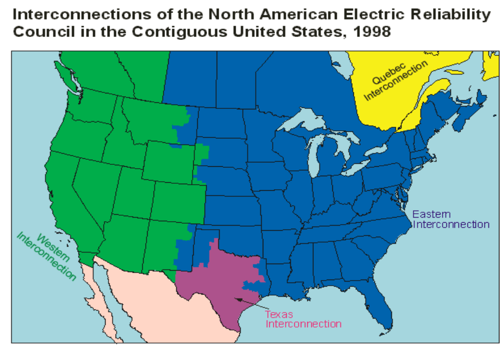
Ultra-Large Scale Control and Communications in Energy Delivery Systems

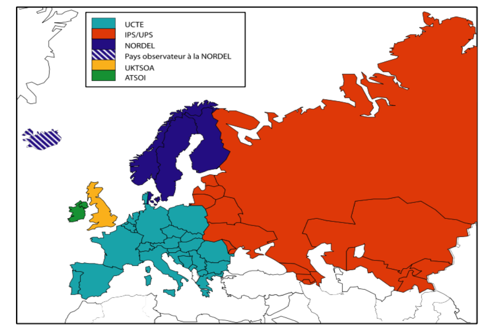
Jeffrey D. Taft, PhD
Chief Architect, Cisco Connected Energy Networks

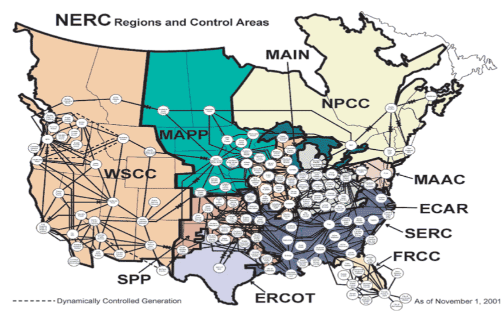
22 May 2013

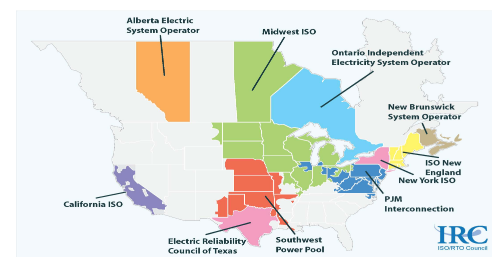
Electric Grid Background

- Highly complex interaction of devices, systems, and organizations
- Each “grid” is a huge complex machine
- Multiple levels of control
- Multiple organizational boundaries as well as system boundaries
- While some vertically integrated utilities still exist, a good deal of disaggregation has taken place in much of Europe and parts of the US









Grid Control Original Conditions

Original key principles:

- Generation is dispatchable
- No significant energy storage in the grid
- Generation follows load
- Power must be kept in balance (flow control)
- Real power flows in one direction only
- Within an interconnection, AC generation is synchronized
- Voltage, reactive power, and system frequency are regulated
- Reliability, not economy!

emerging power grid trends

Advanced Grid Management Issues

- Grid stabilized by inherent rotational inertia
- Dispatchable generation
- Passive loads
- Moderate digital control is adequate

- Reduced rotational inertia due to change in energy source mix
- Stochastic generation (DER/VER)
- Transactive loads and markets
- Grid control as we know it is not adequate

Grid Stabilization in Future Power Systems

"Fly-by-Wire" Air Craft

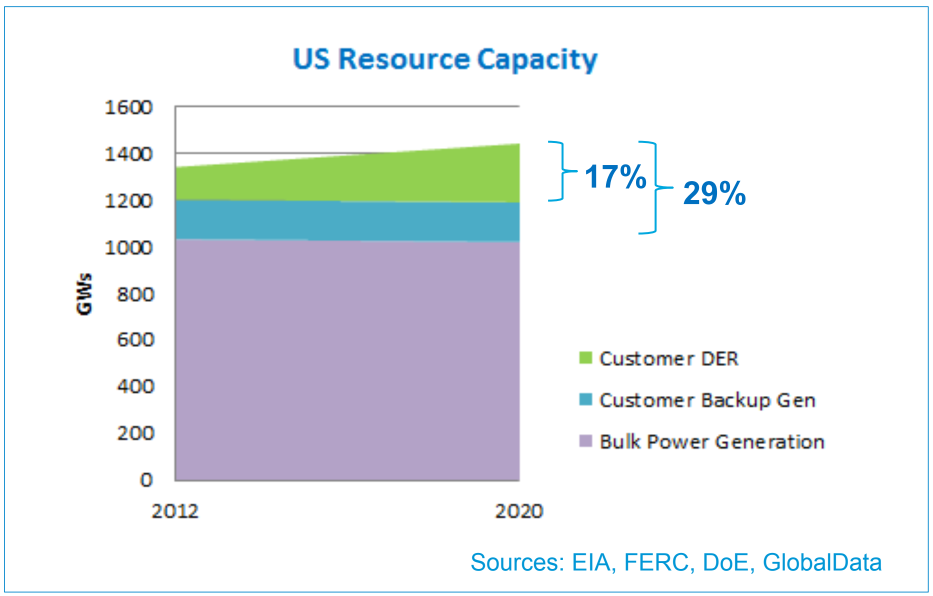
"Fly-by-Wire" Power Grids

- Need for high performance
- Must be agile for combat
- Unstable by design
- Electronically stabilized

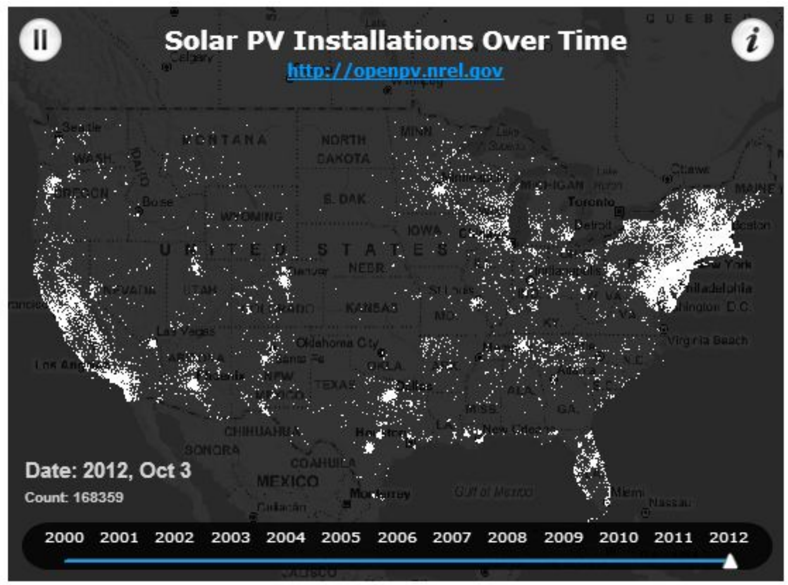
- Need to integrate new capabilities
- Must be agile for reliability
- Unstable by evolution
- Electronically stabilized

