Defending Against Strategic Adversaries in Dynamic Pricing Markets for Smart Grids

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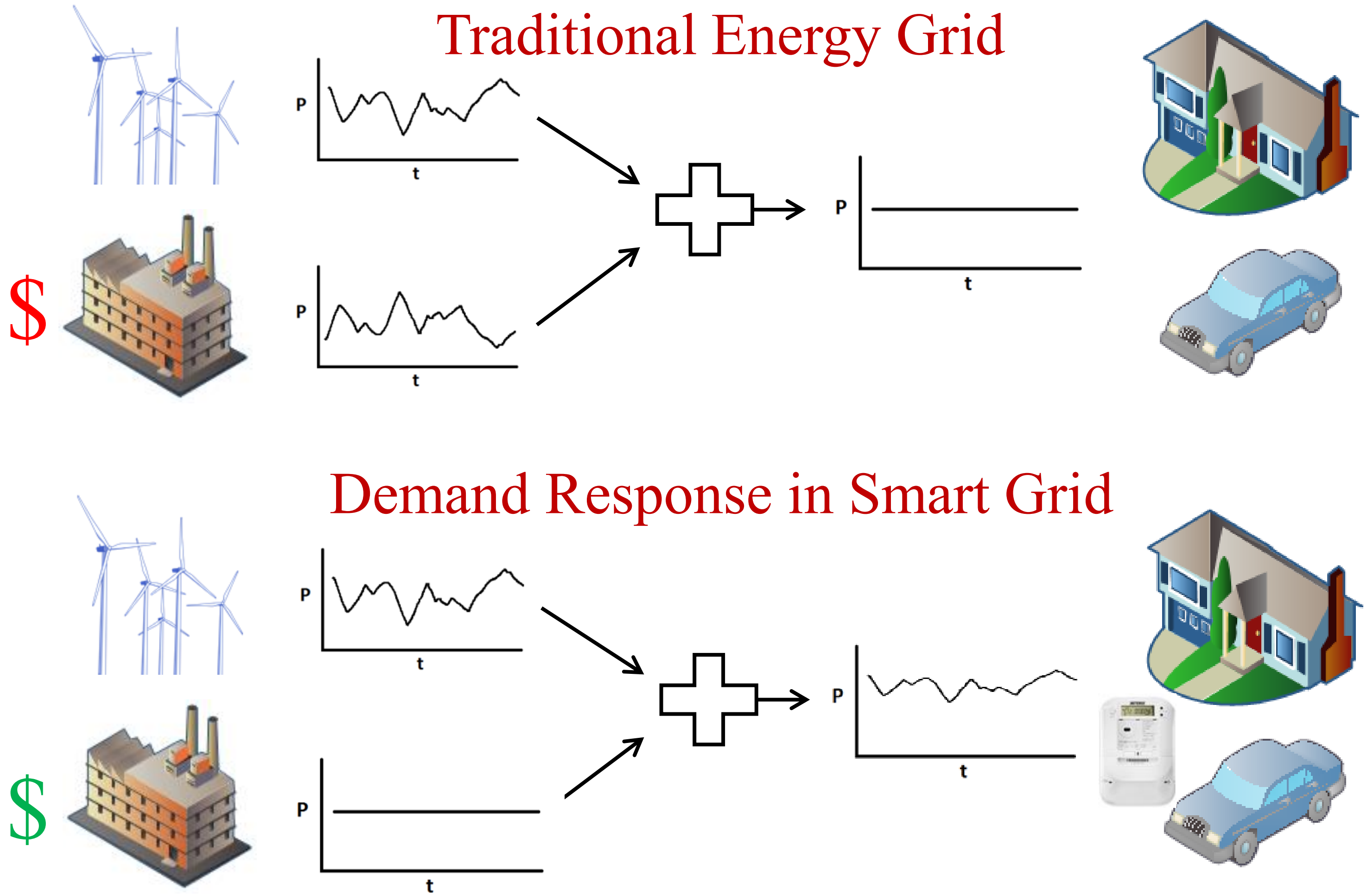
Outline

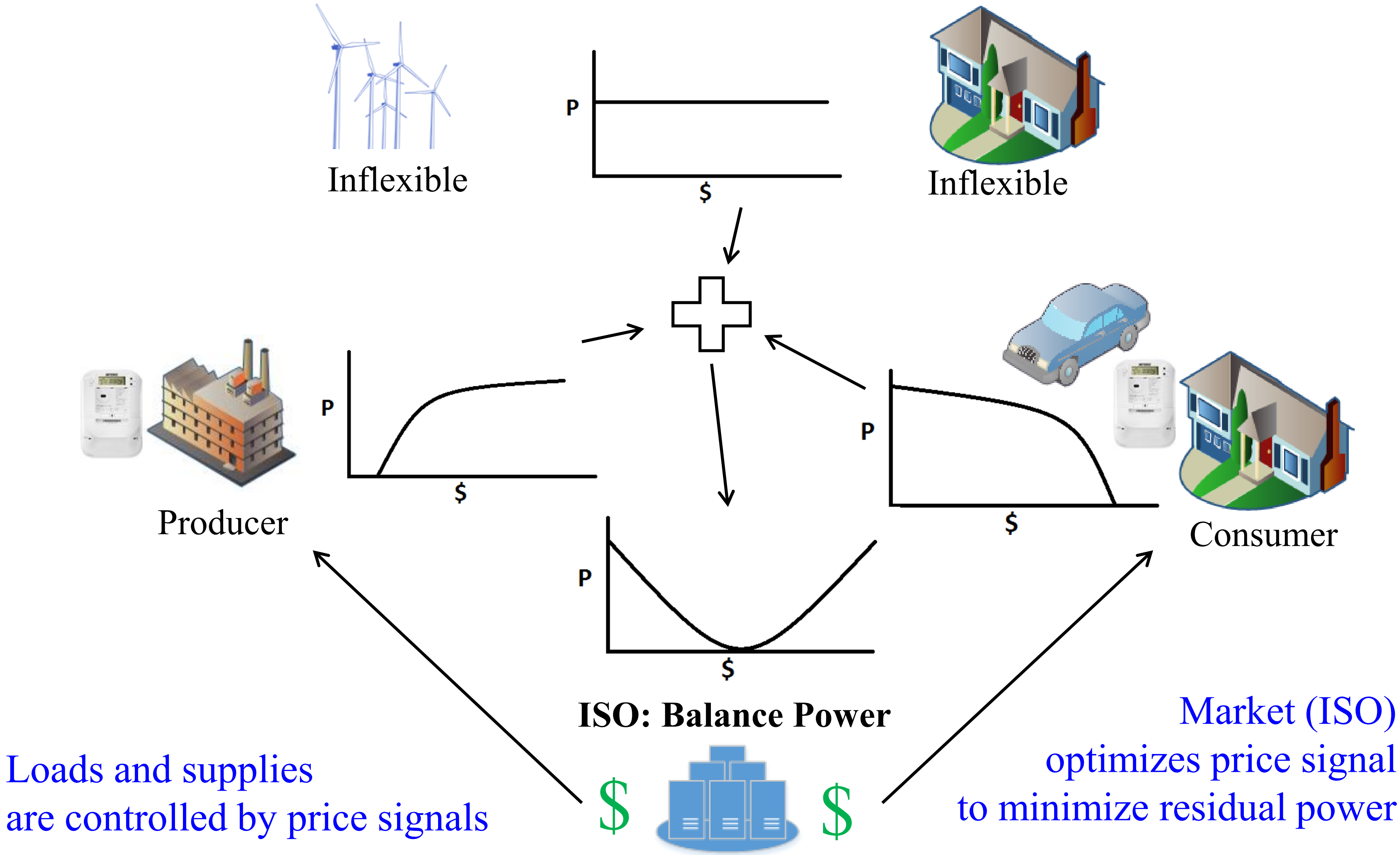
- Smart Grid, Demand Response, and Related Work
- Attack and Defense Strategies
- Experimental Results
- Conclusions

