Smart Grid: The Role of the Information Sciences

Vince Poor
Princeton University

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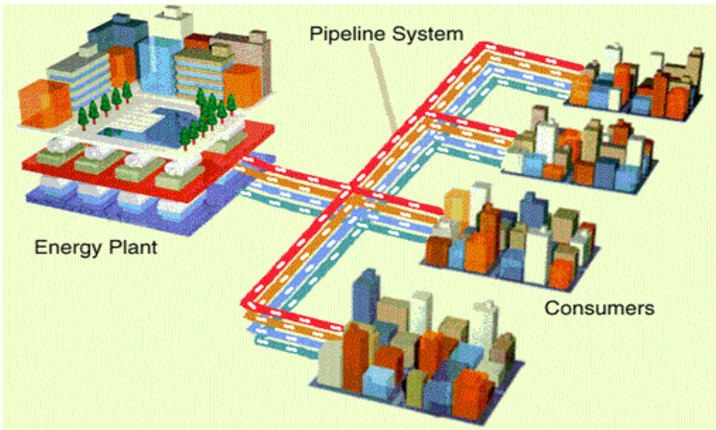
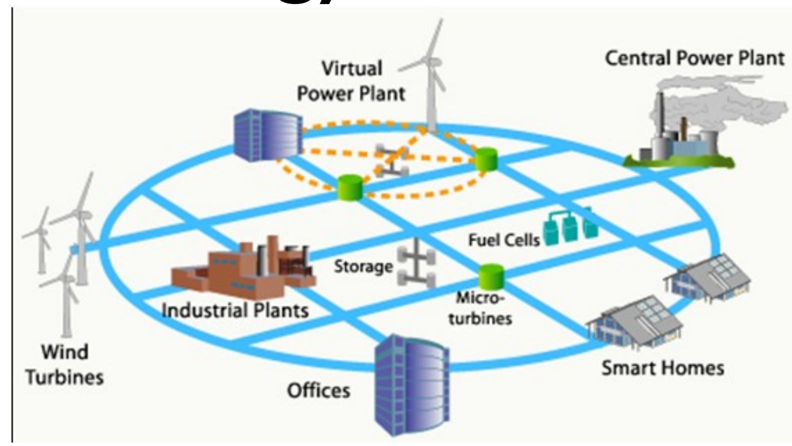
What Is Smart Grid?
"The Internet of Energy"



Traditional Grid

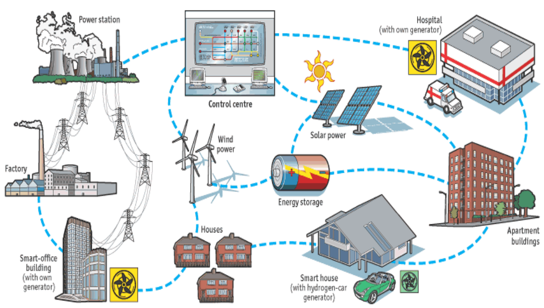
- Electromechanical system
- One-way communication
- Centralized generation
- Few sensors
- Manual monitoring & restoration
- Failures and blackouts
- Limited control
- Few customer choices



Smart Grid

- Cyber-physical system
- Two-way communication
- Distributed generation
- Sensors throughout (big data)
- Self-monitoring & self-healing
- Adaptive and reliable
- Pervasive control
- Many customer choices

What Have a Smart Grid?



- Enhance efficiency of existing generation
- Enable resilience to and self-healing from disruption
- Facilitate deployment of renewable energy sources
- Automate maintenance and operation
- Improve grid security
- Smooth transition to electric vehicles and storage
- Increase consumer choices
- Enable new products, services and markets
- I.e., greater efficiency, security and reliability

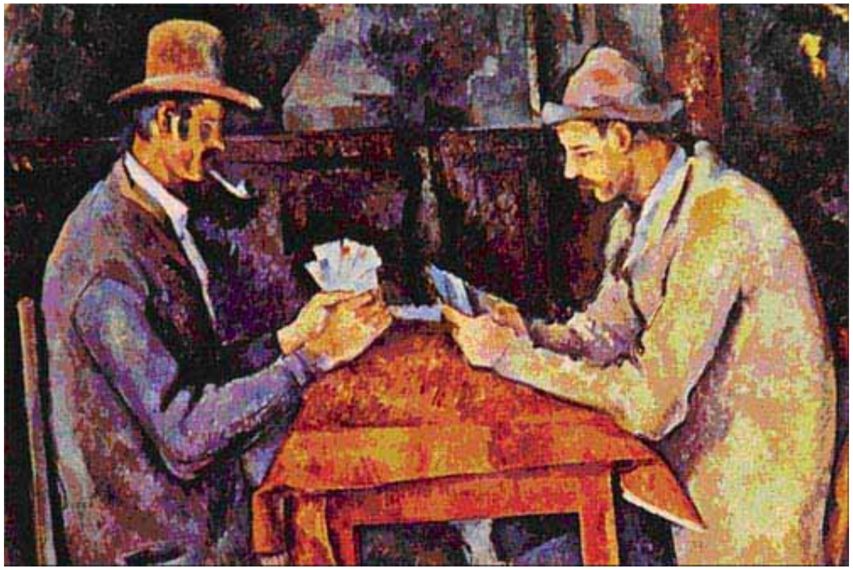
Source: National Institute of Standards and Technology. NIST framework and roadmap for smart grid interoperability standards, release 1.0, http://www.nist.gov/public affairs/releases/upload/smartgridinteroperability final.pdf. January 2010.

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, machine learning & 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 network terms
  - Stochastic dynamics: in terms of demand, supply, etc.

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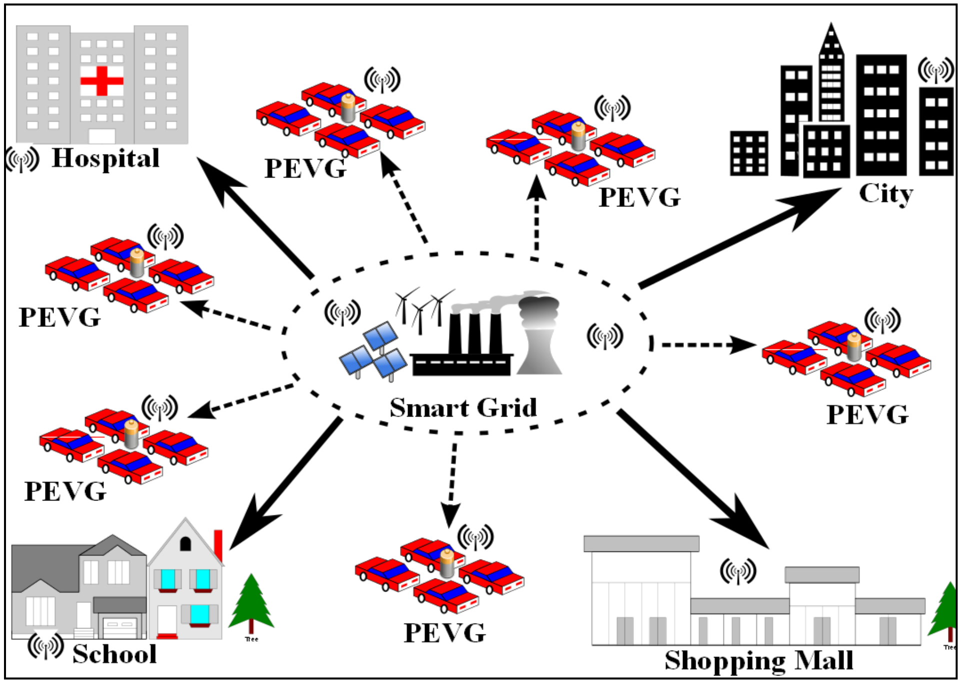
- Game theory for smart grid efficiency:
  - Demand-side management & energy trading
  - Integration and operation of micro-grids

Ex. 1: Energy Trading for Plug-In Vehicles

- Groups of plug-in electric vehicles can trade energy with the main grid.