Key US Utility Market Transitions

- Extensive connectivity with greatly increased security
- Centralized to distributed control and intelligence
  - Destabilizing effects are accumulating rapidly and irreversibly
  - “Human in the Loop” is not sustainable or scalable
  - Utilities recognize these viral trends driving distributed control



Sources: EIA, FERC, DoE, GlobalData



New(er) Grid Functions

- VER integration (wind, solar, etc.)
- Wide area measurement, protection, and closed loop control
- DER/DG integration (distribution level)
- Energy storage integration
- Responsive loads (command, price, and /or system frequency)
- Integrated Volt/VAr control (LTC/cap)
- Advanced distribution fault isolation/service restoration
- Third party energy services integration
- Electric Vehicle (EV) charge management
- Inverter control for fast VAr regulation
- Local energy network and microgrid power balance and flow control
- Multi-tier virtual power plants
- Energy/power market interactions for prosumers; Transactive Energy
- Electronic grid stabilization (FACTS for transmission; DSTATCOM for distribution)
- Load modulation of buildings, electric vehicle chargers, and data centers for local balancing

No single use case predominates; the platform must support ensembles of grid control functions; utilities are being driven to select their function sets.

smart grid heresy

Four Points of Smart Grid Heresy

- Focus on the smart grid “killer app” is misplaced and not helpful
- The work on interoperability has been missing a context
- AMI is not the smart grid
- Most smart grid reference architectures have the same very large gap

The Key Grid Issue

- Business outcomes for utilities derive not from sensors and data, or communication networks, or analytics…
- Business outcomes arise from decision and control processes and systems

The Key Grid Modernization Problem

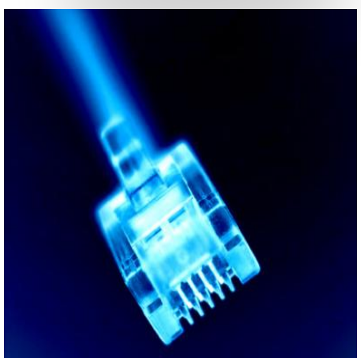
Given the structure and multiple requirements and constraints on the whole power delivery chain, provide a unified multi-tier control that simultaneously optimizes operation across all tiers, including the prosumer tier.

The Modern Grid Turns Out to be About Something Much Larger than Meters or Smart Objects

Power Grids

Convergence occurs at the grid control systems

Financial Networks (Markets)



Information and Communication Networks

Social Networks

It is the decision and control systems and processes that cause business outcomes

grid control issues

Major Control Functions

- Dispatch – generation, DR/Virtual Power Plants, interchange
- Balance – equalization of generation and load in real time
- Flow control (switch settings, mostly, but PFC's emerging)
- Regulation – maintain parameter (e.g. voltage, frequency, reactive power) within limits
- Stabilization – counteract unpredictable disturbances
- Synchronization – maintain phase relationships
- Secondary load control – control of non-utility assets

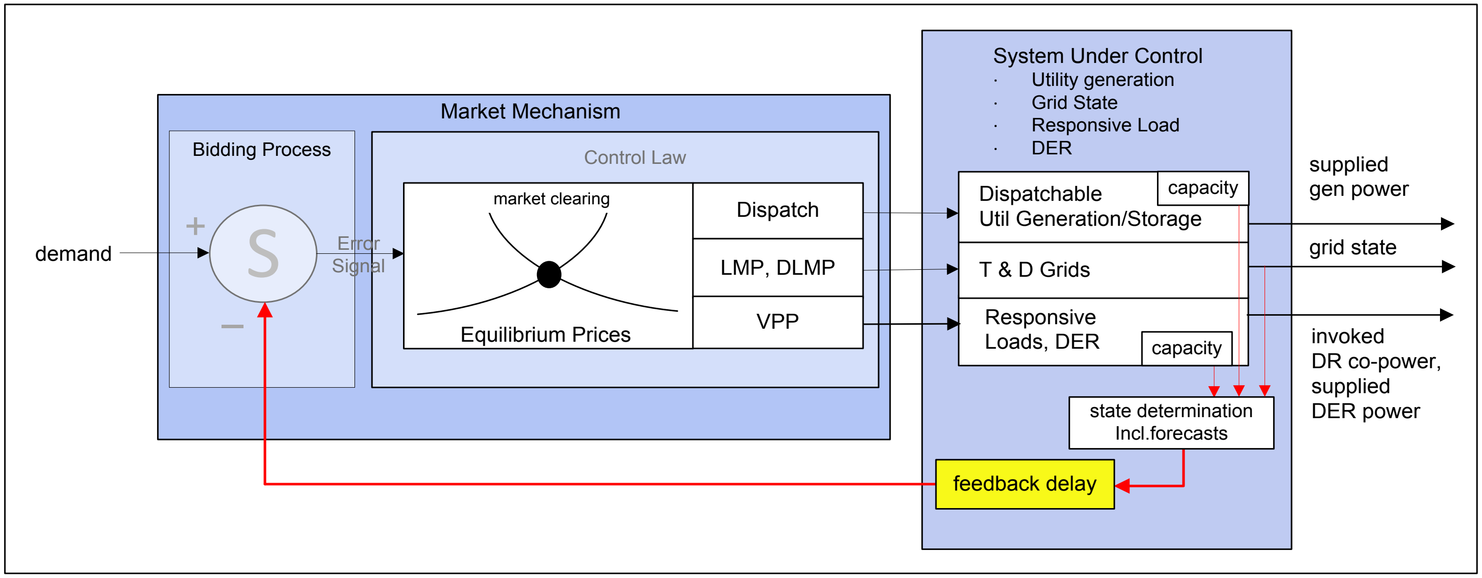
Issue: Hidden Coupling via the Grid

- Electrical physics rules the grid – shaped by grid connectivity
- Business models and software cannot change this
- Must be taken into account in control design to avoid unintended consequences
  - IVVR/DR
  - CVR/PV
  - Market/responsive loads
- Becomes important as new rollouts of smart devices scale to full deployment
- Implications for architecture, design, and control

Jose Medina, Nelson Muller, and Ilya Roytelman, "Demand Response and Distribution Grid Operations: Opportunities and Challenges," **IEEE Trans. On Smart Grid**, vol. 1, pp. 193-198, Sept. 2010.

