Cyber-Physical Architecture for the Power Grid of 2020

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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

distribution automation:

old and new

A Wave of Investment in DA is Coming

- North America presently has about $300 B of aging or obsolete distribution assets
- New investment in DA is coming as AMI winds down:
  - EEI: $20 B-$23 B /year through 2030
  - EPRI: $335 B - $476 B over 20 years -> $17B - $24B /year
  - GreenTech Media: $3 B /year by 2015
- Comms portion historically about 15% but may go higher for new DA
  - New DA comms more complex
  - Also add in DI platform elements
- Multiple factors driving this investment:
  - Renewed industry focus on operational excellence (“smart grid” is toxic)
  - Regulatory mandates in renewables integration and other functions
  - Response to recent weather events -> renewed focus on resilience
  - Aging and/or obsolete assets

Basic Distribution Automation

- Voltage Regulation
  - OL tap changers and SLDC’s
  - Voltage regulators
  - Cap banks for voltage support
- Flow Control and Sectionalizing
  - Feeder switches and breakers
  - Sectionalizers (remotely operated but manually controlled)
  - Feeder inter-tie switches (remotely operated but manually controlled) or just manual
- Protection
  - Breakers with digital relays
  - Reclosers, Fuses
- Distribution SCADA (if any)
  - V/I line sensors
  - FCI’s
  - Low bandwidth comms
- Outage Management
  - Siloed
  - IVR (maybe)
- FISR (manual/HIL)

Basic Distribution Automation Summary

Many devices are manually controlled or control is based on purely local factors.

Much of the control is merely “on-off” and on very slow time scales.

Networking requirements for basic DA are very modest and low cost tend to dominate.

Advanced Distribution Automation

- All of the basic DA plus…
- Advanced Regulation
  - IVVC: UPF, CVR
  - Load Freq Regulation
  - Inverter Control for fast VAr regulation
- Responsive Loads
- Stabilization and Synchronization
  - DSTATCOM
  - DER PCC Sync
  - D level PMU's
- Local Balancing
  - DER integration
  - EV charge control
  - LEN power balance
  - Load modulation (DC, EV)
  - Multi-tier VPP/DR
  - Markets and distrib markets
- Microgrids
- Protection and Flow Control
  - N-way power flow incl. loops
  - D level DG teleprotection

emerging grid control issues

Issue: Faster System Dynamics

Standard Grid Management	Advanced Grid Management
Distribution V/VAR Control (LTC/CAP's) Response times: 5 minutes to hours	Distribution V/VAR (DG/DS/Load Modulation) Response times: msec to sub-second
Transmission Level Stabilization (Ancillary Services) Response times 6-30 minutes	Transmission Level Stabilization (PMU/FACTS) Response times < 1 second
Distribution Level Stabilization Not typically done	Distribution Level Stabilization (DSTATCOM) Response times 32-300 msec
Distribution Fault Isolation (Manual Control) Response times: minutes to hours	Distribution Fault Isolation (FLISR) Response times: sub-second to sub-minute

Response times, sample rates, latencies all are shortening by two or more orders of magnitude.

"Human-in-the-loop" is not sustainable going forward.

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 example
  - CVR/PV example
  - market/responsive load example
- Becomes important as new rollouts of smart devices scale to full deployment
- Implications for architecture, design, and control

