Networked Control Systems

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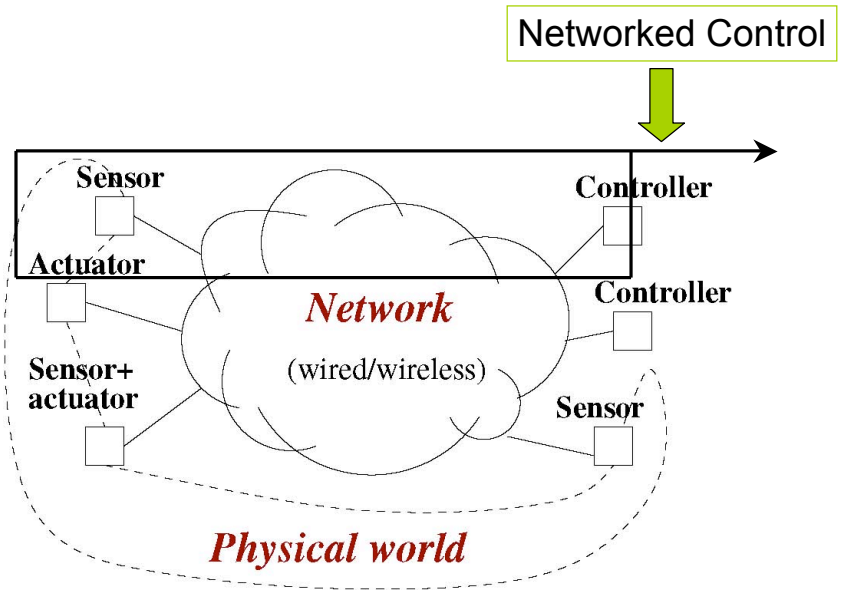
Keynote Lecture

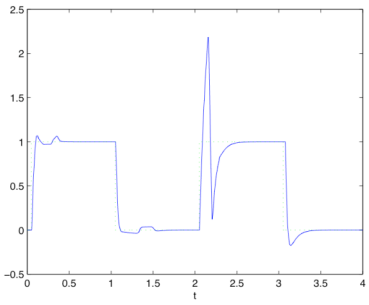
3rd Workshop on Networked Control Systems: Tolerant to Faults
Nancy, FRANCE

20 June 2007

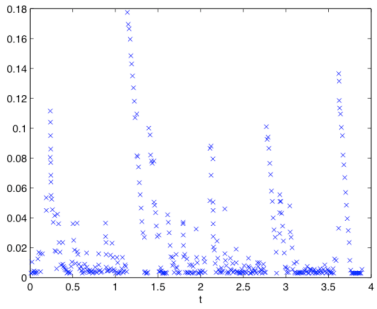


A Quick Example: PID NCS

[simulated in TrueTime; Henriksson, Cervin, Arzen, IFAC'02]



Step responses of plant
- First-order plant (time-driven)
- PI controller (event-driven)
- Connected by a network
- Interfering traffic (48% of BW)



Corresponding round-trip times (s)

[Alldredge, MS Thesis, CWRU, '07]

Outline

- Introduction
  - NCS Issues
  - Models
- Analysis & Design Tools
- Co-Design & Co-Simulation
- Congestion Control
- Research Opportunities

Networked Control Systems (1)

- Numerous distributed agents
- Physical and informational dependencies

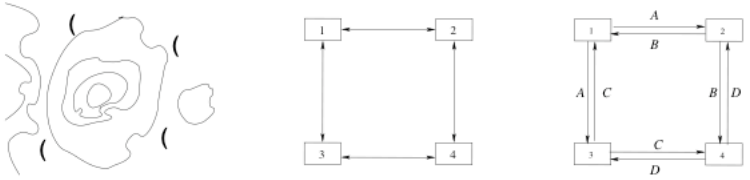


Figure 1: Formation example: physical situation (l), information flow graph (m), network multigraph (r)

[Branicky, Liberatore, Phillips: ACC'03]

Networked Control Systems (2)

- Control loops closed over heterogeneous networks

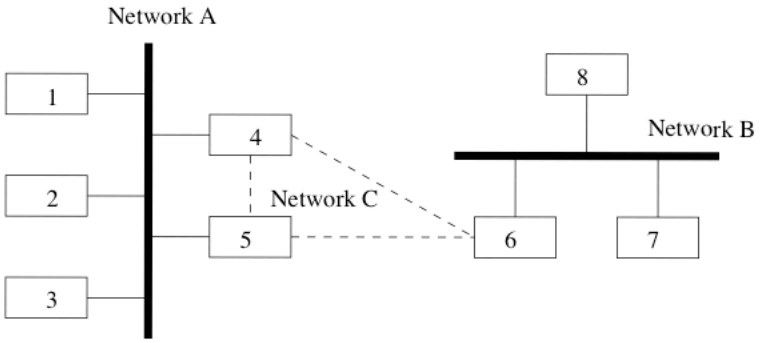
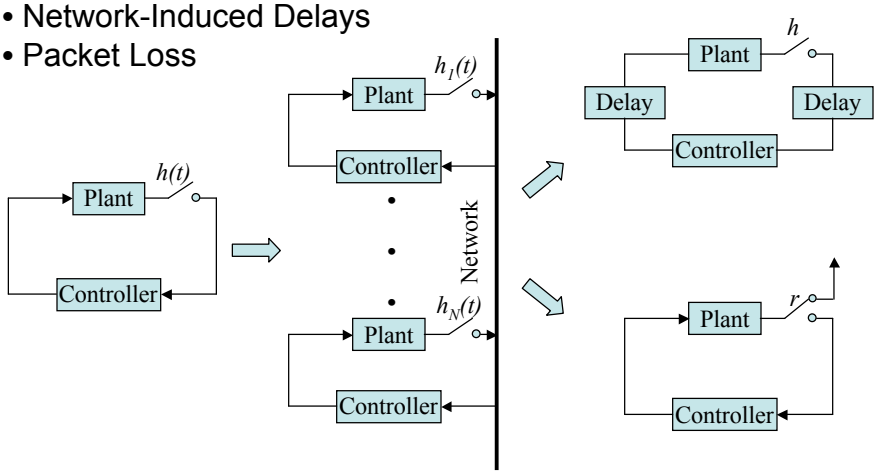


Figure 1: Multiple LANs Example: network architecture

[Branicky, Liberatore, Phillips: ACC'03]

Fundamental Issues

- Time-Varying Transmission Period
- Network Schedulability, Routing Protocols
- Network-Induced Delays
- Packet Loss



[Branicky, Phillips, Zhang: ACC'00, CSM'01, CDC'02]

Mathematical Model: NCS Architecture

An *NCS Architecture* is a 3-tuple:

- Agent Dynamics: a set of stochastic hybrid systems

$$\mathrm{d}X_i(t)/\mathrm{d}t = f_i(Q_i(t), X_i(t), Q_I[t], Y_I[t], R(t))$$
$$Y_i(t) = g_i(Q_i(t), X_i(t), Q_I[t], Y_I[t], R(t))$$

- Network Information Flows: a directed graph

$$G_I = (V, E_I),\ V = \{1, 2, \ldots, N\};\ \text{e.g.,}\ e = (i, j)$$

- Network Topology: a colored, directed multigraph

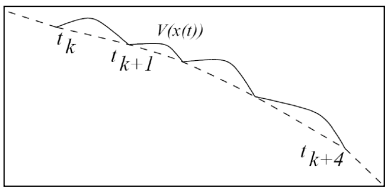
$$G_N = (V, C, E_N),\ V = \{1, 2, \ldots, N\};\ \text{e.g.,}\ e = (c, i, j)$$

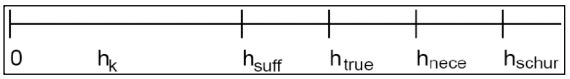
[Branicky, Liberatore, Phillips: ACC'03]

