Networking (related) Challenges for the Smart Grid

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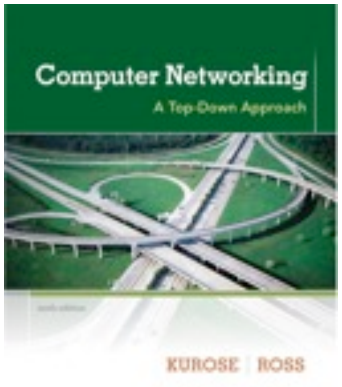
Overview

- yesterday's, today's and tomorrow's electric grid: a networking perspective
- five *(networking) smart grid* challenges
  - richer data gathering and distribution architecture
  - monitoring, measurement
  - dealing with demand: network-inspired approaches
  - security and privacy
  - power routing
- grid v. Internet: similarities and dis-similarities
  - reflections on Keshav's 1st and 2nd hypotheses

This talk: part tutorial, part research, part speculation

A word on my background …

computer networks + power grid networks = ?



joint IITB/UMass smart grid reading seminar

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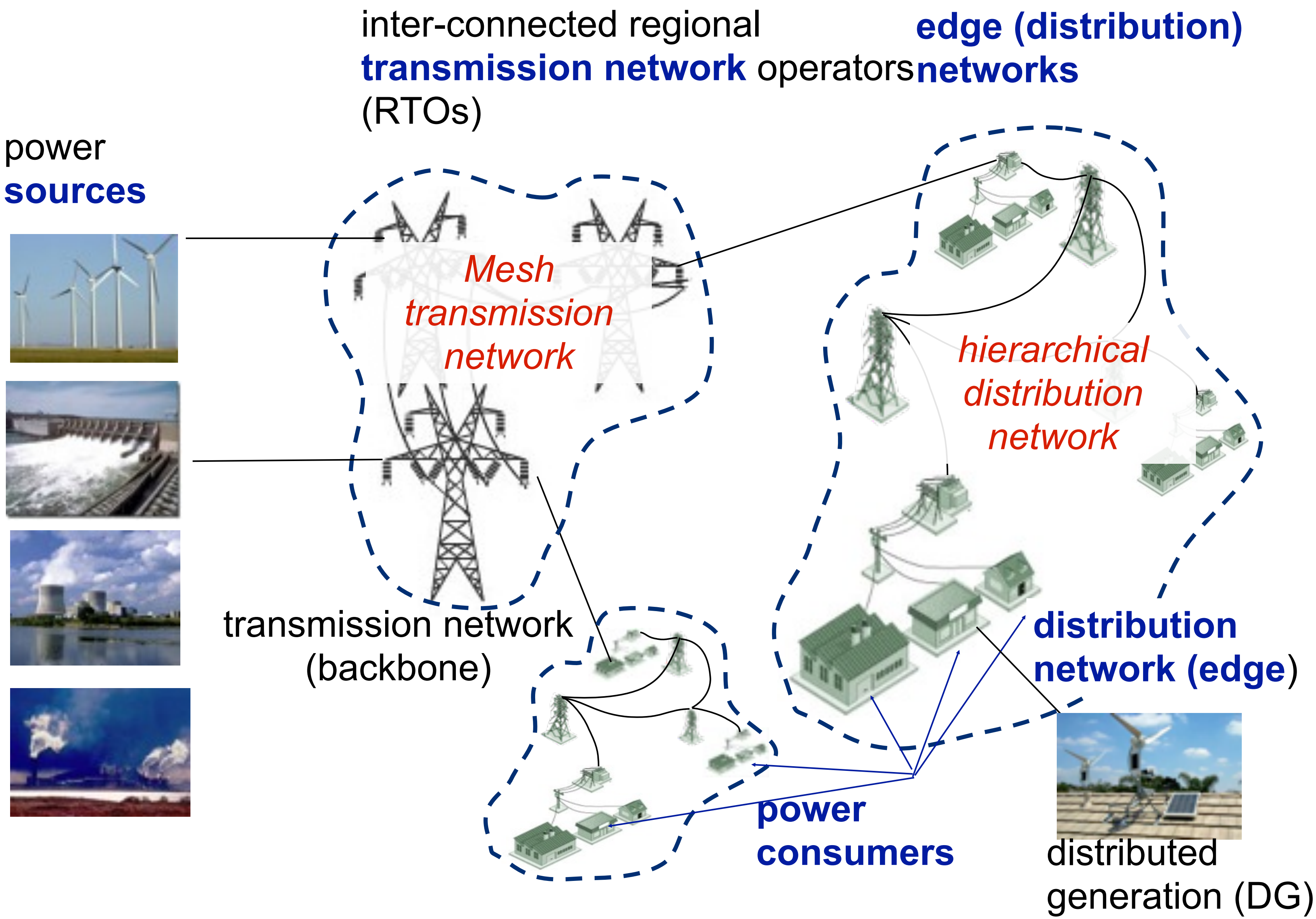
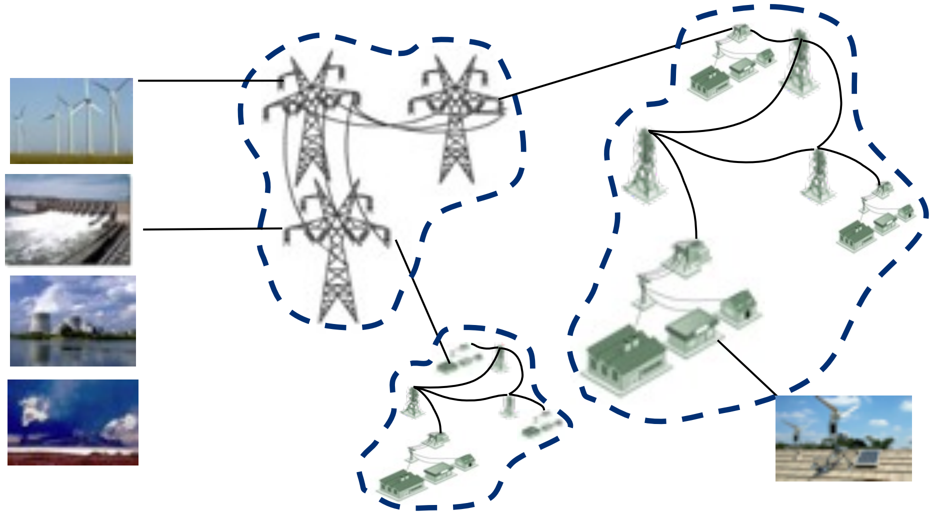
The electric grid: structure (US-centric)



The electric grid: structure (US-centric)

- electricity flows from producers to consumers
- overall supply must equal demand, flowing over links of given capacity
  - brownouts, blackouts



smart grid

using ICT to efficiently, reliably, flexibly and sustainably monitor and control the generation, distribution and use of electricity