Demand Response in Electricity Networks



Demand response improves efficiency of the power market by modulating load in response to fluctuating demands and supplies

Dynamic Markets



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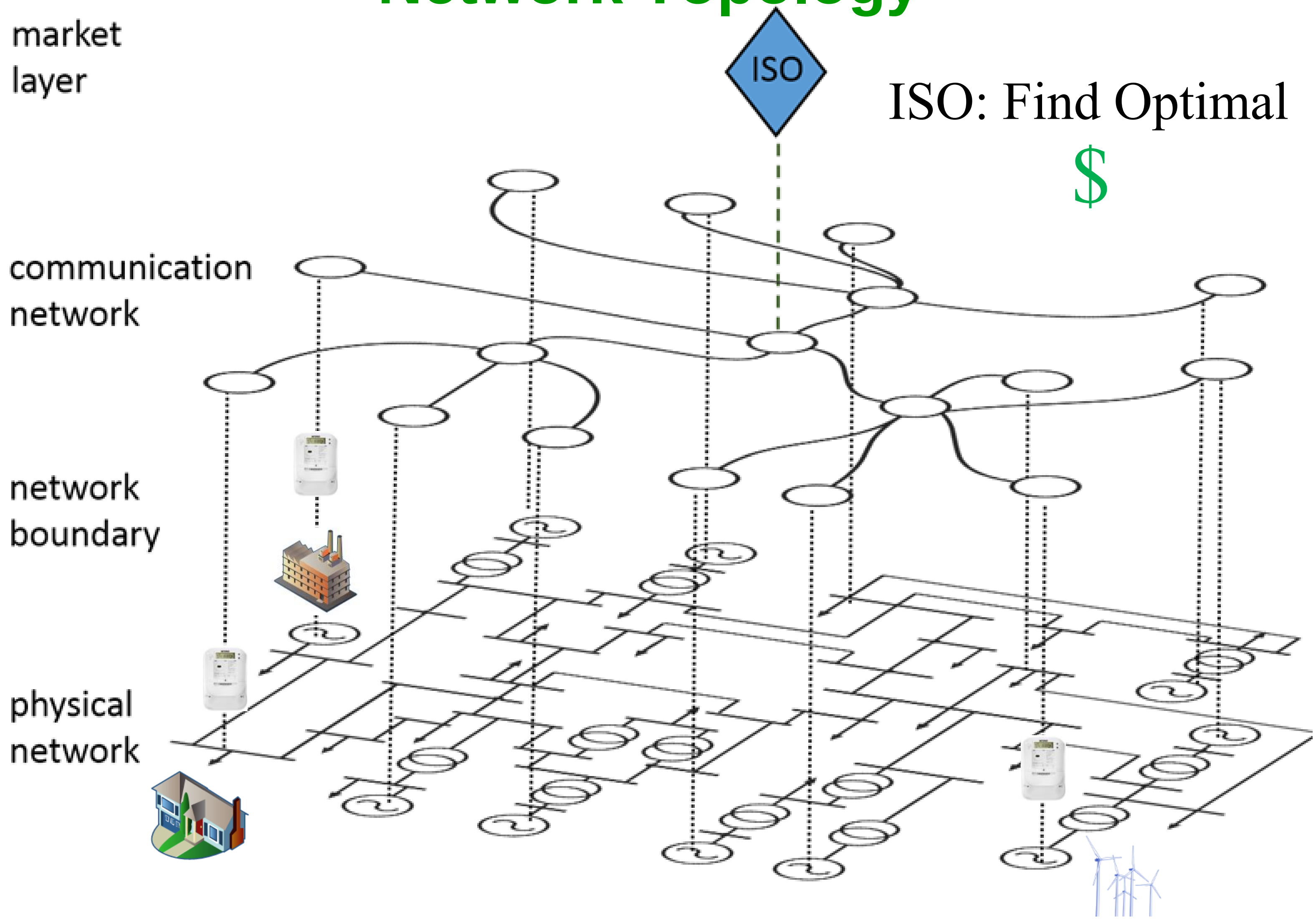
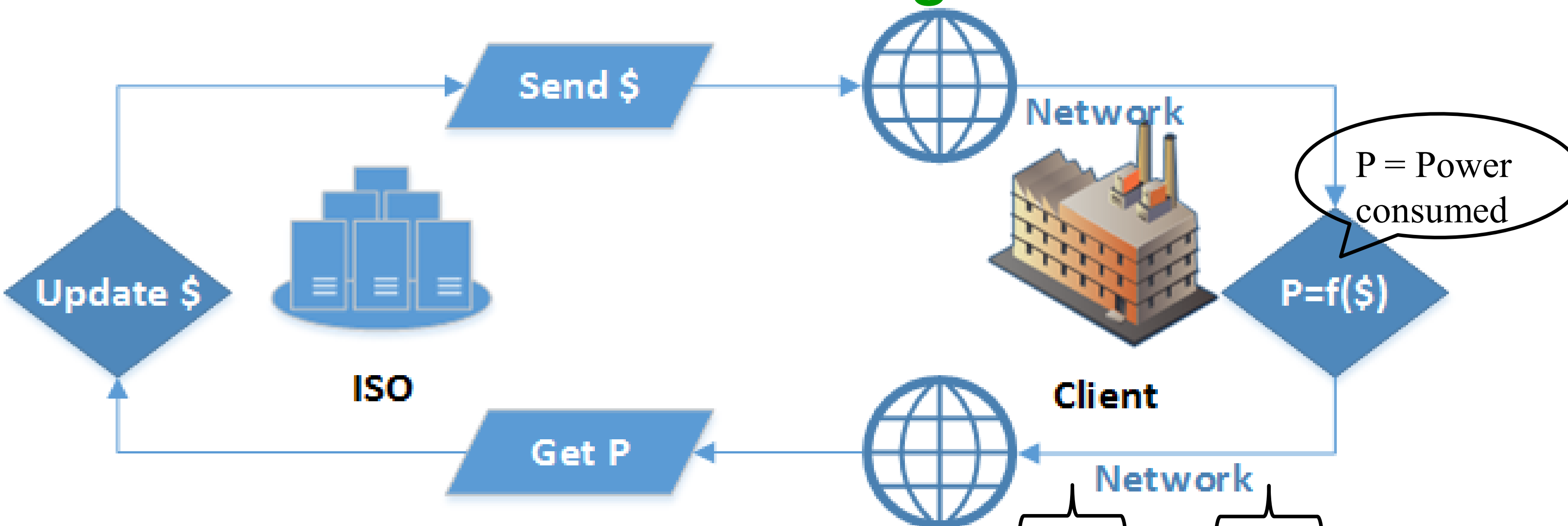
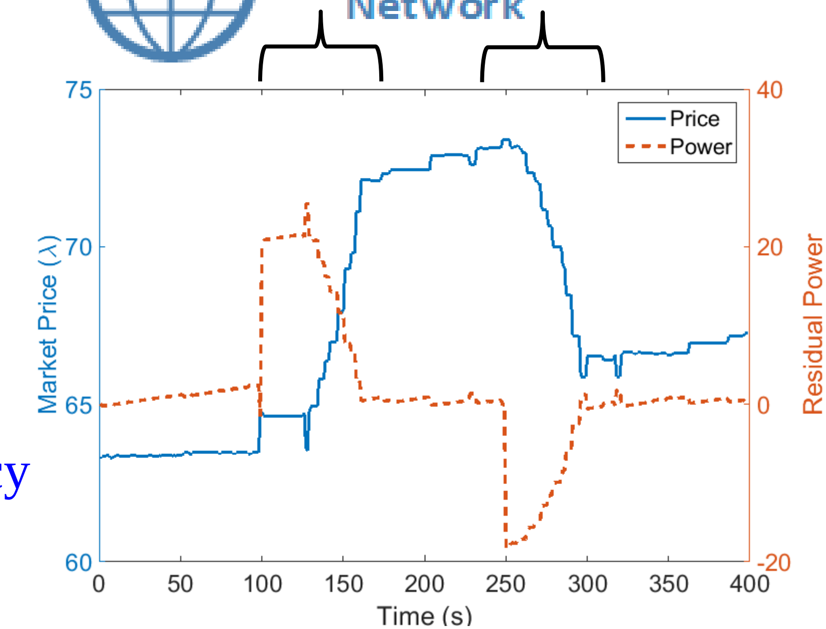
Network Topology



