Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network

Award No: CNS-09-31195

Duration: Sept. 1 2009 - Aug. 31, 2012

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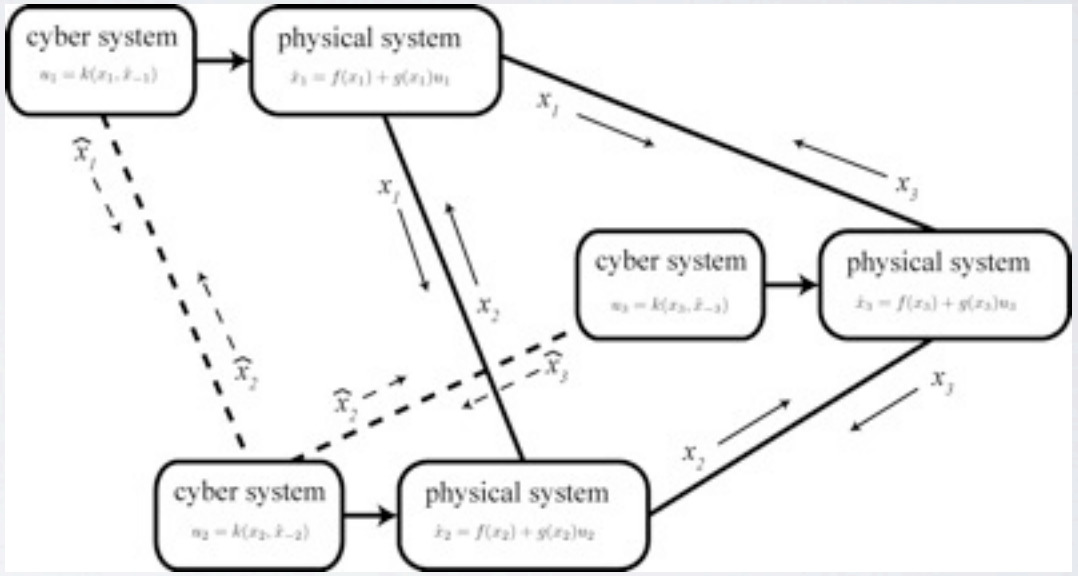


Wireless Sensor-Actuator Network:

Distributed feedback control system whose feedback links are realized over a wireless communication network

Objective:

Distributed algorithm development supporting real-time applications over wireless networks

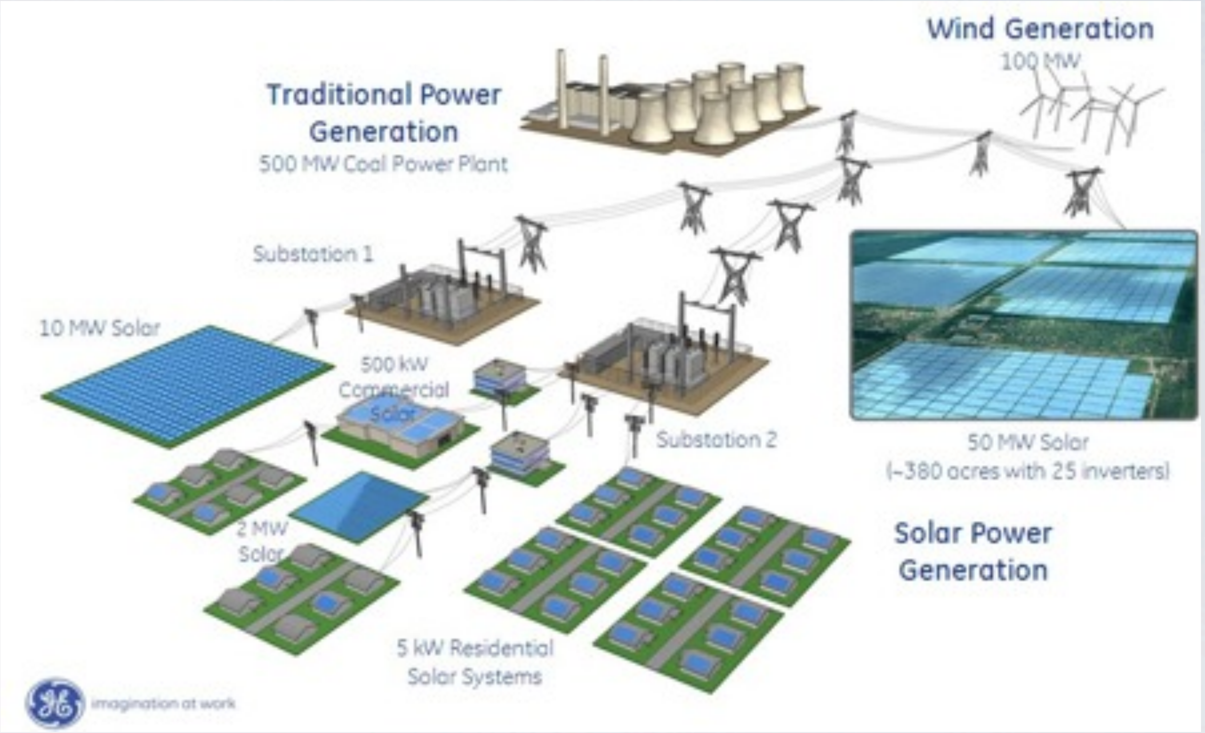
Keywords: firm real-time QoS over wireless channels

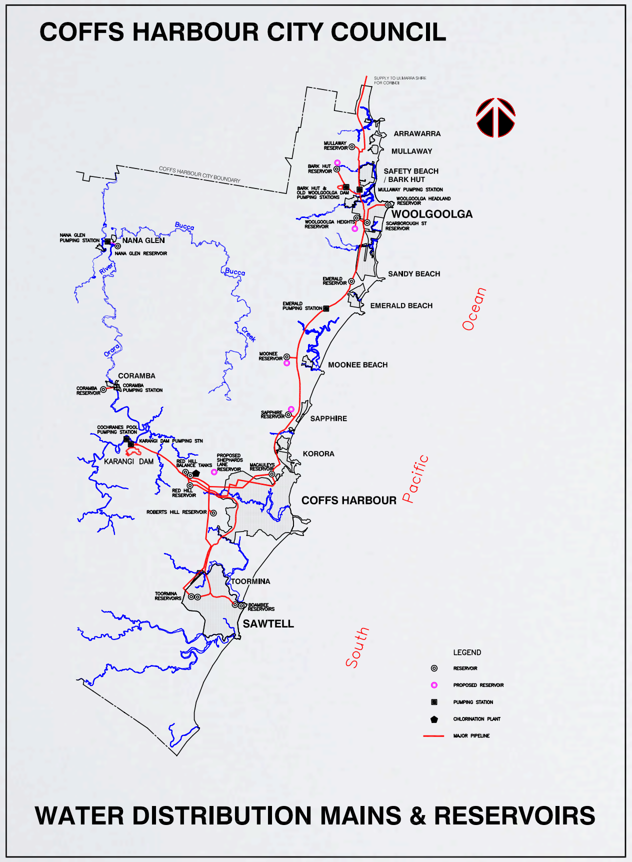
Project Website: http://www.nd.edu/~lemmon/projects/NSF-08-611

Wireless Sensor-Actuator Networks (WSAN)

Networked Control System (NCS) whose feedback channel is realized over a wireless communication network.