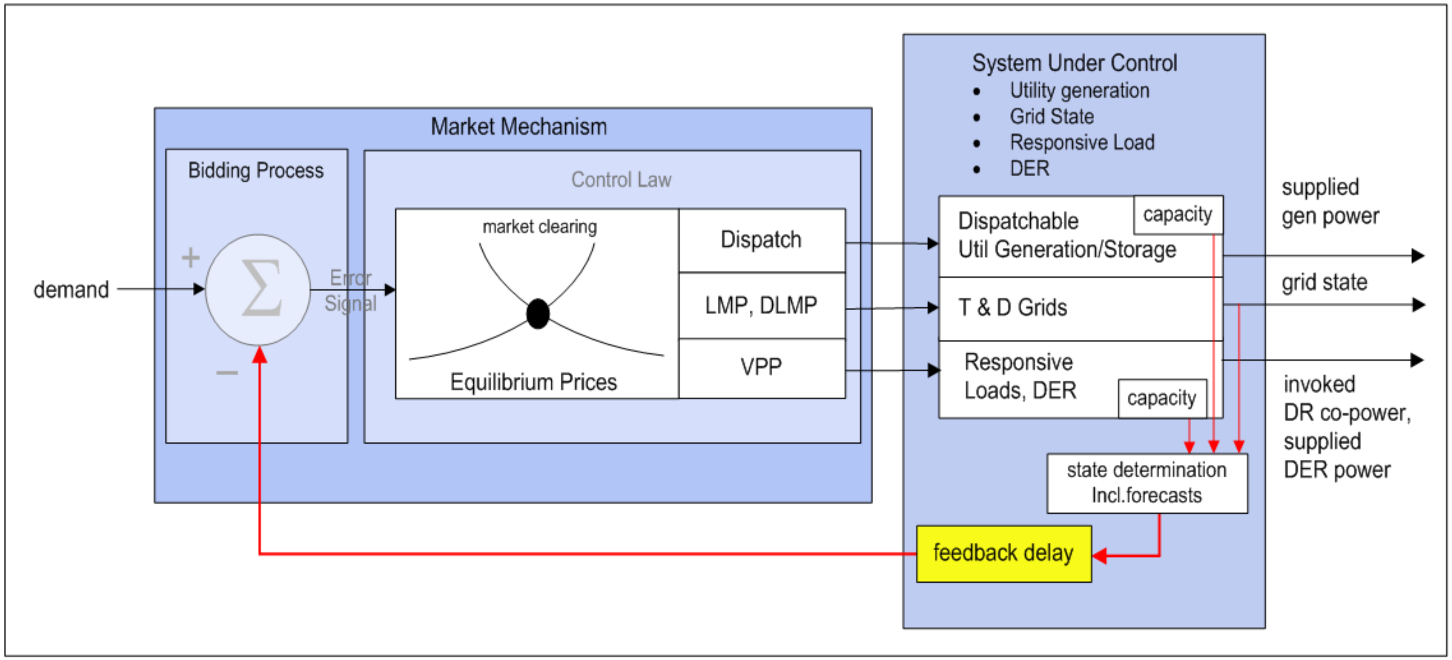
Jose Medina, Nelson Muller, and Ilya Roytelman, "Demand Response and Distribution Grid Operations: Opportunities and Challenges," **IEEE Trans. On Smart Grid**, vol. 1, pp. 193-198, Sept. 2010.

Issue: Synchronized Measurement

- Traditional Distribution SCADA does round-robin polling of endpoints
  - 4 second cycle to collect all points is common today, no synchronization
- Measures RMS voltage, RMS current, real and reactive power
  - Optionally, a few harmonics for power quality
  - No phasor measurement; data is time skewed
- All this is changing for advanced DA:
  - Need for phase measurements
  - Therefore, need synchronized measurement (synchrophasors)
  - Some can be done in substation, but this is not adequate for many functions
  - Need distributed, synchronized SCADA

