NIST Transactive Energy Challenge Preparatory Workshop

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Co-Simulation of Decentralized Grid Control Algorithms

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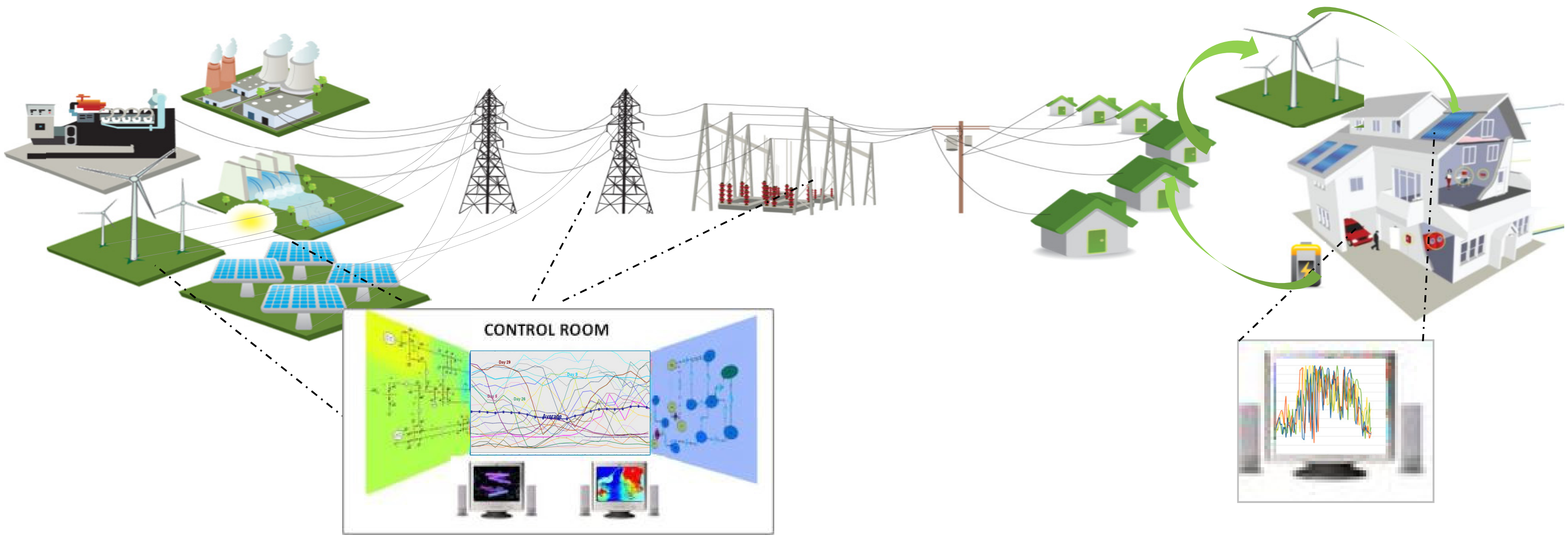
arpa·e Advanced Research Projects Agency • ENERGY

Future Grid

- The future grid will consists of billion smart devices including distributed resources, and millions of decision-makers.
  - Emerging dynamic behavior at new space and time scales.
- Need much faster, better, tighter ***coordination*** across subsystems: ISO, utilities, microgrids, buildings, homes, etc.



The Challenge

- *How can we* ***coordinate*** *the simultaneous operation of a very large number of devices and subsystems (actors) to achieve system-wide objectives such as ultra-reliability, economic optimization, and sustainability?*

- Recognition that (for many reasons) it is impossible to have a single organization making all operational and control decisions.

- Decision making needs to be ***decentralized***.

Decentralized

- Recognizes more than one decision-maker.

- Microgrids
- Demand Response
- Building Energy Management Systems
- Home Energy Management Systems
- Building, Home, Vehicle, X to Grid
- Transmission/distribution effects
- Consumer Empowerment
- Prosumers
- Imbalance Markets
- Distribution System Operators (DSO)
- ISO Seams Issues
- Wide-Area Control
- Etc. . . .

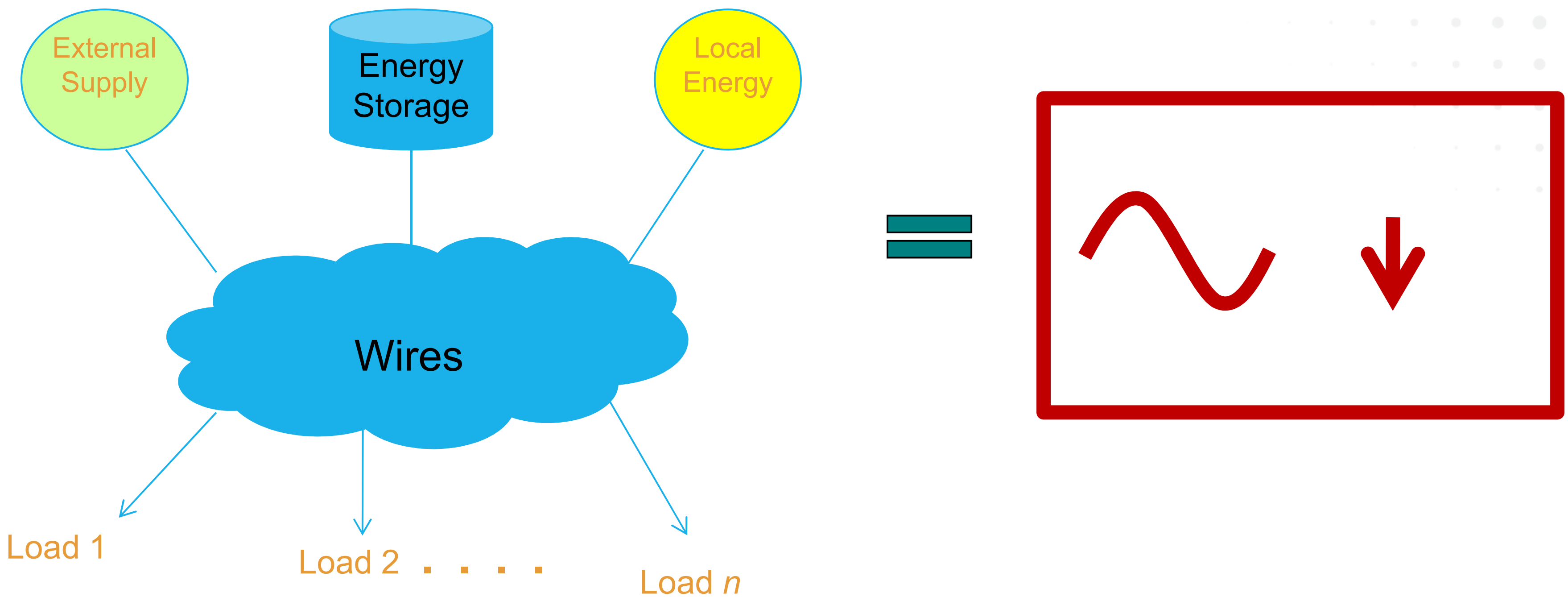
Use cases of decentralized coordination

ARPA-E GENI Project

- Interdisciplinary collaboration including power systems, networked control, cyber-physical systems, and decentralized optimization.

- Project Contribution:
  1. Decentralized Control Reference Architecture
  2. Power/Cyber Co-Simulator
  3. Decentralized Frequency Control Application
  4. Decentralized Energy Scheduling Application

Concept 1: Prosumer Abstraction



- A generic model that captures basic functions (produce, consume, store) can be applied to power systems at any scale.
- The fundamental task is power balancing:

$$P_{INT} = P_G - P_D - P_{Loss} - P_{STO+} + P_{STO-}$$

- Energy services can be virtualized.