Issue: Grid Destabilization

- Variable Energy Resources; reduction in rotational inertia in grid
- Some elements may reside outside of the utility: responsive loads, DG/DER
- Energy Services Organizations operating outside grid control regime
- Inter-tier control loops
- Active load interactions with grid control systems can be unstable; volatility of grid with price sensitive loads; markets as control elements: flash crashes

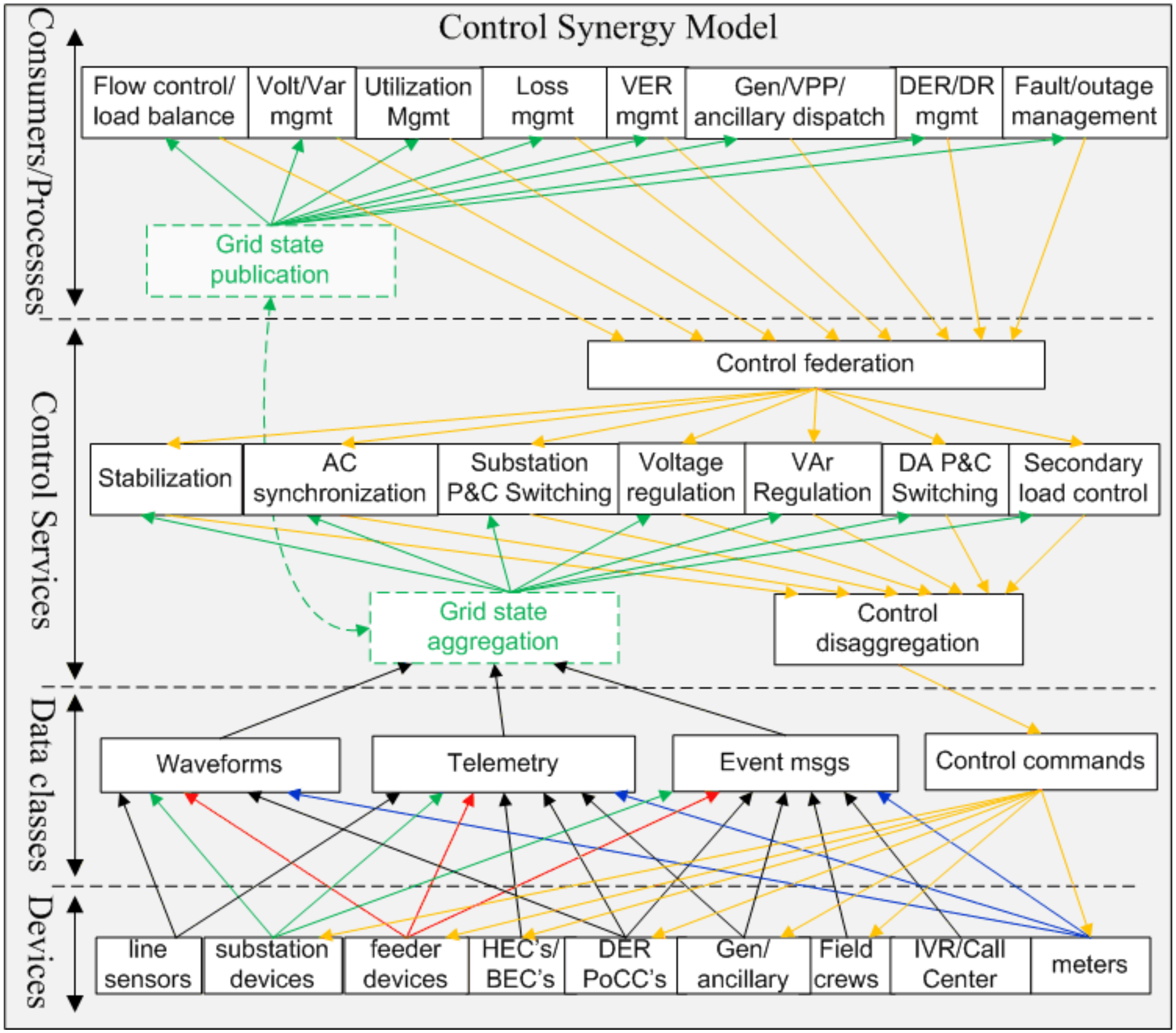


"Volatility of Power Grids Under Real Time Pricing", [www.mit.edu/~mardavij/publications_files/**Volatility**.pdf](www.mit.edu/~mardavij/publications_files/Volatility.pdf)

Issue: Federation and Disaggregation

Multiple processes seek to operate the grid according to differing objectives

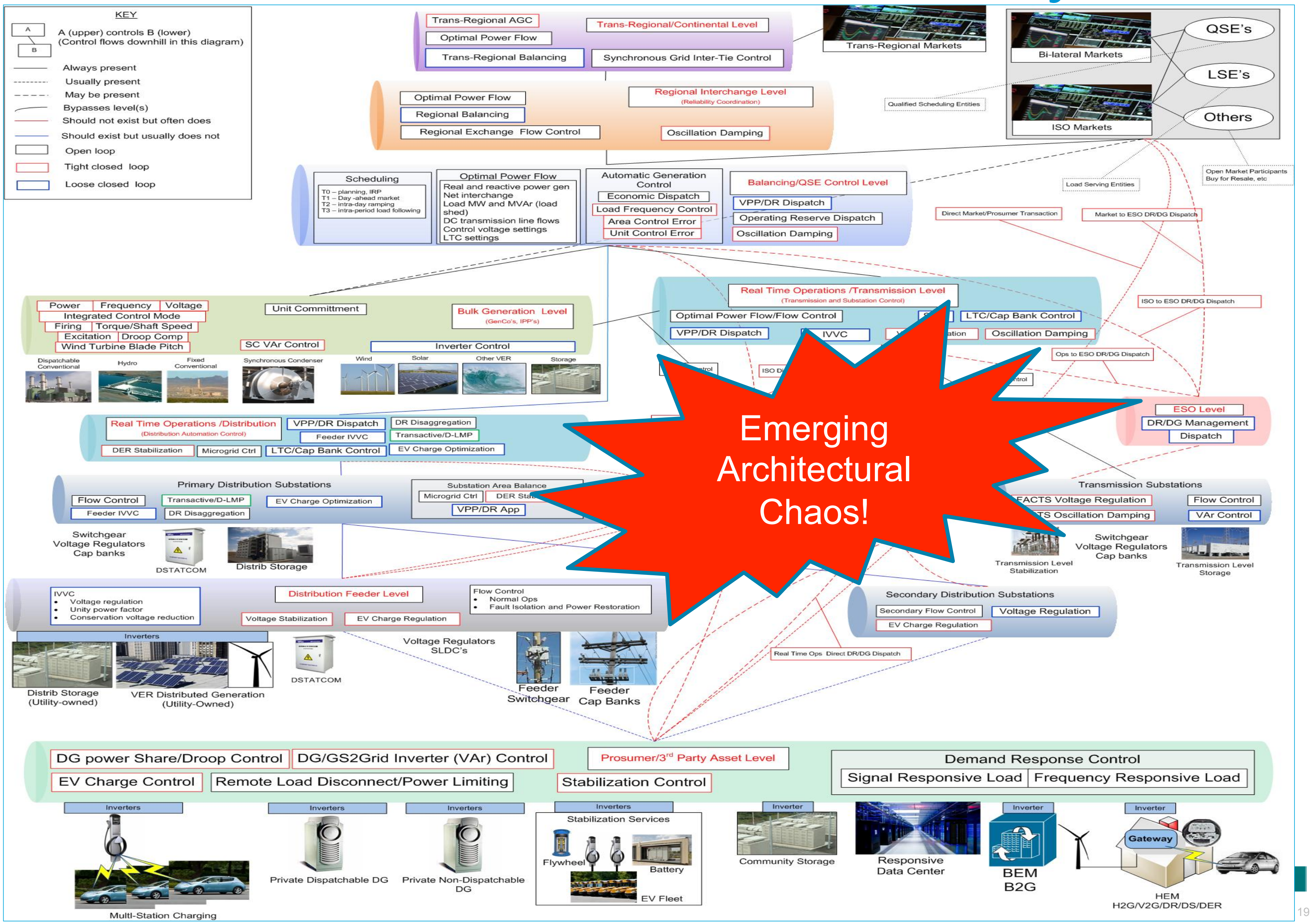
- Federation is needed to ensure that controls do not conflict at the (shared) device level
- Many controls need elements of grid state to operate properly
- Control commands must be disaggregated in alignment with grid structure, leading to distributed hierarchical control structures