Feedback control applications traditionally have hard real-time control constraints on network Quality-of-Service

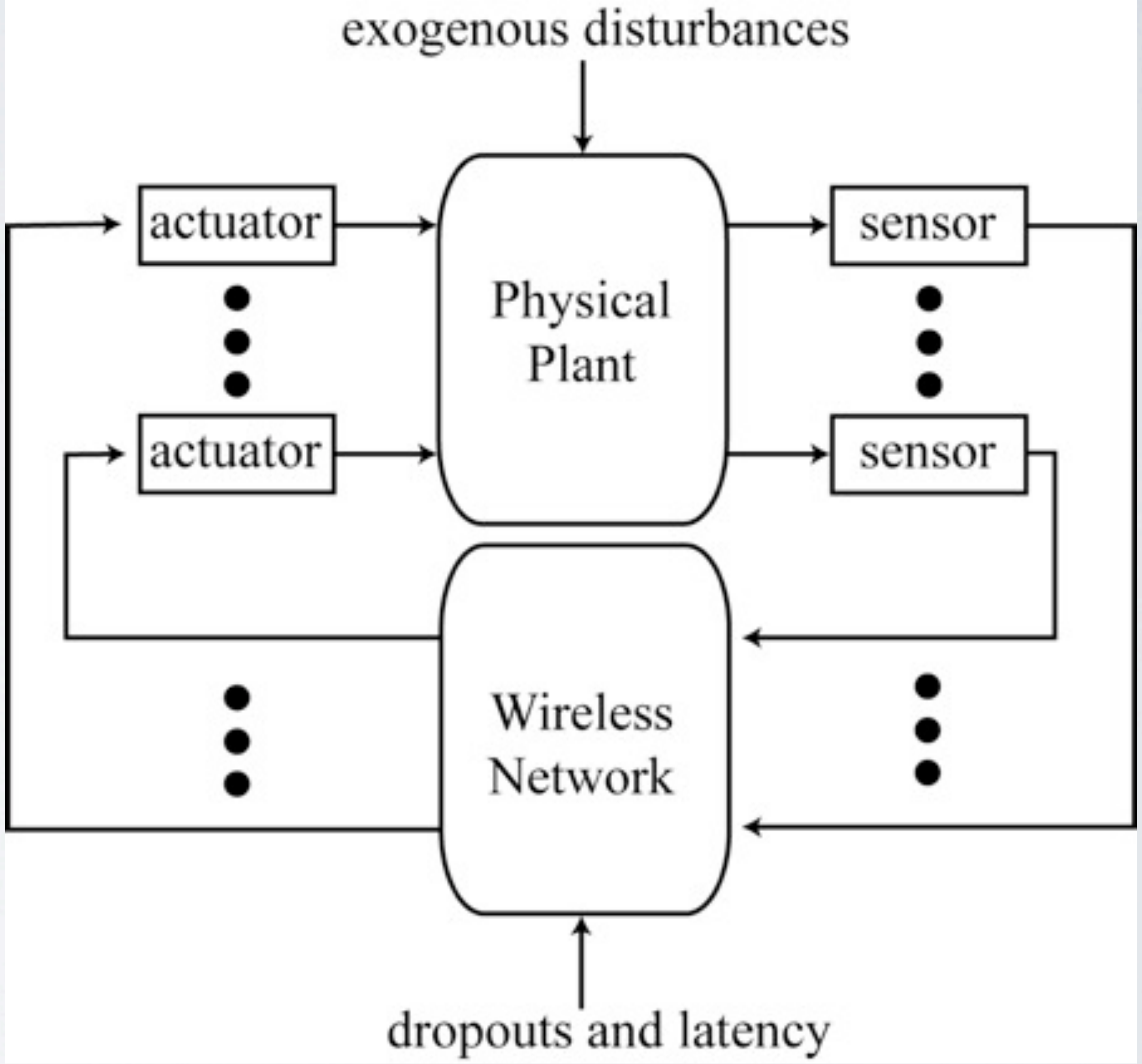




- Networked Control Systems in National Infrastructure
  - National Power Grid
  - Water/Gas Distribution Networks
  - Air Traffic Control Networks
  - Manufacturing and Enterprise Networks
- The use of wireless comm. networks reduces costs of system maintenance, but the lack of hard real-time guarantees limits use in safety-critical applications

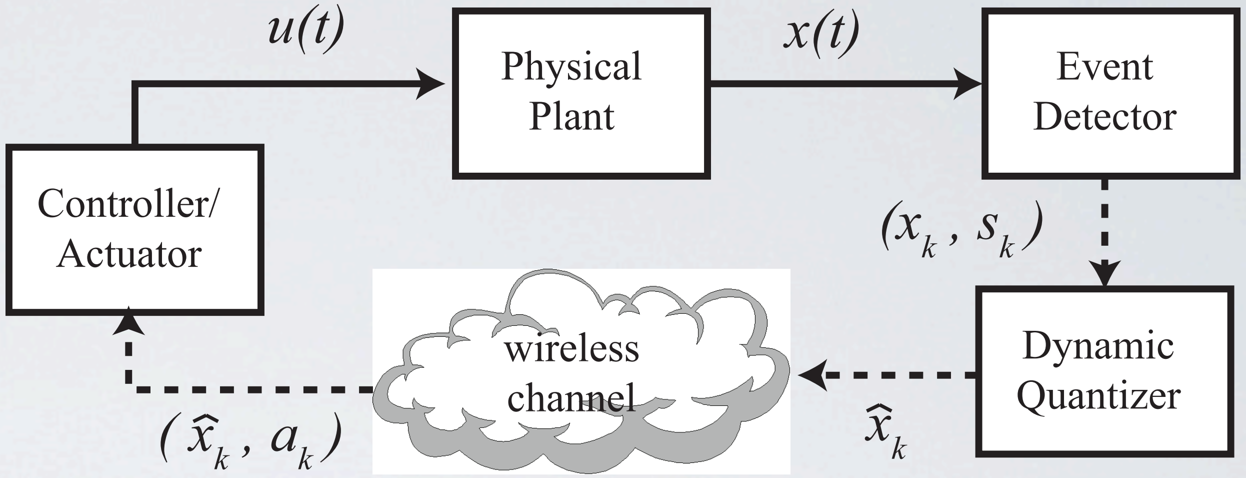
Main Tasks

- "Physical" Side
  - Minimize "information" needed for control
  - Adapt controller to changes in network QoS
- "Cyber" Side
  - Networking protocols enforce a "desired" QoS
- Metrics of Interest
  - Control System Performance
  - End-to-End QoS (latency)
  - Network Energy Consumption
- Simulation Testing of Approach
  - Autonomous Microgrid Controller



Minimizing Feedback Information - Model

- Problem Statement
  - Reduce the amount of feedback information needed to attain a desired control performance level



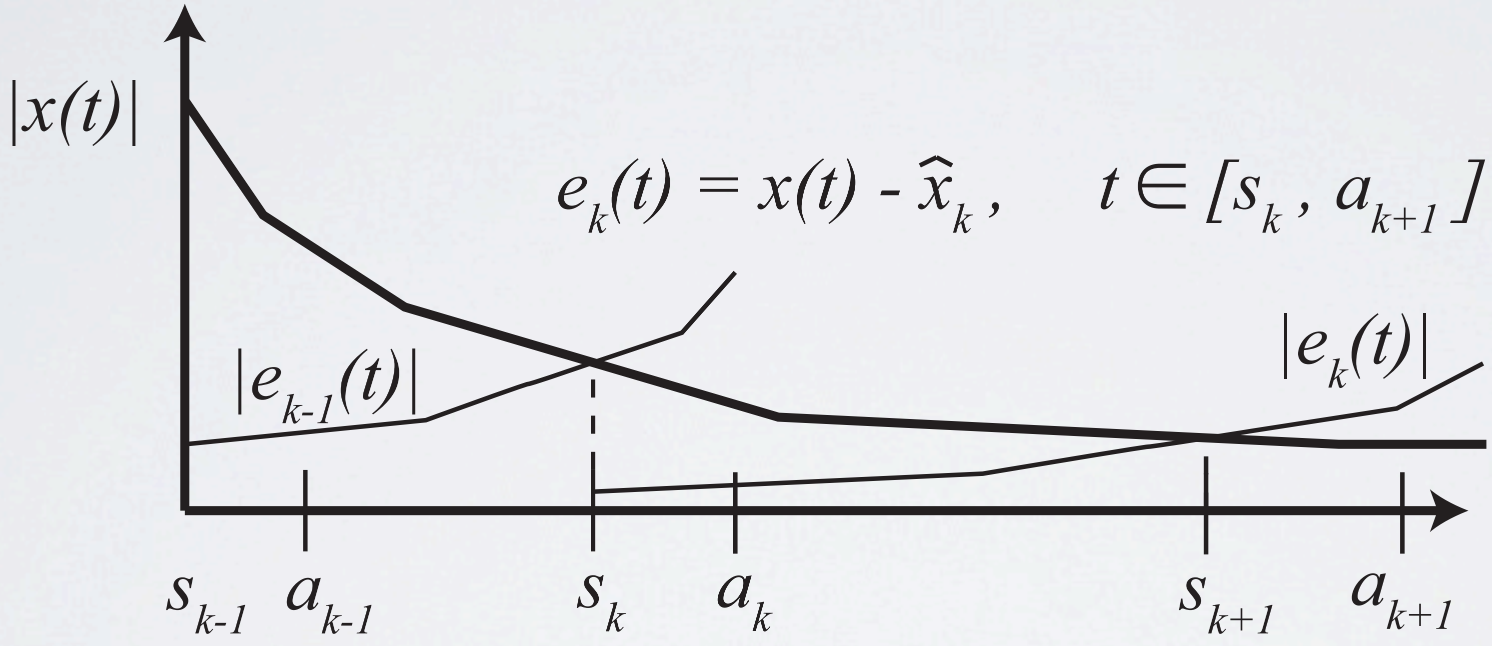
- System Model
  - Physical state is sampled and quantized at discrete time instants

$$\text{Plant State Equation:} \qquad \dot{x}(t) = f(x(t), u(t), w(t))$$

$$\begin{aligned}
\text{Sequence of TX Times} &= \{s_k\}_{k=1}^{\infty} \\
\text{Sequence of RX Times} &= \{a_k\}_{k=1}^{\infty} \\
\text{Sampled State} &= x_k = x(s_k) \\
\text{Quantized State} &= \hat{x}_k = Q(x_k) \\
\text{Control Input} = u(t) &= K(\hat{x}_k), \ \forall t \in [a_k, a_{k+1}]
\end{aligned}$$