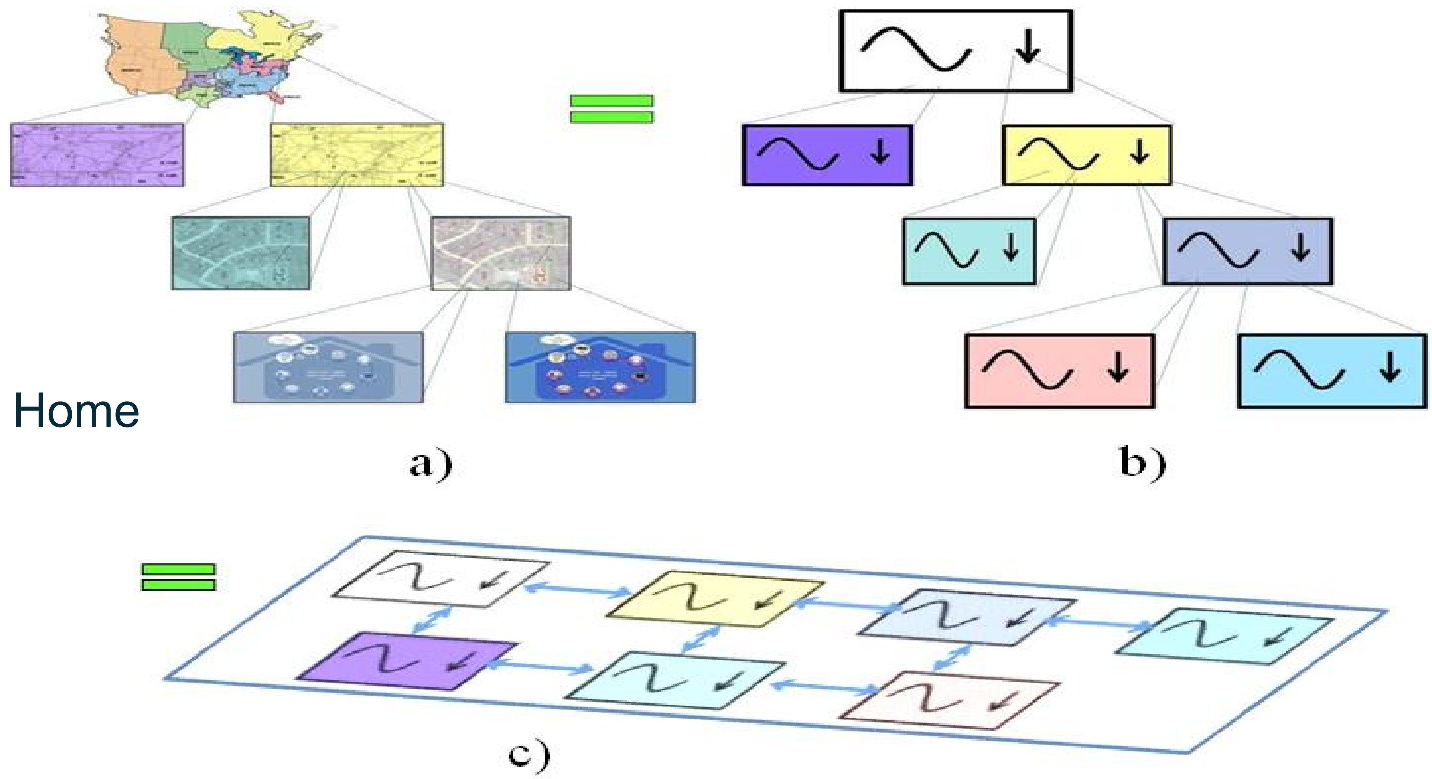
Concept 2: Networked Grid

Interconnection

ISO

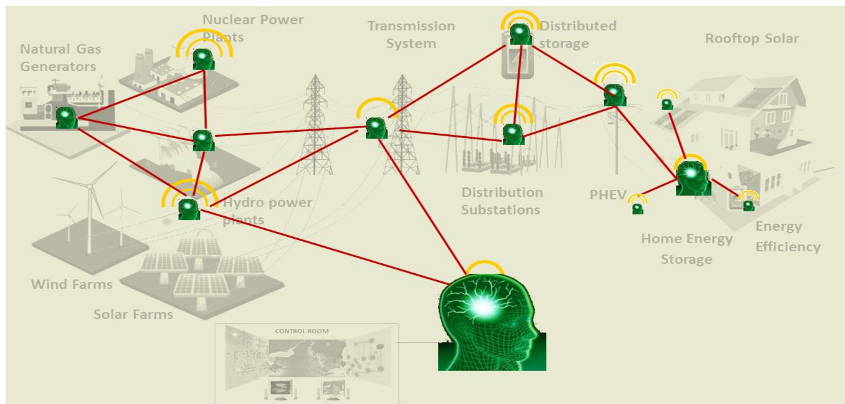
Utility

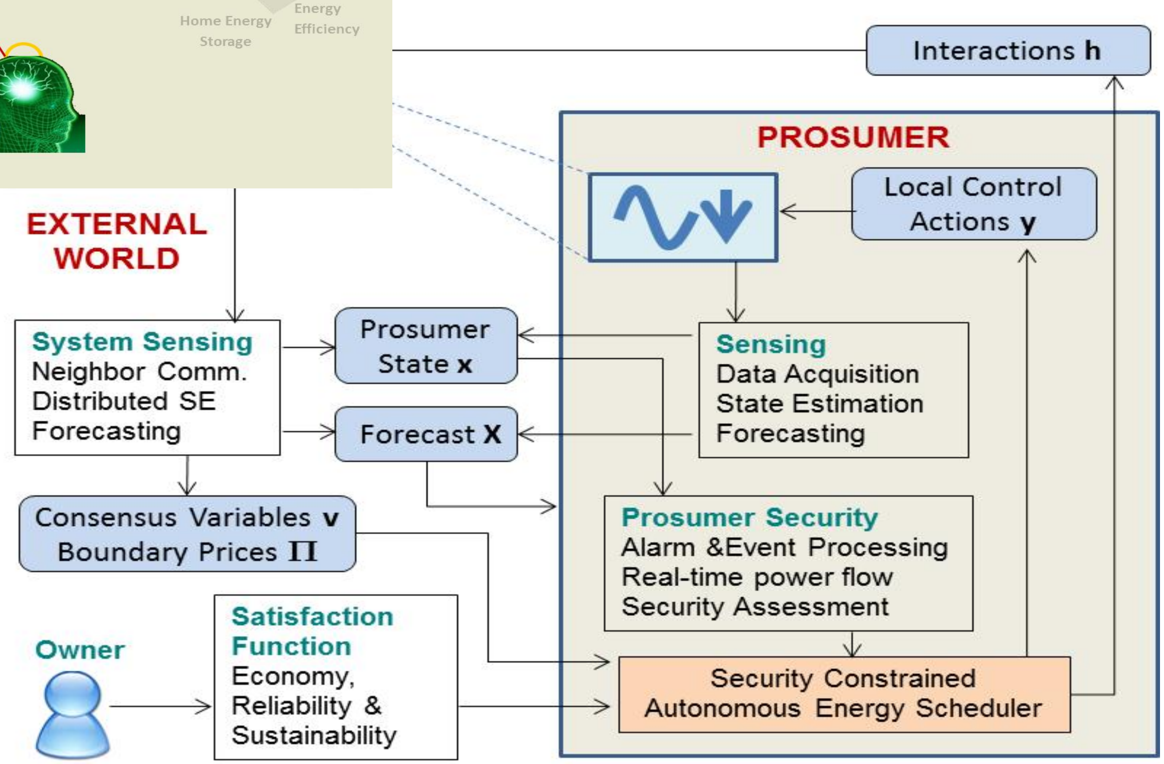
μGrid, Building, Home



- Interactions occur among entities of the same type (prosumers)
- Supports hierarchical or flat paradigms