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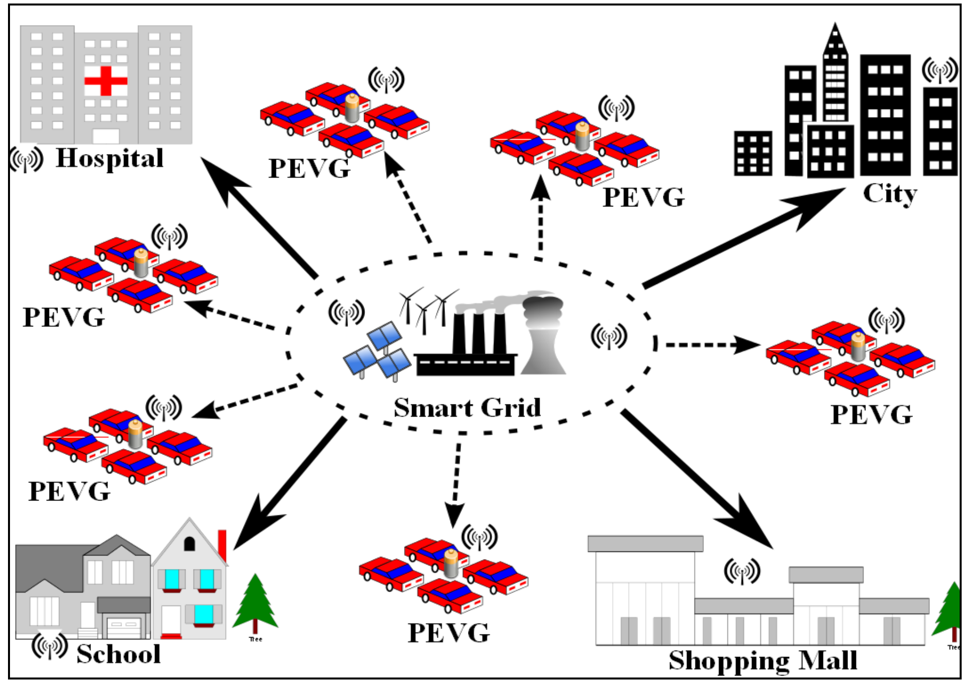
- Non-cooperative games model interactions

  - among such groups (Nash) [w/ Wang, et al. T-SG'14]

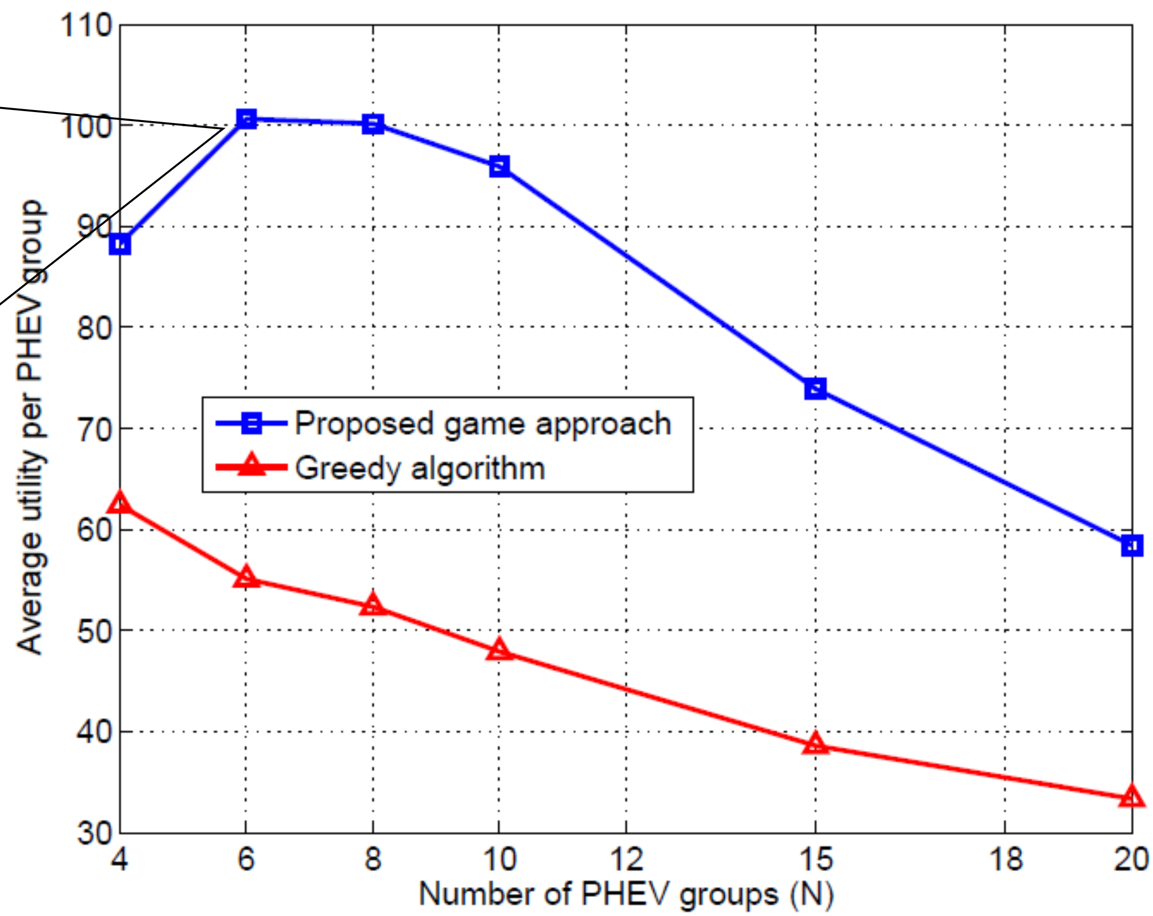
  - between such groups and the grid (Stackelberg) [w/ Tushar, et al., T-SG'14]



