Towards Resilient Smart Cities

WINLAB
Department of Electrical and Computer Engineering
RUTGERS

Narayan B. Mandayam

Acknowledgment: National Science Foundation

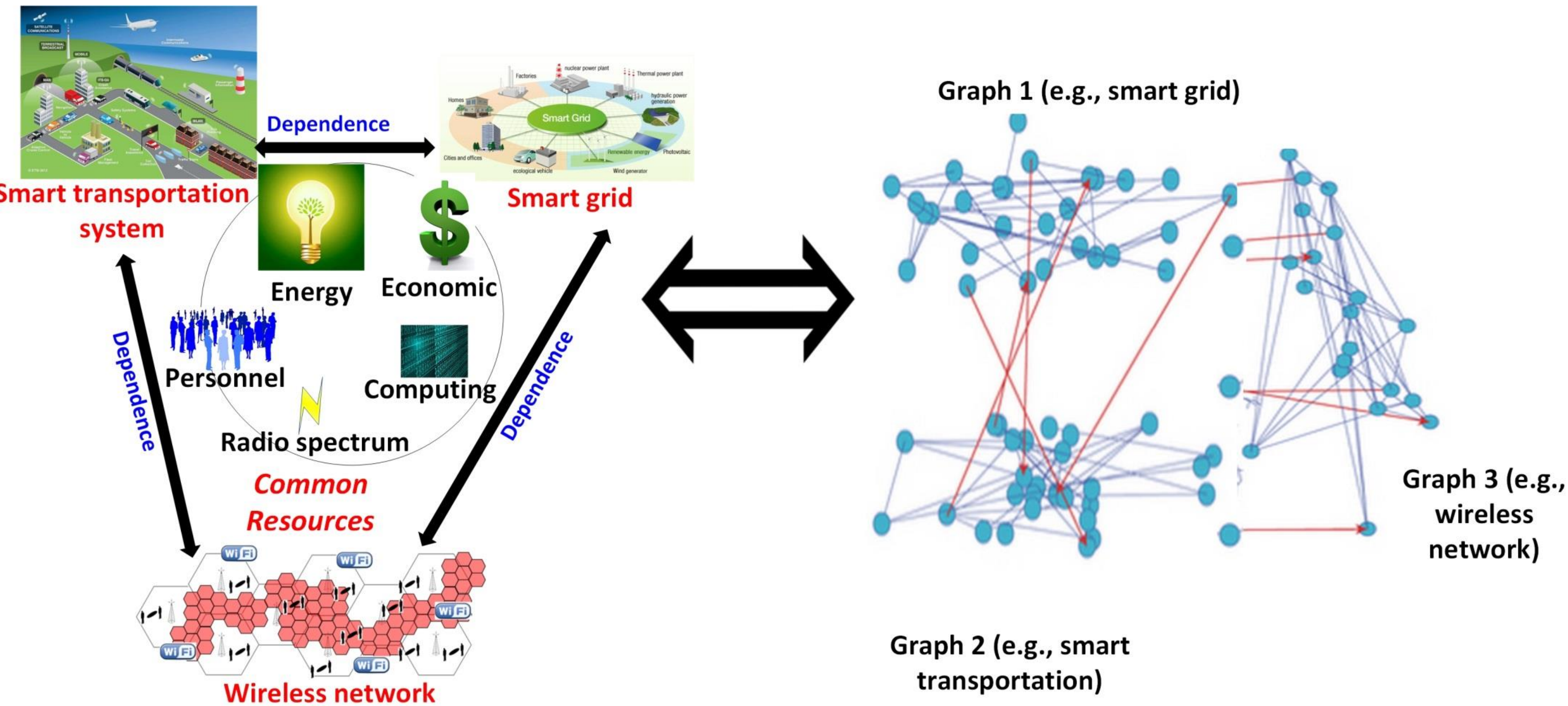
Towards Resilient Smart Cities

- Vision of Smart City requires synergistic integration of cyber-physical critical infrastructures (CIs) such as
  - transportation, wireless systems, water networks, power grids
- Shared Resources
  - energy, computation, wireless spectrum, economic investments, personnel, and end-users
- Correlated failures
  - day-to-day operations, natural disasters, or malicious attacks
- Engineering, Economics, Psychology, Regulation
  - Interaction across these disciplines

