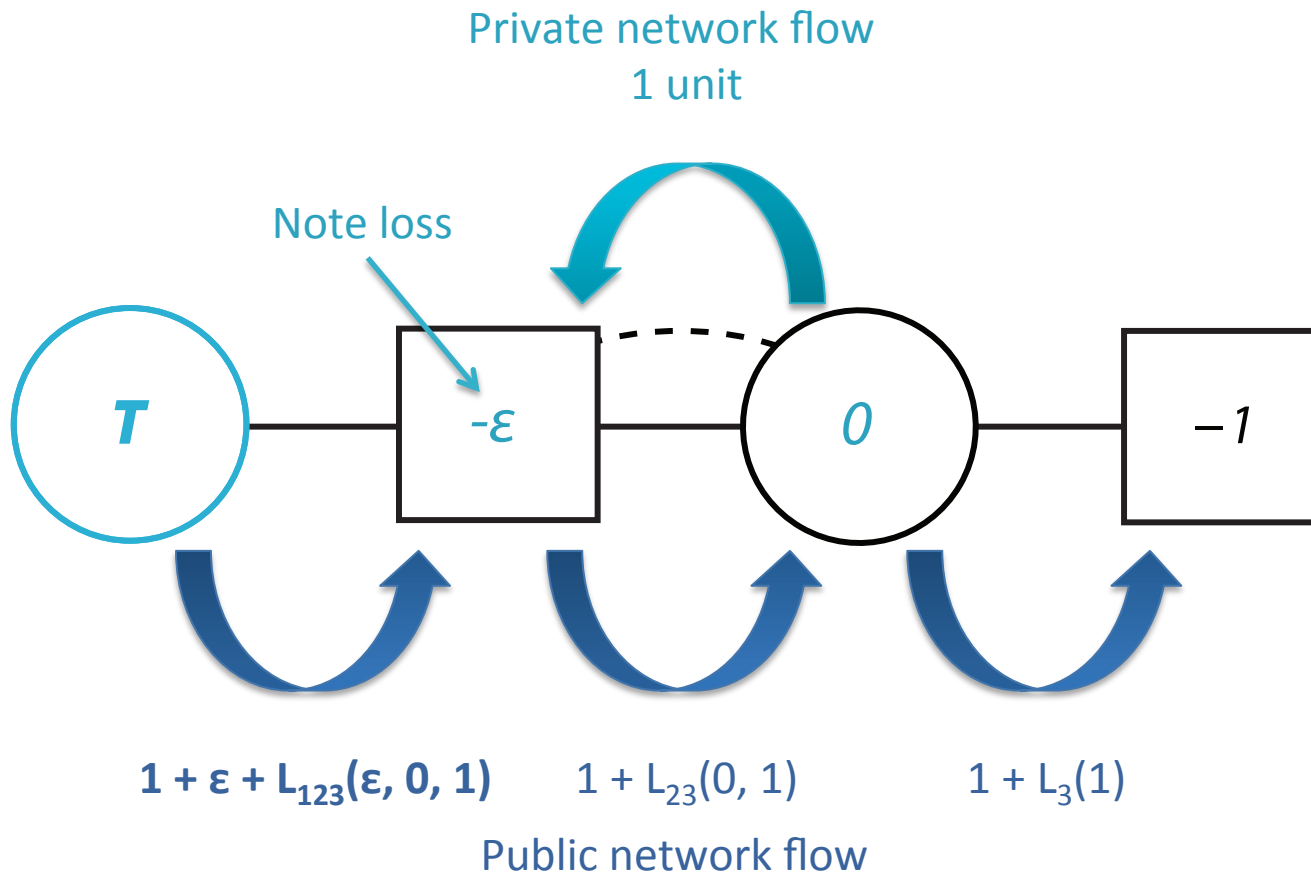- Side deals can reduce overall efficiency