Simulation Example: Selling to the Grid

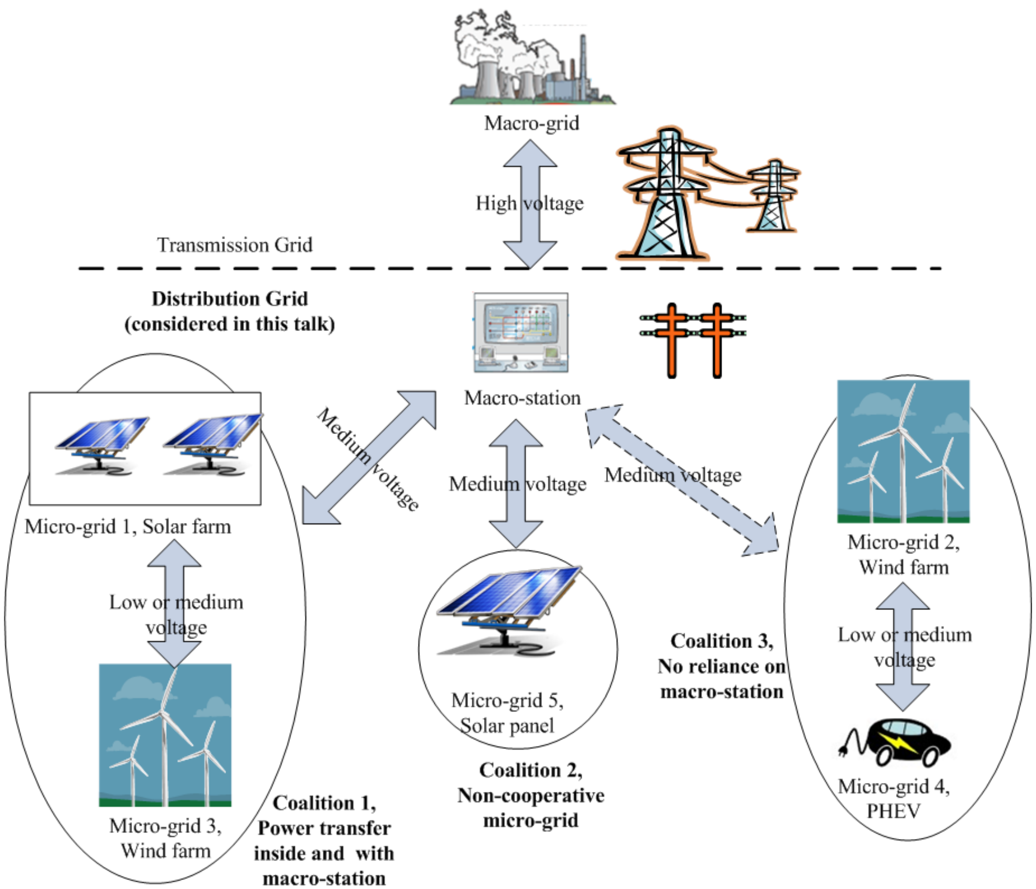
[w/ Wang, et al. , T-SG '14]

- 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



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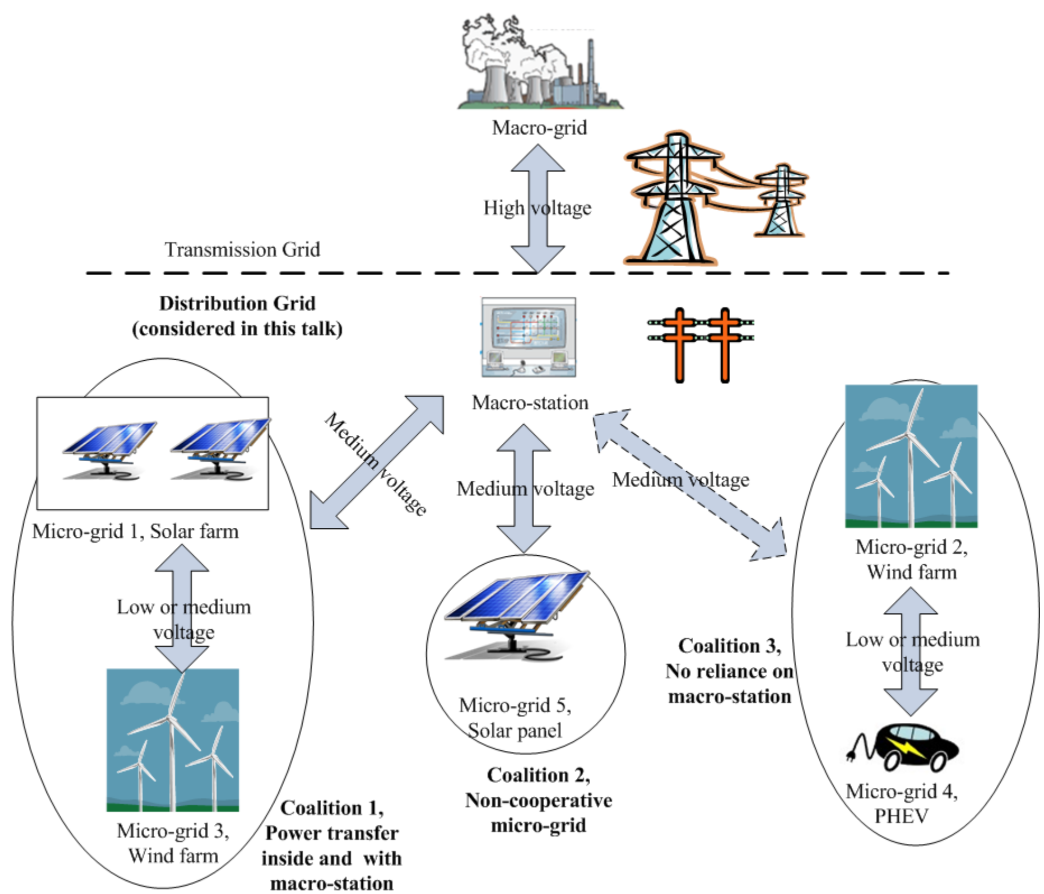
- Energy trading within the distribution network
- Cooperation helps to:
  - Exchange energy: sell surplus and overcome deficiency
  - Reduce power losses over transmission/distribution lines