Selected smart grid applications

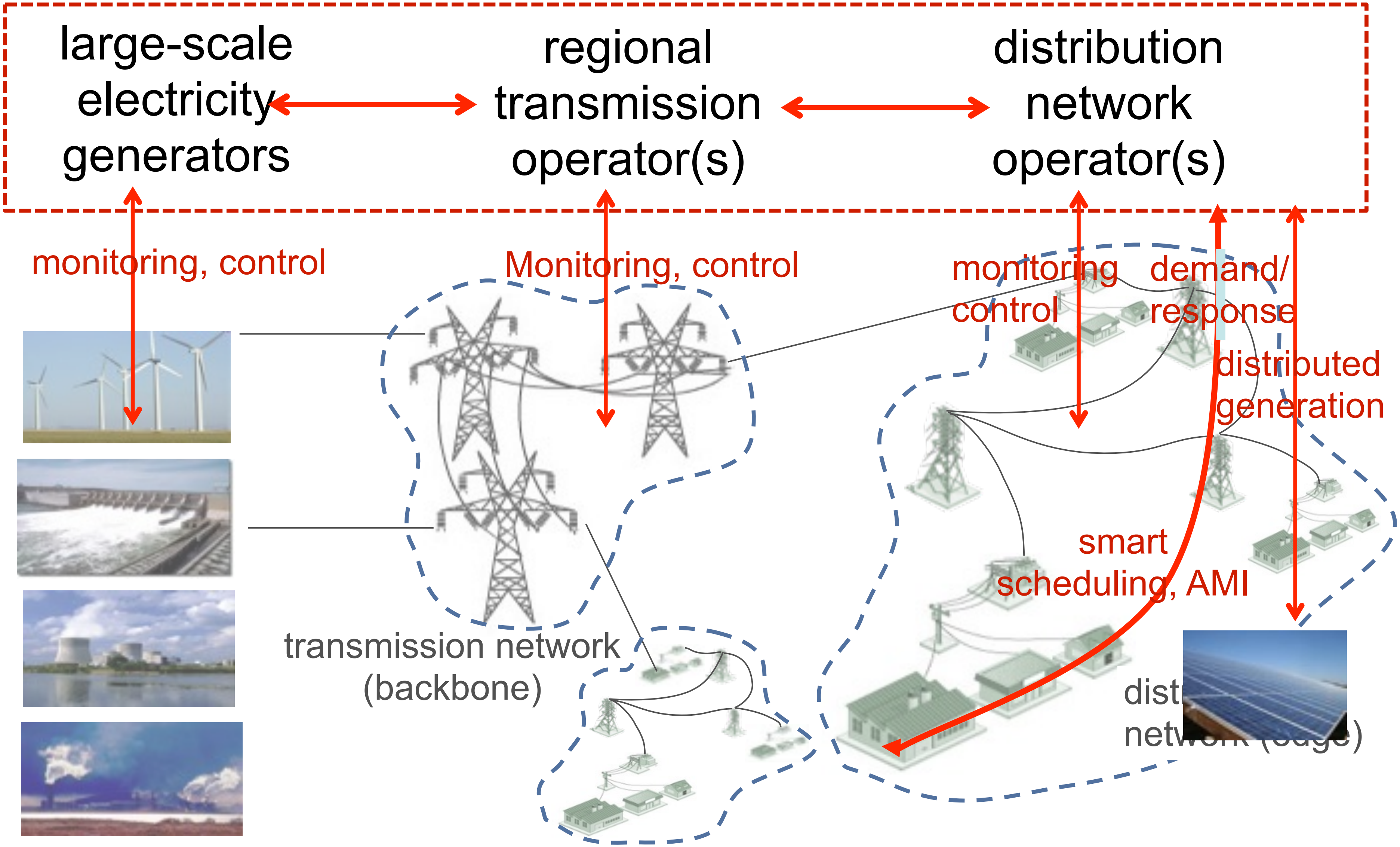
SG Application	Description	Communication: who

SG applications: communication requirements

SG Application	latency	frequency	Geographic scope

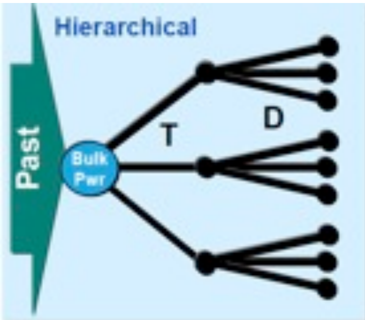
Bakken, D.E.; Bose, A.; Hauser, C.H.; Whitehead, D.E.; Zweigle, G.C., "Smart Generation and Transmission With Coherent, Real-Time Data," Proceedings of the IEEE, 99(6), 2011

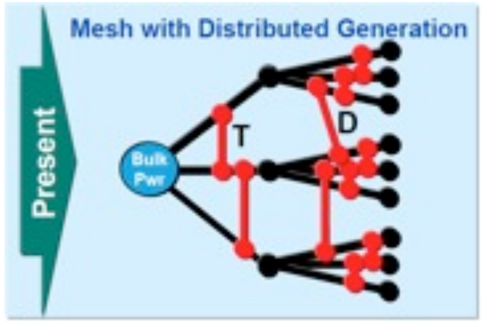
The smart grid: *communication flows*



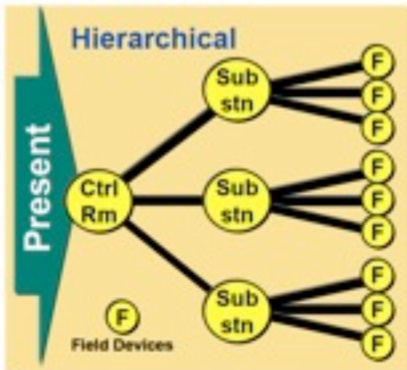
Grid communication network topology: from hierarchical to mesh topologies

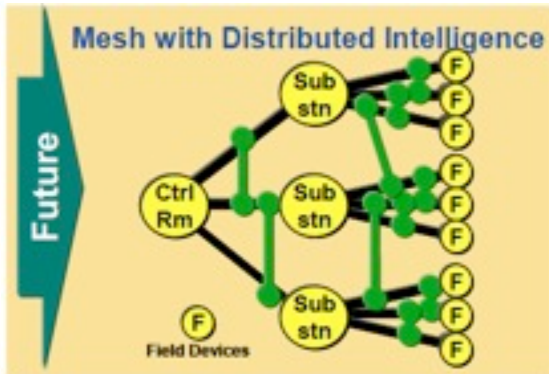
Electricity flow (distribution network)





Data communication flow between control room, substations and field devices



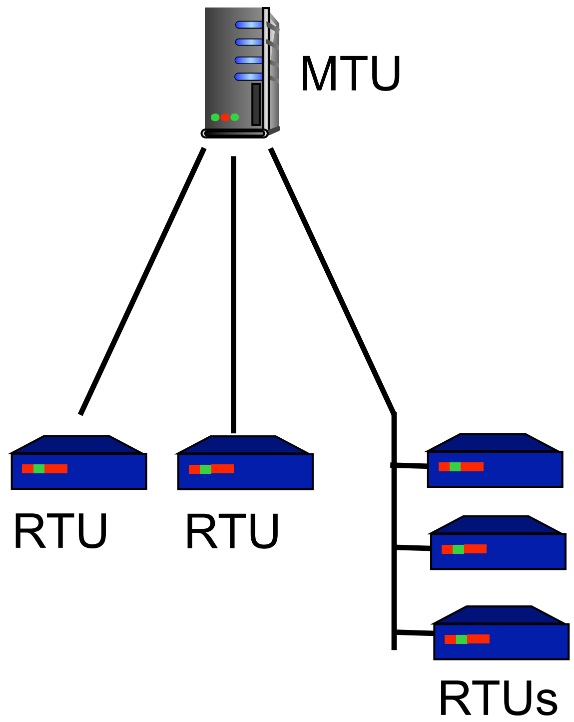


Focus: " enhancing the distributed control signaling architecture such that some level of device collaboration can be performed even when there are losses of control capability from the still dominant hierarchical control system architecture."

T.M. Overman and R.W. Sackman, "High Assurance Smart Grid: Smart Grid Control Systems Communications Architecture," 2010 *SmartGridComm*, 2010.

Today's grid control architecture: SCADA

- supervisory control & data acquisition
- *centralized* industrial measurement/ control system:
  - master terminal unit (MTU)
  - remote terminal units (RTUs): data gathering, control units, *polled* by MTU
- SCADA protocols: often proprietary, sometimes open



- DNP3: point-to-point link-layer polling protocol: addressing multiplexing, fragmentation, error checking/retrans, link control, prioritization
- DNP3: can poll over TCP/IP

Smart grid communication and the Internet

- grid communication:
  - stringent reliability, delay requirements for control
- Internet: *"best effort"* service model
  - network layer (IP):
    - "best effort" to deliver packet between hosts, but no promises
    - unreliable host-host delivery
    - no delay guarantees
  - transport layer (TCP): "laid back" transmission: "send … data in segments at its own convenience." [RFC 793]
  - transport layer (UDP): unreliable datagram transfer between

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Internet’s traditional best effort delivery, transport protocols not well-suited for high assurance grid communication (but that doesn’t mean they can’t be fixed or used!)