Routing Example 1

With Private Edge

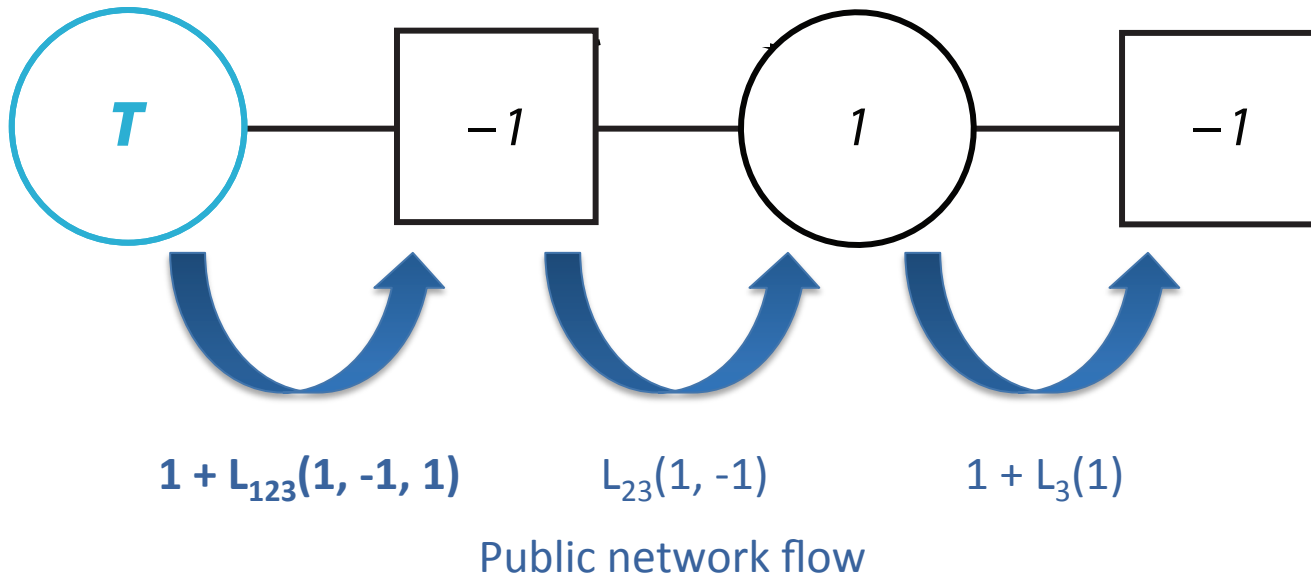Profitable for these agents to trade privately
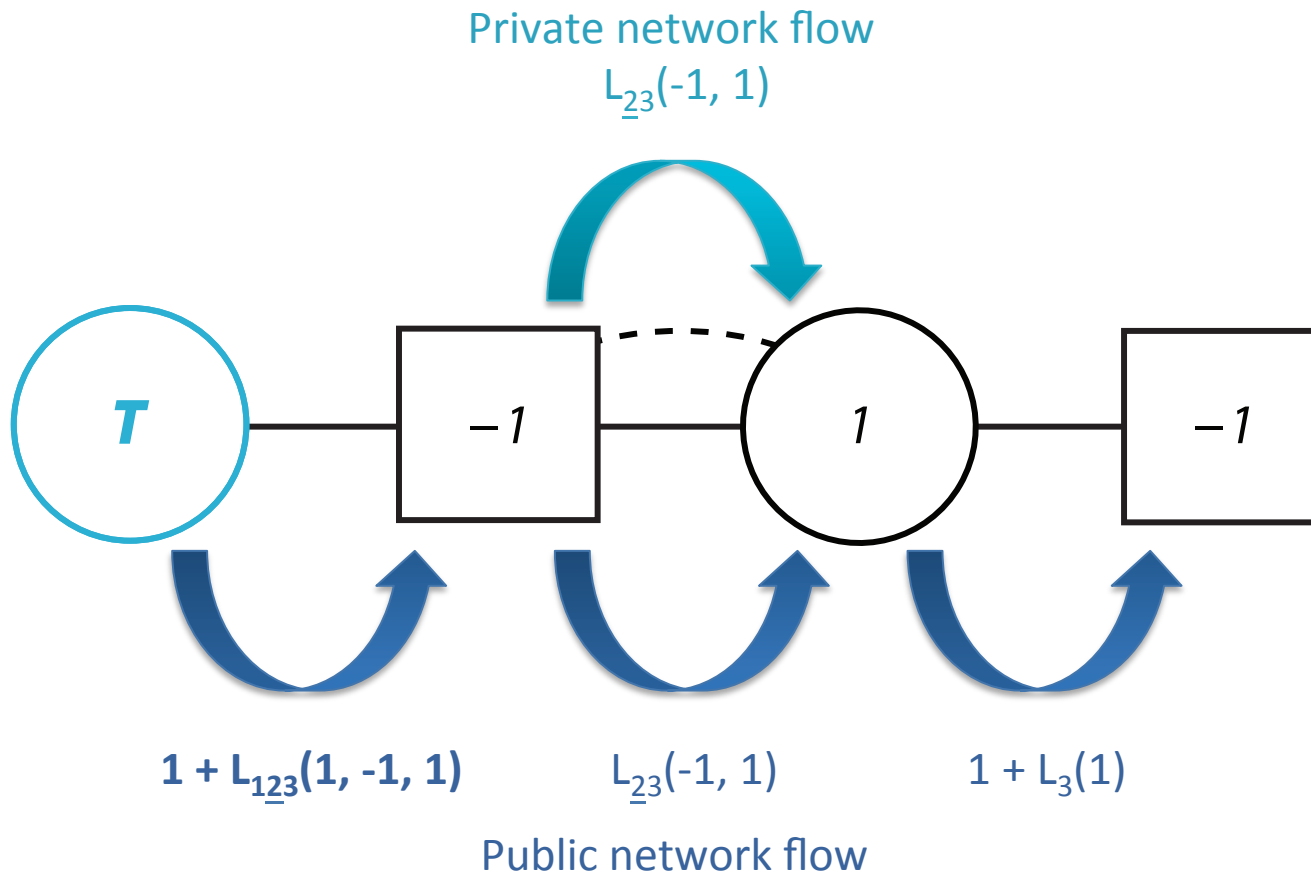
Routing Example 1