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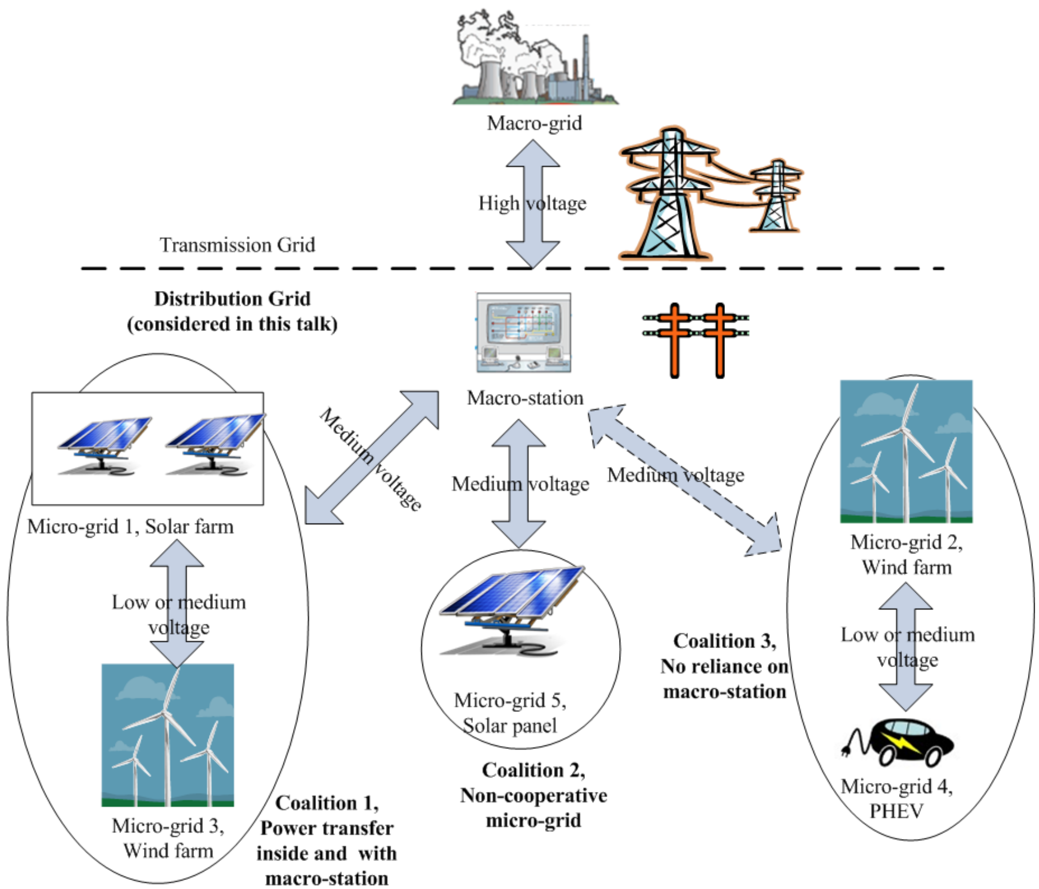

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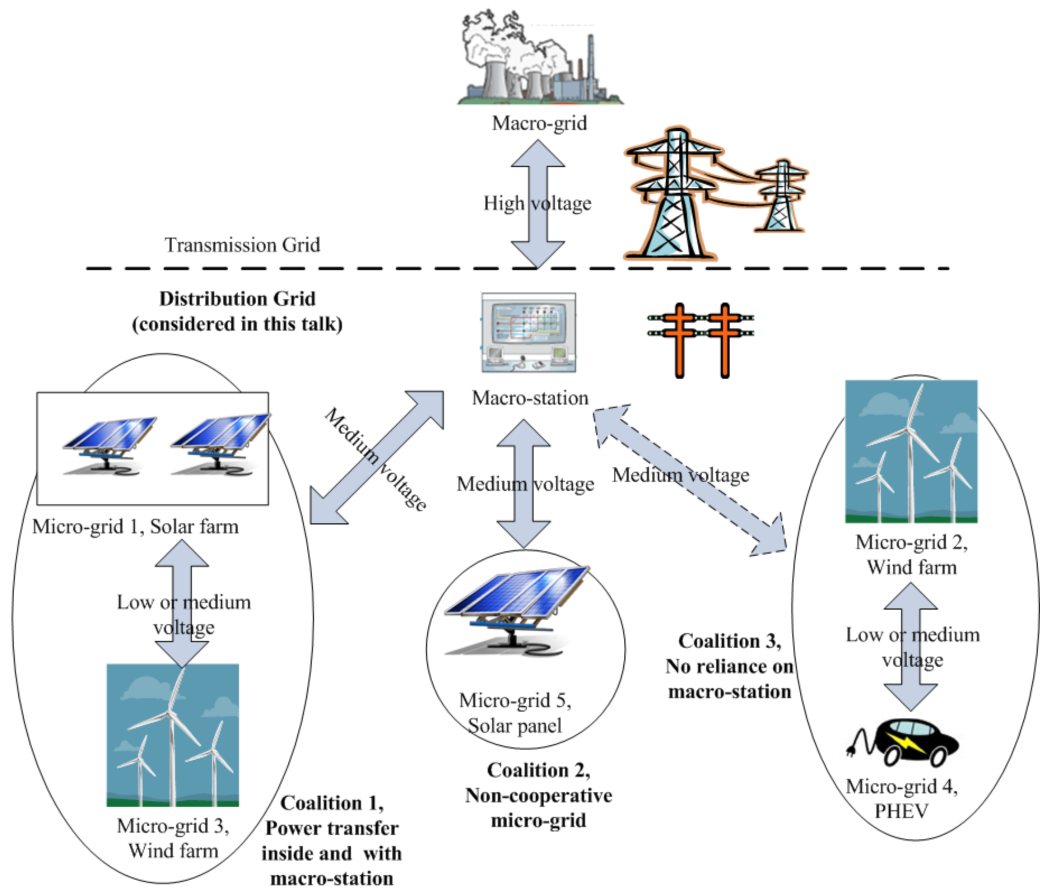
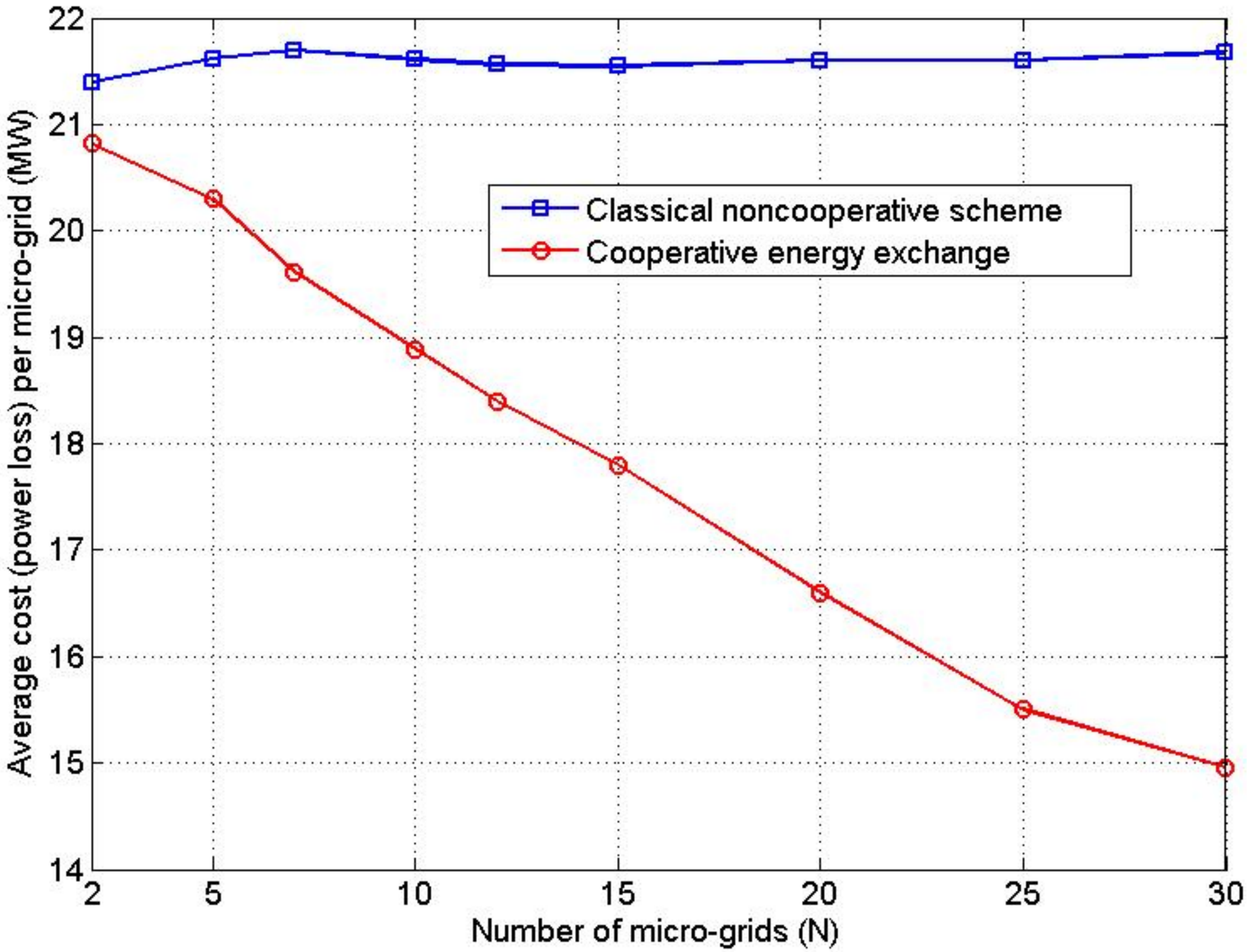
- Can also invoke prospect theory [w/ Xiao, et al., T-SG'15]