Concept 3: Prosumer Services

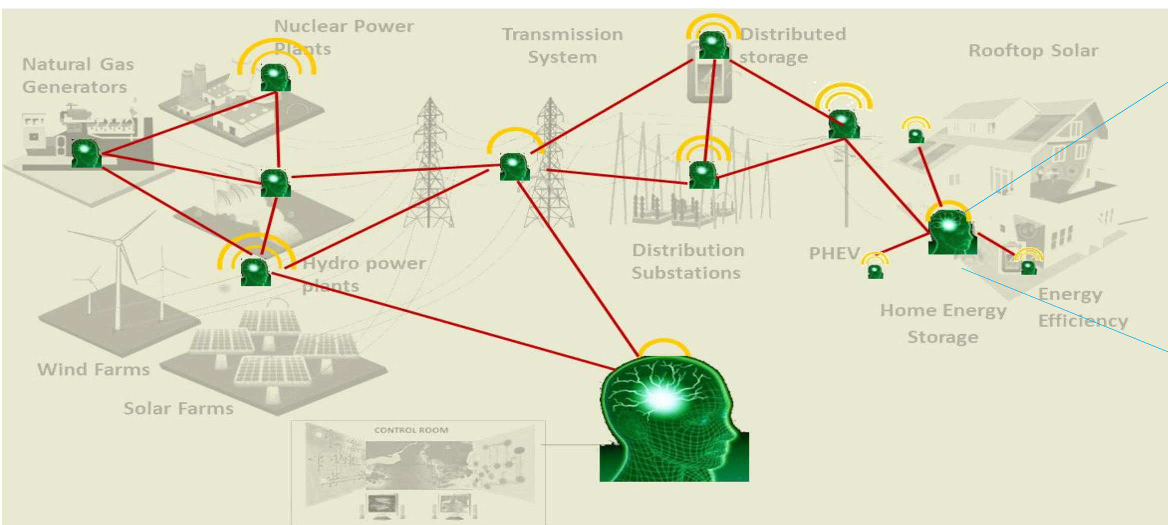




- Prosumer exposes standardized services
  - Energy balancing
  - Frequency regulation
  - Reserve
  - Sensing and Information
  - Forecasting
  - Security
  - Self-identification
  - Voltage control
  - Black Start
  - Etc.

Architecture Summary

- The grid is naturally divided into subsystems.
- All subsystems can produce, consume and store.
  - They become ***prosumers***.
- Prosumers are equipped with distributed intelligence.
- Prosumers interact through formal power protocols.
- Layered cyber-physical network coordination stack.



MARKET Layer
SYSTEM CONTROL Layer
CYBER Layer
DEVICE CONTROL Layer
DEVICE Layer

Grid Co-Simulation

- Two distinct aspects need to be covered:
  - Power System Simulation
    - Numerical solution of a system of differential equations
    - Traditional Tools: PowerWorld, OpenDSS, SimPowerSystem
  - Cyber Systems Simulation
    - Discrete-event simulation
    - Traditional Tools: ns2, ns3, OMNET++

Grid Co-Simulation

- Literature presents two approaches:
- ***Integrated Approach***
  - A new simulation environment with integrated hybrid semantics for Power and Communication aspects

    (e.g. Nutaro et.al "Integrated Hybrid Simulation of Electric Power and Communication Systems")
- ***Federated Approach***
  - Combine existing simulators from the domains of Power Systems and Computer Networks using co-simulation libraries, such as High Level Architecture co-simulation standard
  - Examples: EPOCHS (ns-2 + PSCAD); Godfrey et.al. (ns-2 + OpenDSS)

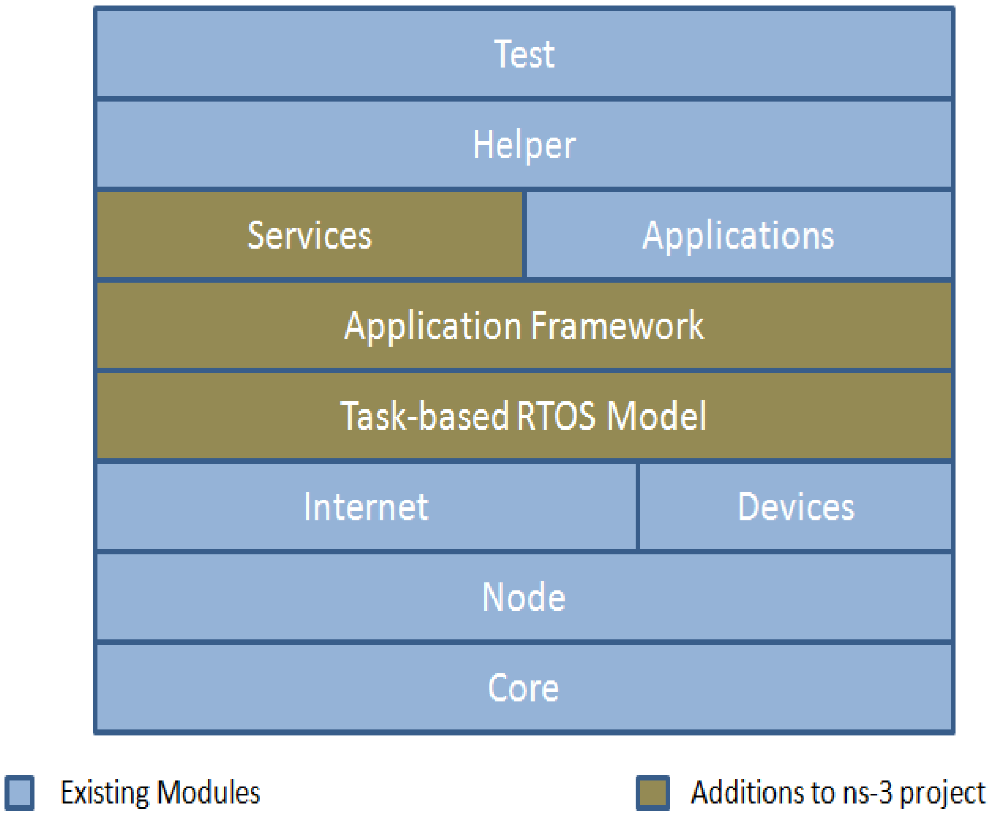
Grid Co-Simulation

- Control and Optimization Algorithms are usually prototyped in domain-specific environments such as MATLAB.

- Decentralized control requires a ***Platform-Aware Integrated Simulation Environment***
  - Demonstrate the integrated operation of individual algorithms.
  - Investigate the effect of computing platform performance on algorithms.
  - Demonstrate the self monitoring (and mode switching) capabilities of algorithms.