How can we, as networking researchers and computer scientists inform design, analysis of smart grid communications

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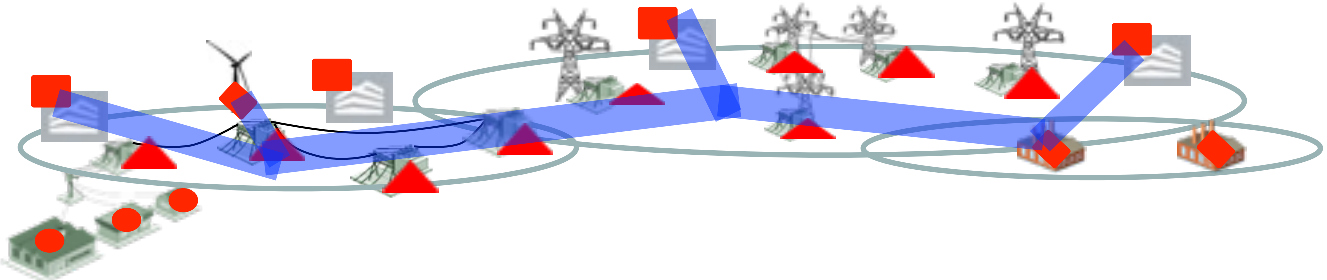
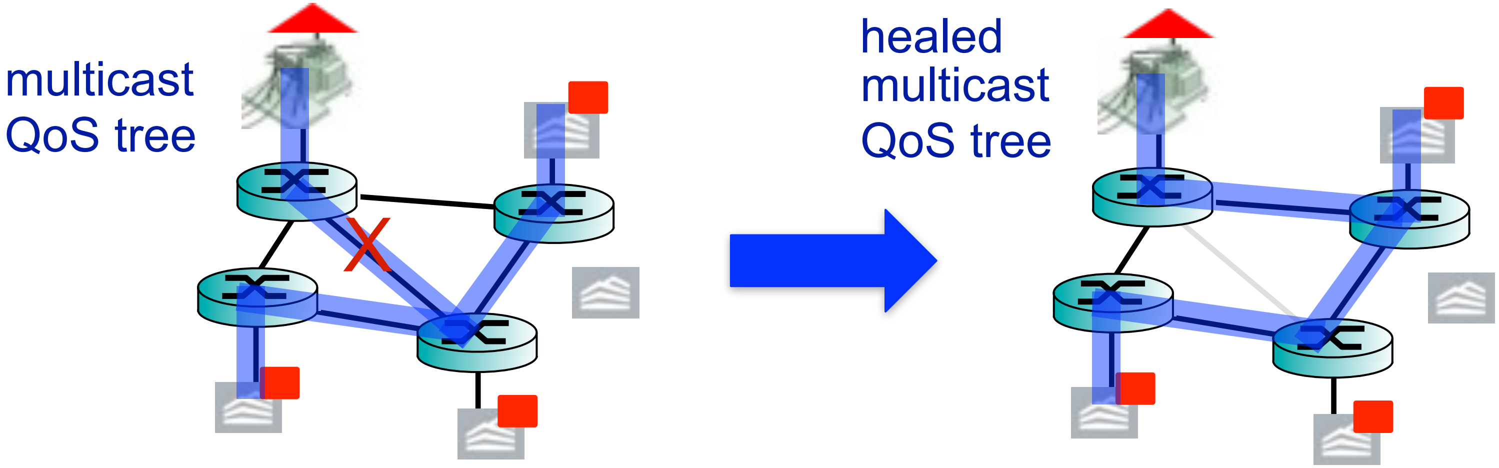
1. Rich data gathering, distribution architecture

- smart grid: many data sources and sink with interests in subsets of data:
  - real-time control, data analytics, archiving

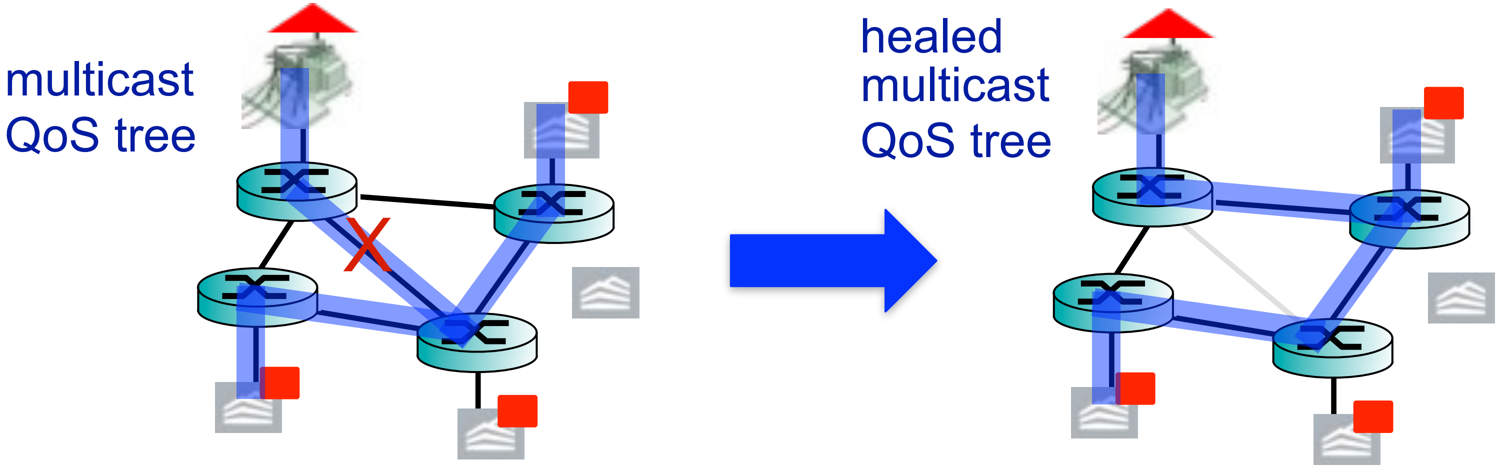


- SCADA: simple centralized polling
- richer communication paradigms:
  - self-healing mesh network
  - QoS bandwidth, delay guarantees
  - multicast (1-many)
  - higher-level abstractions (pub-sub, e.g., Gridstat)

Challenge: self healing, multicast mesh



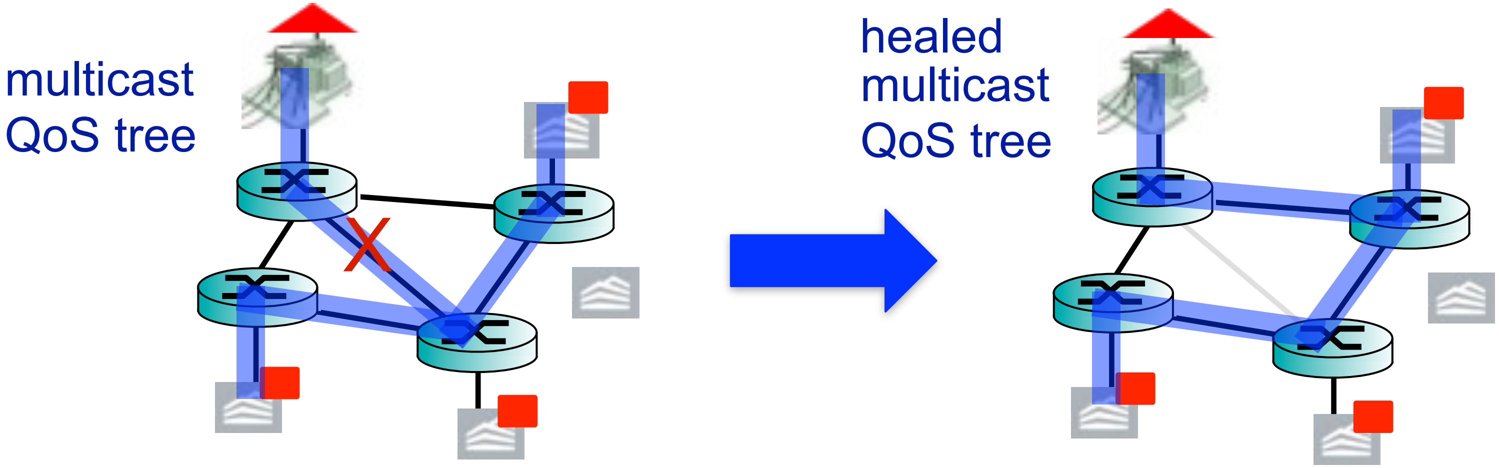
Challenge: self healing, multicast mesh



Multicast QoS: path reservation, as in MPLS

- compute source-specific multicast trees, with known link bandwidths and source-to-destination traffic rates
  - different from public Internet, which has unknown demand
- compute backup multicast trees
  - offline, in case of each link failure scenario
  - minimize # affected hosts, or # affected routers

