Privacy in the Smart Grid: Information, Control & Games*

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Joint work with

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Outline

1. Motivation
2. Information: A General Formalism
3. Control: Smart Meter Privacy
4. Games: Competitive Privacy

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- The smart grid cyber layer generates considerable electronic data:
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- This data can leak information that should be kept secure, or private.
- But, the utility of this data depend on its accessibility.
- How can we characterize this fundamental tradeoff?

Information: A General Formalism

[Sankar-Rajagopalan-Poor, T-IFS'13]

Data Source Model

- A sequence of *n* i.i.d. observations of a vector random variable $\mathbf{X} = (X_1\ X_2\ \ldots\ X_K)$ with a joint distribution:

$$\boxed{p_{\mathbf{X}}(\mathbf{x}) = p_{X_1 X_2 \ldots X_K}(x_1, x_2, \ldots, x_K)}$$

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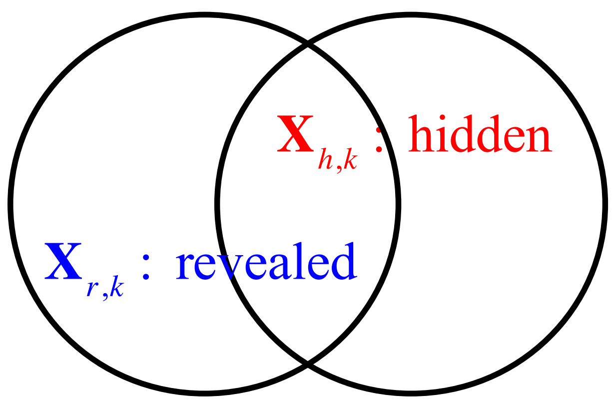
- Variables can be divided into public (revealed) and private (hidden) variables, typically not disjoint:



$$k^{th}\ \text{entry} : \mathbf{X}_k = \left(\mathbf{X}_{r,k}, \mathbf{X}_{h,k}\right)$$

Privacy-Utility Tradeoff

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  - Measure utility by distortion of the public variables as revealed by the data source; and
  - Measure privacy by equivocation of the private variables in information revealed by the source. (Can also use other leakage measures.)
- Then the distortion-equivocation region describes the tradeoff.

Distortion-Equivocation Model

- Encoder maps the original data source to a quantized data source (QDS):

$$\boxed{\text{Encoder}: \mathbf{X}^n \to \mathcal{W} = \left\{QDS_1, QDS_2, \ldots, QDS_M\right\}}$$

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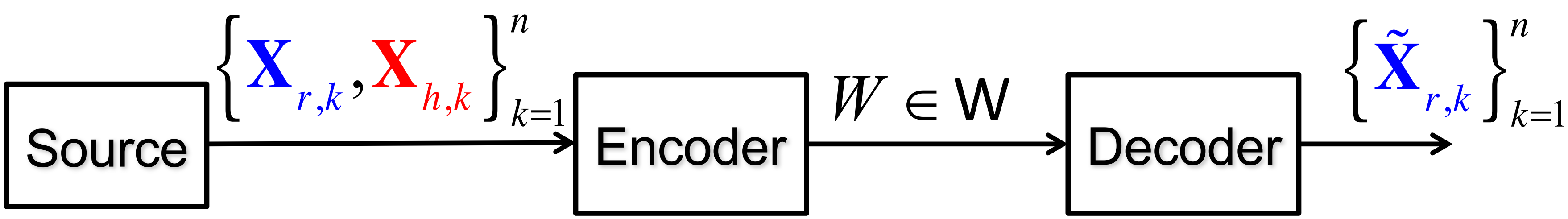

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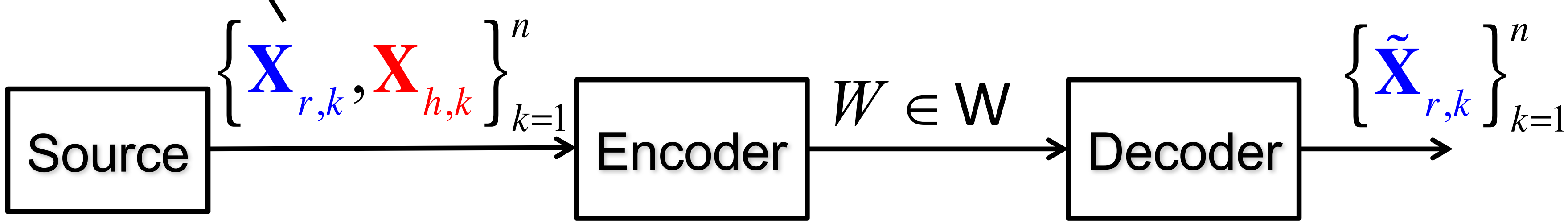
Distortion

$$\Delta_d \equiv \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^{n} \rho\left(\mathbf{X}_{r,i}, \tilde{\mathbf{X}}_{r,i} \right) \right] \leq D + \varepsilon$$



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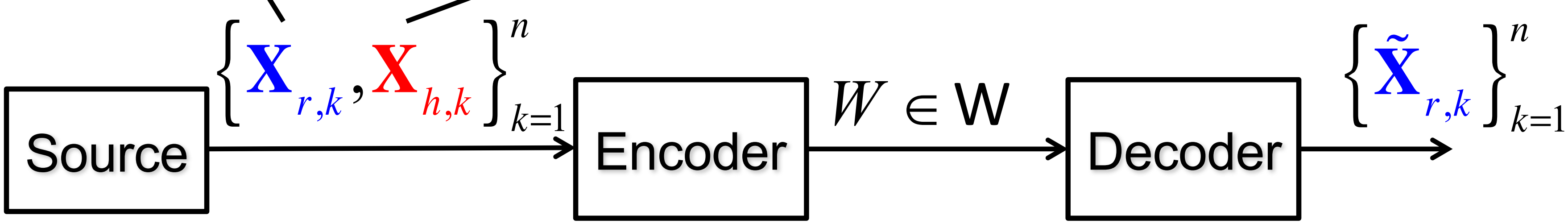
$$\Delta_p \equiv \frac{1}{n} H\left(\mathbf{X}_h^n \,|\, W\right) > E - \varepsilon$$



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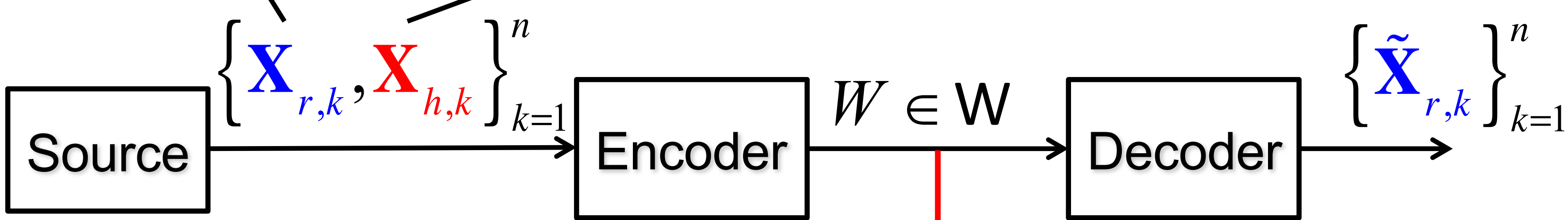
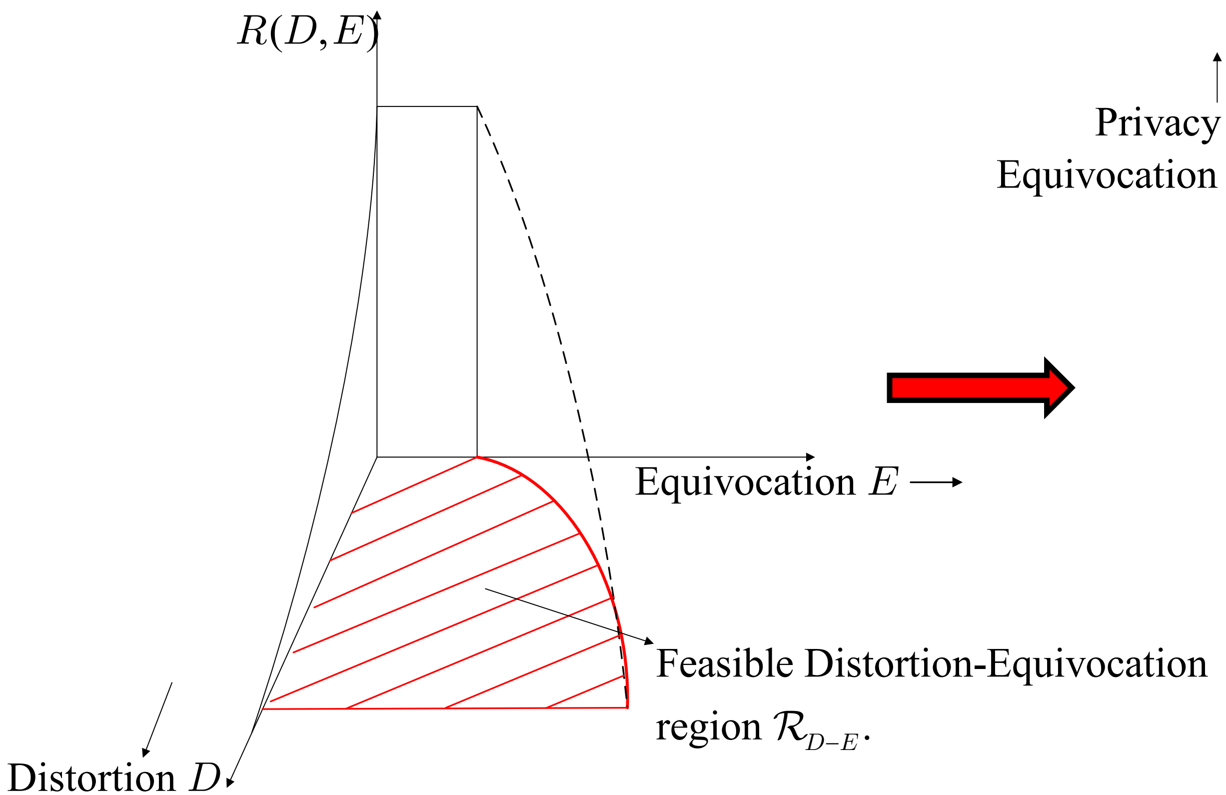
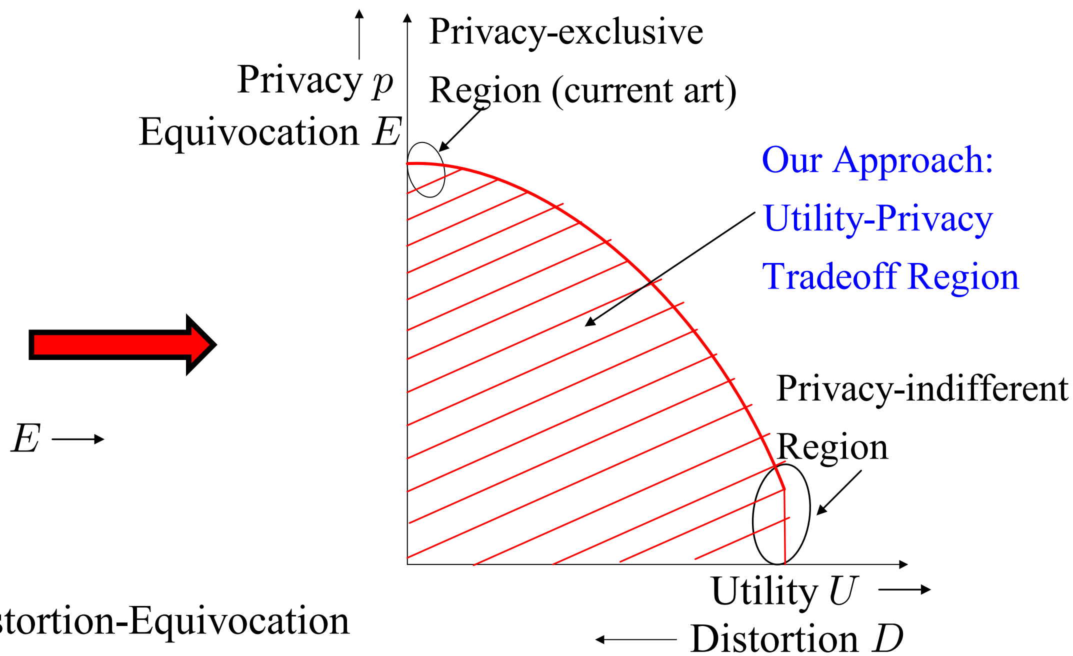


