Virginia Tech
Invent the Future

On Bounded Rationality in Cyber-Physical Systems Security: Game-Theoretic Analysis with Application to Smart Grid Protection

CPSR-SG 2016 – CPS Week 2016

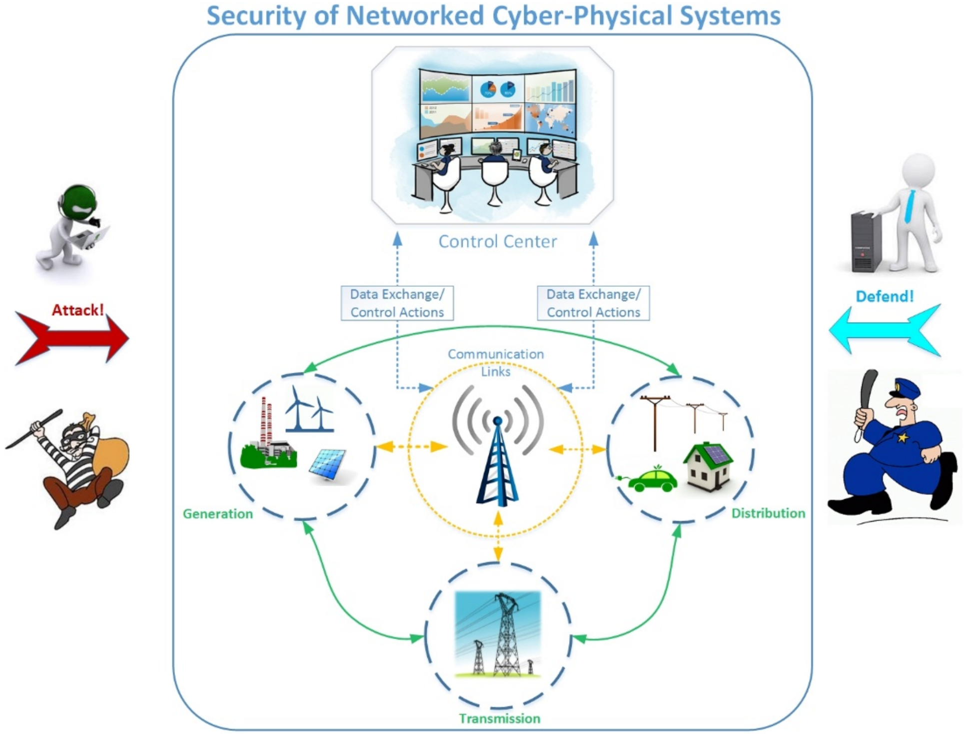
Anibal Sanjab and Walid Saad

April 12, 2016

Vienna, Austria

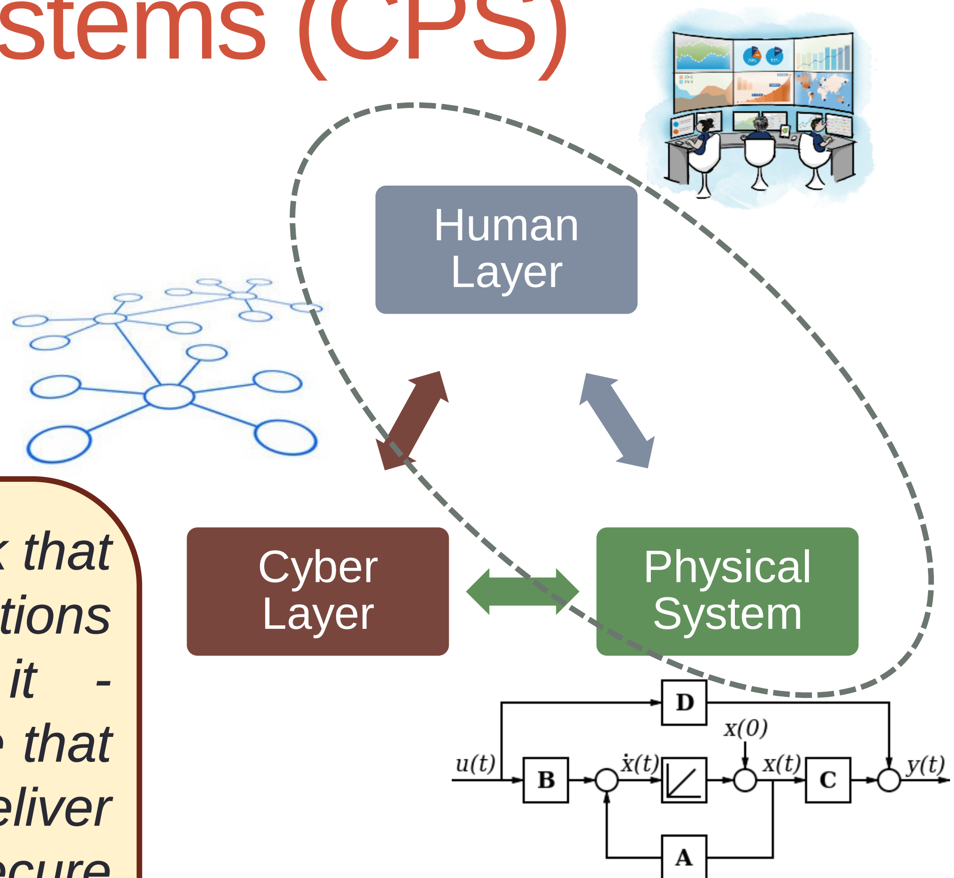
Outline

- CPS Security and its Challenges
- CPS Security Games
- Bounded Rationality in CPS Security Games
- CPS Security Model
  - Attack diffusion model
  - Game-theoretic formulation
  - Bounded rationality
  - Case analysis: smart grid wide area protection



Cyber Physical Systems (CPS)

- *Cyber-physical systems*
  - Physical system
  - Cyber layer
- Purpose: smart systems



Smart Grid: "an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies" – European Technology Platform for Smart Grids 2035 Strategic Research Agenda

CPS Security - Exposed Vulnerability

- Stuxnet (2010):
  - Target: 14 industrial systems in Iran – plant for Uranium enrichment
  - Computer worm targeting control of industrial systems – Programmable Logic Controllers (PLC)
- Water (2000):
  - Target: Maroochy Water Services in Queensland, Australia
  - Block communication links with waste water pumping stations
  - 1 million liters of sewage water spill
- Transportation (2001):
  - Target: Port of Houston, TX, USA
  - Denial-of-Service over its ship assistance system

CPS Security

- Cyber-Physical Systems:
  - Beneficial but vulnerable!