Challenge: self healing, multicast mesh

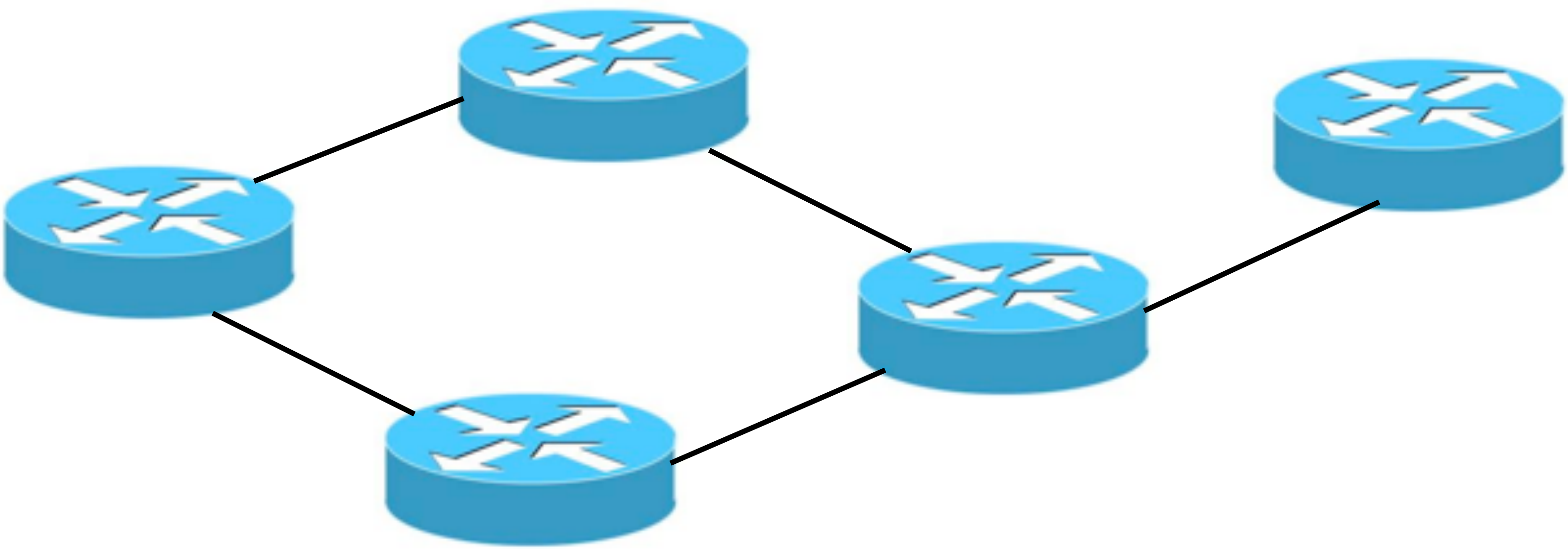


Down link, packet loss detection:

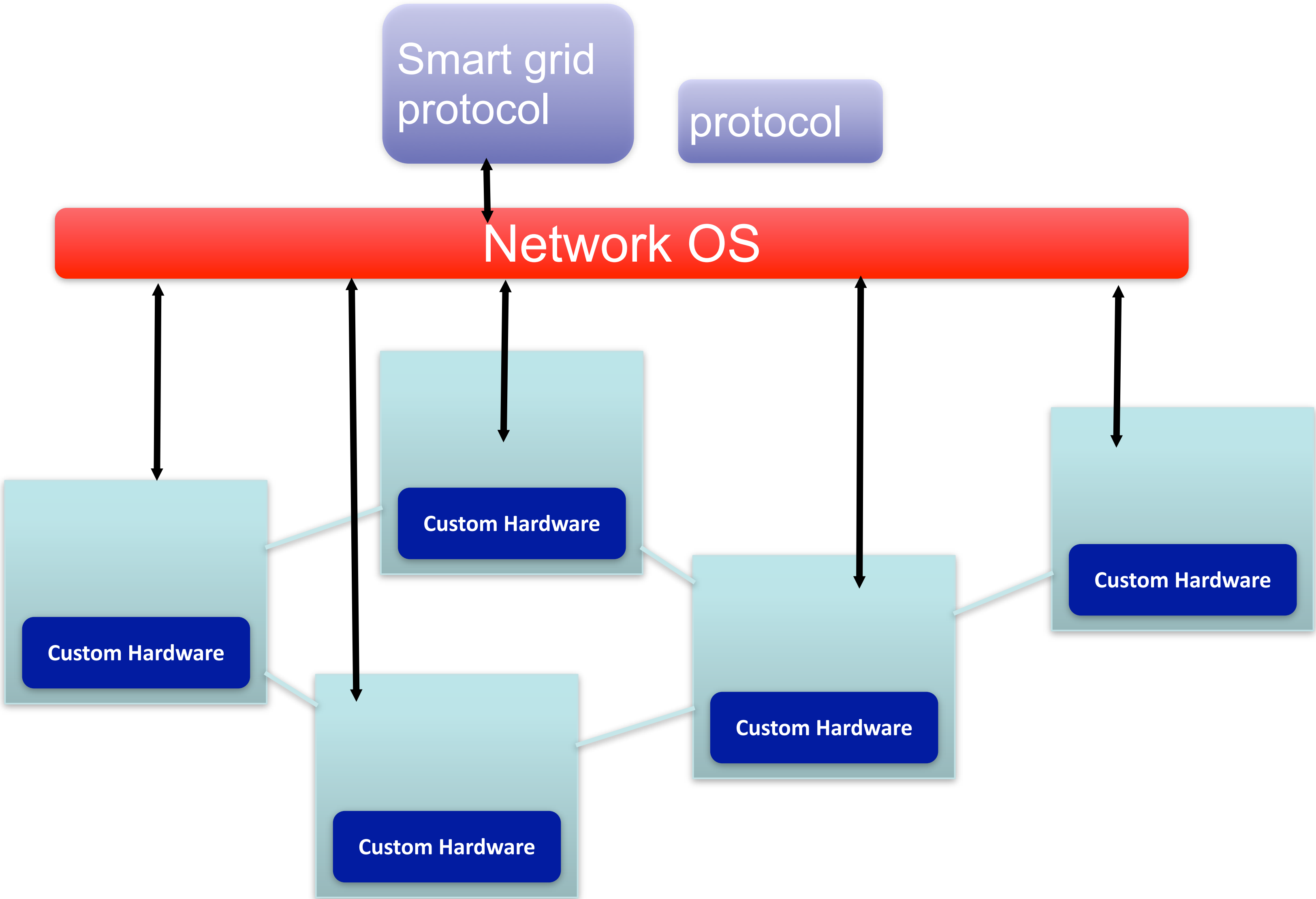
- *in-network*, per-link measurement, monitoring of link flows
- rapid, local link,/flow failure detection
- installation of pre-computed backup multicast forwarding trees

This requires changes to existing routers ….. how?

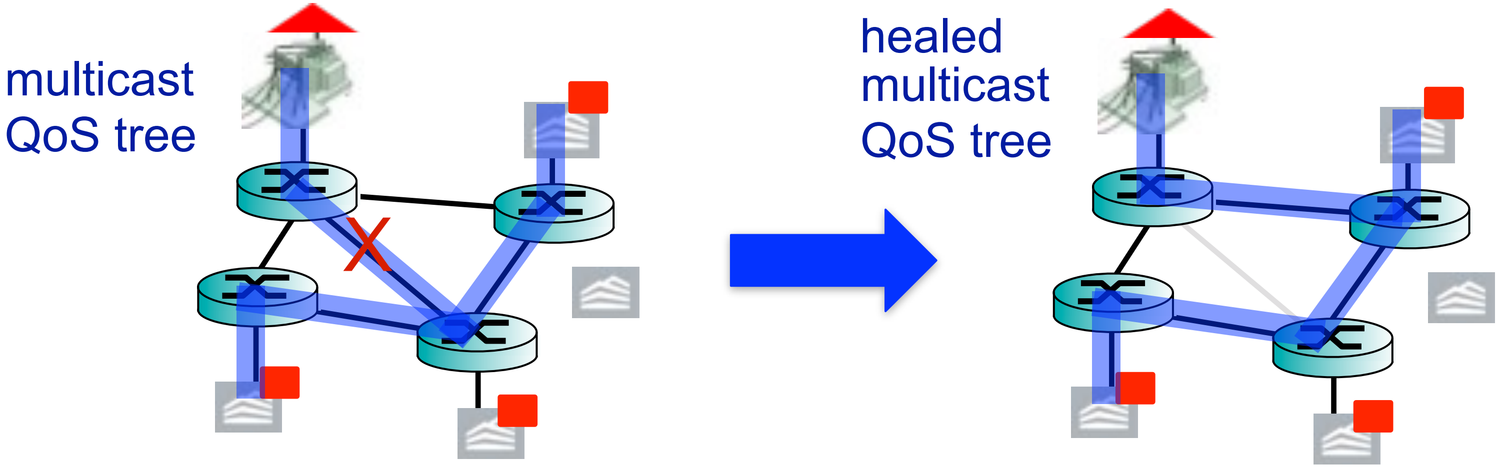
Openflow: open network control plane



Openflow: open smart grid control plane



Challenge: higher-level abstractions



- grid-specific communication protocols (e.g., high reliability data dissemination) enabled via SDN
- high-level data distribution abstractions:
  - publish-subscribe [Gridstat, NASPInet]
  - data-gathering + analytics: closed-loop cyber-physical system
- network virtualization: one physical network to home carrying multiple logically separate networks?
  - smart-grid, security, entertainment

