Distributed Computing & Stochastic Control for Demand Response In Mass Markets

Staff Technical Conference

Federal Energy Regulatory Commission

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Outline

- Overview & Current DR Programs
- Key Challenges of a New Approach
- High Level Process of the New Approach
- Technology and the Load Controller
- ColorPower ™ Algorithm
- Formal Control Problem & Important Constraints
- Control Design Issues
- The Energy Demand Cloud
- Simulation Results
- Conclusions

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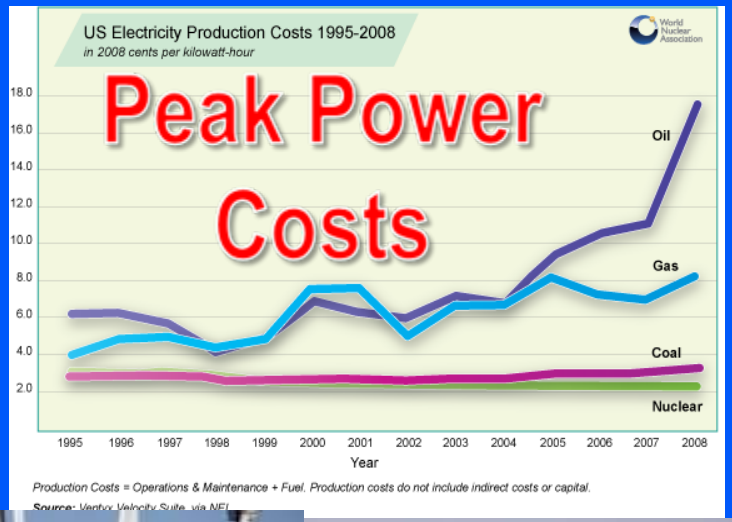
Distributed Power Demand Response



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Then, Where is the problem? (The Era of Coercion Should Come to an End

- Current DR programs are based on command and control approaches; programs are grouped in 4 groups:
- Customers submit their appliances to direct utility on/off load control
- Customers are exposed to price volatility—a concept called “prices-to-devices”; this is the “holy grail” today for activating DR in wholesale organized markets
- DR aggregators pay people for remote shutoff options; growth has stalled because customers see no other value than trading inconvenience for cash
- Finally, some programs rely on advanced analytics to predict customer behavior and drive messaging and pricing; they try to outguess what customers will do instead of asking them for their preferences

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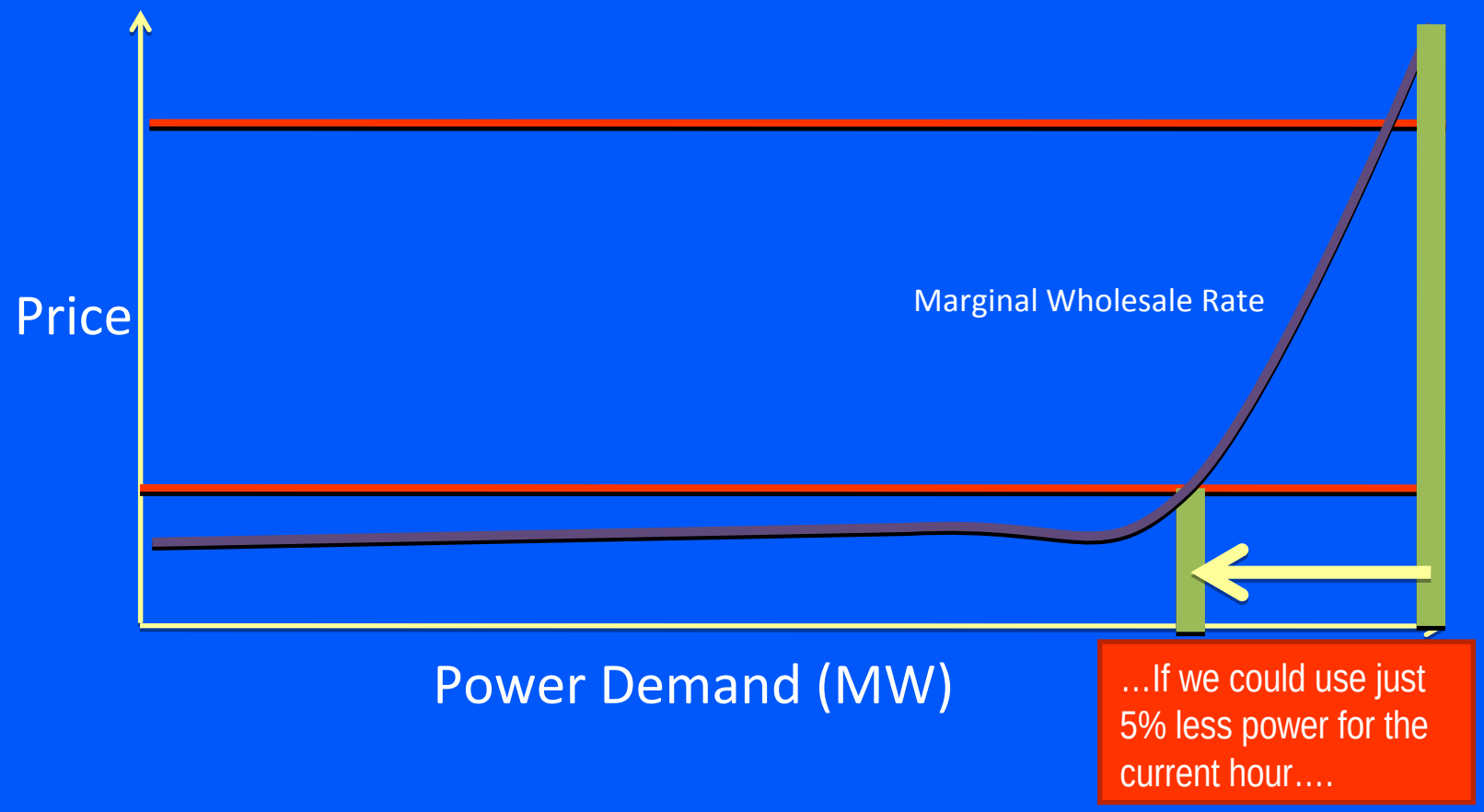
Electricity Markets



No Price-Sensitive Demand -> Inefficiency Everyone Pays For

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Inefficiency of Demand vs. Intention

- Demand/supply mismatch is extremely costly
  - $ billions to utilities, local governments, consumers
- Consumers dramatically reduce demand when:
  - … have financial incentive & there is no impact on convenience
  - ….aware of actual appliance energy use
  - … informed about neighbors' energy use
  - … aware of stress on power grid

Coordination opportunity: peak-shaving & demand management by <u>automating volunteerism</u>

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Key Challenges

- Scalability:
  - Safe, reliable coordinated response from millions of devices in < 2-4 minutes
- Consumer interface:
  - High benefit, low “annoyance factor”
  - Eliciting useful information (preferences)
  - Privacy concerns (detailed data and devices should remain private) – This means computations should be performed on consumer aggregates)
- Deployability:
  - Technology alignment with market & regulatory structure
  - Market fragmentation across grid & in home
- Fairness

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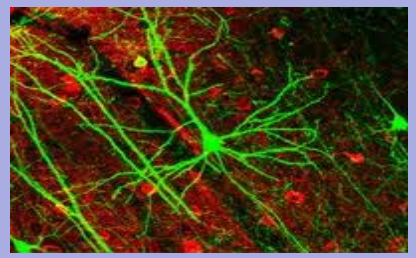
Algorithm Inspiration: NATURE

Natural Self-Organizing Systems

Bacteria Colonies



Neural Networks

Social Insects

Flocks & Schools

- Original algorithm was developed at MIT for biological systems
- Implement a distributed computed based stochastic control algorithm
- We are in the process now of developing the algorithm for energy devices
- Analysis of devices results in constraints similar to generator constraints, such as minimum up time constraints, minimum down time constraints, etc.