Early NCS Analysis & Design

- Nilsson [PhD, '98]: Time-Stamp Packets, Gain Schedule on Delay
- Walsh-Ye-Bushnell ['99]: no delay+**M**ax. **A**llowable **T**ransfer **I**nterval
- Zhang-Branicky [Allerton'01]:

Based on "Multiple Lyapunov Functions" [Branicky, T-AC'98]

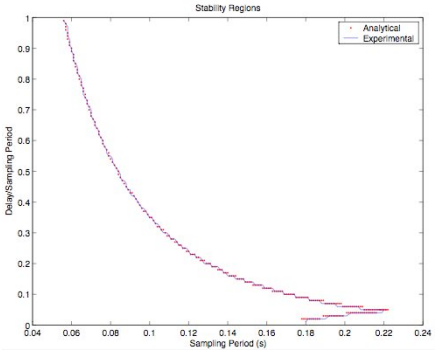


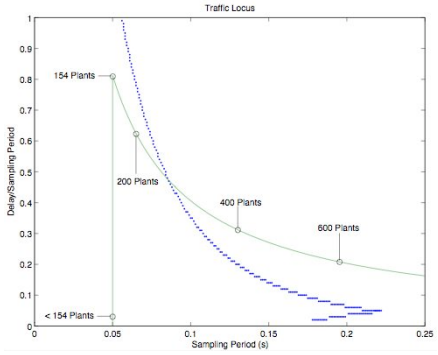


- Hassibi-Boyd ['99]: asynchronous dynamics systems
- Elia-Mitter ['01], others: Info. thy. approach: BW reqts. for CL stability
- Teel-Nesic ['03]: Small gain, composability

Other Analysis and Design Tools

- Stability Regions [Zhang-Branicky-Phillips, 2001] (cf. stability windows)
- Traffic Locus [Branicky-Hartman-Liberatore, 2005]

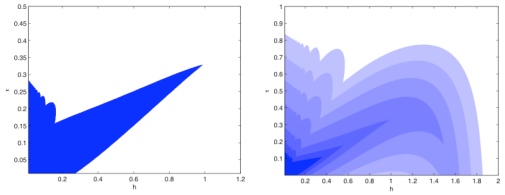




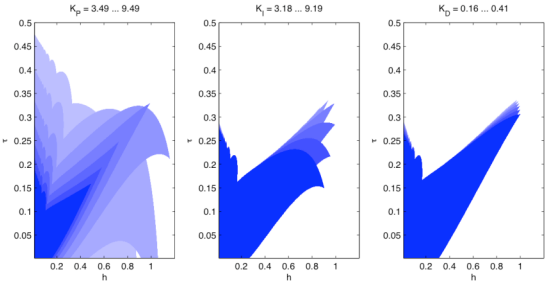
Both for an inverted pendulum on a cart (4-d), with feedback matrix designed for nominal delay of 50 ms. Queue size = 25 (l), 120 (r).

Stability Regions for Time-Delay PID

- First-order plant (T=1)
- PID controller
- Gains designed for τ_p=0.1: (K_P=6.49, K_I=6.18, K_D=0.39)
- τ_p = 0.05, 0.07, 0.1, 0.15, 0.2, 0.25, 0.3 (lighter=increasing)

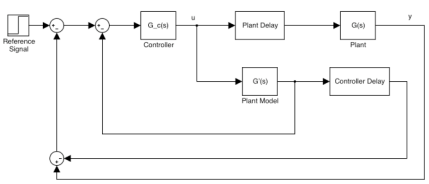


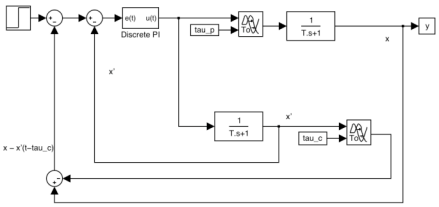
- First-order plant (T=1)
- PID controller
- Gains designed for τ_p=0.3 (K_P=2.46, K_I=2.13, K_D=0.32)



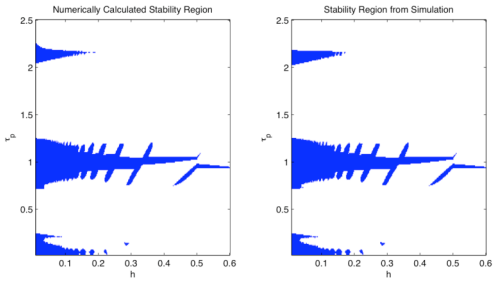
[Alldredge, MS Thesis, CWRU, '07]

Smith Predictor in the Loop



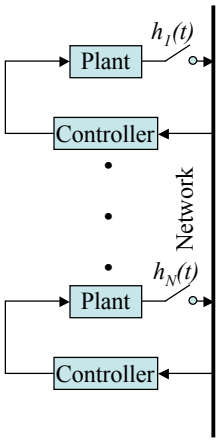


- First-order plant (T=1)
- PI controller
- Delay between Controller/Plant
- Compensate w/predictor (τ_c=1)



[Alldredge, MS Thesis, CWRU, '07]

Network Scheduling in NCSs



Two problems:

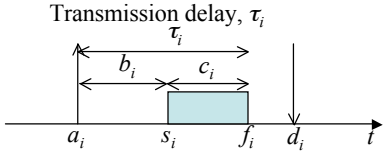
- Schedulability analysis
- Scheduling optimization

An NCS transmission T_i with period h_i is characterized by the following parameters:

Blocking time, $b_i = s_i - a_i$

Transmission time, c_i

Transmission delay, τ_i



Network utilization: $U = \sum_i (c_i / h_i)$

[Branicky, Phillips, Zhang: CDC'02]

Rate Monotonic Scheduling of NCSs

- Rate Monotonic (RM) scheduling [Liu and Layland]
  - Assigns task priority based on its request rate
- From earlier example
  - "Faster" plant requires higher transmission rate
  - Therefore, should be assigned higher priority (based on RM scheduling)
- Can a set of NCSs be scheduled by RM → Schedulability Test [Sha, Rajkumar, Lehoczky]

A set of N independent, non-preemptive, periodic tasks (with $i = 1$ being highest priority and $i = N$ being the lowest) are schedulable if for all $i = 1, \ldots, N$

$$\frac{c_1}{h_1} + \frac{c_2}{h_2} + \ldots + \frac{c_i}{h_i} + \frac{\bar{b}_{1,i}}{h_i} \leq i\left(2^{1/i} - 1\right).$$

where $\bar{b}_{1,i}$ is the worst case blocking time of task i by lower priority tasks, for NCS transmissions:

$$\bar{b}_{1,i} = \max_{j=i+1,\ldots,N} c_j.$$

[Branicky, Phillips, Zhang: CDC'02]

Scheduling Optimization

$$\text{minimize (maximize)} \quad J(h_i) = \sum_{i=1}^{N} J_i(h_i)$$

subject to

- RM schedulability constraints:

$$h_1 \leq \ldots \leq h_N,$$

$$\frac{c_1}{h_1} + \ldots + \frac{c_i}{h_i} + \frac{\bar{b}_{i,i}}{h_i} \leq i(2^{1/i} - 1), \quad i = 1, \ldots, N;$$

- NCS stability constraints:

$$h_i \leq h_{\text{suff,i}} - \bar{b}_i, \quad i = 1, \ldots, N.$$

Performance measure *J(h)* relates the control performance as a function of transmission period *h.*

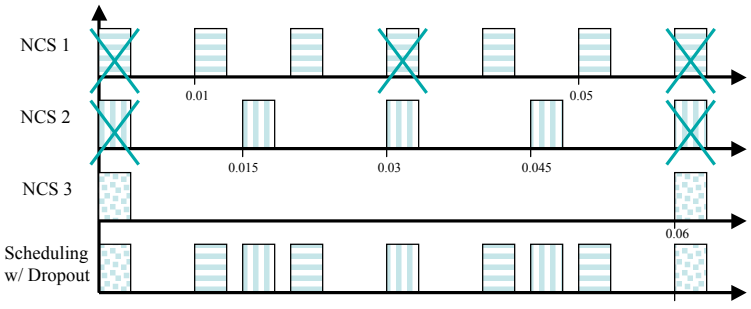
[Branicky, Phillips, Zhang: CDC'02]

Scheduling of NCSs Revisited

- Cf. Eker & Cervin on scheduling for real-time control
- If dynamic (#agents/BW): *distributed BW allocation schemes*
- Using rate constraints or packet-drop-rate results …

Idea: when a set of NCSs is not guaranteed to be schedulable by RM, we can drop some of data packets to make it schedulable and still guarantee stability.

