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A Quantal Response Analysis of Human Decision-making in Interdependent Security Games Modeled by Attack Graphs

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Introduction

- Interdependent systems (e.g., **power grid** and **industrial control systems**) are increasingly vulnerable to sophisticated cyberattacks targeting critical infrastructure.
- These systems involves **multiple defenders** managing different **connected** subsystems.
- Defenders must **allocate their limited security budget efficiently** to reduce security risks.
- Traditional security models assume rational decision-makers, but **human decision-making** often **deviates due to cognitive limitations**.

Research Question:
For large-scale interdependent systems, what are the **impacts of human behavioral errors on security investments** allocated by human defenders and their **effects on the total system's security cost**?

Motivation

- Existing **security models rely on classical decision-making**, assuming perfect rationality, which does not align with real-world human behavior.
- Human defenders **exhibit bounded rationality and probabilistic decision-making**.
- Understanding **quantal response equilibrium (QRE) in interdependent security setup** can help **quantify inefficiencies in security investments** and improve security defense.

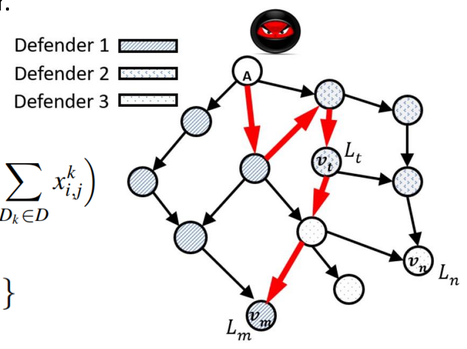
Our Contribution

- We introduce a **security investment model** for **human defenders** in interdependent systems modeled by **attack graphs**.
- We **develop a framework** incorporating **quantal response equilibrium** in order to model probabilistic security decision-making.
- We **quantify inefficiencies** arising **from bounded rationality** on system's security.

Background and Problem Setup

- **Threat & Defense Model:**
- We study security games consisting of **an attacker** and **multiple defenders** interacting through an attack graph G = (V, E).
- Attacker uses **stepping-stone** to launch an attack from source to target assets.
- Each defender $D_k \in D$ has control of a subset of assets $V_k \subseteq V$.
- Among all the assets in the network, a subset $V_m \subseteq V$ contains **critical assets**, the compromise of which entails a *financial loss* for the corresponding defender.
- The **cost of defender** D_k is given by

$$C_k(x_k, x_{-k}) \triangleq \sum_{v_m \in V_k} L_m \left(\max_{P \in \mathbb{P}_m} \prod_{(v_i,v_j)\in P} p_{ij}\,(x_{i,j}) \right)$$



- **Probability of Successful Attack**: $p_{i,j}(x_{i,j}) = p^0_{i,j} \exp\left(-s_{i,j} \sum_{D_k \in D} x^k_{i,j} \right)$
- **Defense Strategy Space:** $X_k := \{\mathbf{x}_k \in \mathbb{R}^{|\mathcal{E}|}_{\geq 0} \,|\, 1^T \mathbf{x}_k \leq B_k\}$

Quantal Response Equilibrium (QRE)

- **Quantal response equilibrium (QRE)** is a solution concept in game theory which provides an **equilibrium notion with bounded rationality**.
- It is a statistical tool to model **human errors** in choosing effective strategies.
- In our interdependent security game, we use *logit* QRE, where **defender's security investment profiles would be chosen according to the probability distribution**:

$$\sigma_{kl} = \frac{\exp(-\lambda_k\, EC_{kl}(\sigma_{-k}))}{\sum_{\mathbf{x}_l \in X_k} \exp(-\lambda_k\, EC_{kl}(\sigma_{-k}))}$$

where σ_{kl} is the **probability of defender D_k choosing investment profile** $x_l \in X_k$