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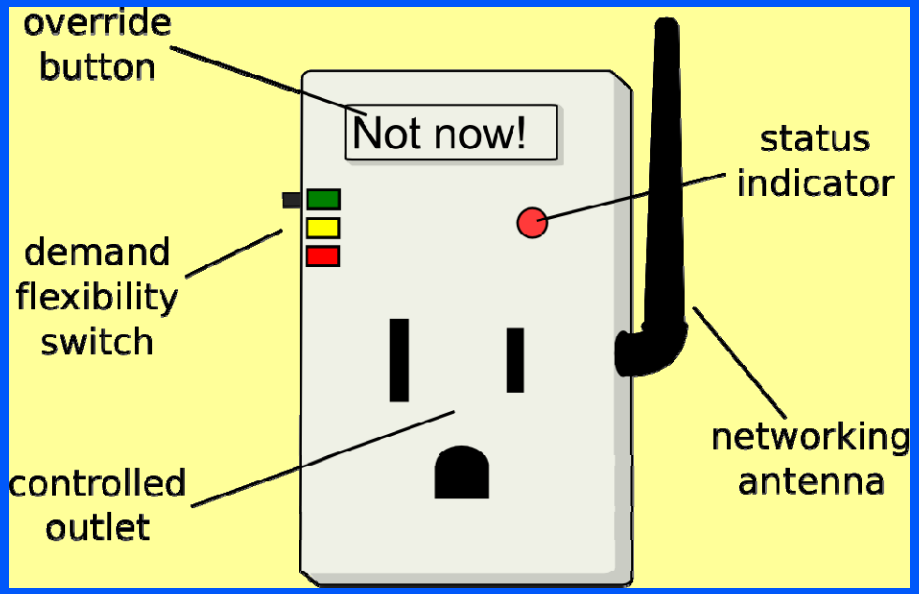
Capturing User Requirements



Qualitative
Energy Flexibility

Smart plugs, new appliances, home automation, …

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High Level Process

- ColorPower agent (say customer's meter) aggregates device flexibility information which is further aggregated across a network
- This forms a model of the overall system flexibility
- This system flexibility, along with a demand shaping target provided by the Utility or the Aggregator, is redistributed to every device in the system
- The devices then execute a distributed control algorithm (like flipping weighted coins) to determine if they respond or not

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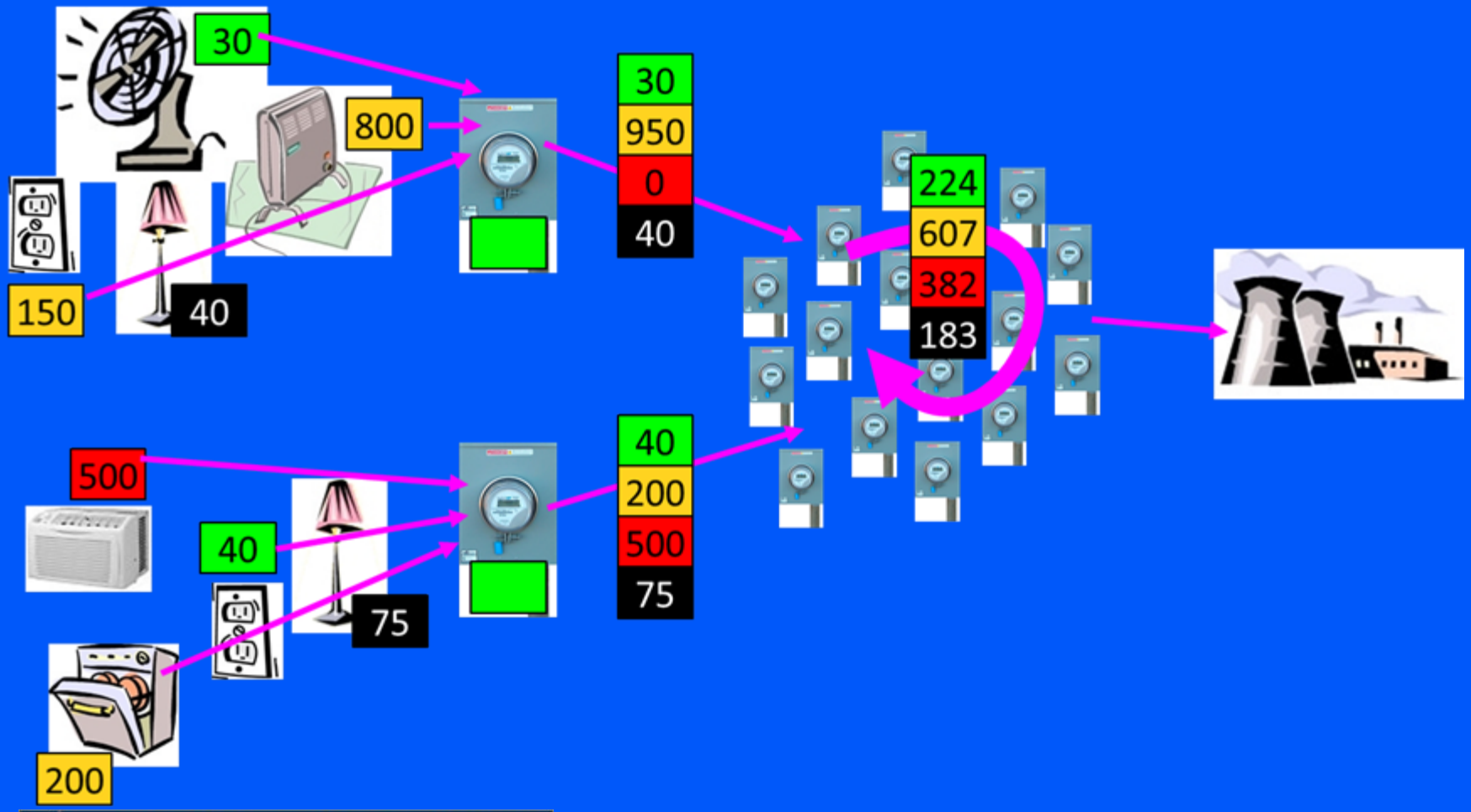
Distributed Creation of the Aggregate Model