Issue: The Coordination Problem

- Control engineering terminology: hierarchical control
- Techniques available since at least the 1960's
- Power grids do not have a strong multi-tier coordination framework
  - Distribution "floats" on transmission
- Conditions are changing so new control methods are needed
- DER as a "threat" and an opportunity

Lines of Grid Control Today



Issue: Grid Control Problem Complexity Exceeds Capability of Standard Design Tools

- Multi-variable dynamic control
- Multi-controller/multi-objective systems
  - Multiple processes want to use the same infrastructure
    - Example: use DER inverter for real power injection and for VAr control (reactive power injection)
  - Processes may have competing or conflicting objectives
    - Example: maximize wind/solar, but maintain voltage stability
- Multi-tier hierarchical control problems
  - such problems arise in the use of DR at scale, for example
- *Standard grid control methods are not powerful enough to solve such problems well or sometimes to solve them at all*

Grid Management Evolution

- Increasing need for (fast) electronic stabilization
- Need for wide area measurement; grid state observability; deep situational awareness
- Evolving cross tier and vertically integrated control -> control complexity
- Need for adaptive protection, granular control
- Need for control system federation, hierarchical disaggregation
- Need to handle complex constraints

emerging approach

Control Abstraction Model

Control System	Virtual Domain	LAYER 6	Control Strategy	Policy Objectives Admissibility
Control System	Virtual Domain	LAYER 5	Control Structure	Modes Topology Coordination
Control System	Virtual Domain	LAYER 4	System Model	Explicit/Implicit Sequence/Continuous Stochastic/Deterministic
Control System	Virtual Domain / Physical Domain	LAYER 3	Cyber Platform	Storage Compute Networking
Control System	Physical Domain	LAYER 2	Cyber-Physical Interface	Conversion Sensors/FCE's Physical Coupling
Plant	Physical Domain	LAYER 1	System	Physics Economics Social Behavior

The Ultra-large Scale System PoV

- Decentralized data, development, and control
- Inherently conflicting diverse requirements
- Continuous (or at least long time scale) evolution and deployment
- Heterogeneous, inconsistent, and changing elements
- Normal failures (failures are expected as a normal part of operation)

Optimization and Power Grids

- Integrated Volt/VAr control is already formulated as an optimization problem with minimization of LTC operations as the cost function, constrained by keeping voltage in bounds
- Demand response problems are increasingly being formulated as optimization problems
- Electric vehicle charging control is now being formulated as an optimization problem to take into account multiple constraints
- Optimization is not yet being widely applied at larger scale and across multiple utility/grid tiers, but should be
  - Needed to coordinate multiple controls/objectives
  - Needed to take complex constraints into account
  - Needed to solve distributed control problems
- Net: optimization is not just desirable for power grid control, *it is necessary*

Grid Control and Optimization

- Large scale grid control problems are becoming increasingly complex as we add new functions/requirements
- In many cases, we wish to do optimization as a matter of the goals we seek
  - Optimize load profiles, or minimize carbon emissions, for example
- In more cases, we need to use optimization just to be able to solve the control problems at all
- Present grid control systems are not structured for large scale optimization
- The cross tier modes are increasingly important:
  - DR/DG should be dispatched from Balancing Authorities (VPP models)
  - End users want to perform “selfish” control that conflicts with optimal system control
  - But, need to take into account impact on distribution operations to maintain grid stability and ensure efficacy of DR, for example
  - Need to avoid the “flash crash” problem as we let grid be driven by energy markets
- As a result, multi-tier, hierarchical control structures and control solutions are needed to make the grid do the things we expect going forward while maintaining grid stability and efficient operations – we need to use optimization tools to design and operate such systems

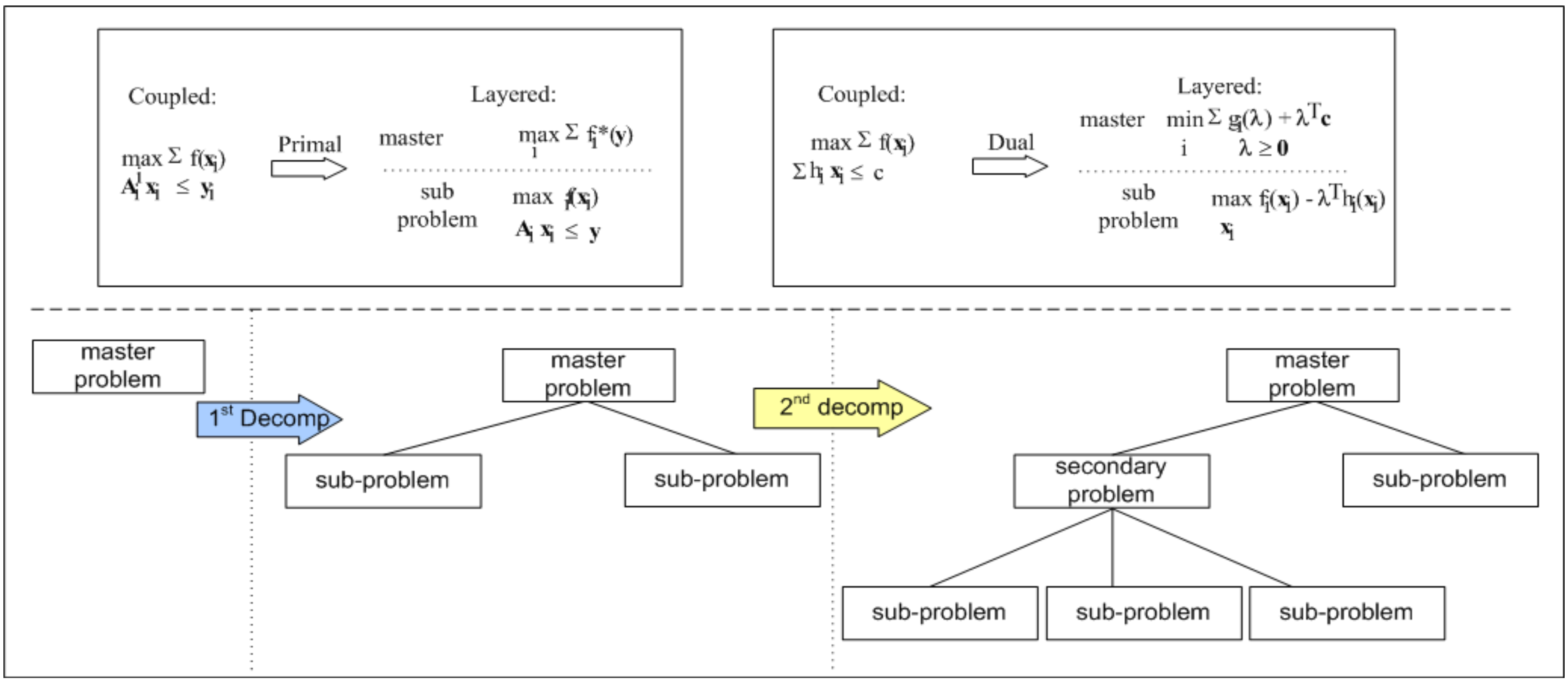
Multi-Layer Optimization and Grid Control