Grid Co-Simulation for Decentralized Algorithms

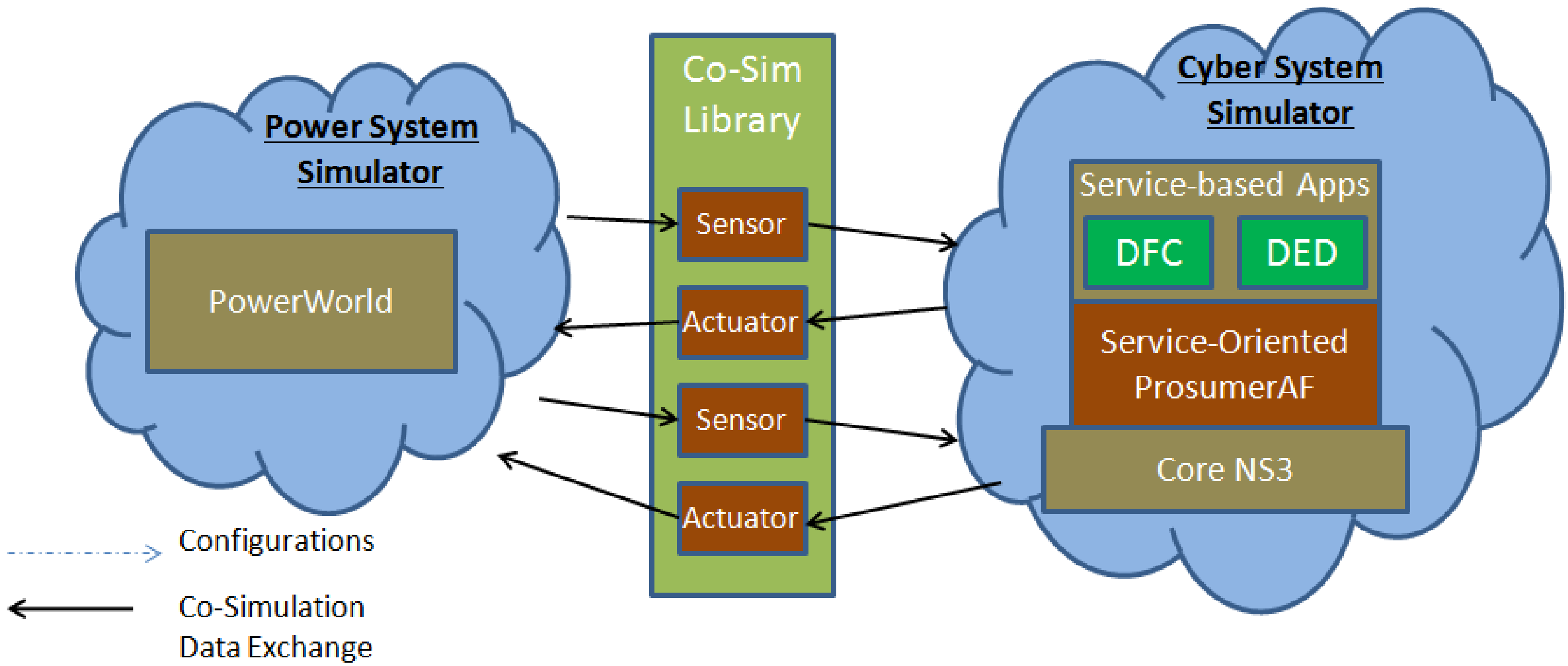
- Uses ns-3 as the basis of ‘computing platform’ simulation
  – Simulate “appropriate” software layers as ns-3 extensions
- Consistent with ns-3 philosophy
  – Ns-3 has an inherently extensible design in order to simulate the software stack involved in networking



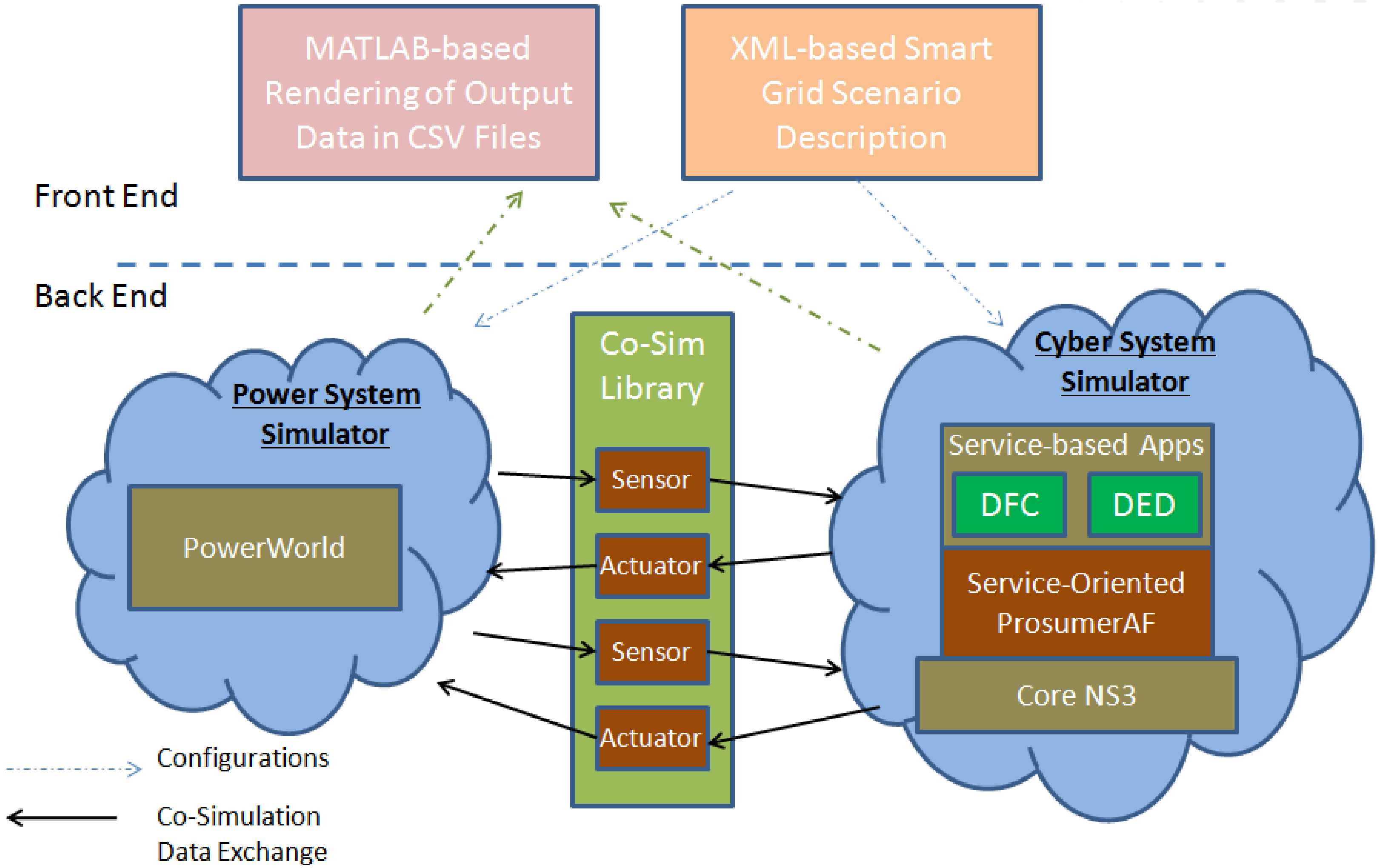
Ns-3 Software Organization

Grid Co-Simulation for Decentralized Algorithms

- ns-3 + Existing Power System Tools (e.g. PowerWorld)
- ns-3 nodes extended with system-level software modules