  - Solution: devise solutions to make systems less vulnerable, more robust, and more resilient to attacks.
- CPS Security Research:
  - Type of threats/attacks: data injection, DoS, time synchronization …
  - Purpose: prevention, detection, mitigation …
  - Area of research: smart grids, transportation systems, water distribution, smart cities …
  - Attack vs. Defense: Game Theory!

CPS Security Games

- What is Game Theory?

Set of mathematical tools to analyze strategic interaction and decision making between entities with interconnected interests.

- CPS Security Games:
  - Players: Attacker(s) and Defender(s)
  - Actions: set of attack strategies | set of defense strategies
  - Objective:
    - Attackers: optimize a payoff function reflecting
      - Level of caused damage to the system
      - Financial benefit that it can earn through attack, etc.
    - Defenders: optimize a payoff function reflecting
      - Deviation from normal operating state (minimize)
      - Operation performance level and/or amount of uncompromised resources (maximize)

Bounded Rationality

- Game theory requires *rationality*:
  - Players are purposeful: optimize an objective function
  - Players do not make mistakes
- Risk, stress, incomplete information, extreme complexity, constraints (time, etc.) → limited rationality
- Prone to making mistakes
  - 1965 Northeast blackout → 30 million people affected in Ontario and 8 U.S states → cause: Human mistake: incorrect setting of a protective relay by maintenance personnel!

