# Smart Grid: The Role of the Information Sciences

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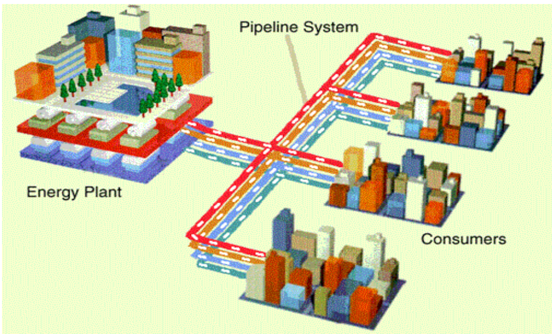
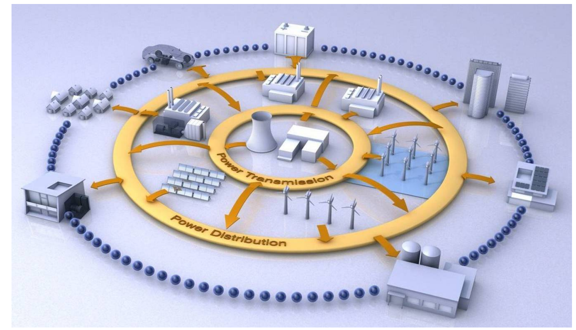
Princeton University

# What Is Smart Grid?




**Traditional Grid System**

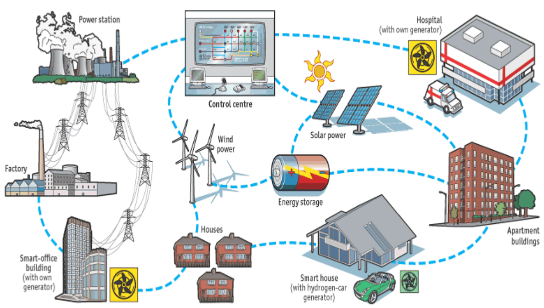
- Electromechanical system
- One-way communication
- Centralized generation
- Few sensors
- Manual monitoring
- Manual restoration
- Failures and blackouts
- Limited control
- Few customer choices




**Smart Grid System**

- Cyber-physical system
- Two-way communication
- Distributed generation
- Sensors throughout
- Self-monitoring
- Self-healing
- Adaptive and reliable
- Pervasive control
- Many customer choices

# What Have a Smart Grid?




- Improve power reliability and quality.
- Enhance capacity and efficiency of existing power plant.
- Improve resilience to disruption.
- Enable self-healing response to system disturbances.
- Facilitate expanded deployment of renewable energy sources.
- Accommodate distributed power sources.
- Automate maintenance and operation.
- Reduce fossil fuel consumption and green house emission.
- Improve grid security.
- Enable transition to electric vehicles and new storage options.
- Increase consumers choice.
- Enable new products, services and markets.
- Optimize facility utilization.
- I.e., greater efficiency, security and reliability

Source: National Institute of Standards and Technology. NIST framework and roadmap for smart grid interoperability standards, release 1.0, http://www.nist.gov/public affairs/releases/upload/smartgridinteroperability final.pdf. January 2010.

# The Role of Information Sciences

The introduction of a cyber layer invites the application of methodologies from the information sciences:

- optimization, game theory & control
- communications, networking & information theory
- statistical inference & signal processing

# Game Theoretic Methods for Greater Efficiency

# Motivation

- Salient characteristics of smart grid:
  - Heterogeneity: many grid elements, each having its own objective
  - Large-scale interactions: geographically and in terms of number of elements
  - Stochastic dynamics: in terms of demand, supply, etc.

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- Useful framework - game theory in its two branches:
  - Non-cooperative game theory
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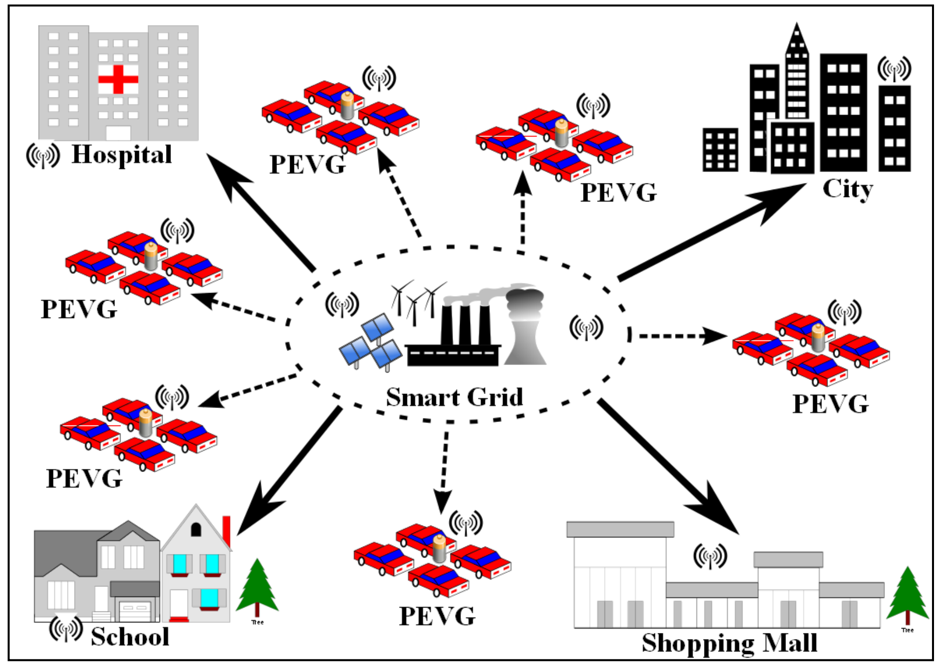
- Useful framework - game theory in its two branches:
  - Non-cooperative game theory
  - Cooperative game theory
- Game theory for smart grid efficiency:
  - Demand-side management, energy trading and markets
  - Integration and distributed operation of micro-grids

# Ex. 1: Energy Trading for Plug-In Vehicles

- Groups of plug-in electric vehicles (or other entities) can trade energy with the main grid.



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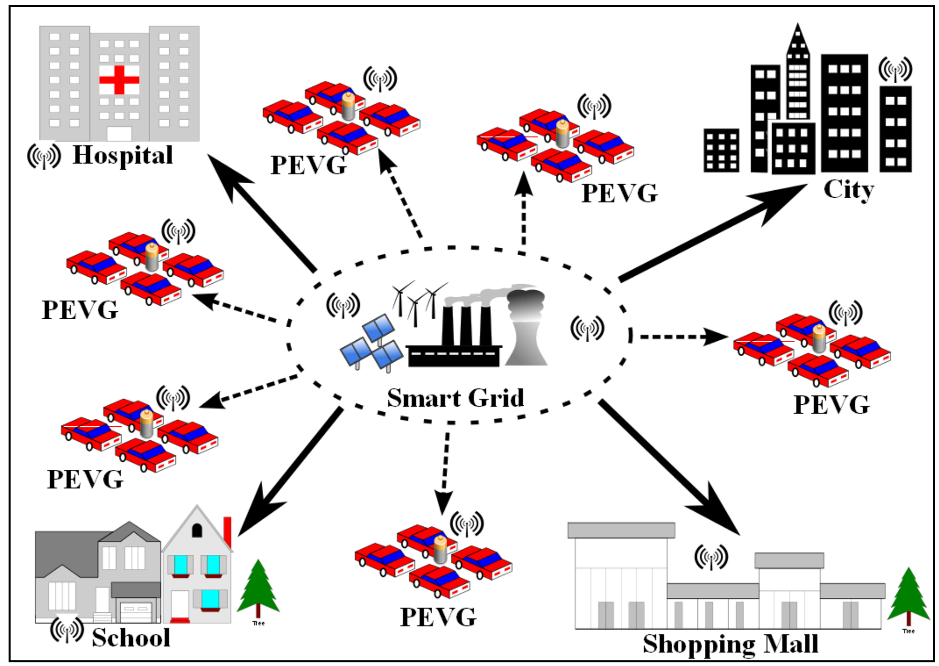
- Non-cooperative games can model interactions
  - among such groups (Nash) [w/ Wang, et al. - T-SG'14]
  - between such groups and the grid (Stackelberg) [w/ Tushar, et al. - T-SG'14]