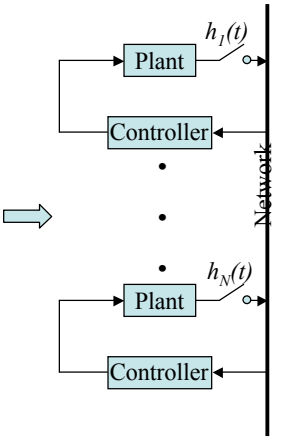
Ex.: scheduling of the set of scalar plants [Branicky, Phillips, Zhang: CDC'02]



Control and Scheduling Co-Design

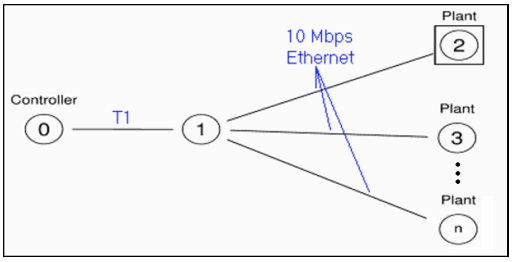
- Control-theoretic characterization of stability and performance (bounds on transmission rate)
- Transmission scheduling satisfying network bandwidth constraints

Simultaneous design/optimization of both of these = **Co-Design**



[Branicky, Phillips, Zhang: CDC'02]

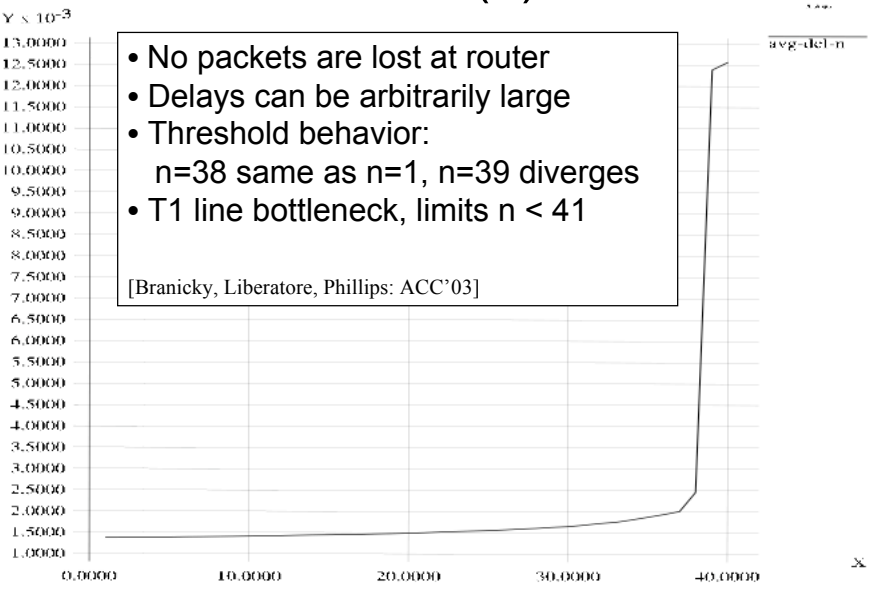
"Dumbbell" Network Topology



- 10 Mbps link between plants (2-n) and router (1), with 0.1 ms fixed link delay
- 1.5 Mbps T1 line between router (1) and controller (0), with 1.0 ms fixed link delay
- First plant (2) under observation
- Delays are asymmetric

[Hartman, Branicky, Liberatore: ACC'05]

NCS over Ethernet (1): Infinite Buffer



- No packets are lost at router
- Delays can be arbitrarily large
- Threshold behavior:
  n=38 same as n=1, n=39 diverges
- T1 line bottleneck, limits n < 41

[Branicky, Liberatore, Phillips: ACC'03]

Figure 1: One-way delays (plant to controller) as a function of n for the case of infinite buffers.

NCS over Ethernet (2): Finite Buffer

- Packets are dropped (up to 14% at n=39), delays bounded
- Plant output degrades at high loads
- Average inter-arrival times nearly constant
- Detailed history determines performance

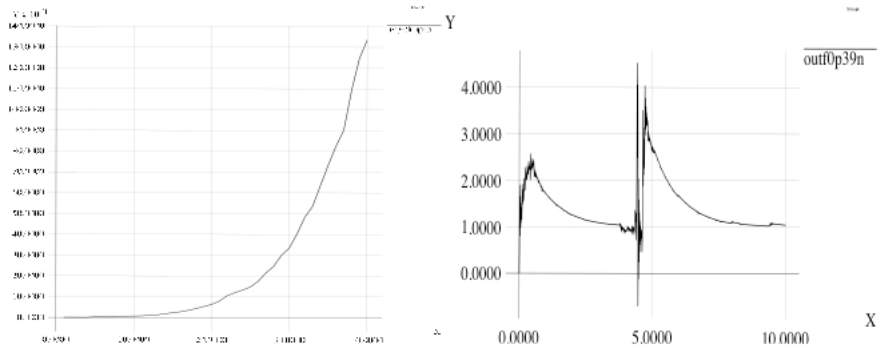


Figure 1: Buffer of size 4. Drop rate up to $n = 39$ (l); plant output (r) for $n = 39$.

[Branicky, Liberatore, Phillips: ACC'03]

NCS over Ethernet (3): Minimal Buffer

- Packets are dropped (up to 28% at n=39)
- Errors are small up to n=25
- Plant output diverges for n=39

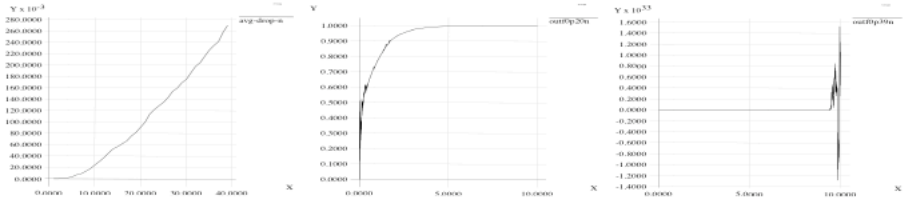
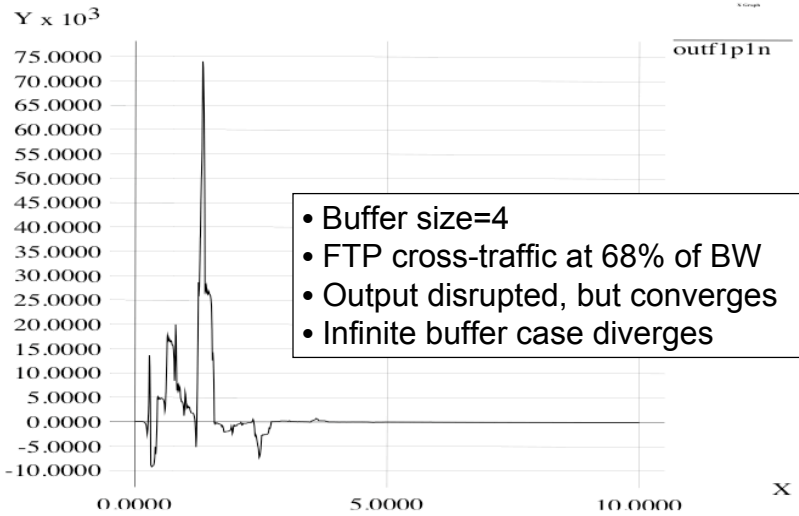


Figure 1: Buffer of size 2. Drop rate up to $n = 39$ (l); plant output for $n = 20$ (m), $n = 39$ (r).