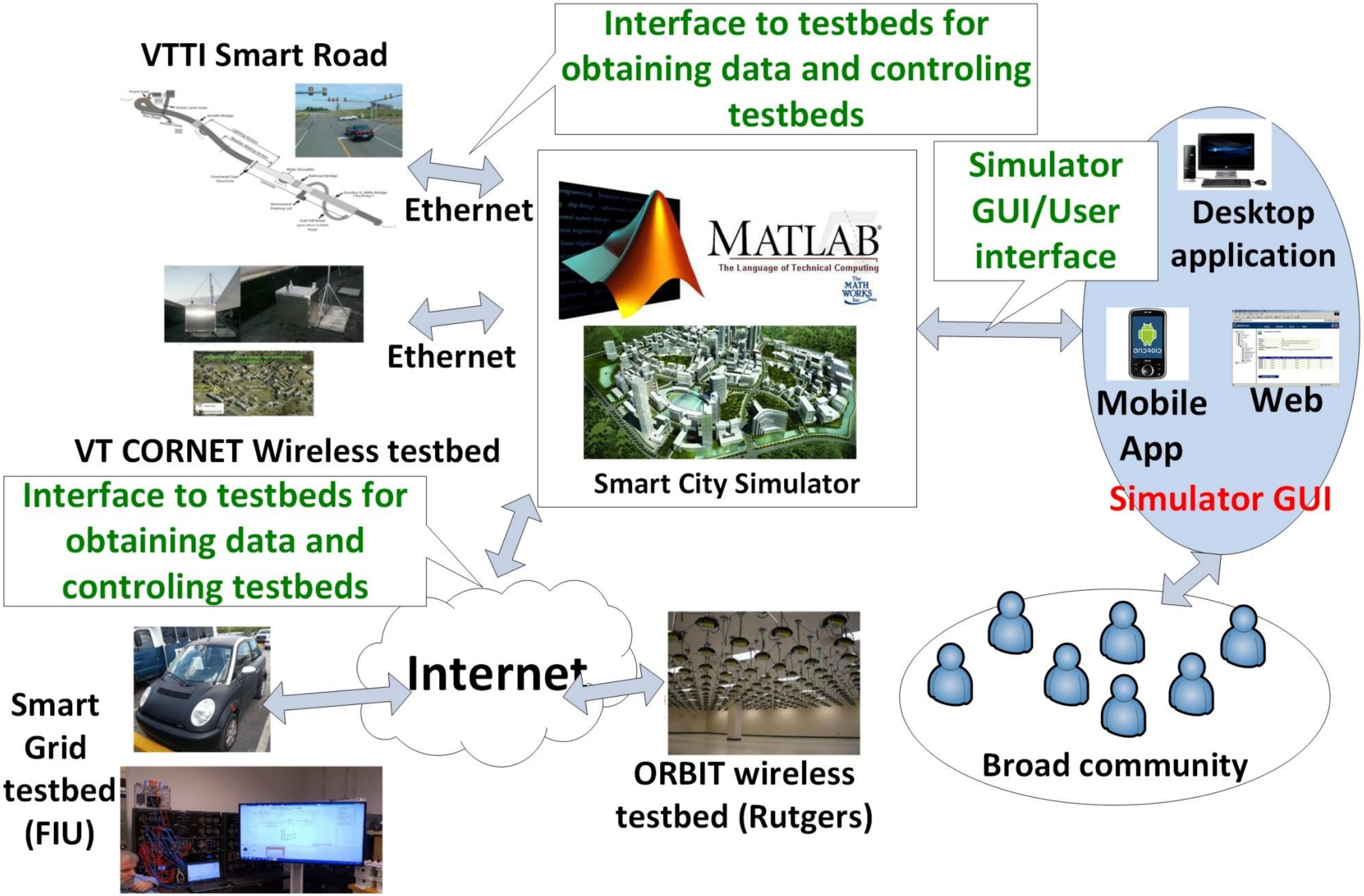
NSF CRISP Project

- NSF Critical Resilience Interdependent Infrastructure Systems and Processes (CRISP) Program
- Collaborative Project between Rutgers University, Virginia Tech and Florida International University
- Team of engineers, cognitive psychologists, economists
  - Rutgers - Narayan Mandayam, Arnold Glass, Janne Linqvist
  - Virginia Tech - Walid Saad , Sheryl Ball, Myra Blanco, Danfeng Yao
  - FIU - Arif Sarwat, Ismail Guvenc
- Scope of Study
  - Analytical models and algorithms for resource sharing
  - Human subject studies
  - Simulators, emulators and testbeds

- Communication/Grid Models
- Economic Models
- Behavioral Models/Prospect Theory
- Graph Theory
- Game Theory
- Machine Learning



Integration of Testbeds



What is Resilience of Critical Infrastructure (CI)?

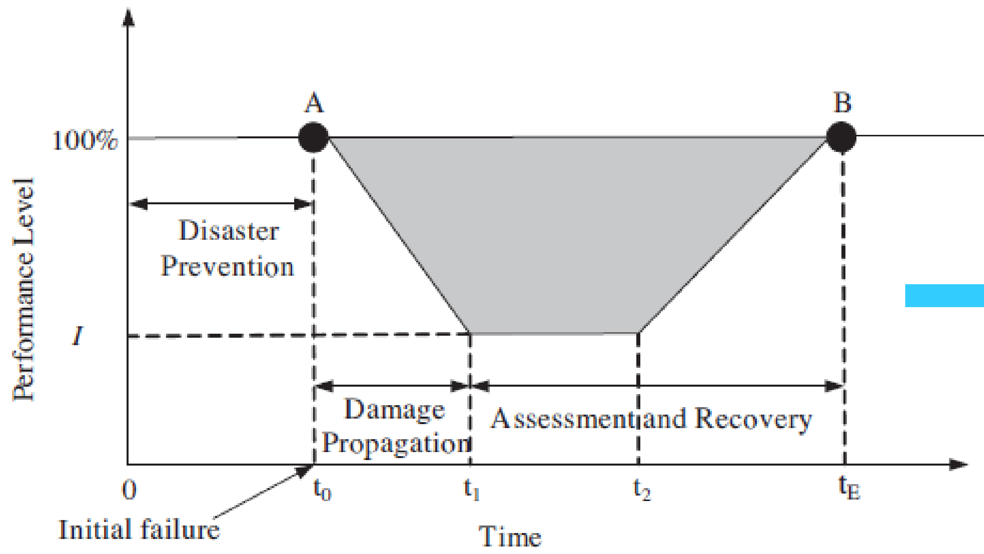
- Reliability: frequency/likelihood of CI's failure
- Resilience: Multiple definitions, application dependent
  - response to a change or corruption to a critical infrastructure's normal functionality
  - multiple dimensions – technical, organizational, social and economic
- President Obama Proclamation for National Preparedness:

"Our goal is to ensure a more resilient Nation—one in which individuals, communities, and our economy can adapt to changing conditions as well as withstand and rapidly recover from disruptions due to emergencies"

- DHS Advisory Council (Technical): *"capacity of an asset system or network to maintain its function during or to recover from a terrorist attack or other incident"*

Characteristics of Resilience in Interdependent CIs

Typical Performance Response of a CI following a Disruptive Event (*Ouyang et al.*)