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Trading price (auction outcome)

Quantity sold (auction outcome)

Pricing factor

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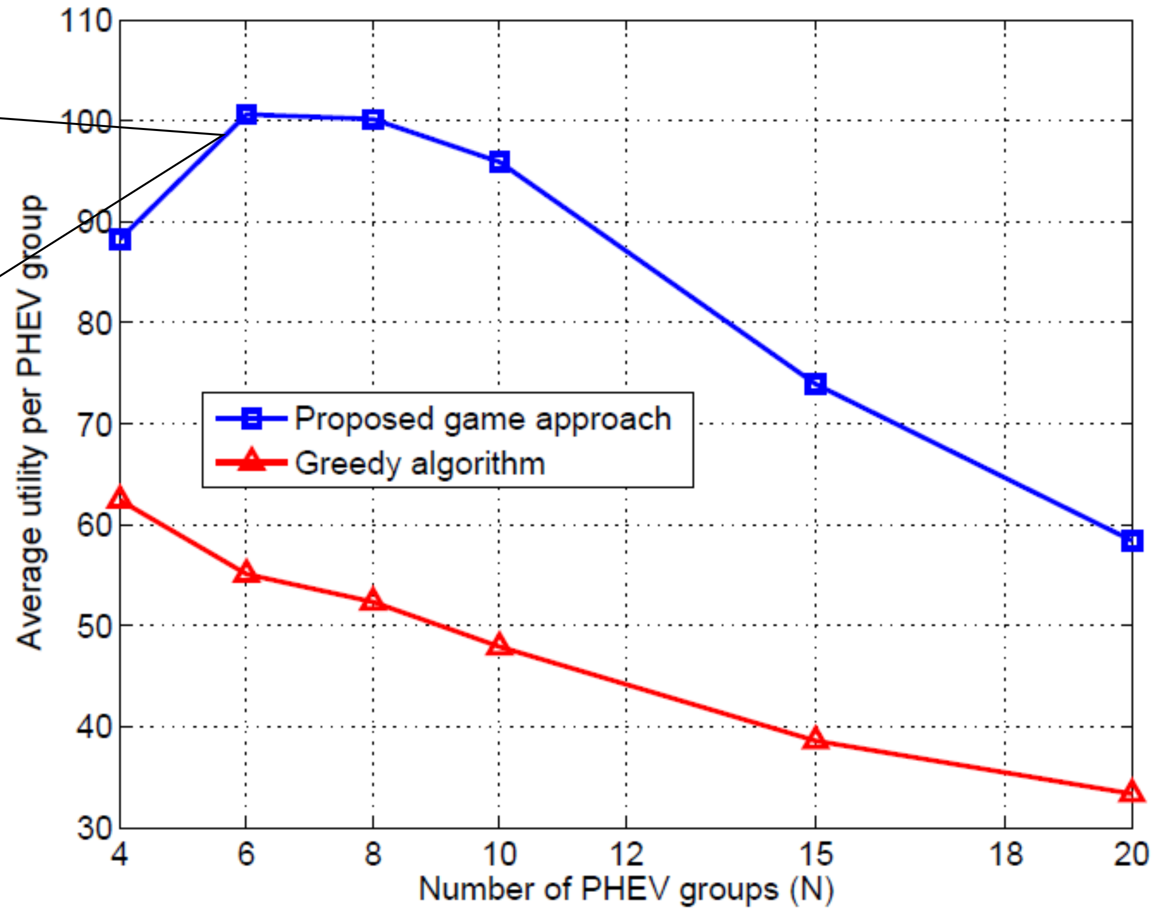
- How to solve the game and find the Nash equilibrium?
  - Auction introduces a discontinuity => difficult analytically
  - Algorithmic approach (based on best-response)

# Simulation Example: Selling to the Grid

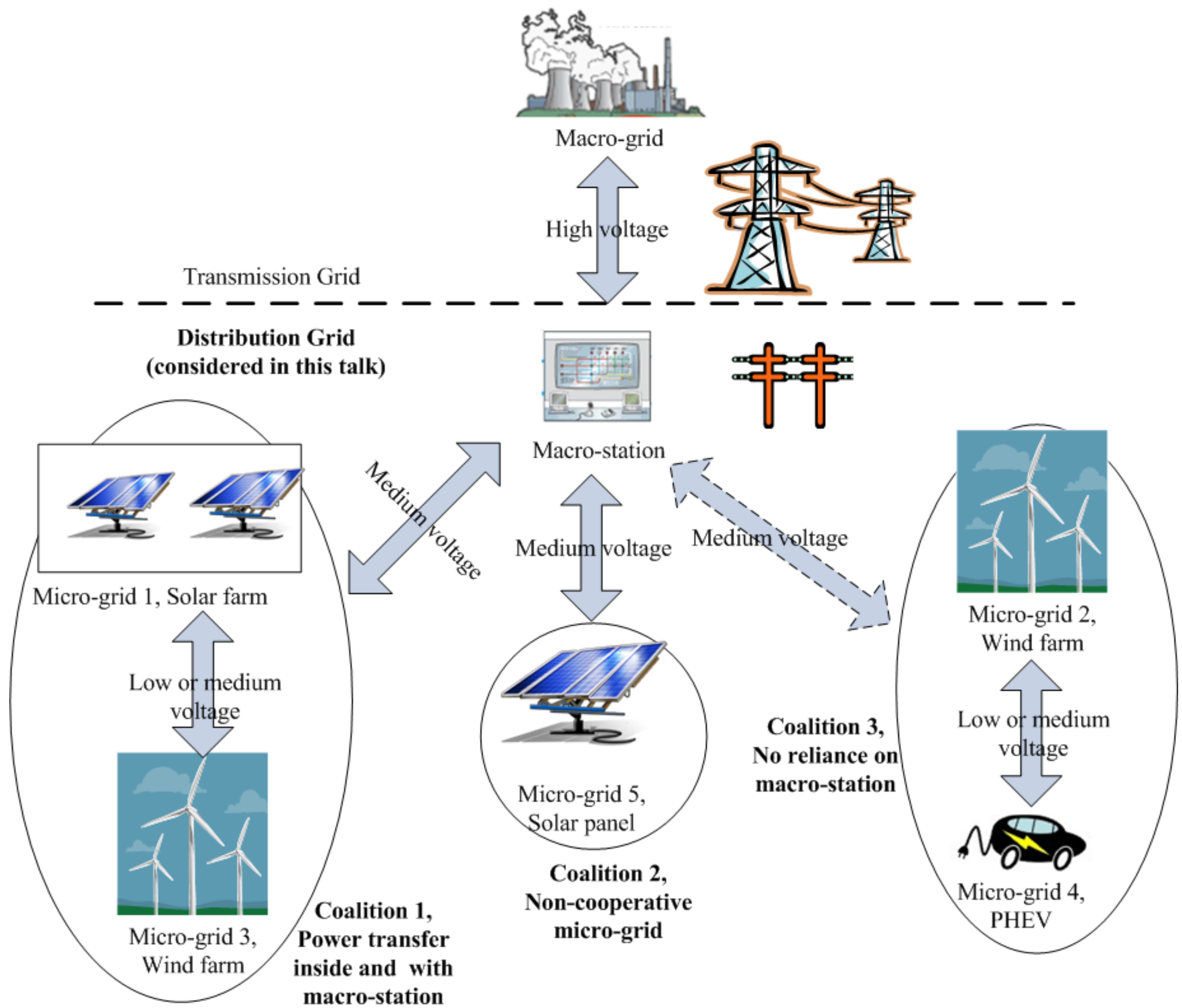
[w/ Wang, et al. – T-SG '14]

- Initially, the utility increases as more players enter the game leading to more energy sold.
- Then, the utility decreases as the presence of more sellers deflates the price.