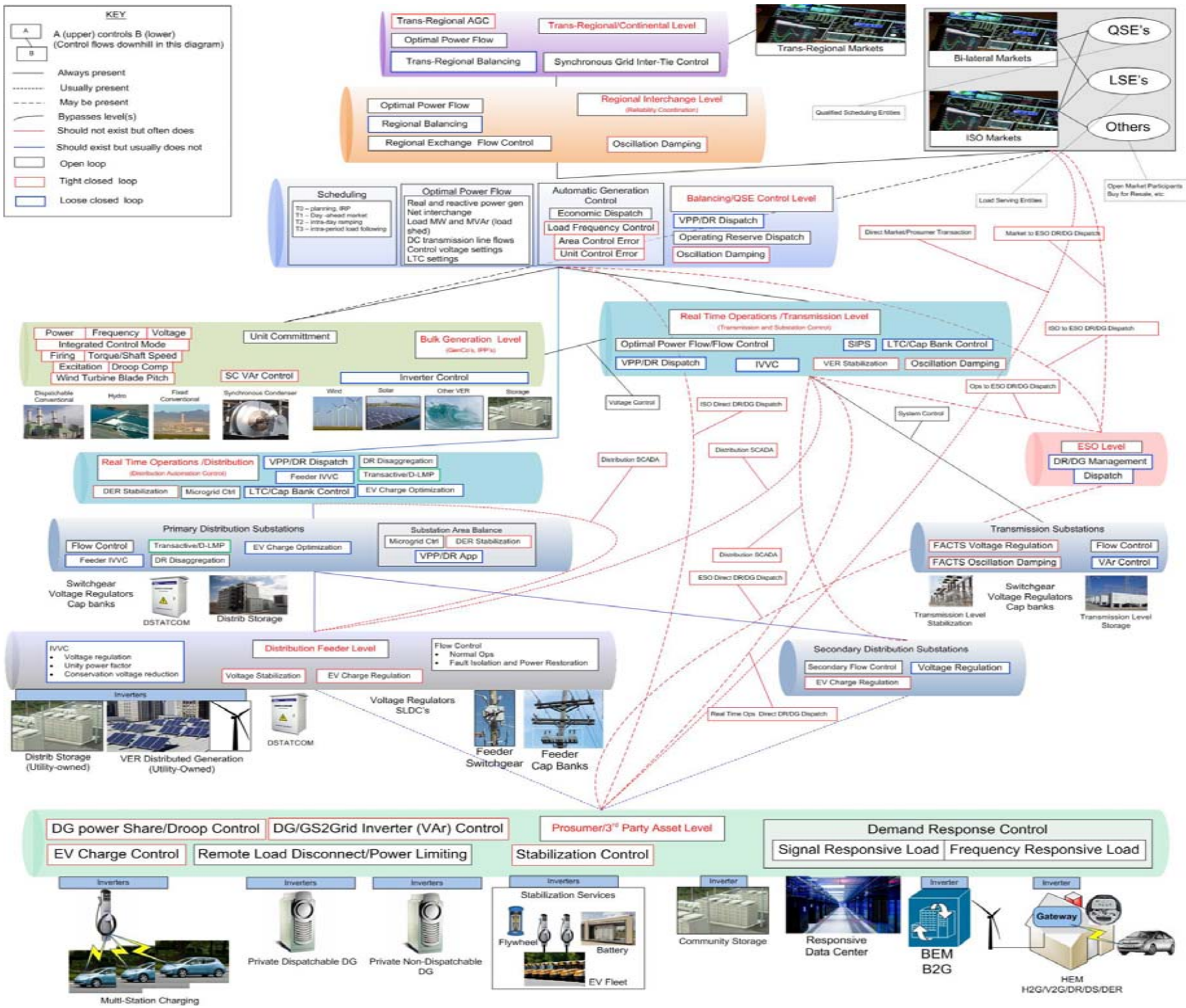
Issue: New Instability Sources

- 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*

Issue: Emerging Structural Chaos



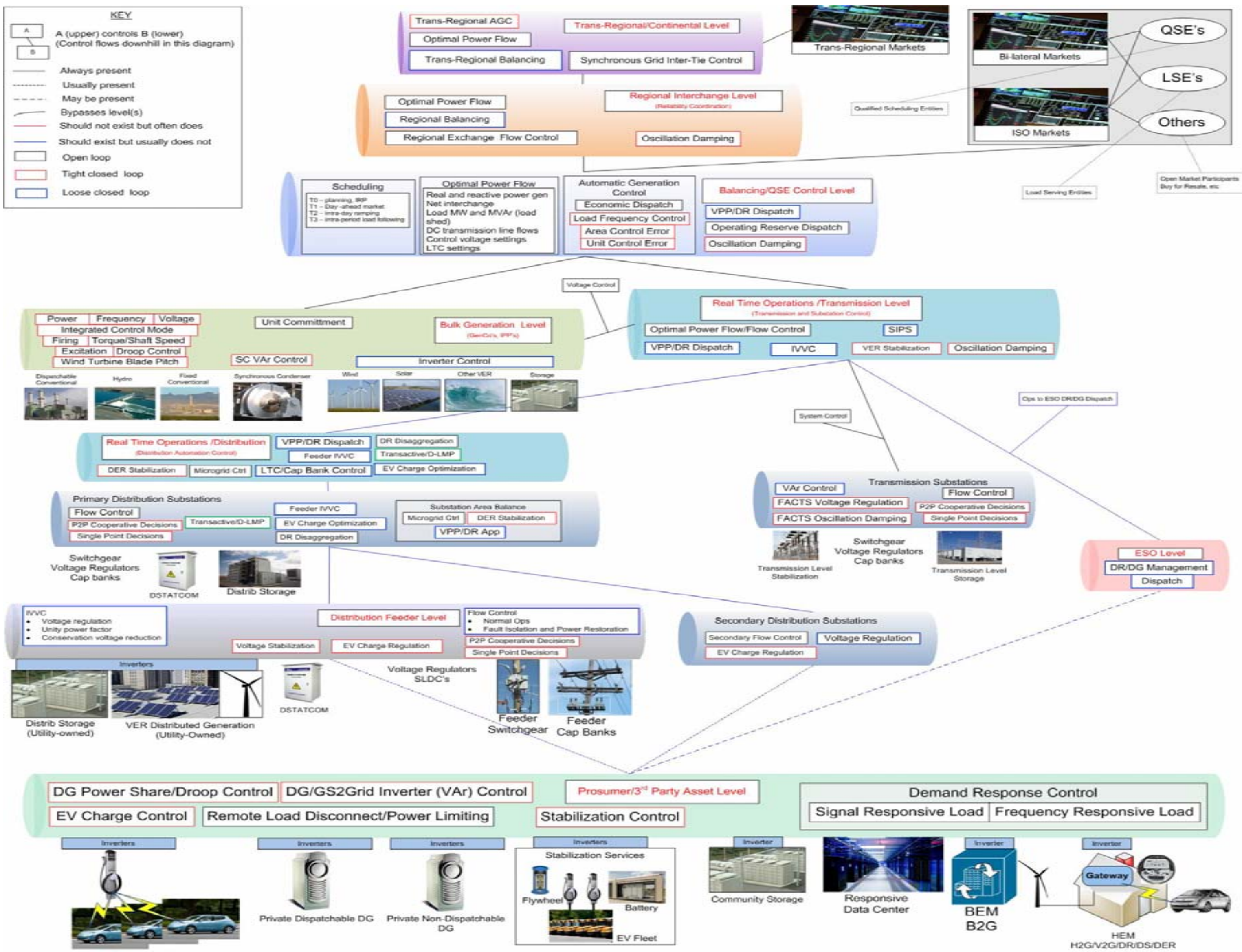
ultra-large scale power grid

control architecture

What to Do

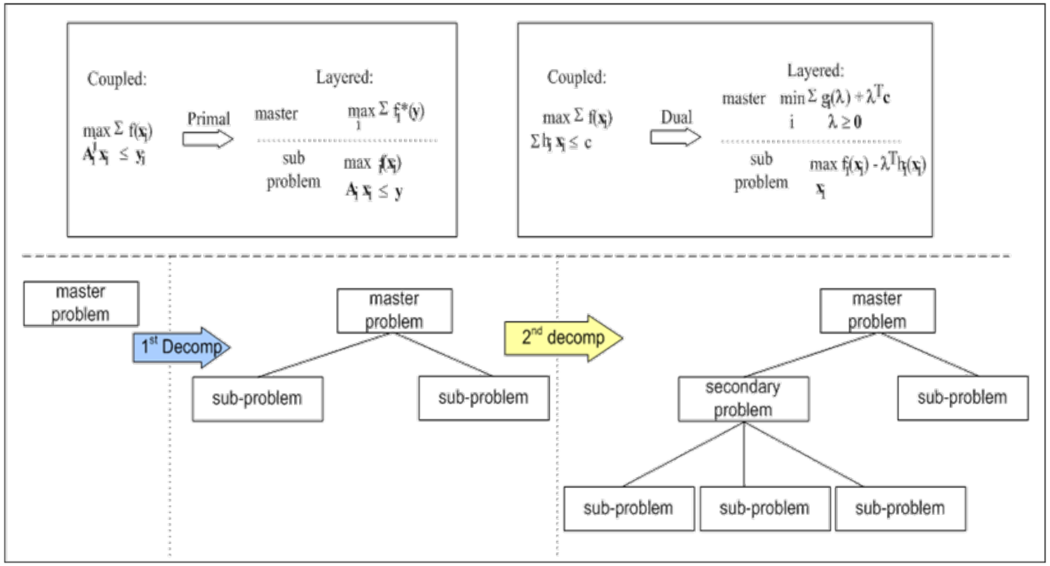
- Regularize the structure
  - Eliminate “tier hopping” control
  - Avoid closing loops around multiple tiers
  - Use the layer architectural paradigm
- Introduce layered optimization
  - Can match inherent grid hierarchy
  - Can match functional boundaries
- Distribute the control
  - Flows logically from the first two steps
  - Preserves much traditional control
  - Addresses new control needs

