CPS: Medium: Collaborative Research: Co-Design of Multimodal CPS Architectures and Adaptive Controllers

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Objective

Efficient implementation of multiple control applications in a Network Control System (NCS)

Rationale

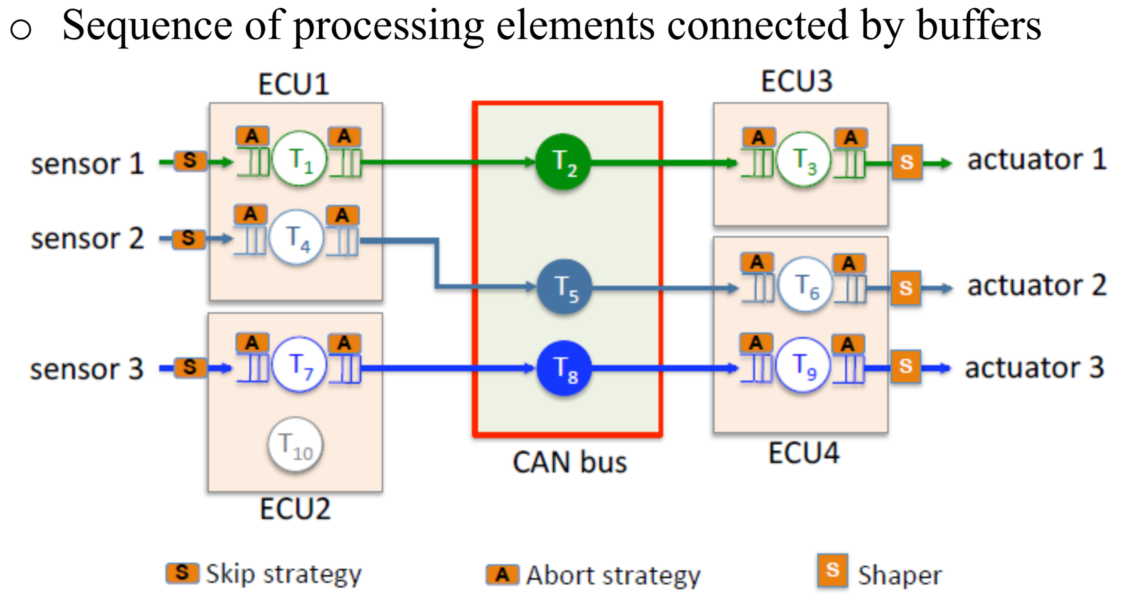
- Several complex systems consist of multiple control and non-control applications mapped onto a NCS
- Resource sharing introduces delays
- Significant transparency and flexibility available in platform design
- Powerful analytical methods exist both for stability of switched delay-systems in control theory and for estimation of end-to-end delays in real-time calculus
- Co-design of control and platform can leverage these methods

Problem Statement

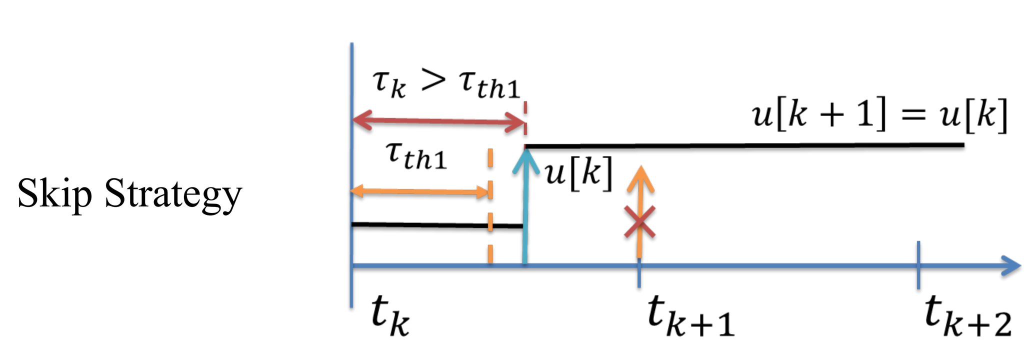
- Control multiple applications with shared resources
- Co-design of controllers and implementation platform
- Approach – ANCS (Arbitrated Network Control Systems)
  - use of arbitration and an overrun framework for skipping/aborting messages
  - stability analysis of switched systems
  - automata models and verification-based analysis