With Private Edge

Private network flow
1 unit

Note loss

T $-\varepsilon$ 0 -1

$1 + \varepsilon + L_{123}(\varepsilon, 0, 1)$ $1 + L_{23}(0, 1)$ $1 + L_3(1)$

Public network flow

Routing Example 2

Without Private Edge

T -1 1 -1

$1 + L_{123}(1, -1, 1)$ $L_{23}(1, -1)$ $1 + L_3(1)$

Public network flow

Routing Example 3

Central Control of Private Edge

Private network flow
$L_{\underline{2}3}(-1, 1)$

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$1 + L_{1\underline{2}\underline{3}}(1, -1, 1)$ $L_{\underline{2}3}(-1, 1)$ $1 + L_3(1)$

Public network flow

Approach

- Calculate flow that maximizes efficiency under organizational assumptions
  - Quadratically-constrained quadratic program in our model
- Find payments that support that flow
  - Required because we don't control the private infrastructure
  - Cooperative/competitive game with non-independent coalitions

Incentives

- Cooperative/competitive game
  - Agents form coalitions—only agents in the same coalition can trade
  - Coalitions act strategically
  - Coalitions pay or are paid by their members
  - *Values/strategy spaces of coalitions not independent*
- "Satisfy incentives" = stabilize grand coalition

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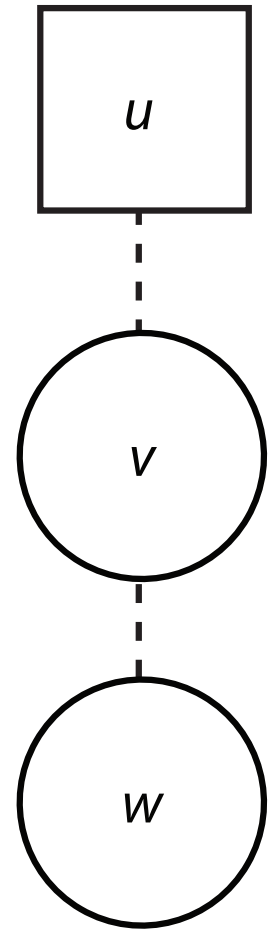
Coalitions Are Not Independent