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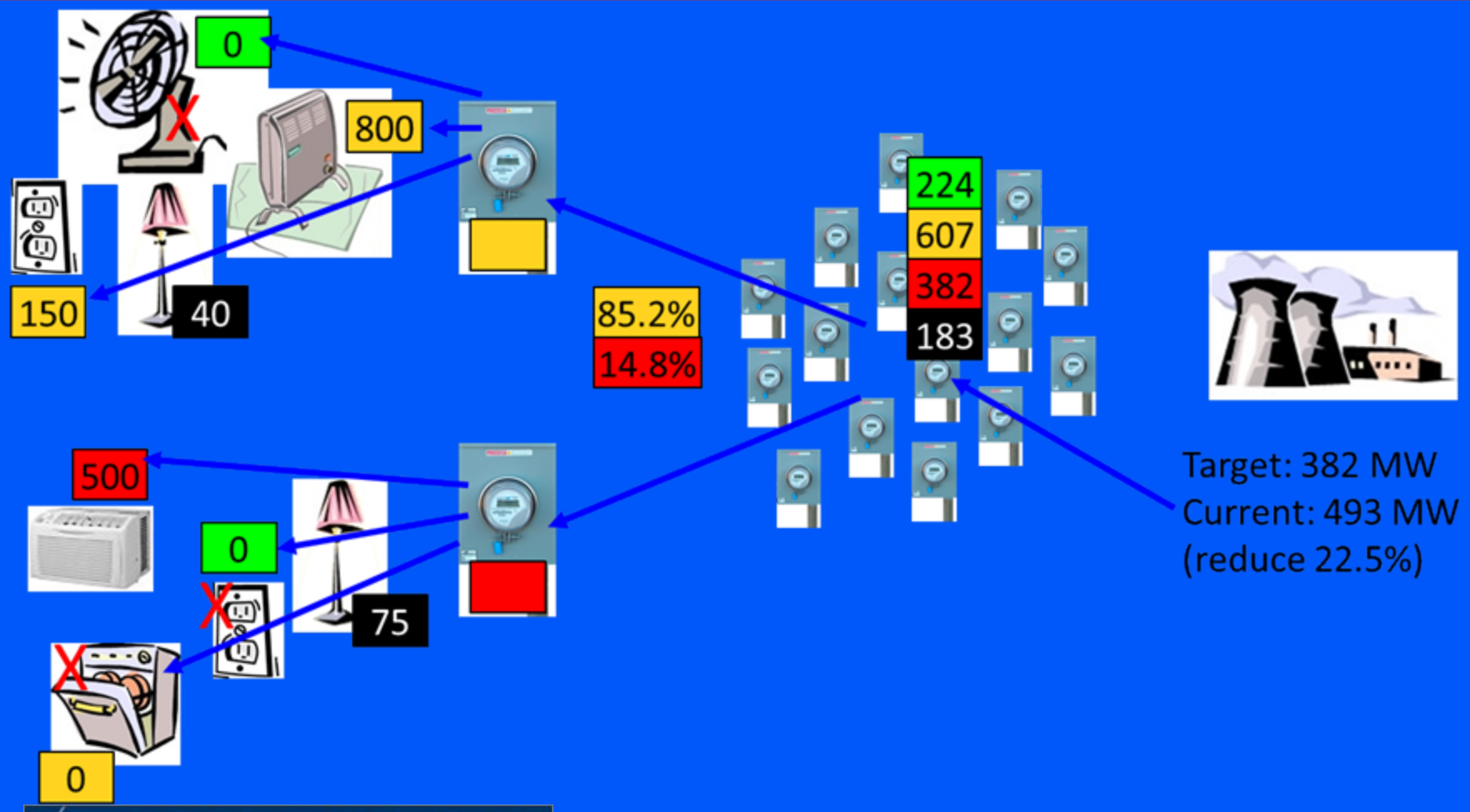
Model Coordinates Local Control Actions



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ColorPower ™ Algorithm

- Challenge: fast, private, robust, non-intrusive
- Approach: randomized distributed control
  - Aggregate flexibility information to shared model
  - Disseminate control signals
  - Local decision; coin-flip for fractional color
  - Weight for availability, over-damped control

Control problem: long timeouts on state changes

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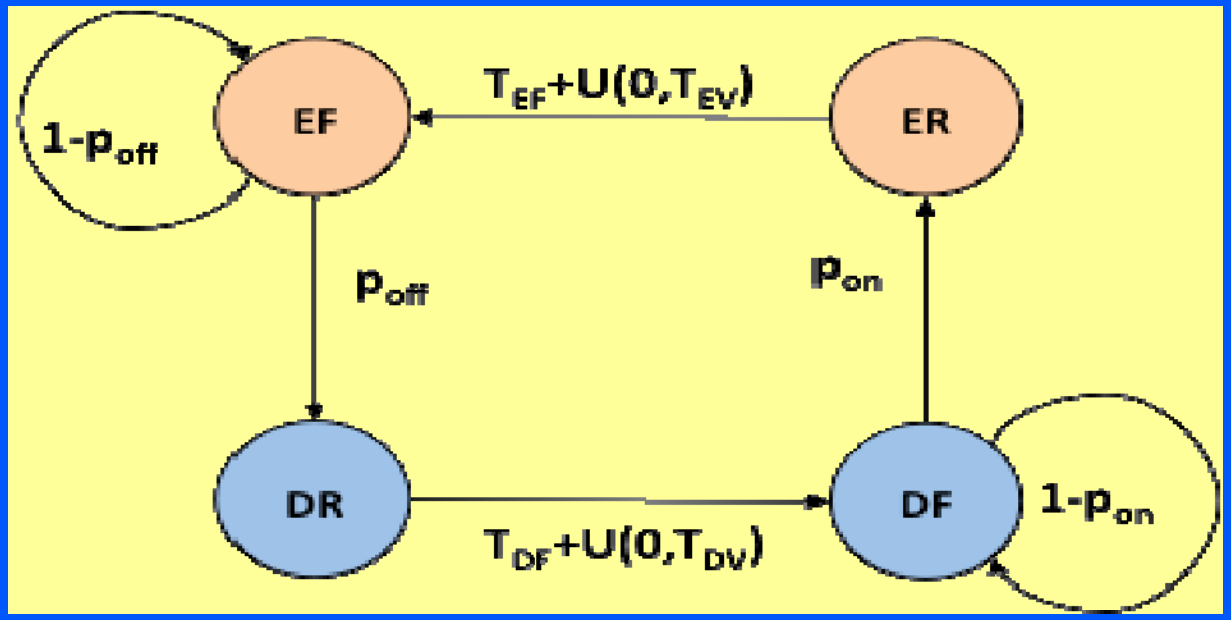
ColorPower ™ State Transitions



- Within each color, each device: (E)nabled vs. (D)isabled
- (R)efractory (it cannot switch states) vs. (F)lexible (eligible to switch)

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ColorPower ™ State Transitions

- The evolution of each device is modeled like a modified Markov process
- In each round devices in state EF randomly switch off to state DR
- Once in DR device waits for certain rounds before transitions to state DF; the waiting time is a fixed number PLUS a uniform random addition to feather the distribution (so not many devices switch states at once)
- The other two distributions are complementary