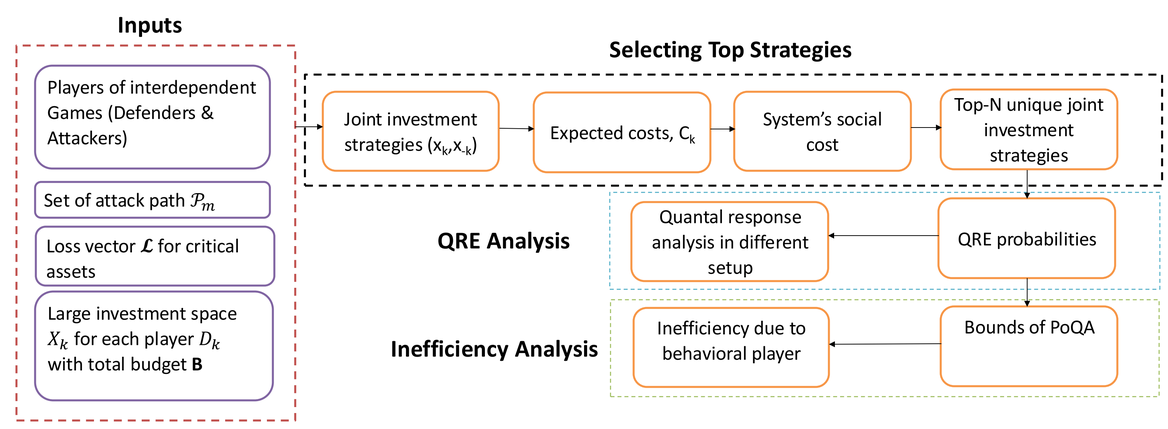
  - $EC_{kl}(\sigma_{-k})$ is the expected cost of defender D_k,
  - $\lambda \in [0, \infty)$

- We **introduce a metric to quantify the inefficiencies** of defenders' behavioral decision-making characterized by *quantal errors*

$$PoQA = \frac{\sum_{D_k \in \mathcal{D}} \left(\sum_{\mathbf{x}_l \in X^{\text{QRE}}_k} \sigma_{kl} \times EC_{kl}(\sigma_{-k}) \right)}{C(\mathbf{x}^*)}$$

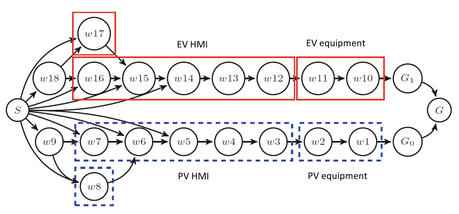
- PoQA is upper bounded by: $PoQA \leq \exp(B)$

Model Overview

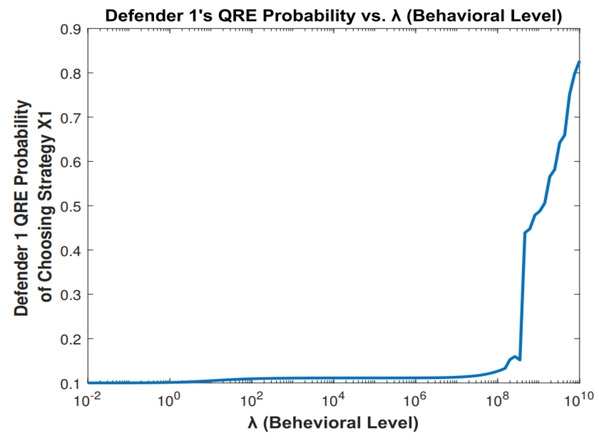


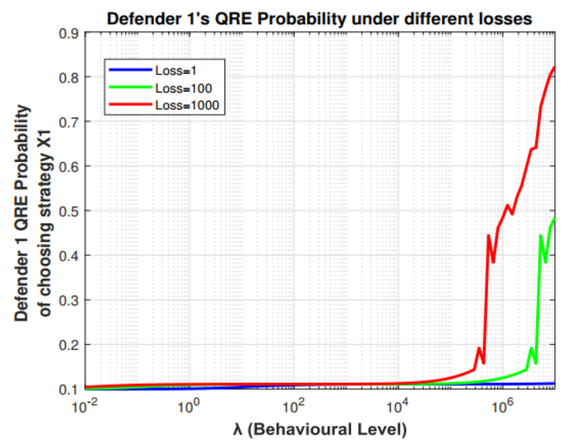
Overview of Quantal Response Analysis of Human Decision-making in Interdependent Security Games