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$<< 0$

Other coalitions

Edge can be blocked
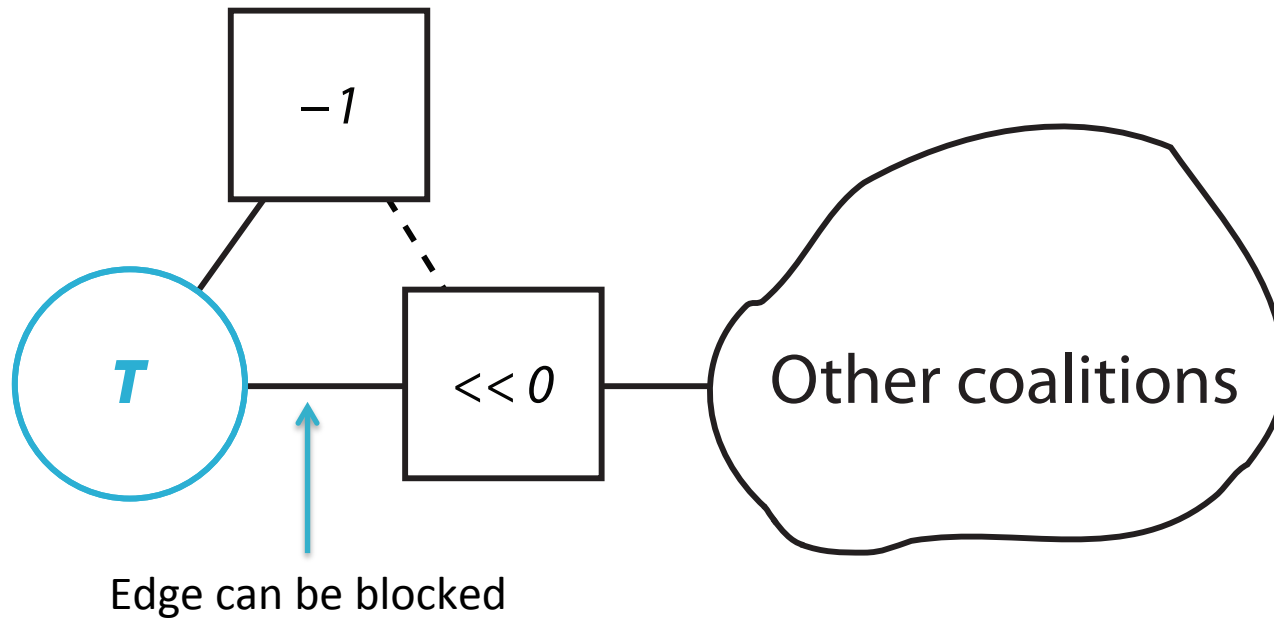
Incentives

- Can use properties of optimization to compute supporting payments *if they exist*
- Market Games (Shapley and Shubik, 1975) are closest existing game-type
  - Each agent has an endowment, utility function
  - Core always exists, easy to find if losses between agents are independent
  - No natural generalization to non-independent losses