1965 Northeast Blackout – North America

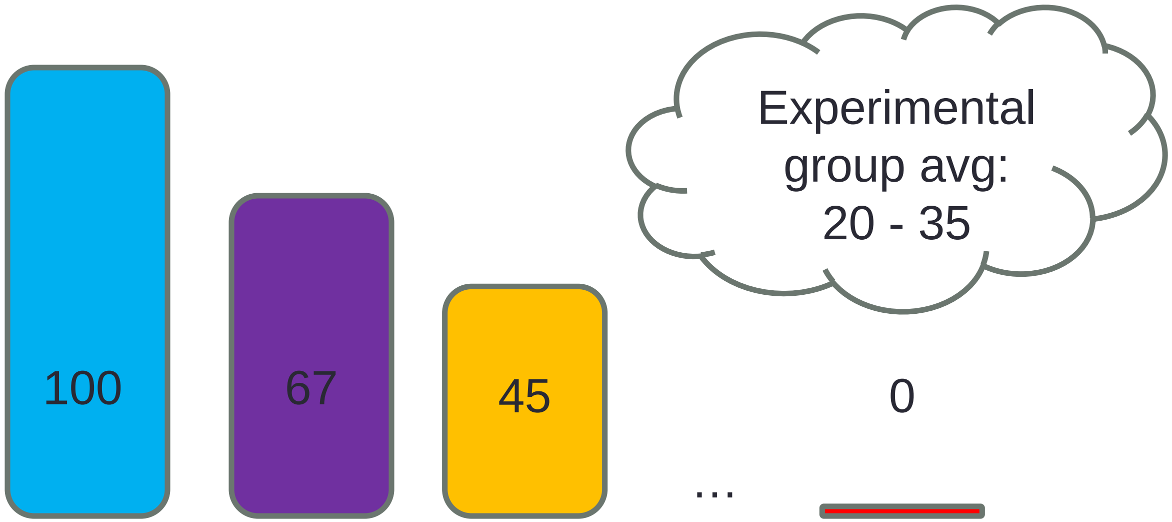
Cognitive Hierarchy

- Perception over the skill levels of opponents
- Multiple thinking steps
  - Example: the beauty contest
- In criminology studies, attackers carry out a reconnaissance phase
  - Accuracy of their perception?
- k thinking steps:
  - Player assumes having most sophisticated strategy (level k)
  - Presume a probability distribution over the skill levels of opponents
    - Proportion of opponents at each thinking step $0 \rightarrow k - 1$
- CPS security application:
  - Example: defensive has highest knowledge of system model → uses perception of adversaries skill levels distribution to design a defense strategy.

Beauty Contest – Cognitive Hierarchy

General Theory of Employment, Interest, and Money (1936) – John Keynes

Beauty contest game: A number of participants are asked to choose a number from 0 – 100. The player whose number is closest to 2/3 of the average of all chosen numbers wins.



Cognitive Hierarchy

- Perception over the skill levels of opponents
- Multiple thinking steps
  - Example: the beauty contest
- In criminology studies, attackers carry out a reconnaissance phase
  - Accuracy of their perception?
- k thinking steps:
  - Player assumes having most sophisticated strategy (level k)
  - Presume a probability distribution over the skill levels of opponents
    - Proportion of opponents at each thinking step $0 \to k-1$
- CPS security application:
  - Example: defensive has highest knowledge of system model → uses perception of adversaries skill levels distribution to design a defense strategy.

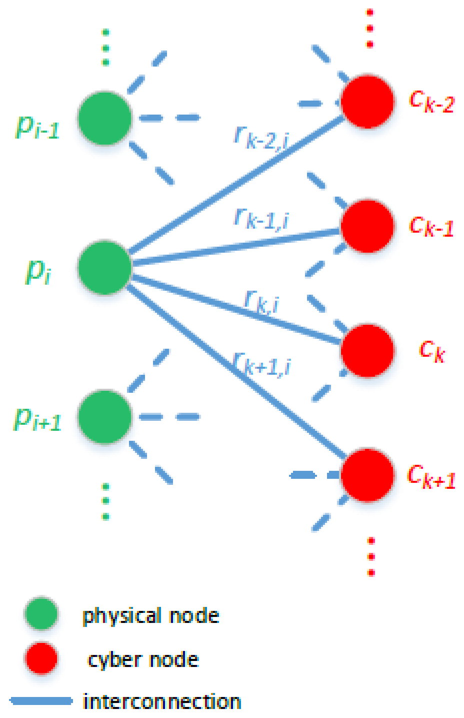
CPS SECURITY MODEL

Game-Theoretic Formulation | Application to Smart Grids' Security

Attack Diffusion Model

- CPS Model:
  - N_c cyber nodes, N_p physical nodes
  - $r_{c,p}$: weight interconnection between physical node p and cyber node c.
    - Weight of data sent by c on control action over p
    - $r_{c,p} = \Pr(p \text{ fails} \mid c \text{ has failed})$
    - Failure of c :
      - Implication: send corrupt data
      - Reason: cyber attack, misconfiguration,…
  - π_p: probability of failure of p due to failures in the cyber layer