The ISO must communicate price signals across a network to the grid-connected loads

Iterative Market Negotiation

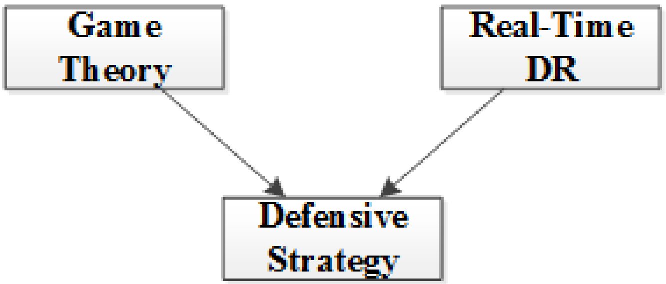




- Real-time communication of price signal by ISO to consumers used for controlling the market
  - Lower latency means better efficiency

Related Work

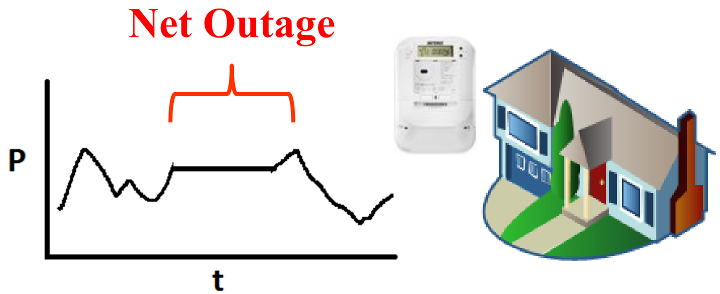
- In [1], latency impacts in real-time communication in DR is evaluated but without any economic incentives
- In [2], economic incentives are introduced but without real-time communications
- Our work combines real-time DR with game theory to formulate defensive strategies



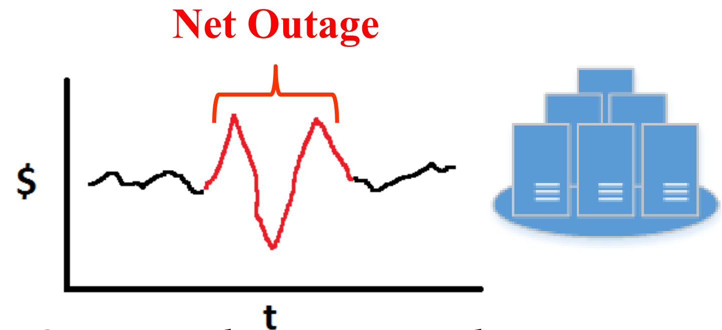
[1] Tan, Rui, et al. "Impact of integrity attacks on real-time pricing in smart grids." *Proceedings of the 2013 ACM SIGSAC conference on Computer & communications security (CCS)*. ACM, 2013.

[2] Barreto, Carlos, et al. "CPS: market analysis of attacks against demand response in the smart grid." *Proceedings of the 30th Annual Computer Security Applications Conference (ACSAC)*. ACM, 2014.