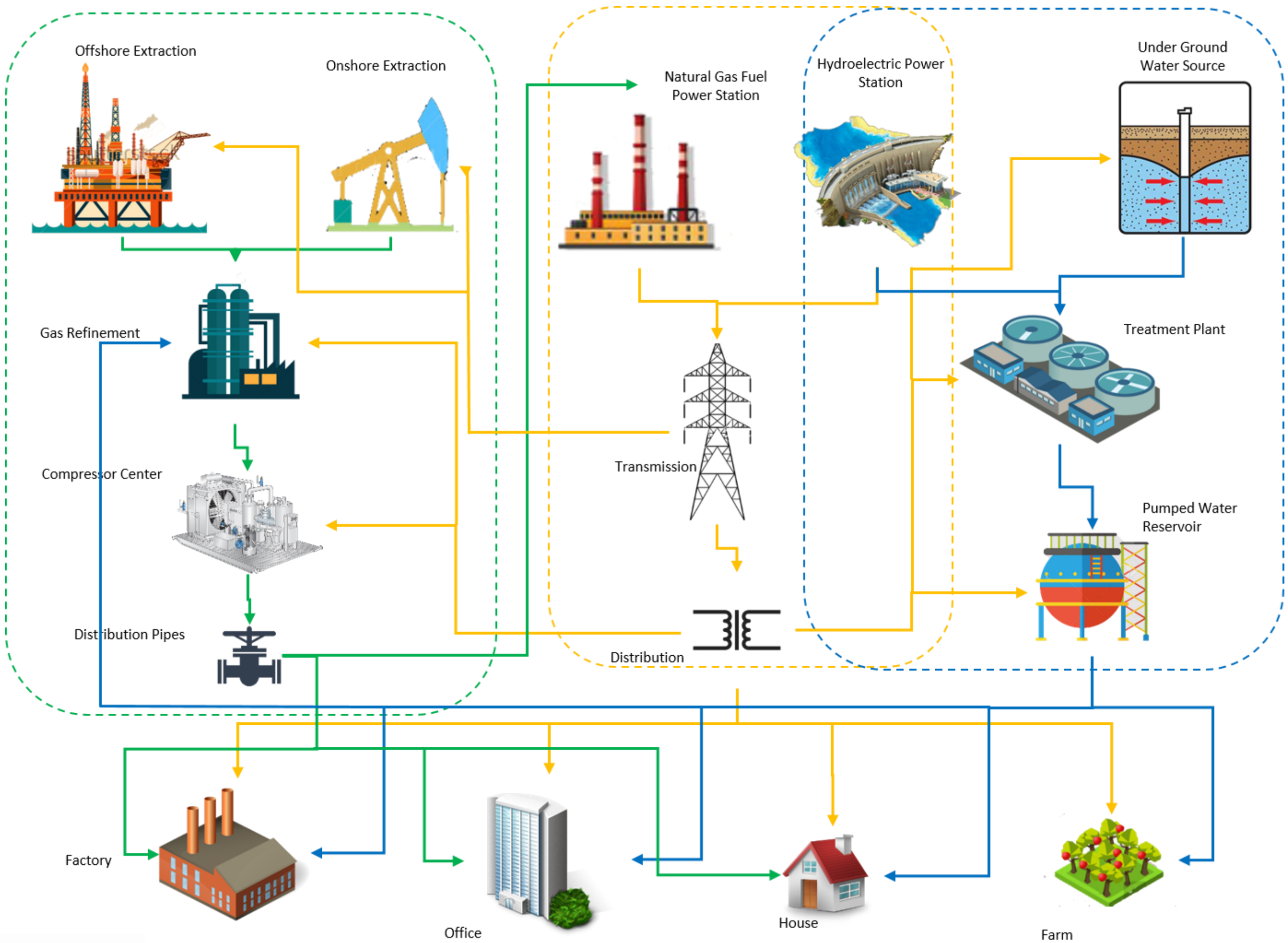
Damage Propagation, Assessment & Recovery lot more complex for Interconnected CIs

- Time Dependent Modeling of Interconnected Systems
- Time Dependent Metrics for Resilience
- Dynamic Resource Allocation for Prevention and Recovery
- Human and Engineered System Interactions (Non Expected Utility Theory Models)

RUTGERS

WINLAB

Case Study 1: Securing Critical Interdependent Gas-Power-Water Infrastructure (Ferdowsi, Sanjab, Saad, Mandayam @Resilience Week 2017)



Case Study 1: Interdependence of Gas-Power-Water and Communications CI

- **Power-Water interdependence:** Generators consume water for cooling down and temperature control; water CI use power to control water flow and pressure
- **Power-Natural gas interdependence :** Generators consume natural gas to produce electric power; Natural gas CI use power to control gas flow and pressure
- **Communications-Power-Water-Gas interdependence :** Sensing infrastructure to sense and allocate resources to CIs

State Vectors and Matrices capture gas, power and water CI parameters, e.g. angular speeds, voltage phases, water and gas pressure, etc.

$$
\underbrace{\left[\begin{array}{ccc|cc|cc}
I & O & O & & & & \\
O & M & O & O & & O & \\
O & O & O & & & & \\
\hline
 & O & & R_c & O & O & \\
 & & & O & O & & \\
\hline
 & O & & O & & R_t & O \\
 & & & & & O & O
\end{array}\right]}_{\boldsymbol{E}}
\left[\begin{array}{c}
\dot{\delta} \\ \dot{\omega}_G \\ \dot{\omega} \\ \dot{\theta}_c \\ \dot{\theta}_t \\ \dot{\theta} \\ \hline \dot{h}_s^G \\ \dot{h}_j^G \\ \hline \dot{h}_s^W \\ \dot{h}_j^W
\end{array}\right]
=
\underbrace{\left[\begin{array}{ccc|c|c}
O & I & O & O & O \\
-L_{gg} & D & L_{gl} & C^G & C^W \\
-L_{lg} & O & L_{ll} & O & O \\
\hline
 & O & & C^G & O \\
\hline
 & O & & O & C^W
\end{array}\right]}_{\boldsymbol{A}}
\underbrace{\left[\begin{array}{c}
\delta \\ \omega_G \\ \omega \\ \theta_c \\ \theta_t \\ \theta \\ \hline h_s^G \\ h_j^G \\ \hline h_s^W \\ h_j^W
\end{array}\right]}_{\boldsymbol{x}},
$$

Case Study 1: Game Theoretic Model for Securing Critical Interdependent Gas-Power-Water CI

- Dynamics of interdependent critical infrastructure (ICI):

  $$E\dot{x} = Ax, \qquad x \text{ : State vector of ICI}$$

- Sensor network collecting data from ICI:

  $$y = Cx, \qquad y \text{ : Sensor data vector}$$

- ICI under "attack" due to disruptive event:

  $$E\dot{\tilde{x}} = A\tilde{x} + bv, \qquad v \text{ : State "attack" vector}$$

  $$\tilde{y} = C\tilde{x},$$

- Interaction of "attacks" on state vector and "defense" modeled using dynamic games