$$\pi_p = \sum_{c=1}^{N_c} r_{c,p} \kappa_c$$

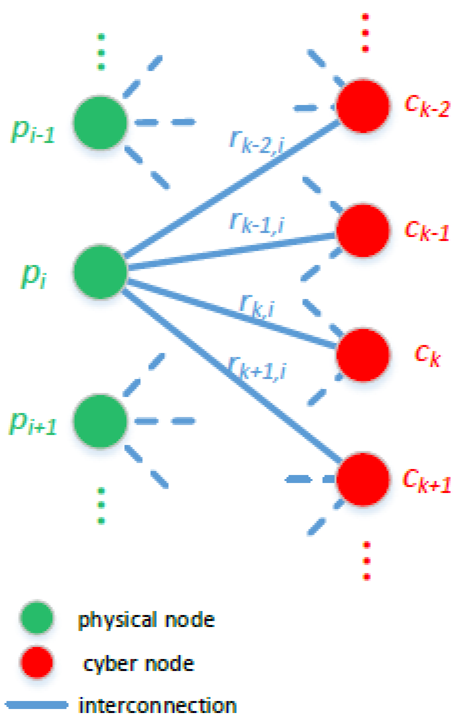


Attack Diffusion Model

- $\boldsymbol{R} = [r_{c,p}]_{N_c \times N_p}$: cyber-physical interconnection matrix
- $\boldsymbol{\pi} = [\pi_1, \dots, \pi_{N_p}] \in [0,1]^{N_p}$: failure probability vector of physical nodes
- $\boldsymbol{\kappa} = [\kappa_1, \dots, \kappa_{N_c}] \in [0,1]^{N_c}$: failure probability vector of cyber nodes

$$\pi_p = \sum_{c=1}^{N_c} r_{c,p} \kappa_c$$

$$\boldsymbol{\pi} = \boldsymbol{\kappa} \boldsymbol{R}$$



- f_p: cost of failure of physical node p
- Expected total loss to system: $E_f = \sum_{p=1}^{N_p} \pi_p f_p$

Game Formulation

- Under no attack:
  - $\boldsymbol{\kappa} = [\kappa_1, \dots, \kappa_{N_c}]$ small → $\boldsymbol{\pi} = [\pi_1, \dots, \pi_{N_p}]$ small
  - Minimize $E_f = \sum_{p=1}^{N_p} \pi_p f_p$ is a reliability evaluation problem.
- Under cyber-attack
  - c is attacked → $\kappa_c = 1 \rightarrow \boldsymbol{\pi} \uparrow \rightarrow E_f \uparrow$
  - c is defended → $\kappa_c = 0 \rightarrow \boldsymbol{\pi} \downarrow \rightarrow E_f \downarrow$
  - Attacker vs. Defender Game
    - Players: defender d, attacker a
    - Set of actions: which cyber nodes to attack/defend $|S_d| = \binom{N_c}{n_d}$, $|S_a| = \binom{N_c}{n_a}$
    - Utility function: $U_d(s_d, s_a) = -U_a(s_d, s_a) = -E_f$
    - $s_i \in S_i, n_i$ = number of concurrently attacked/defended nodes

Bounded Rationality

- Under full rationality (standard game theory)
  - Defender and attacker play best response strategies

    → Full knowledge of $E_f = \sum_{p=1}^{N_p} \pi_p f_p$ is needed
  - Defender vs Attacker
    - CPS are very complex → obtaining $\boldsymbol{f}$ (vector of f_p's) is challenging
    - Solution: build own perception of $\boldsymbol{f}$ → $\hat{\boldsymbol{f}}_{i\in(a,d)}$
    - Level of thinking of $i \in (a, d)$: how close is $\hat{\boldsymbol{f}}_i$ **to** $\boldsymbol{f}$
    - Higher level thinkers *(Analogous to Cognitive Hierarchy Theory)*
      - More intelligent
      - Have better knowledge of the system
      - Better computational capabilities

