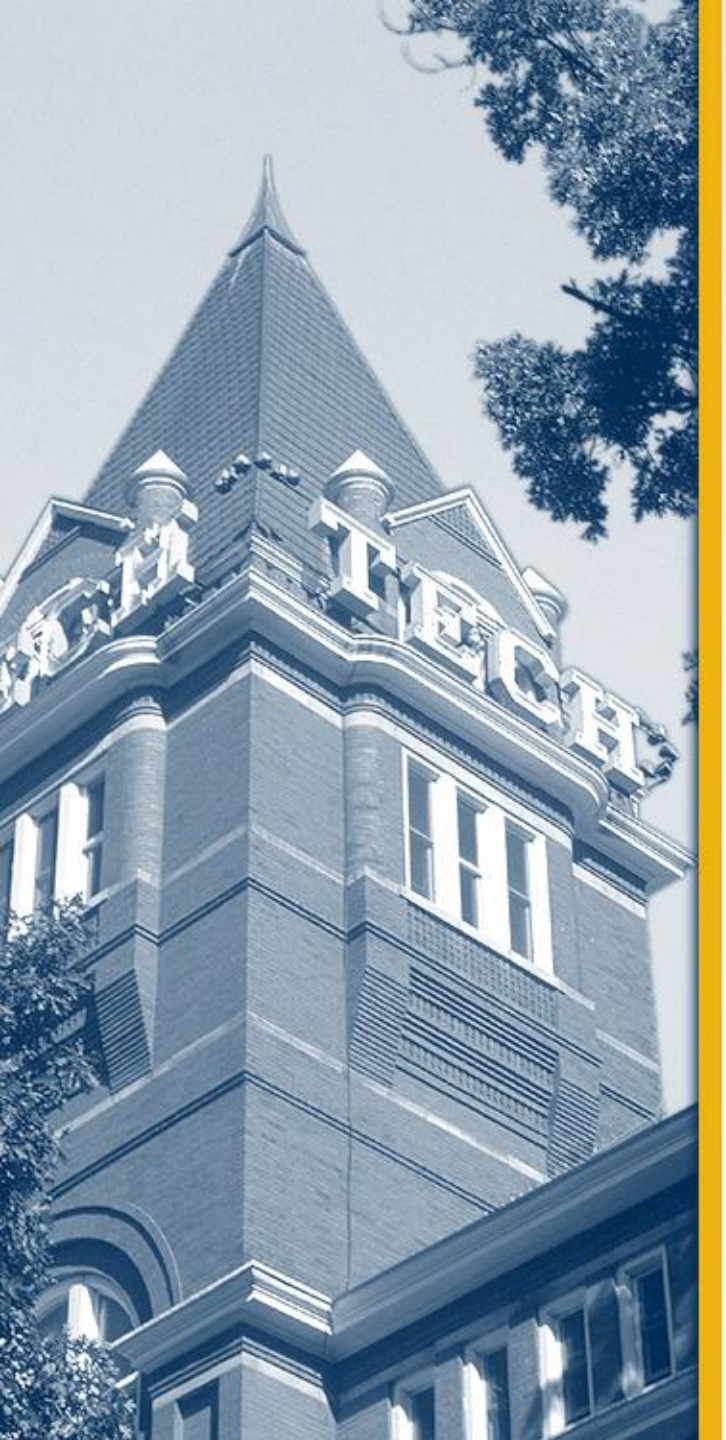


Cyber-Physical Platforms and Design Tools for Distributed Smart Grids

Muhammed Umer Tariq, Brian Swenson, Arun Narasimhan, Santiago Grijalva, Marilyn Wolf

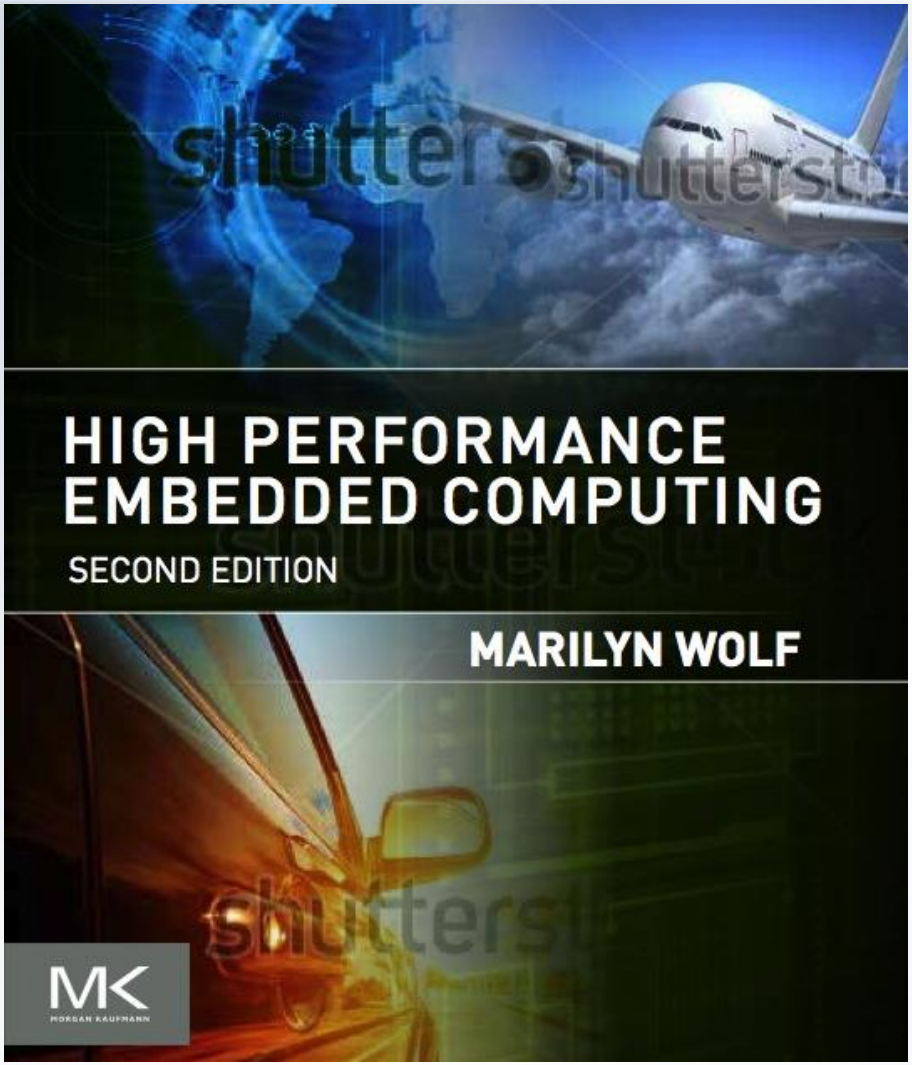
School of ECE

Georgia Institute of Technology

Outline

- The cyber side of CPS
- Distributed Smart Grid
  - Computing Platform
    - Prosumer-based computing platform
  - Tools
    - A simulation framework for energy CPS design.

Shameless Plug Dept.



- High-Performance Embedded Computing, 2nd ed. out soon!
- Check out my YouTube channel!

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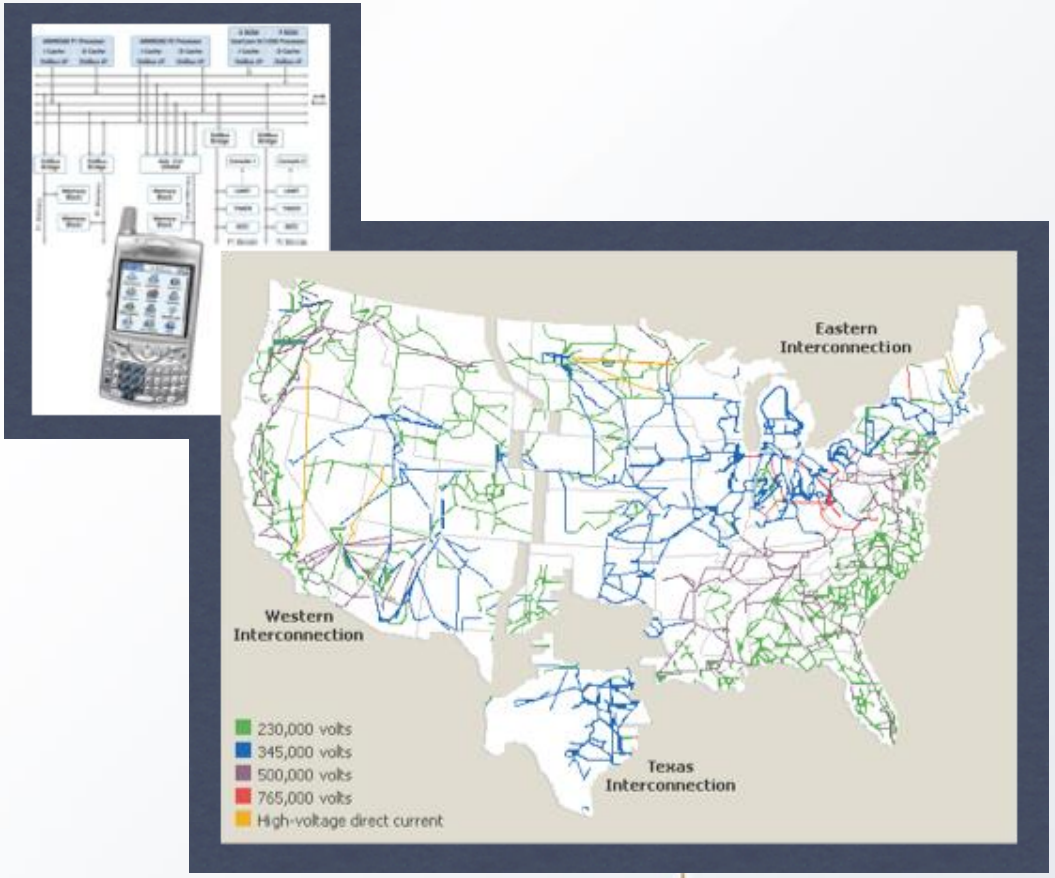
Computers are everywhere

- High-performance computing, but:
  - Real time.
  - Low power.
  - May be safety-critical.
- Embedded/CPS computing is a superset of laptop/cloud computing.