[Branicky, Liberatore, Phillips: ACC'03]

NCS over Ethernet (4): Cross-Traffic



- Buffer size=4
- FTP cross-traffic at 68% of BW
- Output disrupted, but converges
- Infinite buffer case diverges

Figure 1: Plant output in the presence of one FTP flow.

[Branicky, Liberatore, Phillips: ACC'03]

Overall NCS Technical Approach

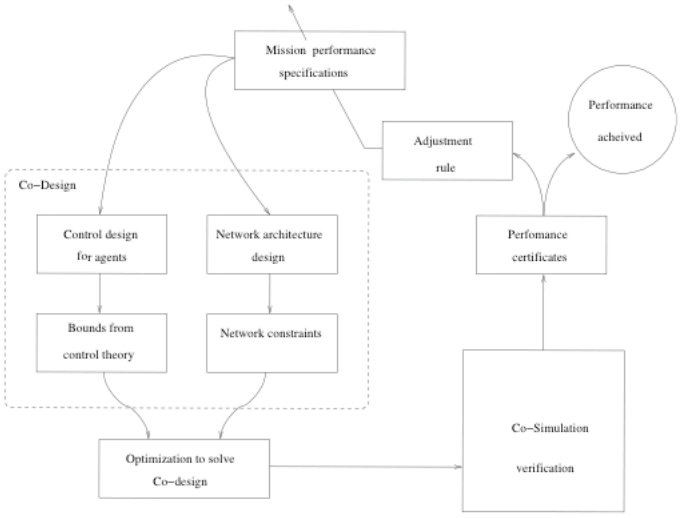


Figure 1: Overall NCS Design Loop

[Branicky, Liberatore, Phillips: ACC'03]

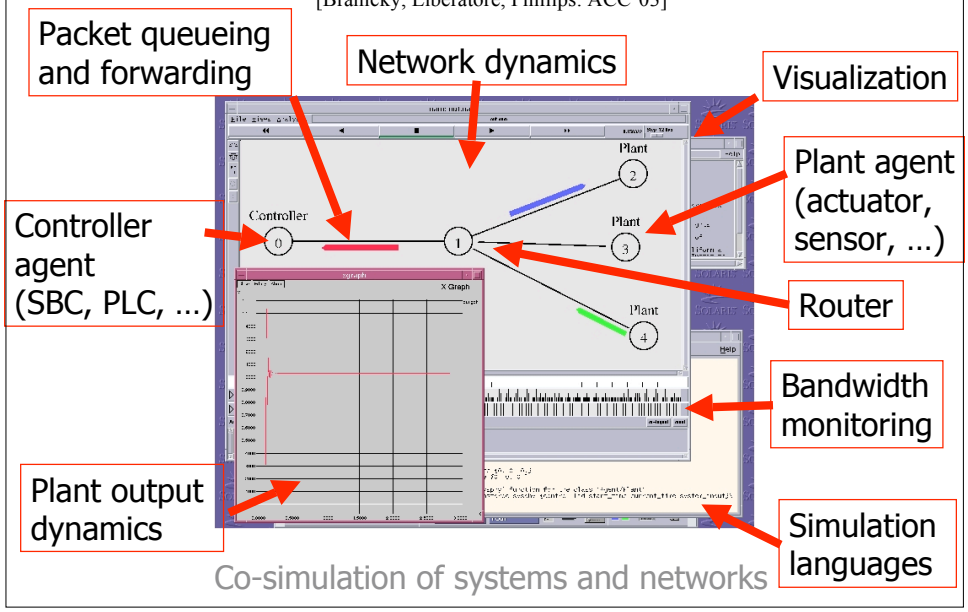
Co-Simulation Methodology

- Simultaneously simulate both the dynamics of the control system and the network activity
- Vary parameters:
  - Number of plants, controllers, sensors
  - Sample scheduling
  - Network topology, routing algorithms
  - Cross-traffic
  - Etc.

[Branicky, Liberatore, Phillips: ACC'03]

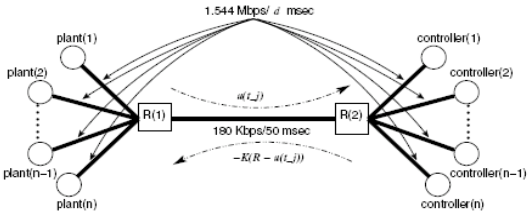
Co-Simulation

[Branicky, Liberatore, Phillips: ACC'03]



Co-simulation of systems and networks

Co-Simulation Components (1): Network Topology, Parameters



Capability like ns-2 to simulate network at packet level:

- state-of-art, open-source software
- follows packets over links
- queuing and de-queuing at router buffers
- GUI depicts packet flows
- can capture delays, drop rates, inter-arrival times

[Branicky, Liberatore, Phillips: ACC'03]

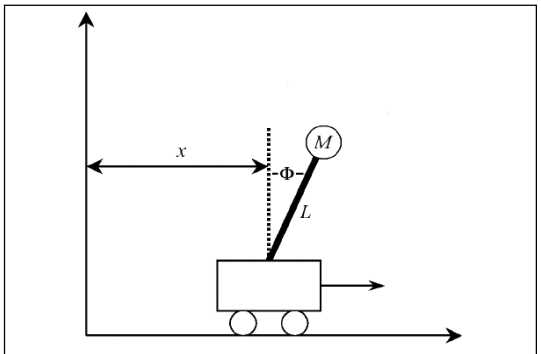
Co-Simulation Components (2): Plant and Controller Dynamics

Extensions of ns-2 release:

- plant “agents”: sample/send output at specific intervals
- control “agents”: generate/send control back to plant
- dynamics solved numerically using Ode utility, “in-line” (e.g., Euler), or through calls to Matlab

[Branicky, Liberatore, Phillips: ACC’03]

Inverted Pendulum NCS

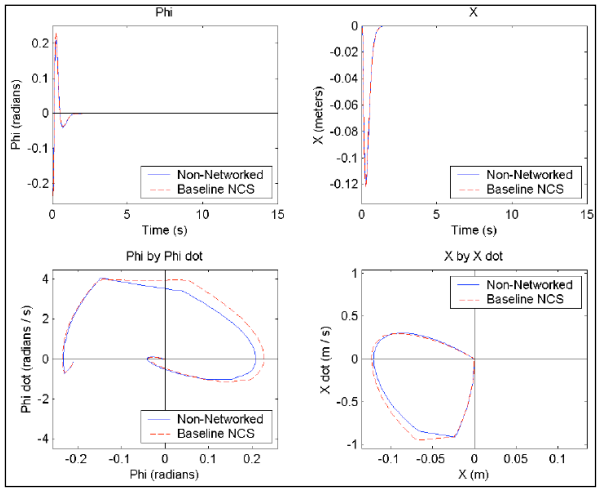


$$\ddot{\phi} + \frac{3B_R}{4ML^2}\dot{\phi} - \frac{3g}{4L}\sin\phi = -\frac{3}{4L}\ddot{x}$$

- Same “dumbbell” network topology as before
- Full-state feedback
- Non-linear equations linearized about unstable equilibrium
- Sampled at 50 ms
- Feedback designed via discrete LQR
- Control is acceleration

[Hartman, Branicky, Liberatore: ACC’05]