      } Generate better $\hat{\boldsymbol{f}}_i$

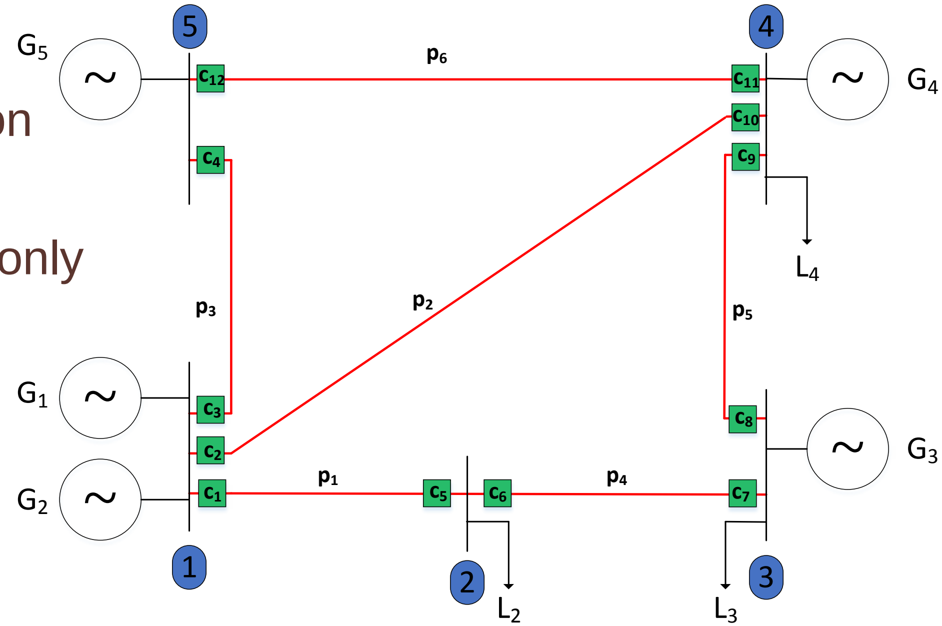
Application to Wide Area Protection

- Wide area monitoring and protection schemes:
  - Rely on global data
  - React to disturbances
    - Ex: disconnection of a transmission line, generator, or load shedding

→ Availability of a physical node dependent on spread cyber nodes

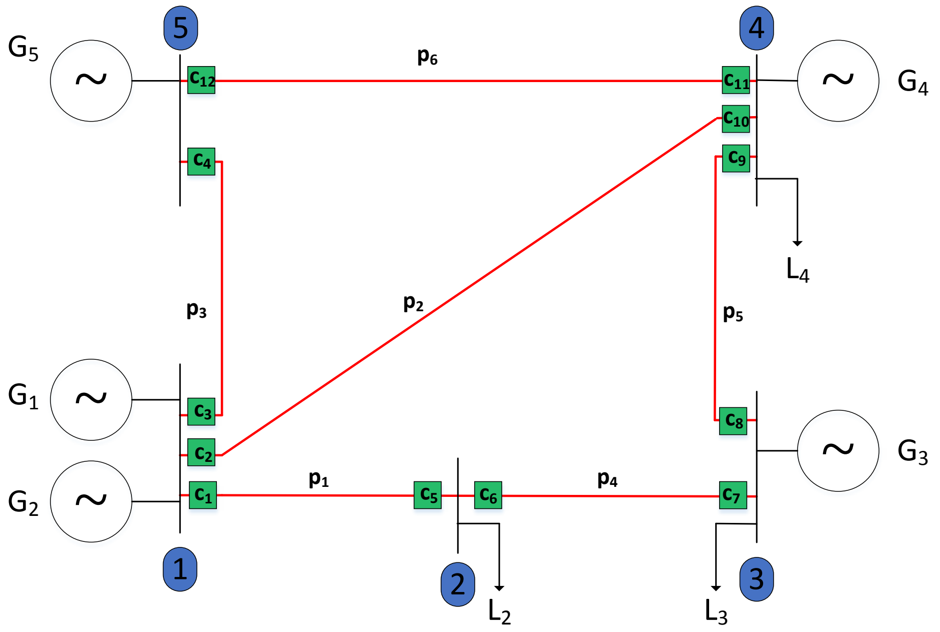
- Dependability vs Security
  - Dependability: successful isolation of a fault when it happens
  - Security: take protection actions only when disturbance occurs.