Minimizing Feedback Information - Analysis

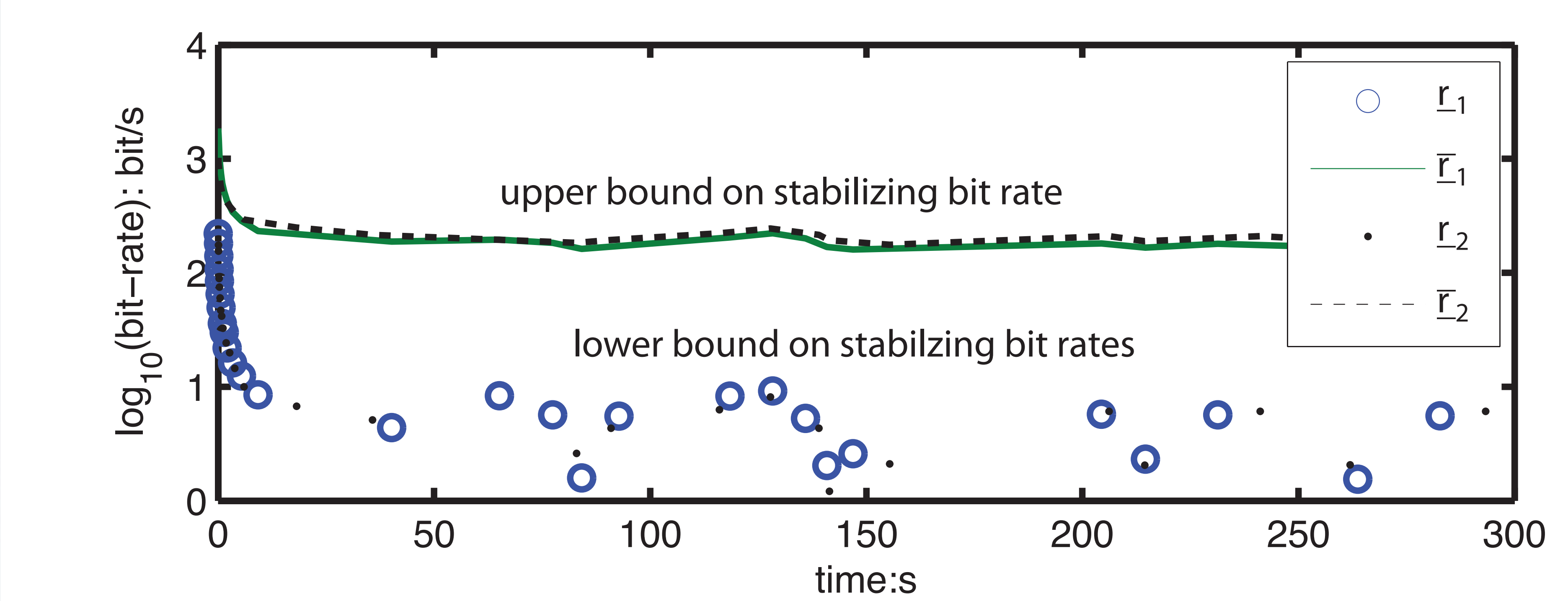
- Control Performance Requirement
  - Input-to-State Stability specifies desired transient and steady-state behavior
- Sampling and Quantization Rules
  - State is re-sampled when local error exceeds a state-dependent bound
  - Quantization level is usually a function of state (dynamic quantization)



- Stabilizing Sampling/Quantization
  - Bounds on inter-sampling interval and stabilizing delay
  - Bounds on Stabilizing Quantization Levels
  - Bounds on the Stabilizing Bit-rates required in the channel

Stabilizing Bit Rate Results

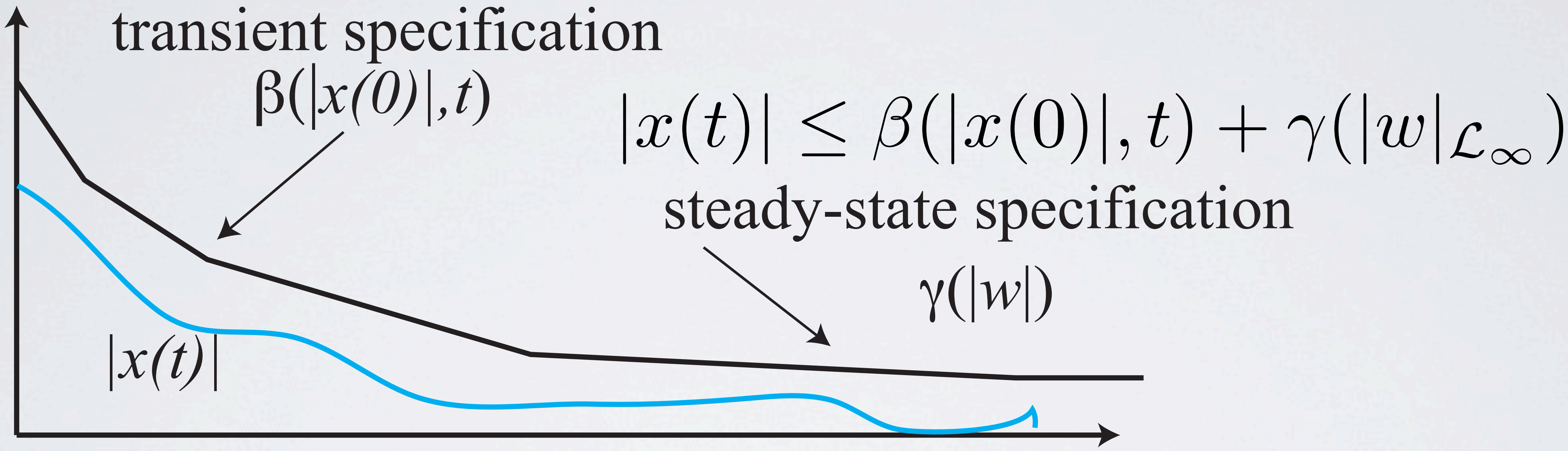
- Upper and Lower Bounds for Simulated System



- Efficient Attentiveness
  - Stabilizing bit rate decrease monotonically as system approaches equilibrium
  - In the absence of disturbances, these rates asymptotically go to zero

Controller Reconfiguration

- Stabilizing bit rates are function of the ISS-pair characterizing the system's input-to-state stability



$$|x(t)| \leq \beta(|x(0)|, t) + \gamma(|w|_{\mathcal{L}_\infty})$$

- Given a channel bit-rate, this suggests we can identify an admissible ISS-pair and use this to re-configure the controller.
  - Preliminary results suggest this is promising approach to controller reconfiguration

Minimum Energy Rate Control

- Problem Statement
  - minimum inter-sampling interval, and maximum acceptable delay to characterize the real-time end-to-end QoS required of the channel
  - Minimize transmission energy over a given time interval

$$\min_{r(t)} \int_{t_0}^{t_1} P(r(t))dt$$

where $P(r)$ and $r(t)$ and the transmission power and transmission rate of the encoder and t_0 and t_1 are start and end time of a given time interval