Typical Simulation Results

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



Information Theoretic Methods for Greater Security

Motivation: Data Security

- The smart grid cyber layer will generate considerable electronic data:
  - Power flow sensors, phasor measurement units, smart meters, etc.

- The utility of this data depend on its accessibility.
- 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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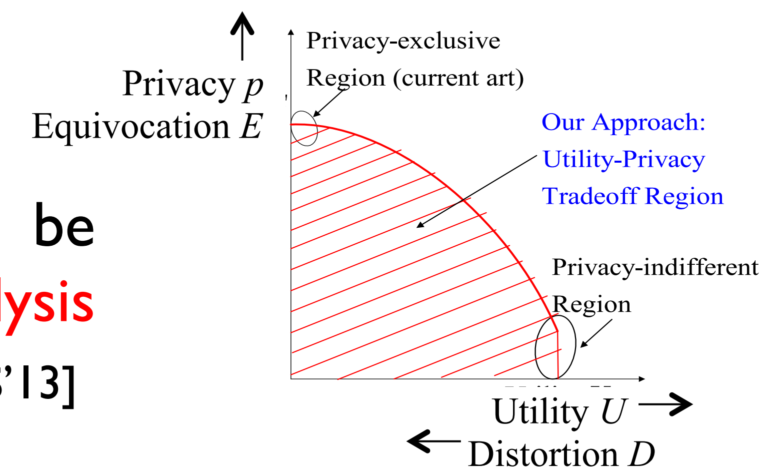
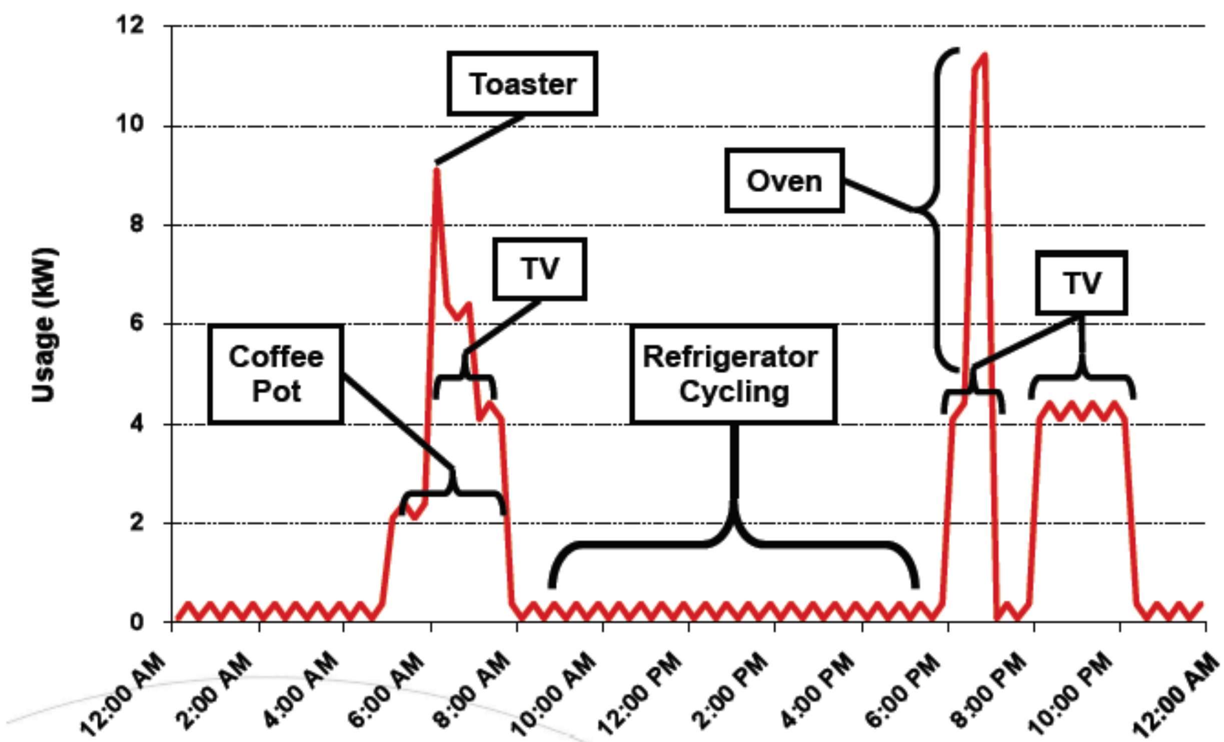
- Problems in this framework can be solved via information theoretic analysis for many cases. [w/ Sankar, Rajagopolan, T-IFS'13]