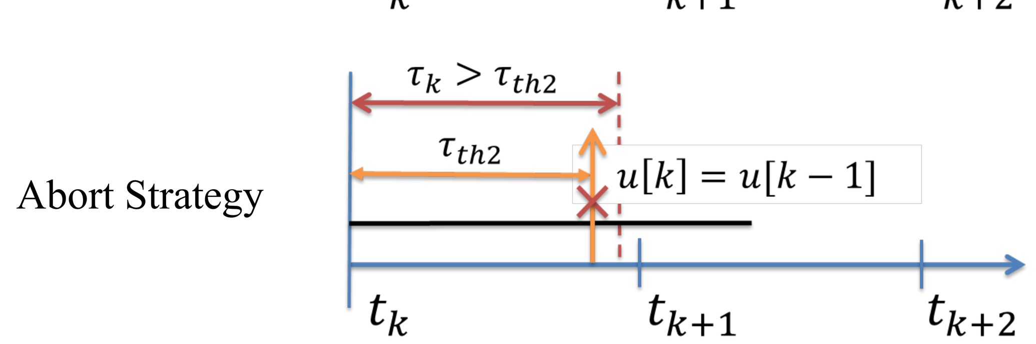
Platform Architecture

- Sequence of processing elements connected by buffers



- Skip and abort manages delays experienced by messages





Overrun Framework

Overrun Strategies

- Nominal Mode
  - stabilizing controller (ex. LQR)
- Skip Strategy

  If delay exceeds a small threshold τ_{th1}, skip next message
  - $u[k] = u_{LQR}[k]$, if $\tau_k \leq \tau_{th1}$ $X[k+1] = \Gamma_n X[k]$
  - $u[k+1] = u[k]$, if $\tau_k > \tau_{th1}$ $X[k+2] = \Gamma_s X[k]$
- Abort Strategy

  If delay exceeds a large threshold τ_{th2}, abort computations of current message
  - $u[k] = u_{LQR}[k]$, if $\tau_k \leq \tau_{th1}$ $X[k+1] = \Gamma_n X[k]$
  - $u[k] = u[k-1]$, if $\tau_k > \tau_{th2}$ $X[k+1] = \Gamma_a X[k]$

Stability with Skip and Abort Strategies

Theorem: The system

$$X[k+N] = \Gamma_a^{s_p}\Gamma_s^{j_p}\Gamma_n^{i_p} \cdots \Gamma_a^{r_1}\Gamma_s^{j_1}\Gamma_n^{i_1} X[k]$$