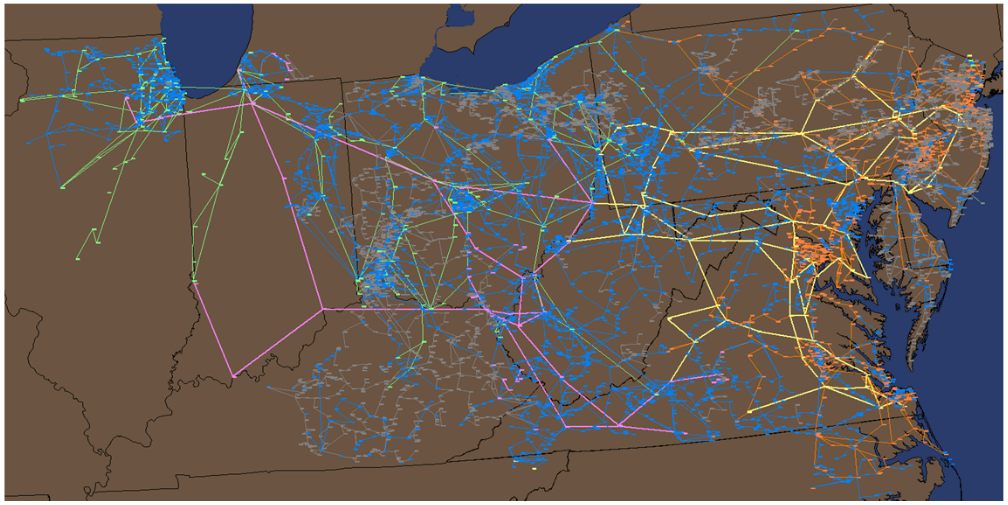


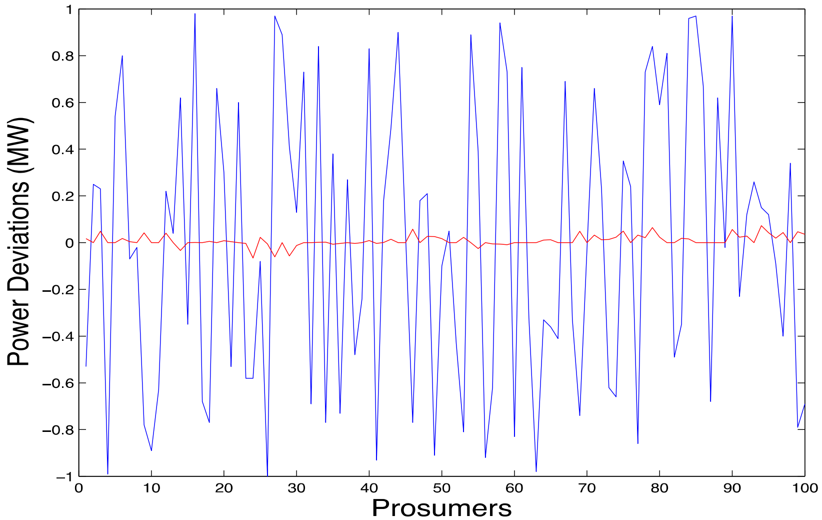
Grid Co-Simulation for Decentralized Algorithms



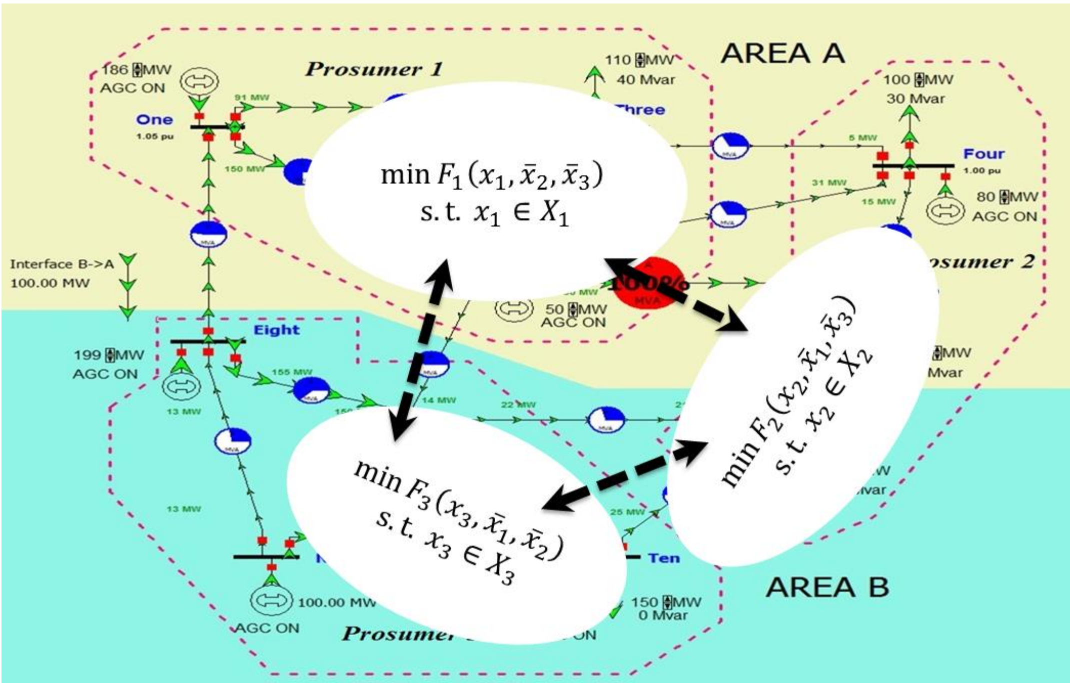
Decentralized Frequency Control

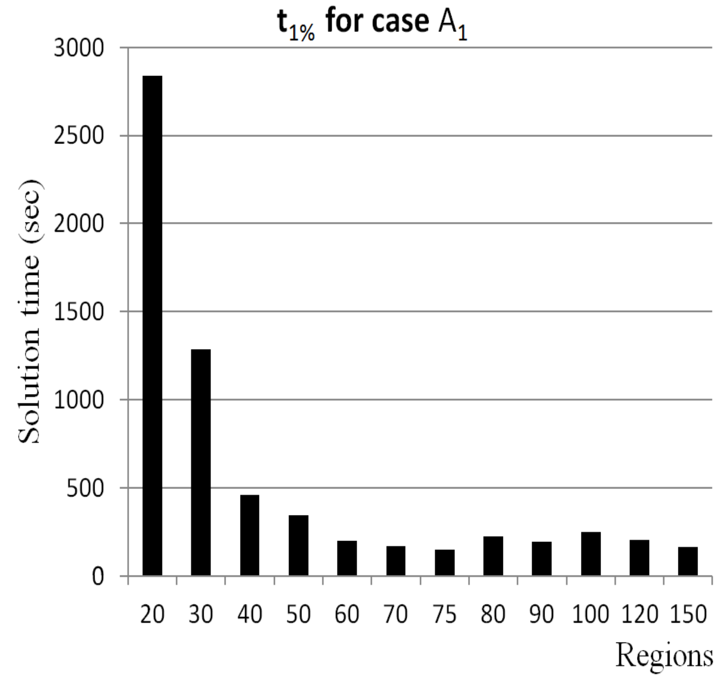
- Bring steady-state frequencies to desired value while:
  - Returning output power to the scheduled interchange
  - Minimizing system-wide control effort
  - Avoiding oscillations
  - Performing only local computations (distributed!)