Ex. 1: Smart Meter Privacy

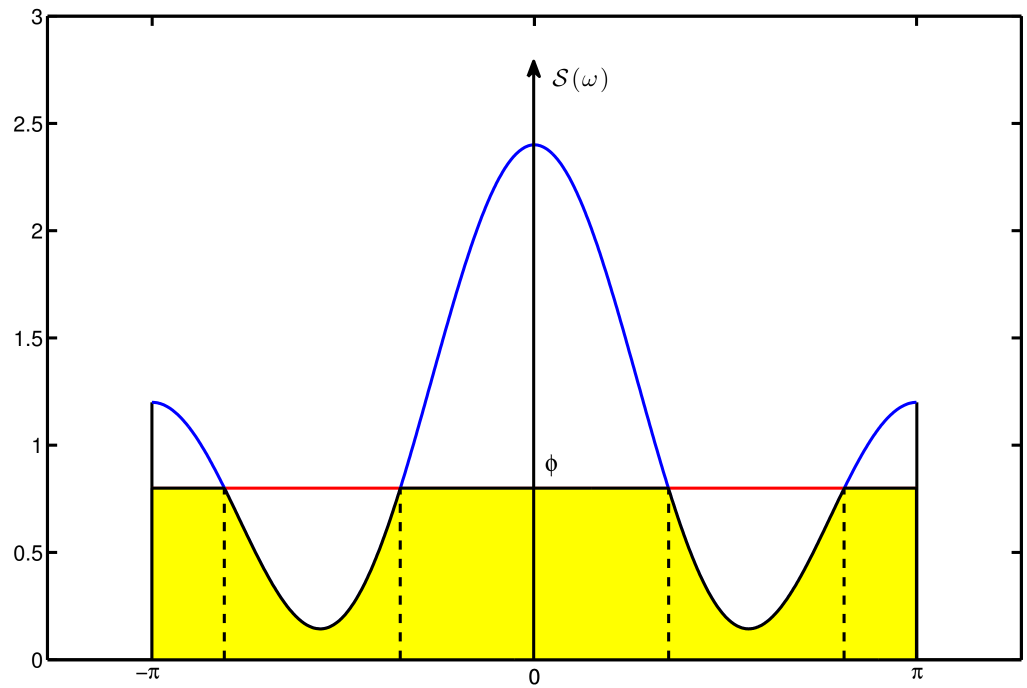
- Smart meter data is useful for price-aware usage, load balancing
- But, it leaks information about in-home activity



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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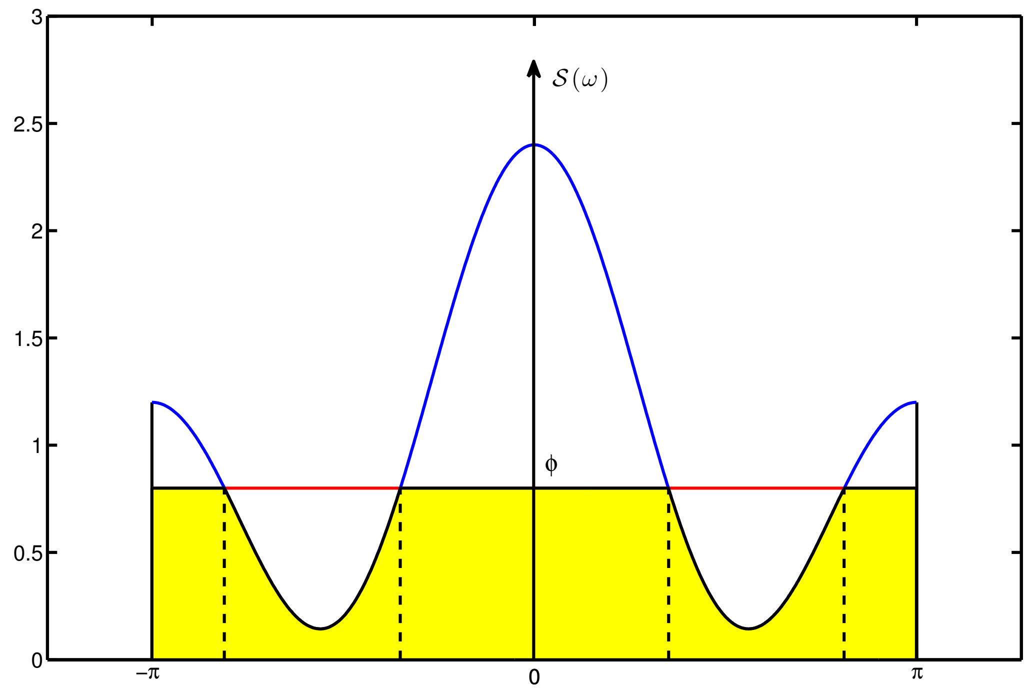
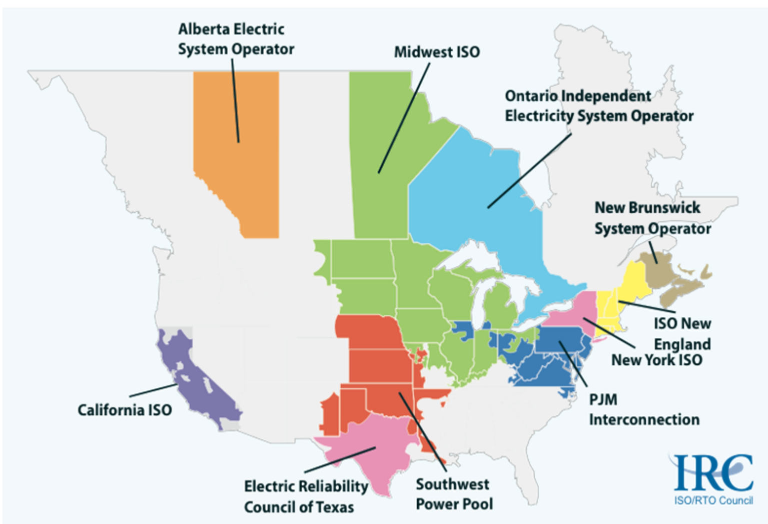
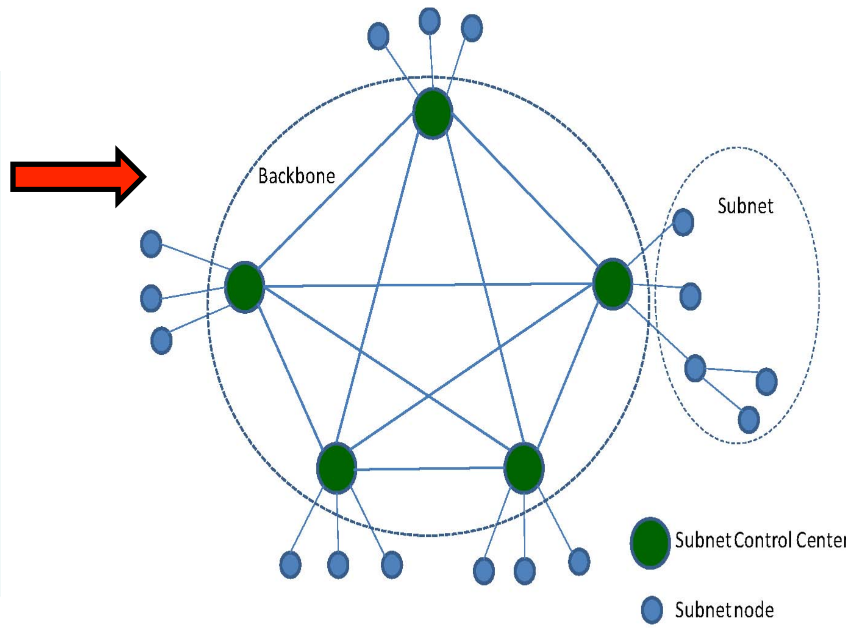


Can also use energy storage to aid privacy – leads to control theoretic solutions [w/ Tan, Gündüz, JSAC:SGC Series'13][w/ Yang, et al., T-SG'15] [w/ Giaconi, Gündüz, ICC'15]