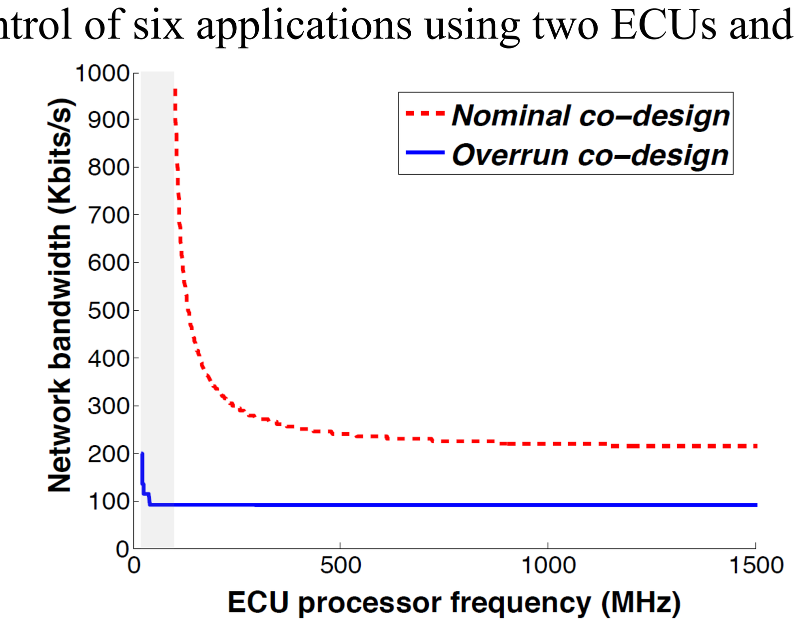
is stable if

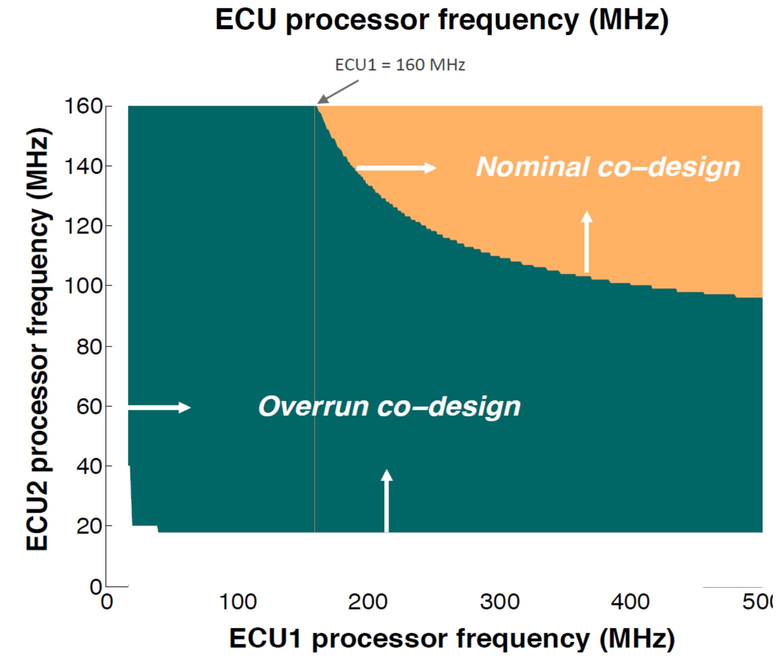
$$\gamma \overset{\text{def}}{=} \gamma_n^{1-2r_{skip}-r_{abort}} \gamma_s^{r_{skip}} \gamma_a^{r_{abort}} \leq 1,$$

where γ_n, γ_s, and γ_a are the combined decay rates of the system in nominal, skip, and abort modes, and r_{skip} and r_{abort} are maximum skip and abort rates, respectively.

Case Study

- Control of six applications using two ECUs and a CAN bus



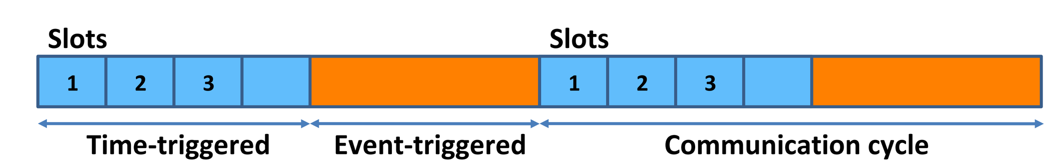


- Co-design computes τ_{th1} and τ_{th2}
- Desired control performance achieved for all applications
- Co-design can result in significant reduction in bandwidth requirements-anywhere between 40% and 90%