Add a <u>rate constraint</u> → $M \le 2^{n(R+\varepsilon)}$

Utility-Privacy/RDE Regions



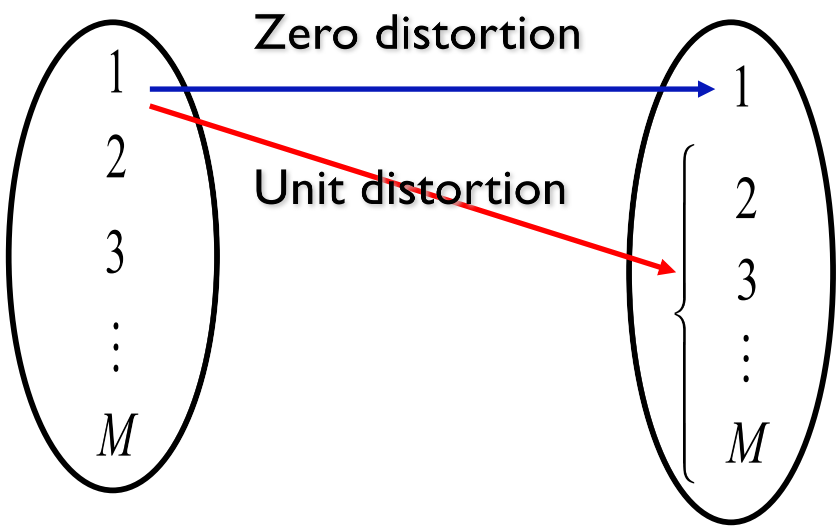
(a): Rate-Distortion-Equivocation Region



(b): Utility-Privacy Tradeoff Region

Example: Categorical Data

- Categorical data: finite alphabet data
  - e.g.: SSN, zipcode, etc.



Original variable X   Distorted variable $\tilde{X}$

Hamming Distortion D :

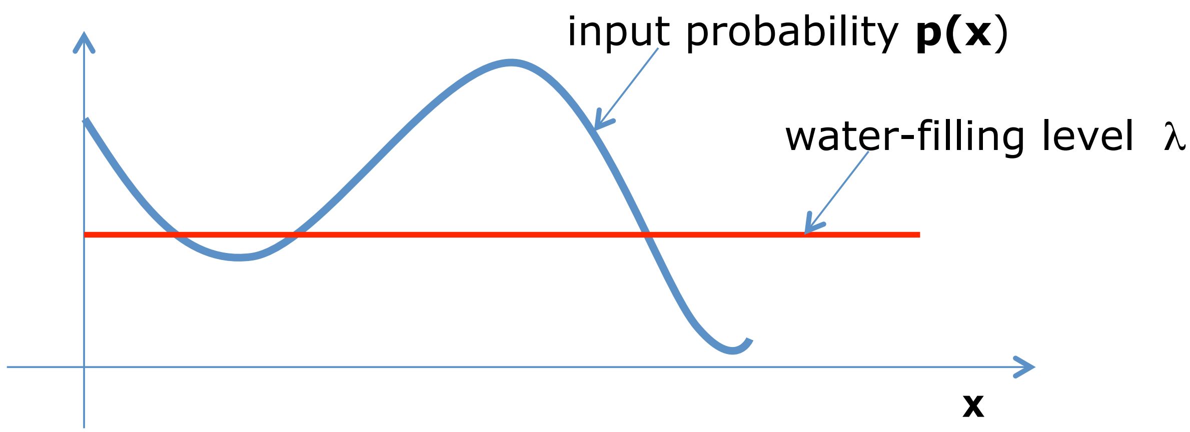
$$D = \Pr(X \neq \tilde{X})$$

Equivocation E :

$$E = H(X \mid \tilde{X})$$

Example: Categorical Data

- Optimal input to output mapping: reverse 'water-filling'
  - Only x with p(x) > λ revealed (λ: water-level).



- Eliminates samples with low probabilities (relative to level λ)
  - Equivalent to outlier aggregation/suppression
  - Such samples reveal the most information
- As D ↑, λ ↑,revealing fewer samples

Summary (General Formalism)

- A data source is divided into private and public variables
  - Leads to an equivocation-distortion characterization
  - Adding rate: a rate-distortion problem with an equivocation constraint

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- A data source is divided into private and public variables
  - Leads to an equivocation-distortion characterization
  - Adding rate: a rate-distortion problem with an equivocation constraint
- We can also consider
  - multiple sources (side information)
  - other measures of privacy and/or utility

Control:

Smart-Meter Privacy

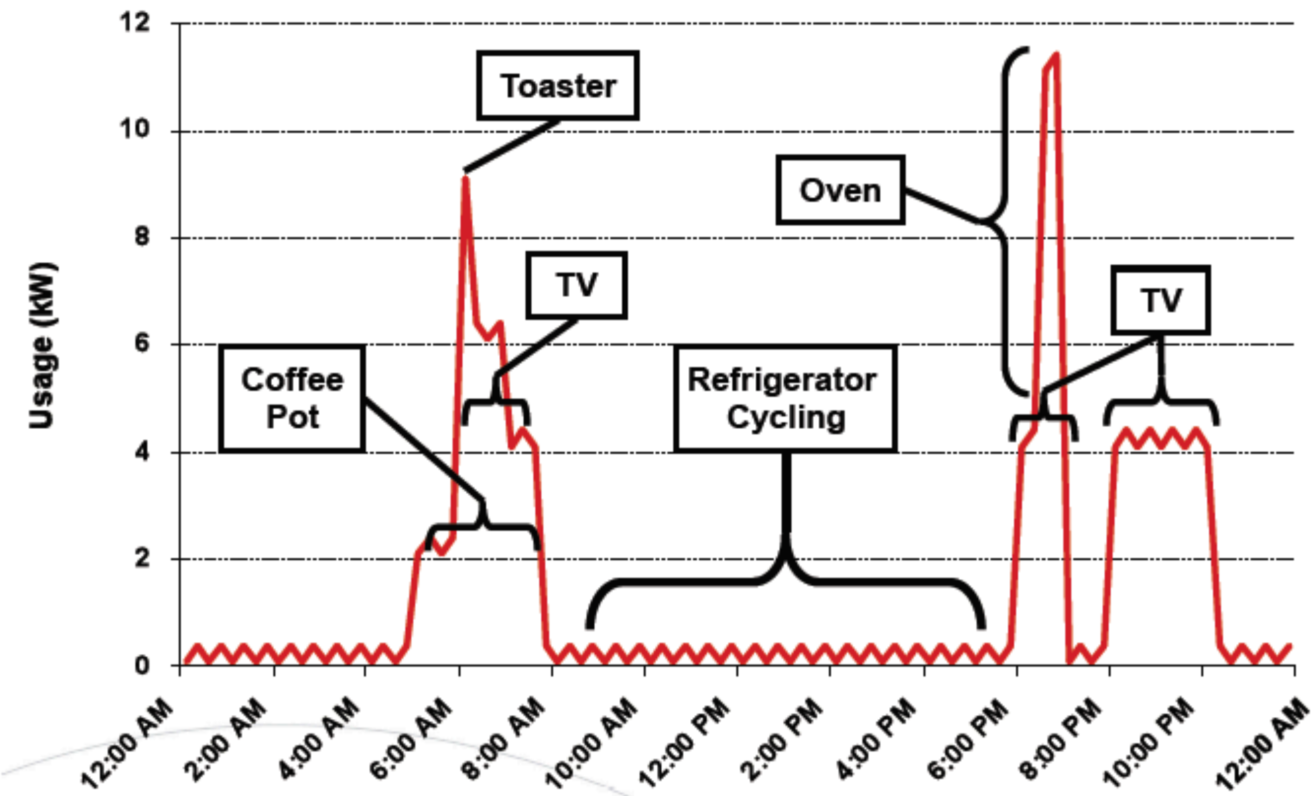
[Sankar-Rajagopolan-Mohajer-Poor, T-SG'13]

[Tan-Gündüz-Poor, JSAC: SG Series'13]

[Yang-Chen-Zhang-Poor, T-SG'15]

Smart Meter Utility & Privacy

- Smart meter data is useful for price-aware usage, load balancing.