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*

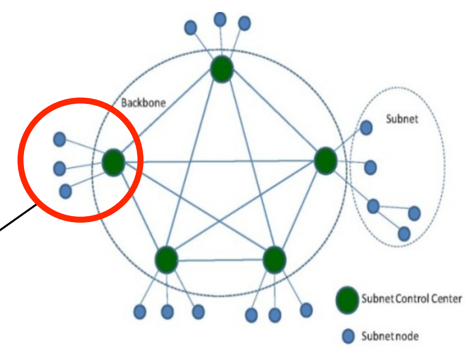
Competitive Privacy Model

[w /Sankar, Belmega, J-STSP, to appear]

- 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



- 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

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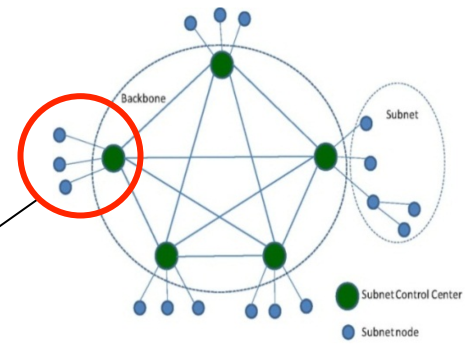

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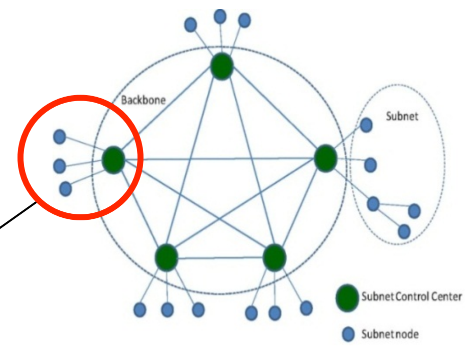

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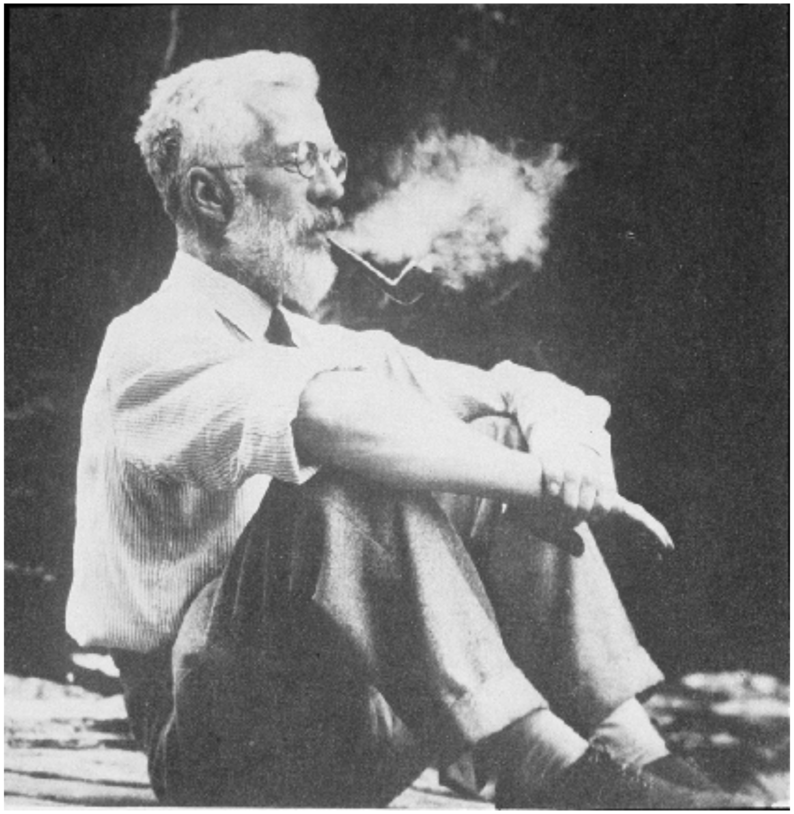
- Game theory can explain the interactions.

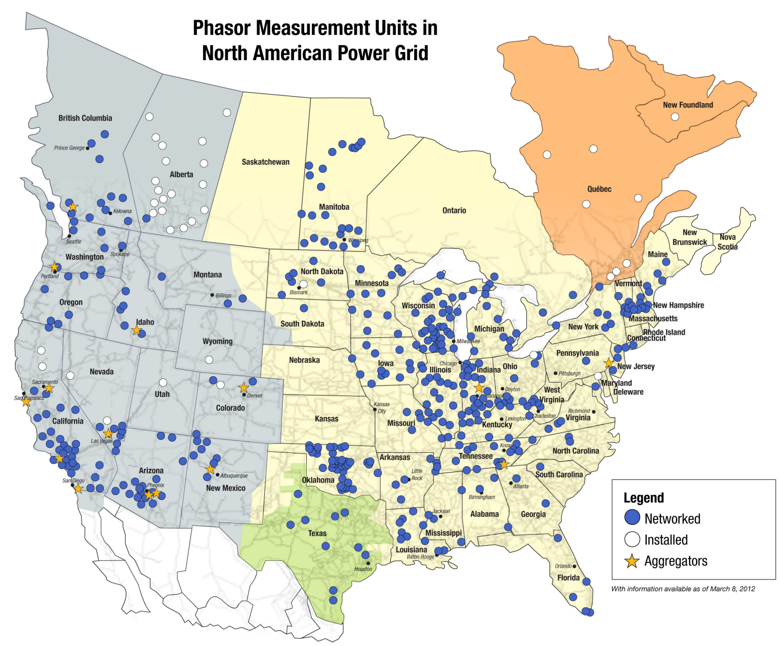
Inferential Methods for Greater Reliability



R.A. Fisher

Motivation

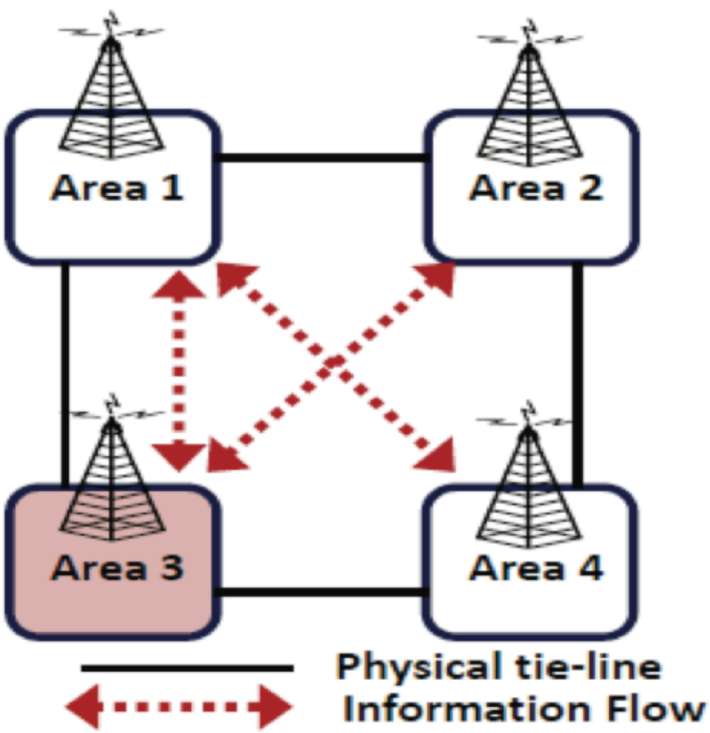
- Computational & communications challenge:
  - fast sensing produces big data, and communications bottlenecks
- Control can be decentralized into control areas (CAs)
- Of interest:
  - distributed algorithms to obtain system-wide situational awareness through local information exchange among CAs.