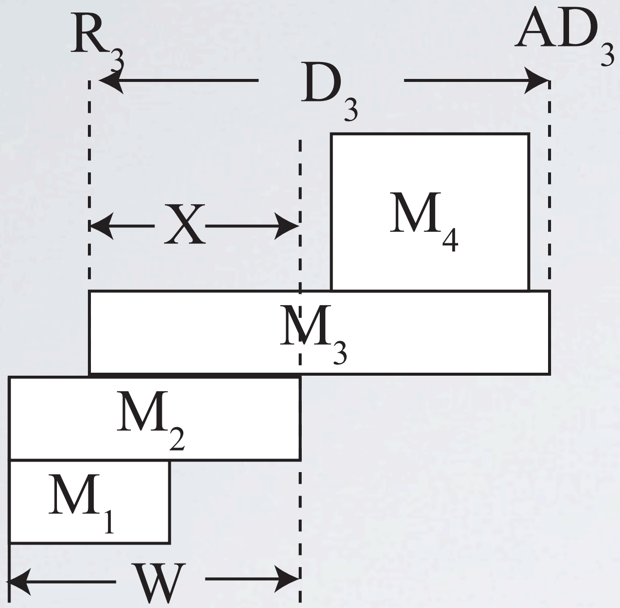
- Guarantee real-time requirements of messages under EDF
  - Jitter, packet non-preemptive property, and dynamic interference make it difficult to meet all message deadlines
  - Make as many messages as possible meet their deadlines

Dynamic Transmission Rate Adjustment

- Original Lp-EDF
  - Original Lp-EDF is a DVFS algorithm proposed by Yao et al. (FOCS 1995) which is optimal for scheduling pre-emptive jobs on a single processor under EDF scheduling

- Modified Lp-EDF
  - Respect the non-preemptive property of a packet during transmission
  - When computing transmission rates, not only consider the message already released, but also predict some future messages
  - These predictions are based on bounds for intersampling interval and max stabilizing delay tolerated by the control system application
  - Two approaches considered:
    - Proportional Prediction (Lp-EDF-p)
    - Complete Prediction (Lp-EDF-c)

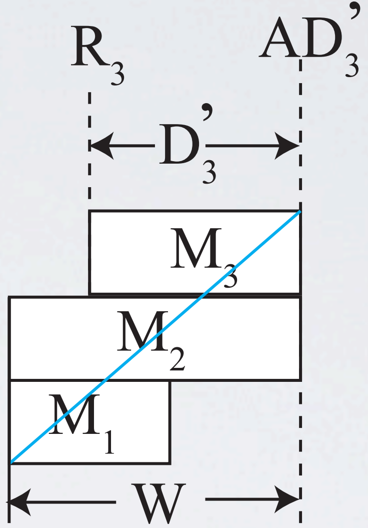
Proposed Rate Adjustment Algorithms



Message Pattern

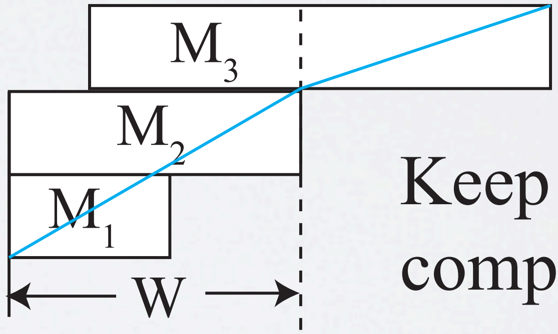
M_i = *i*th message
R_i = release time of M_i
D_i = relative deadline of M_i
AD_i = absolute deadline of M_i
W = scheduling window

Proportional Prediction



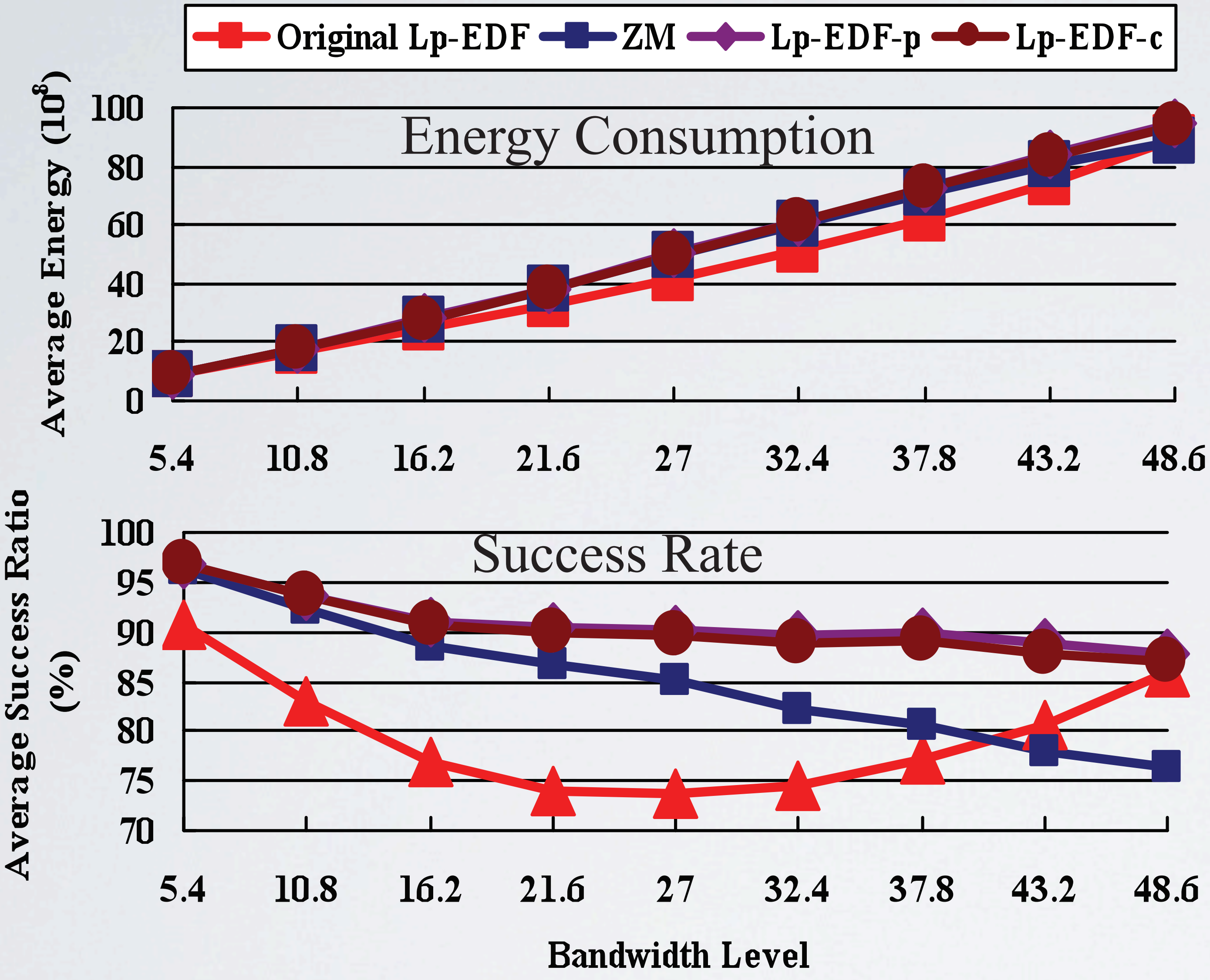
Modify size of M_3 and absolute deadline