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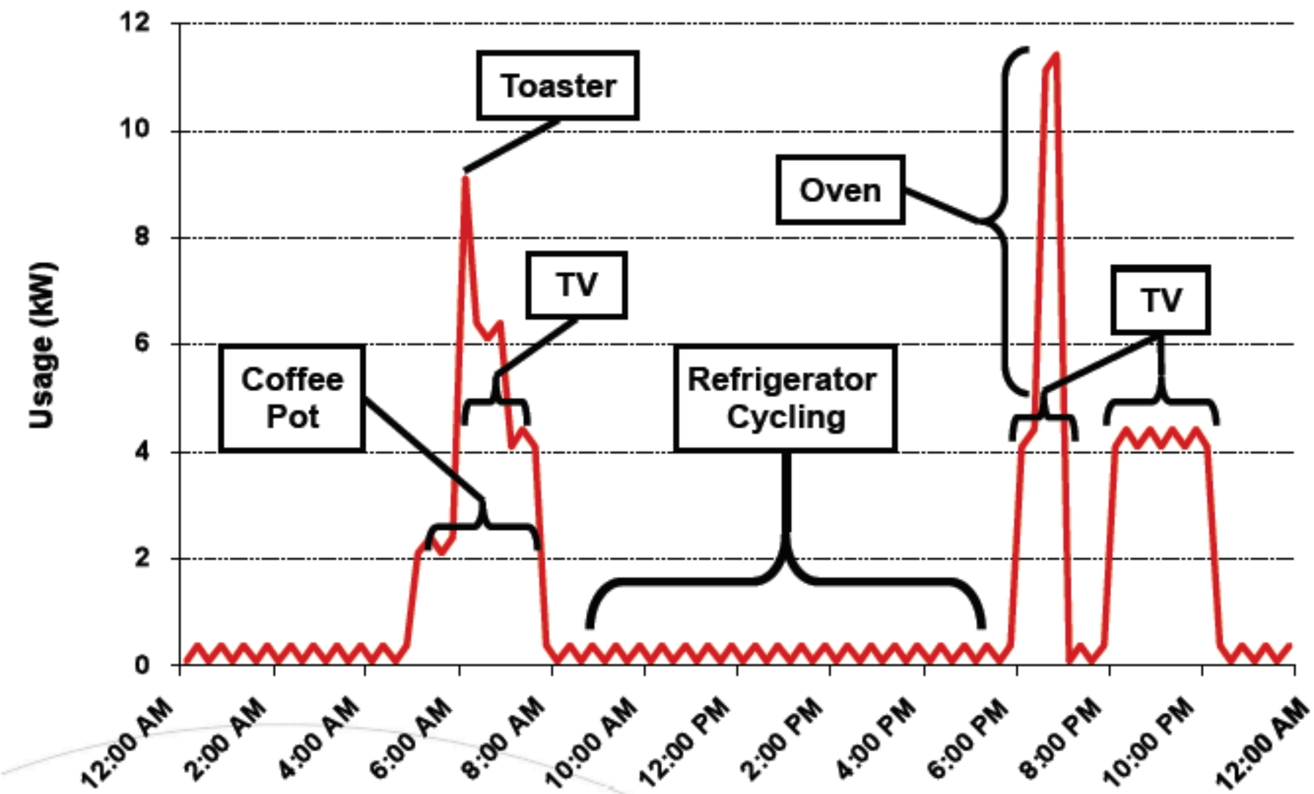
- But, it leaks information about in-home activity.



A Source-Coding Approach

[Sankar-Rajagopolan-Mohajer-Poor, T-SG'13]

<u>Model</u>:

- hidden Gauss-Markov
- hidden state is in {continuous, intermittent}
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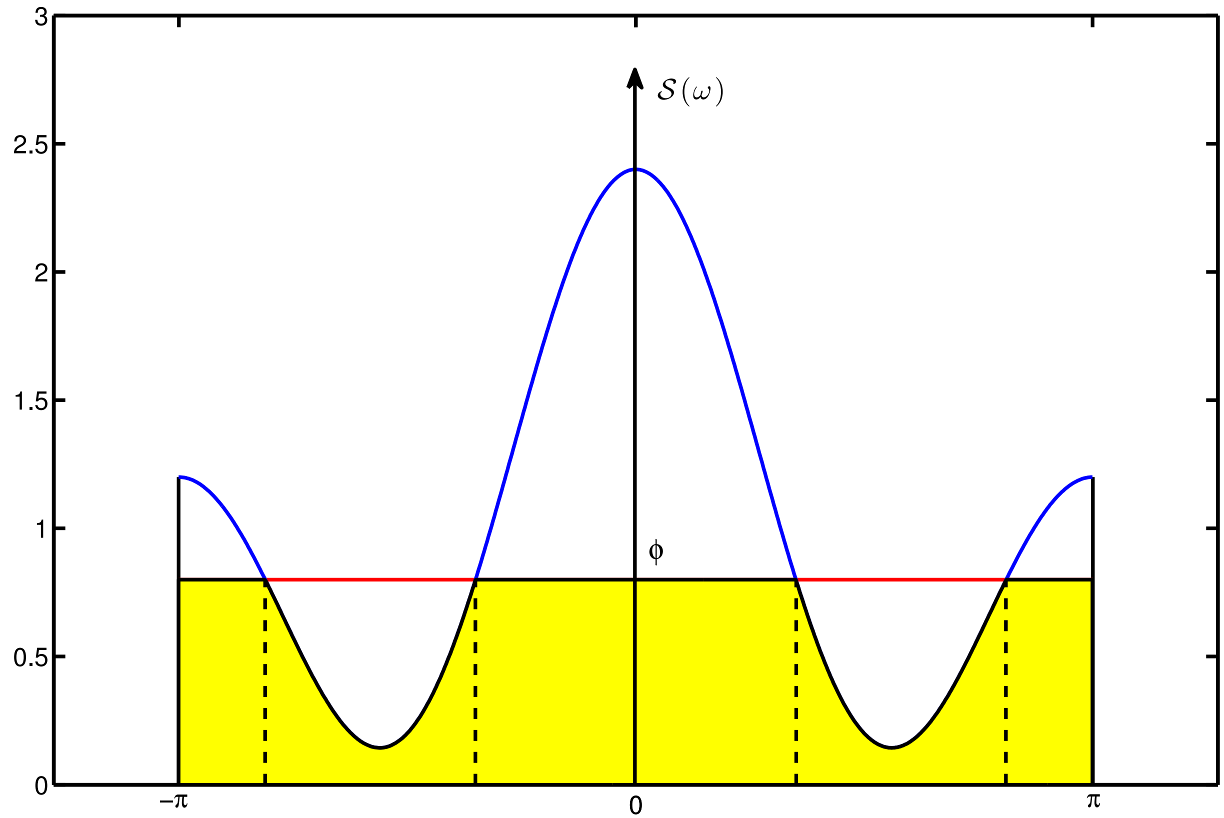
Solution:

a type of "reverse water-filling"
(i.e., rate-minimizing source coding for Gaussian sources)

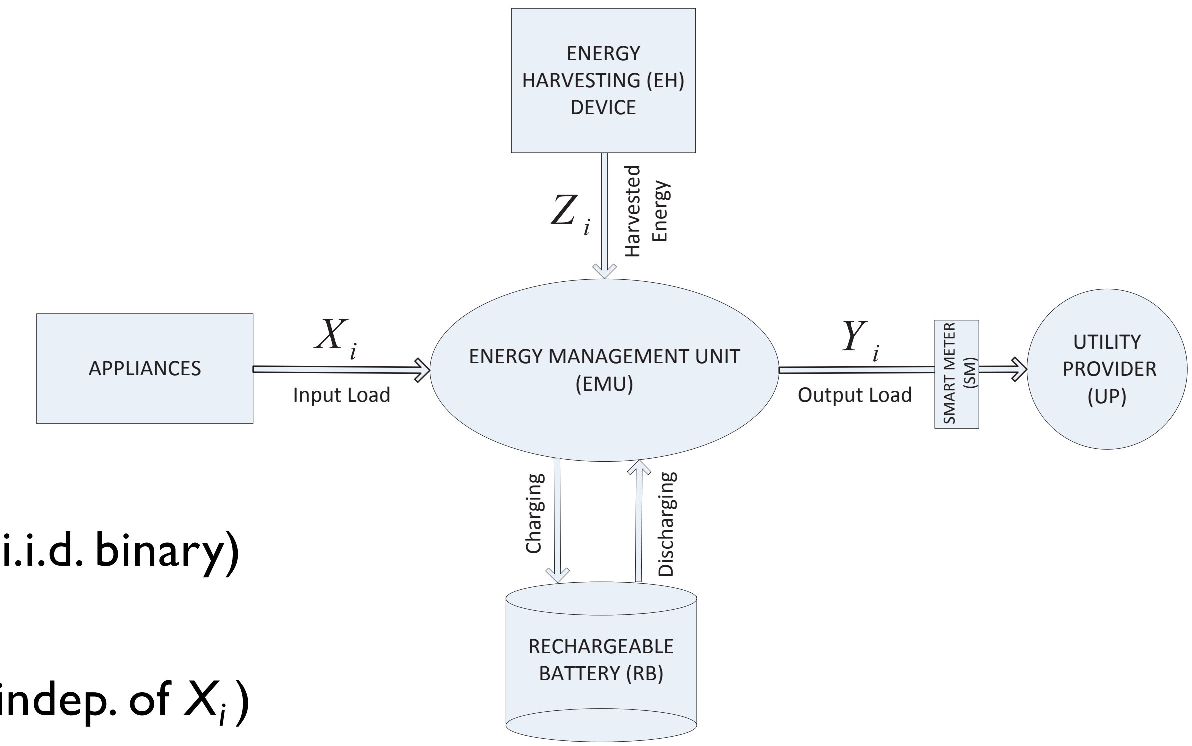
Reverse Water-Filling



A Control Approach

[Tan-Gündüz-Poor, JSAC: SG Series'13]