# Ex. 2: Micro-grid Interaction

- Energy trading within the distribution network
- Cooperation helps to:
  - Exchange energy: sell surplus and overcome deficiency
  - Reduce power losses over transmission lines



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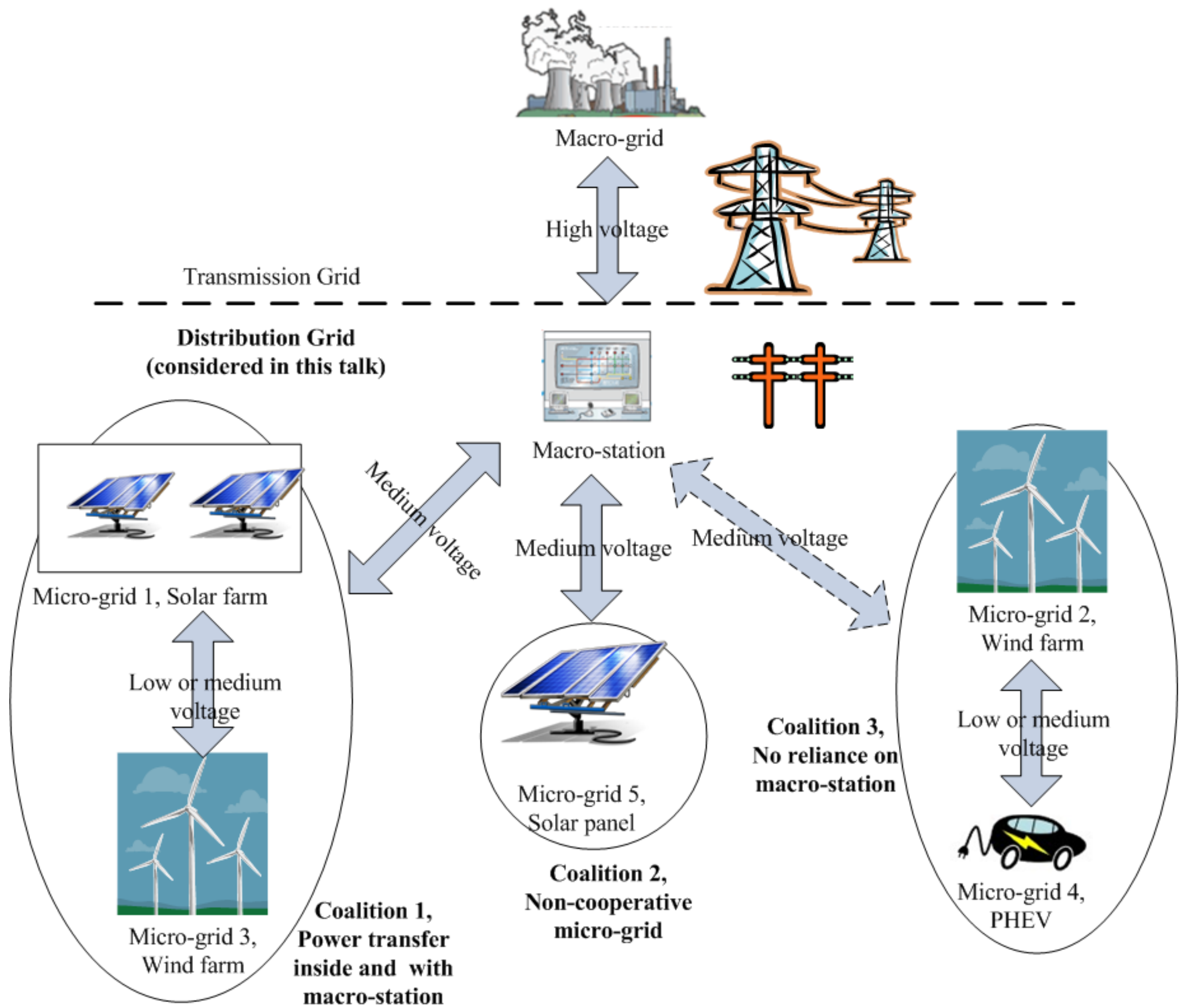
- Coalitional games – models the process of elements' forming cooperatives to trade energy



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- Coalitional game (*N*,*v*)
  - In a set of players *N***,** *a coalition* S is a group of cooperating players
  - Value (utility) of a coalition *v(S)*
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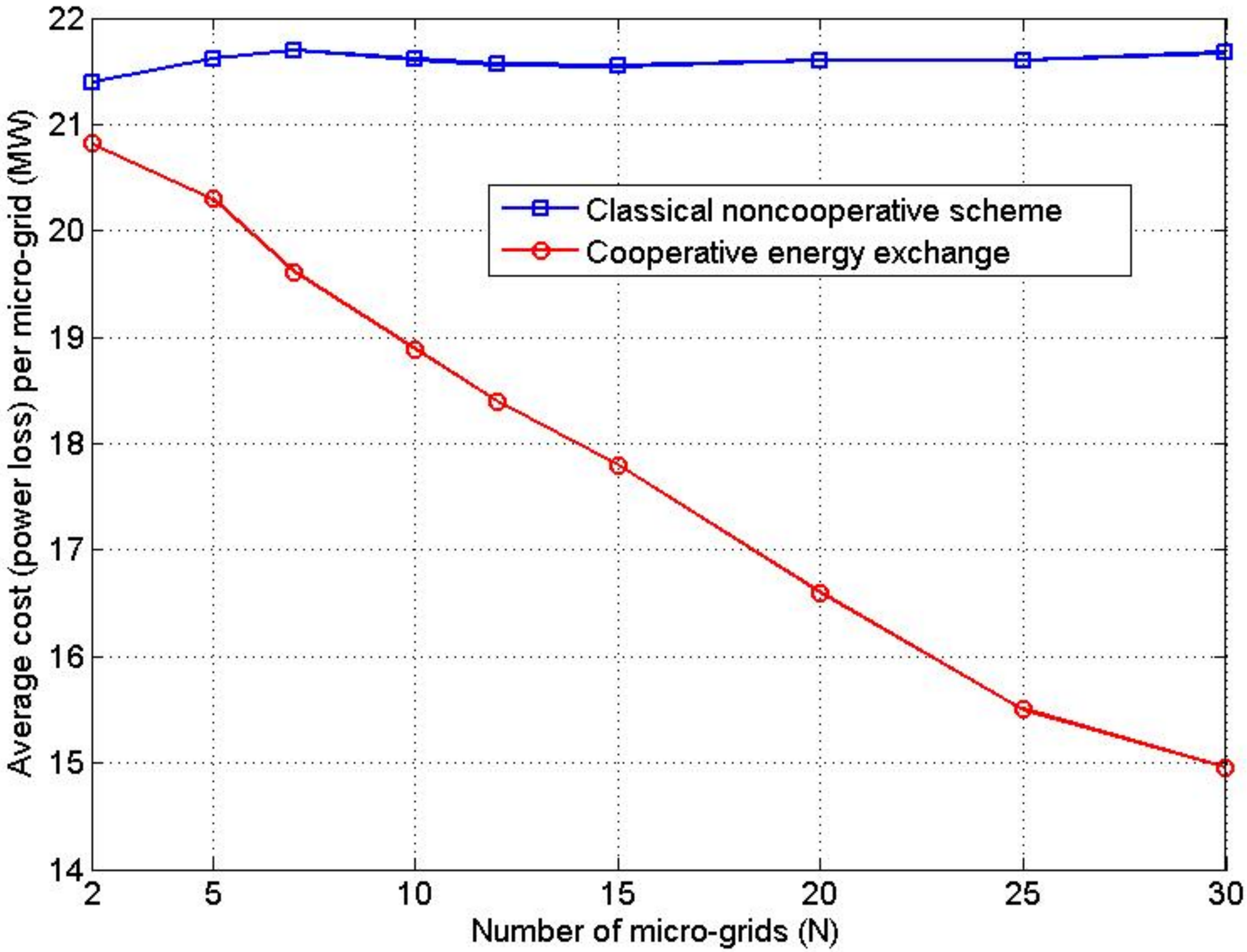
- Coalition formation
  - Coalitions can be compared based on Pareto ordering of user payoffs
  - Merges and splits can be used to iterate on coalitions
  - Convergence to a stable, merge-and-split-proof limit