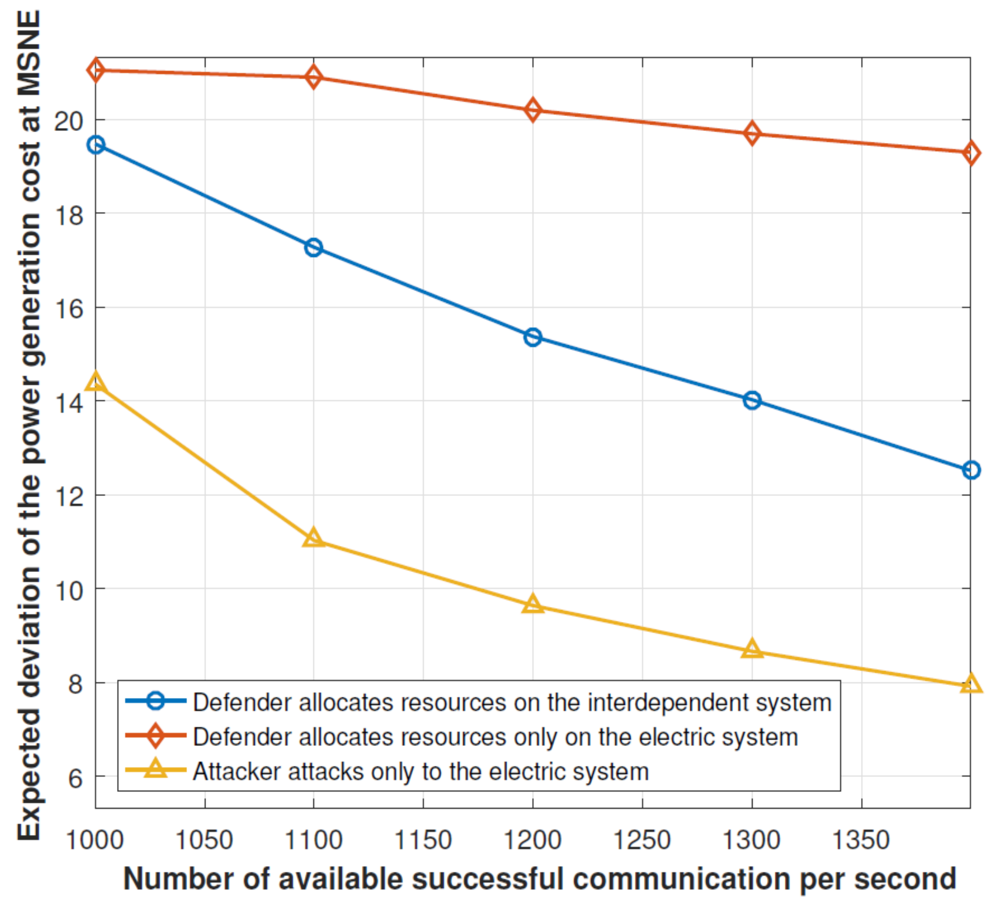
Case Study 1: Noncooperative Game for Securing Critical Interdependent Gas-Power-Water Infrastructure

- Distributed attack detection filter requires communication between the subsystems
- If communication is faster between the subsystems the filter detects the attack faster
- If the attack detection filter of each subsystem j takes T seconds to detect the attack, increasing the number of sensing messages to subsystem j with a factor of m_j the filter will detect the attack in $\frac{T}{m_j}$ seconds.
- The defender has limited number of communications in T seconds: $\sum_{i=1}^{N} m_i \leq TM$
- The attacker's strategy: choose subset κ from states to attack
- The defender's strategy: allocate m_j to each subsystem j: $\mu = \left\{ m_i \in \{1, \ldots, TM\} \middle| \sum_{i=1}^{N} m_i \leq TM \right\}$
- The utility function (power generation cost due to an attack on κ states for a time period μ): Attacker maximizes it and Defender minimizes it

$$\Delta p(\kappa, \mu) = \sum_{j \in \kappa} \int_0^{\frac{T}{m_j}} \mathscr{L}^{-1} \left\{ \left(\sum_{i=1}^{n} (-1)^{i+j} c_{p_i} \frac{|(sE - A)_{\bar{i},\bar{j}}|}{|sE - A|} \right) v_j(s) \right\}$$

Case Study 1: Resource Allocation for Securing Critical Interdependent Gas-Power-Water Infrastructure

- When the defender protects only the power infrastructure, the expected cost deviation increases by 30%, approximately.
- Due to interdependence between the CIs, the defender must protect all the three CIs to reduce the power generation cost



Human-Engineered System Interactions
Prospect Theory: An Alternative to Expected Utility Theory

- Prospect L: a contract yields M outcomes, e.g., $\{o_{1,\ldots,}o_M\}$, each occurring with probability p_i
  - How to valuate a prospect?

<u>Expected Utility Theory (EUT)</u>

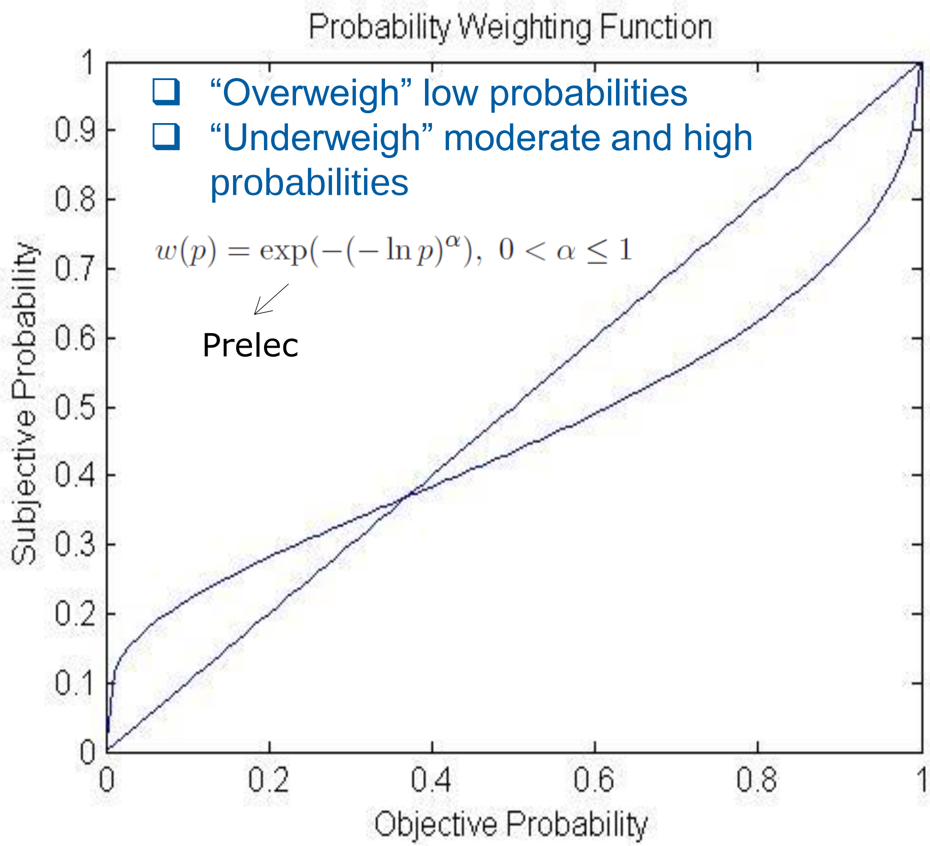
- Proposed by Bernoulli, developed by Von Neumann, Morgenstern, others
- Game Theory heavily depends on it
  - E.g. game theoretic models in radio resource management
- Value of a prospect is estimated as the mathematical expectation of values of possible outcomes
- However, violations to EUT have constantly been observed in real-life decision-making