PJM 5-bus system:



Application to Wide Area Protection

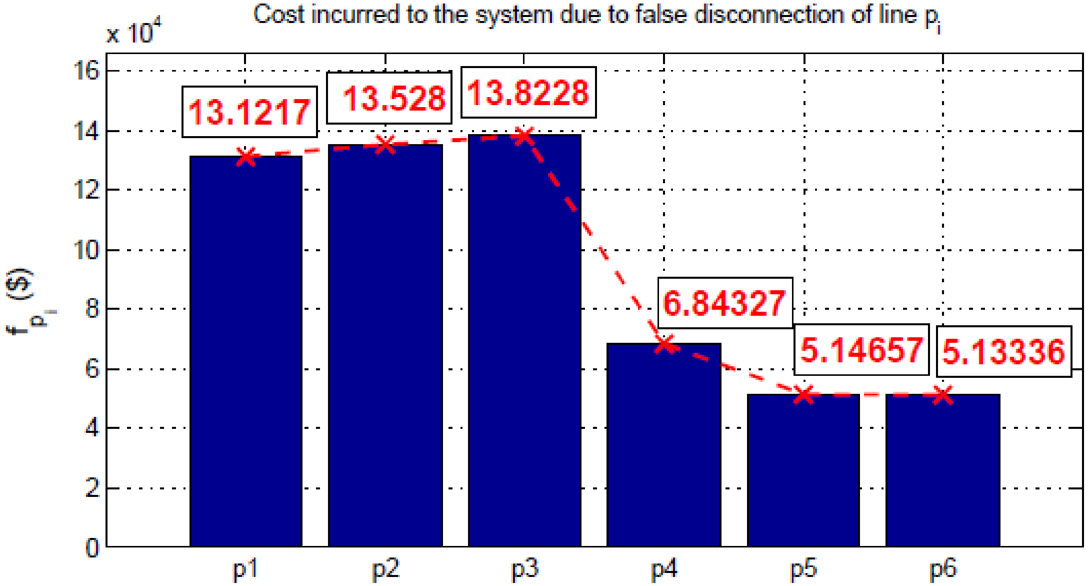
- Application:
  - 1 attacker vs. 1 defender
  - # concurrent attacks = 2
  - # secured nodes = 2
  - Energy markets implications
    - Optimal Power Flow



Application to Wide Area Protection

- V^o: value function of the original OPF (\$/h)
- V^{p_i}: value function of the OPF with loss of p_i (\$/h)
- T^{p_i}: time needed to bring p_i back to operation (h)
- CR^{p_i}: cost of repair of p_i

$$f_{p_i} = (V^{p_i} - V^0)T^{p_i} + CR^{p_i}$$

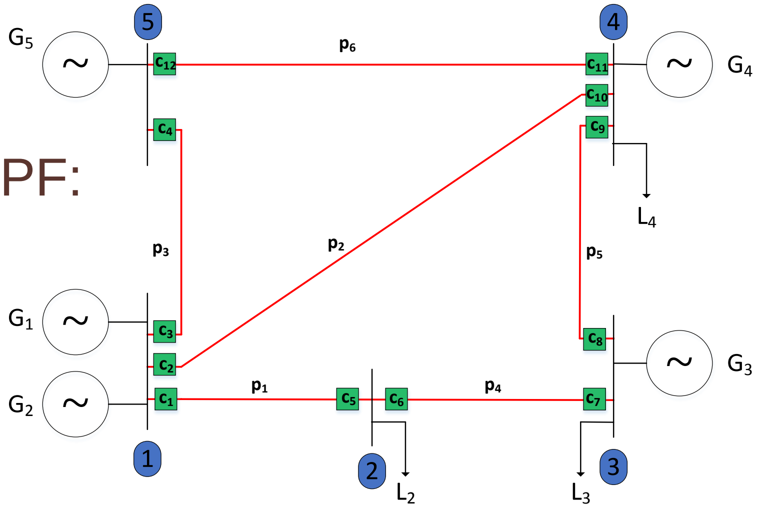


Nash equilibrium strategies:

$$\gamma_d^* = [0.2931, 0.3034, 0.3107, 0.0842, 0.0047, 0.0040]$$
$$\gamma_a^* = [0.1276, 0.1244, 0.1222, 0.1922, 0.2167, 0.2169]$$

$$\overline{U}_d = -\overline{U}_a = -\$110{,}240$$

Application to Wide Area Protection



- Bounded rationality:
  - Requirements for the solution of the OPF:
    - knowledge of the full system
    - high computational capabilities
  - 3 types of attackers:
    - Level 0 (l_0): chooses attack randomly
    - Level 1 (l_1): attacks line with highest power flow
    - Level 2 (l_2): can solve OPF, attacks line with highest f_{p_i}
  - Defender:
    - Can solve OPF
    - Strategic thinker