# Typical Simulation Results

[w/ Saad, et al. - SPM'12]



# Summary

- Game theory for smart grid modeling:
  - Demand-side management, energy trading and markets
  - Integration and distributed operation of micro-grids
  - "Game theoretic methods for the smart grid," [w/ Saad, Han, Basar - SPM'12]

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- Other problems of interest
  - Network formation games for PLC backhaul [w/ Saad, Han - Gamenets'11]
  - Trading markets with a single power provider [w/ Tushar, et al. – T-SG'12, T-SG'14]

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  - Trading markets with a single power provider [w/ Tushar, et al. – T-SG'12, T-SG'14]
- Additional issues
  - Optimizing jointly over three layers: economic, cyber, and physical
  - Incorporating dynamics (generation/load/mobility/etc.)

# Information Theoretic Methods for Greater Security

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- But, it can also leak information that should be kept secure, or private.
- How can we characterize this fundamental tradeoff?

# Privacy-Utility Tradeoff

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- Problems in this framework can be solved via information theoretic analysis for many cases. [w/ Sankar, Rajagopolan - T-IFS'13]

# Distortion-Equivocation Model

- Encoder maps the original data to a "sanitized" database (SDB):

$$\text{Encoder}: \mathbf{X}^n \rightarrow \mathcal{W} = \left\{ SDB_1, SDB_2, \ldots, SDB_M \right\}$$

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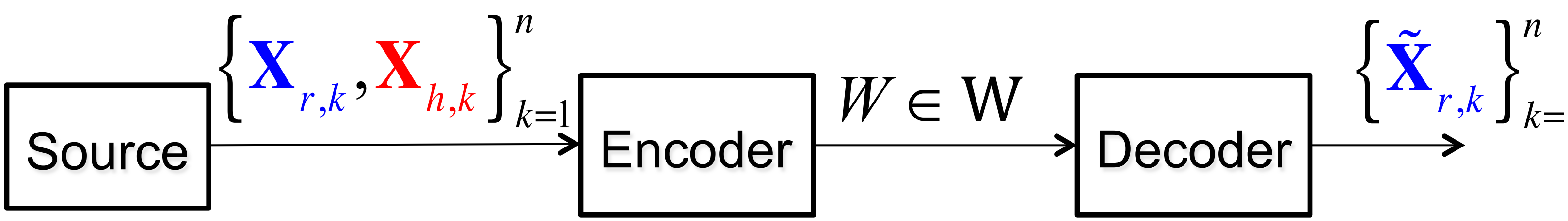

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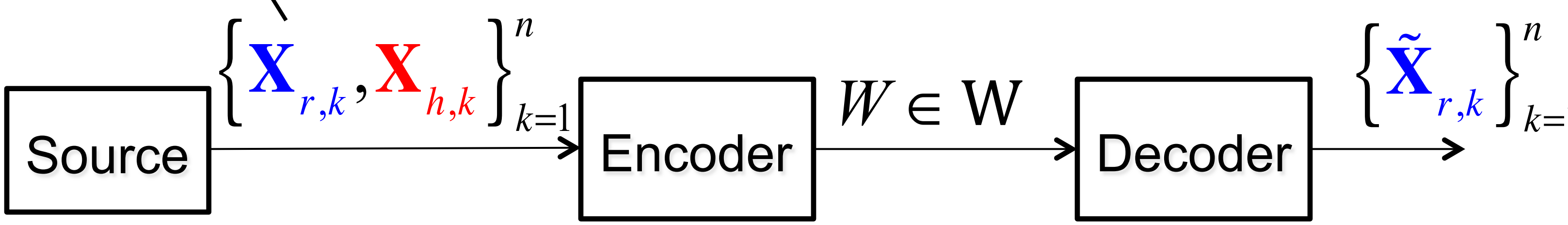
Distortion

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



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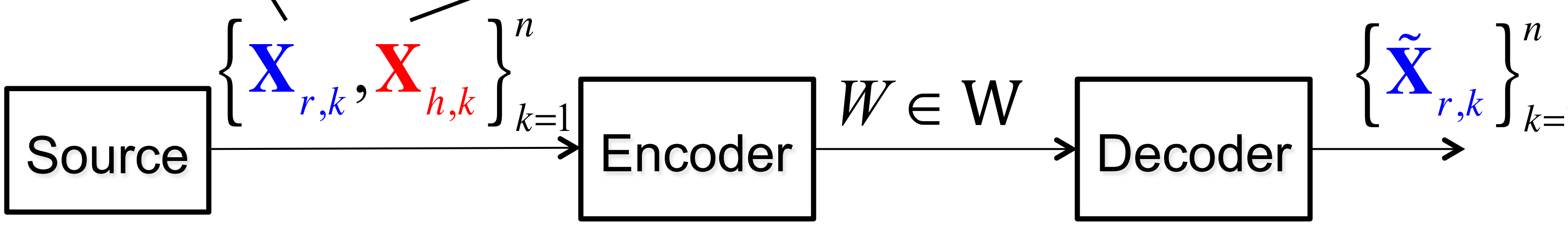