- Consider situations with energy harvesting (e.g., solar or wind) and rechargeable storage devices (e.g., electric vehicle):



At discrete time i :

- X_i : energy demand of appliances (i.i.d. binary)
- Y_i : energy taken from UP
- Z_i : harvested energy (i.i.d. binary, indep. of X_i)
- B_i : battery state (≤ 1)
- the meter reads and reports Y_i
- (stochastic) control: $(X_i, Z_i, B_{i-1}) \longrightarrow (Y_i, B_i)$ with $X_i \leq Z_i + (B_i - B_{i-1}) + Y_i$

Energy Management Policies

<u>Tradeoff</u>:

wasted energy rate: $P_W^n = \frac{1}{n}\sum_{i=1}^{n}(Z_i + Y_i - X_i)$

versus

information leakage rate: $I^n = \frac{1}{n} I(X^n; Y^n)$

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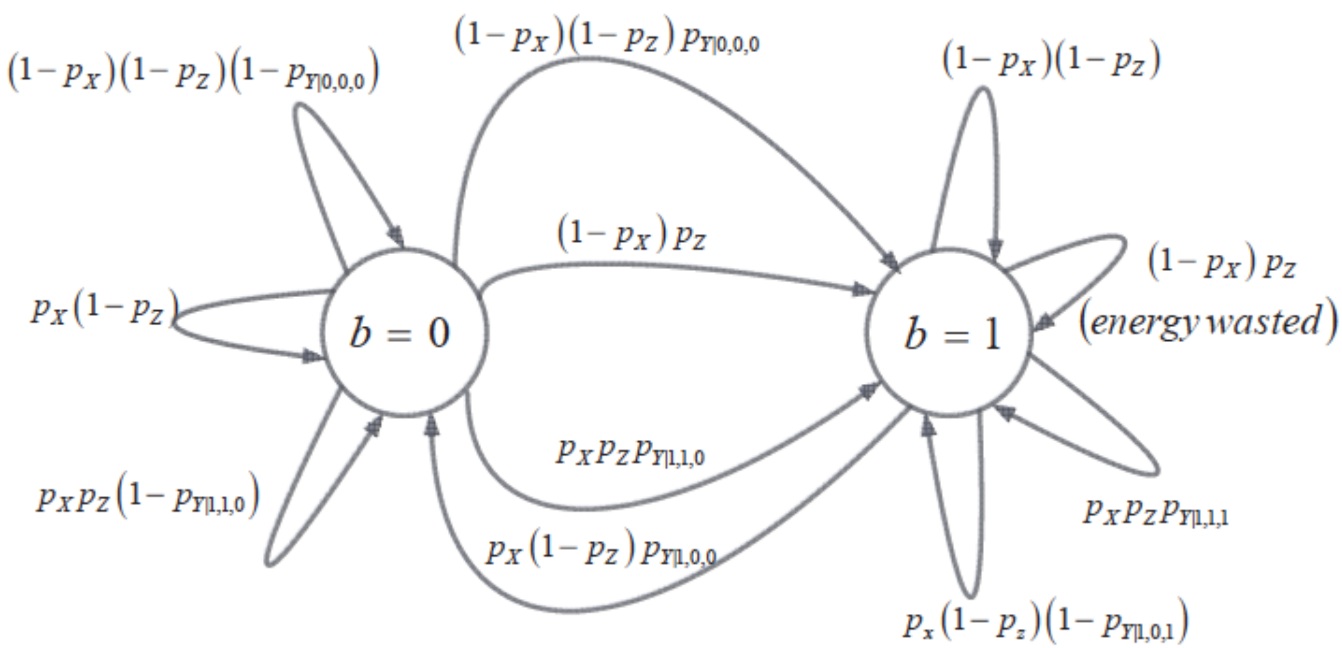
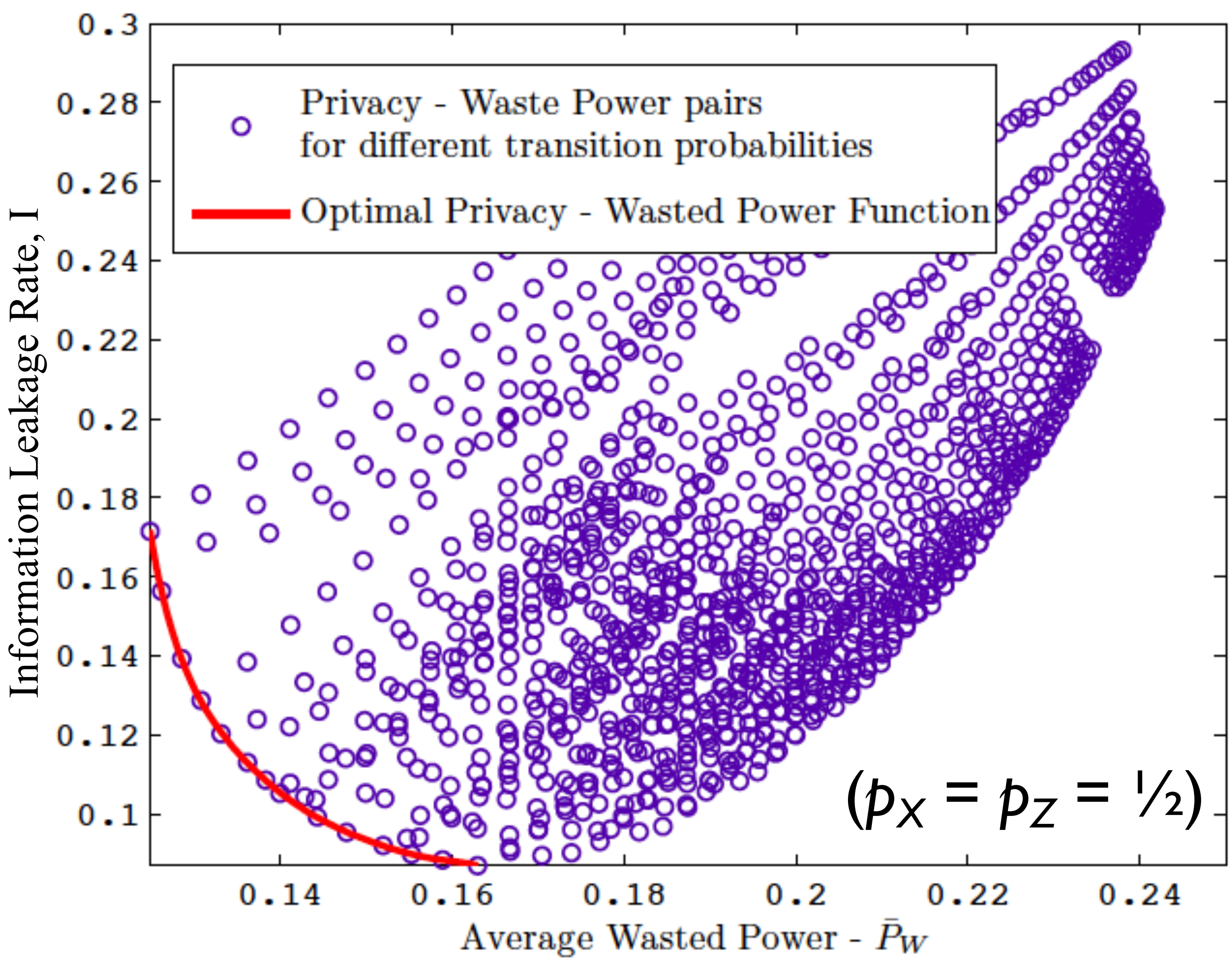
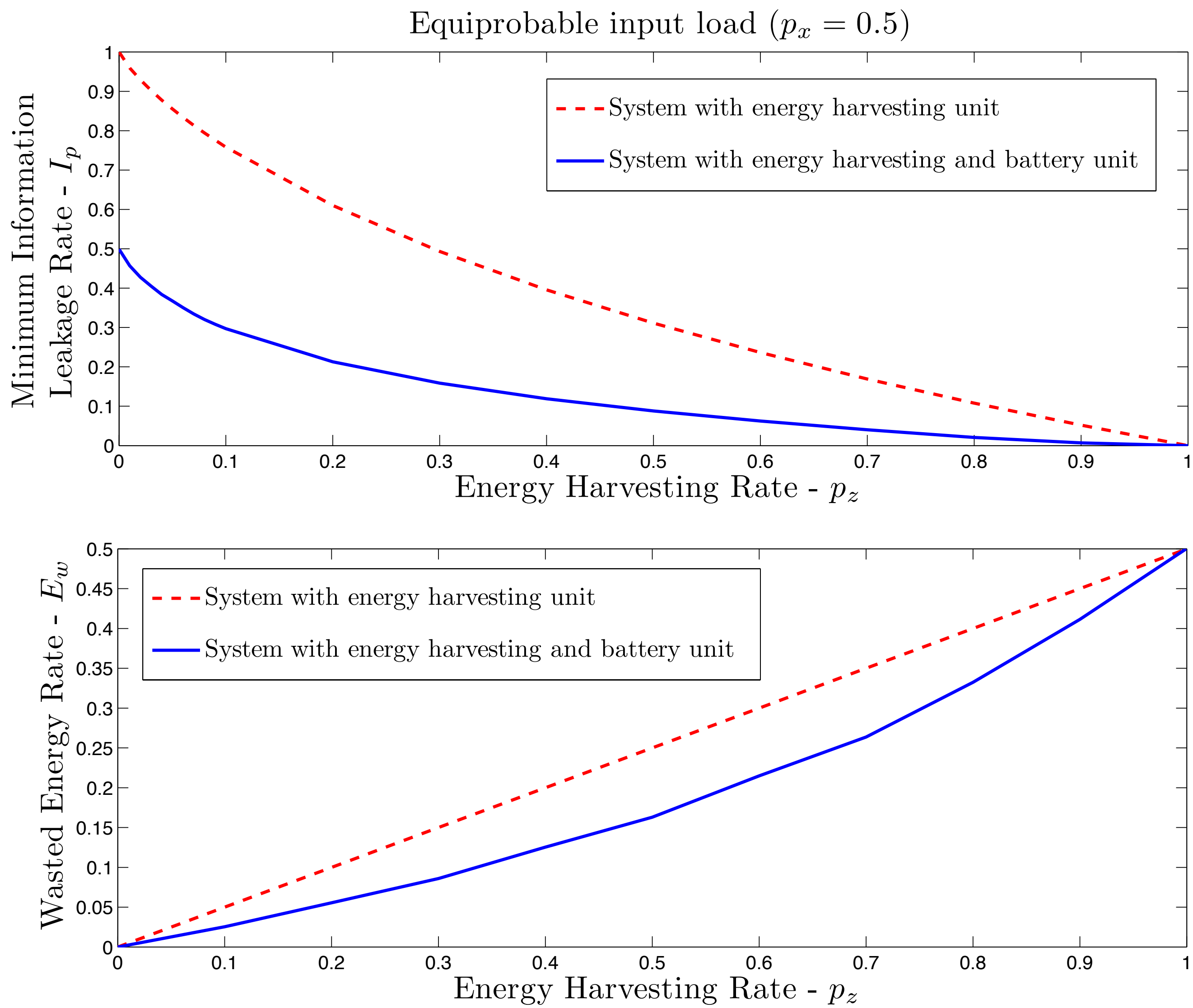