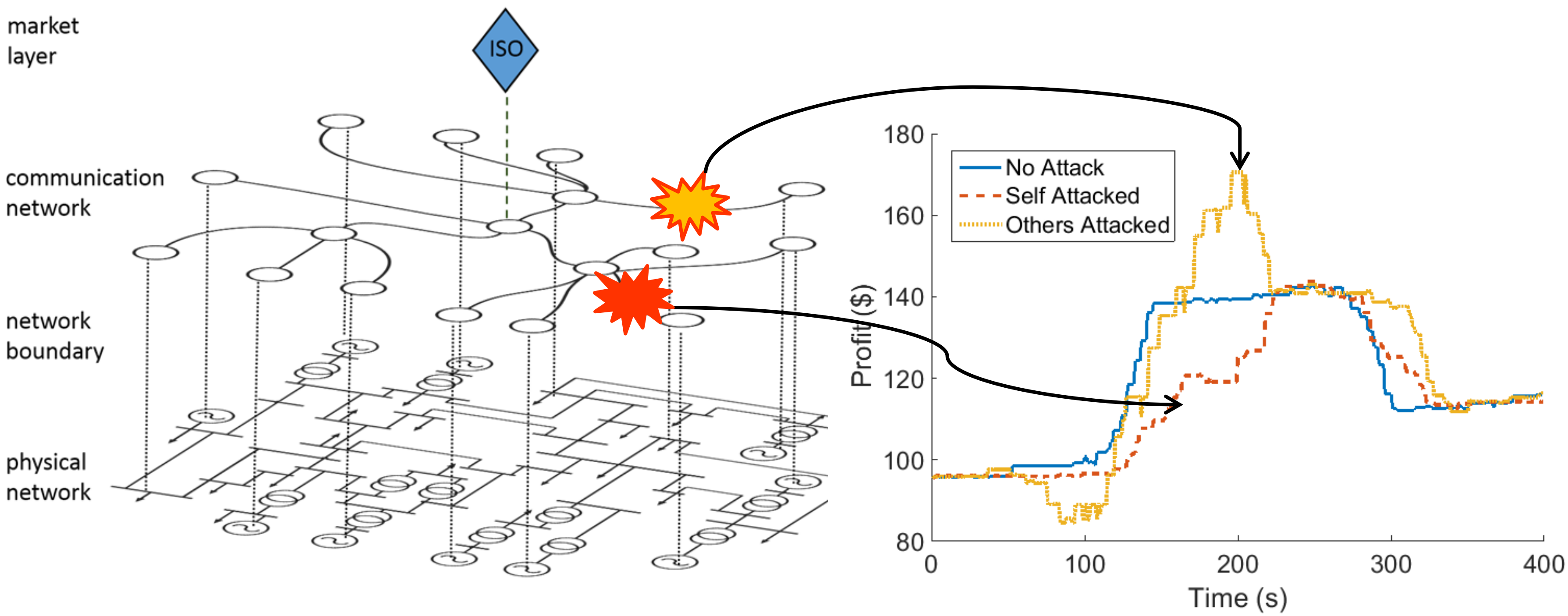
Faults and Attacks



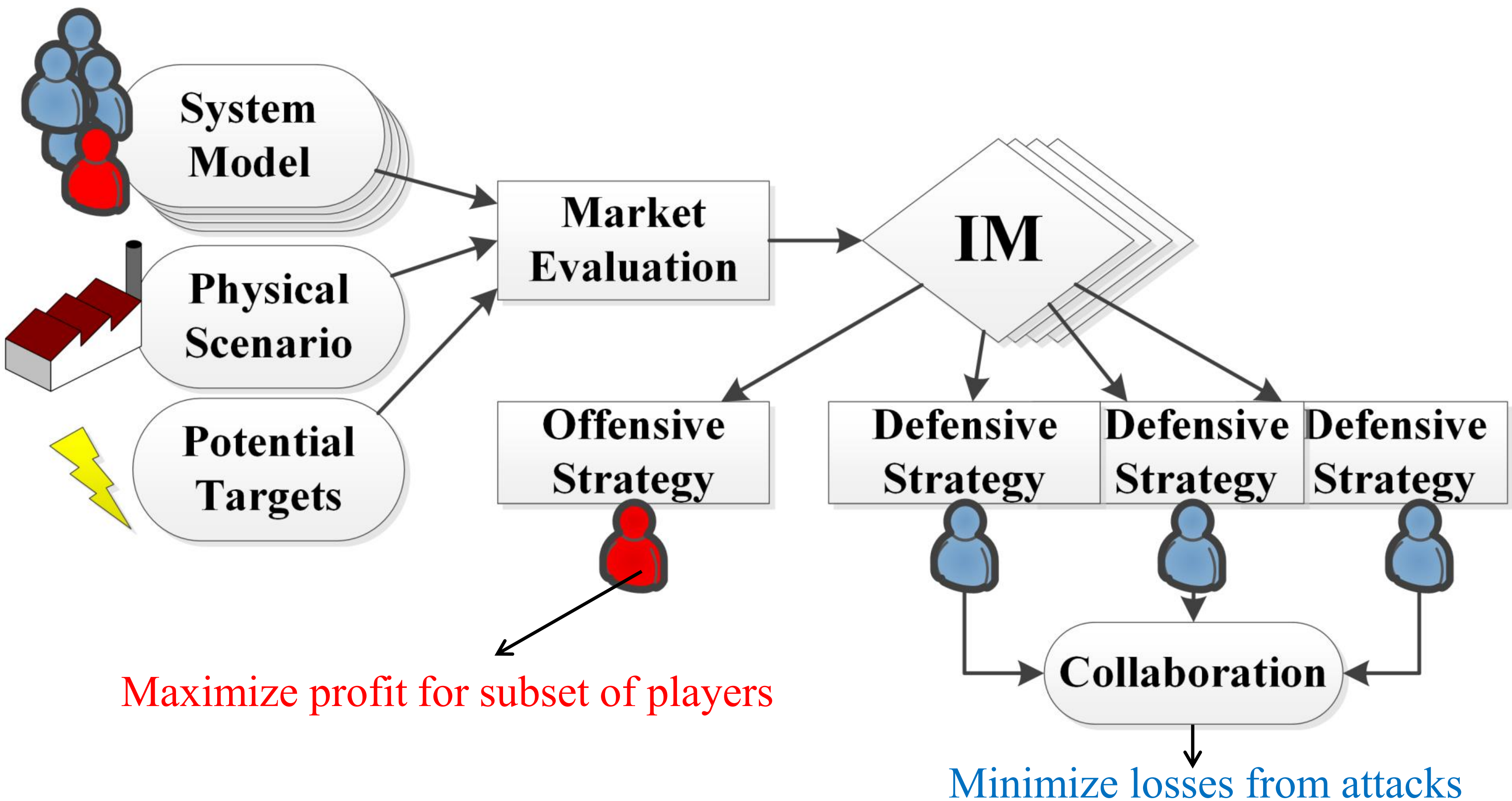
Outage reduces demand response



Outage changes market price



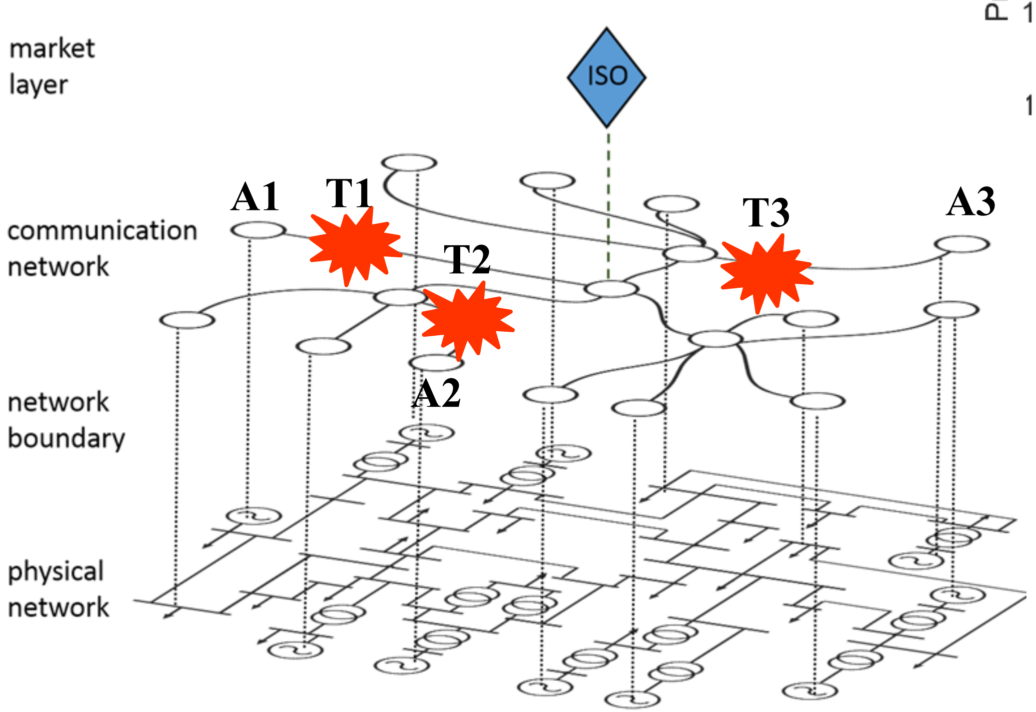
Attack and Defense

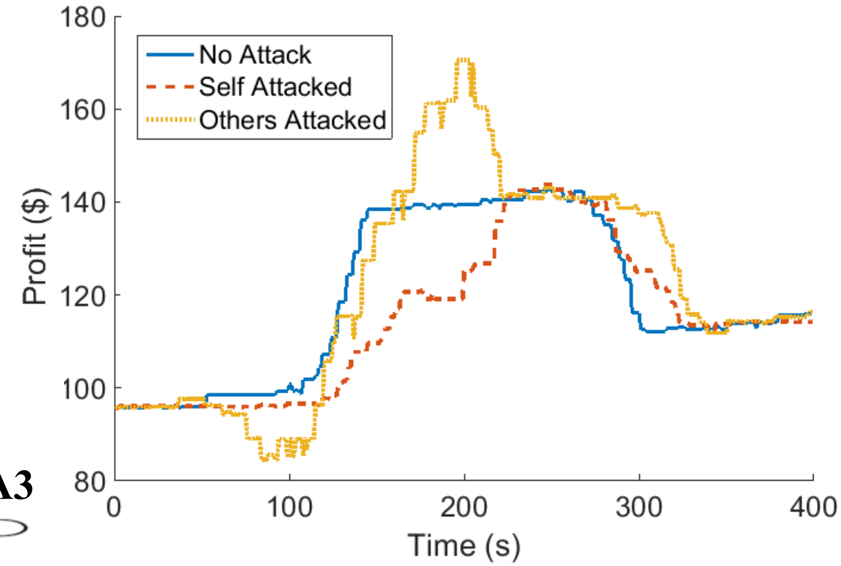


Target Impact Matrix

The impact of attacking different targets is captured in a matrix (IM)

No-attack compared with attack profits

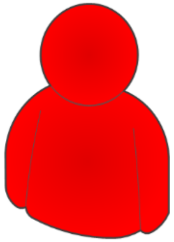


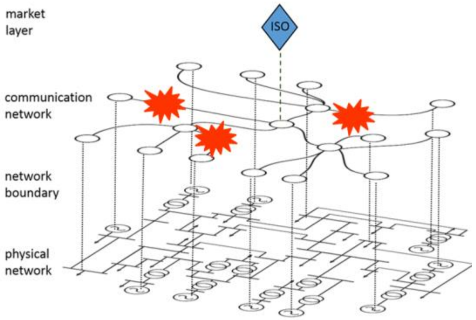


	T1	T2	T3
A1	-2	-2	3
A2	4	-4	-2
A3	-4	2	-4

Impact Matrix (IM)

Attacker Strategy





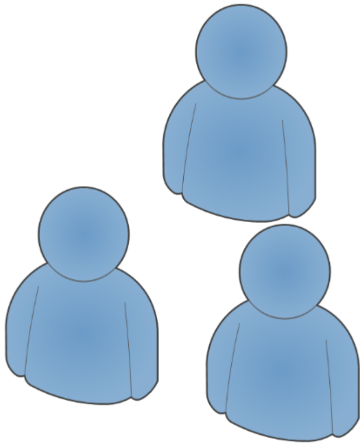