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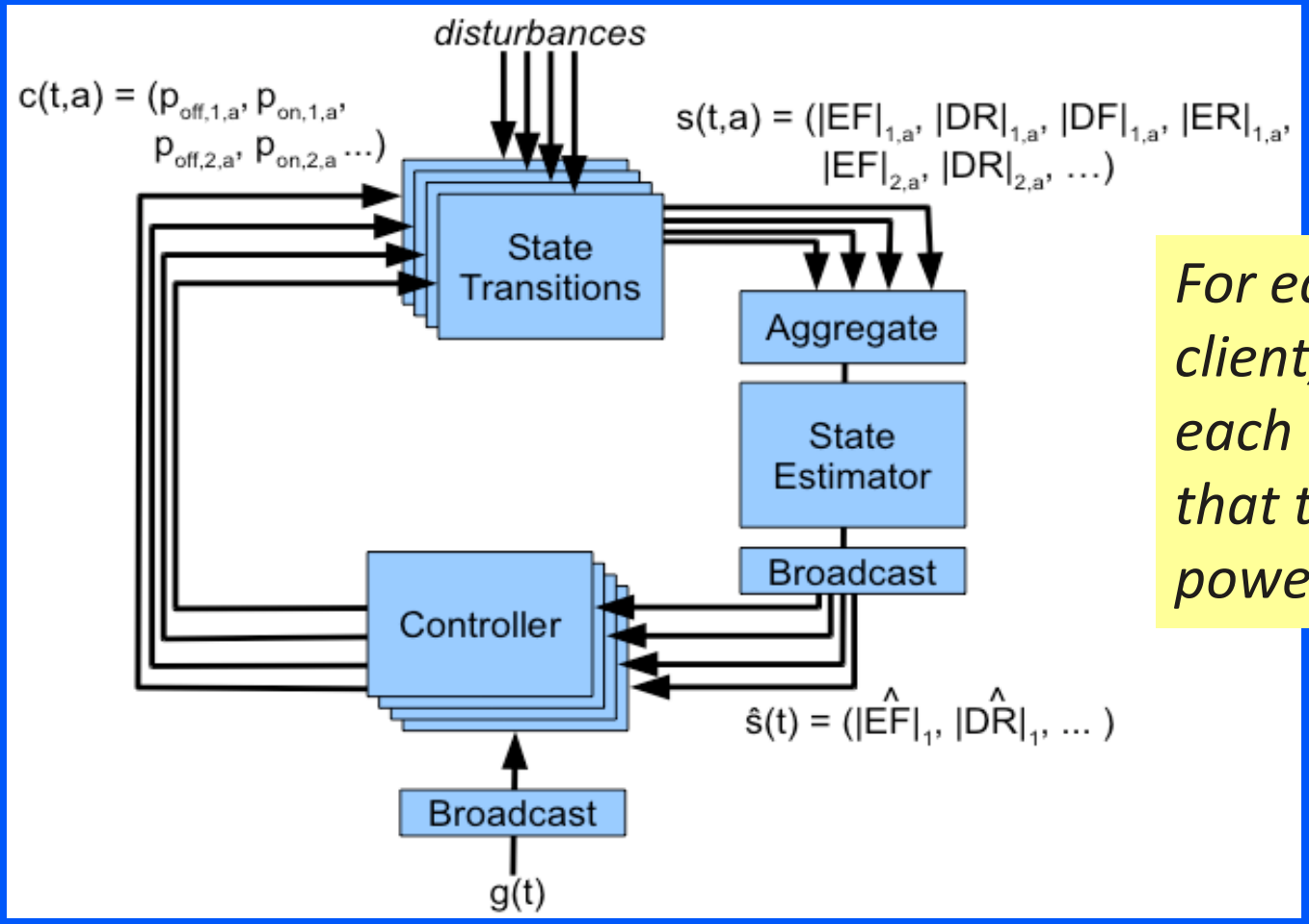
Formal Control Problem



For each ColorPower client, set p_{on}, p_{off} for each device group, such that the total enabled power in s(t) tracks g(t)

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Formal Control Problem

- The control problem is to set the transition probabilities such that the total Enabled Demand tracks the target as closely as possible, subject to the constraints
- Device with lower numbered colors are shut off first
- If a color has devices that are Enabled and Disabled, then every device is equally likely to be disabled
- No device is unfairly burdened by its initial bad luck in becoming Disabled

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Additional Important Constraints

- **1. Goal tracking:** *shape power demand*

$$g(t) = \sum_i |EF_i| + |ER_i|$$

- (Sum of Enabled Demand over all colors i is equal to the goal)
- **2. Color priority:** *respect user preferences*

$$|EF_i| + |ER_i| = \begin{cases} D_i - D_{i+1} & \text{if } D_i \leq g(t) \\ g(t) - D_{i+1} & \text{if } D_{i+1} \leq g(t) < D_i \\ 0 & \text{otherwise} \end{cases}$$

$$D_i = \sum_{j \geq i} |EF_j| + |ER_j| + |DF_j| + |DR_j|$$

- Demand D_i is the demand for the ith color and above
- Devices are Enabled from the highest color down until the goal is reached

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Additional Important Constraints

- **3. Fairness:** *no devices are favored*

$$\forall_{a,a'} c(t,a) = c(t,a')$$

- Meaning that the control state is identical for every agent
- **4. Cycling:** *don't keep the same devices off*

$$(|EF_i| > 0) \cap (|DF_i| > 0) \implies (p_{on,a,i} > 0) \cap (p_{off,a,i} > 0)$$

- This means that as long as there are both Enabled and Disabled devices , some of them should be changing from Enabled to Disabled to vice versa

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Controller Design Issues

- It is possible that not all constraints can be satisfied; some of them are more important than others
- Customer preferences are the most important ones
- Goal tracking is the second most important
- Least important is the Cycling constraint
- The Fairness constraint is the easiest to satisfy (simply the same stochastic algorithm on all clients is executed)
- We view the controller as having a “budget” of flexibility to spend with each color offering up to $|EF|_l$ of potential reduction in demand

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Controller Design Issues

- Flexibility builds up as Refractory devices finish their time outs and move to the Flexible state
- The controller is formulated as a cascade of priorities of how to spend the “Flexibility budget” indicated by the state s(t)
- As the controller considers each constraint in turn, it allocates flexibility to satisfy that constraint (as much as possible)
- Then it attempts to satisfy the rest of the constraints with whatever flexibility remains unallocated
- Any unallocated flexibility is allowed to accumulate as a reserve improving future controllability

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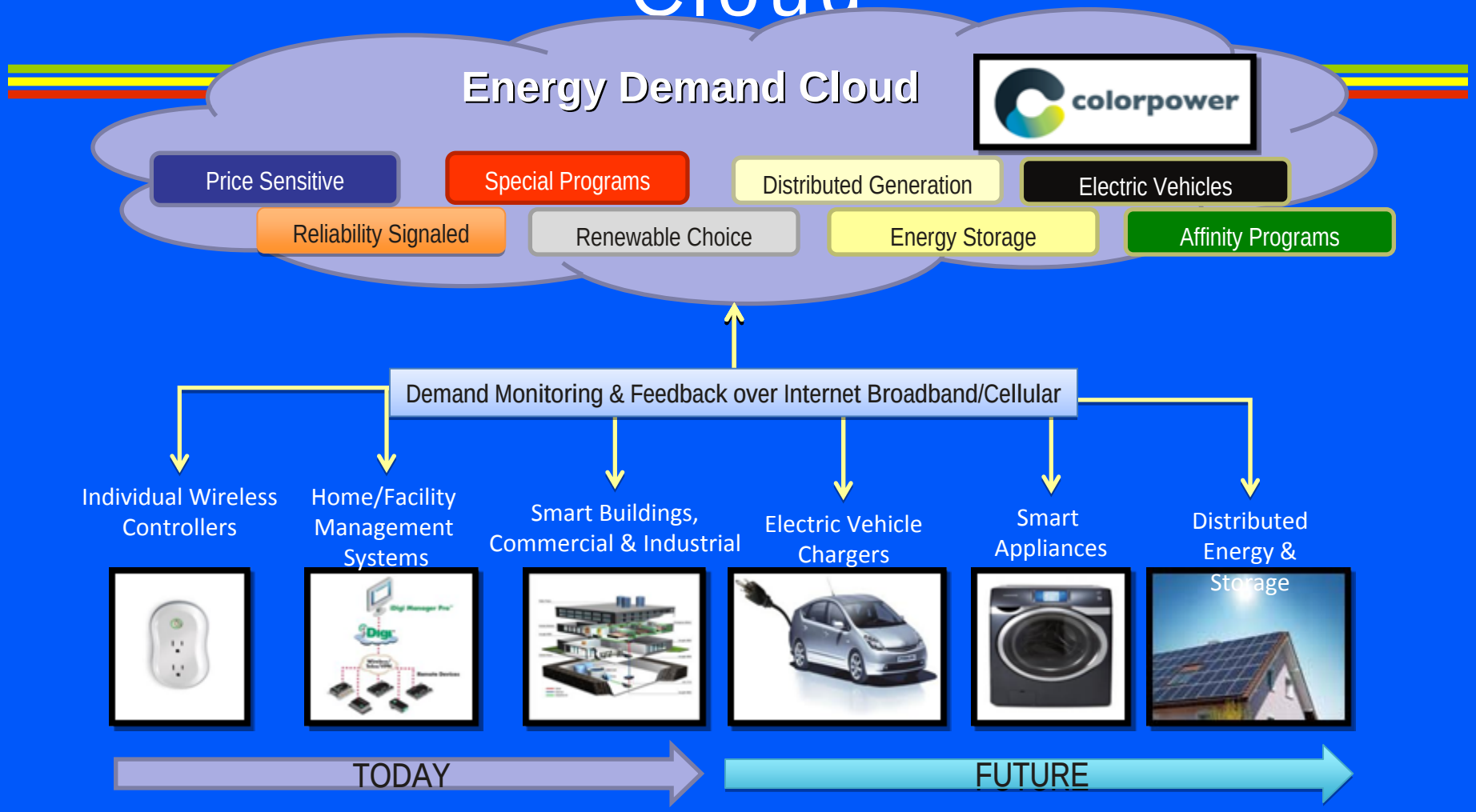
ColorPower™ Energy Demand Cloud