Decentralized Energy Scheduling



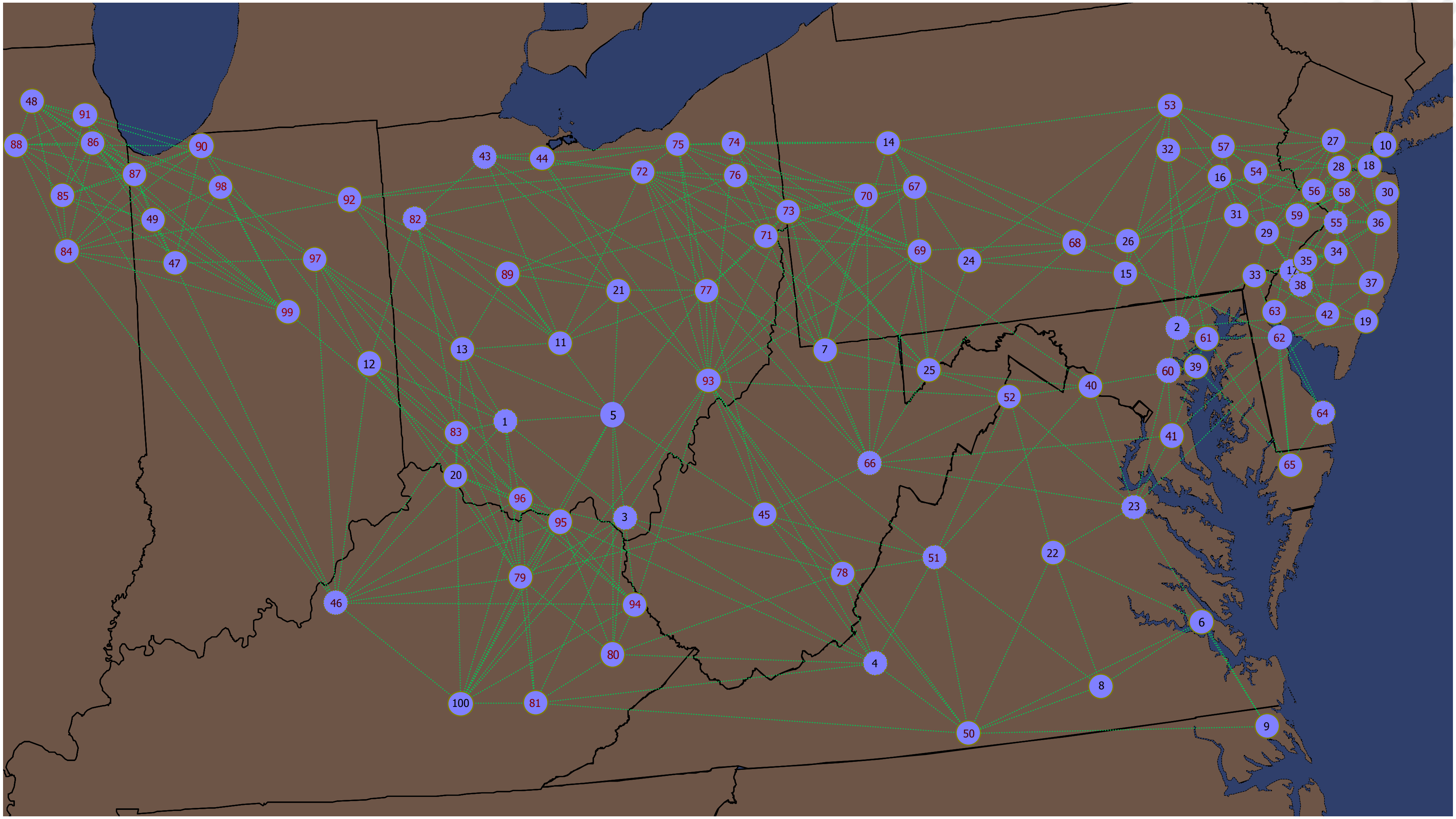


- Application able to schedule energy in the day-ahead timeframe in a decentralized manner.
- Large-Scale ISO with realistic Unit-Commitment Data
- Solution orders of magnitude faster.

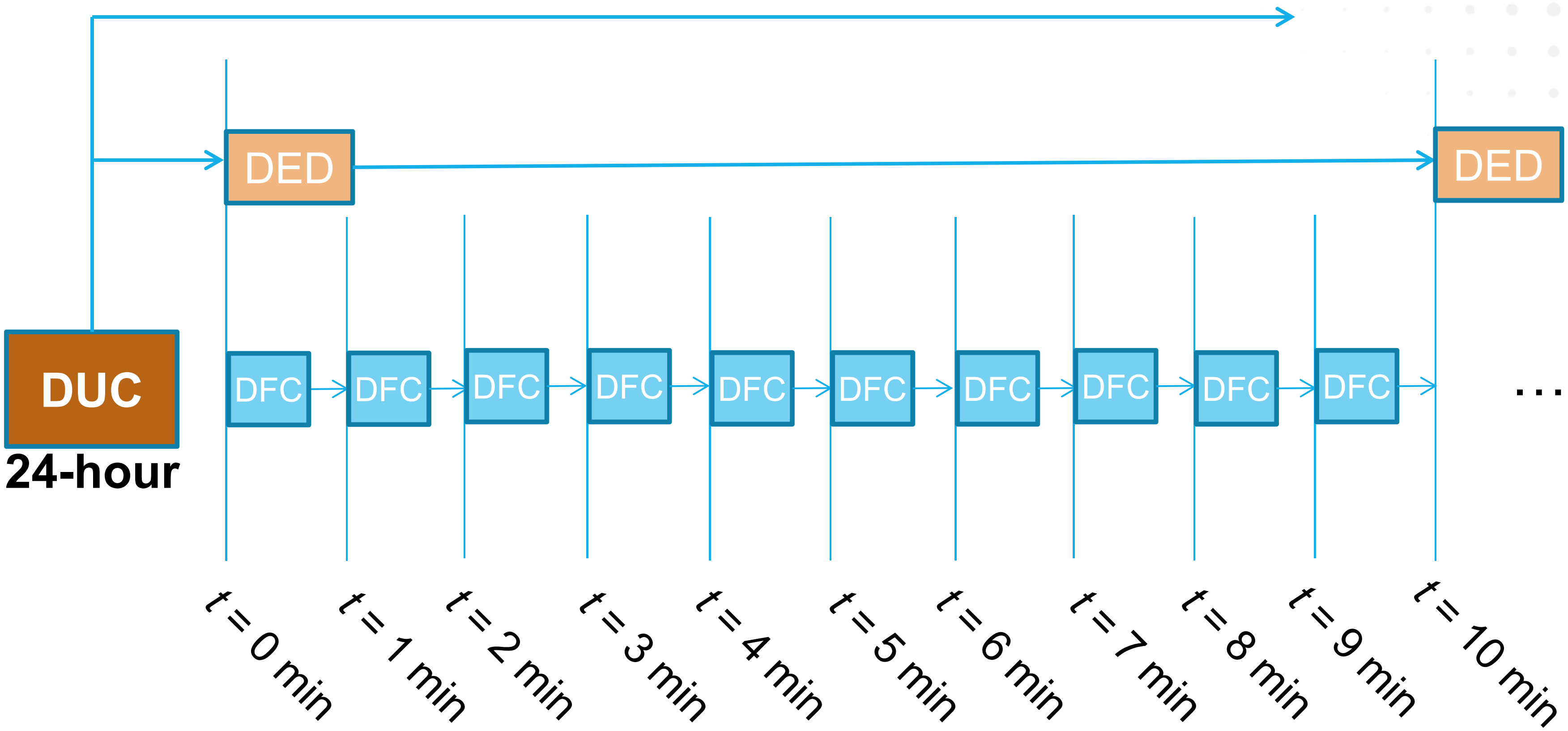
Final Co-Simulator State

- Large Scale ISO (PJM) System
  - Divided into 100 prosumers
  - Described as XML document
  - Outputs the rolling horizon generator set points as .csv files
  - Mfile reads the csv file and plots the behavior of a generator under the “integrated influence “ of various algorithms