The Privacy-Utility Tradeoff

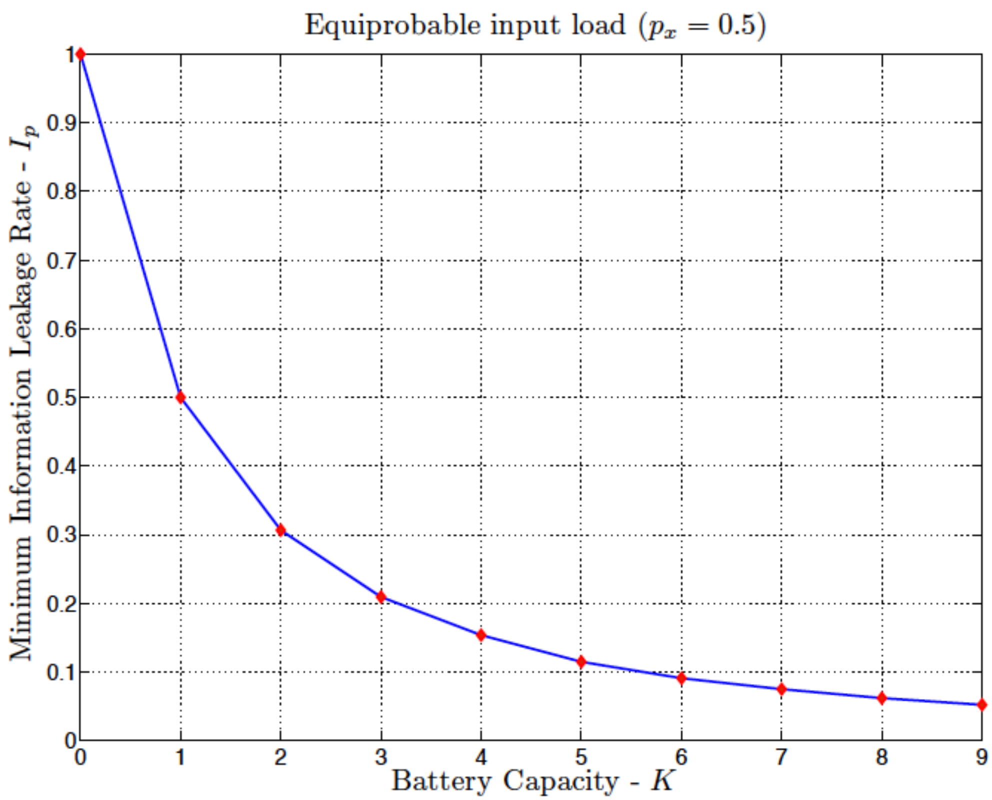
- battery introduces memory: closed form expressions are elusive
- numerically compute mutual information



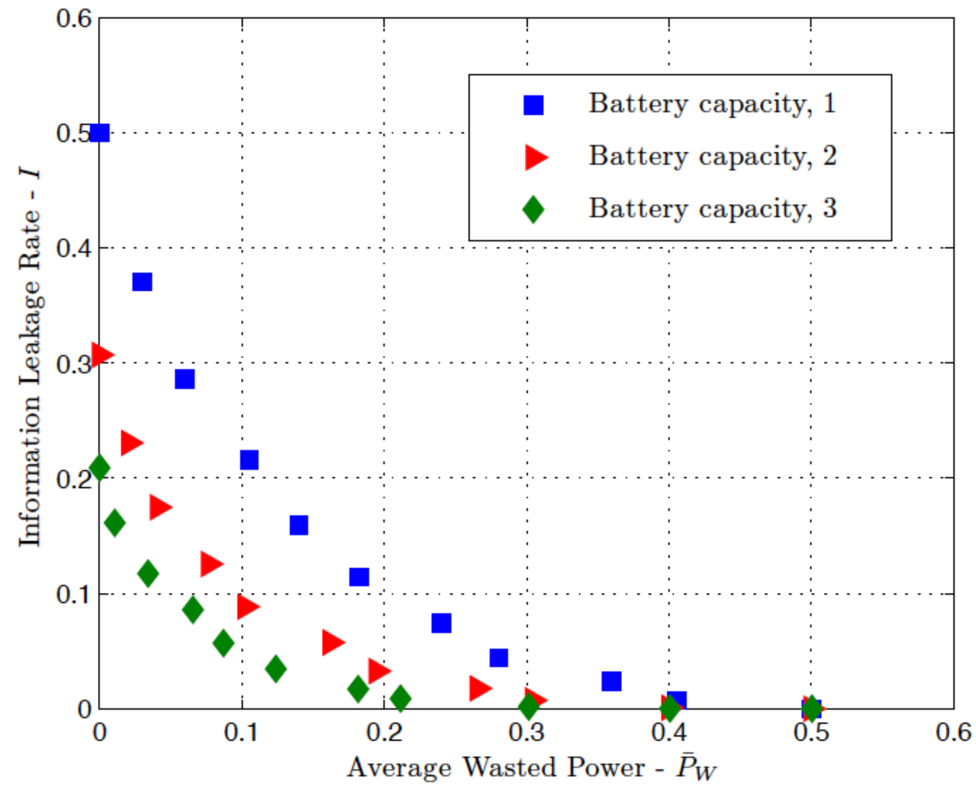
With/ Without a Battery Vs. EH Rate



With No Energy Harvesting



Privacy vs. battery capacity



Tradeoff vs. battery capacity
(allow wasted grid energy)

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- Two approaches to smart meter privacy:
  - source coding at the meter (reverse water filling)
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- Two approaches to smart meter privacy:
  - source coding at the meter (reverse water filling)
  - control with storage and local supply
- We can also consider [Yang-Chen-Zhang-Poor, T-SG'15]:
  - adaptive control
  - jointly consider privacy and cost (exploit price variations)

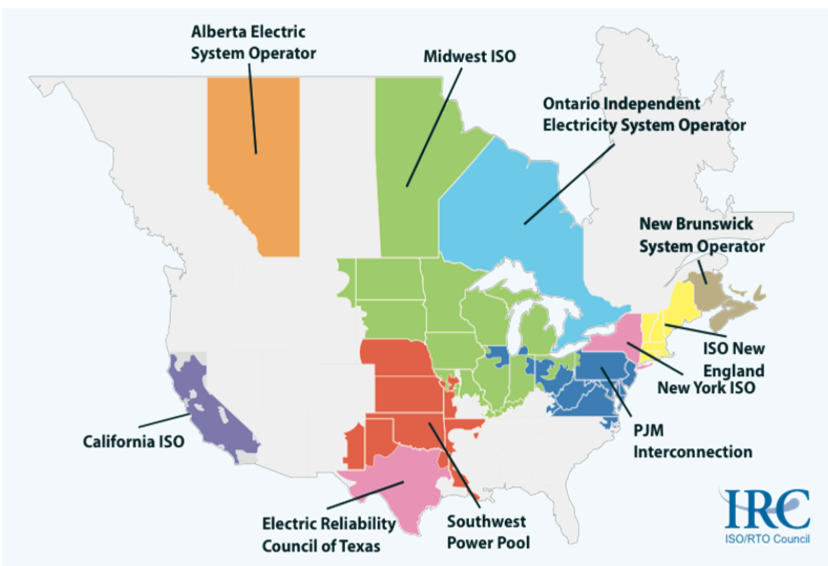
Games:

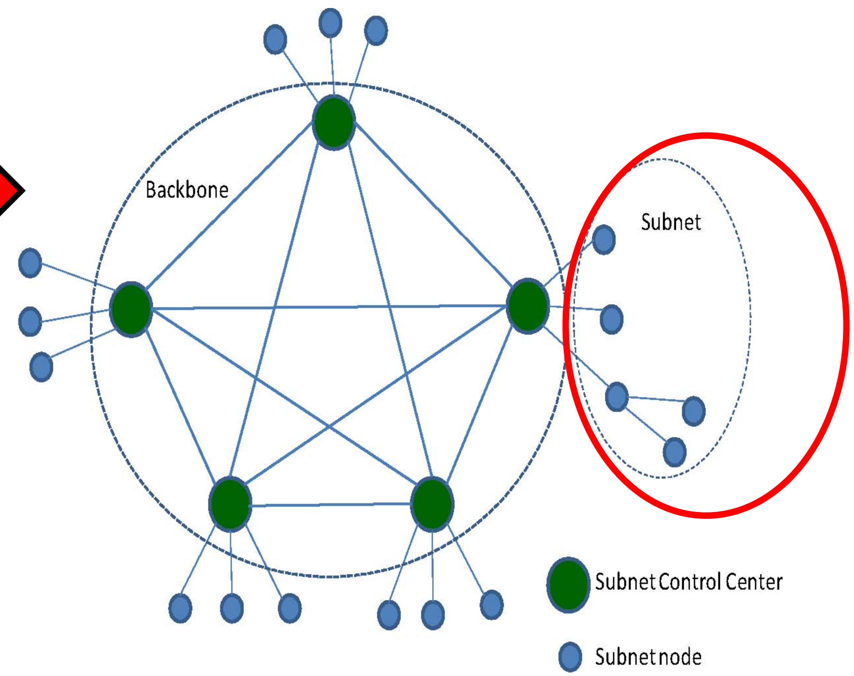
Competitive Privacy

[Belmega-Sankar-Poor, JSTSP'15]

Motivating Example: Multiple RTOs

- N.A. Grid: interconnected regional transmission organizations (RTOs)





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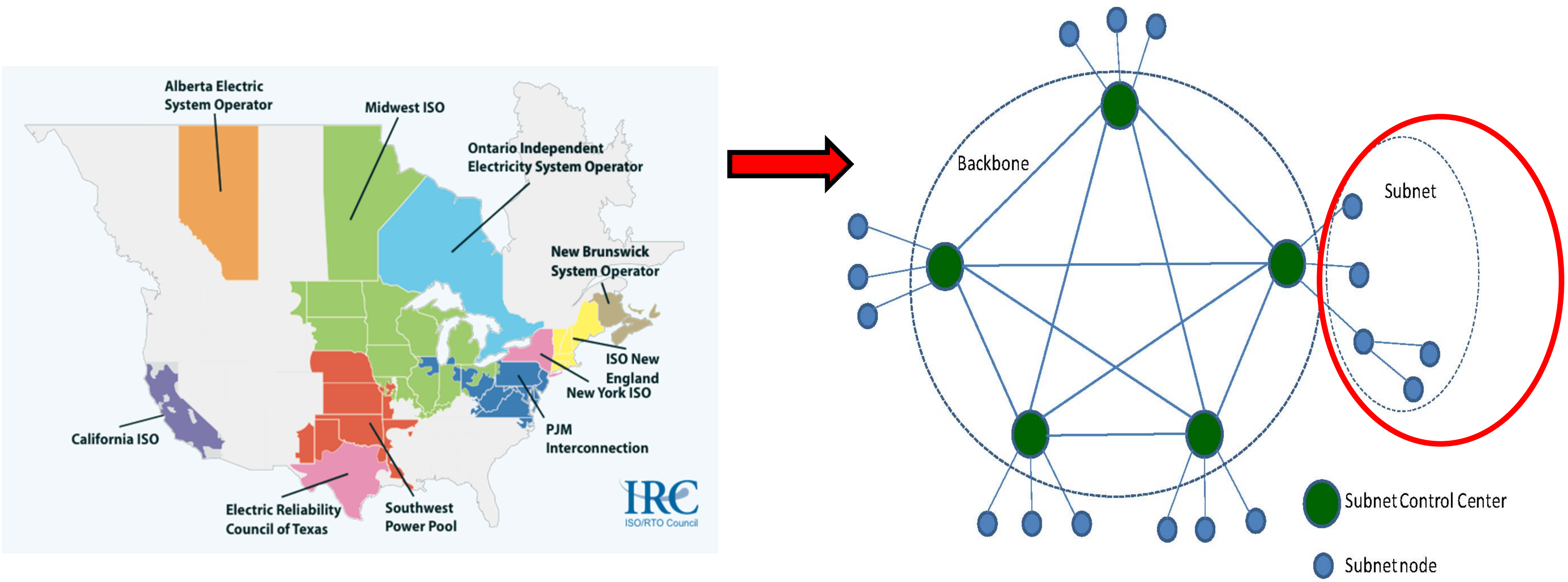

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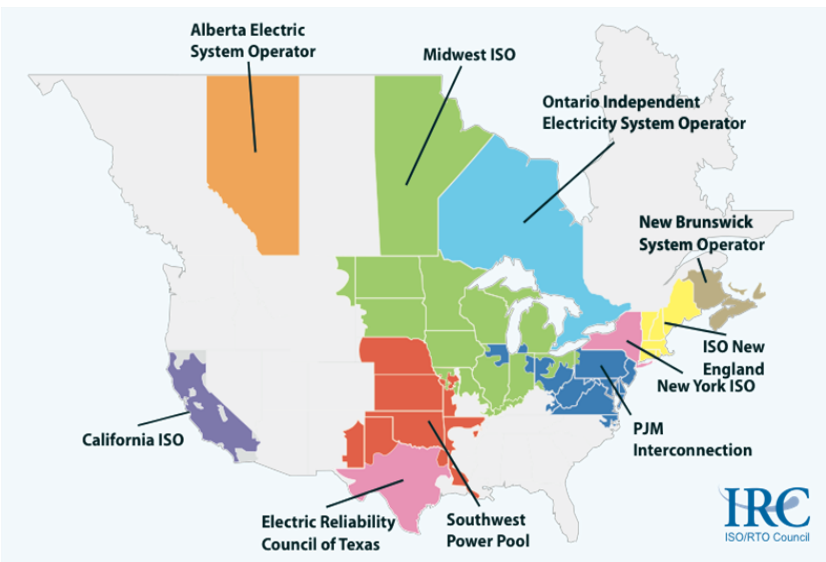