<u>Prospect Theory (PT)</u>

- Proposed by Kahneman and Tversky
- A better theory in describing people's real life decisions facing alternatives with risk
- Able to successfully explain the observed violations to EUT
- People use subjective probability to weigh values of outcomes
- People valuate outcomes in terms of relative gains or losses rather than final asset position

Prospect Theory: An Alternative to Expected Utility Theory for Modeling Decision Making

Probability Weighting Effect

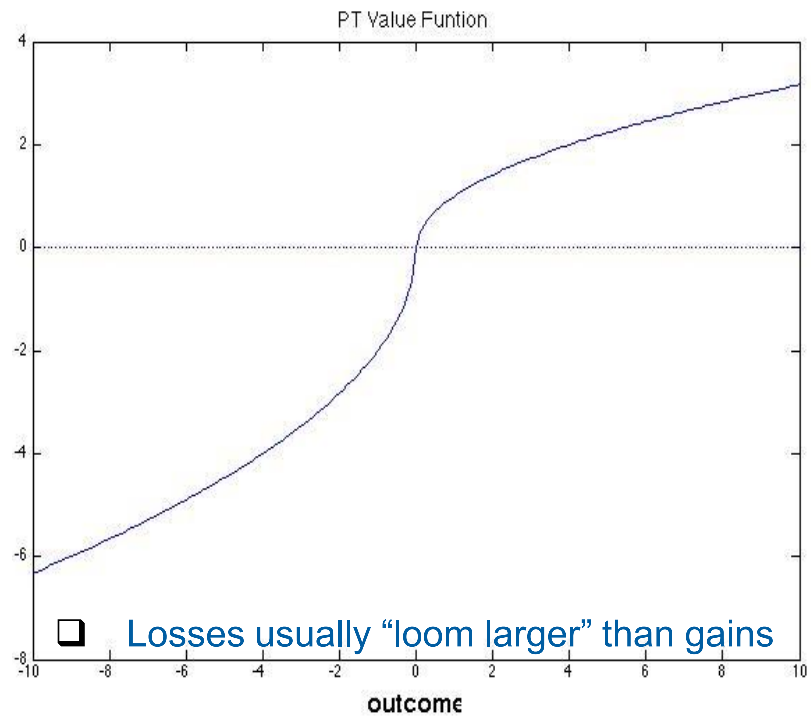


- "Overweigh" low probabilities
- "Underweigh" moderate and high probabilities

$$w(p) = \exp(-(-\ln p)^{\alpha}),\ 0 < \alpha \le 1$$

Prelec

Framing Effect



- Losses usually "loom larger" than gains

RUTGERS WINLAB

Prospect Theory: Valuation of a Prospect

- Expected Utility Theory (EUT)

$$u^{EUT}(L) = \sum_{i=1,\ldots,M} p_i v^{EUT}(o_i)$$

  - Expectation of values of all possible outcomes

- Prospect Theory (PT)

"The Psychophysics of Chance"

Probability Weighting Effect

Framing Effect

$$u^{PT}(L) = \sum_{i=1,\ldots,M} w(p_i) v^{PT}(o_i)$$

When EUT Fails, PT Explains

- Variation of Allais' Paradox

AN EXAMPLE OF EUT VIOLATION

Problem \ Prospect	A	B
1	\$2500 *with probability* 0.33 \$2400 *with probability* 0.66 \$0 *with probability* 0.01	\$2400 *with certainty*
2	\$2500 *with probability* 0.33 \$0 *with probability* 0.67	\$2400 *with probability* 0.34 \$0 *with probability* 0.66

- 61% respondents choose 1B and 2A → **Paradox**
  - Under EUT,
    - 1B implies $0.34v^{EUT}(2400) > 0.33v^{EUT}(2500)$
    - 2A implies $0.34v^{EUT}(2400) < 0.33v^{EUT}(2500)$

- Under PT with $\alpha = 0.5$ and linear value function with zero as the reference point, the two choices established simultaneously

Case Study 2: Prosumer Decision Making in a Smart Grid

(Rajabpour, Mulligan, Glass, Mandayam @2017 To be Submitted)

- Examine prosumer decision making under uncertainty
  - Homeowners are both consumers and producers of electricity, i.e., prosumers
- 10 wk study; 57 participants imagined they had solar panels, battery storage, and ability to sell surplus energy back to grid
- Each prosumer starts with 5 units stored energy; 0, 1 or 2 units of surplus energy generated every day
- Each day participants were told "today's price" and must decide whether to sell and, if so, how many units
- Price varied stochastically daily over a known range ($0.10 - $1.50/unit in 10 cent increments; Mean=$0.60)
- Price Distribution based on published wholesale energy prices
- Participants incented to maximize profit from surplus energy
- Data fit to decision models based upon EUT and CPT

Case Study 2: Prosumer Behavior – Sample Daily Email

Today is Thursday, December 1st, (Day 60 of 70).

Added 2 units yesterday. Total of **8** units stored.
You have earned **$82.90** so far.
Today's price is **$0.40** per Unit

Below are the probabilities that each possible price will occur **at least once** between today and Day 70:

- $0.10 - 28.5% chance
- $0.20 - 49.4% chance
- $0.30 - 64.6% chance
- $0.40 (today's price) - 75.5% chance
- $0.50 - 81.0% chance
- $0.60 - 72.2% chance
- . . .
- $1.30 - 28.5% chance
- $1.40 - 19.9% chance
- $1.50 - 10.5% chance

Would you like to sell any units today? Please reply "Yes" or "No" and, if "Yes", how many stored units you would like to sell at today's price of $0.40/unit.