	T1	T2	T3
A1	-2	-2	3
A2	4	-4	-2
A3	-4	2	-4

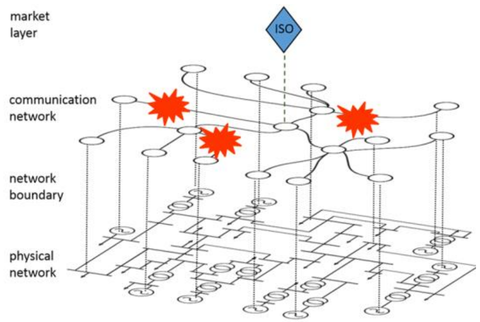
$$\text{argmax}_{A,I} \sum_{a \in A, i \in I} \text{IM}[a, i]$$

A set of market players
I set of target network links

$\text{IM}[a, i]$ impact or change in profit realized by market player a when network link i is attacked

Defender Strategy





T1 most likely attacked

	T1	T2	T3
A1	-2	-2	3
A2	4	-4	-2
A3	-4	2	-4

A1,A3 share benefit from defending T1, so can share costs

$$\max \sum_{\forall a \in A} \sum_{i \in I} A_i \overbrace{\mathrm{IM}[a,i]}^{\text{Comes from defender's estimate}}(1 - D_i) - D_i C_i$$