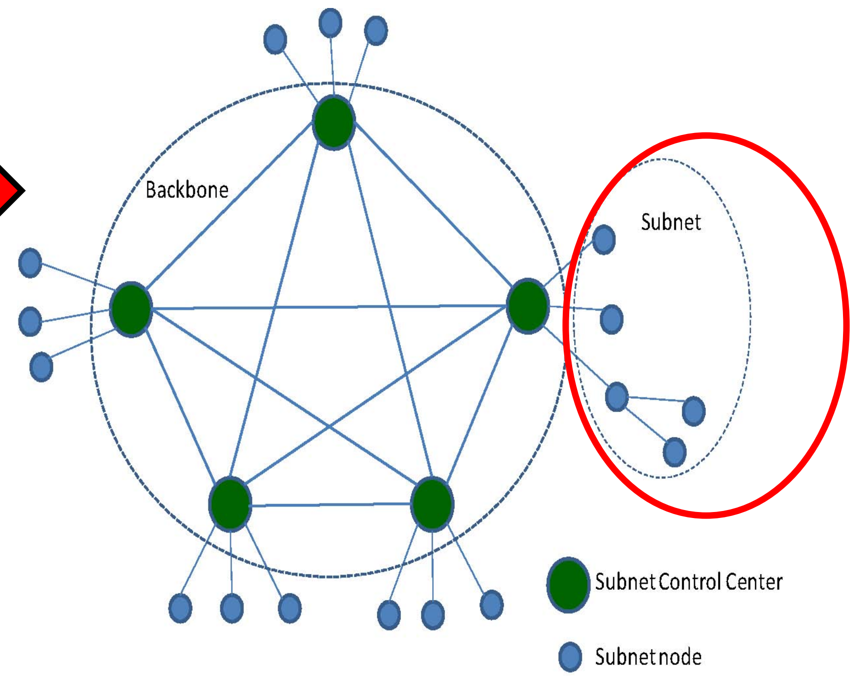

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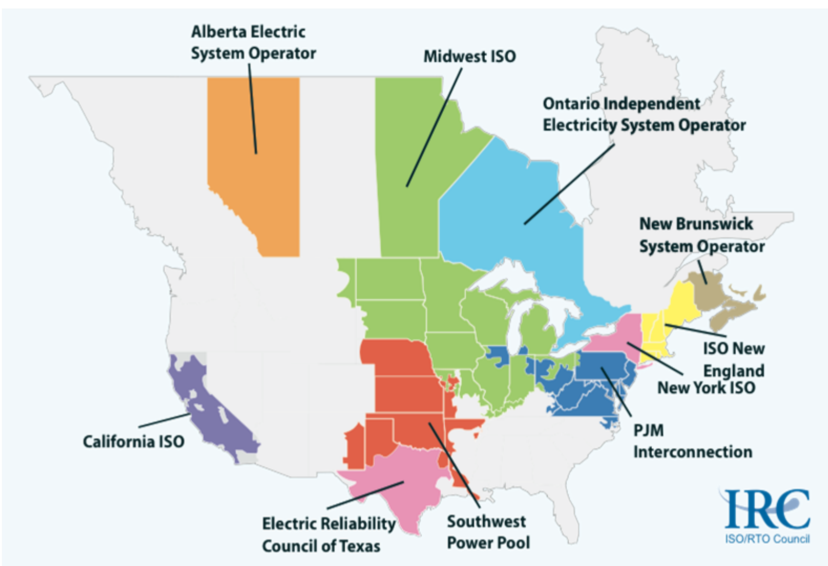
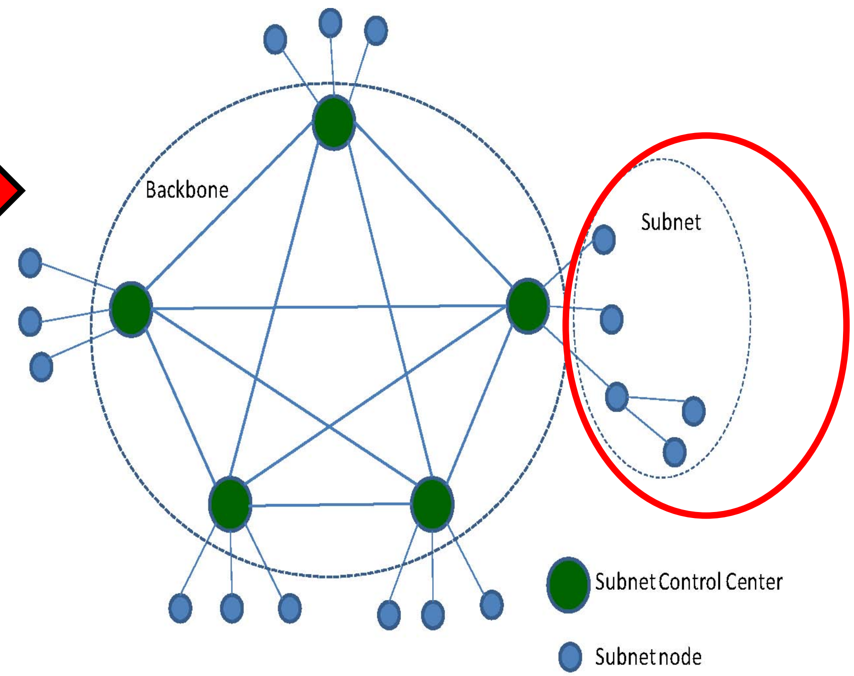




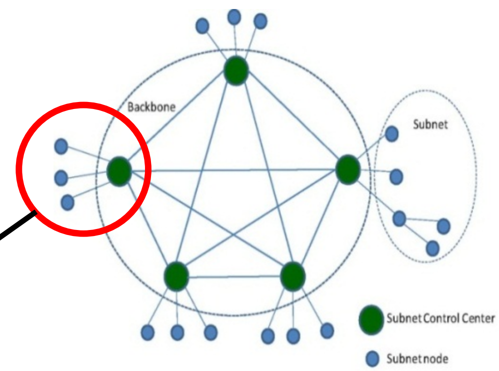
- Leads to a problem of competitive privacy

Competitive Privacy Model

- Noisy measurements at RTO *k*:

$$\boxed{Y_k = \sum_{m=1}^{M} H_{k,m} X_m + Z_k,\ k = 1,2,\ldots,M}$$

m[th] system state



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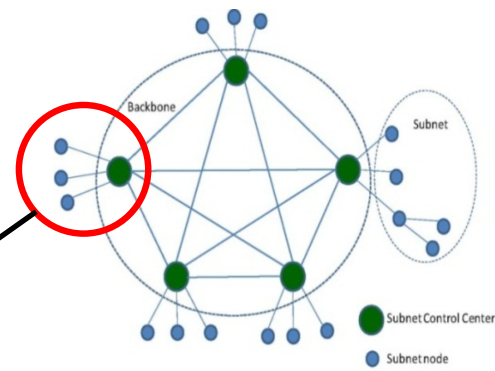

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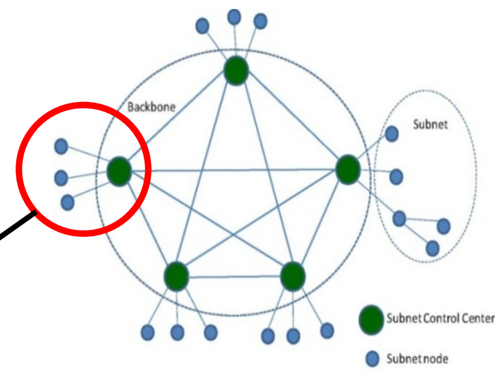

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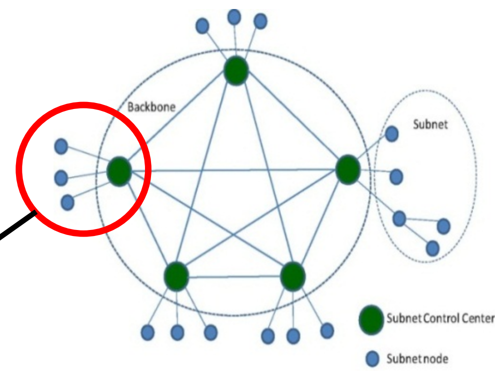

- Cooperation leads to inevitable leakage of state information.
- Utility for RTO *k*: mean-square error for its own state X_k
- Privacy for RTO *k*: leakage of information about X_k to other RTOs

Two-Agent Case

n i.i.d. observations at each RTO:

$$\boxed{\begin{aligned} Y_{1,i} &= X_{1,i} + \alpha X_{2,i} + Z_{1,i},\ i = 1,\ldots,n \\ Y_{2,i} &= \beta X_{1,i} + X_{2,i} + Z_{2,i},\ i = 1,\ldots,n \end{aligned}}$$

Stochastic model:

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$$\boxed{\begin{aligned} D_j &= \frac{1}{n}\sum_{i=1}^{n} E\left[\left(X_{j,i} - \hat{X}_{j,i}\right)^2\right] \\ L_j &= \frac{1}{n} I\left(X_j^n; J_j, Y_{3-j}^n\right) \end{aligned}}$$

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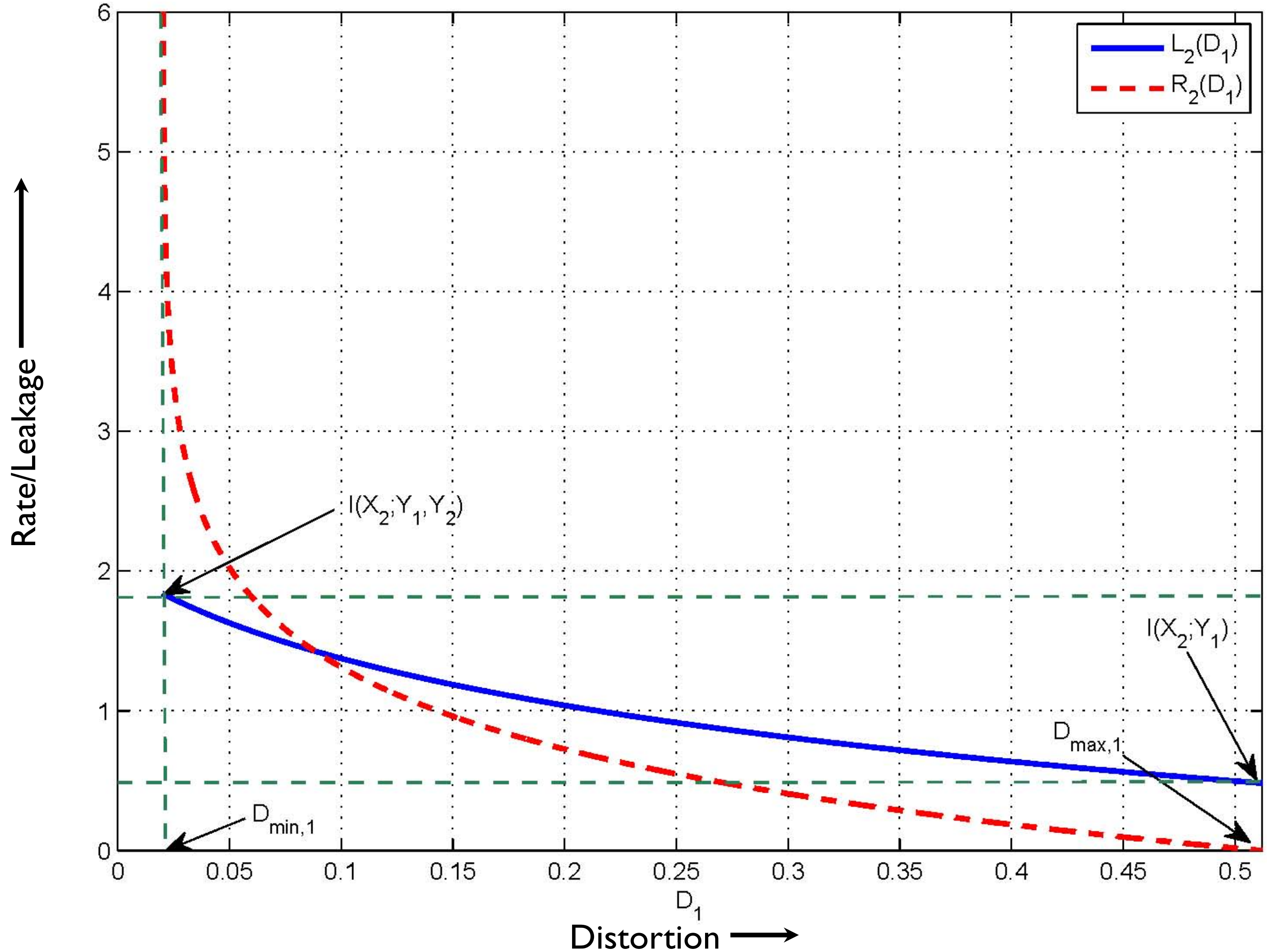
We can study this issue via game theory [Belmega-Sankar-Poor].