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 Estimation Algorithms

[w/ Xie, et al., T-SG'12; w/ Kar & Moura, SICON'13; w/ Di, et al., T-IT'15]

- Consider iterative estimates at each CA of the form:

new est. = previous est. + residual-error correction + consensus correction

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- Consider iterative estimates at each CA of the form:

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- For properly chosen parameters:

global observability of the grid

+

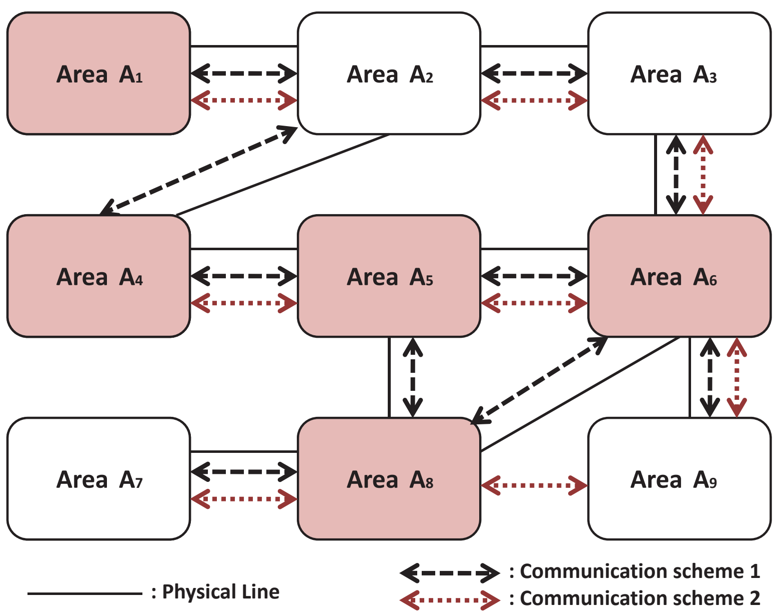
connectivity of the network

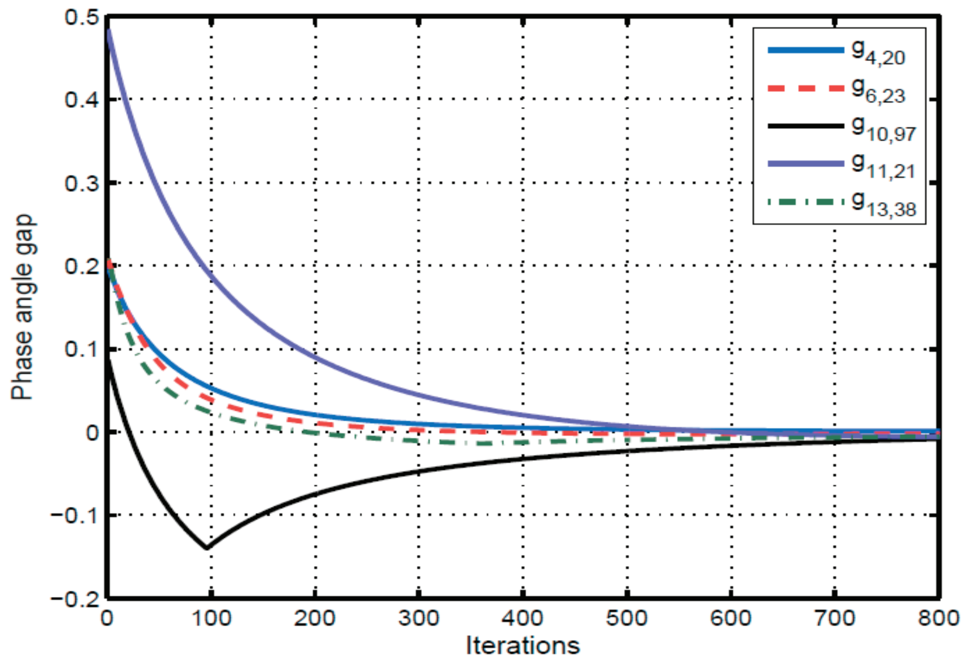
$\Rightarrow$

convergence to global least squares

Convergence of Phase Estimates

IEEE 118-Bus Test System

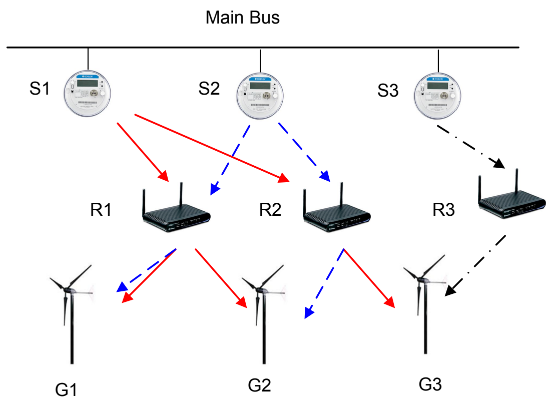




- Overall system is globally observable
- CAs are globally unobservable
- Shaded CAs are locally unobservable

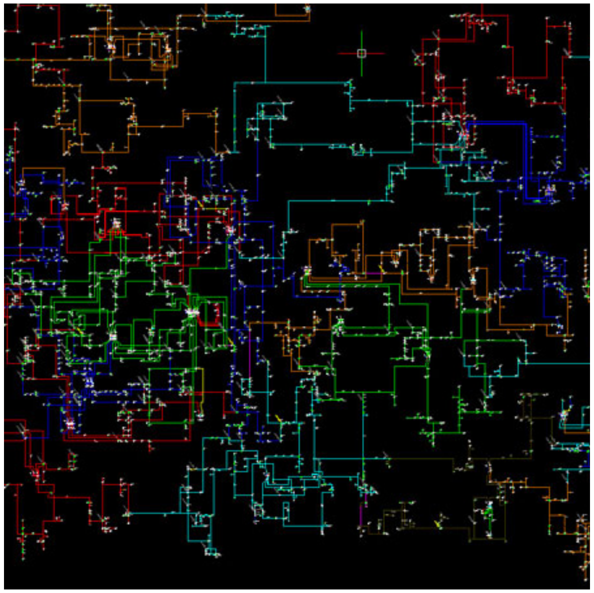
Related Work

- Multi-cast routing [w/ Li, Lai, JSAC:SG Series'12]



- Detection of data attacks, line outages, etc. [w/ Zhao, et al., J-STSP'14]

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!