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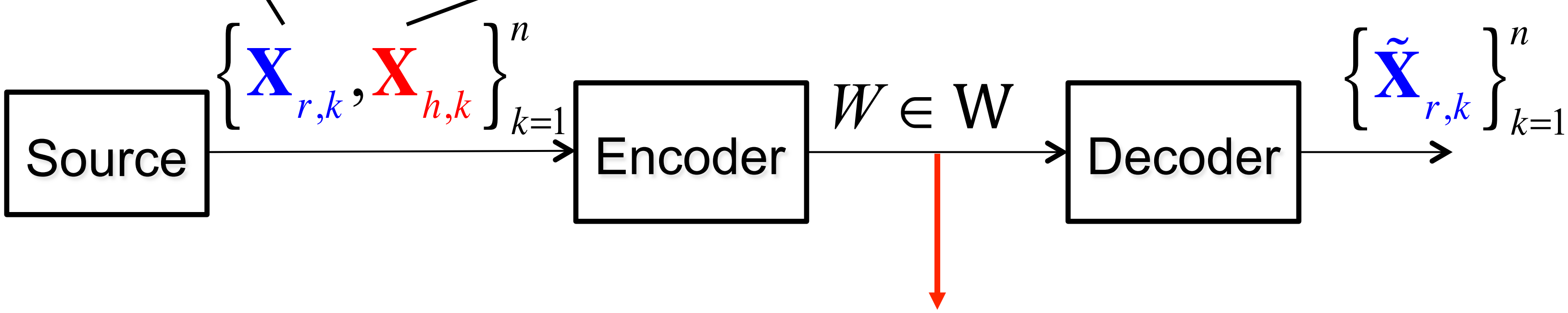
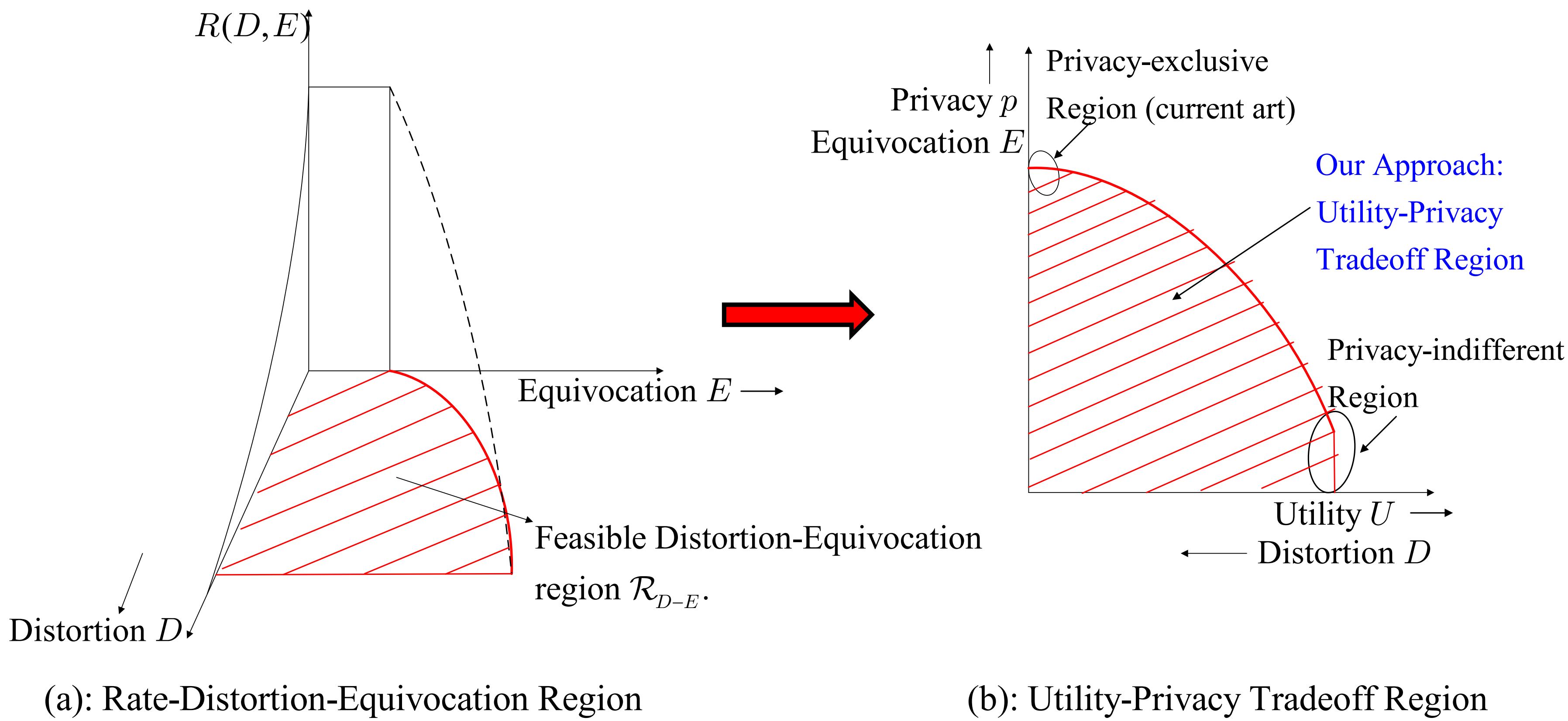