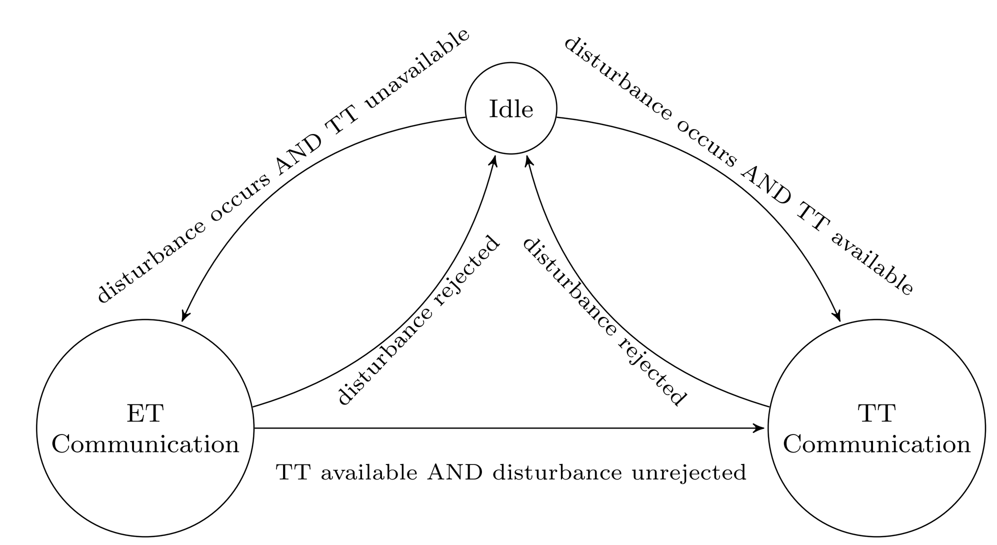
Non-Monotonicity of System Dynamics

Hybrid communication protocols such as Flexray are often used in DES.

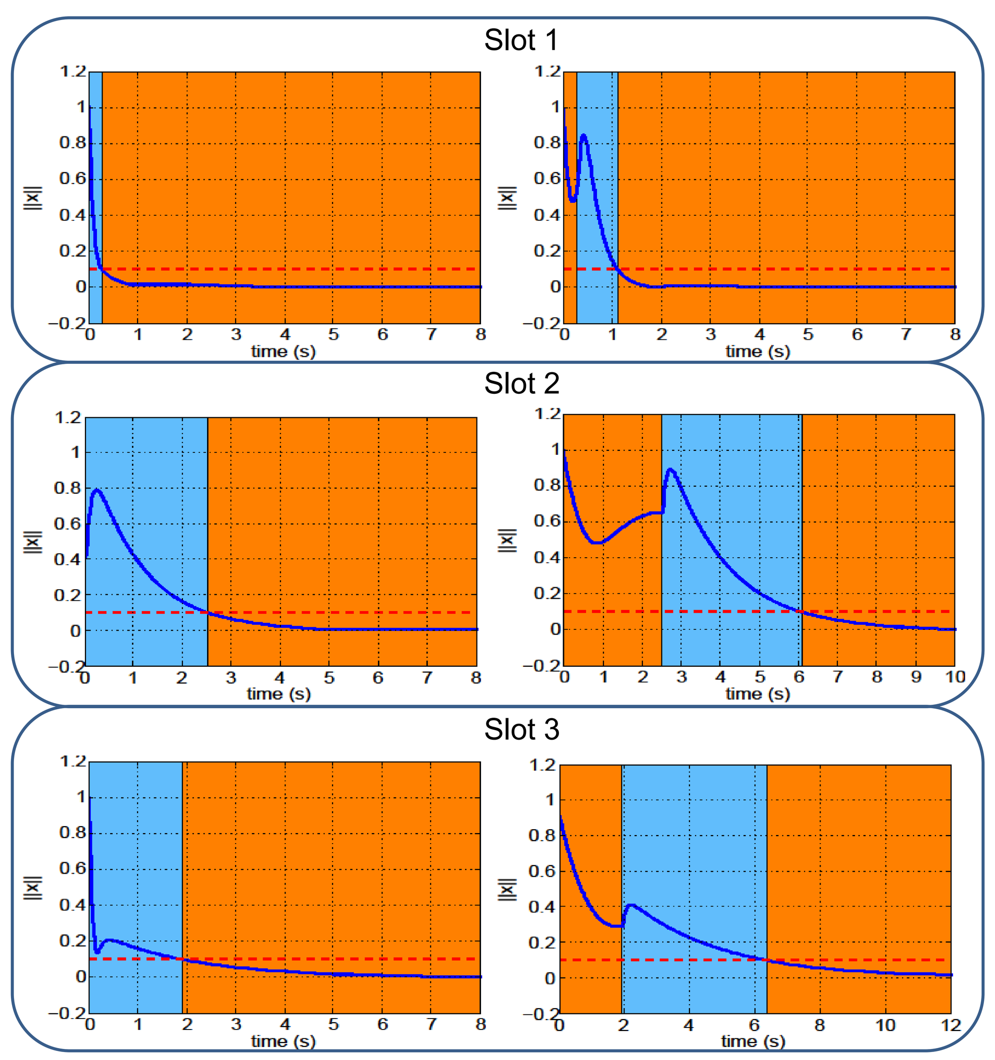
- Messages are sent through segments



We propose a co-design that uses information from closed-loop responses to determine an efficient resource utilization for control systems under hybrid communication protocols.