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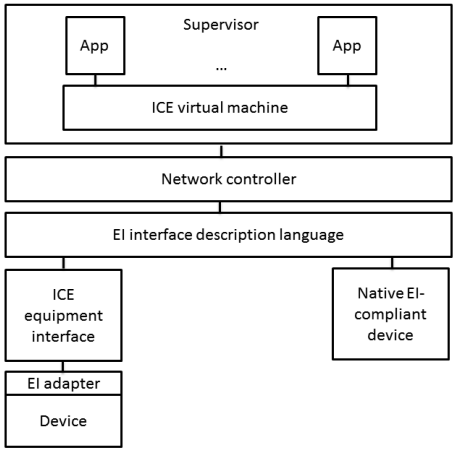
CPS Venn diagram

Examples: medical, automotive

- Medical Application Platform:
  - Wrappers adapt existing components to system.
  - Network controller guarantees QoS.
  - Provides alarm, logging, workflow, etc.
- AUTOSAR:
  - Operating system interface.
  - Run-time environment.
  - Software components.



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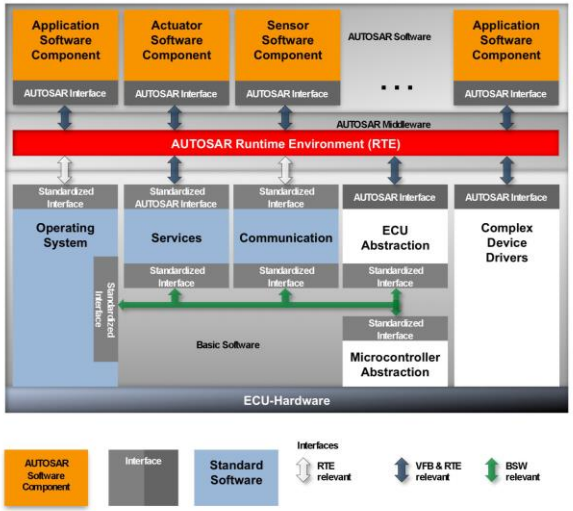

[AUTOSAR]

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Energy vs. automotive

- Huge geographic extent.
- Heterogeneous networks with dynamically scheduled bandwidth.
- Can’t turn it off and reboot.
- Can’t limit who plugs in.
- Extremely long life.

Platforms vs. proprietary products

- Platforms provide open extensibility:
  - Cell phone OS, app markets.
  - Multimedia.
- Extensibility and longevity are linked.
- Platforms reduce the burden of integration for customers.
- Design reuse reduces development costs for component manufacturers.
- Competition can expand the market for all players.

Standards and platforms

- Many high-volume markets are standards-driven:
  - wireless;
  - multimedia;
  - networking.
- Standard defines the basic I/O requirements.
- Reference implementation speeds development.

MPEG Tampere meeting

bluetooth.com

9

Platform definition issues

- Model of computation: what are the fundamental abstractions that define platform operation?
  - Real-time systems, safety-critical systems require new abstractions.
- Composability: how do we know that new components will operate correctly within the system?
  - Hybrid systems theory doesn't adequately address composability.
- Abstraction: does the platform provide for implementation freedom?
- Economics: who will make it happen?

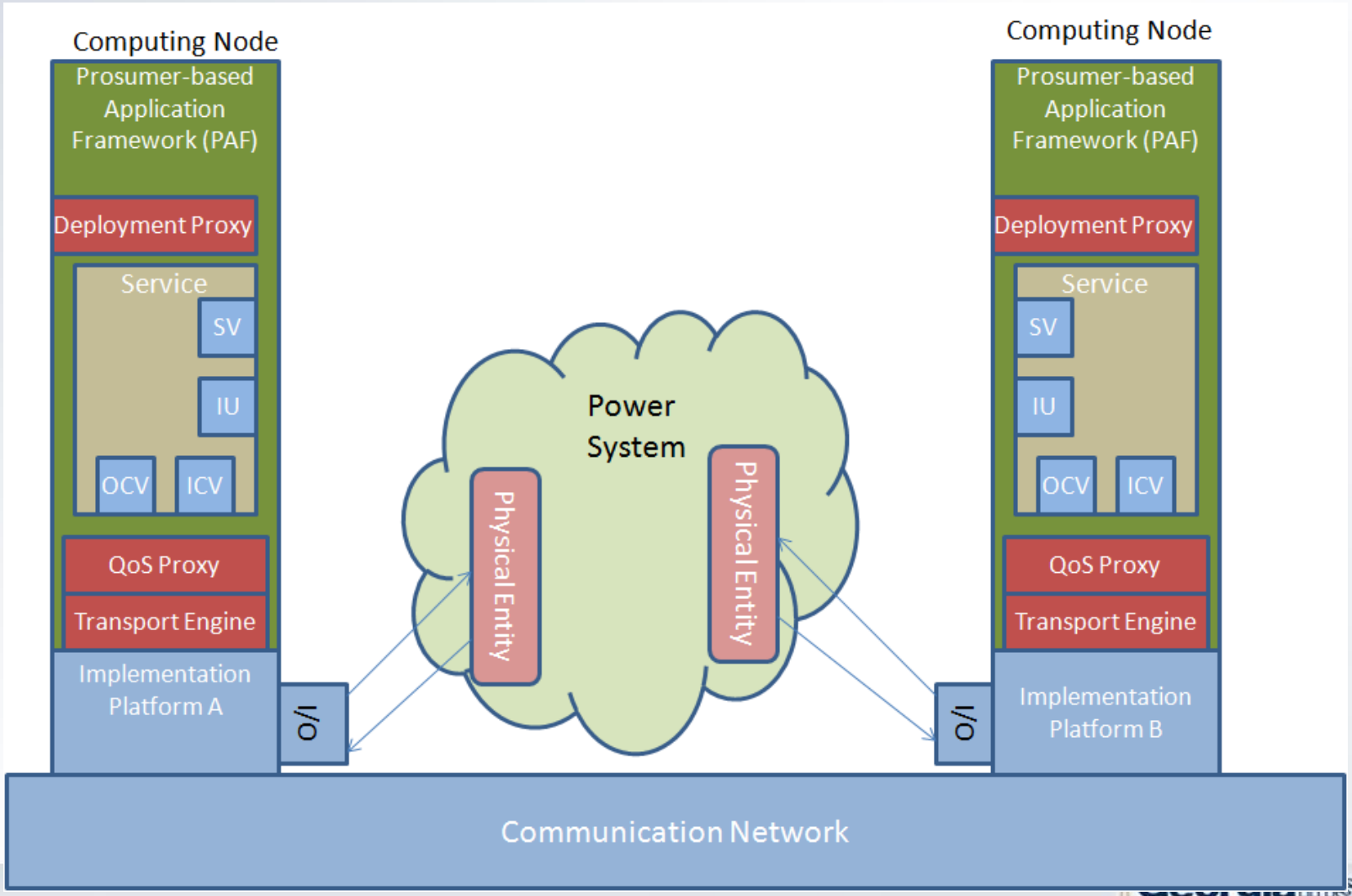
Prosumer Application Framework (ProsumerAF)

- Incorporates the control and optimization ‘algorithms’ for ‘distributed operation” of power system
- Mapped to multiple “implementation platforms” (= network + OS + middleware) present in the current and future smart grid
- Provides a consistent application development environment to make life easy for “utility application developers” as well as “building application developers”

Why Use An Application Framework?

- Complex software for desktop and mobile computing has been enabled by a variety of application framework
- Traditional real-time computing lacks the use of such application frameworks due to performance sacrifice
- However, at some point, “complexity management” and “correctness guarantees” become more important than the “performance penalty”

ProsumerAF layer diagram



Distributed Power Agreement Protocol (Control Design)

$$\dot{q} = -LWL\,q + LWP$$

$$P = Required\ Power = \begin{bmatrix} P_1 \\ P_2 \\ . \\ . \\ P_n \end{bmatrix} \qquad q = Potentials = \begin{bmatrix} q_1 \\ q_2 \\ . \\ . \\ q_n \end{bmatrix}$$