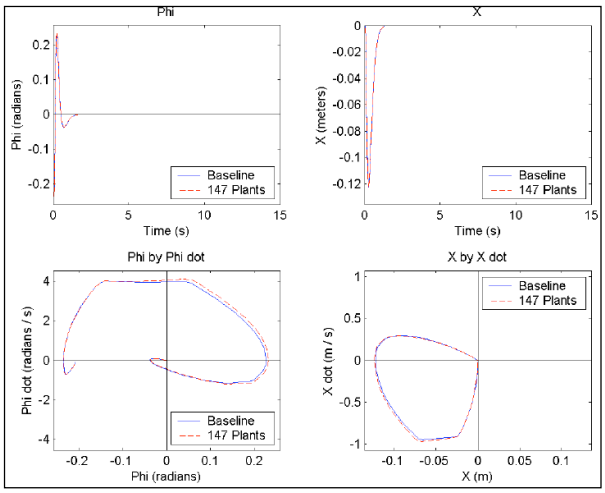
Baseline Simulation



- One plant on the network
- No cross-traffic
- No bandwidth contention
- Delays fixed at τ_{min}
- No lost packets
- Slight performance degradation due to fixed delays

[Hartman, Branicky, Liberatore: ACC'05]

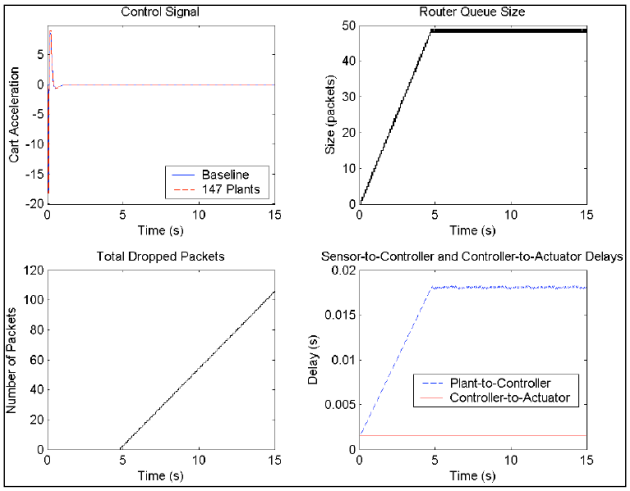
Threshold Behavior (1)



- 147 Plants on the network (just more than the network bottleneck)
- No cross-traffic
- Performance slightly worse than baseline

[Hartman, Branicky, Liberatore: ACC'05]

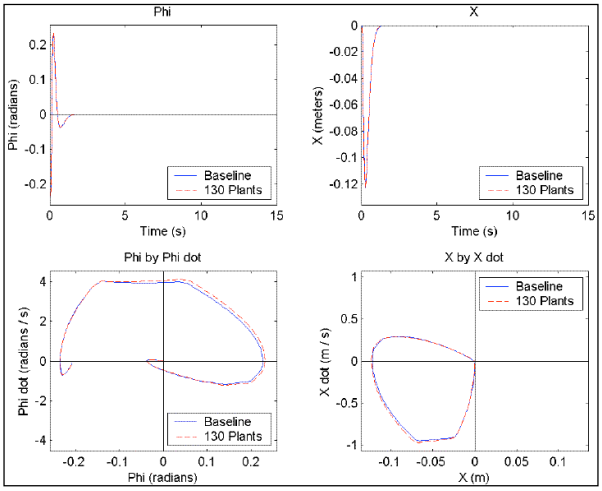
Threshold Behavior (2)



- Delays are asymmetric and variable
- Delay ranges from τ_{min} to τ_{max}
- 147 plants slightly exceeds network bandwidth
- Packet drops due to excessive queuing

[Hartman, Branicky, Liberatore: ACC'05]

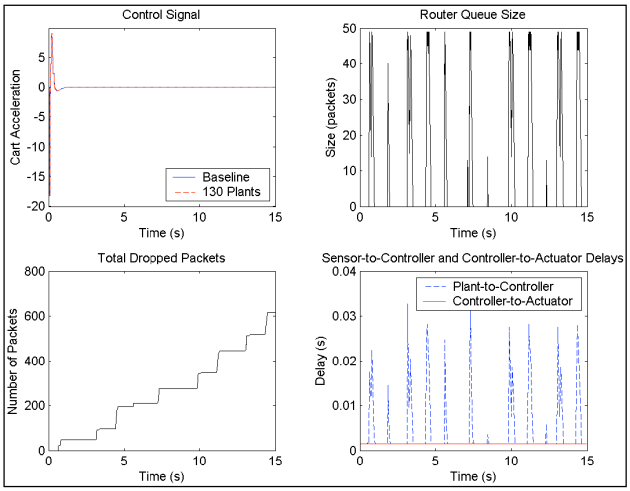
Cross-Traffic (1)



- 130 Plants on network
- Bursty FTP cross-traffic at random intervals
- Performance similar to threshold case

[Hartman, Branicky, Liberatore: ACC'05]

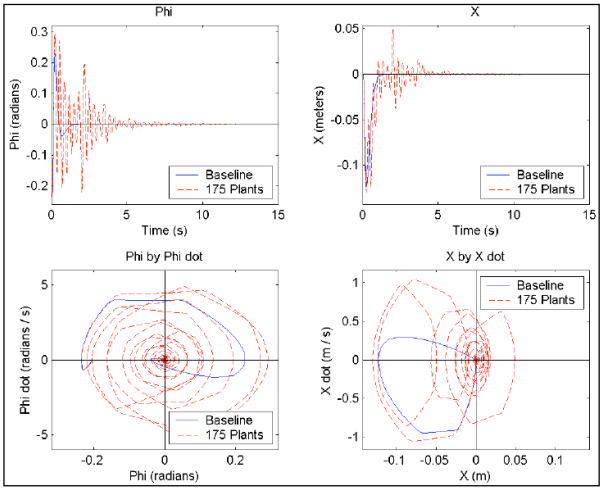
Cross-Traffic (2)



- Delays are asymmetric and variable
- Delay ranges in τ_{min} to τ_{max}, depending on traffic flow
- 130 plants below network bandwidth, but cross-traffic exceeds
- Packet drops due to queuing

[Hartman, Branicky, Liberatore: ACC'05]

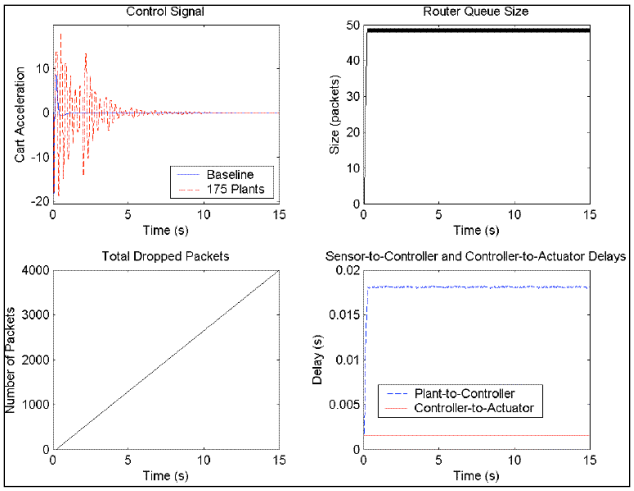
Over-Commissioned (1)



- 175 Plants on network – well above network bandwidth
- No cross-traffic
- Performance degrades substantially

[Hartman, Branicky, Liberatore: ACC'05]

Over-Commissioned (2)



- Delays asymmetric
- τ_{sc} quickly fixed at τ_{max}
- τ_{ca} still fixed at τ_{min}
- 175 plants well above network bandwidth
- Many packet drops due to excessive queuing

[Hartman, Branicky, Liberatore: ACC'05]