1. Regularize the Structure



2. Introduce Layered Optimization

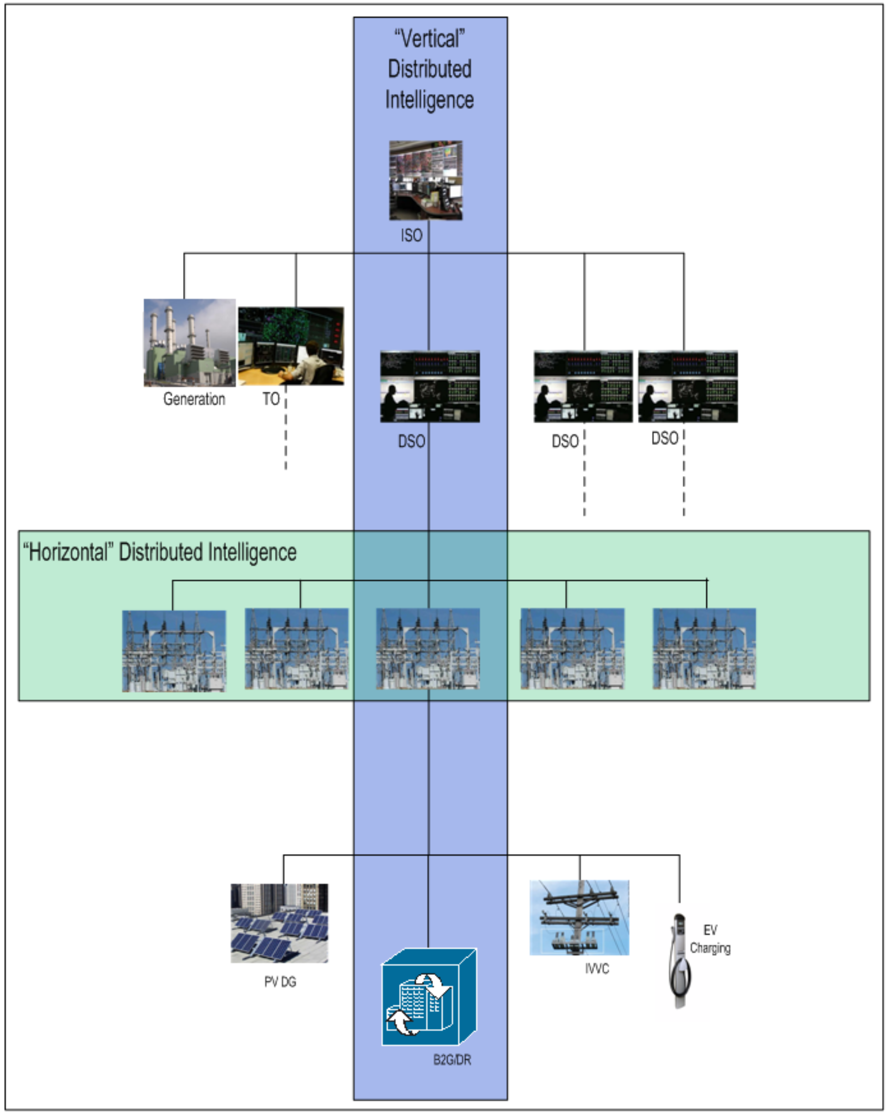
- Decompose problem into distributed solvable problems coordinated by a master problem -> Network Utility Maximization
  - ❑ Master and sub-problem solvers communicate across layers via signaling
    - o Master: system-wide control solution; sub-problems: “selfish” endpoints
    - o Primal decomposition: master directs sub problems by allocating resources
    - o Dual decomposition: master directs sub problems by providing pricing
- Solve federation, disaggregation, and complex constraint fusion problems
- Extend to multiple layers to fit the utility hierarchical model
- Append constraints, dynamics at each level
- Modular approach to ultra-large scale control