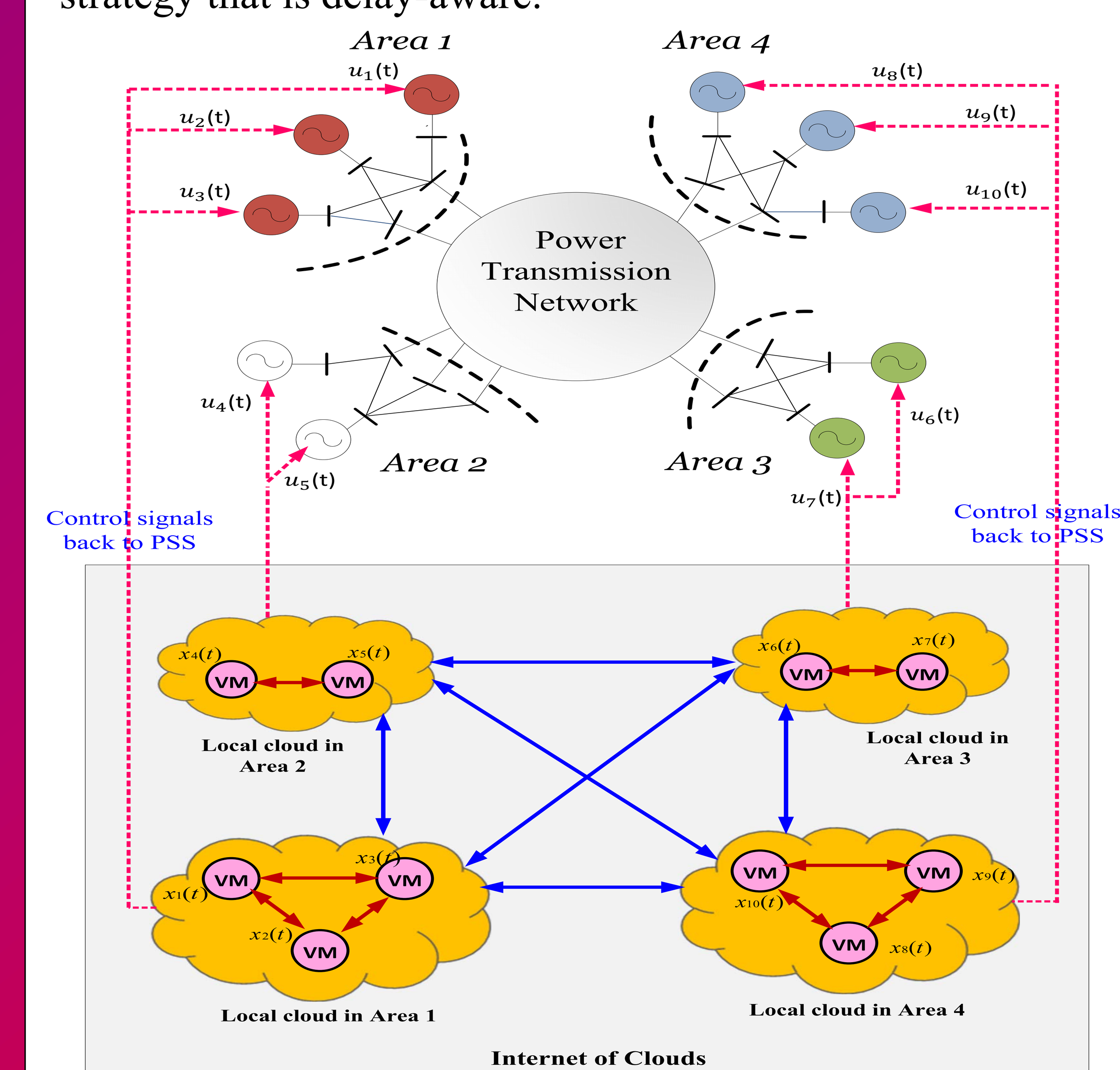
- Used multi-mode control structure
- Analyzed systems with non-monotonic behavior
  - Leads to a less conservative schedulability analysis.