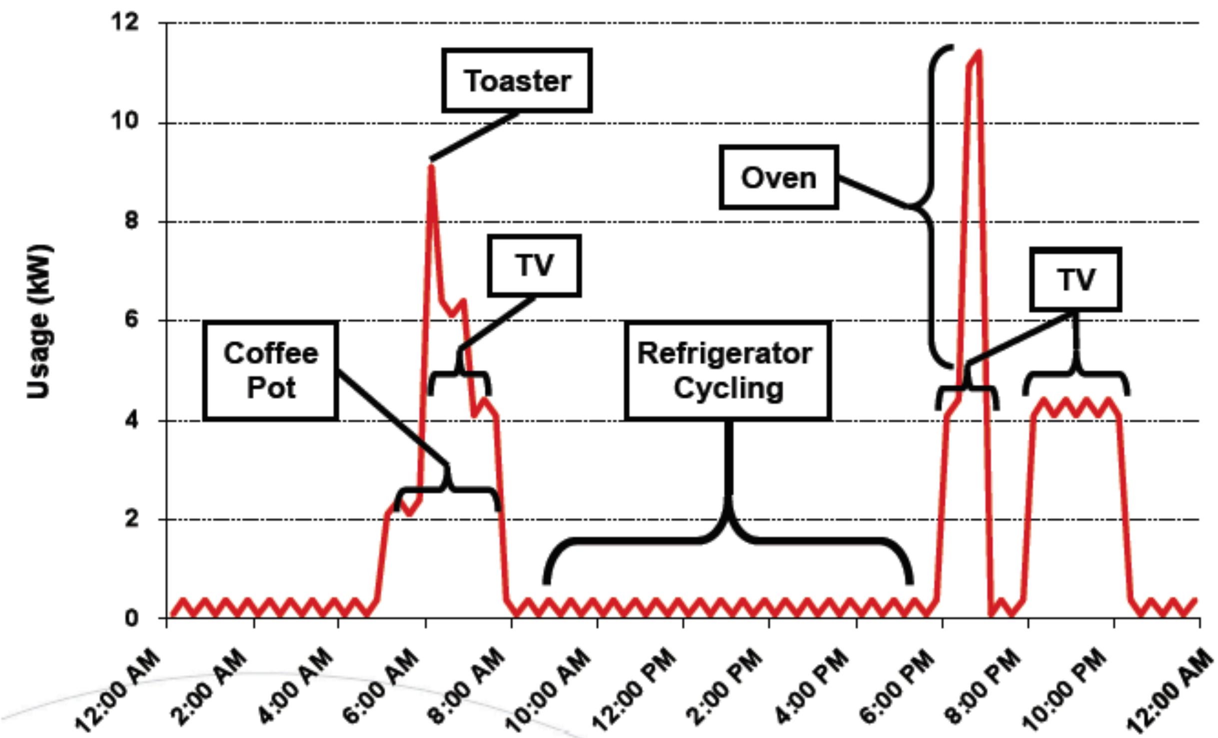

Add a rate constraint → $M \leq 2^{n(R+\varepsilon)}$

# Utility-Privacy/RDE Regions



# Ex. 1: Smart Meter Privacy

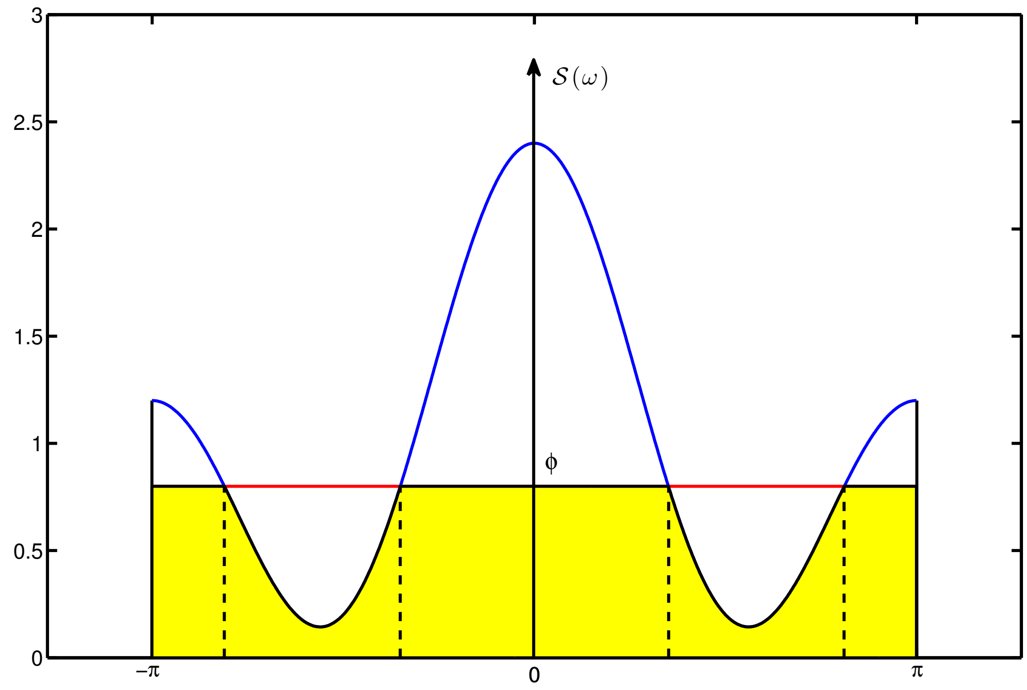
- Smart meter data is useful for price-aware usage, load balancing
- But, it leaks information about in-home activity



# Source Coding Solution

[w/ Sankar, et al. - T-SG'13]

P-U tradeoff leads to a spectral 'reverse water-filling' solution



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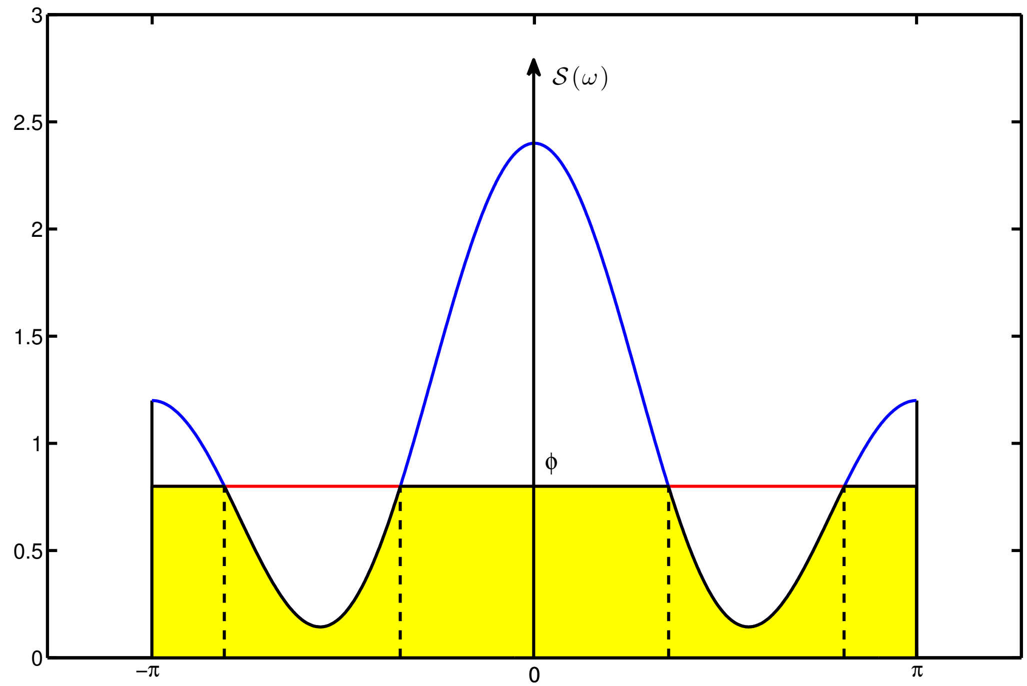
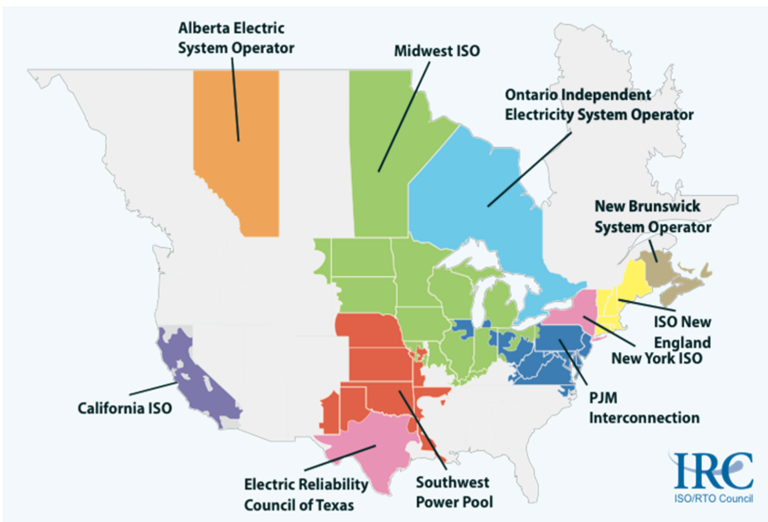
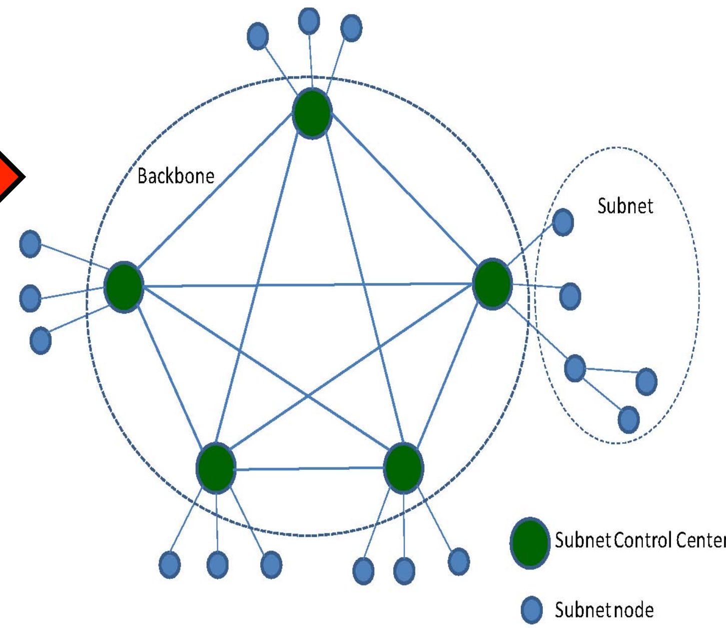



Can also use energy storage to aid privacy [w/ Tan, Gunduz - JSAC:SG Series'13]

# Ex. 2: Competitive Privacy

- N.A. Grid: interconnected regional transmission organizations which
  - need to share measurements on state estimation for reliability (utility)
  - wish to withhold information for economic competitive reasons (privacy)