ColorPower client is ~10kb—virtually any embedded device can run it

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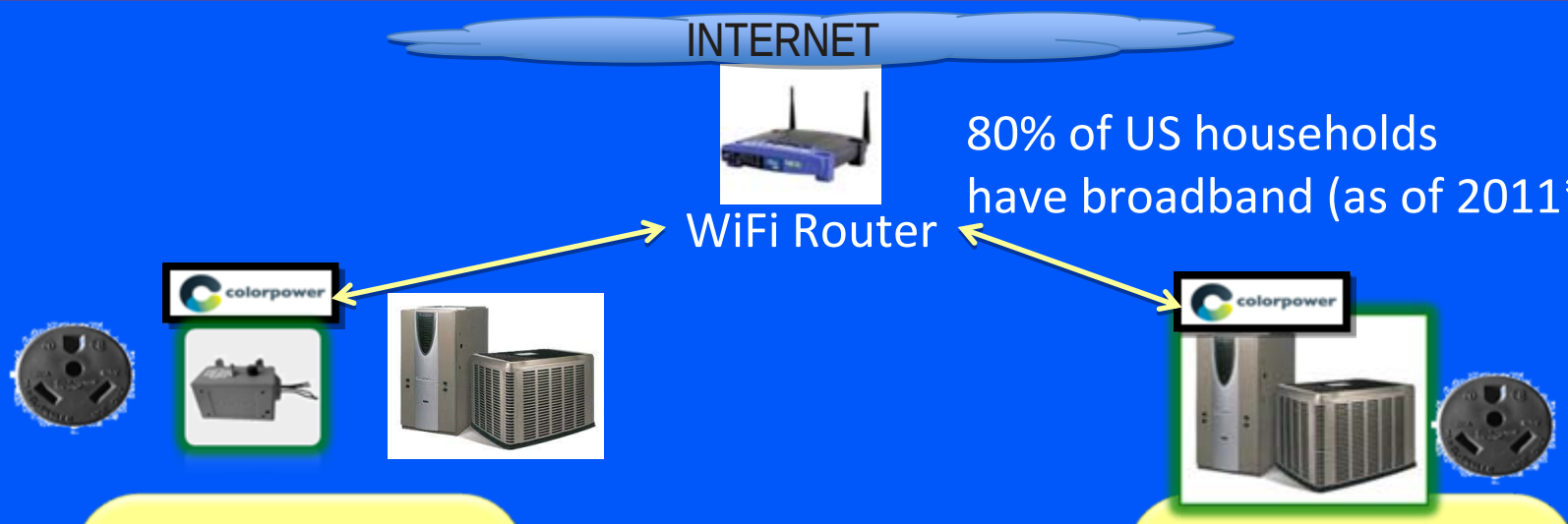
ColorPower™ Software in Devices



80% of US households have broadband (as of 2011*)

Today - Retrofit

External Load Controller
OEM Products to Seed Market

Future - Embed

Internal Load Controller
ColorPower Logo Testing & Certification

*Source: Point Topic Broadband Database 2012

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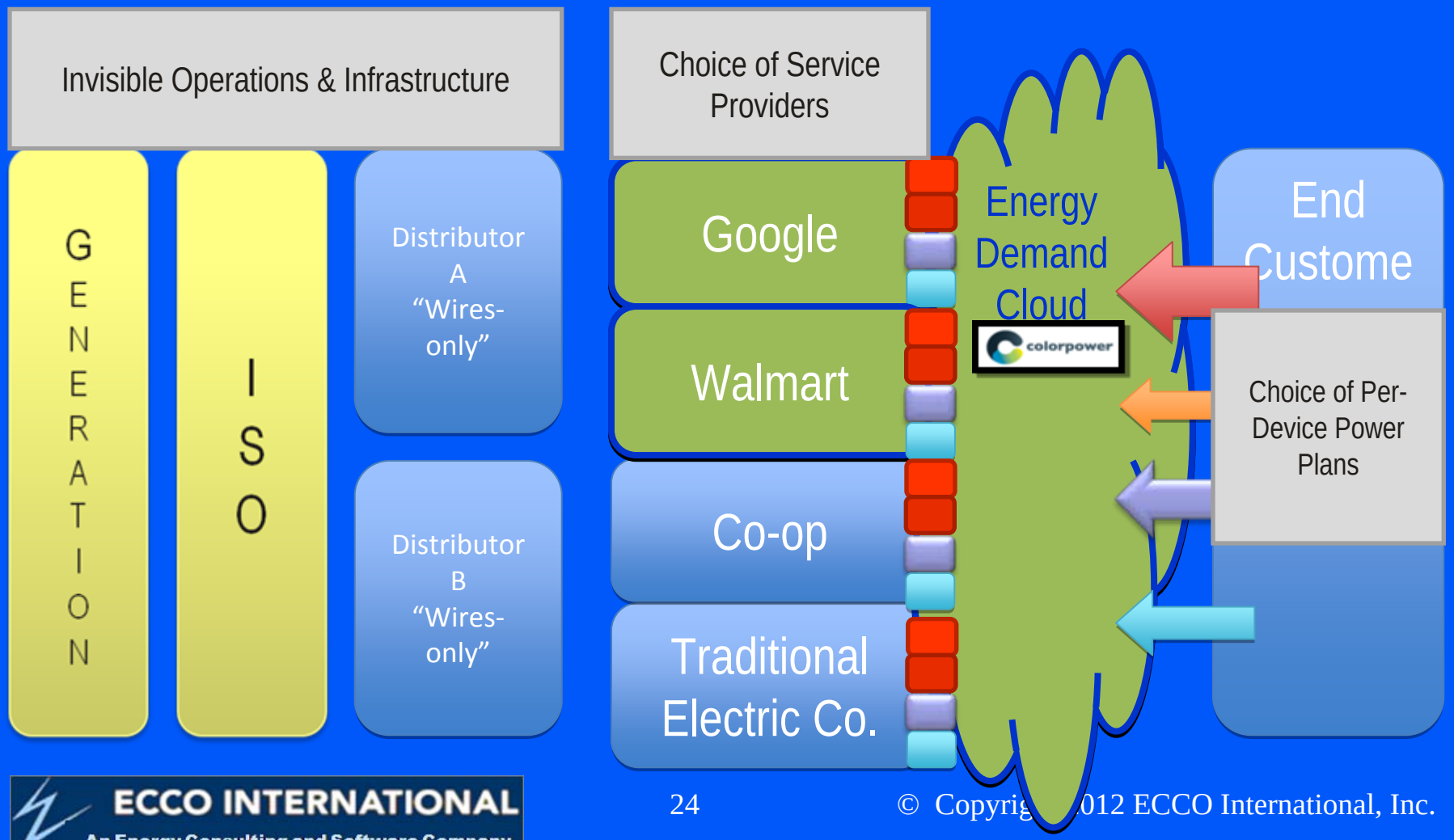
The Telecom – Like Retail Model for the Energy Business



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ColorPower™ creates Smart Energy Options

Do I want my pool pump to run at night?