- Approach: “Laminar Control” via NUM
  - Decompose problem into distributed solvable problems coordinated by a master problem
  - Master and sub-problem solvers communicate via signaling
    - Master: system-wide control solution
    - Sub-problems: “selfish” endpoints
- Primal decomposition: master directs sub problems by allocating resources
- Dual decomposition: master directs sub problems by providing pricing
- The concept is easily extended to multiple layers to fit the utility hierarchical model

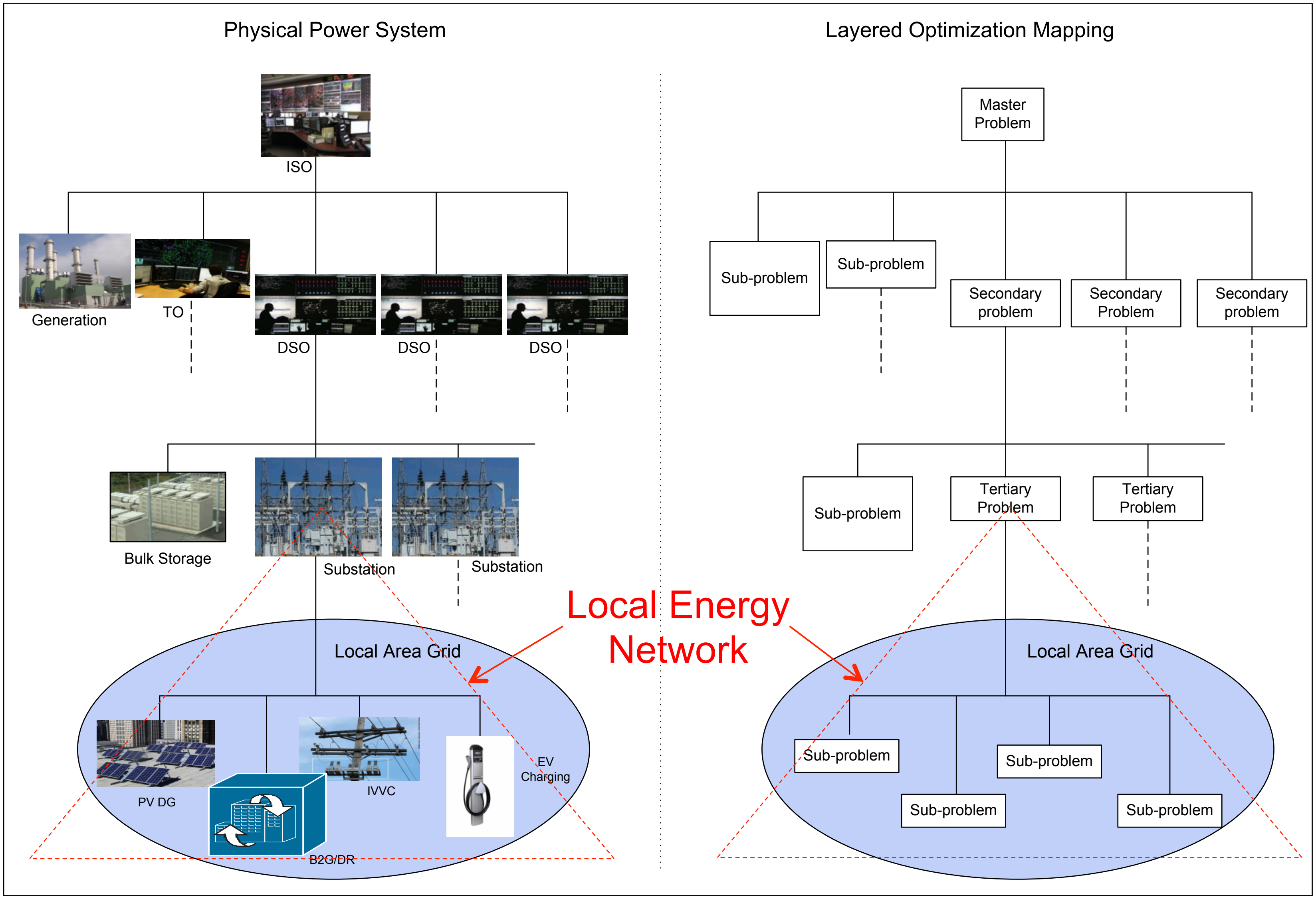
Daniel Palomar and Mung Chiang, “Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications,” **IEEE Transactions on Automatic Control,** Vol. 52, No 12., December 2007