- Leads to a problem of *competitive privacy*

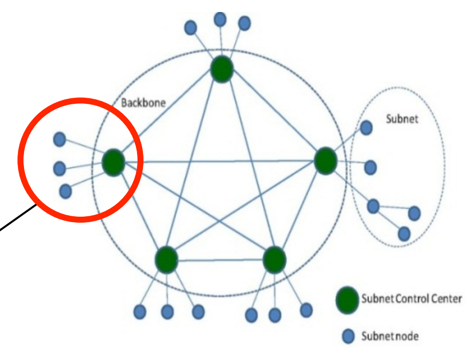
# Competitive Privacy Model

[w /Sankar, Belmega - preprint]

- Noisy measurements at RTO k:

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

$m^{th}$ system state



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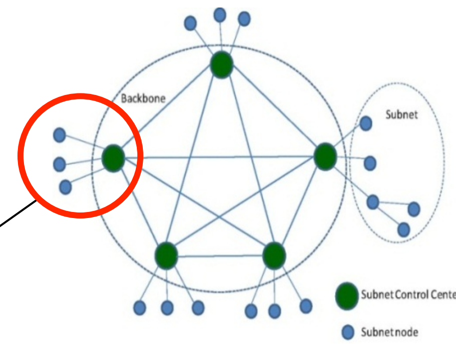


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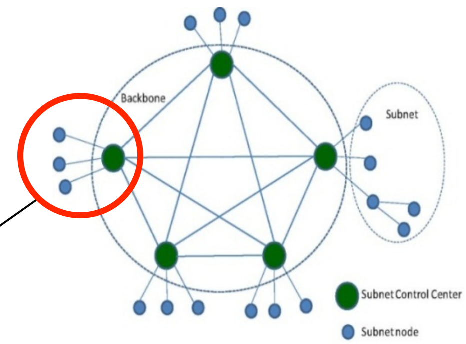


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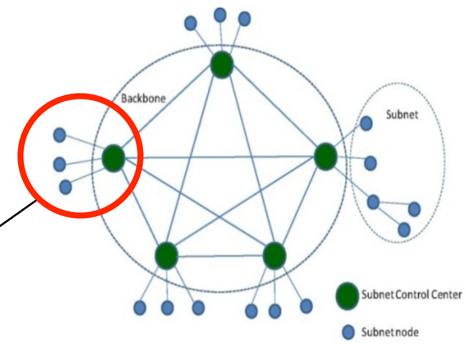


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- Game theory can explain the interactions.

# Summary

- An information source is divided into private and public variables

- Leads to an information-leakage/distortion characterization of the privacy-utility tradeoff

- Applications in smart grid include: smart metering & competitive privacy

# Inferential Methods for Greater Reliability

# Motivation

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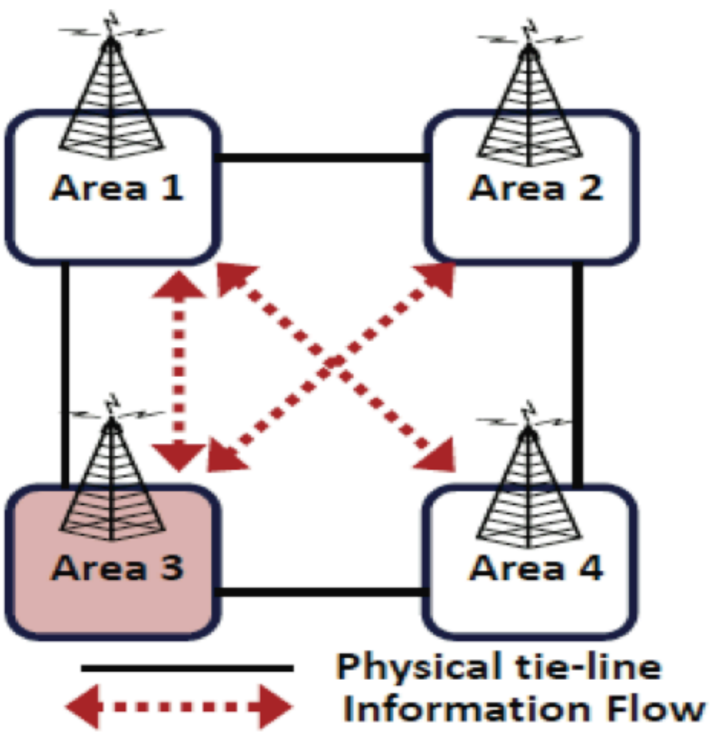
- Computational & communications challenge:
  - fast sensing produces big data, and communications bottlenecks
- Control can be decentralized into control areas (CAs)
- Of interest:
  - distributed algorithms to obtain system-wide situational awareness through local information exchange among CAs.

# Ex.: Distributed Estimation

Wide area state (bus-phase) estimation via distributed processing:

### Conceptual Model




### Desired Properties

- No central coordinator
- Only local information required at CAs
- CAs not necessarily observable
- Flexible in communication topology
- Equivalent performance to centralized estimation

# Distributed Measurement Model

- **System State**
  - $\theta \in \mathbb{R}^M$: The network system state (vector) consisting of voltage phase angles of buses in all CAs.

- **CA Local Observation Model**
  - $\mathbf{z}_n \in \mathbb{R}^{M_n}$: The local observation at CA $n$

$$\mathbf{z}_n = H_n\theta + \mathbf{e}_n,$$

    where the Jacobian $H_n \in \mathbb{R}^{M_n}$ sub-block represents the local physical interconnections.

# Distributed Estimation Algorithms

[w / Xie, et al. - T-SG'12]

- Consider iterative estimates at each CA of the form:

$$\mathbf{x}_n(t+1) = \mathbf{x}_n(t) - \beta_t \sum_{l \in \Omega_n} \left(\mathbf{x}_n(t) - \mathbf{x}_l(t)\right) + \alpha_t \overline{H}_n^T \left(\overline{\mathbf{z}}_n - \overline{H}_n \mathbf{x}_n(t)\right)$$

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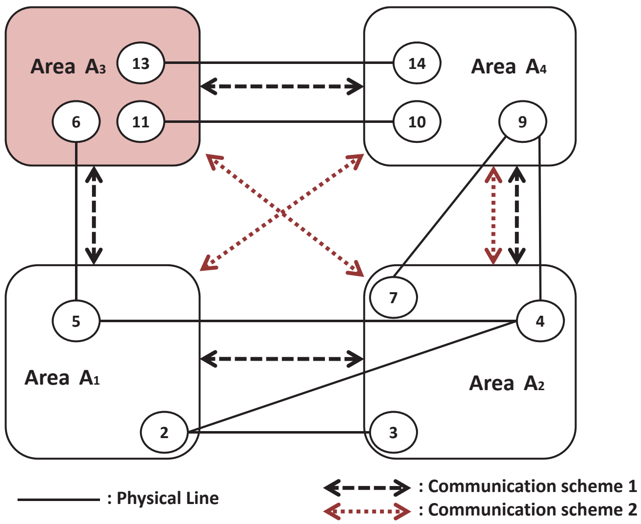
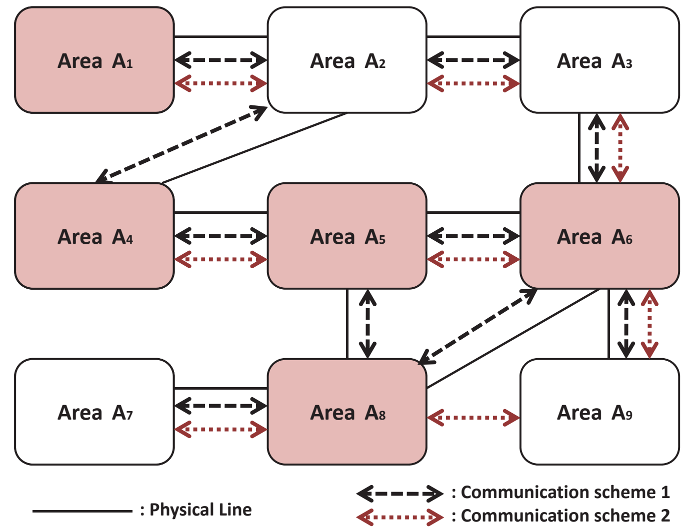
- For properly chosen parameters:

global observability of the grid + connectivity of the network implies convergence of the local estimates to global least squares