Highest level thinker

Application to Wide Area Protection

- Defender faced with an attacker of type k with probability:

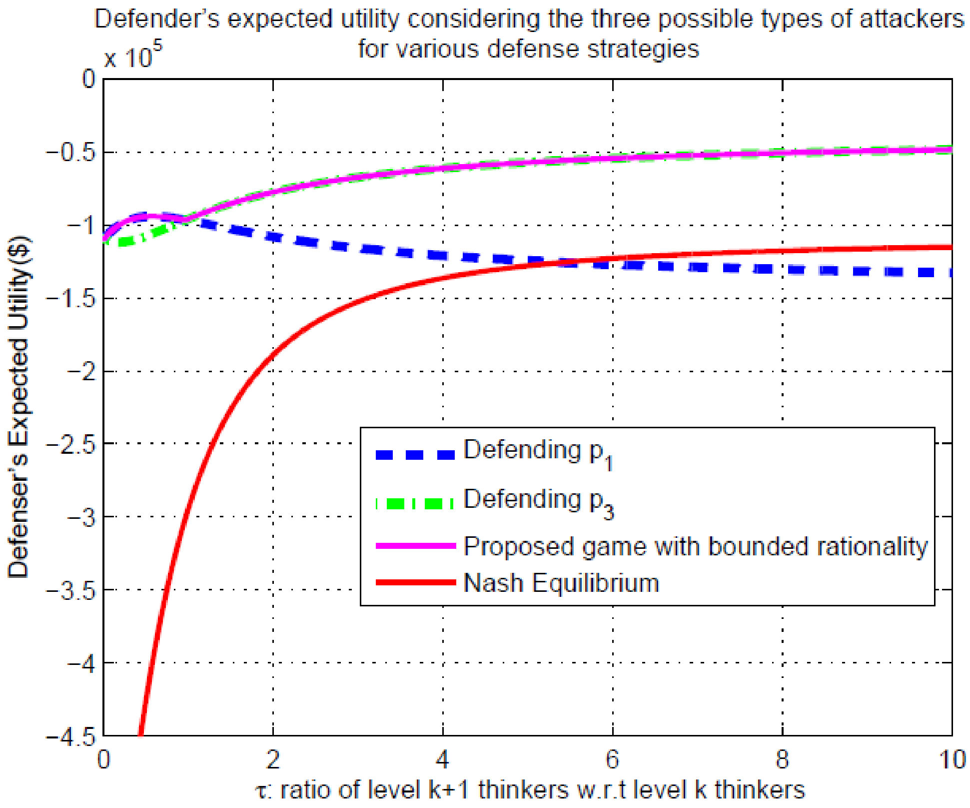
$$\alpha(k) = \frac{e^{-\lambda}\lambda^k}{k!}$$ → Poisson distribution

$$\rightarrow \begin{cases} \dfrac{\alpha(1)}{\alpha(0)} = \dfrac{\alpha(2)}{\alpha(1)} = \tau \\ \alpha(0) + \alpha(1) + \alpha(2) = 1 \end{cases}$$

- $\tau < 1 \rightarrow$ a low level attacker is most probable
- $\tau > 1 \rightarrow$ a high level attacker is most probable
- Optimal defense against: $\alpha(0)l_0 + \alpha(1)l_1 + \alpha(2)l_2$

Application to Wide Area Protection

- Advantage for accounting for multiple possible types of attackers
- Probability of facing a higher attacker *increases*, the gain from deviating from the NE *decreases*



Conclusions

- Introduced general CPS security model showing propagation of attacks from cyber to physical
- Attacker vs. Defender Game
- Bounded rationality
- Application to wide area protection
  - Optimal defense strategy accounting for multiple attacker types
  - Beneficial deviation from the NE defense strategy

ACKNOWLEDGEMENT

National Science Foundation

National Science Foundation
WHERE DISCOVERIES BEGIN

Contact information: anibals@vt.edu, walids@vt.edu

Thank you!

Questions…