- Simulation using Truetime + Simulink
- For 6 non-monotonic control applications:
  - Our approach: 3 slots
  - Monotonic upper-bound: 5 slots
- Reduced number of TT slots compared to those based on monotonic upper-bound

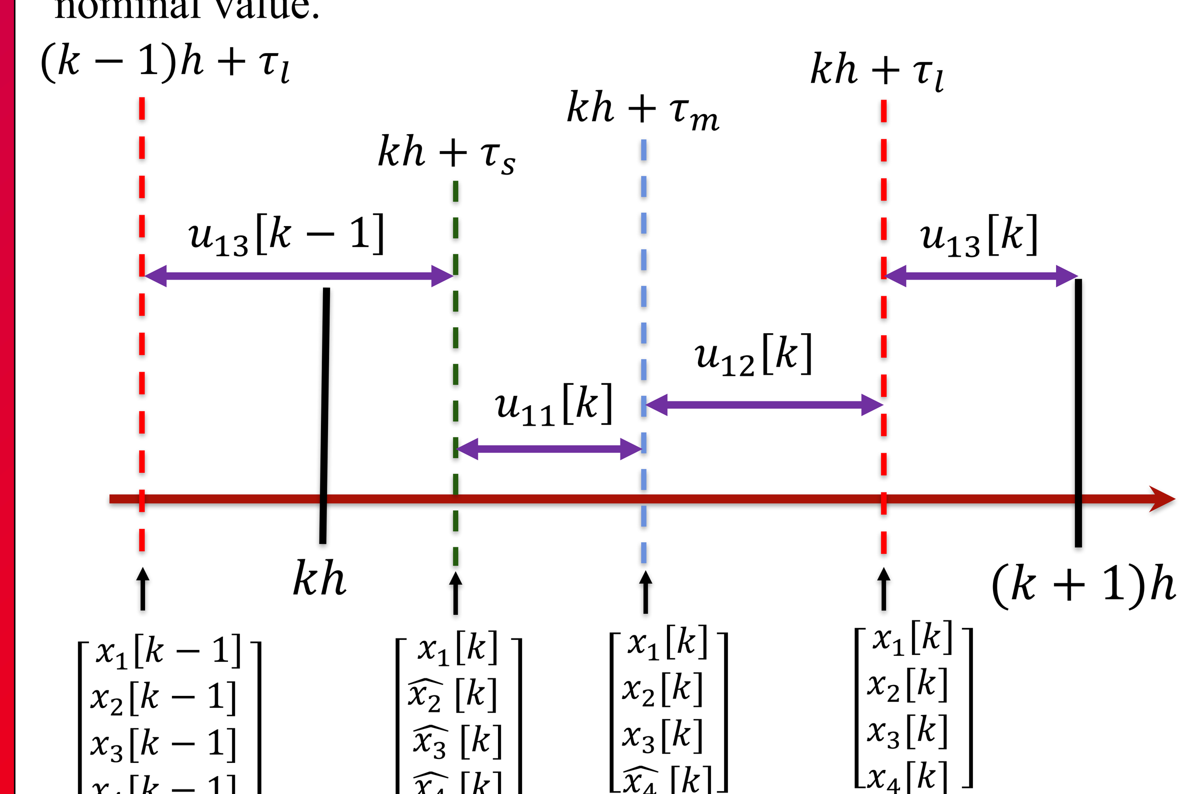
Application to Wide Area Control

Wide-area control of power grids helps in suppression of undesired oscillations in power flows, but requires real-time feedback of large volumes of PMU data from one operating region of the grid to controllers located at other regions. We have developed a novel cyber-physical architecture that utilizes distributed PMU measurements, cloud computation using a virtual machine, and an arbitrated network control strategy that is delay-aware.



The Delay-Aware ANCS

Using Real-Time Calculus (RTC), we estimate the local delay τ_s, the intra-area delay τ_m, and the inter-area delays τ_l. The control strategy is delay-aware, uses the estimates of signals until they arrive at the actuator-location, and aborts the message if it arrives with a delay larger than its nominal value.



Acknowledgement

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