Large-Scale ISO Subsystems



Integrated Demo



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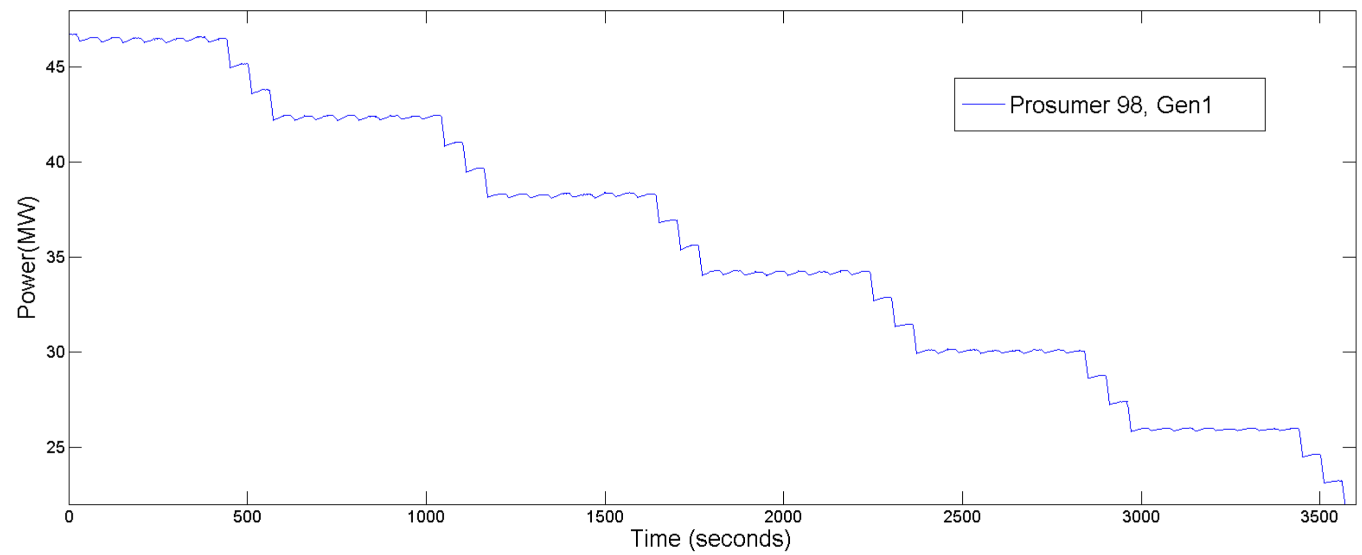
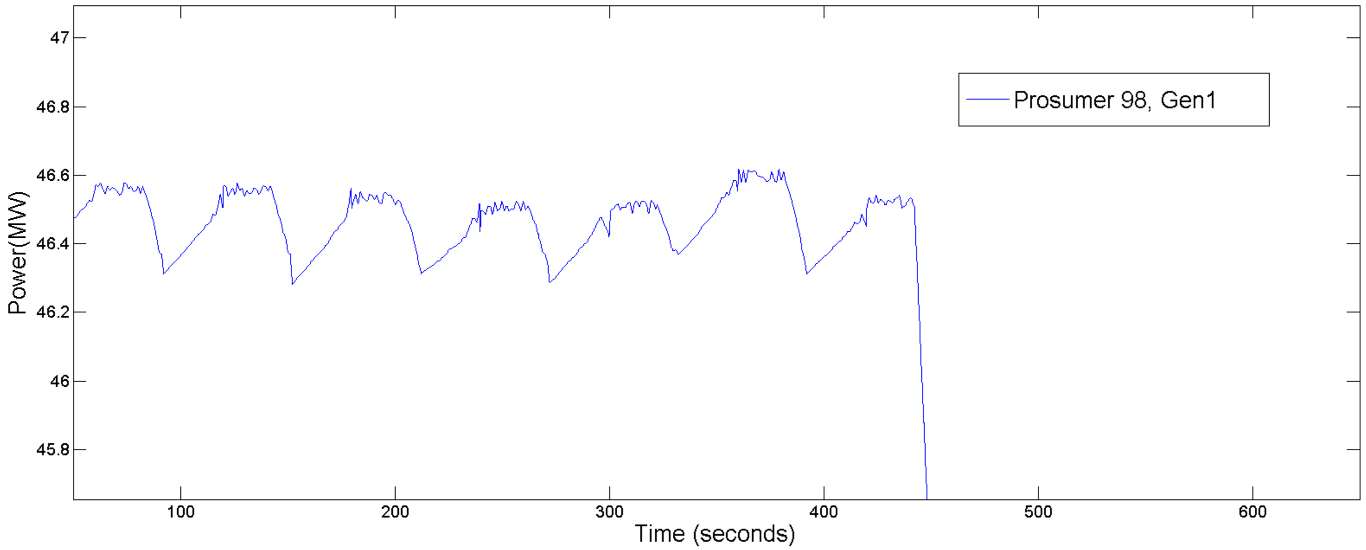
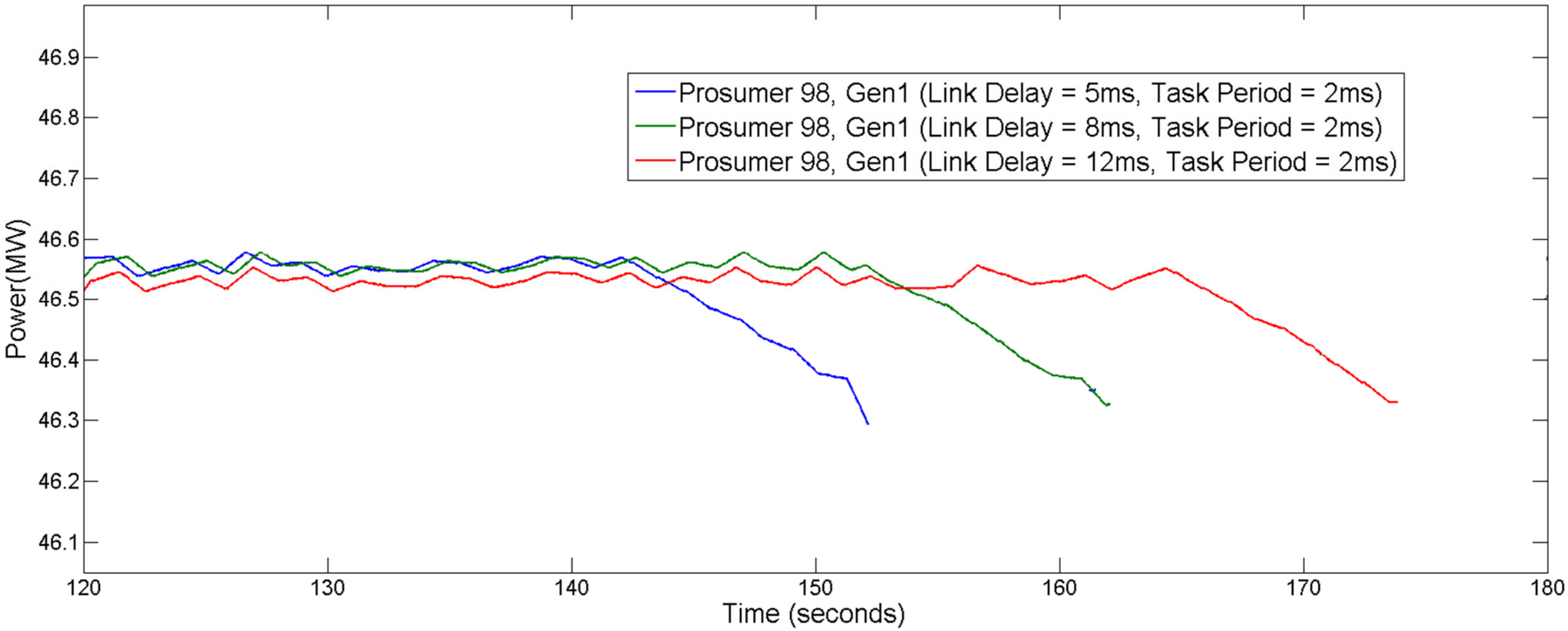
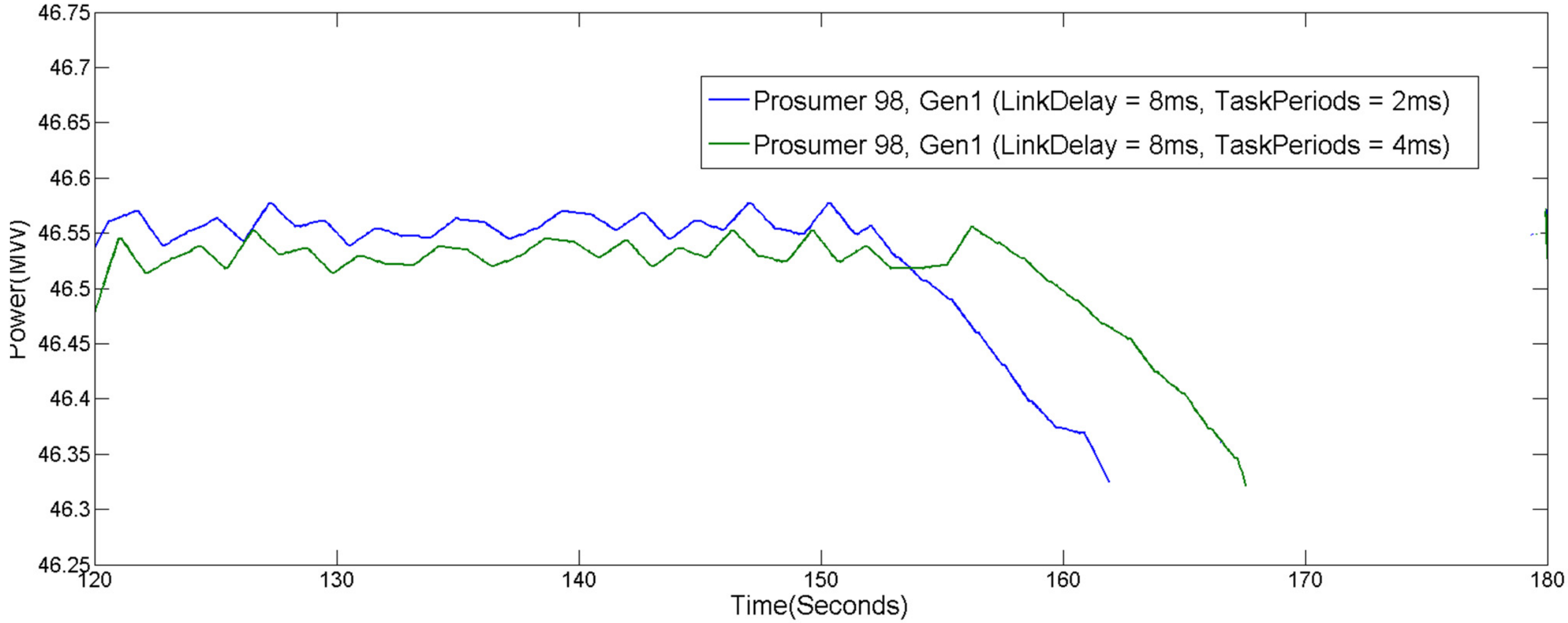