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

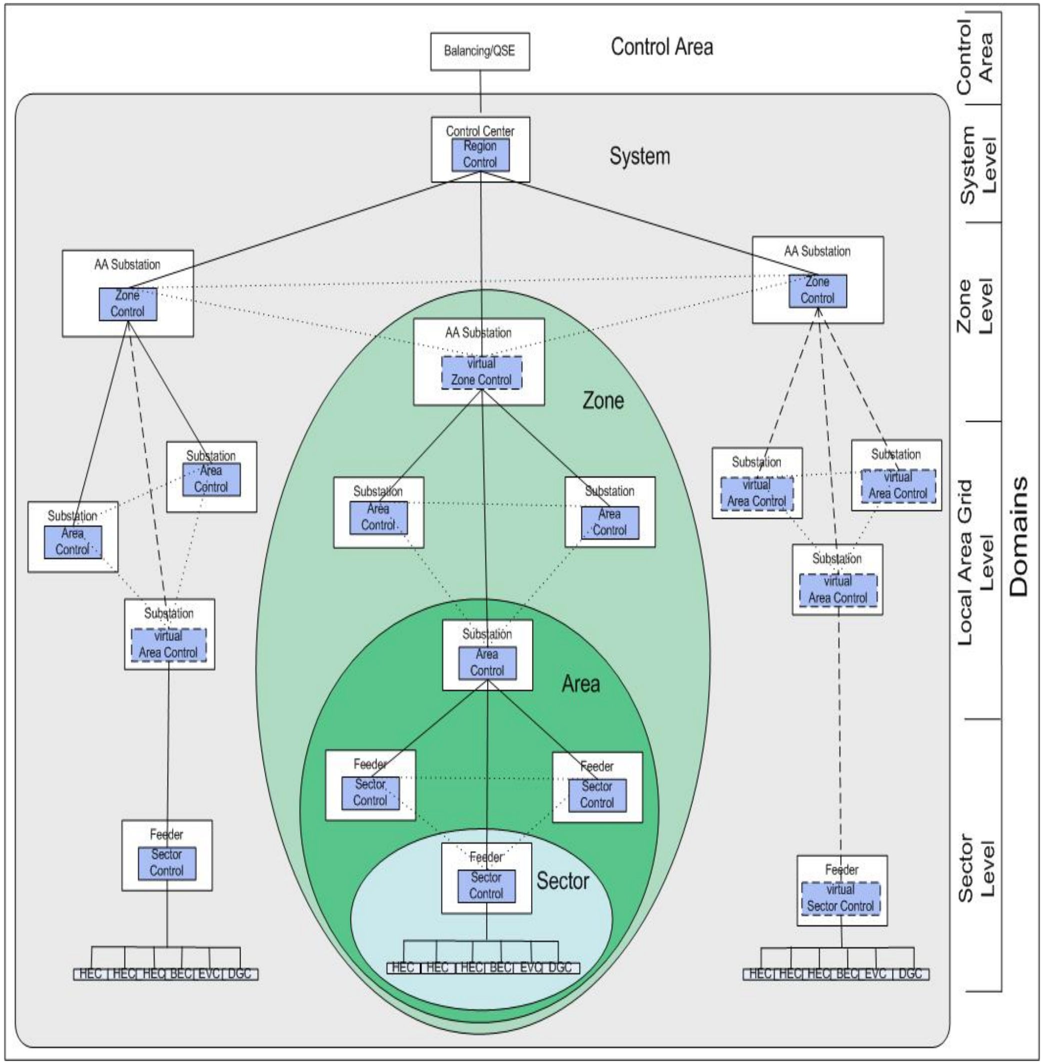
3. Distribute the Control

- Layered Optimization Decomposition leads directly to distributed control
- Layers can be matched to grid tiers
- May be more than one horizontal control tier
- Scalable and robust structure
- Sub-problems may be “selfish”
  - Local goals
  - Local constraints and states
  - Bounded local autonomy