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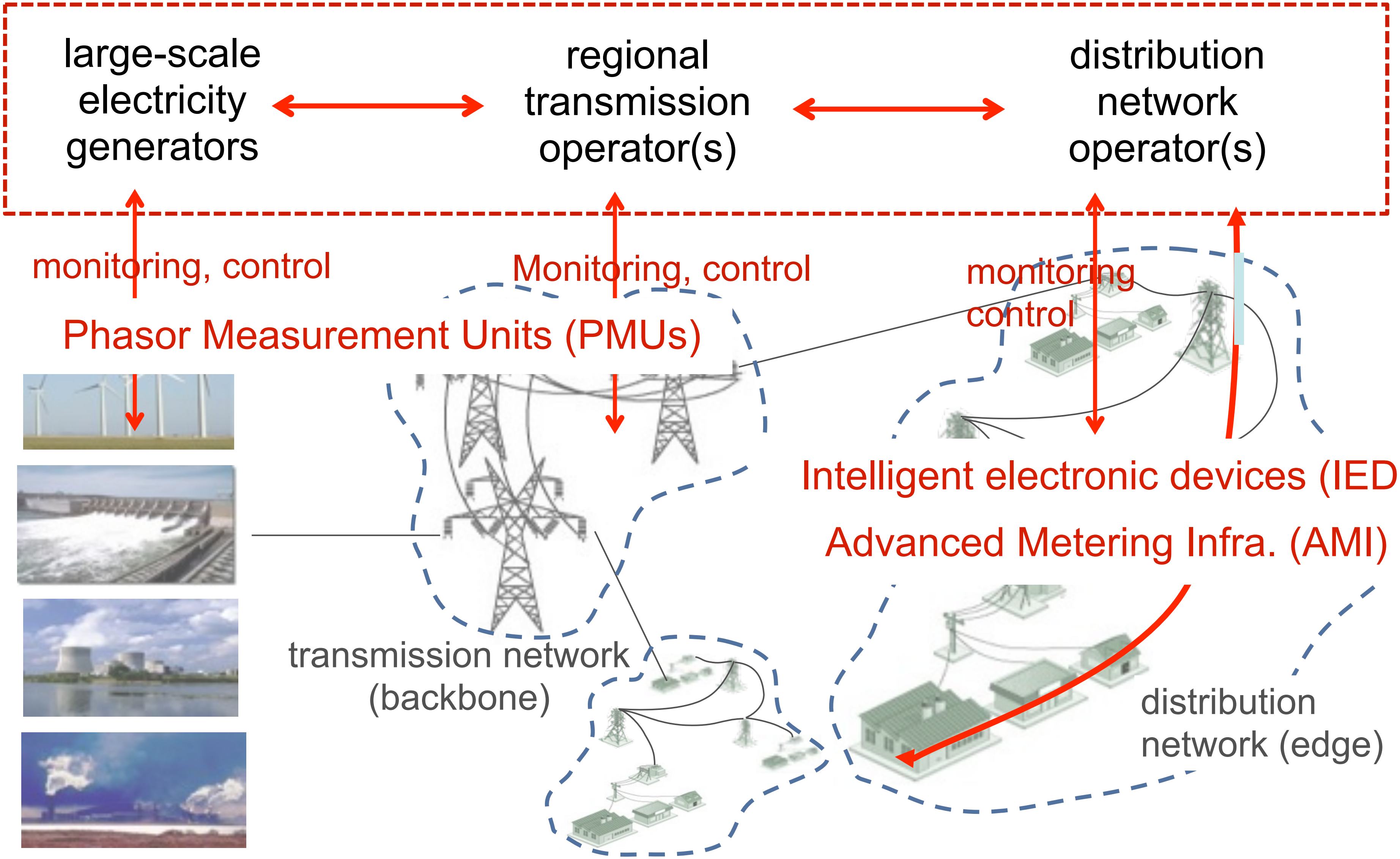
Control plane: measurement

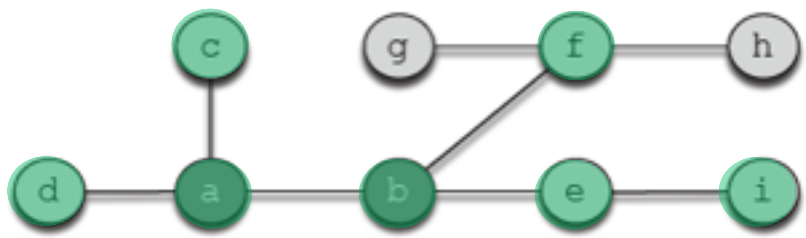


Grid measurement/monitoring

- where to place measurement devices to maximize observability?

  - *Observability rule 1:* if PMU placed at a, then a and its neighbors are observable
  - *Observability rule 2:* if a node is observable and all but one neighbors are observable, then all neighbors observable

D. Brueni and L. Heath. The PMU Placement Problem. SIAM Journal on Discrete Math, 2005



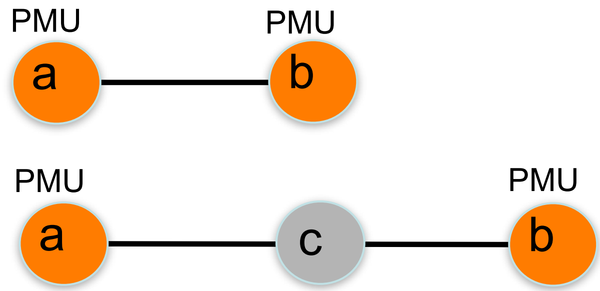
MaxObserve: Given graph, G=(V,E) and k PMUs, place k PMUs to maximize number of observed nodes

- MaxObserve is NP-complete, Reduce from Planar 3SAT (P3SAT)

PMU placement with cross validation

- where to place measurement devices to maximize measurement cross validation?

- *Observability rule 3:* If PMUs placed on adjacent nodes, they cross-validate each other
- *Observability rule 4:* If two PMUs share a common neighbor, the two PMUs cross-validate each other



MaxObserve-XV: Given graph, G=(V,E) and k PMUs, place k PMUs to maximize number of observed nodes, requiring that all PMUs be cross-valided

- MaxObserve-XV is NP-complete,

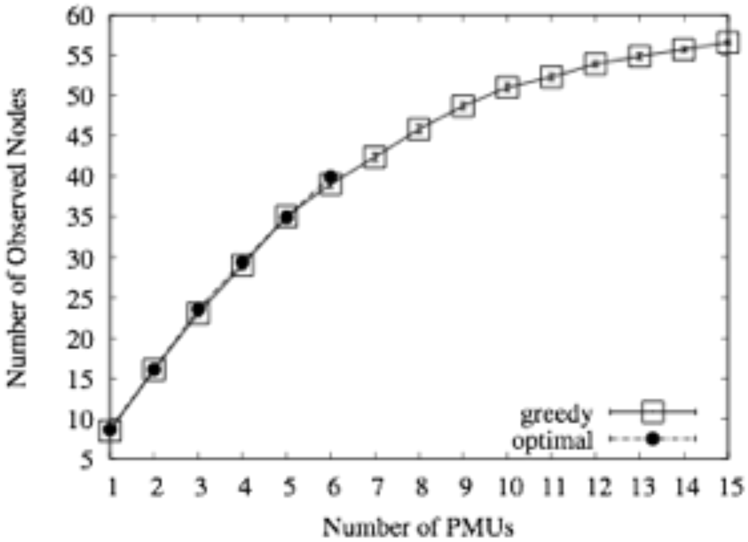
Vanfretti et al. A Phasor-data-based State Estimator Incorporating Phase Bias Correction. IEEE Transactions on Power Systems, 2010