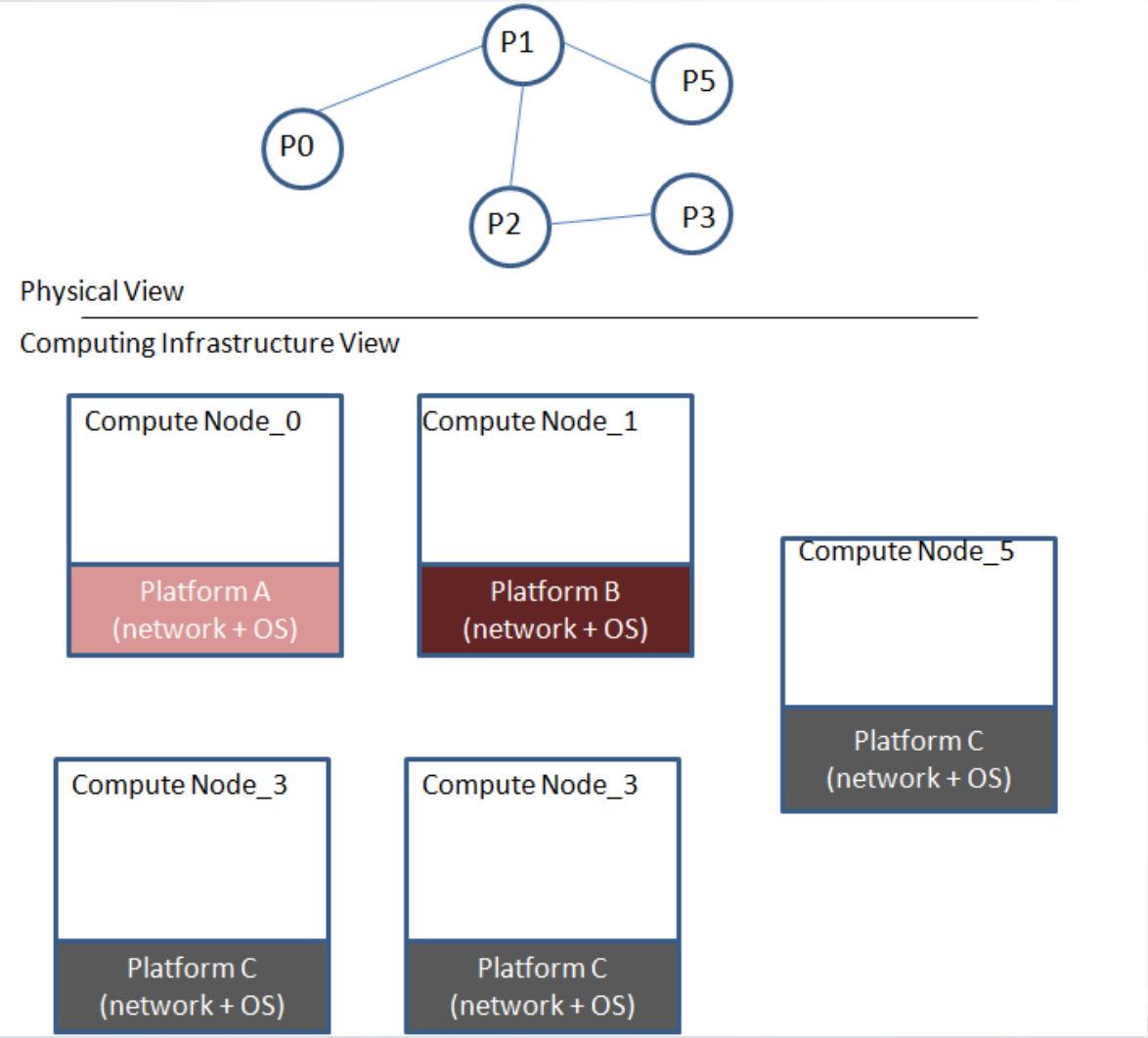
$L = Graph\ Laplacian\ Matrix$ $\qquad$ $W = Weight\ Matrix = I$

$$\tilde{P} = L\,\tilde{q}$$

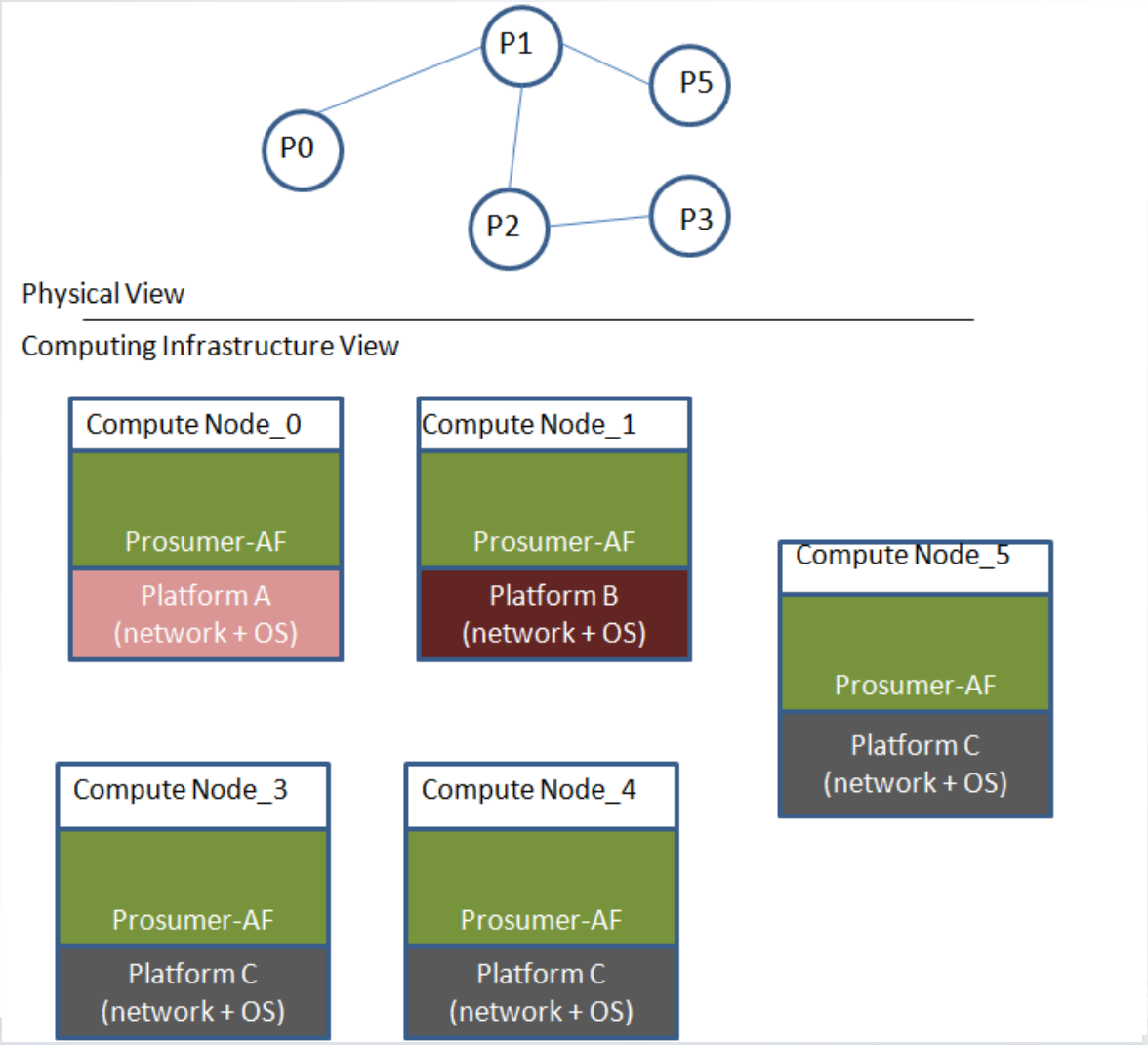
$$\tilde{P} = Agreed\ Power = \begin{bmatrix} \widetilde{P_1} \\ \widetilde{P_2} \\ . \\ . \\ \widetilde{P_n} \end{bmatrix} \qquad \tilde{q} = Final\ Potentials = \begin{bmatrix} \widetilde{q_1} \\ \widetilde{q_2} \\ . \\ . \\ \widetilde{q_n} \end{bmatrix}$$

Reference: Ramachandran, T., et al. *Distributed Power Allocation in Prosumer Networks∗*. in *Estimation and Control of Networked Systems*. 2012.

Distributed Power Agreement Protocol (Implemented through ProsumerAF)



Distributed Power Agreement Protocol (Implemented through ProsumerAF)



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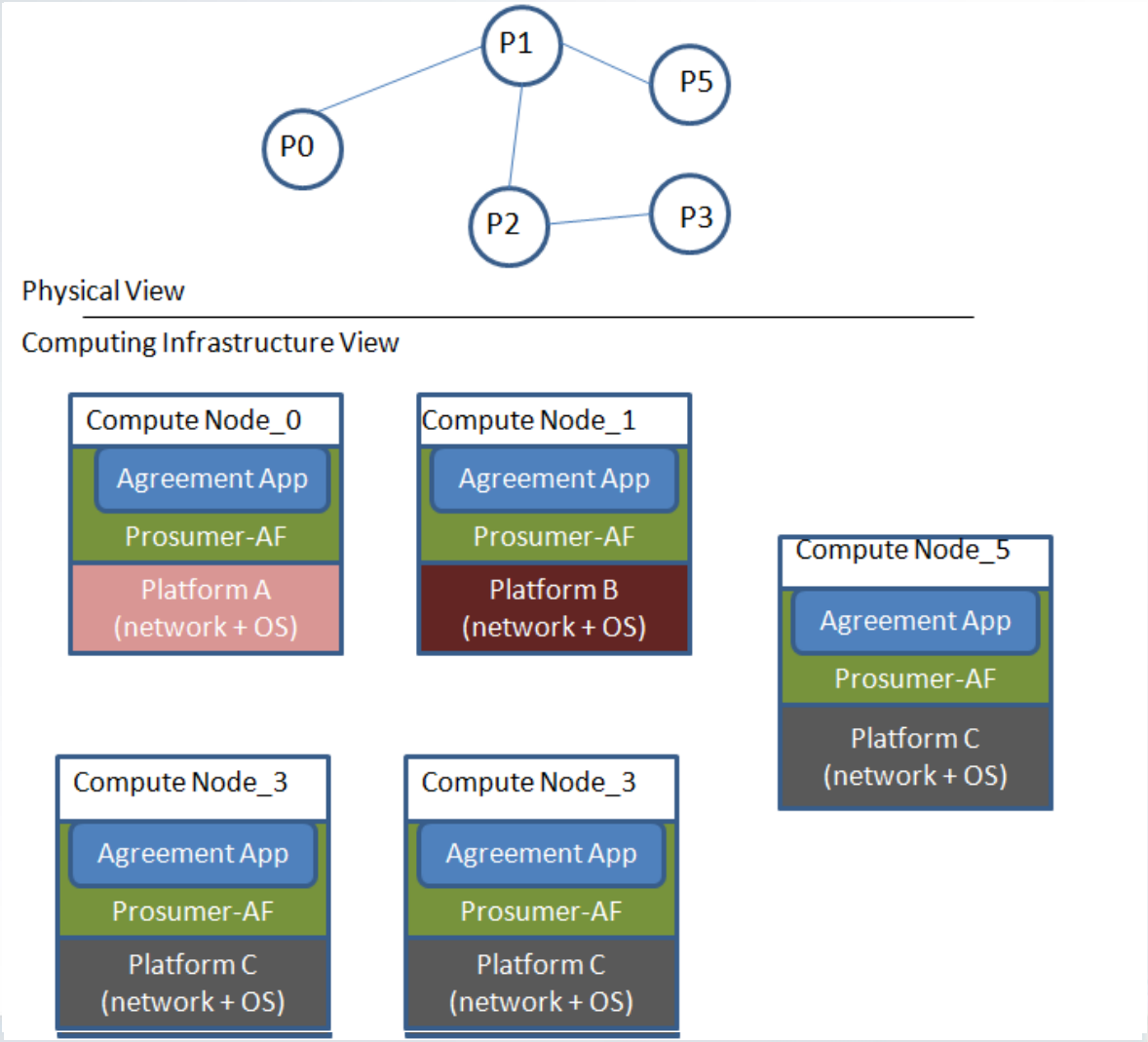
Distributed Power Agreement Protocol (Implemented through ProsumerAF)