- Open problem: show that supporting payments always exist or find a counterexample
  - All instances to date have supporting payments

Models of Agent Behavior

- **Ad hoc**: self-interested, limited information
- **Private self-interest**: self-interested, full information
- **Cooperative**: global social welfare-maximizing assuming no control of public infrastructure
- **Integrated**: global social welfare-maximizing and fine-grained control of public infrastructure
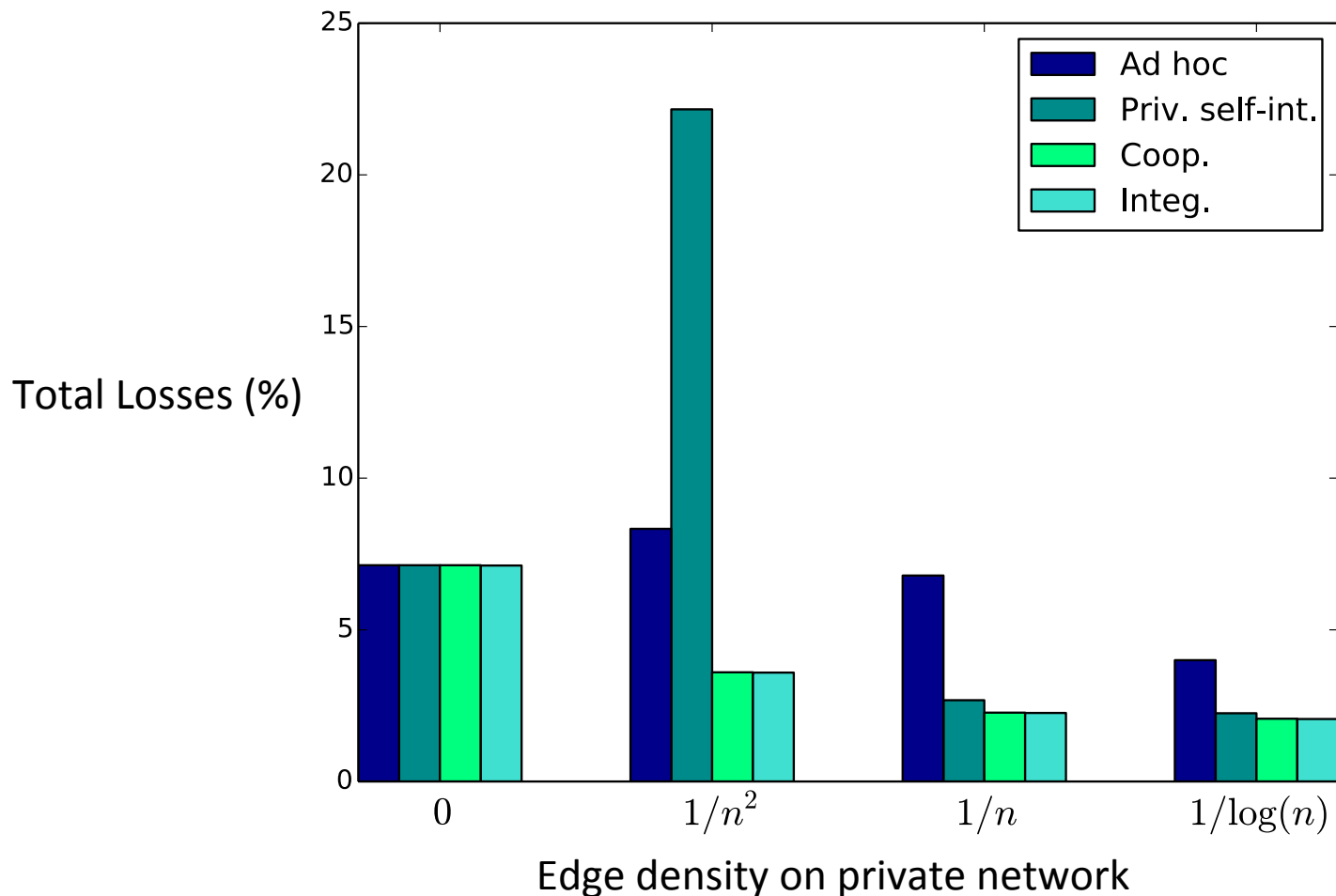
Empirical Evaluation of Impact