D_i boolean indicating if network link i is defended

C_i cost to defend asset i

A_i boolean indicating if network link i is attacked

Sampling and Solving

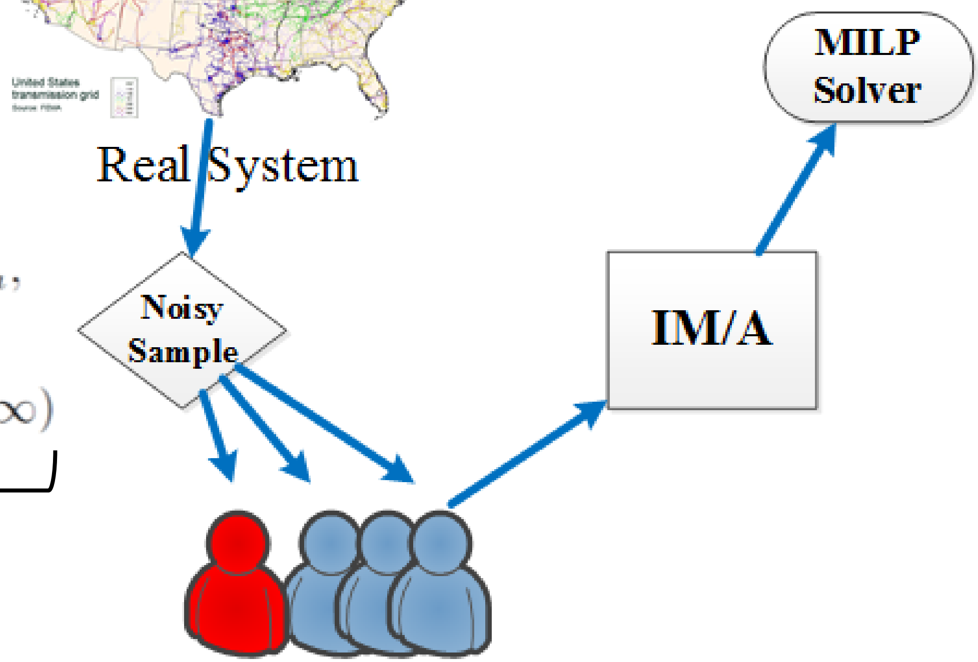
The real system is sampled
to provide mixed strategies
for the attackers and defenders

Knowledge level

$$\underbrace{\begin{gathered} x' = \mathcal{N}(x, \sigma_a^2)\ \forall x \in GA,\ x \notin O_a, \\ x' = x\ \ \forall x \in GA, x \in O_a \\ x' \in (-\infty, 0] \text{ if } x' < 0,\ \text{else } x' \in [0, \infty) \end{gathered}}_{\textit{Constraint maintenance}}$$

$$\text{argmax}_{A,I} \sum_{a \in A, i \in I} \text{IM}[a, i]$$

$$\max \sum_{\forall a \in A} \sum_{i \in I} P_i^a \text{IM}[a, i](1 - D_i) - D_i C_i$$



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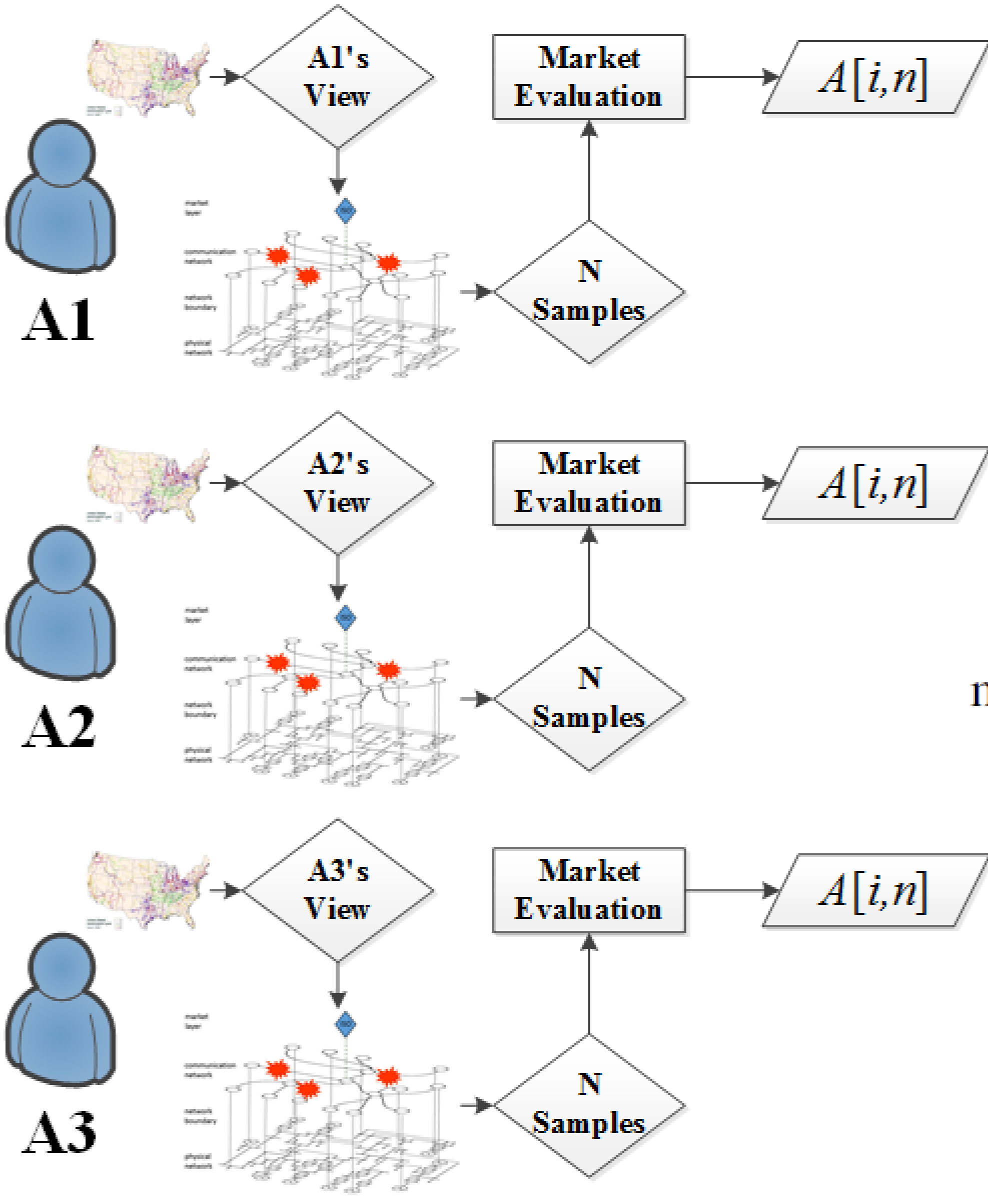
Mixed Defender Strategies



$$P_i^a = \frac{\overbrace{\sum_{n \in N}}^{\textit{N samples of underlying game}} A[i,n]}{N}$$

$$\max \sum_{\forall a \in A} \sum_{i \in I} P_i^a \mathrm{IM}[a,i](1 - D_i) - D_i C_i$$

Each A1-A3 has a different market view, thus different view on probability of attack