Do I just want maximum price savings?

Should I run it only with renewable energy?

Maybe I don't want to coordinate it with the power grid at all today.

Settings

Select Power Plan

Plan	Description	Price
Eco Max	Support Clean Energy—Run Only When Solar/Wind Is Available	$.12
Night Run	Run between 11PM and 4AM	$.08
Max Saver	Maximum Cost Savings	$.07
Eco	Help Lower Prices and Reduce CO2	.085
Blackout Fighter	Help Prevent Blackouts Only	$.095
Classic	Do Not Coordinate With Grid	$.10

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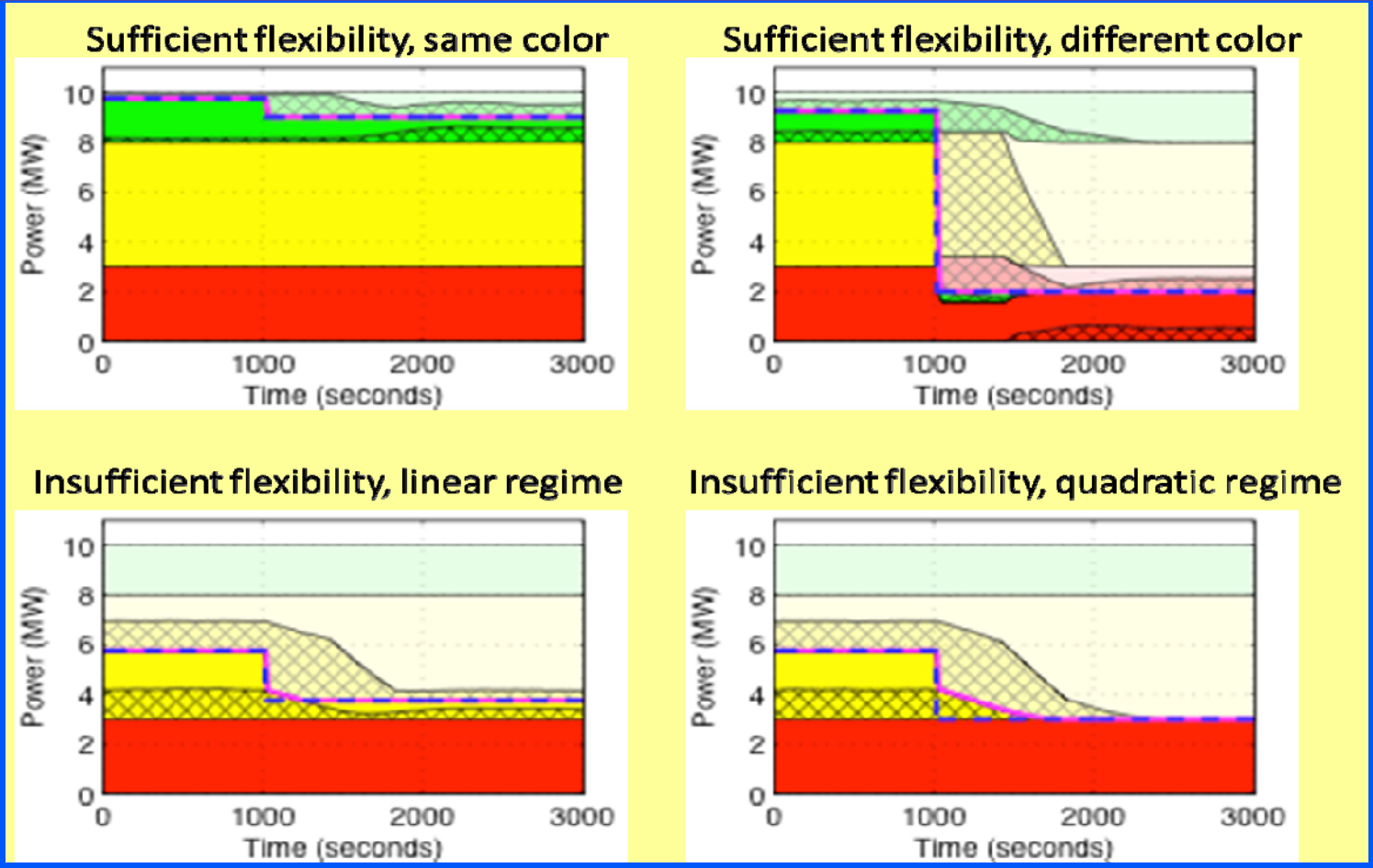
Examples of Control



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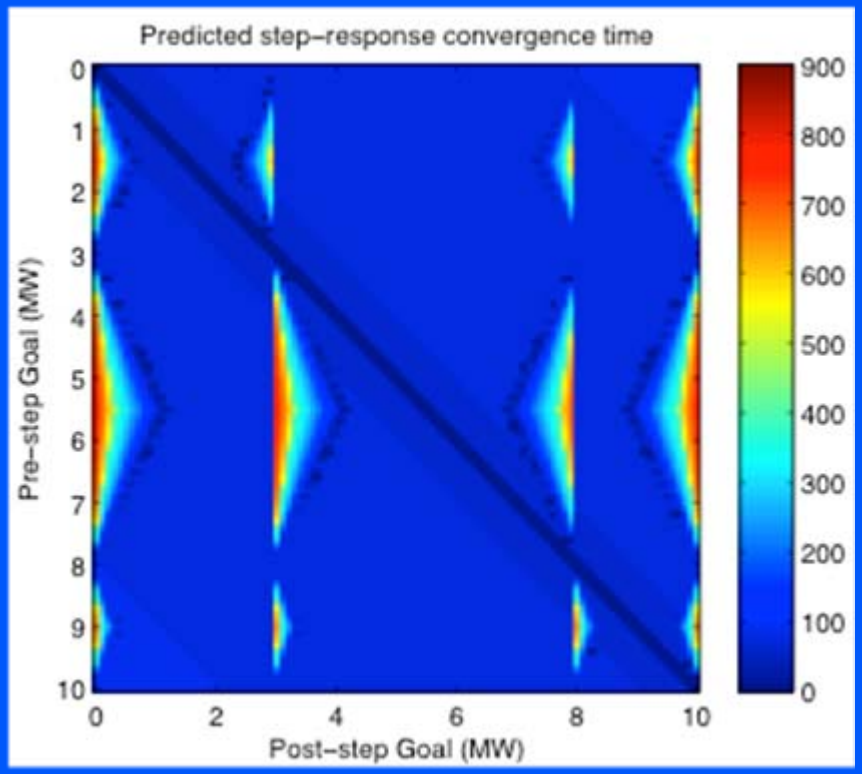
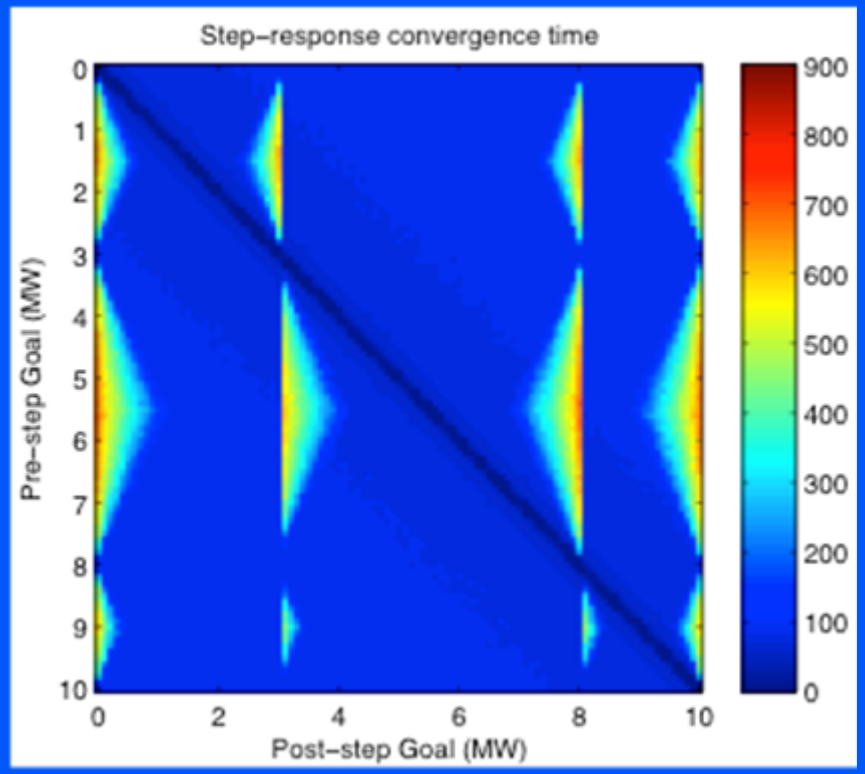
Simulation Studies: Convergence