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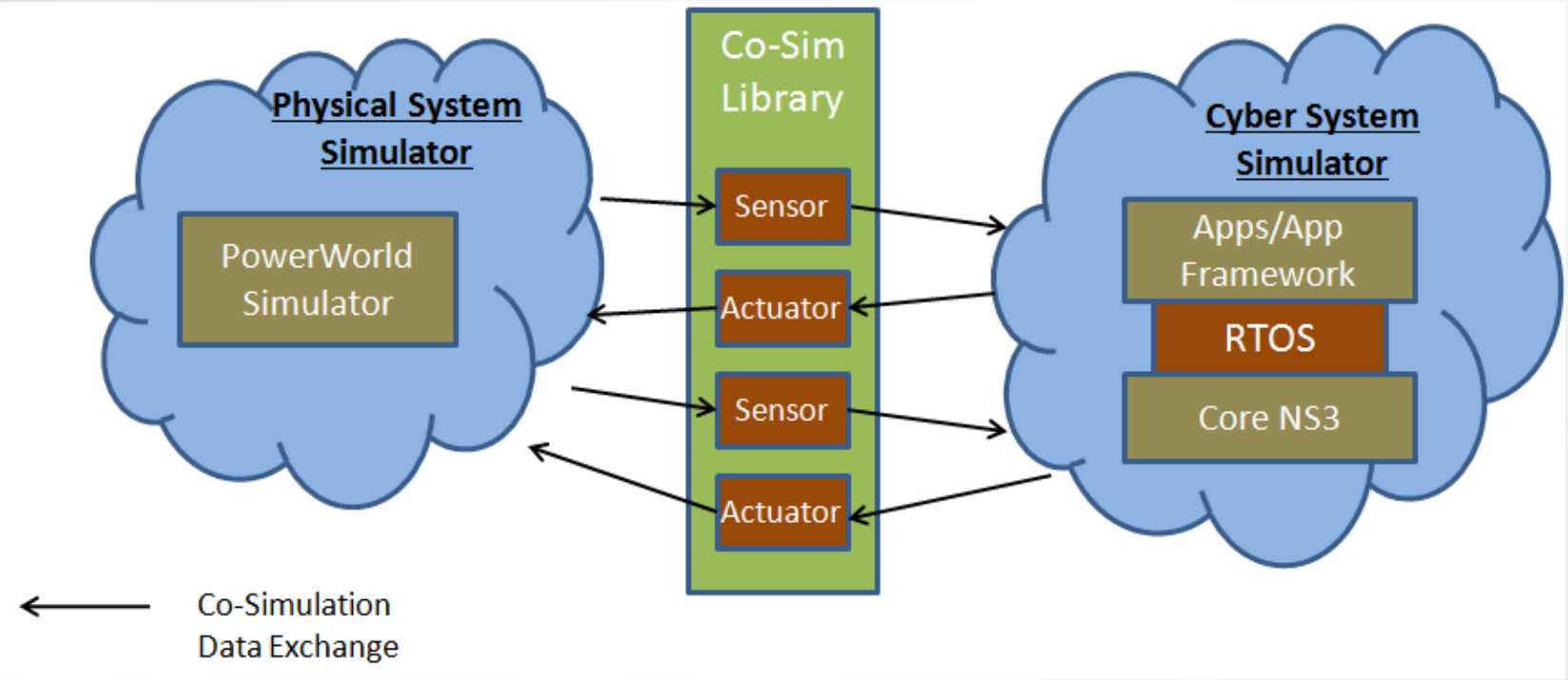
Distributed Smart Grid: Simulation Infrastructure Requirements

- Complex physical plants and their interaction with computing platform.
- Analytical methods are insufficient to characterize the design space of verify a design.
- Co-simulation of power system and cyber system:
  - Network delays.
  - Computing delays---typically not added to network simulation.
  - Physical plant model.

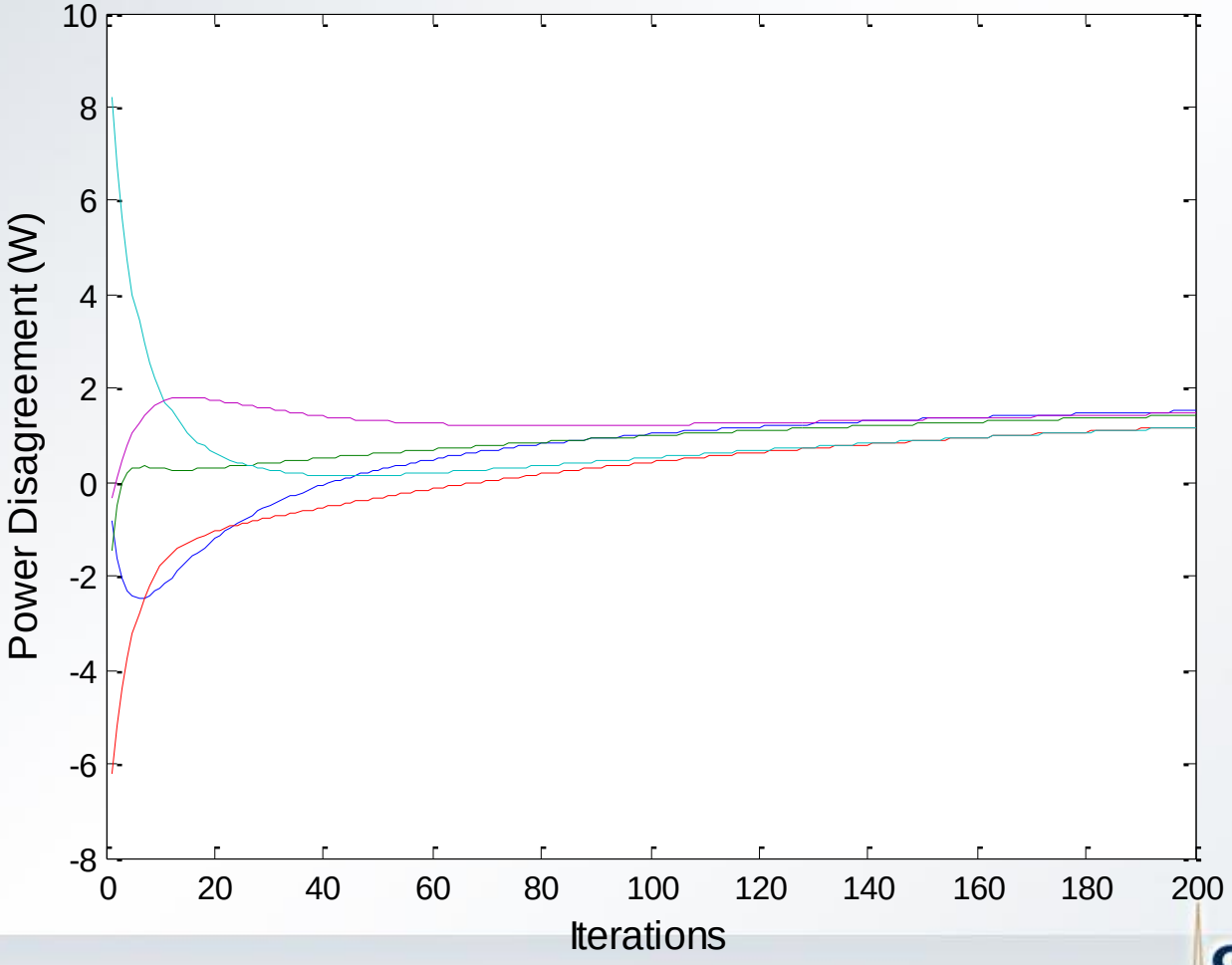
Distributed Smart Grid: Simulation Infrastructure

- State-of-the-art
  - Network simulator (ns-2) combined with power system simulator.
  - No consideration for operating system and application layers.
- Our Approach
  - Modify a state-of-the-art network simulator ns-3 to add support for real-time operating system (RTOS) and middleware layer.
  - NS-3 already supports application layer simulation.
  - Target multiple physical simulators.