Case Study 2: Prosumer Behavior- Gain and Loss Model

- Outcomes: $x = x_1 + x_2$

Gain (x_1) Loss (x_2)

$$x_1 = f.c_i + (F - f)\sum_{j=i+1}^{J} c_j.p_{j,d}$$

$$x_2 = -f\sum_{j=i+1}^{J}(c_j - c_i)\,p_{j,d} + (F - f)\sum_{j=1}^{i-1}(c_j - c_i)\,p_{j,d}\prod_{k=i+1}^{J}(1 - p_{k,d})$$

- $J = 15$, c_i: *Today's price*, F: *Stored units*, f: *Sold units*
- $p_{j,d} = 1 - (1 - mp_i)^d$ ← Probability of price showing up at least once
- d: *Remaining days*

Case Study 2: Prosumer Behavior - PT & EUT Models

- EUT

$$x = f\overbrace{\left(c_i - \sum_{j=i+1}^{J} c_j . p_{j,d} - \sum_{j=i+1}^{J} (c_j - c_i)\, p_{j,d} - \sum_{j=1}^{i-1} (c_j - c_i)\, p_{j,d} \prod_{k=i+1}^{J} (1 - p_{k,d})\right)}^{\tilde{c}}$$
$$+ F\left(\sum_{j=i+1}^{J} c_j . p_{j,d} + \sum_{j=1}^{i-1} (c_j - c_i)\, p_{j,d} \prod_{k=i+1}^{J} (1 - p_{k,d})\right)$$

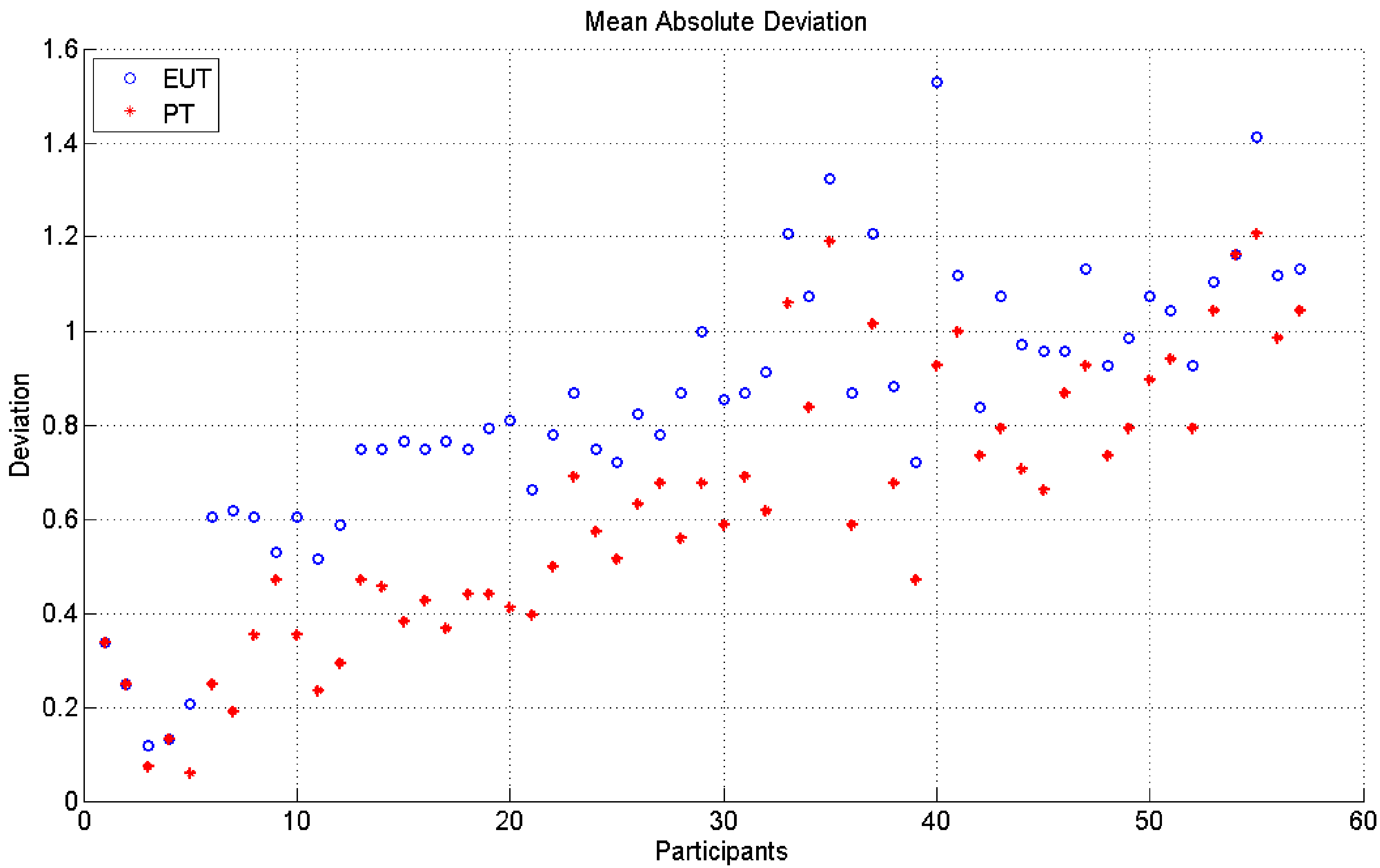
- $\begin{cases} if\ \tilde{c} > 0 \Rightarrow f^*_{EUT} = F \\ if\ \tilde{c} < 0 \Rightarrow f^*_{EUT} = 0 \end{cases}$ ⟹ EUT predicts sell all or nothing everyday

- PT

$$u(x) = \begin{cases} x^{\alpha} & x \geq 0 \\ -\lambda(-x)^{\beta} & x < 0 \end{cases}$$
$$w(p) = exp\left(-\left(-ln(p)\right)^{\gamma}\right)$$

- $f^*_{PT} = arg\{\max_{f} x\}$ ⟹ PT predicts resulting optimum

Case Study 2: Prosumer Behavior - PT predicts Prosumer behavior better than EUT



RUTGERS

WINLAB

Case Study 3: Framing Altruism in Emergencies

(Glass, Ingate@2017 Eastern Psychological Association Meeting)