Network Utility Maximization:
Layering for Optimization Decomposition

- Multi-tier control coordination
- Benefits from layered architectural paradigm

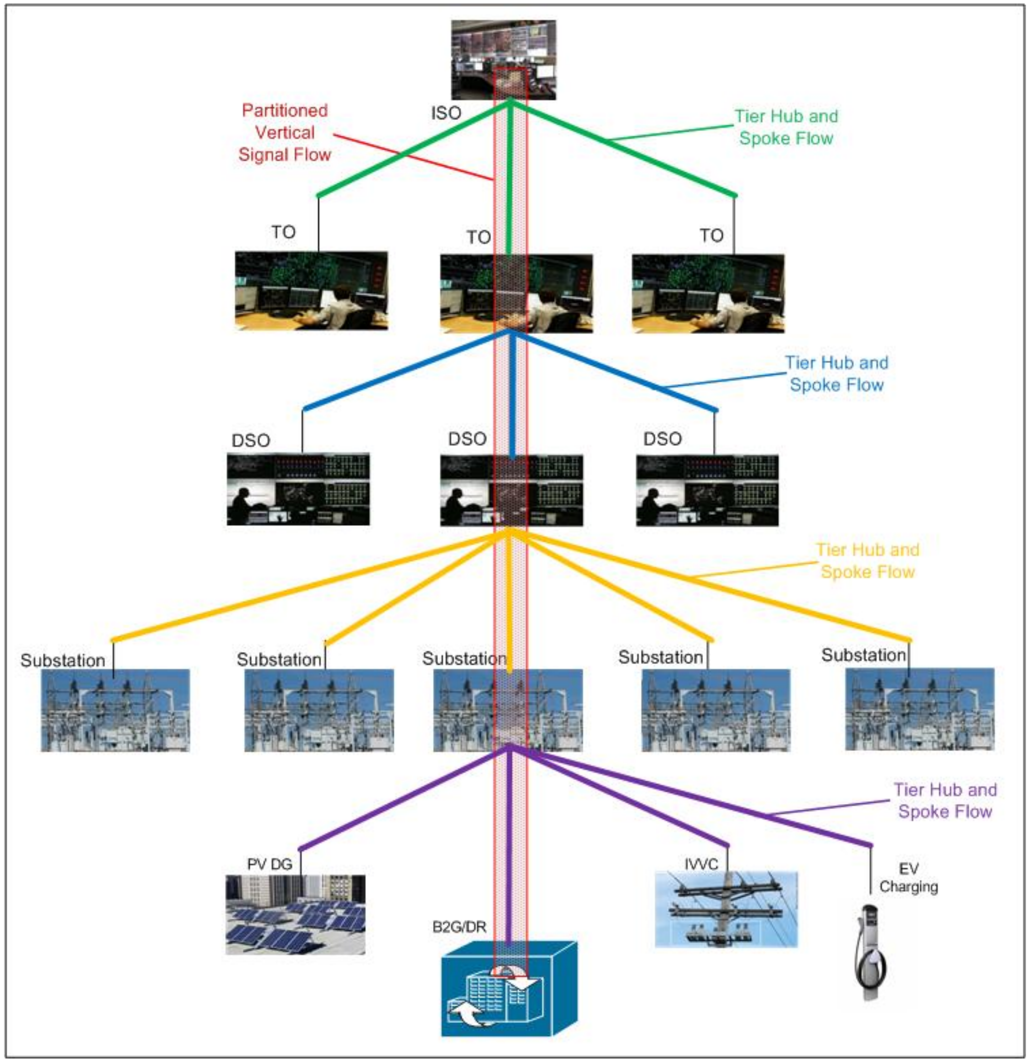


Mapping to Grid Structure

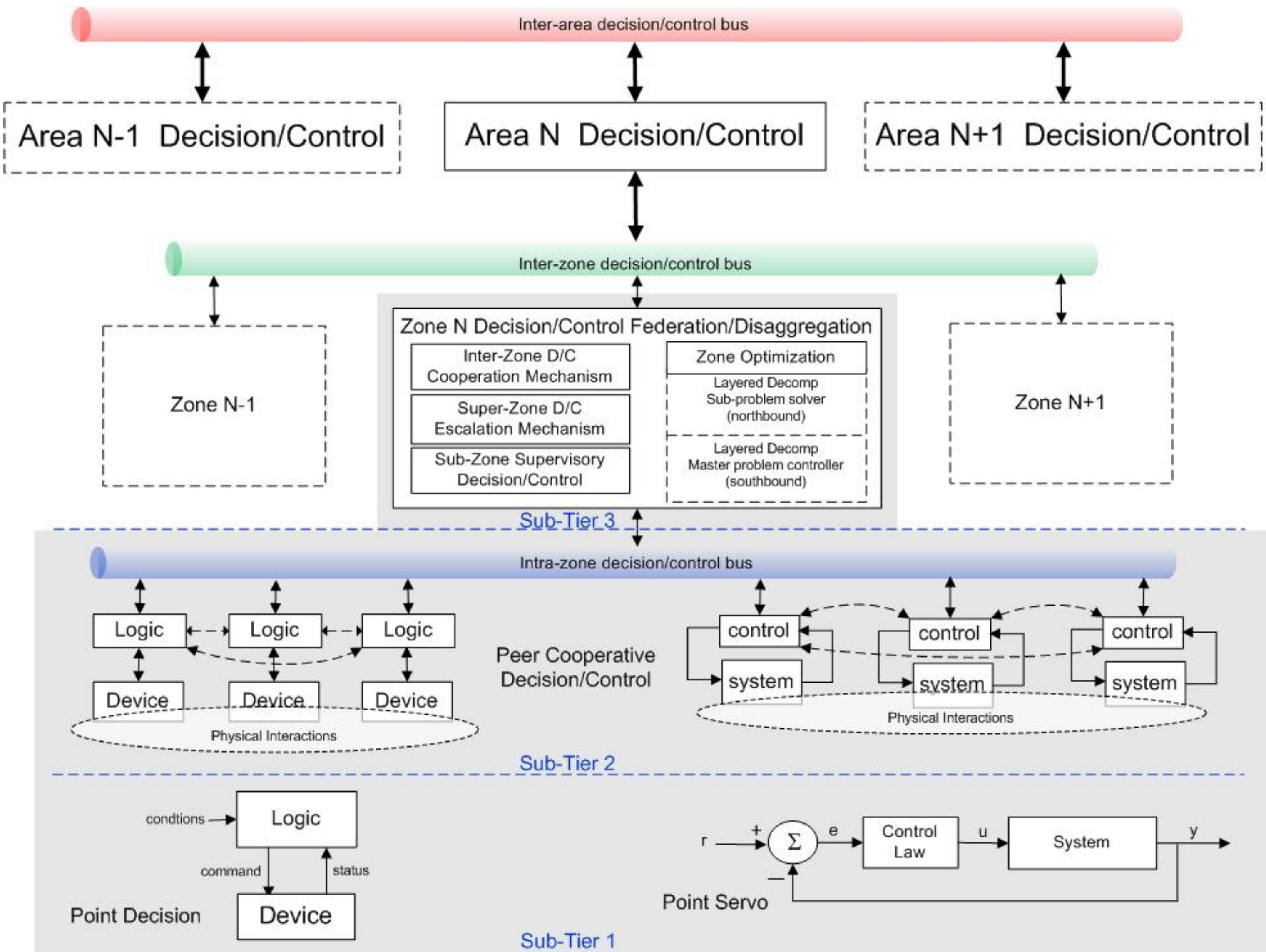


Scalability and Resilience via Layered NUM Structure (?)