Other Co-Simulation Tools

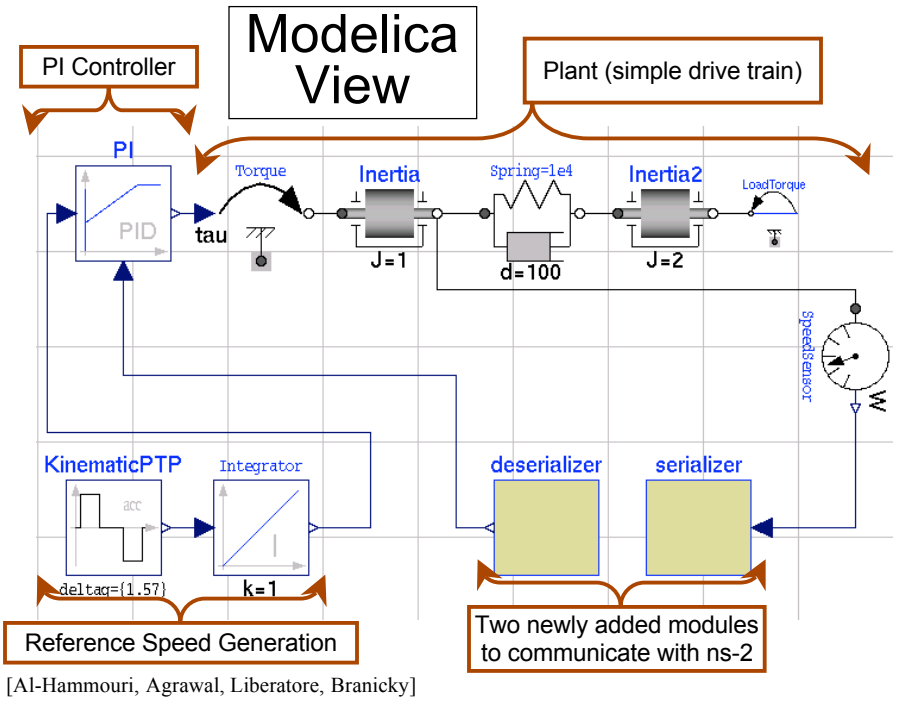
- TrueTime [Lund; IFAC'02] (Simulink plus network modules)
- SHIFT [UCB], Ptolemy [Ed Lee et al., UCB]: case studies
- ADEVS + ns-2 for power systems [Nutaro et al,. '06]

Needs:
- comprehensive tools
  ns-2 + Simulink/LabView/Modelica [+ Corba]
- various Hardware-in-loop integrations
  sensor/actuator/plant HW, µprocessors, emulators, …

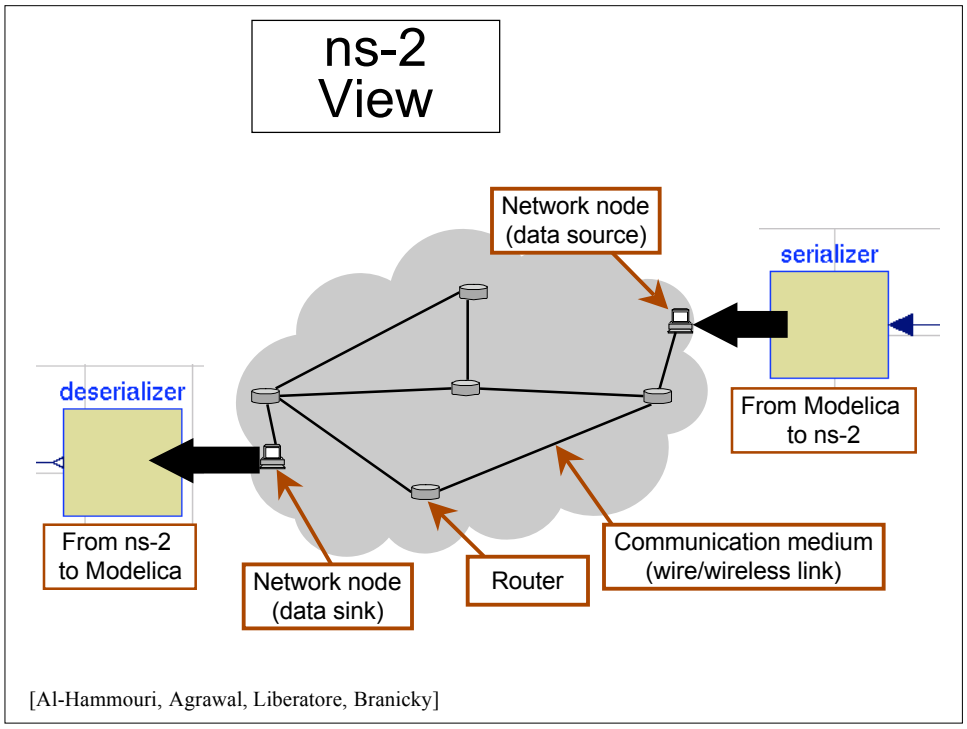
“Industrial-Strength” Co-Simulation

[On-going work: A.T. Al-Hammouri, D. Agrawal, V. Liberatore, M. Branicky]

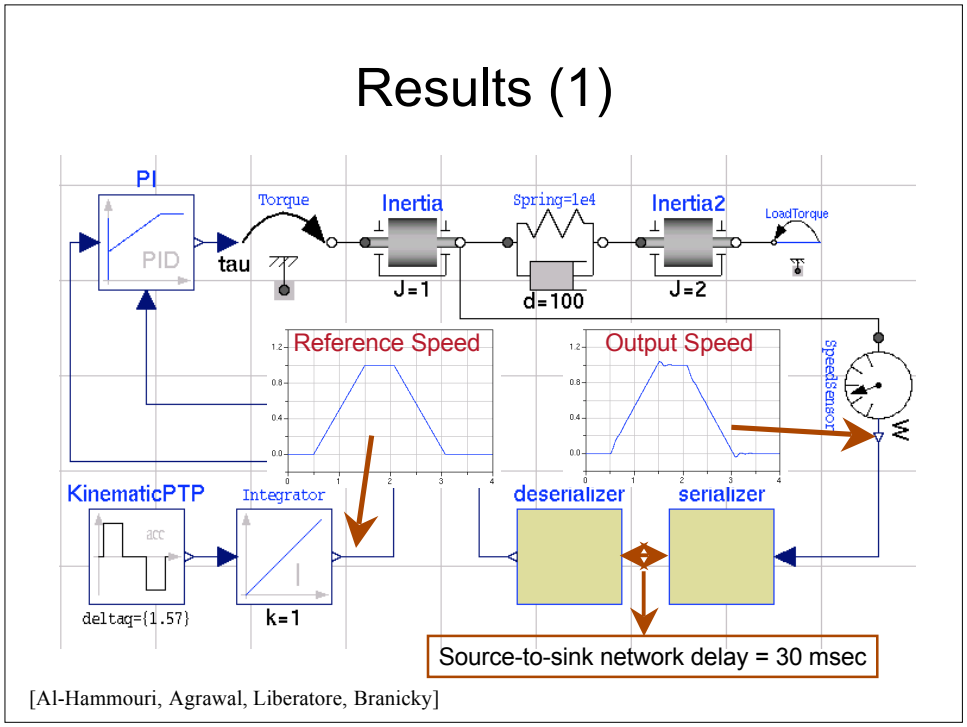
- Integrating two state-of-the-art tools:
  - ns-2 network simulator
  - Modelica language/simulation framework
- Modelica (`www.modelica.org`)
  - Modeling and simulating large-scale physical systems
  - Acausal Modeling
  - Libraries (e.g., standard, power systems, hydraulics, pneumatics, power train)
  - One free simulation environment, some commercial
- ns-2 (`www.isi.edu/nsnam/ns/`)
  - Simulate routing, transport, and application protocols over wired, wireless, local- and wide area networks



[Al-Hammouri, Agrawal, Liberatore, Branicky]