Complete Prediction



Keep M_3 as is and compute TX rates

Simulation Results

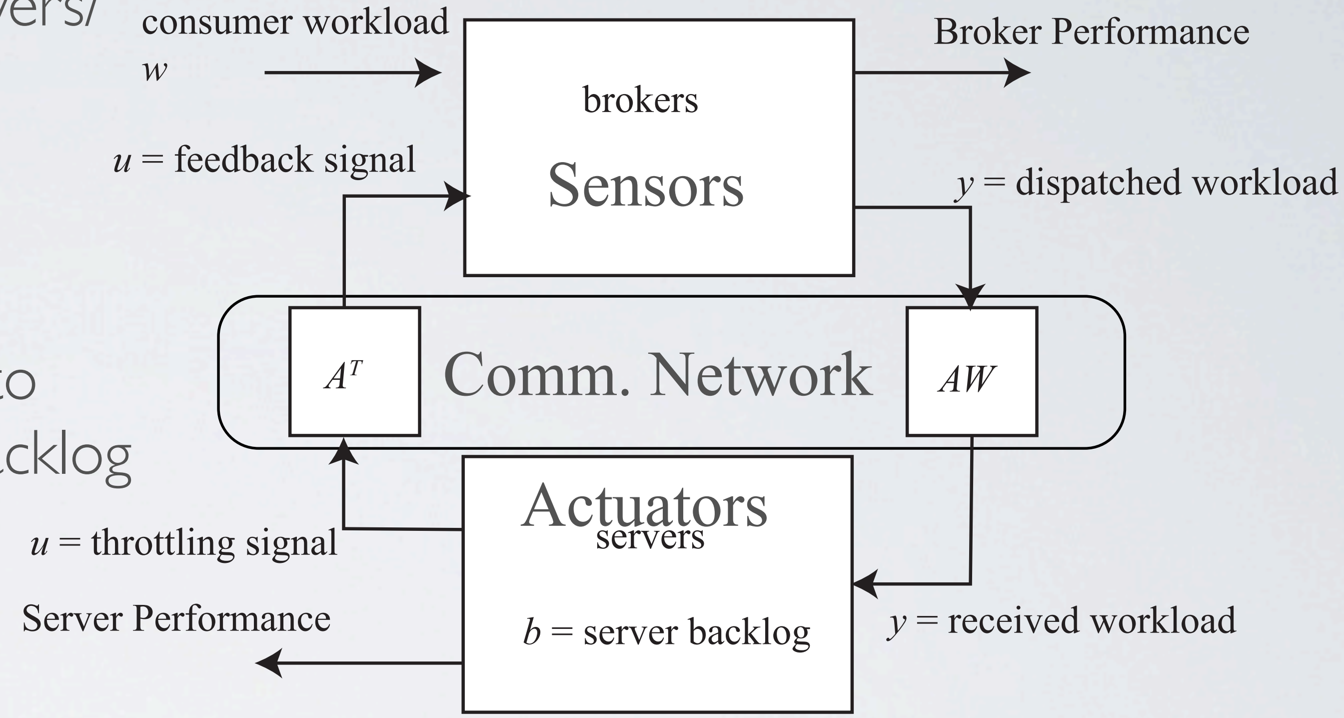


Lp-EDF: Yao et. al., FOCS 1995
ZM: Zafer and Modiano, IEEE Trans. Networking, 2009.

- Energy consumption of modified Lp-EDF comparable to energy optimal schemes proposed by Yao and ZM
- Modified Lp-EDF has higher success rates than Yao or ZM algorithms.
- Results suggest the "bounds" specified by controller can be used to manage energy consumption in the network.

Modular Framework for Rate Control

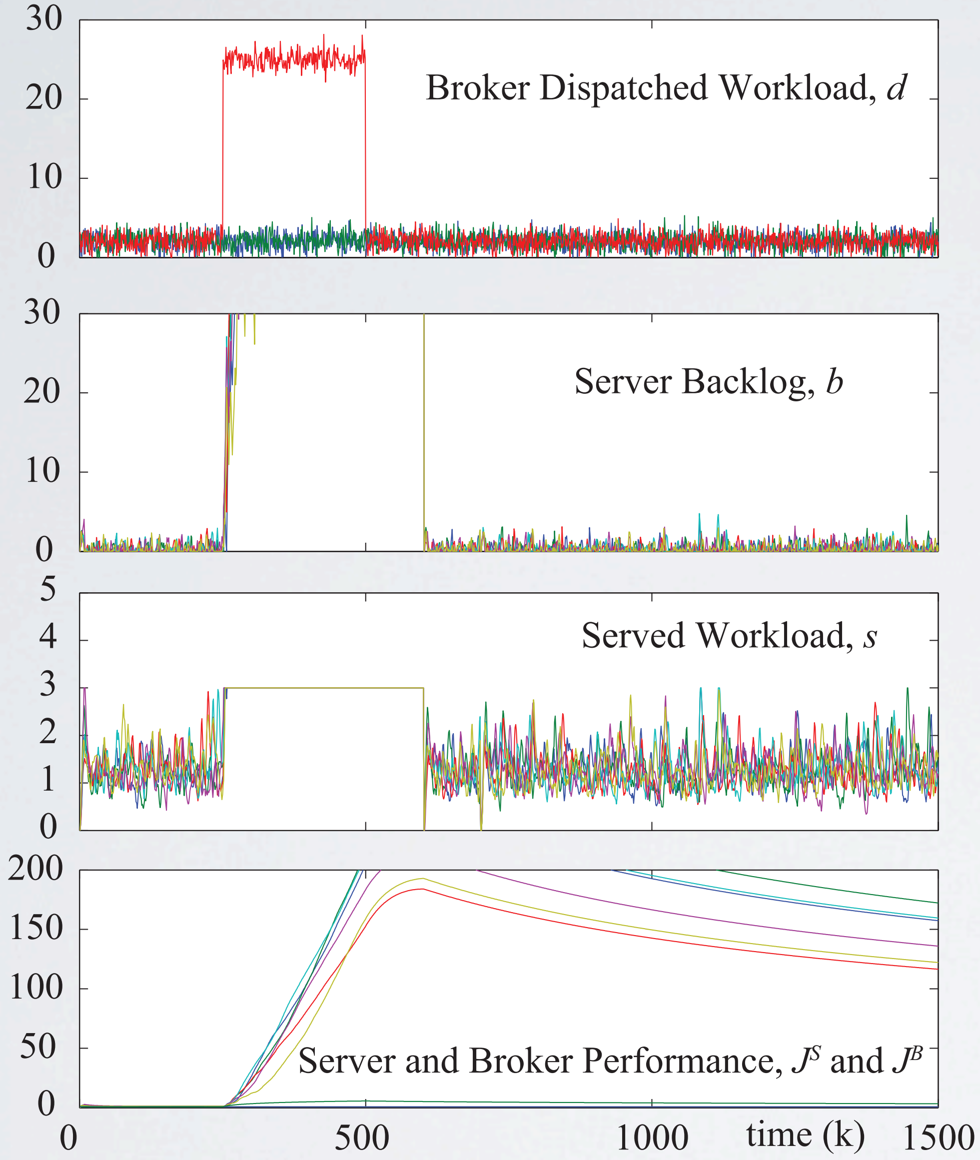
- System Framework
  - Collection of "brokers/sensors" and "servers/actuators" in a WSAN.
  - Brokers send "information" to multiple actuators over a comm network with changing topology.
  - Servers provide "throttling" information to limit broker's transmit rate when their backlog gets too large



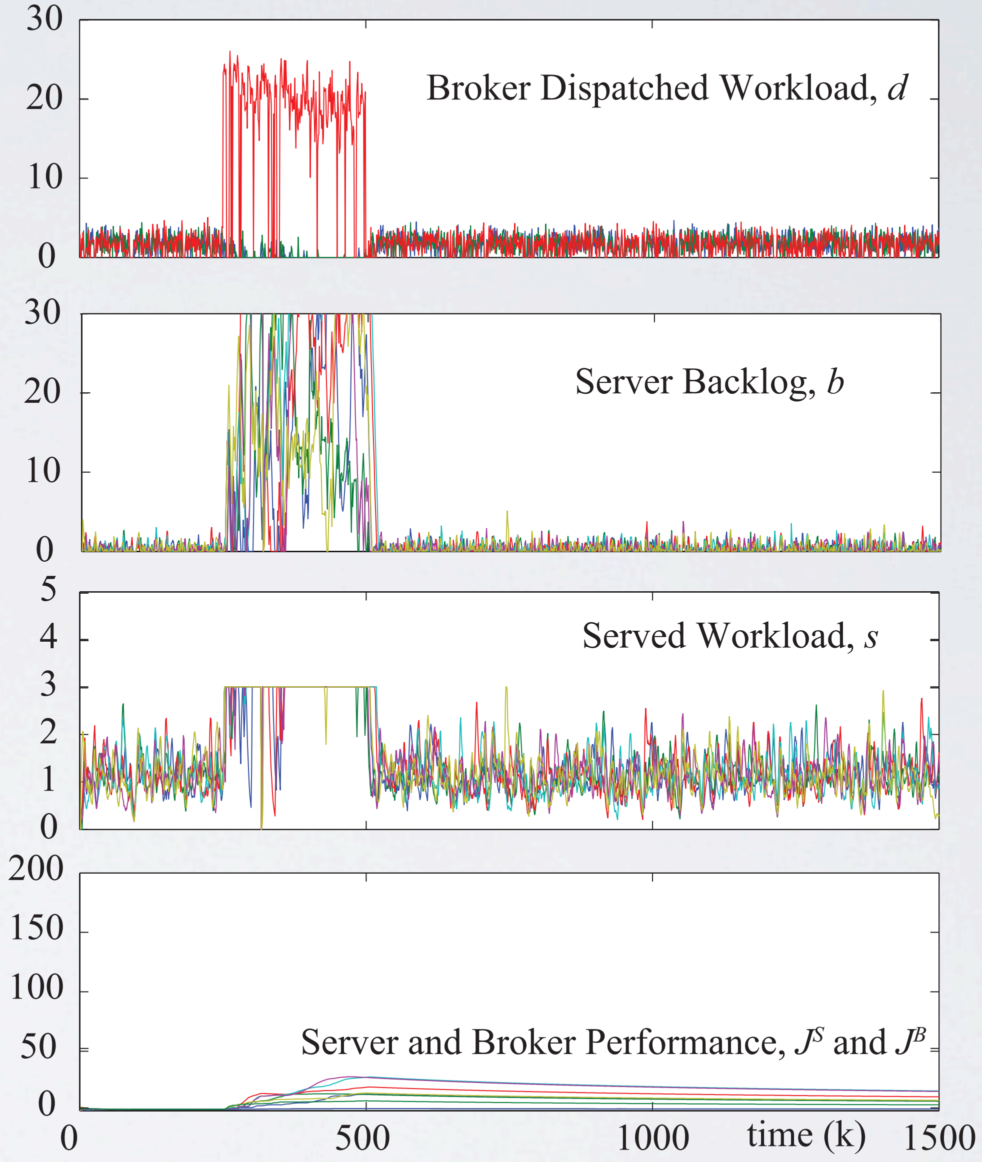
- Challenges
  - Brokers and Servers control their service rates in a manner that is "optimal" with respect to a "private" utility function.
  - How does one ensure that this "interconnection" of independent agents keep their backlogs bounded.
  - Use of "passivity certificates" to ensure dissipative nature of networked system's interconnected agents.