Greedy Solutions to PMU placement

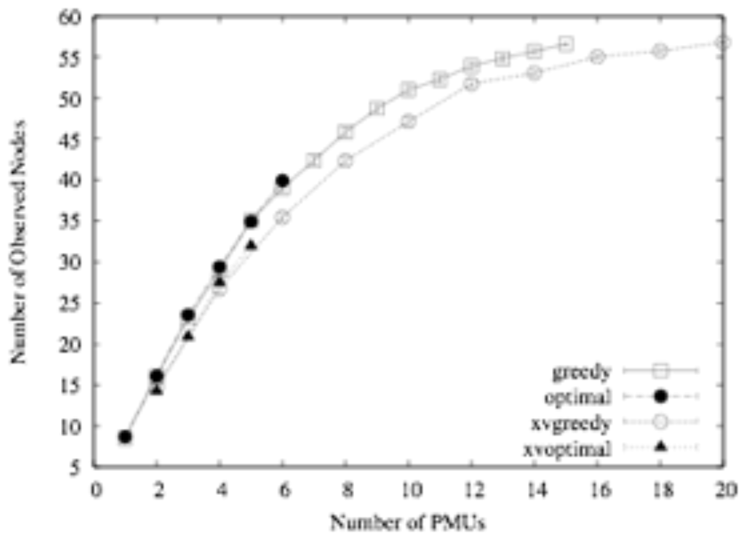
- MaxObserveGreedy: iteratively place k PMUs: iteratively at node that results in observation of max # new nodes
- MaxObserveGreedy-XV: iteratively place PMU pairs at nodes{u,v}, such that u and v are cross-validated and result in observation of max #new nodes

- evaluation:
  - generate grid networks with same degree distribution as IEEE Bus 57
  - brute force optimal solution by enumeration for small # PMUs

Greedy Solutions: evaluation



- MaxObserveGreedy within 98.6% of optimal



- MaxObserveGreedyXV within97% of optimal
- cross-validation requirement on decreases # observed nodes by ~ 5%

D. Gyllstrom, E. Rosensweig, J. Kurose, “On the Impact of PMU Placement on Observability and Cross-Validation,” Proc. ACM *e-Energy 2012*

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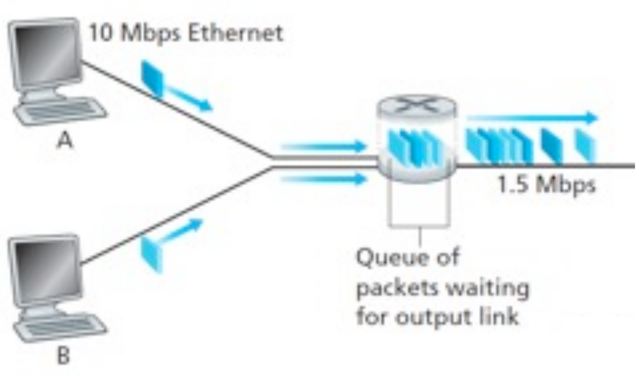
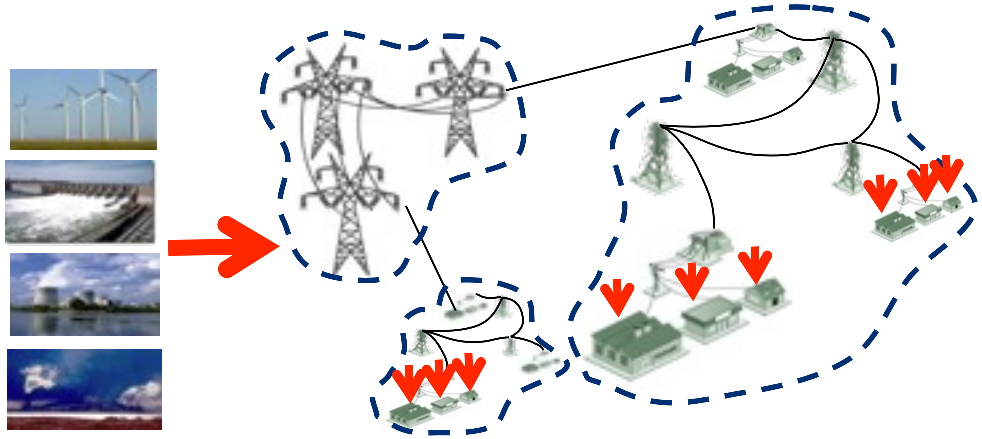
Dealing with demand





computer network:

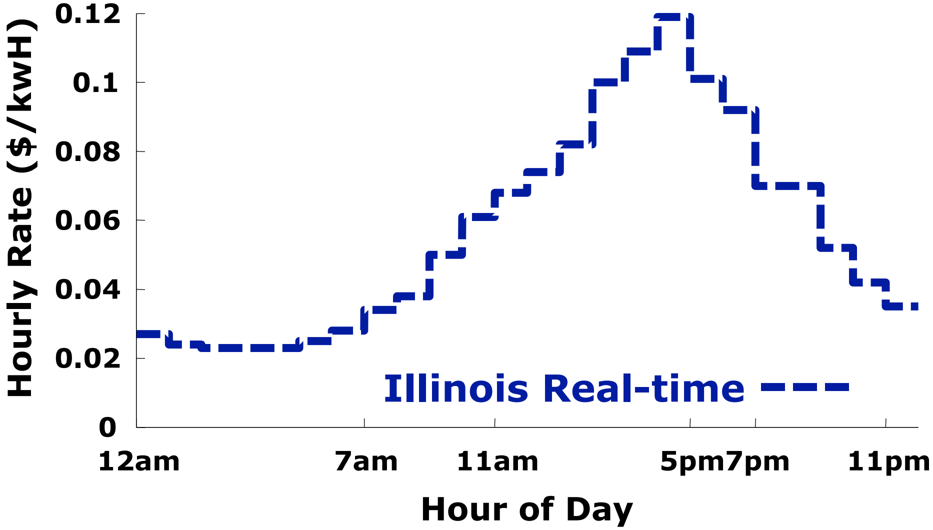
- packet-level congestion
- local
- reactive: buffer, defer load

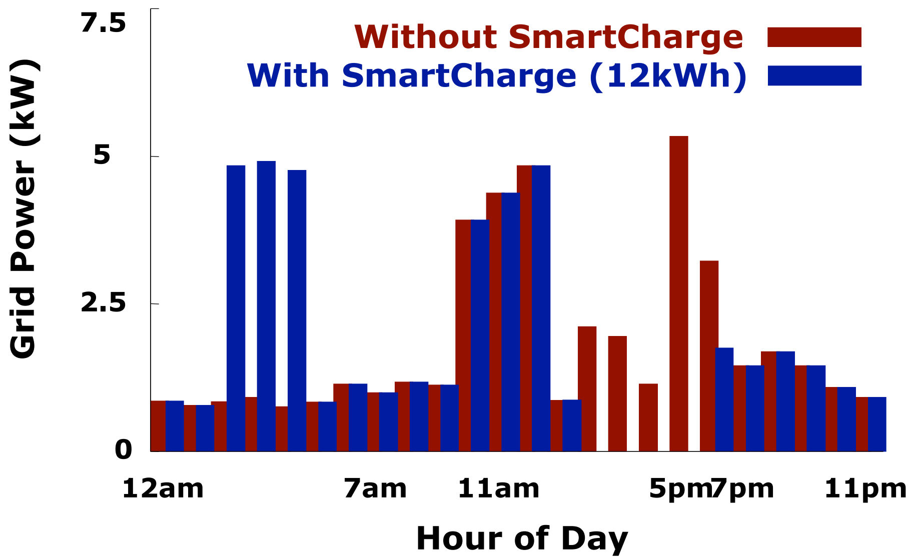
smart grid network:

- balancing power supply, demand
- global
- reactive: load, source shedding
- proactive: buffering via storage
  - pumped hydro, battery
  - prediction crucial