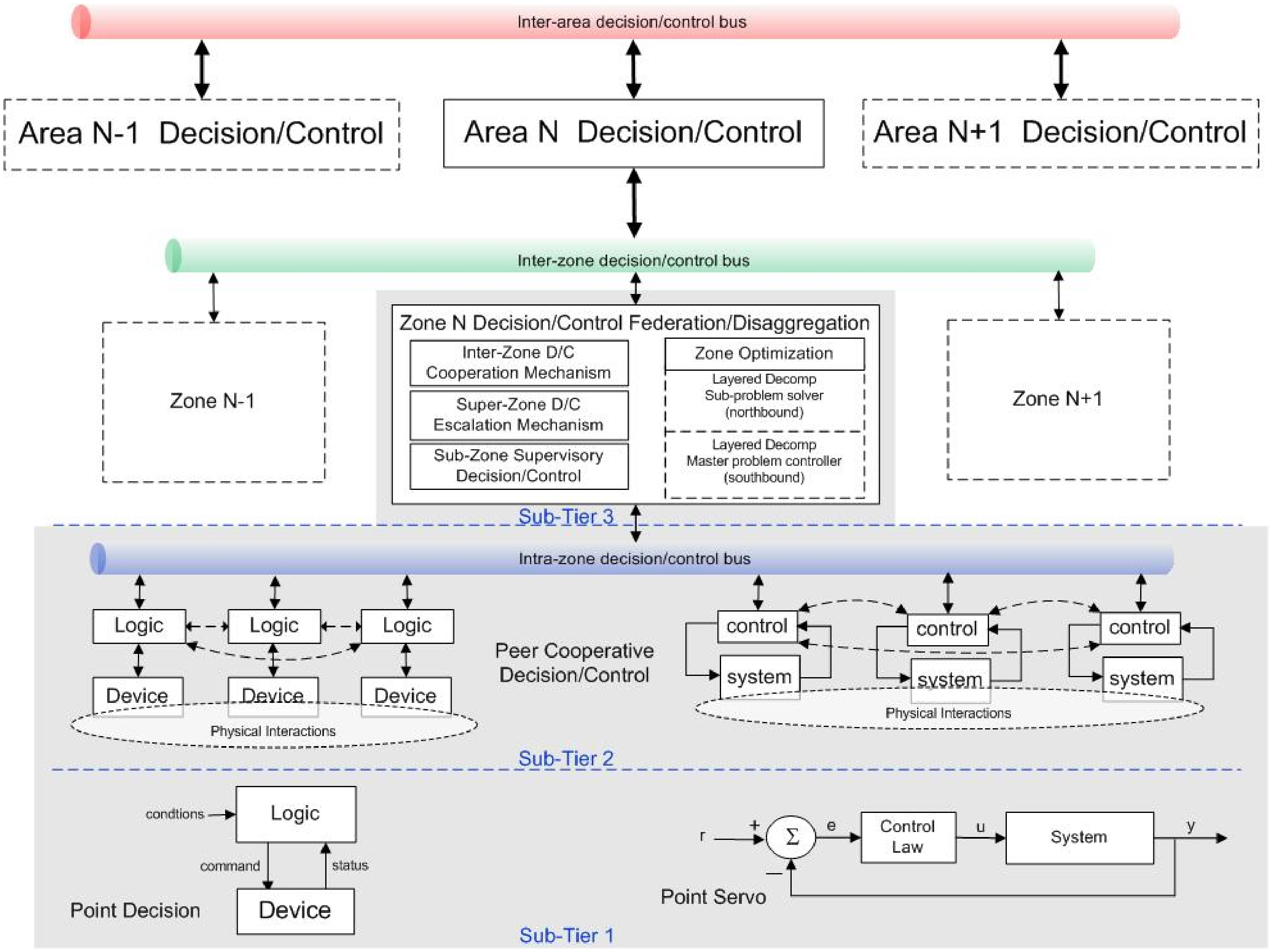


DI Allocation; Dynamic Re-allocation

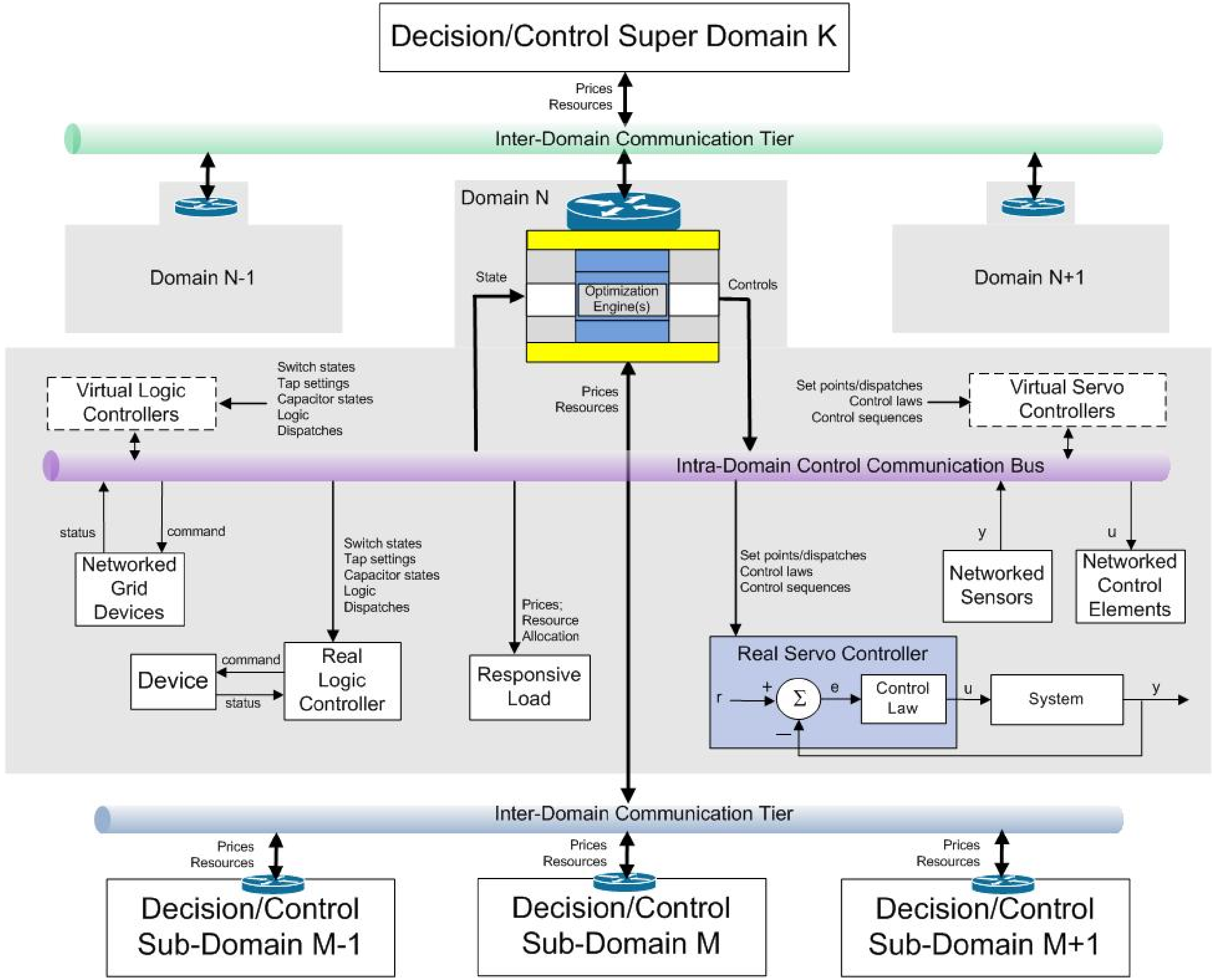
- Decentralized control
  - o Remote apps
- Distributed Control
  - o Remote, cooperating apps
- Static DI element allocation
  - o Not 1:1 per substation
- Dynamic topology
  - o Must change over time



Layer and Sub-Tier Structure



Intra-Tier Practical Structure



Benefits of Distributed Approach

- Low Latency Response
  - A distributed intelligence architecture can provide the ability to process data and provide it to the end device without a round trip back to a control center.
- Low Sampling Time Skew
  - Multiple data collection elements can minimize first-to-last sample time skew for better system state snapshots
- Scalability
  - No single choke point for data acquisition or processing; analytics at the lower levels of a hierarchical distributed system can be processed and passed on to higher levels in the hierarchy
- Robustness
  - Local autonomous operation
  - Continued operation in the presence of network fragmentation
  - Graceful system performance and functional degradation in the face of failures
- Ease of incremental rollout

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.

Use Case Ensemble

- The "killer app" is grid control. It has many sub-use cases, most well-known and more coming as the utilities are pushed (as in *driven*) by the regulators to meet renewable portfolio and other goals by 2020.
- The sub-use cases include:

  - VER integration (wind, solar, etc)
  - Wide area measurement, protection, and closed loop control
  - DER integration (distribution level, incl VER DG)
  - Energy storage integration
  - Responsive loads (command, price, and /or system frequency)
  - Integrated Volt/VAr control for V reg, CVR, UPF in the presence of DER and DR
  - Advanced distribution fault isolation/service restoration
  - Electric Vehicle (EV) charge management
  - Third party energy services integration
  - Inverter control for fast VAr regulation
  - Local energy network and microgrid power balance and flow control; load power modulation (EV's, DC's)
  - Multi-tier virtual power plants
  - Energy/power market interactions for prosumers; transactive energy and distributed markets
  - Electronic grid stabilization (FACTS for transmission; DSTATCOM for distribution)

Grid Control Macro Requirements

- Increasing need for low latency electronic stabilization in the presence of fast grid dynamics
- Need for wide area measurement; grid state observability; deep situational awareness -> sensing
- Evolving cross tier and vertically integrated control
- Need for:
  - Control federation
  - Control disaggregation
  - Constraint fusion
  - Agility
  - Robustness
  - Stability

thank you