Predicted



Measured



Excellent agreement

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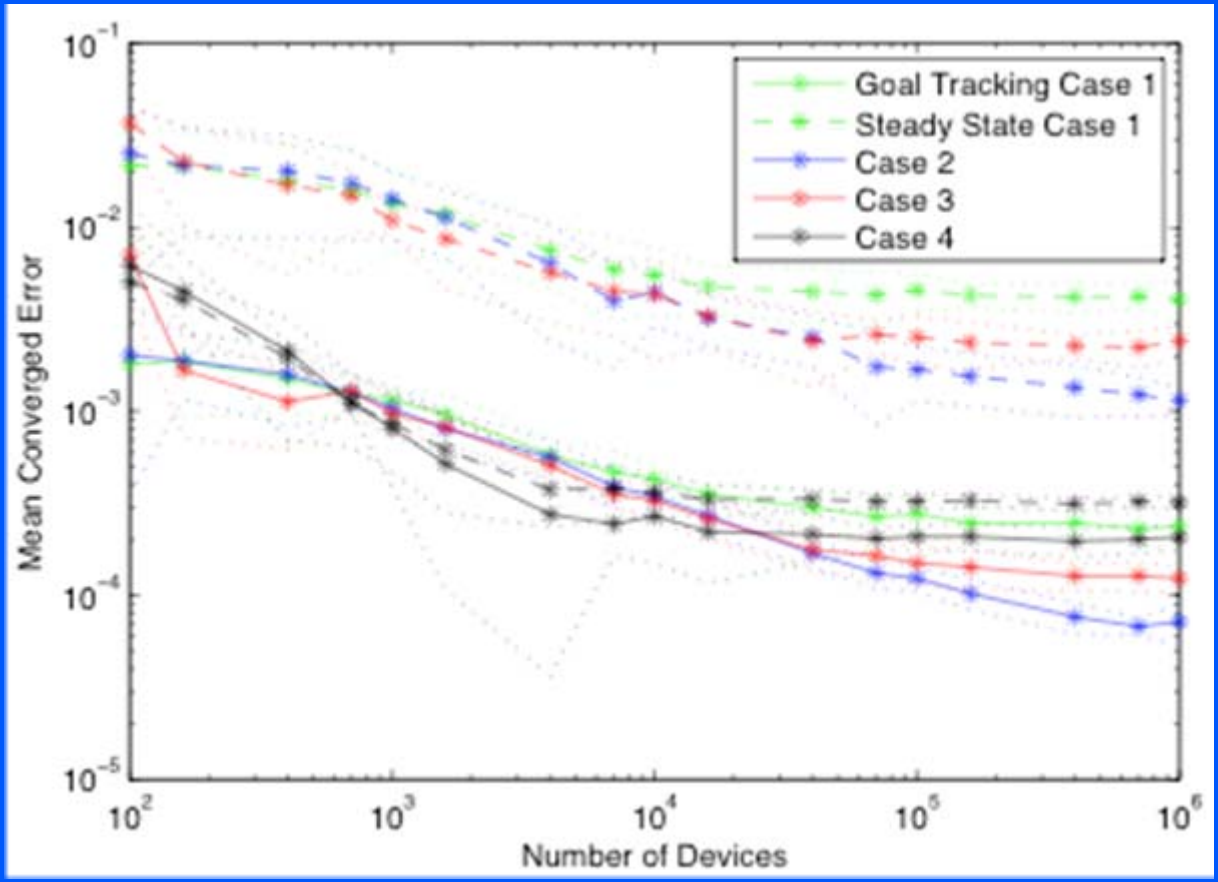
Simulation Studies: Scaling



More devices = better accuracy

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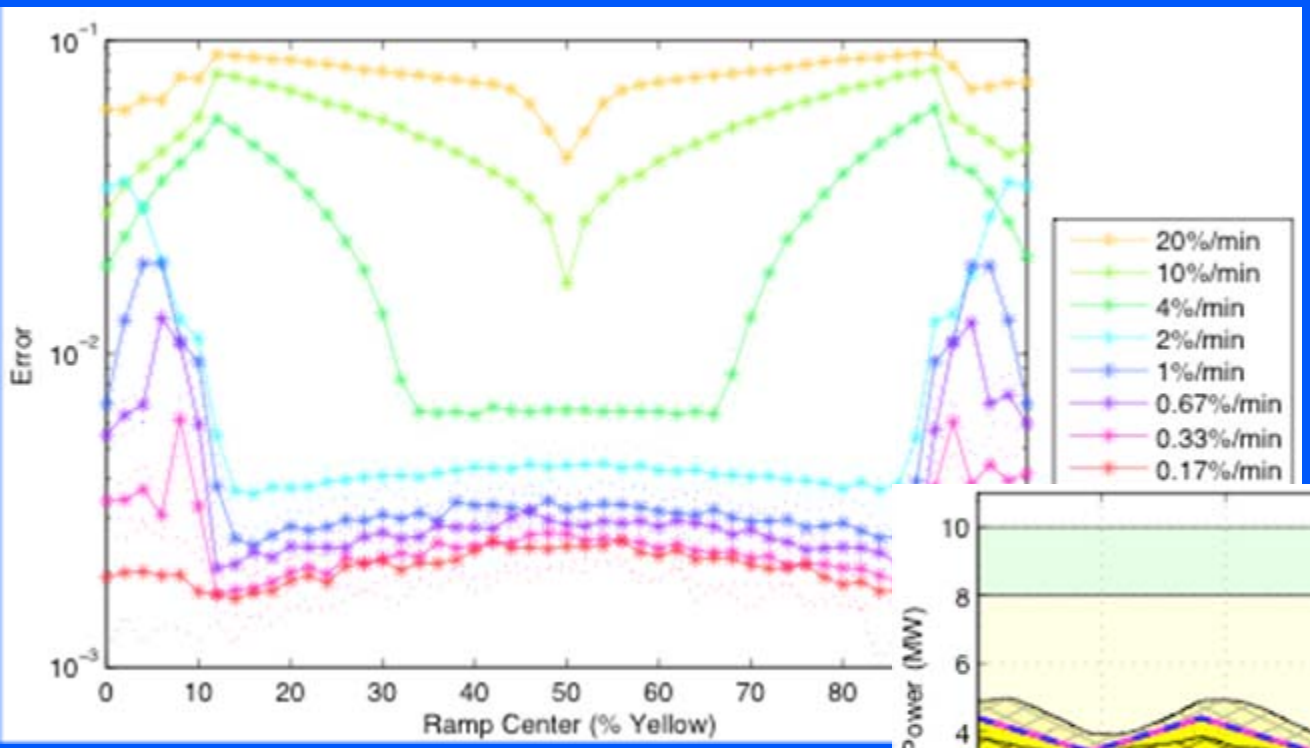
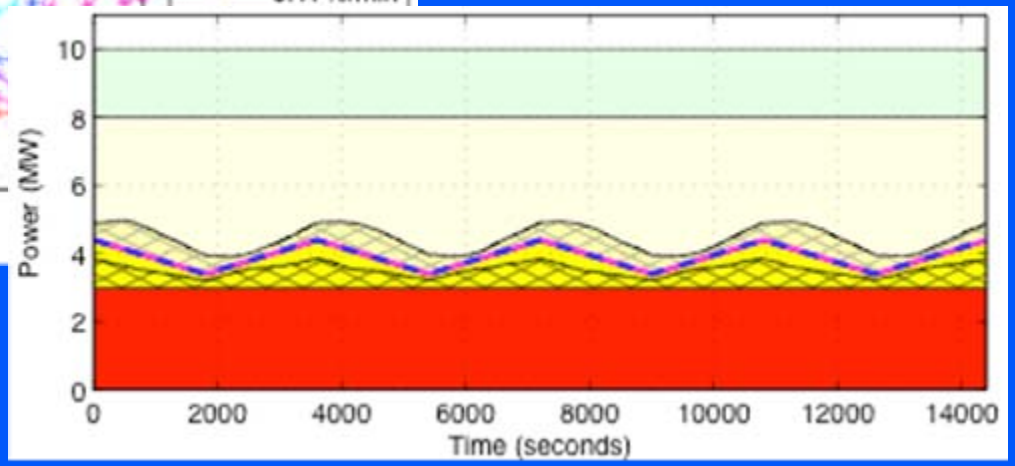
Simulation Studies: Ramp Response