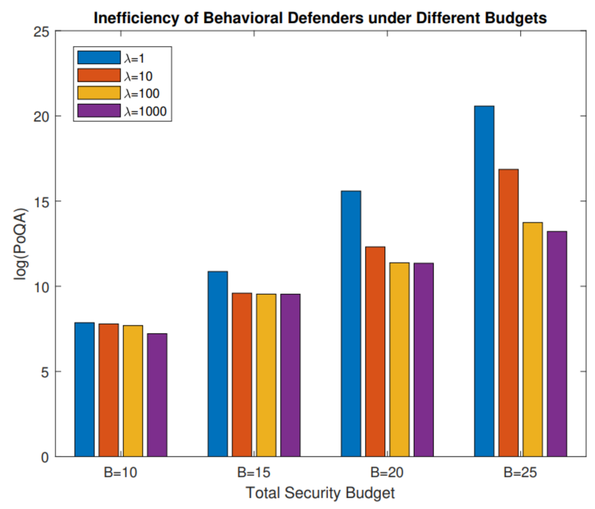
Main Results

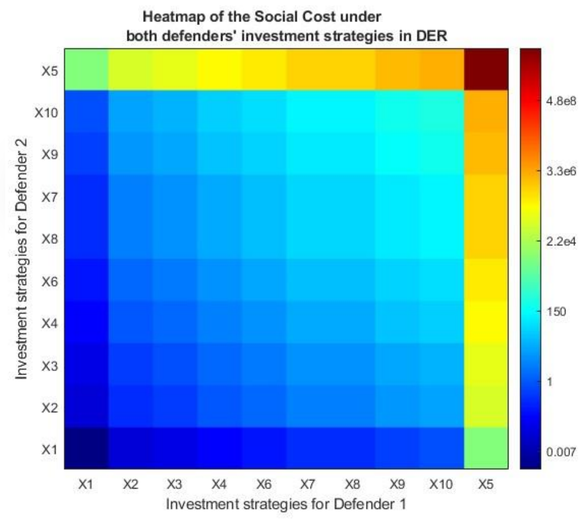


Strategy \ Edge Investment	$x_{1,0}$	$x_{2,1}$	$x_{3,2}$	$x_{4,3}$	$x_{5,4}$	$x_{6,5}$	$x_{7,6}$	$x_{9,7}$	$x_{s,9}$	$x_{s,5}$	$x_{s,6}$	$x_{s,7}$	$x_{s,8}$	$x_{9,8}$	$x_{8,6}$
X_1	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X_2	2.5	2.5	2.5	2.5	2.5	2.5	0	0	0	0	0	0	0	0	0
X_3	0	3	3	3	3	3	0	0	0	0	0	0	0	0	0
X_4	0	0	3.75	3.75	3.75	3.75	0	0	0	0	0	0	0	0	0
X_5	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0
X_6	2.14	2.14	2.14	2.1429	2.14	2.14	2.14	0	0	0	0	0	0	0	0
X_7	0	0	0	5	5	5	0	0	0	0	0	0	0	0	0
X_8	0	2.5	2.5	2.5	2.5	2.5	2.5	0	0	0	0	0	0	0	0
X_9	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	0	0	0	0	0	0	0
X_10	0	0	3	3	3	3	3	0	0	0	0	0	0	0	0









Key Takeaways

- Human defenders **do not always make perfectly rational security investment decisions**, leading to **suboptimal protection of interdependent systems**.
- The **introduction of QRE provides a more realistic approach** to modeling human security investments in interdependent systems.
- PoQA analysis reveals **that inefficiencies in security investments grow exponentially with defenders' security budget**, emphasizing the need for improved resource allocation.

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