Server Backlog as Throttling Signal

No throttling signal



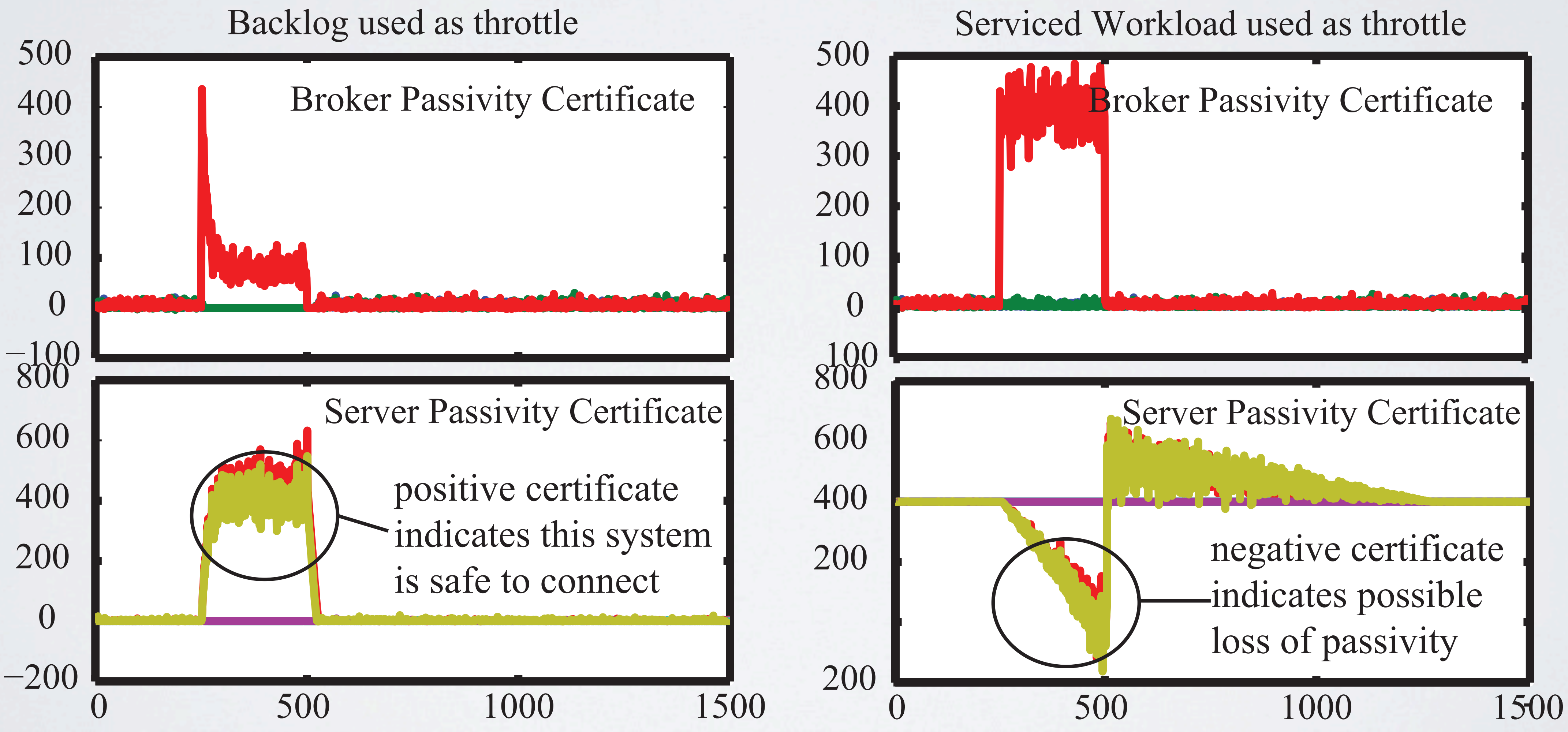
Backlog Throttle Used



- backlog throttle limits congestion under overload conditions

Passivity Certificates

- Passivity certificate is positive if the subsystem is "passive"
  - passivity certifies it is "safe" to interconnect the subsystem to the network
- Future work will investigate the use of these concepts in managing the real-time traffic generated by multiple sensors/actuators in WSAN



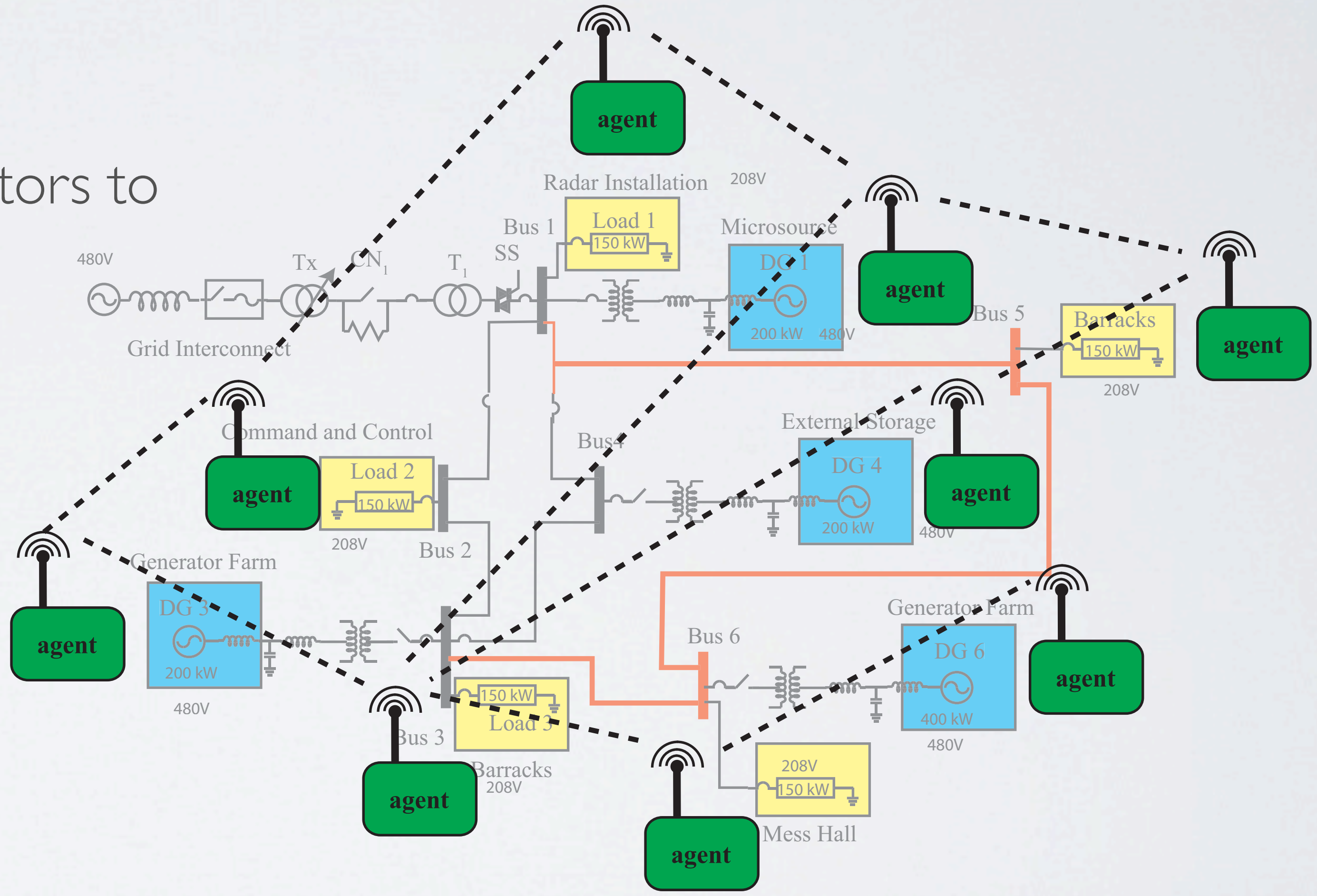
positive certificate indicates this system is safe to connect