SmartCharge: residential battery storage

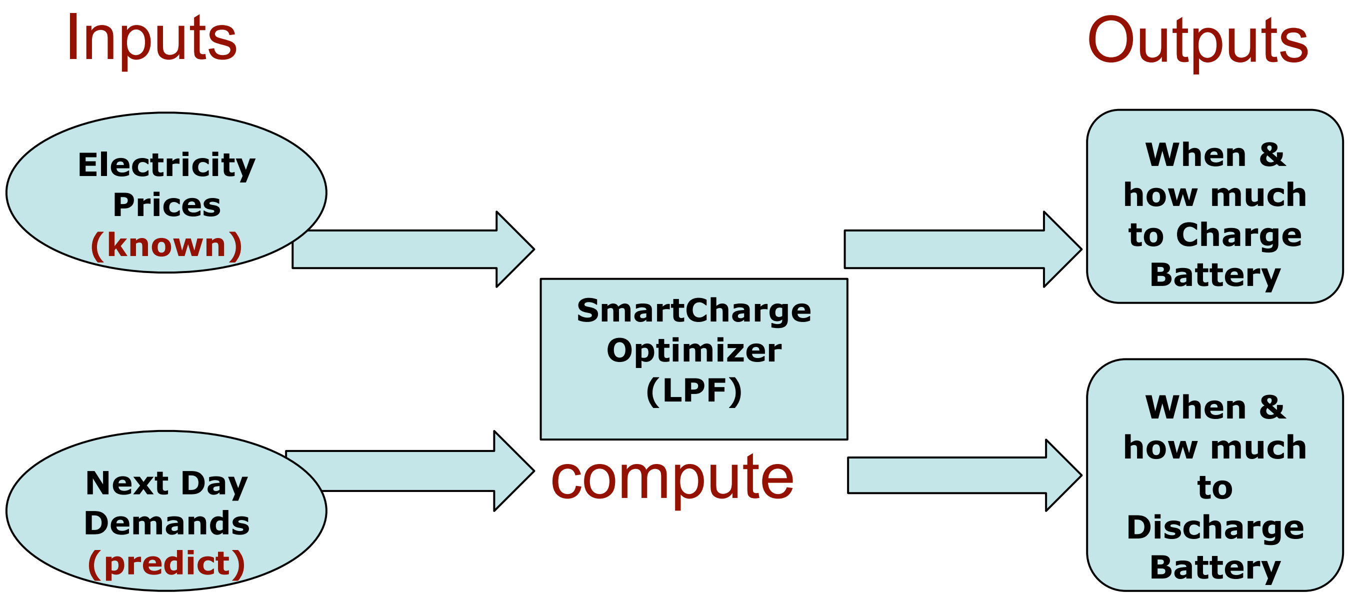
- Key idea: charge battery at off-peak hours
  - off-peak price < peak price
  - shift residential grid use from peak to off peak hours: charge battery when prices are low, use battery (reducing grid use) when prices are high





SmartCharge: Charging-Discharging Decision

- given: electricity price from day-ahead market
- predict: consumption
- compute: optimal battery charge/discharge schedule



Demand prediction via machine learning

- predict future energy usage, training using past historical data
  - data features:
    - weather (temperature + humidity)
    - time (month, day, weekend, holiday)
    - history (previous day)
- best predictions with SVM-Poly
  - within 5.75% of real usage
  - best at night (within 4%)

SmartCharge: LPF

Min cost with battery storage for ToU pricing

1. Objective

$$\min \sum_{\{i=1\}}^{T} m_i$$

2. Energy charged >= 0

$$s_i \geq 0, \forall i \in [1, T]$$

3. Energy discharged >= 0

$$d_i \geq 0, \forall i \in [1, T]$$

4. Max charging rate

$$s_i \leq C/4, \forall i \in [1, T]$$

5. Charge conservation

$$\sum_{\{t=1\}}^{i} d_t \leq e * \sum_{\{t=1\}}^{i} s_t, \forall i \in [1, T]$$

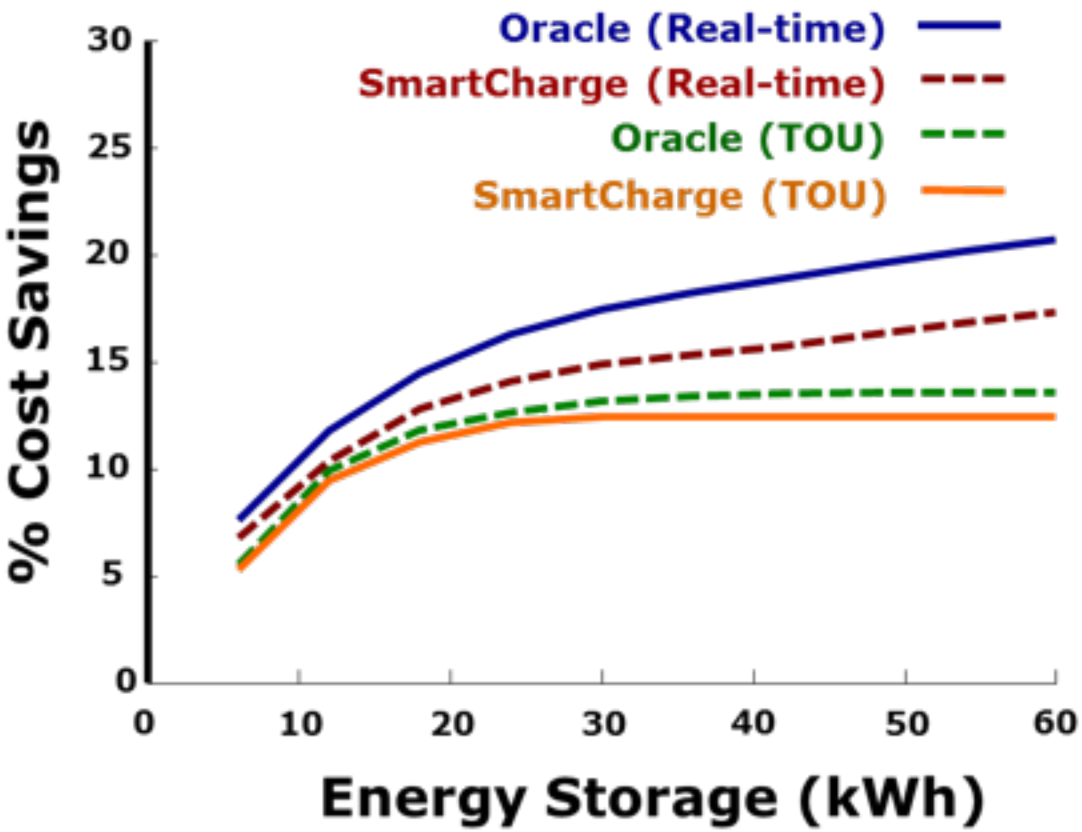
6. Capacity constraint

$$\left(\sum_{\{t=1\}}^{i} s_t - \sum_{\{t=1\}}^{i} \frac{d_t}{e} \right) * I \leq C, \forall i \in [1, T]$$

7. Price calculation

$$m_i = (p_i + s_i - d_i) * I * c_i, \forall i \in [1, T]$$

SmartCharge: Household Savings



- 10-15% savings
- within 8-12% of Oracle
- savings flatten >24kWh

A. Misra, D. Irwin, P. Shenoy, J. Kurose, T. Zhu, “SmartCharge: Cutting the Electricity Bill in Smart Homes with Energy Storage,” Proc. ACM *e-Energy 2012*

Prediction: many opportunities

- home demand
- peak demand flattening (via shiftable loads, storage)
- renewable sources (wind, hydro) generation
- transmission grid demand
- .....