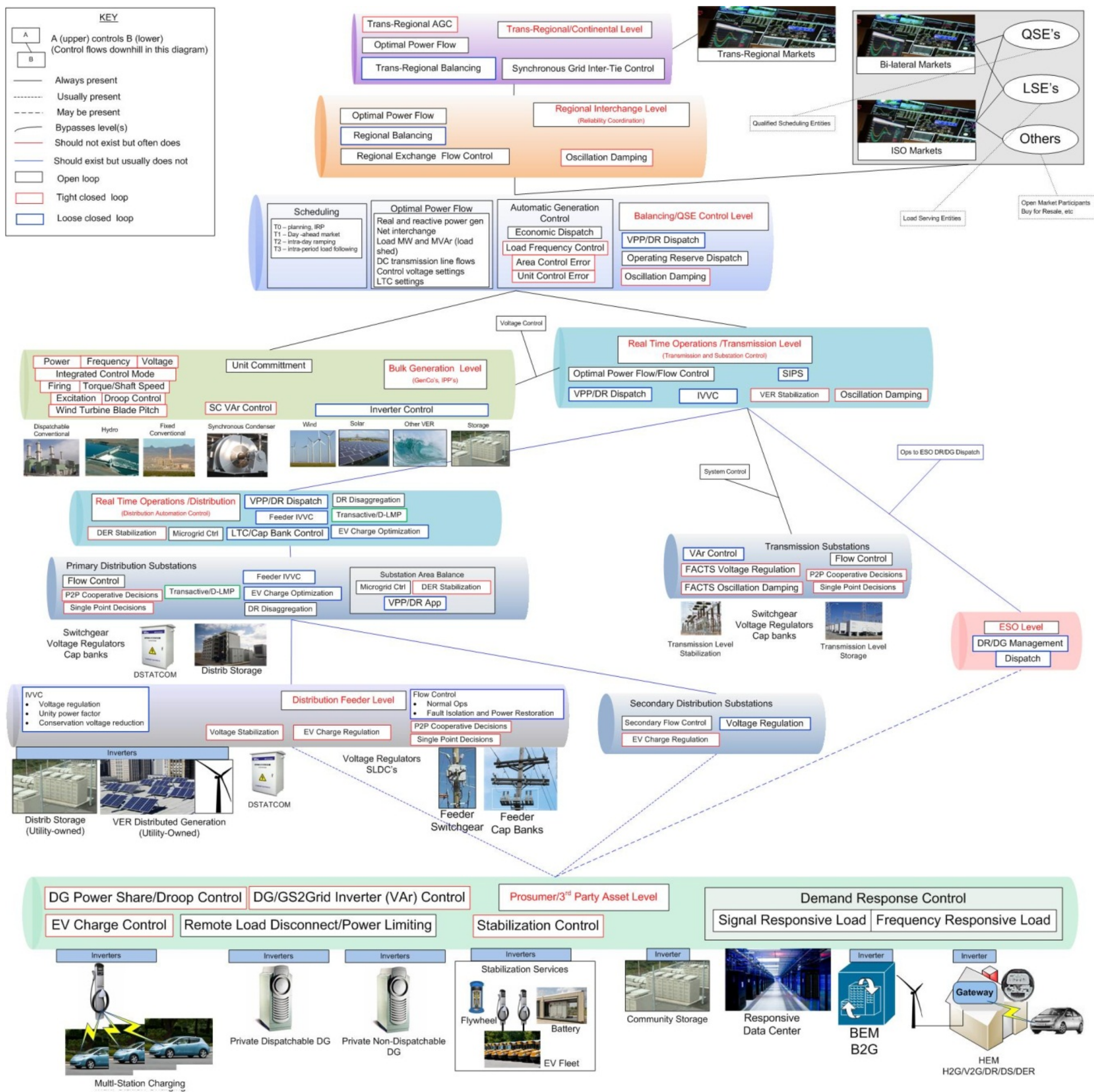
- Multi-resolution hub and spoke flow patterns
- Scalability of data flows
- Auto-abstraction of grid state
- Computational burden limiting via domain specification
- Adaptation to grid structural changes



Layer and Sub-Tier Structure



The Layered Architecture Opportunity



Issues Posed by Distributed Approach

- **Device/system/application management** – smart devices residing in substations, on poles, in underground structures represent significant cost to visit. It is impractical to send a person out to any of these devices to install a patch, reset a processor, or upgrade an application. Zero-touch deployment and remote management are necessary.
- **Harder to design, commission, and diagnose** – distributed intelligence systems can inherently involve a larger number of interfaces and interactions than centralized systems, making design, test, and installation more complex than with centralized systems.
- **More complex communications architectures required** – distributed intelligence involves more peer-to-peer interaction than with centralized systems, so that the communication network must support the associated peer-to-peer communications.

Power Grid Data Flows

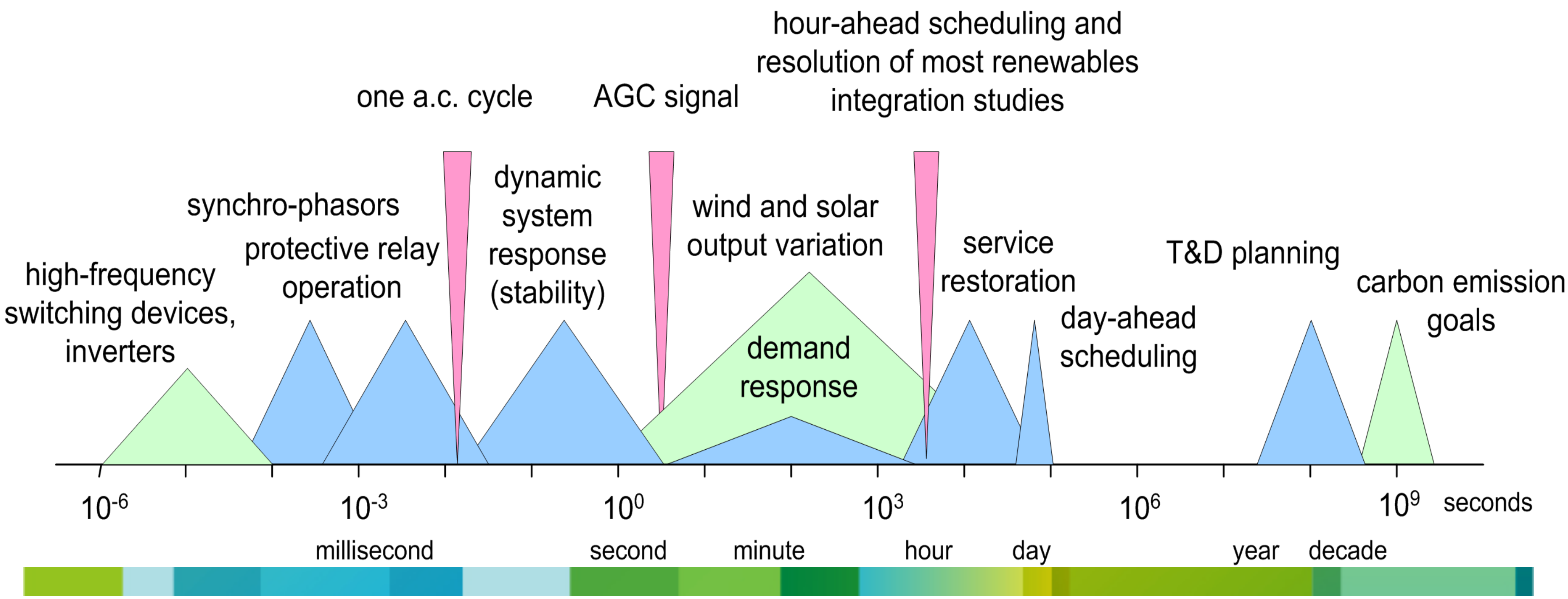
Data classes:

- Telemetry
- Oscillography
- Events
- Meta-data

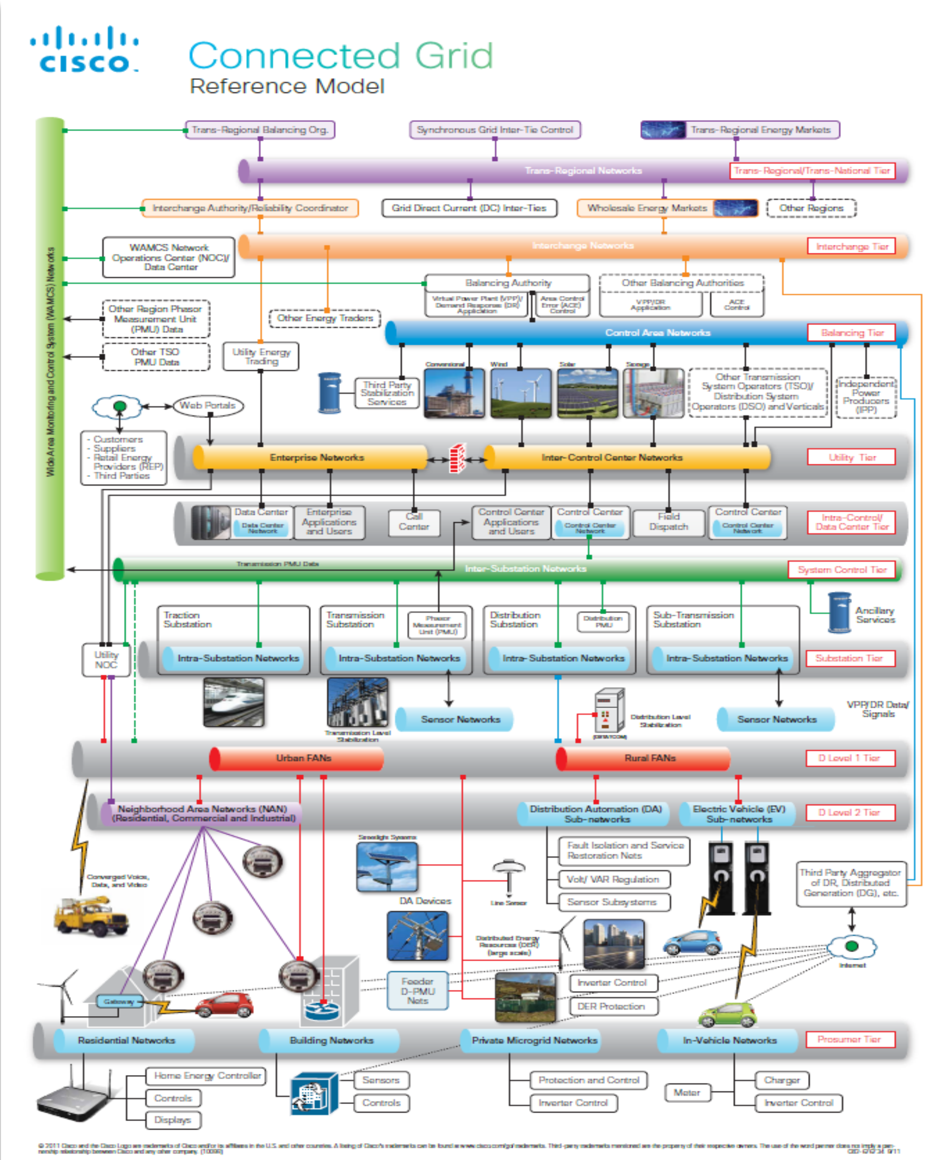
Data modes:

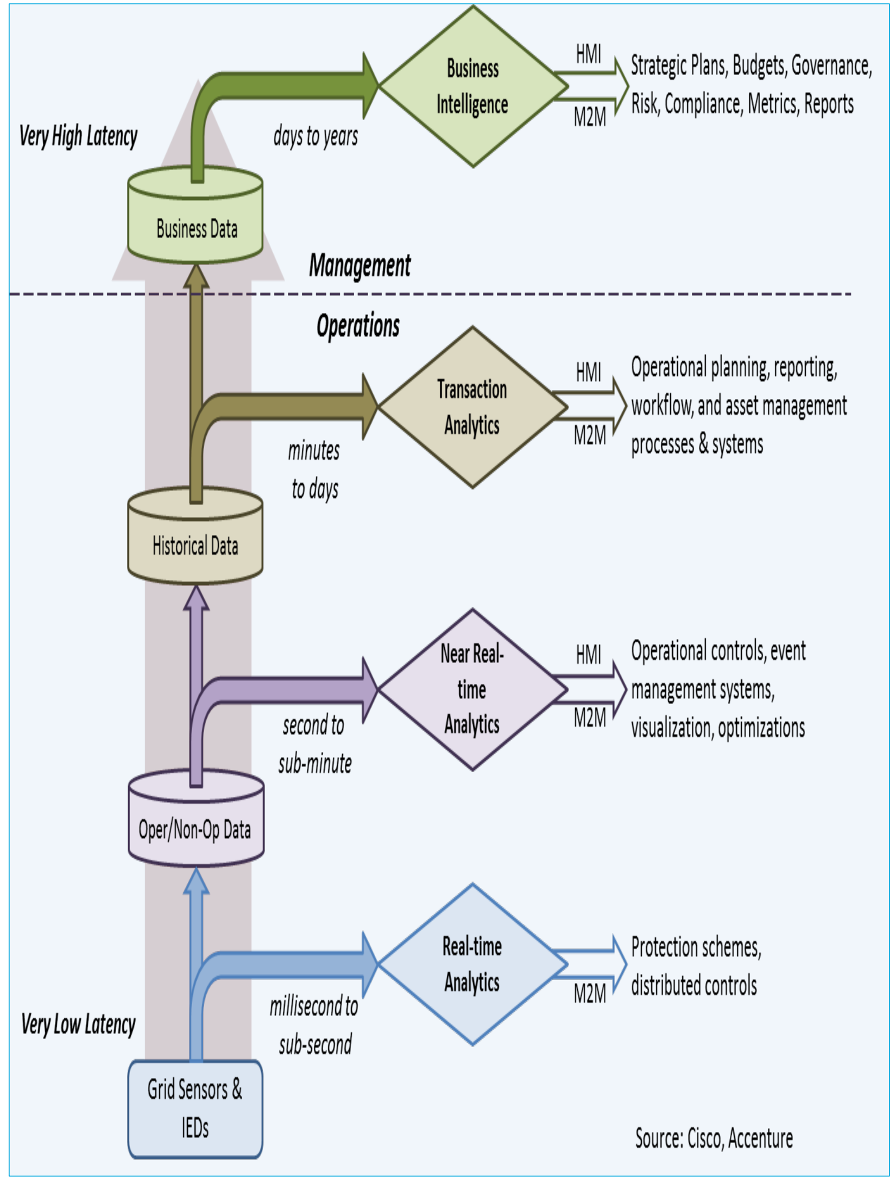
- Polling
- Streaming
- Asynch Events

- Data life span classes:
- Transit
- Operational
- Transactional
- Archival



Power Chain Communications Model





Conclusion: Challenges and Opportunities

- The ULS grid control framework problem has many open issues that need solutions soon
- NUM formulations are not even nearly complete
- Communication issues abound:
    - XMPP vs. SSM vs. ReST/CoAP/EXI vs. ??
    - Extended network management
    - Lossy RF networks are not adequate for control
- Exciting time in the energy field – the pace of change is rapid
- We need the Research community to help!

thank you