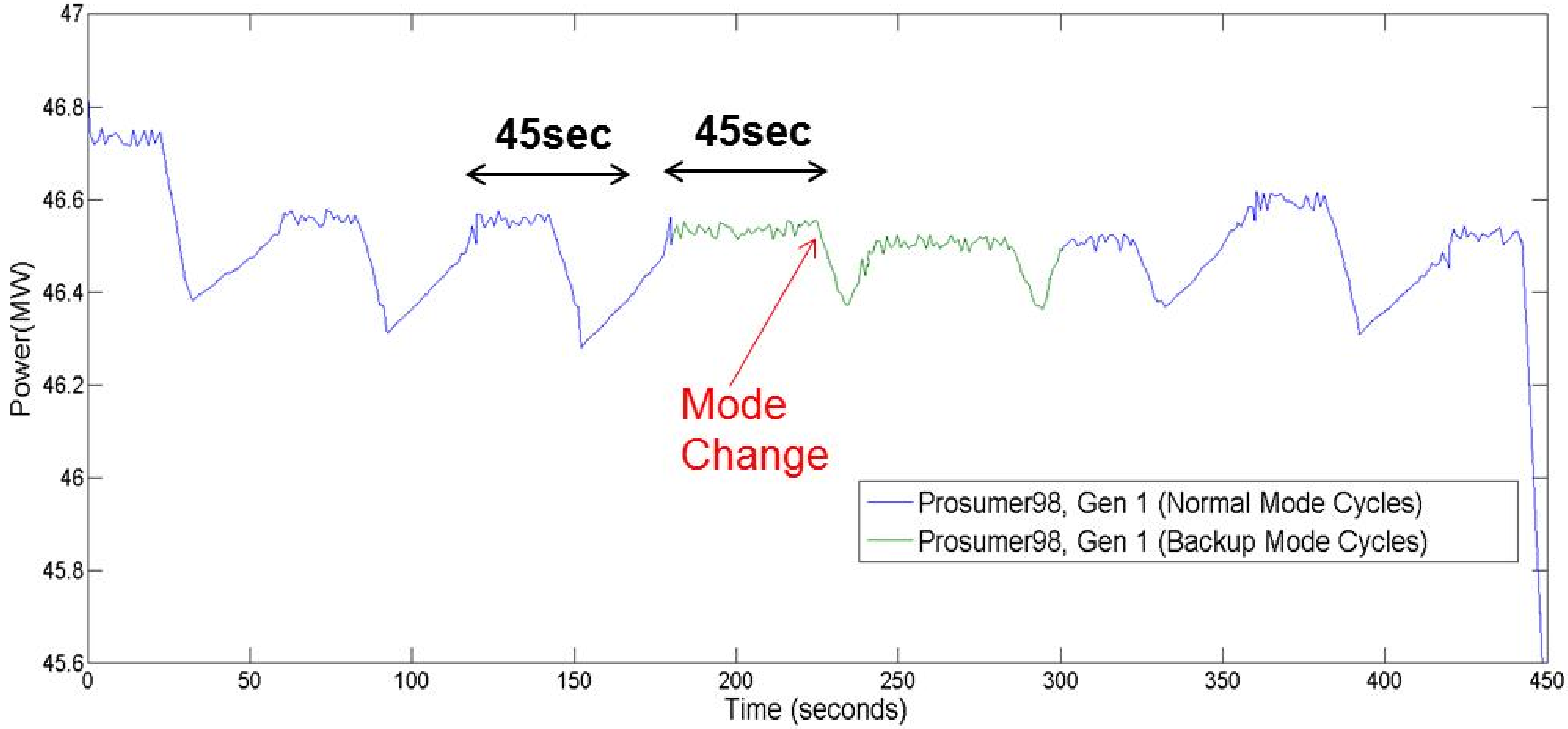
Effect of Link Delay



Effect of Task Execution Time



Mode Switching



Summary

- Proposed decentralized control and management of the future grid using an energy prosumer paradigm.

- Simulation of decentralized coordination algorithms is key for a large number of future grid use cases.

- Project has developed an infrastructure for simulation environment for decentralized control algorithms.
  - Based on extension of ns-3
  - Achieves combined cyber-physical simulation
  - Provides flexible integration with existing simulation tools
  - Supports testing of decentralized algorithms in large-scale systems using realistic data.

Thanks

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