Distributed Smart Grid: ns3-PowerWorld Co-Simulation Infrastructure



Power Agreement Protocol
(MATLAB)



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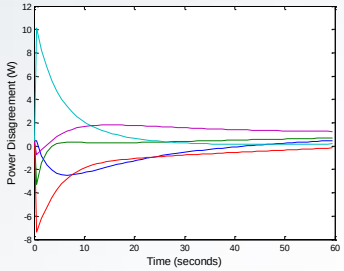
Power Agreement Protocol
(ns3-PowerWorld Co-Simulation)

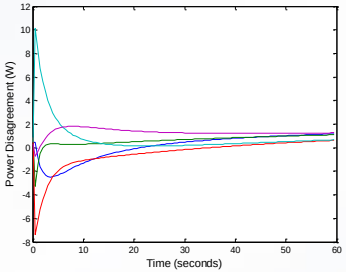
Prosumer Update Period (sec)

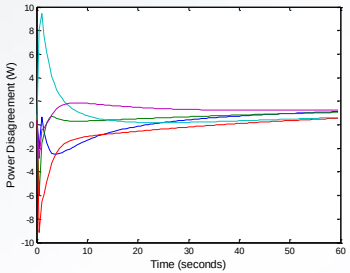
1.0

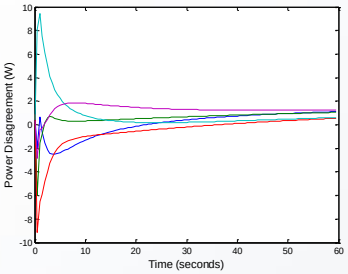
0.5

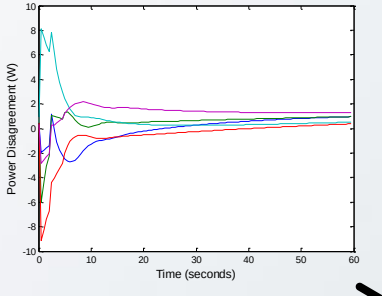
0.2











1000

2000

Link delay (msec)

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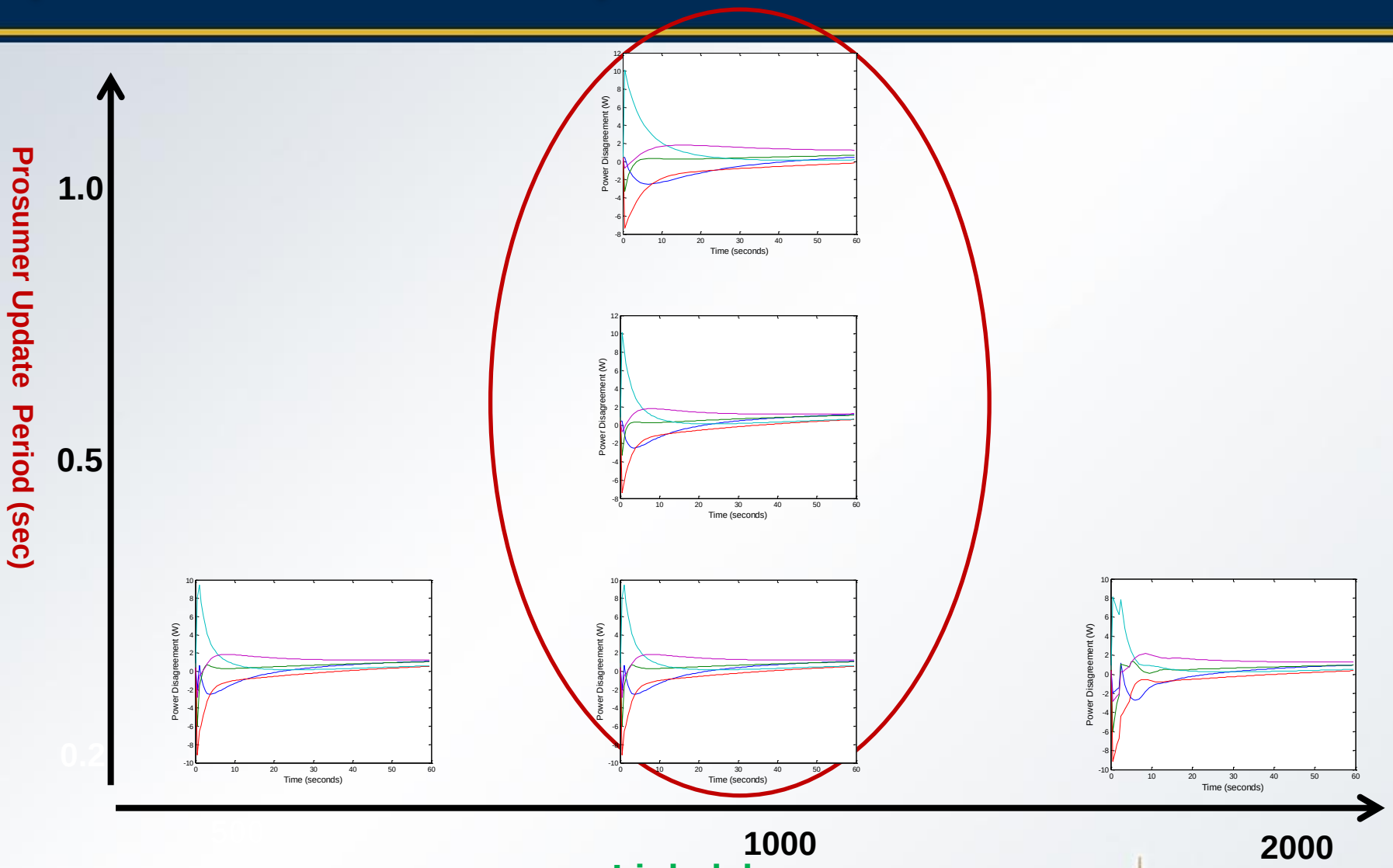
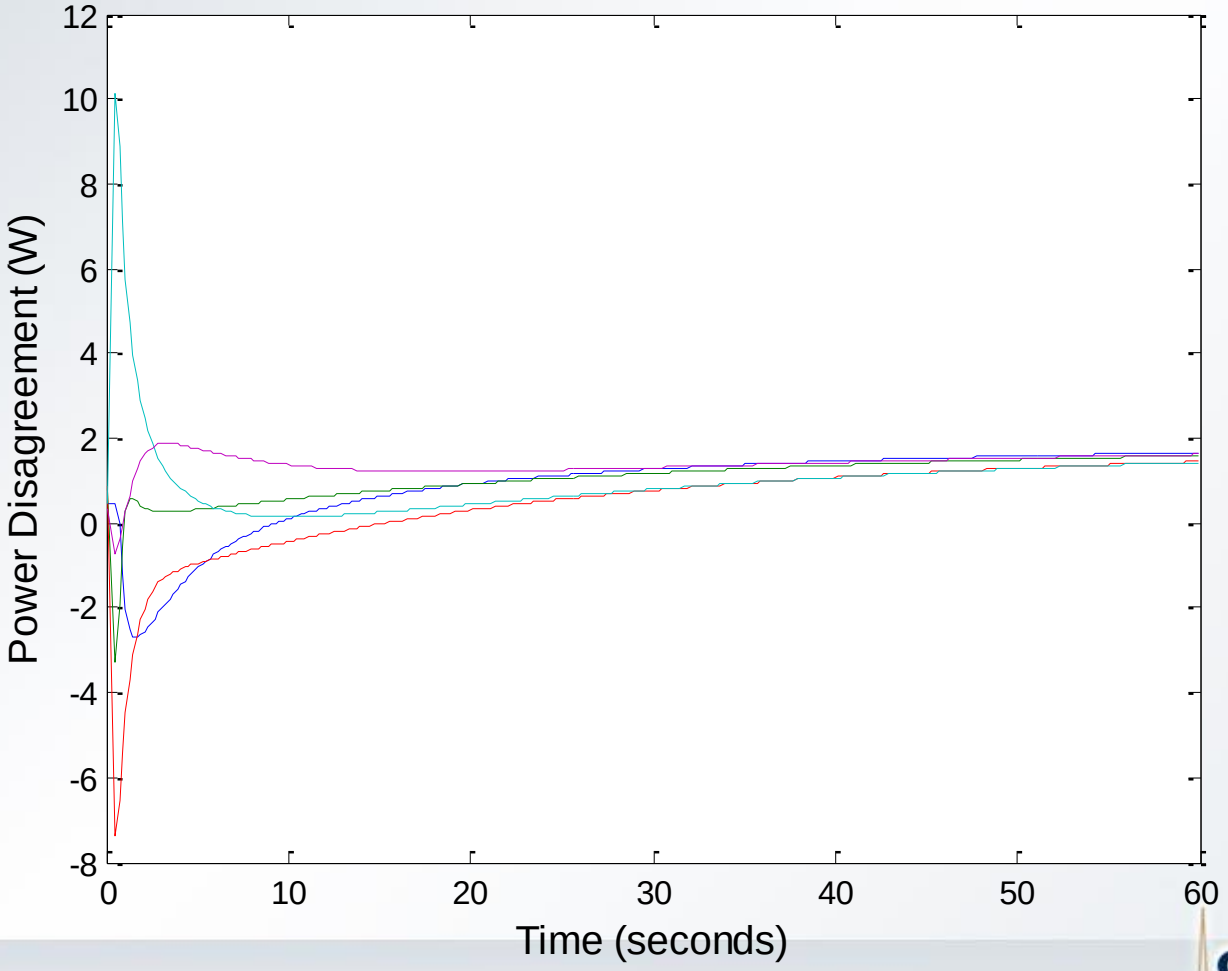
Power Agreement Protocol
(ns3-PowerWorld Co-Simulation)



Power Agreement Protocol
(Effect of Prosumer Update Period)