negative certificate indicates possible loss of passivity

Autonomous Microgrid Control

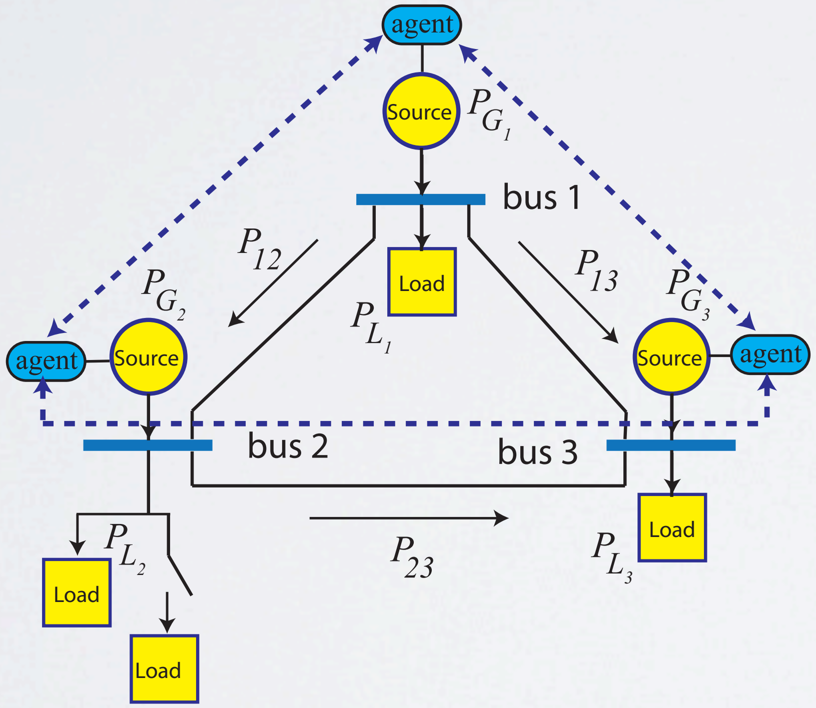
- Problem Statement
  - What benefits does wireless networking bring for the control and management of autonomous microgrids?
  - Microgrids are low voltage power distribution networks where generation sources are relatively close to loads.

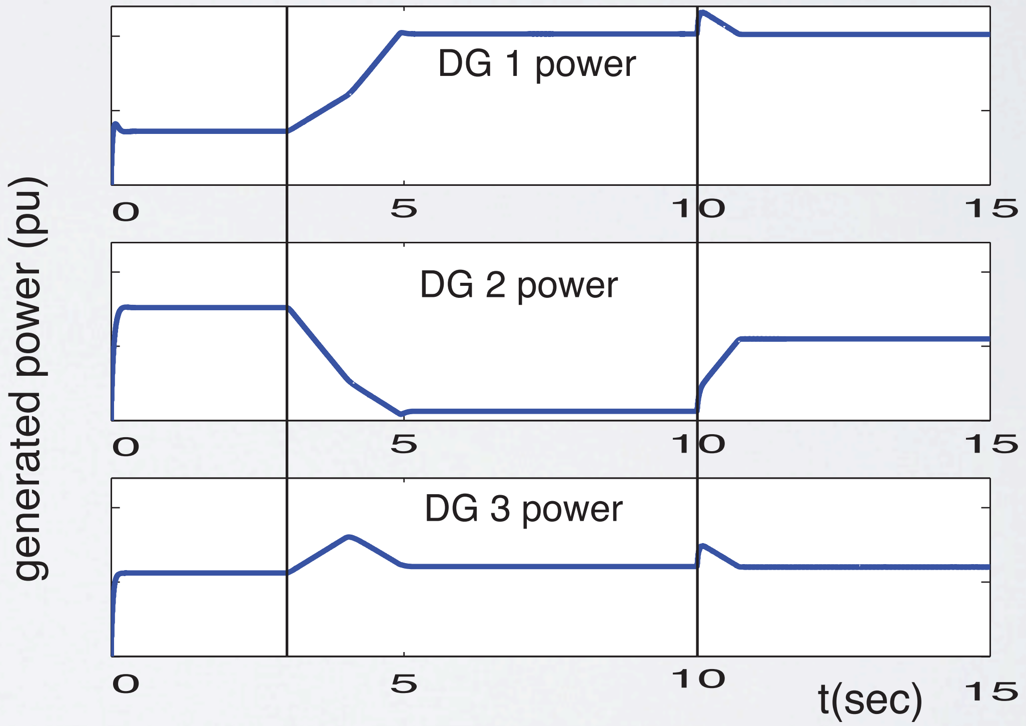
- Peer-to-peer dispatching
  - Computational agents enable generators to make control decisions locally
  - Enabling technologies are
    - wireless networking
    - distributed optimization
    - decentralized control
  - Objective (future work) is to use autonomous microgrid control as a testbed for this project's network management algorithms



Event-triggered Dispatching (islanded case)

- Communication triggered by local "events" at each source
  - optimal dispatcher turned on (t = 3 sec)
  - abrupt change in bus 2 load (t = 10 sec)
  - DG2 most expensive generating unit
  - power line constraint force DG2 to address load change