# Linear Estimation in Test Systems



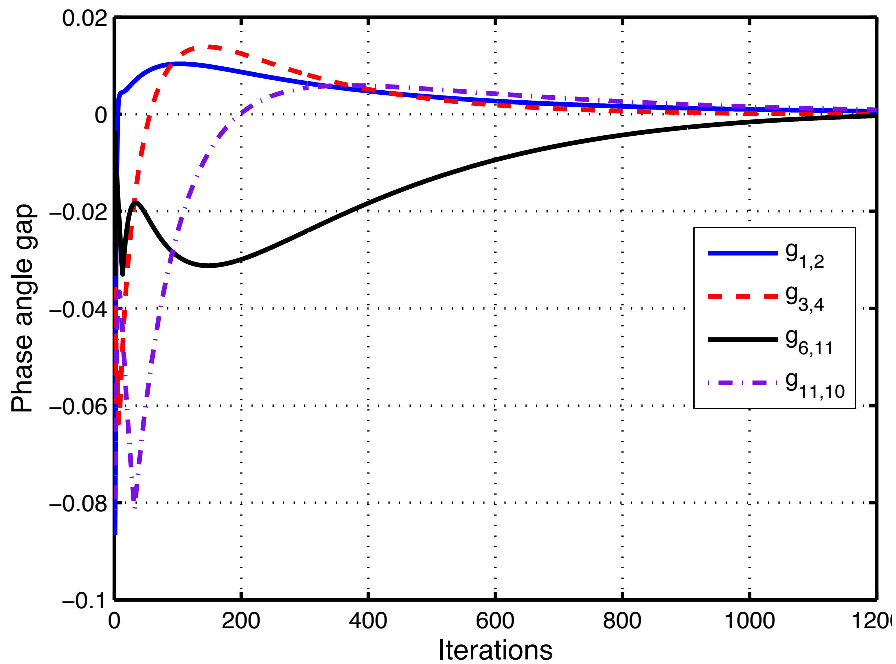

(a) The IEEE 14-bus system



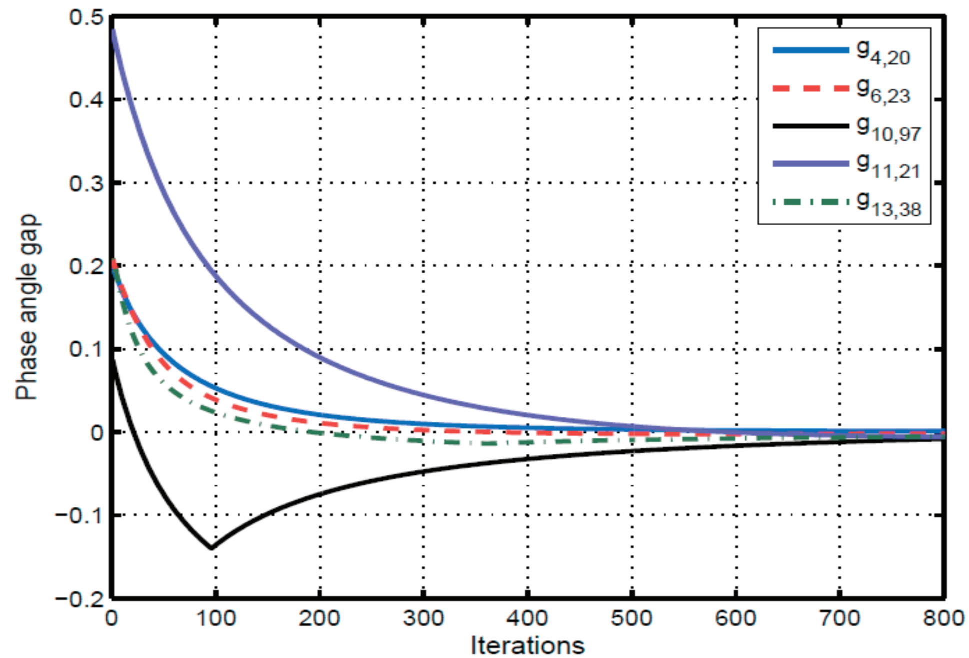

(b) The IEEE 118-bus system

- Overall systems are globally observable
- CAs are globally unobservable
- Shaded CAs are locally unobservable

# Convergence of Phase Estimates

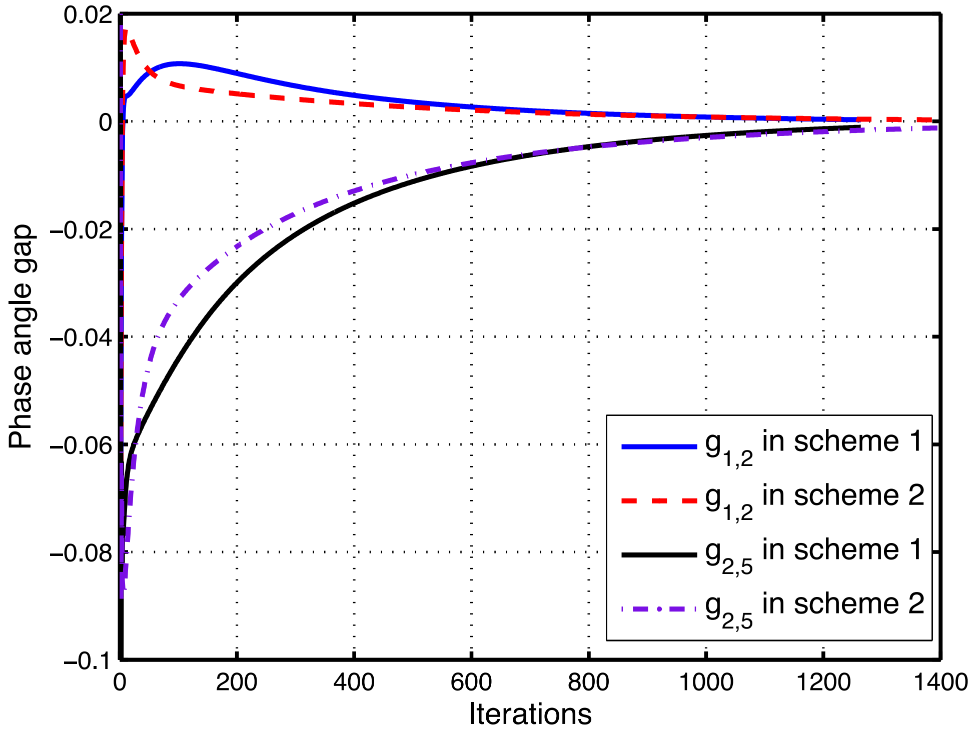



14-Bus System




118-Bus System

# Communication Topology Flexibility




14-Bus System

# Related Work

- Nonlinear (AC) state estimation [w/ Xie, et al. - T-SG'12]
- Multi-cast routing [w/ Li, Lai - JSAC:SG Series'12]
- Detection of data attacks, line outages, etc. [w/ Zhao, et al. - IEEE PES Annual Meeting'13]

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- Techniques from the information sciences are promising for application in this setting.

# Summary

- Smart grid is a cyber-physical approach to greater power system efficiency, security & reliability.
- Techniques from the information sciences are promising for application in this setting.
- E.g, game theory, information theory and statistical inference can be applied.

Thank You!