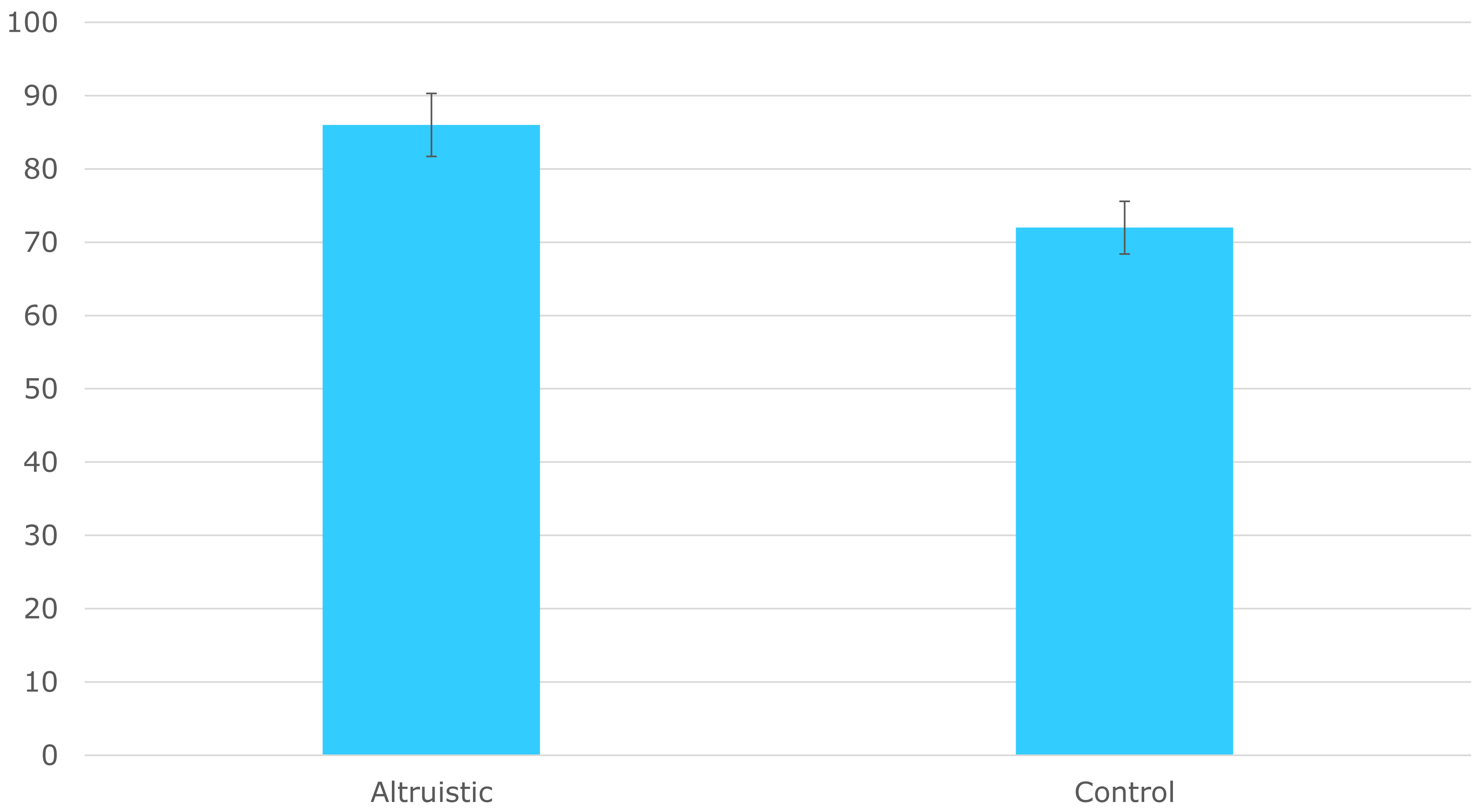
- During an emergency, cell phone use may exceed capacity of the network that may impede relief efforts
- To preserve network capacity, an alert is sent in the affected area asking users to refrain from cell phone use
- Experiments investigated whether wording ("framing") of the alert influenced compliance
  - Participants were Rutgers students and a national mTurk sample
- Participants received a mock alert on cell phone and were asked whether they would comply
- Participants who indicated they would comply were asked more specific questions about compliance

Case Study 3: Framing Alerts - Control versus Altruistic

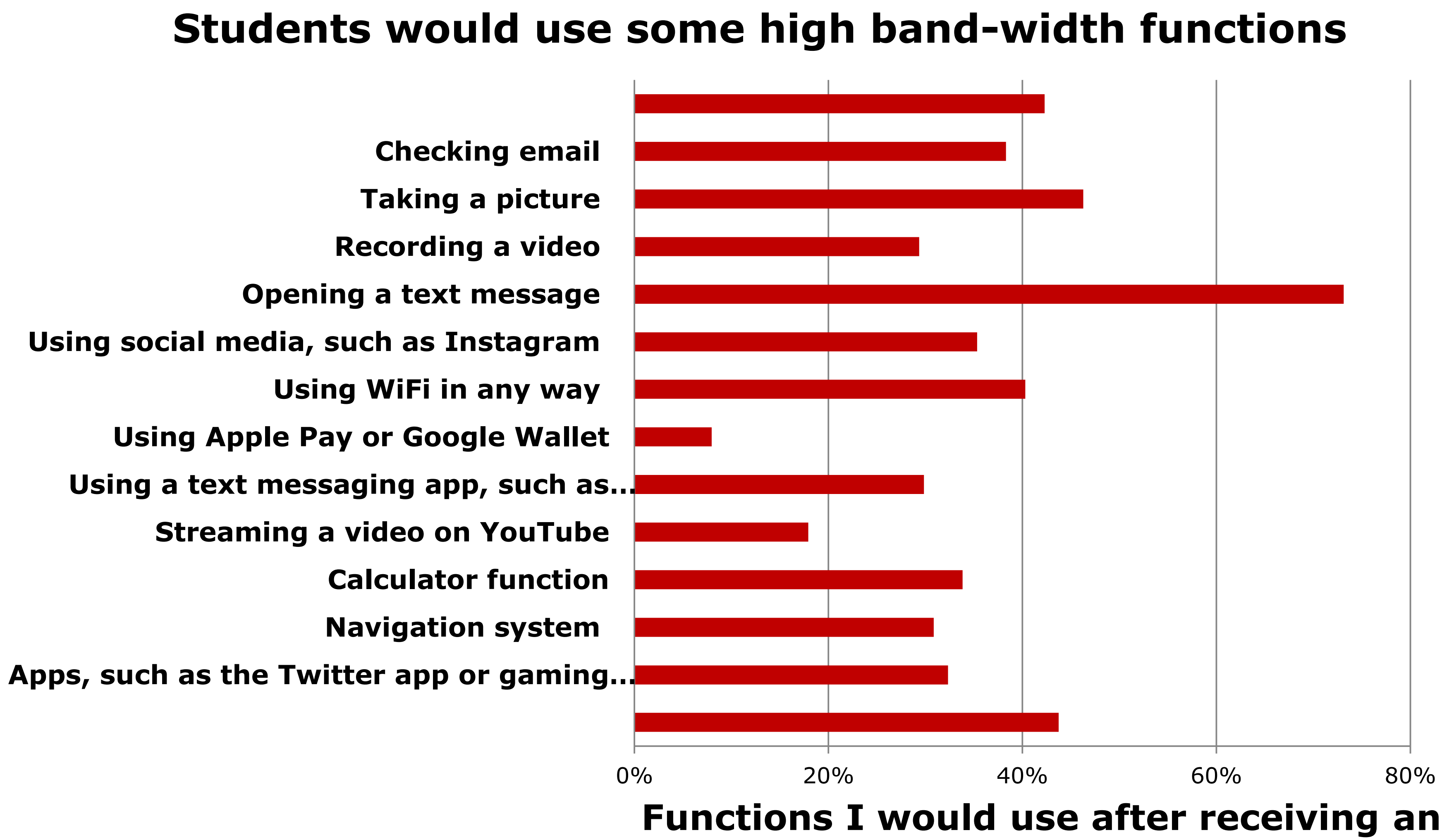
- **Control:** Please do not make any calls on your cell phone until further notice. Emergency services require all broadband bandwidth due to the current weather conditions. Thank you for your cooperation.