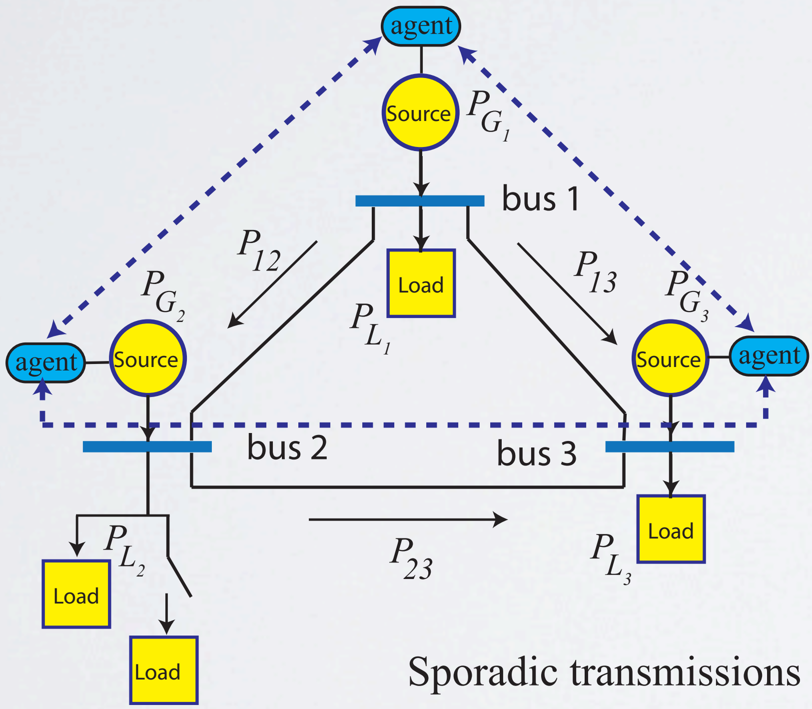


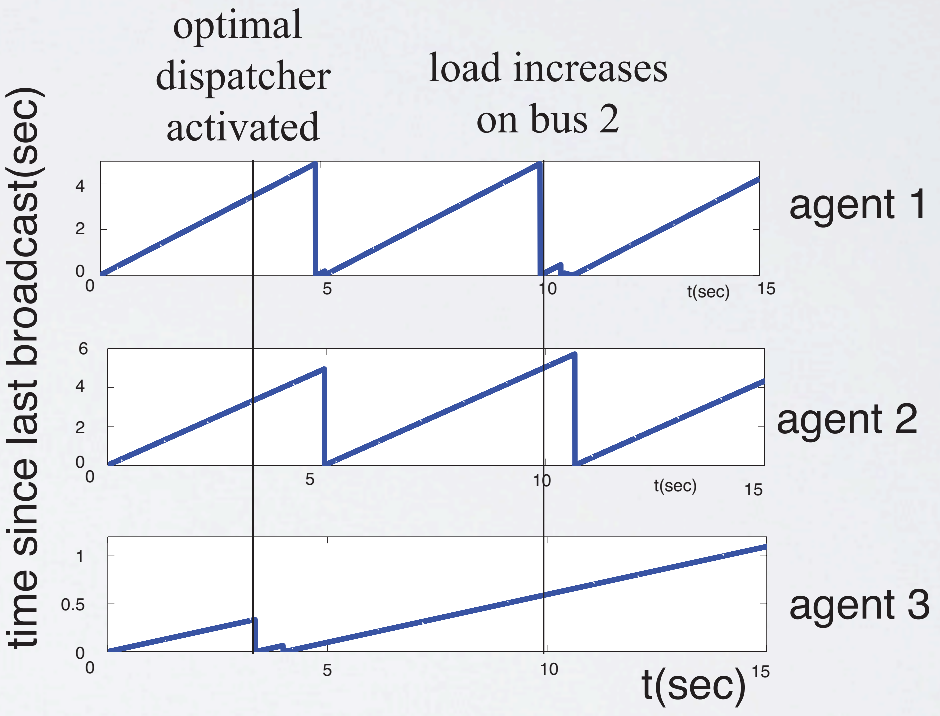
optimal dispatcher activated

load increases on bus 2

Event-triggered Dispatching (islanded case)

- Communication triggered by local "events" at each source
- Power dispatch with great reduction in network message passing
  - message passing reduction can be by several orders of magnitude over periodically triggered distributed optimization method





Sporadic transmissions between agents occur in response to changes in system

Integration with MV Distribution Feeders

- **Objective**

  Manage generations coordinatively to export **maximum real power** and maintain **voltage levels within limits**.

- **Results**
  - A **hierarchical control architecture** includes: Microgrid Consortium Manager (**MCM**), Microgrid Interface Controller (**MIC**), and CERTS droop controller.
  - Two levels of optimization problems in MICs: microgrid states are determined **locally**; set points of microsources are solved in a centralized manner.

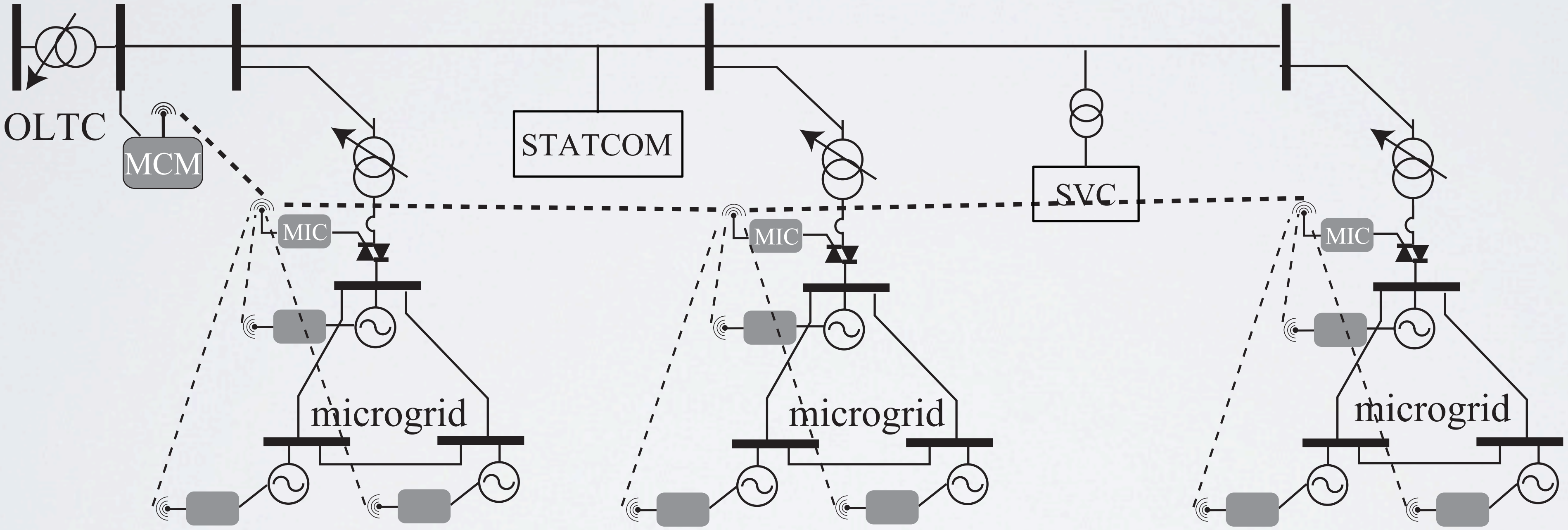


Fig. 2 Hierarchical Control Architecture

- **Future Work**

  - integration of quantization and event-triggering into this structure
  - include constraints for transient stability in weak networks
  - study of communication network limitations.

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Education

1. Formal Methods in the Design and Verification of Cyber-Physical Systems, University of Notre Dame, Spring 2010
2. Special Studies in Networked Control Systems, University of Notre Dame, Spring 2011, Spring 2012

Technology Transfer

1. Odyssian Technology South Bend, Indiana, An intelligent distributed control architecture for microgrids, 2009-2011
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CPS: Small:
Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network

Project Number: CNS-09-31195
Investigators: M.D. Lemmon and X.S. Hu
Start Date: 9/1/2009 - 8/31/2012

Wireless sensor-actuator networks (WSAN) consist of numerous sensing and actuation devices that share information over an ad hoc wireless communication network. WSANs may be used to manage networked systems that distribute goods and services over large spatially distributed domains. Examples of such systems include the national power grid, ground/air traffic networks, and water/gas distribution networks.

This project studies the implementation of feedback control algorithms over WSANs, particularly with regard to the management of large-scale networked systems such as the electric power grid or water distribution networks. Controlling such physical processes usually requires some form of hard real-time support, so that each packet of feedback data must be serviced within a specified deadline. It has, in practice, been difficult to provide such guarantees in real-life wireless networks. This project addresses that issue by developing algorithms that allow control applications and wireless network nodes to work together in maximizing application performance subject to hard real-time service constraints. Given that energy is a precious resource in WSANs, additional effort is devoted to investigate how to effectively trade off energy with control performance, again subject ot hard real-time service constraints.

The algorithms being developed by this project are based on a three-prong approach. First, one must control network interference to provide a stable platform upon which real-time guarantees become possible. Second, network flows must be scheduled in a manner that achieves the real-time capacity of the stabilized network. Third, if the network's quality of service falls below application requirements, then the application must modify the controllers to maintain minimum levels of performance under reduced network capacity. Furthermore, to include energy into consideration, approaches are being developed through a novel extension of distributed power control algorithms to real-time flows, recent advances in elastic scheduling of real-time tasks, and recent advances in our understanding of sporadic sampled-data control systems. Energy-aware real-time scheduling theory is also being extended to handle unique challenges present in WSANs.

The impact of this project is being broadened through interactions with industry and graduate curriculum development. A first year graduate course (EE67036) on cyber-physical systems focusing on modeling, verification, and control synthesis has been developed. The project is also working with businesses to develop real-time WSAN application for environmental monitoring (EmNet LLC) and microgrid control (Odyssian LLC, General Electric Energy).