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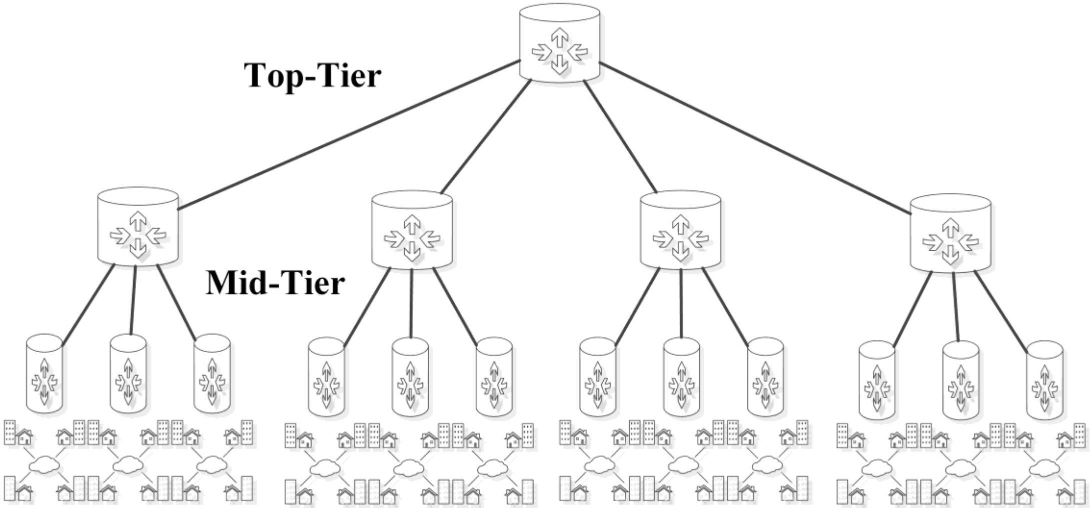
Experimentation Topology



20 Generators 100 Consumers

Iterative Nelder-Meade (NM) used to solve market

Cost parameters for attacking or defending each target = 1

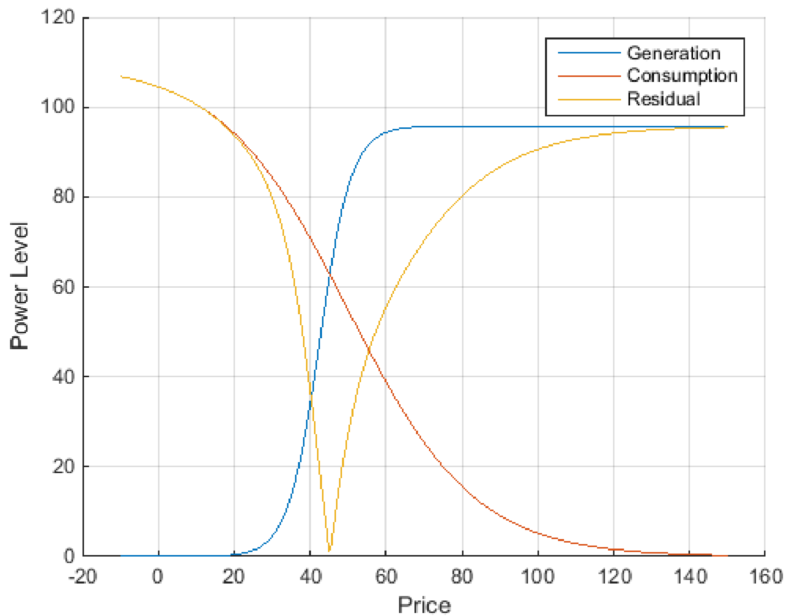
Power-Price Model

Price Scaling (Min/Max Price)

$$\lambda_s = 6 * \frac{\lambda - \lambda_{\min}}{\lambda_{\max} - \lambda_{\min}} - 3$$

Price to Power Mapping (Min/Max Power)

$$P(\lambda) = \underbrace{\frac{P_{\max} - P_{\min}}{1 + e^{\lambda_s}}}_{\textit{Sigmoid function}} + P_{\min}$$



Full parameter definitions in paper

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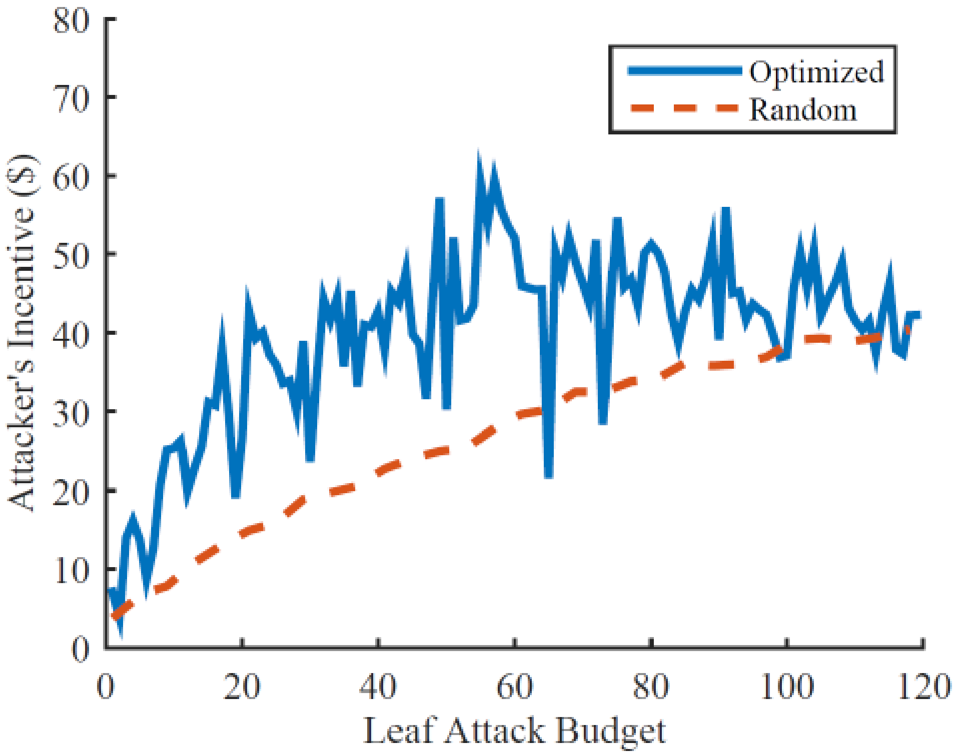
Attack Profits – Leaf Attacks