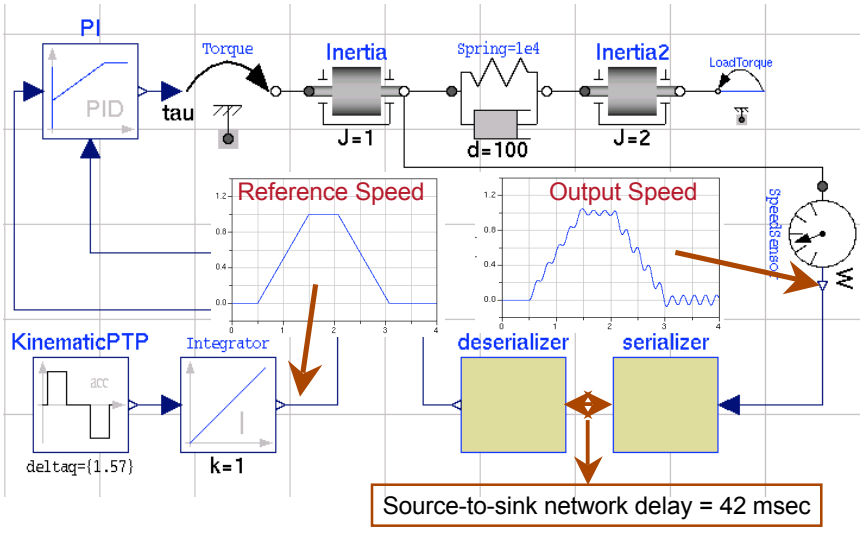


[Al-Hammouri, Agrawal, Liberatore, Branicky]



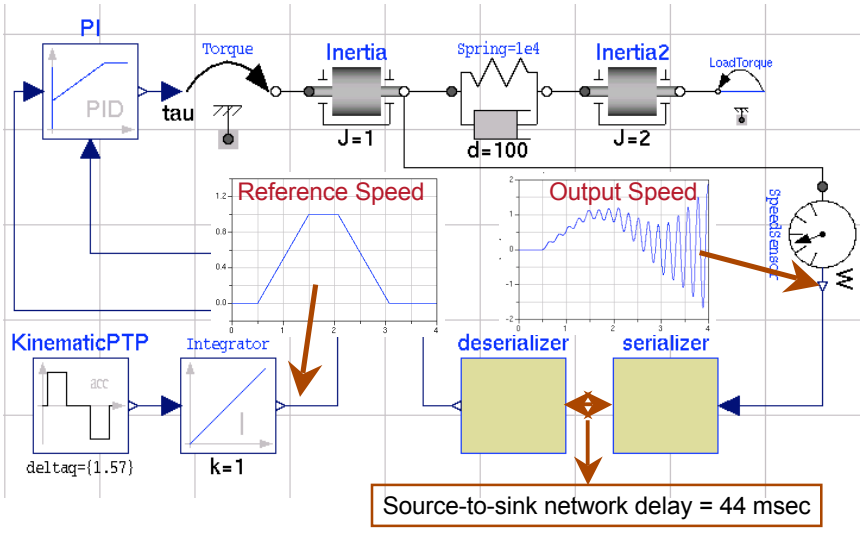
[Al-Hammouri, Agrawal, Liberatore, Branicky]

Results (2)



[Al-Hammouri, Agrawal, Liberatore, Branicky]

Results (3)

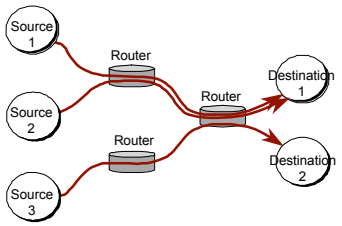


[Al-Hammouri, Agrawal, Liberatore, Branicky]

Congestion Control / BW Allocation

In general:

- Congestion caused by
  - Contention for BW w/o coordination
- Congestion control (CC)
  - Regulates sources xmit rates
  - Ensures fairness, BW efficiency
- CC facilitated by cooperation btw
  - Routers (AQM)
  - End-hosts (elastic sources)



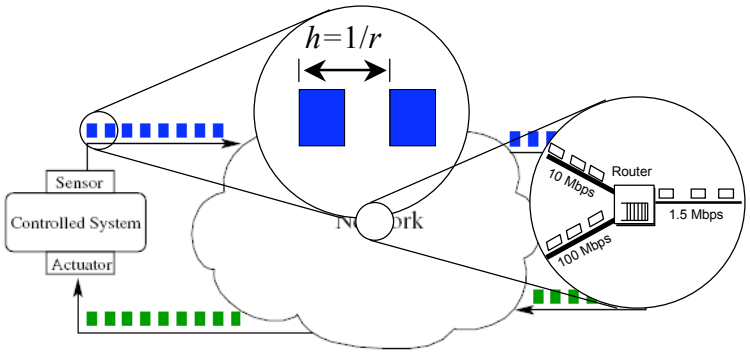
Our objectives:

- Efficiency & fairness
- Stability of control systems
- Fully distributed, asynchronous, & scalable
- Dynamic & self reconfigurable

[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

Mathematical Formulation (1)

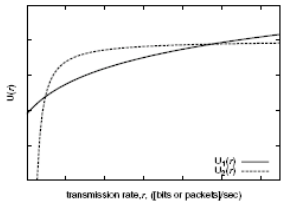
- NCSs regulate h based on congestion fed back from the network



[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

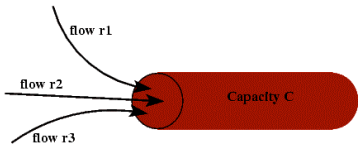
Mathematical Formulation (2)

- Define a utility fn $U(r)$ that is
  - Performance measure
  - Monotonically increasing
  - Strictly concave
  - Defined for $r \geq r_{\min}$ (Stability)



- Optimization formulation

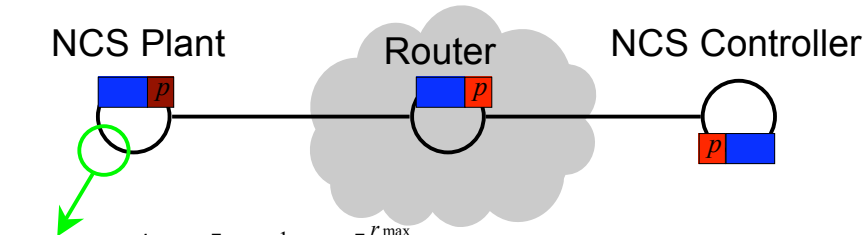
$$\max \sum_i U_i(r_i)$$
$$\text{s.t.} \sum_{i \in S(l)} r_i \leq C_l, l = 1, \ldots, L$$
$$\text{and } r_i \geq r_{\min, i}$$



[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

Distributed Implementation

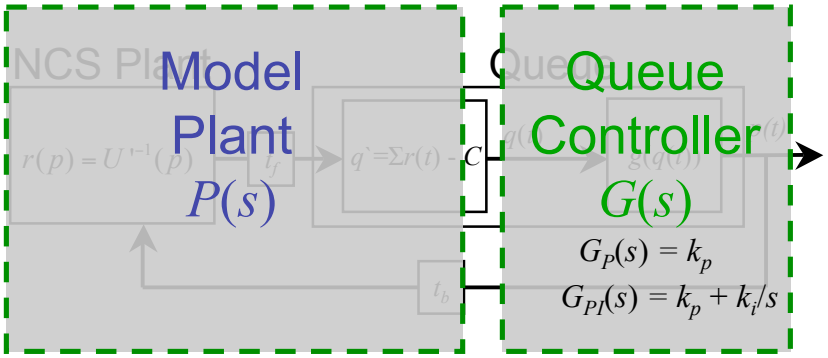
- Two independent algorithms
  - End-systems (plants) algorithm
  - Router algorithm (see refs.)



$$r(p_t) = 1/h = \left[U'^{-1}(p_t) \right]_{r\,\min}^{r\,\max}$$

[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

NCS-AQM Control Loop

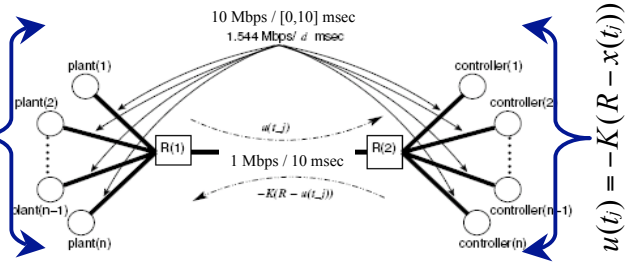


[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

Simulations & Results (1)