Rate and Privacy Leakage (Illustration)

$$\alpha = 1,\ \beta = 8,\ \sigma_1^2 = 0.05,\ \sigma_2^2 = 1$$



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Any behavior can then be incentivized within the limits of the model.

A Common-Goal Game

A common payoff:

$$u_{sys}(a_1, a_2) = -L(a_1) - L(a_2) + \frac{q}{2}\log\left(\frac{\bar{D}_1 + \bar{D}_2}{a_1 + a_2}\right)$$

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Nontrivial equilibria exist; the nature of these depends on the value of q.

A Multi-Stage Game

T-stage game, with a discounted payoff for agent *j*:

$$\sum_{t=1}^{T} \rho^{t-1} u_j(a_j^{(t)}, a_{3-j}^{(t)})$$

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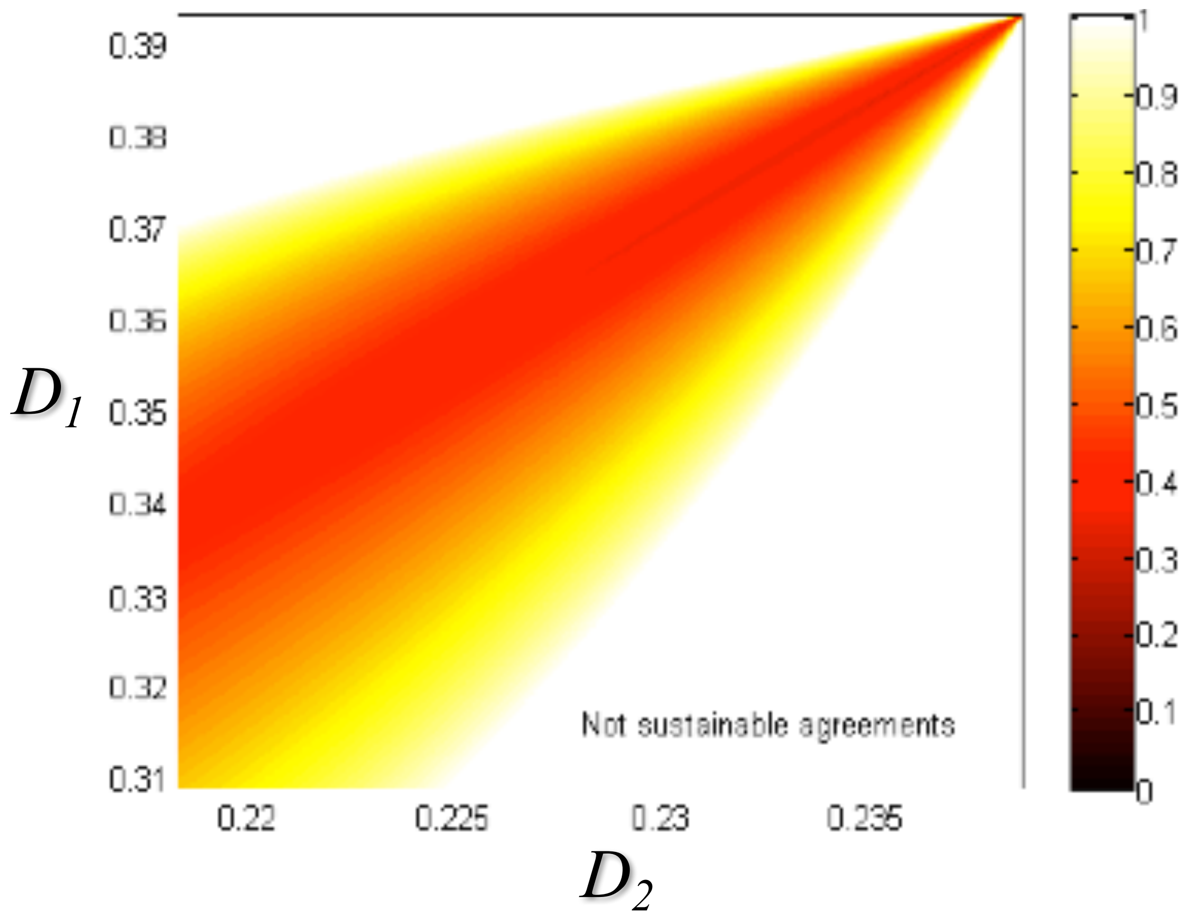
But, with $T = \infty$, any (D_1^*, D_2^*) satisfying the condition below is also a subgame perfect equilibrium for large enough $\rho < 1$:

$$u_j(D_j^*, D_{3-j}^*) > u_j(\bar{D}_j, \bar{D}_{3-j}); j = 1,2$$

Minimal Discount Factor for Sustaining Non-trivial Equilibria

$$\alpha = 0.9, \beta = 0.5, \sigma_1^2 = \sigma_2^2 = 0.1, w_j' = 5w_j$$



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- An additional dimension to privacy vs. utility tradeoff is added when there are multiple competing agents.
- Wyner-Ziv coding gives optimal information exchange.
- Game theory can help in modeling and understanding this problem:
  - one-shot games: prisoner's dilemma/pricing
  - multi-stage games: finite vs. infinite time window
  - common-goal games: enables cooperation

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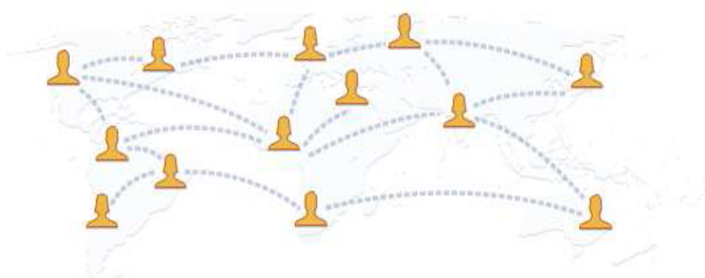
- Competitive Privacy: game theoretic approach
- Information-, control- and game-theoretic ideas allow fundamental examination of privacy issues in smart grid.

Basic P-U Tradeoff: Other Potential Applications

Biometric Systems: tradeoff between security & privacy



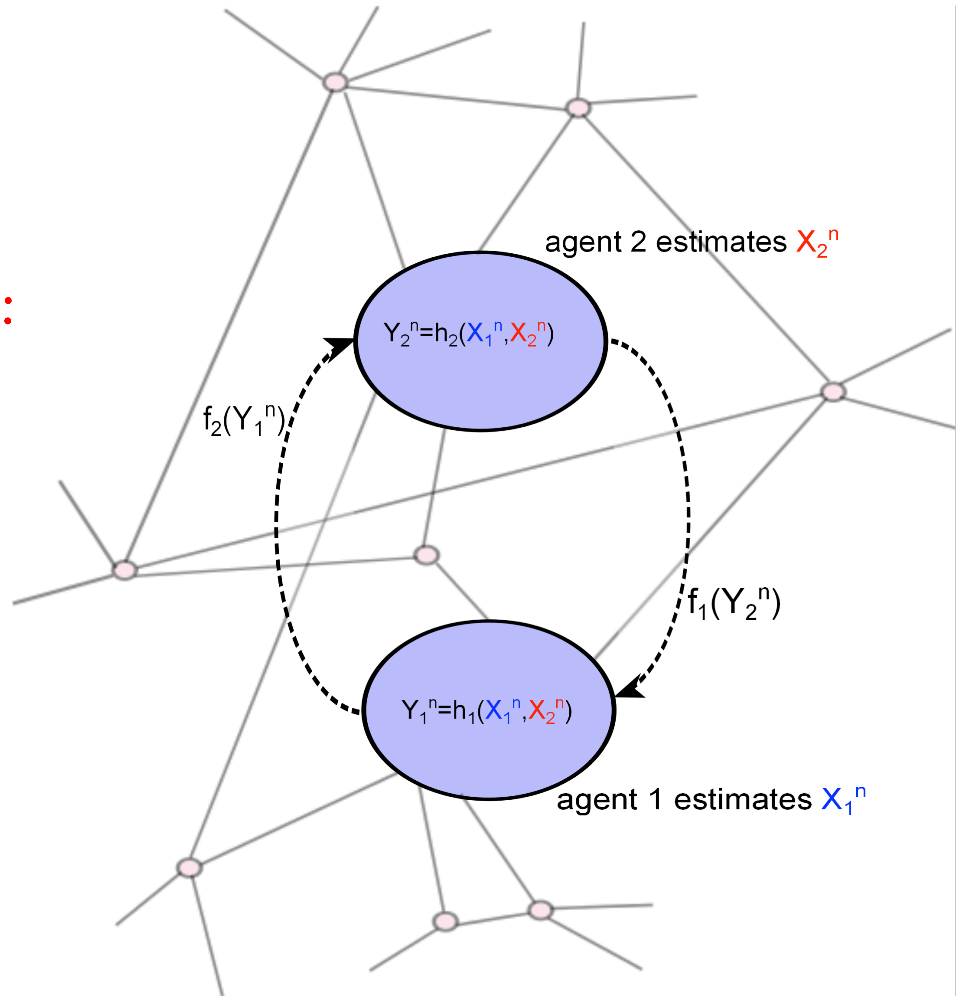
Social Networks: tradeoff between sharing & privacy

E-Commerce: tradeoff between economic benefit & privacy

Competitive Privacy: Other Potential Applications

Other Networks of Interacting Agents, e.g.:

- resource localization in competitive environments
- joint sensing with untrustworthy allies



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Thank you