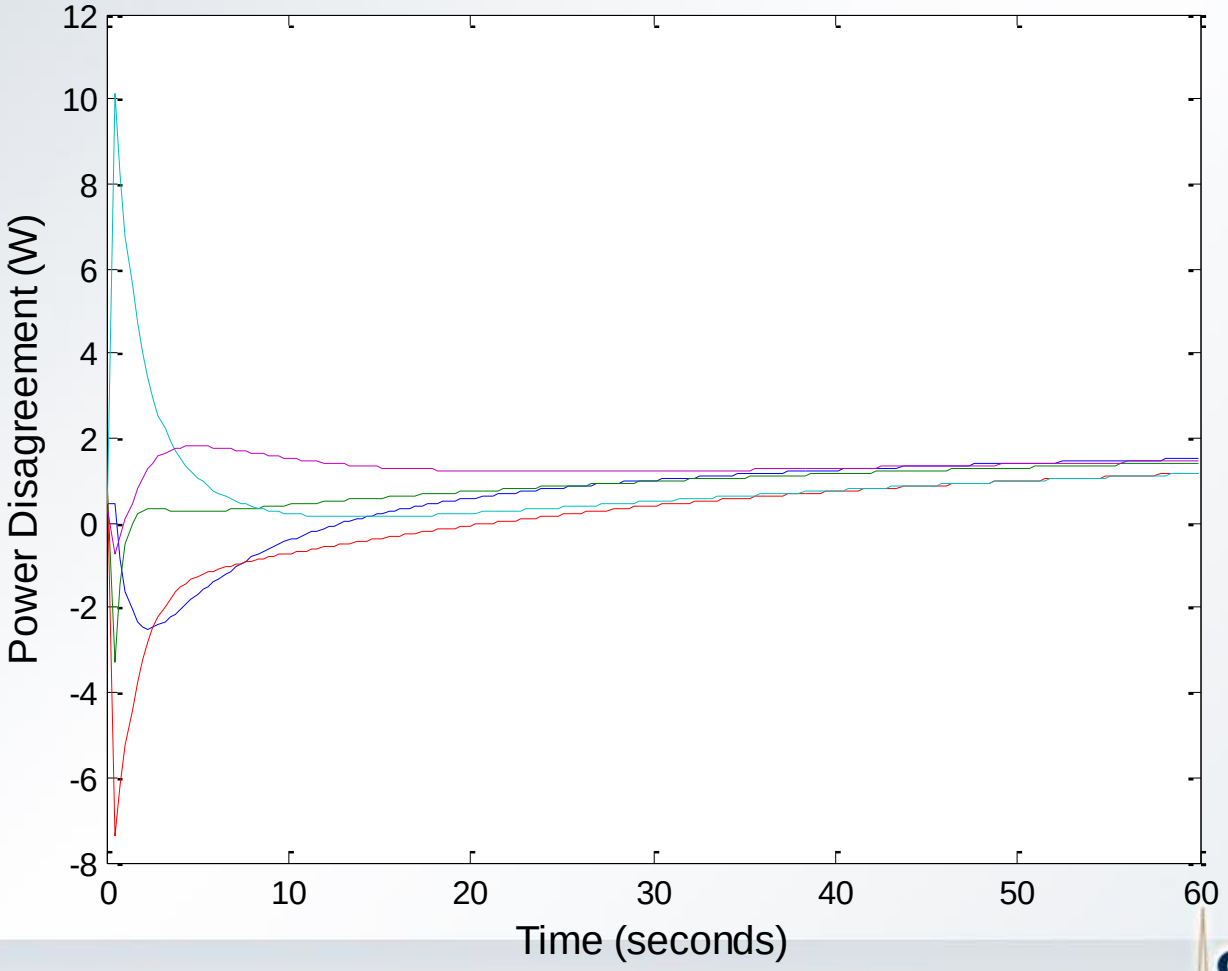
Prosumer Update Period: 0.2 sec



Power Agreement Protocol

(Effect of Prosumer Update Period)

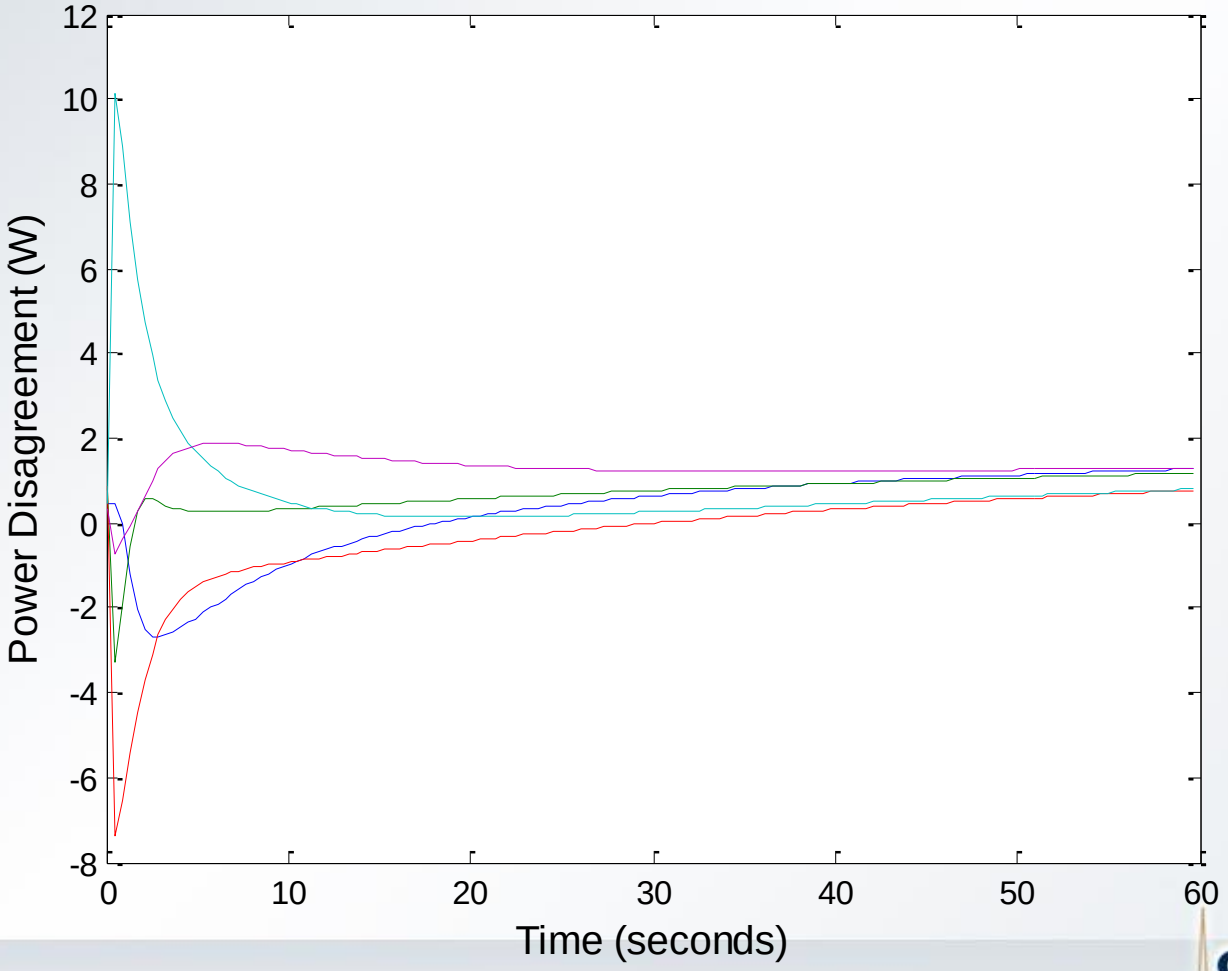
Prosumer Update Period: 0.3 sec



Power Agreement Protocol

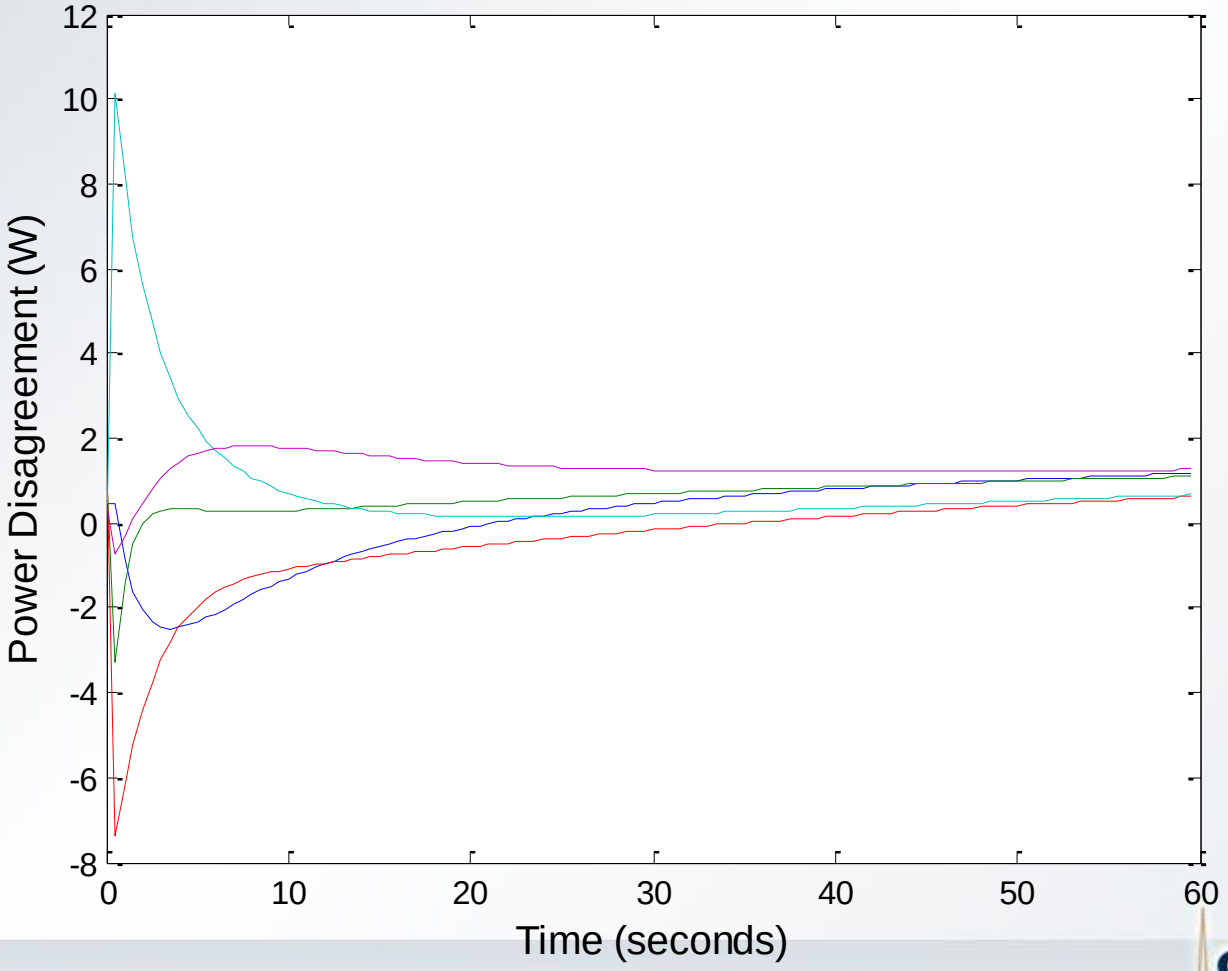
(Effect of Prosumer Update Period)