- Public network: IEEE 300-bus test system
- Private network: random graph on same nodes
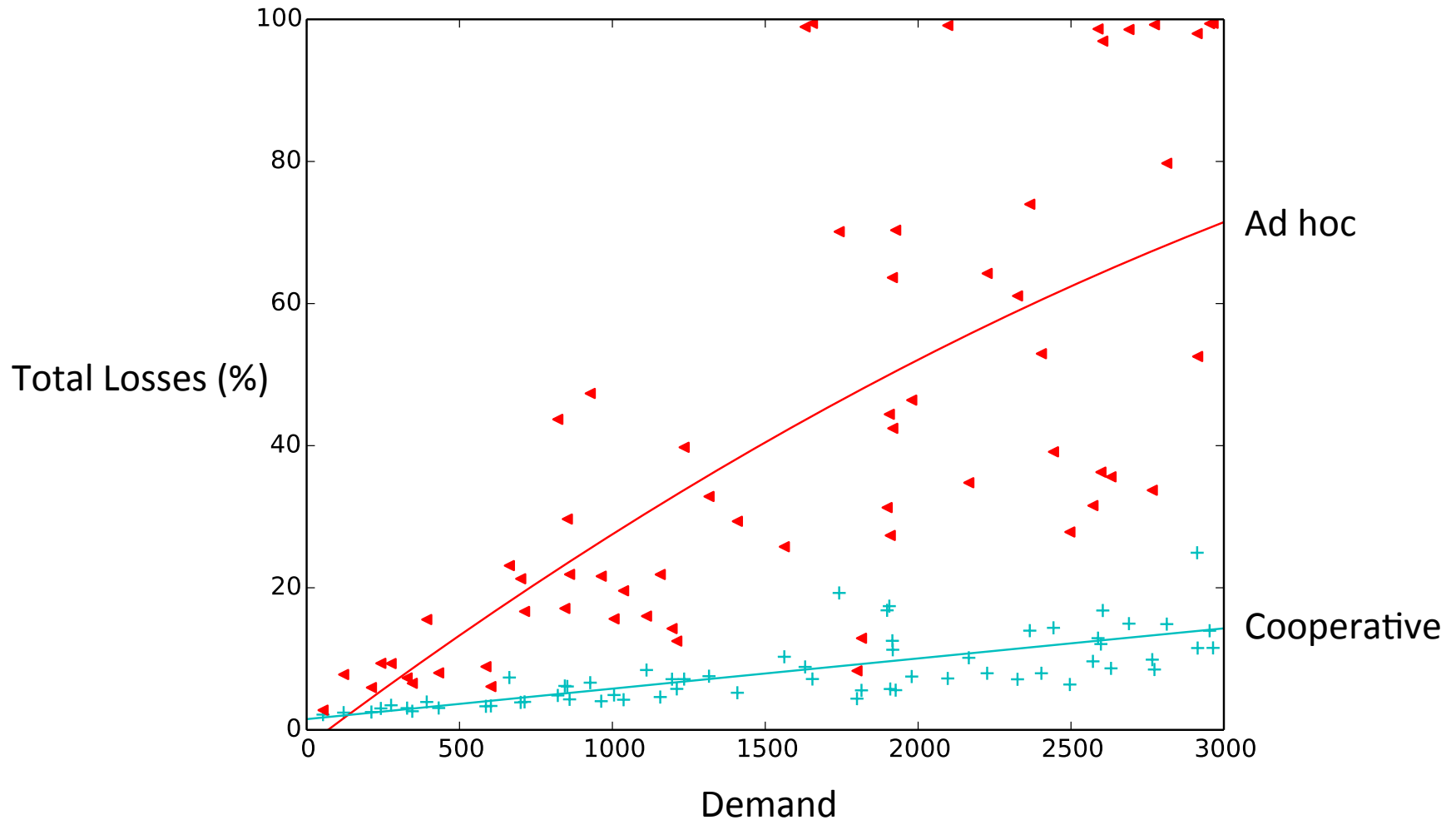 - Each edge included independently with equal probability
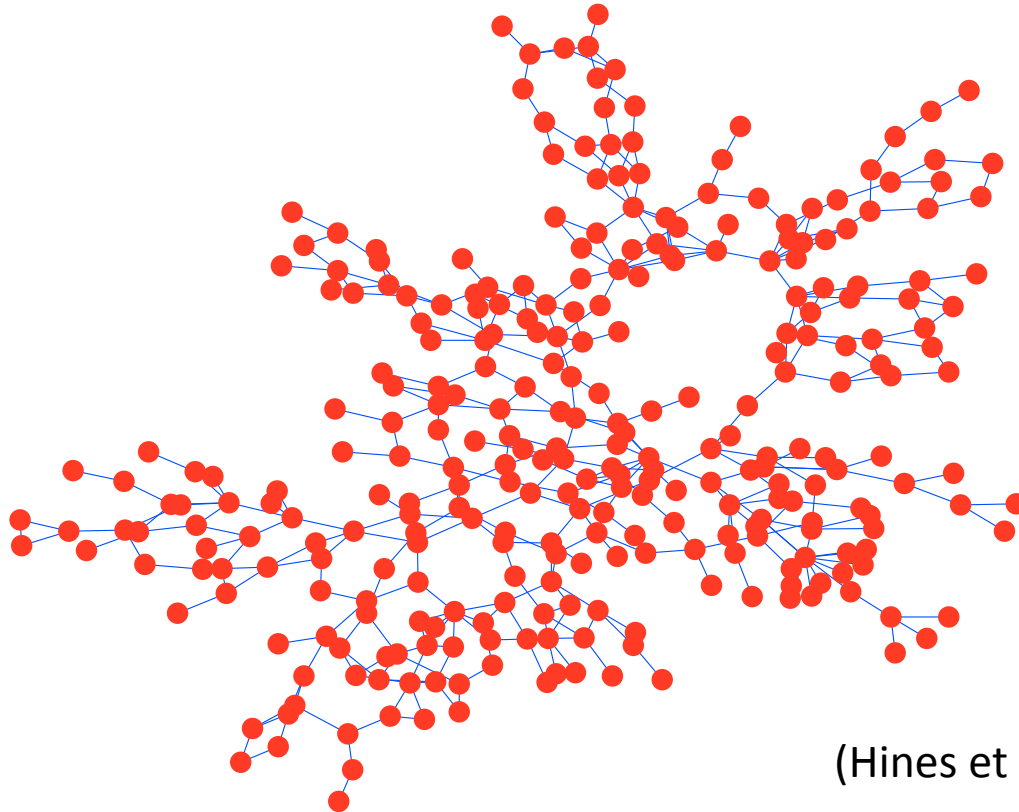
(Hines et al., 2010)

Empirical Evaluation of Impact

- Losses: smaller = better

Empirical Evaluation of Impact

Conclusions

- Contributions
  - Calculate optimal flow, payments in idealized model
  - Open problem: market games with non-independent losses
  - Coordination is critical
- Future work
  - Richer agent preference space
    - Time-based decisions
    - Comfort vs. cost
  - New game type—representation as potential function game?

Questions?
Further discussion: poster session at
lunch today.