- Attack strategy run for fixed computation limit
  - Impractical to completely search large MILP
    - Best found solution used
- Attack saturated at high budgets
  - Target value is imbalanced



$$\operatorname{argmax}_{A,I} \sum_{a \in A, i \in I} \mathrm{IM}[a, i]$$

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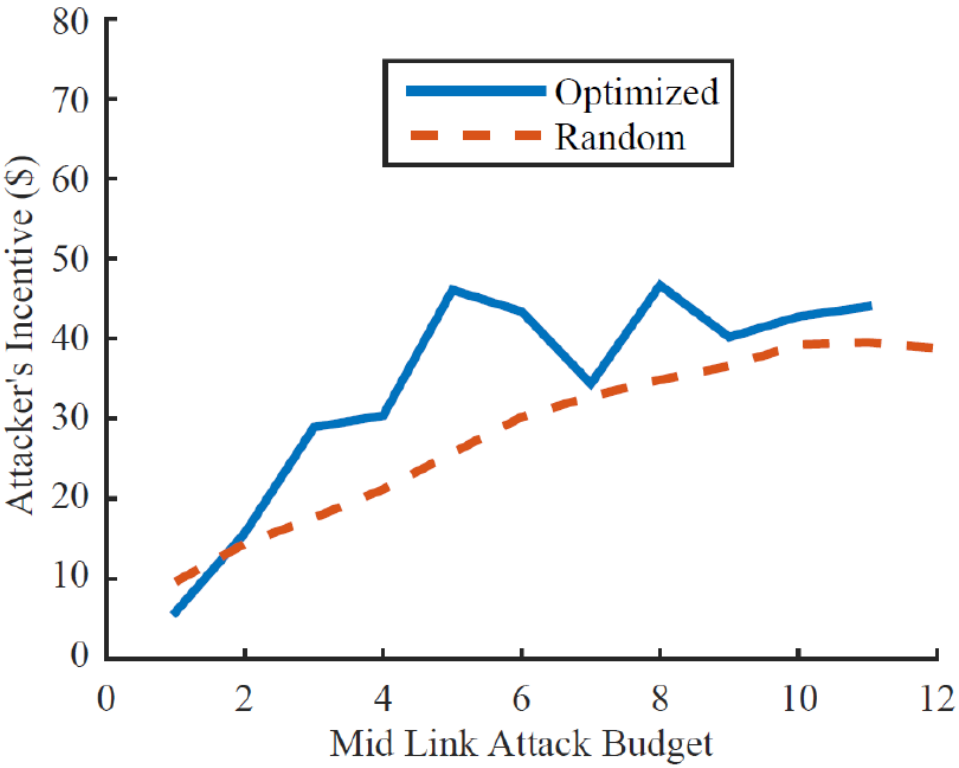
Attack Profits – Mid-Tier Attacks

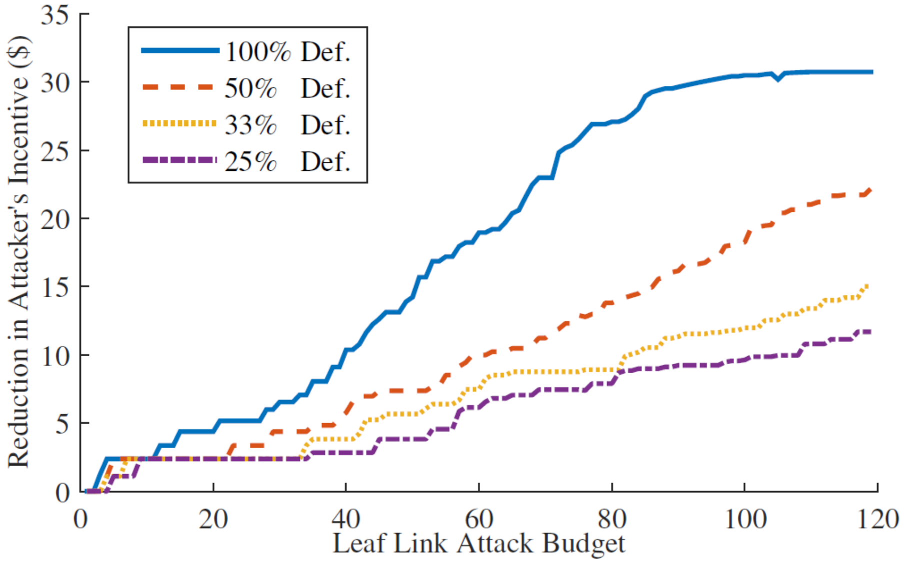
- In this experiment, multiple mid-tier links are attacked
  - IM calculated from mid-tier link attacks only
- Only a few links at this layer need to be attacked to extract profit



$$\text{argmax}_{A,I} \sum_{a \in A, i \in I} \text{IM}[a, i]$$

Defensive Strategy

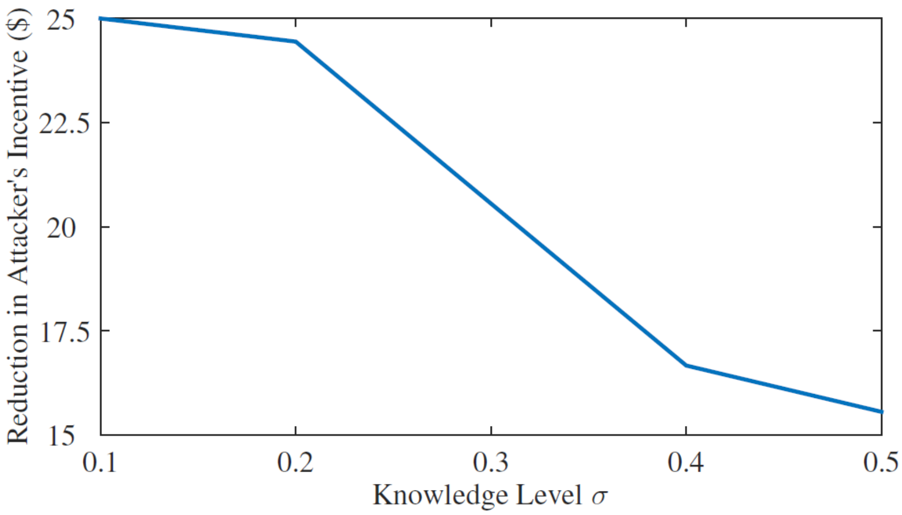
- The defensive strategy is tested with increasing defensive budgets
  - With 100% defense the attacker has no success
  - The attacker is unaware of defensive maneuvers
  - Defenders have imperfect system knowledge



$$\max \sum_{\forall a \in A} \sum_{i \in I} A_i \mathrm{IM}[a,i](1-D_i) - D_i C_i$$

Reduced System Knowledge

- The defenders' knowledge is reduced (higher σ) and a defensive strategy for 75 targets is optimized
  - The strategy's effectiveness decreases with less system knowledge
  - Defenders should share system information when possible to maximize effectiveness



$$x' = \mathcal{N}(x, \sigma_a^2)\ \forall x \in GA,\ x \notin O_a,$$
$$x' = x \quad \forall x \in GA, x \in O_a$$
$$x' \in (-\infty, 0] \text{ if } x' < 0,\ \text{else } x' \in [0, \infty)$$

Conclusions and Future Work

Conclusion

- Future smart grid (DR) may be vulnerable to attacks
- Attack/defense strategies
  - Attacker can improve profits by planning attacks based on estimated impact matrix
  - Defender can reduce impact by optimally selecting targets
  - Knowledge sharing and cost sharing among defenders can improve system resilience

Future Work

- On-line strategies
  - Attack/defense in response to real-time, unpredictable transients
  - Strategy improvement over time (machine learning)
- Topology optimization
  - Defense via architecture
  - Select topology to minimize impact of attacks