Prosumer Update Period: 0.4 sec



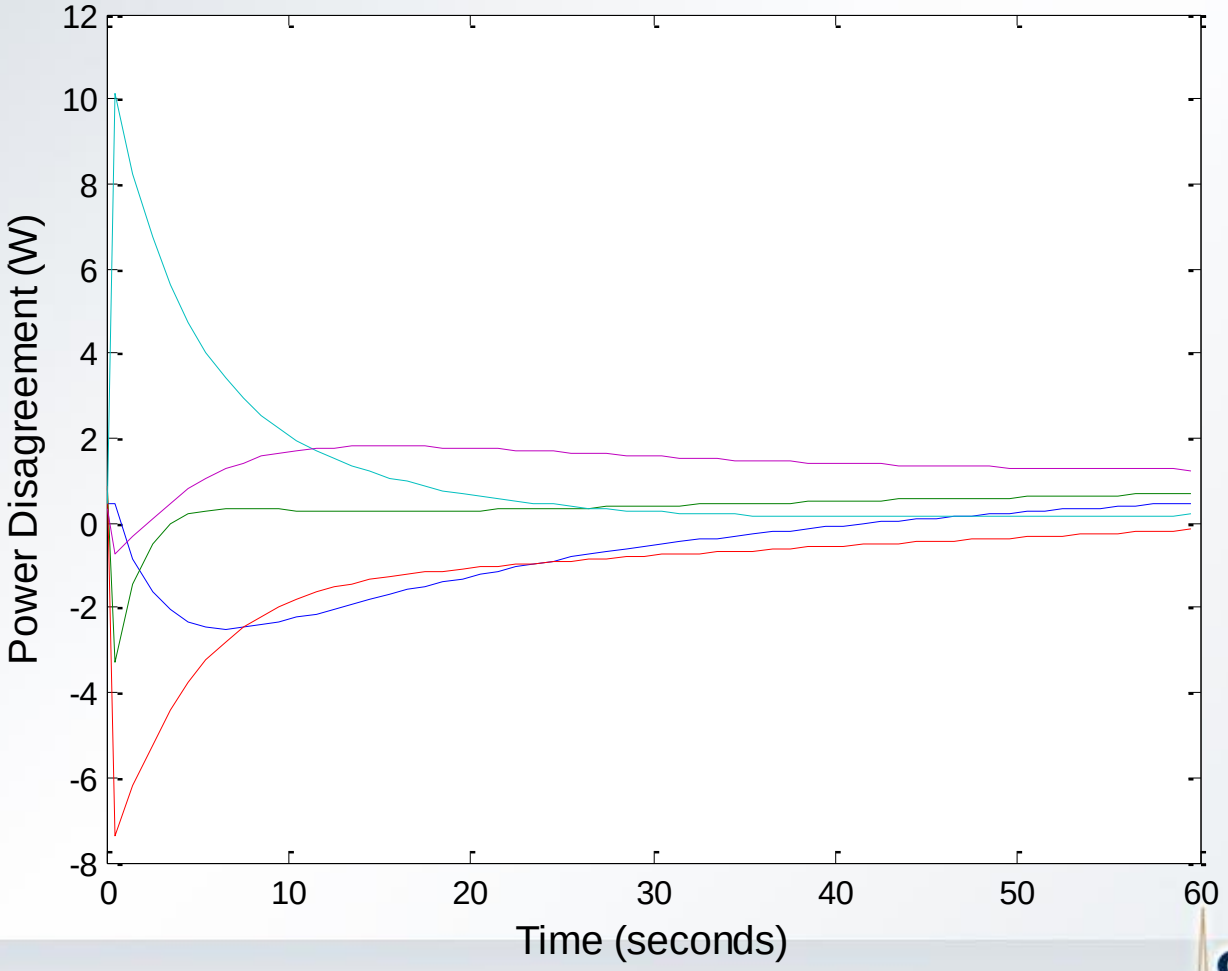
Power Agreement Protocol
(Effect of Prosumer Update Period)

Prosumer Update Period: 0.5 sec



Power Agreement Protocol
(Effect of Prosumer Update Period)

Prosumer Update Period: 1.0 sec



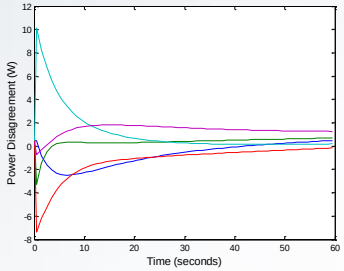
Power Agreement Protocol
(ns3-PowerWorld Co-Simulation)

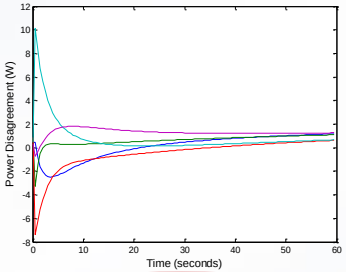
Prosumer Update Period (sec)

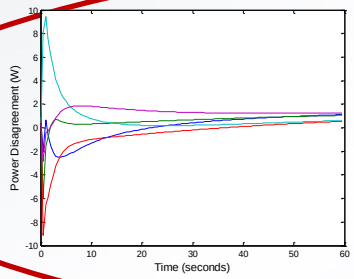
1.0

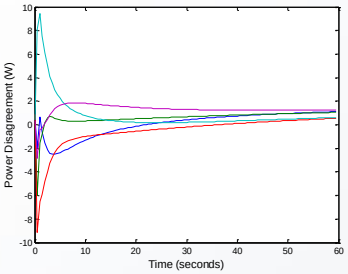
0.5

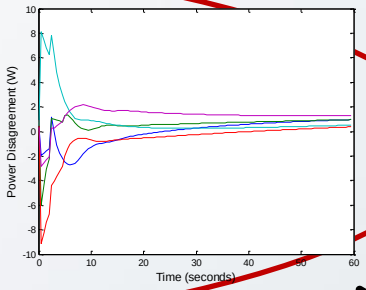
0.2











1000

2000

Link delay (msec)

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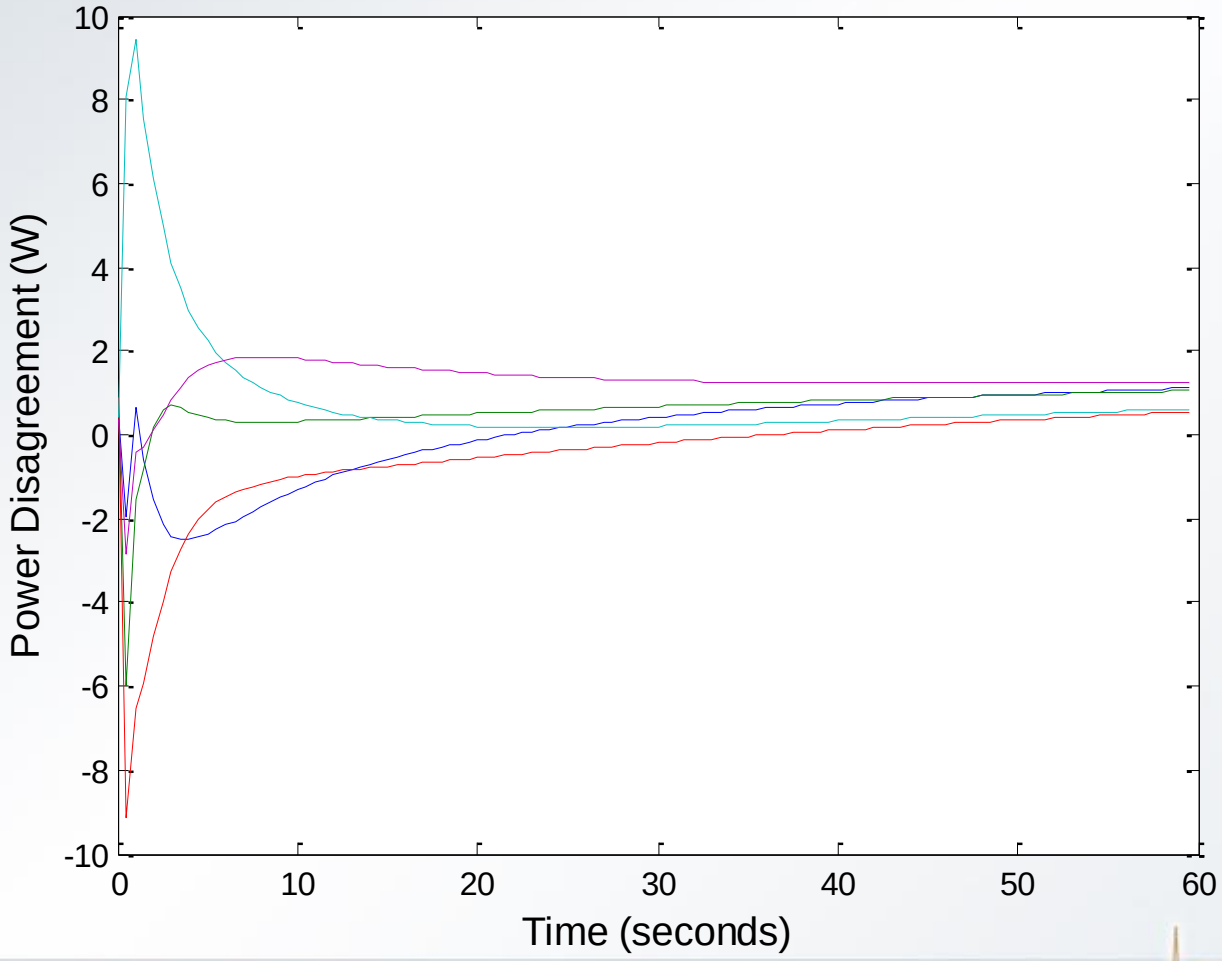
Power Agreement Protocol