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Security and Privacy

- many Internet analogies (indeed, communication infrastructure needs to be protected)
- securing infrastructure
- securing data
  - protection from eavesdroppers
  - detecting injection attacks
- *privacy:* randomized AMI to allow accurate aggregate load prediction, while maintaining individual privacy

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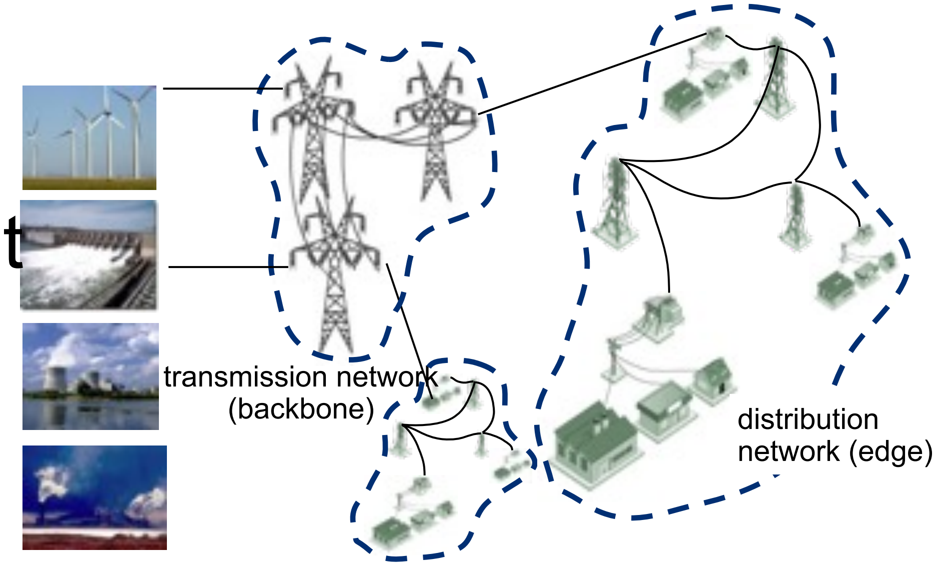
Electric grid: sources, destinations

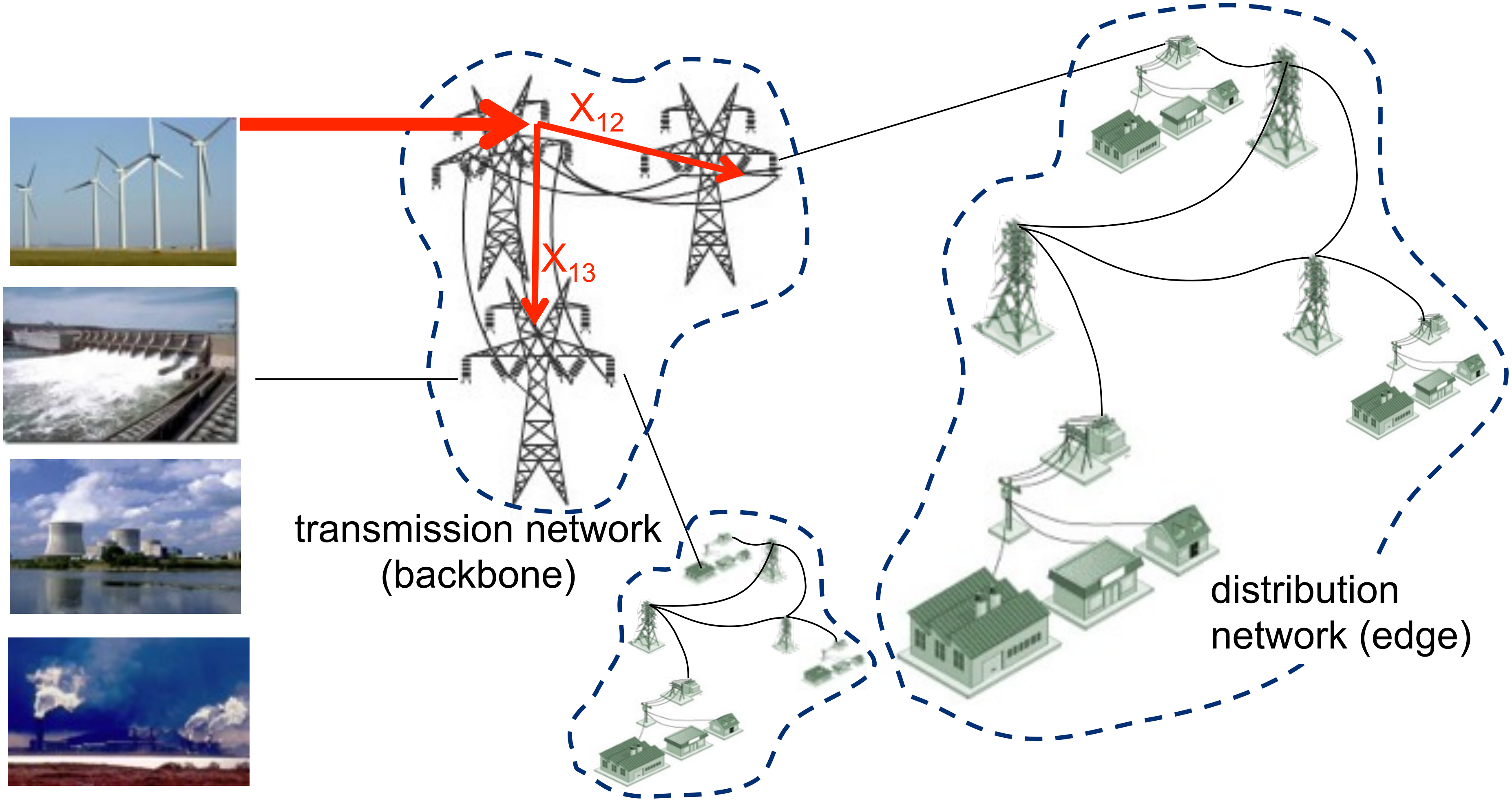
Observation: transmission networks move power from sources to destinations - seems analogous to **routing**!

- power flows not distinct, not addressable (no packet headers)
- traditionally: power passively flows following Kirchoff's and Ohm's laws(no "active" routing)

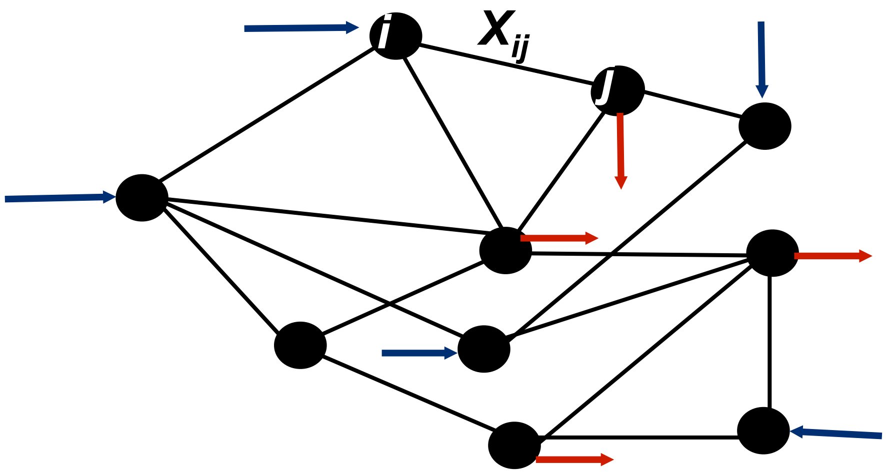


Electric grid: power routing

FACTS (flexible AC transmission system) devices – dynamically change transmission line impedance, changing passive power flow!



Power routing



S_i: source (generated) flow at i

L_i: load (consumed) flow at i

X_{ij}: flow from node i to node j

Find X_{ij} to minimize some cost function of X_{ij} subject to:

- flow conservation (flow in = flow out)
- capacity constraints ($X_{ij} < C_{ij}$)

Routing algorithms are the "bread and butter" of networking researchers

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What can the smart grid learn from 40 years of computer networking research?

Grid versus Internet: network of networks

Q: Regional transmission network $\stackrel{?}{==}$ Autonomous System

A: analogy is a bit strained

- low degree of inter-RTO connectivity (rather than dense connectivity)
- geographic proximity determines RTO connectivity (rather than peering, customer-provider relationships)
- distribution network connects to single RTO (albeit at multiple points for redundancy)

Reflection: what can the Internet teach us?

Keshav 1st hypothesis

Internet technologies, research developed over past 40 years, can be used to green the grid

The "sweet spot" is in developing the control plane architecture!

- but….
  - Internet *best effort service* model won't cut it
  - *manageability, security, reliability* (five 9's) not yet Internet main strengths

Reflection: what can the Internet teach us?

Keshav 2nd hypothesis

The next decade will determine the structure of the grid in 2<u>1</u>20

architecture: punctuated equilibrium?

- today's IP v4: 30+ years old
- telephone network: manual to stored-program-control to IP over 100 years
- today's meteorological sensing network: 30+ years old

…… the time is indeed now

Conclusions

- smart grid: many research opportunities
- ICT can/must inform smart grid design operation
- importance of working with domain experts
  - two-way collaboration with significant “start up” costs, e.g., bioinformatics, sense-and-response hazardous weather prediction
- IITB/Umass joint seminar: spring 2013

the end

\- thank you -

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