- **Altruistic**: Please do not make any calls on your cell phone until further notice. Due to the hurricane that has struck our community, emergency personnel are having difficulty retrieving stranded and injured survivors and require all broadband bandwidth to contact them rapidly. By refraining from all cell phone use, you are personally assisting the efficient retrieval and aid of these victims. Thank you for your kindness and cooperation.

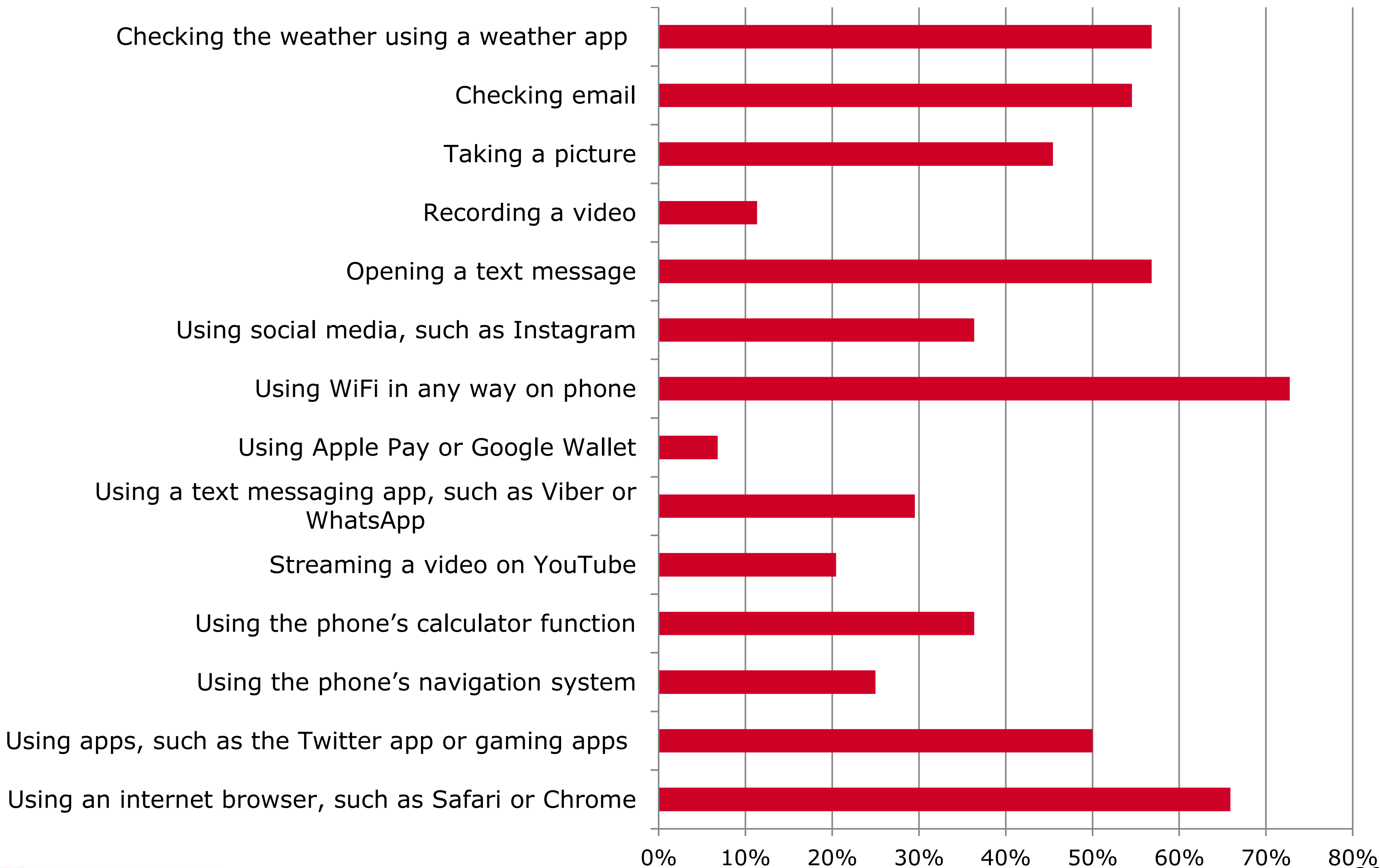
Case Study 3: Framing Altruism -Significantly more participants reported they would comply with the altruistic alert



Case Study 3: Framing Altruism - Follow-up questions indicate low levels of compliance



Case Study 3: Framing Altruism- mTurk respondents would also use multiple functions



Conclusion and Future Directions

- Resilience (distinct and different from reliability) needs to be engineered into CI design
- Expected Utility Theory (EUT) based designs work well for engineered systems
- Prospect Theory and Behavioral models needed for human interactions with engineered systems
- Framing in Emergencies: One cannot assume that an alert will produce sufficient compliance in an emergency
  - Incentive Mechanisms
  - More research is needed into how social media can be used to achieve the highest possible levels of compliance

Acknowledgements

- Rutgers University: Arnold Glass, Margaret Ingate, Tianming Li, Robert Mulligan, Mohsen Rajabpour
- Virginia Tech: Aidin Ferdowsi, AbdelRahman Eldosouky, Walid Saad, Anibal Sanjab