(Effect of Link Delay)

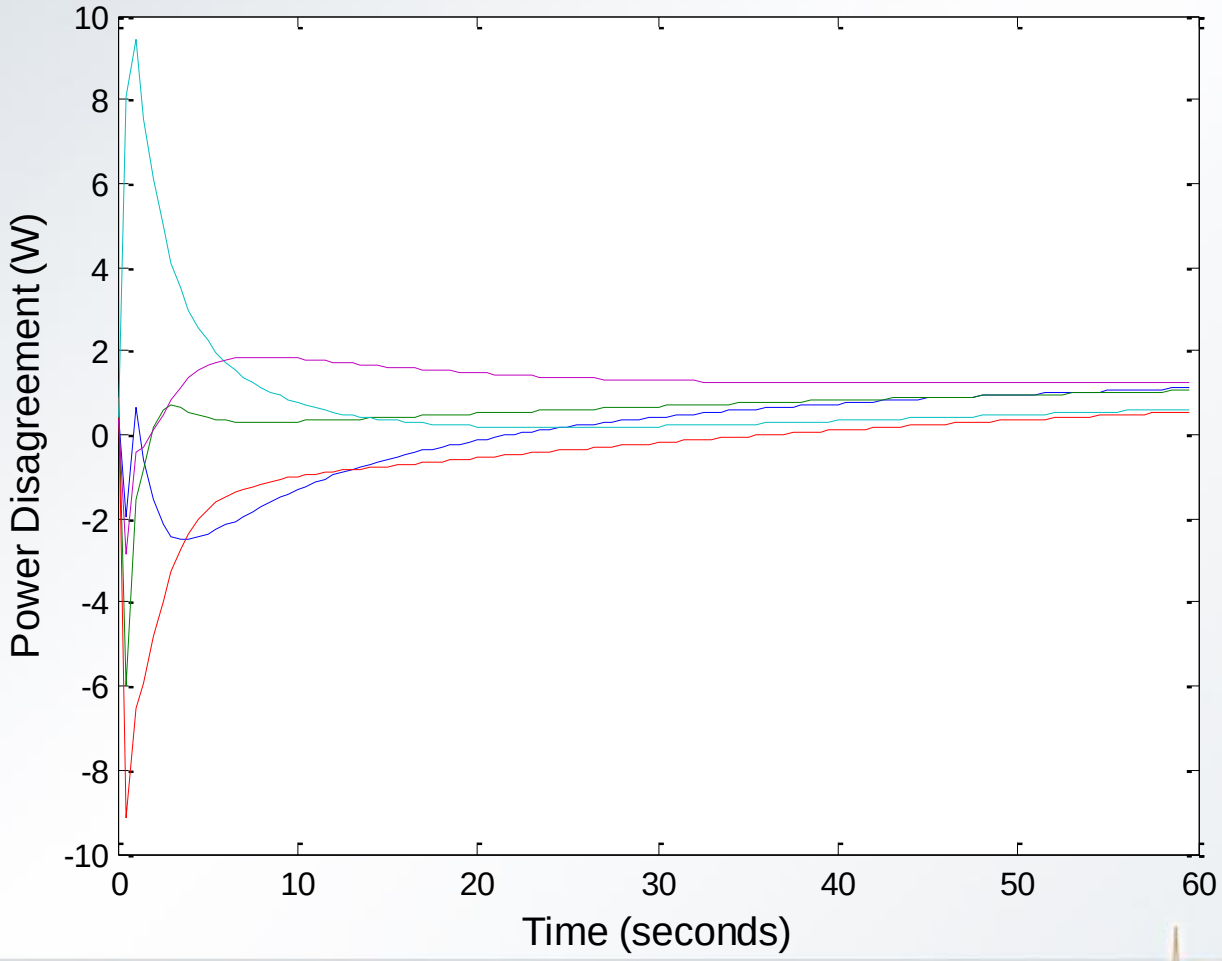
Link Delay: 400 msec



Power Agreement Protocol

(Effect of Link Delay)

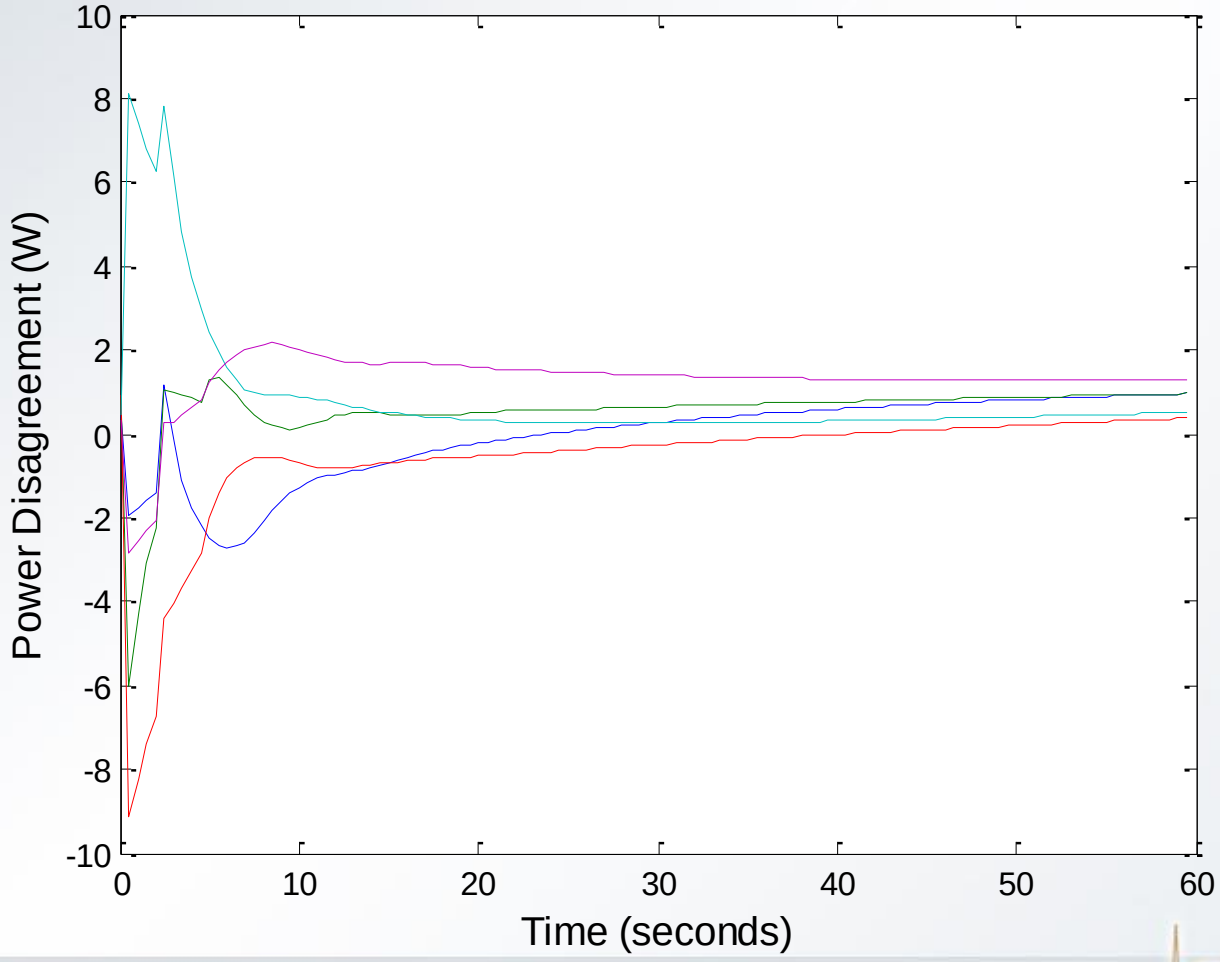
Link Delay: 800 msec



Power Agreement Protocol

(Effect of Link Delay)

Link Delay: 2000 msec



Summary

- CPS formalisms and modeling need to be super-sized to large-scale systems.
- Computing platforms are well-understood for cyber IT systems.
  - Need to be adapted for CPS.
  - Platform provides benefits for multiple players in the energy ecosystem.
- Simulation is a key tool in any large-scale CPS design methodology.
  - Our co-simulator allows exploration of both the cyber and physical axes of the design space.