Results



Good behavior unless fairly steep or close to hard bounds

Example



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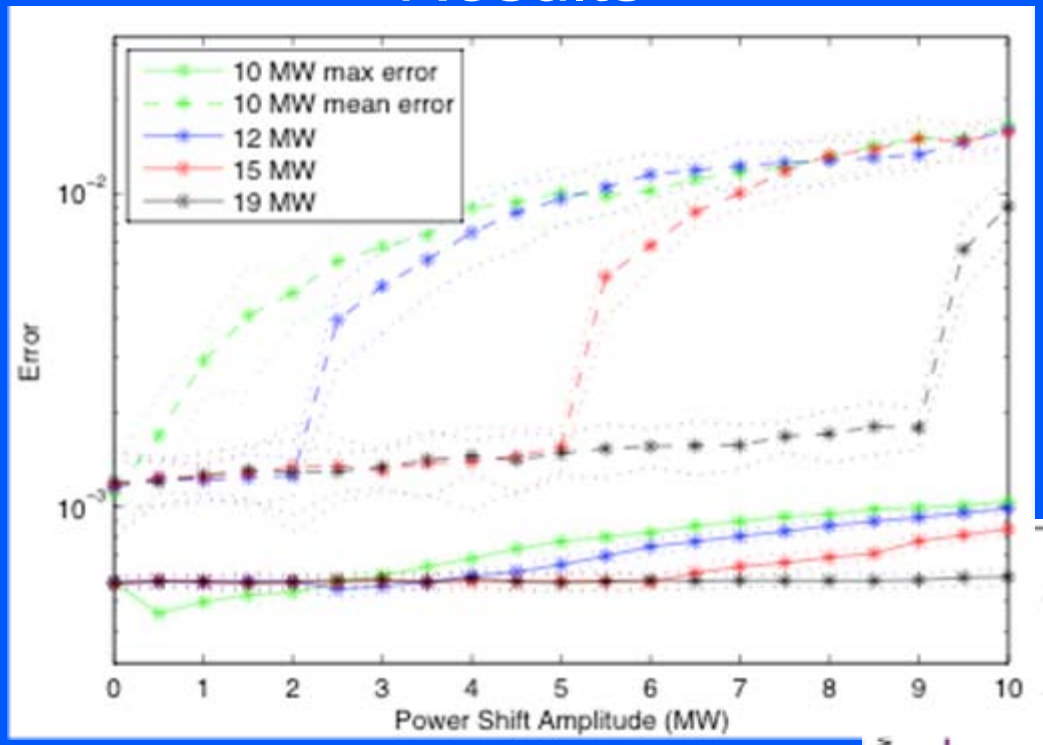
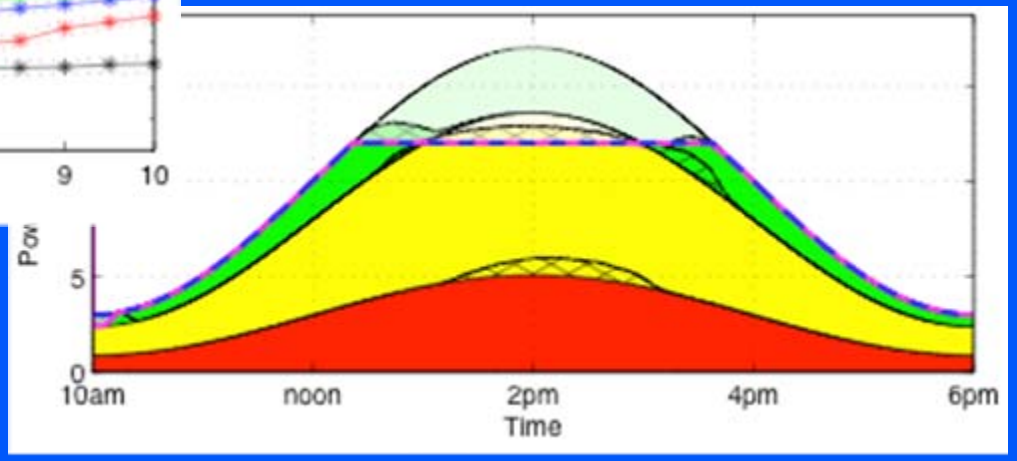
Simulation Studies: Peak Shaving

Results



Small tracking errors only while crossing color boundaries

Example



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ColorPower vs. Old DR

Area	Old Demand Response	ColorPower
Speed of Effect	Depends on notification requirements	Seconds
Precision	Wild variation in response magnitude	Achieves within 1% of population demand target within 1 minute
Reliability	Send and pray	Population feedback loop ensures additional resources are recruited until demand reduction target is reached
Measurement	Effects estimated days after the event	Real-time DR capacity continuously measured, settlement instantaneous
Reliable Substitute for Power Procurement	No	Yes

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ColorPower vs. Old DR

Area	Old Demand Response	ColorPower
Duration of Inconvenience	Hours	Minutes
Inconvenience Distribution	Concentrated on Industrial, Residential Poor	Diffuse, fair, widespread, least inconvenience first as customer-expressed
Measurement of Customer Preferences	None, Must comply with contracted demand reduction when called upon or penalties	Customers presented with color-coded price-participation choices
Simplicity	Complex event participation/TOU pricing rules	Color-coded opt-in/out at any time
Management Complexity	Forecast and ManualEvent-oriented	Continuous and automatic
Incentive Model	Compensation payments for submission to load control	Per-device rate discounts for identifying devices with flexibility
Central Decision Maker	Utility	Customer

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Conclusions

- Current DR programs are not successful
- The new proposed algorithm is based on a distributed computing based stochastic control algorithm allows fast, accurate and robust control of thousands to millions of devices
- Performance can be accurately predicted from stochastic model analysis
- The algorithm operates well in both emergencies (steps) and planned ramps
- Performance is robust against fluctuations, errors, and variation between devices
- We are in the process of commercializing the technology

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Thank You!

- To learn more, see
- http://www.colorpower.org

- alexp@eccointl.com

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