N NCS Plants:

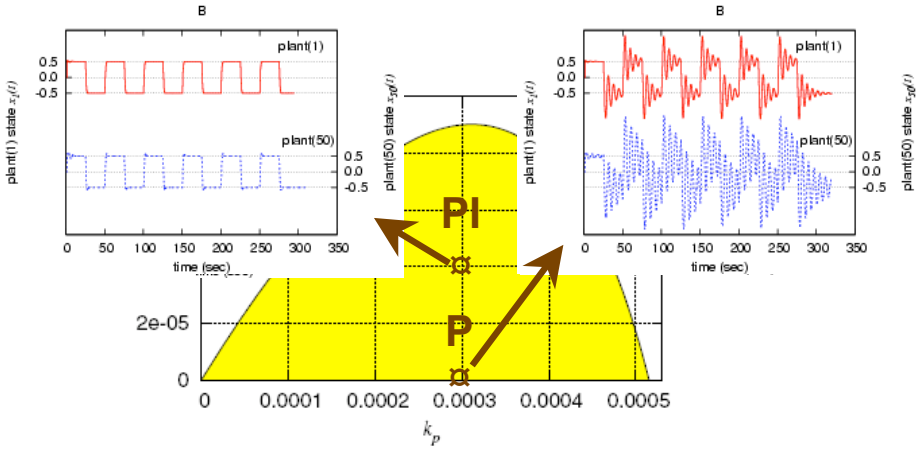
- $\frac{dx}{dt} = ax(t) + bu(t)$
- $U(r) = \frac{a - bK}{a} e^{a/r}$
- $r_{\min} = \frac{a}{\ln \frac{bK + a}{bK - a}}$



- [Branicky et al. 2002]
- [Zhang et al. 2001]

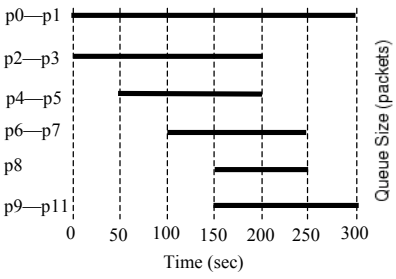
[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

Simulations & Results (2)

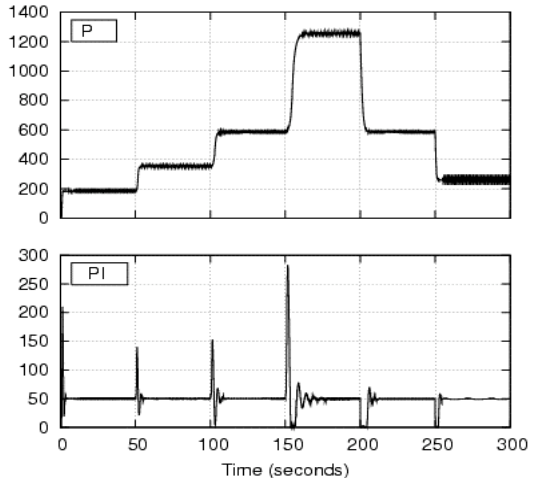


[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

Simulations & Results (3)



Note: $q_0 = 50$ pkts

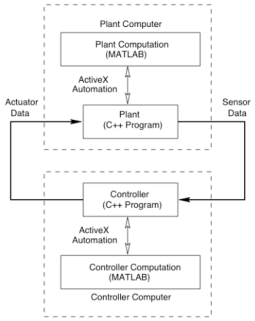


[Al-Hammouri-Branicky-Liberatore-Phillips, WPDRTS'06]
[Al-Hammouri-Liberatore-Branicky-Phillips, FeBID'06]

NCS Research Opportunities

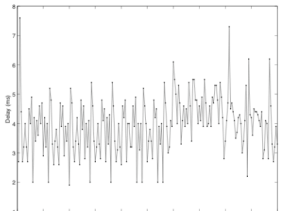
- Control theory:
  (stoch.) HS, non-uniform/stoch. samp., event- vs. time-based, hierarachical and composable (cf. Omola/Modelica), multi-timescale (months to ms)
- Delays, Jitter, Packet Loss Rates, BW
  - Characterization of networks (e.g., time-varying RTT, OWD delays)
  - Application and end-point adaptability to unpredictable delays
    - Buffers (e.g., Liberatore's PlayBack Buffers)
    - Gain scheduling, hybrid/jump-linear controllers
    - Time synchronization
- Application-oriented, end-to-end QoS (beyond stability to performance)
- Bandwidth allocation, queuing strategies, network partitioning
  - Control theoretical, blank-slate designs, Stankovic's *SP protocols
- Co-Design and Co-Simulation Tools
- Distributed, real-time embedded Middleware:
  - Resource constraints vs. inter-operability and protocols
  - Sensors/transducers (cf. IEEE 1451, LXI Consortium), distributed timing services (IEEE 1588 PTP, NTP; Eidson: "Time is a first-class object"), data gathering (Sha's "observability"), resource management (discovery, "start up"), "certificates"
- Applications:
  - power systems, robotics, & haptics/tele-surgery (Case); manufacturing, T&M, …

Ex.: Control Over CWRU Network

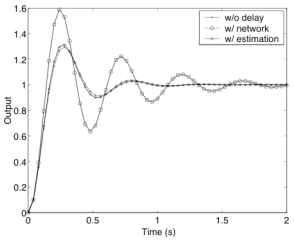


Experimental Setup

RTTs



Scaled Step Responses

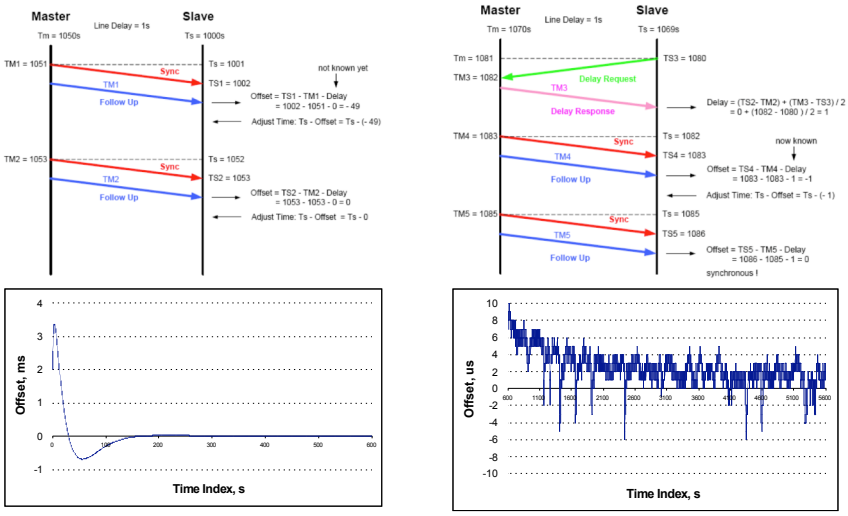


Need: Clock Synchronization

[Zhang, PhD Thesis, CWRU, '01]

IEEE 1588: Precision Time Protocol

[Dirk S. Mohl's "IEEE 1588--Precise Time Synchronization" (top row); Correll-Barendt-Branicky, *IEEE-1588 Conf.* '05 (bottom row)]



PTPd (software-only PTP) Slave Offset: 0-10 min (l), 10-90 min (r)

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  - Prof. Vincenzo Liberatore (CS, Case)
  - Prof. Stephen M. Phillips (EE, ASU)
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  - Justin Hartman (MS 2004)
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  - Nick Barendt (VXI Technology)

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  - Department of Commerce TOP 39-60-04003
  - Department of Energy DE-FC26-06NT42853
  - Lockheed-Martin
  - Cleveland State University

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