CPSL
Cyber-Physical Systems Laboratory

Real-Time Wireless Control Networks for Cyber-Physical Systems

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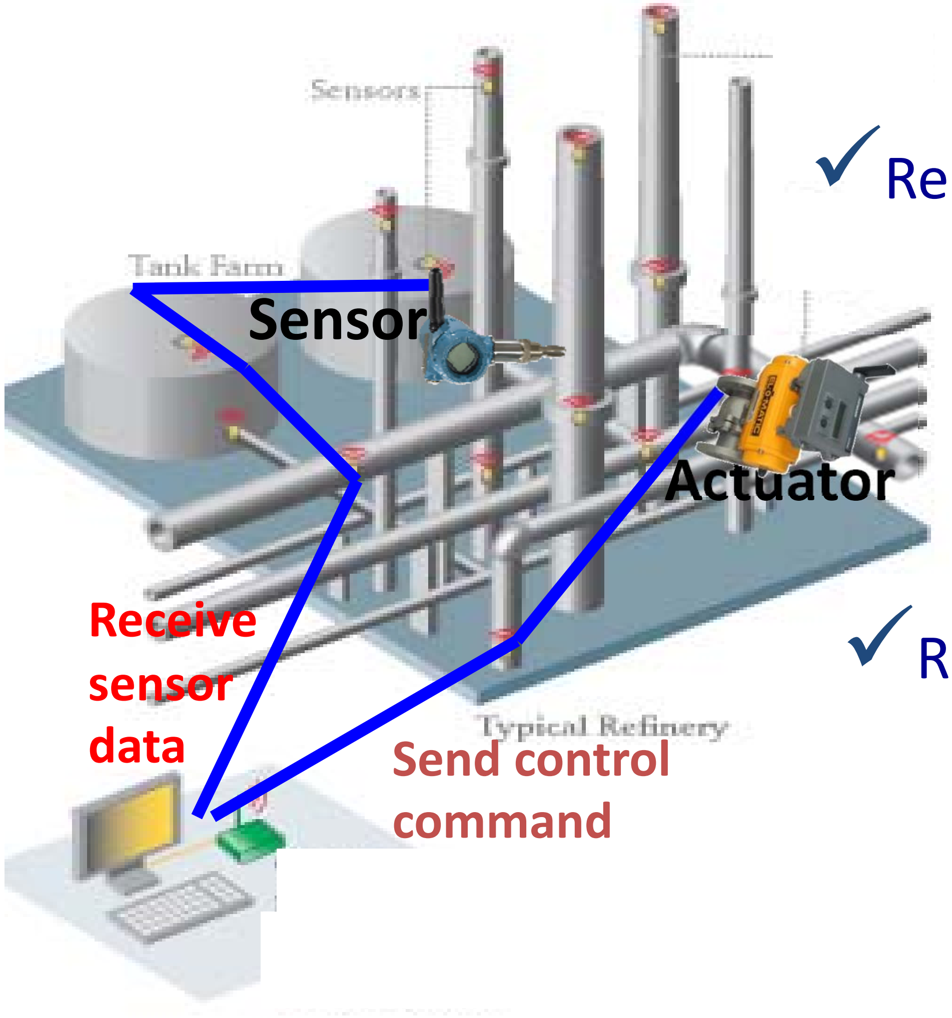
Wireless Control Networks



Sensor

Actuator

Receive sensor data

Send control command

✓ Real-time

✓ Reliability

✓ Control performance

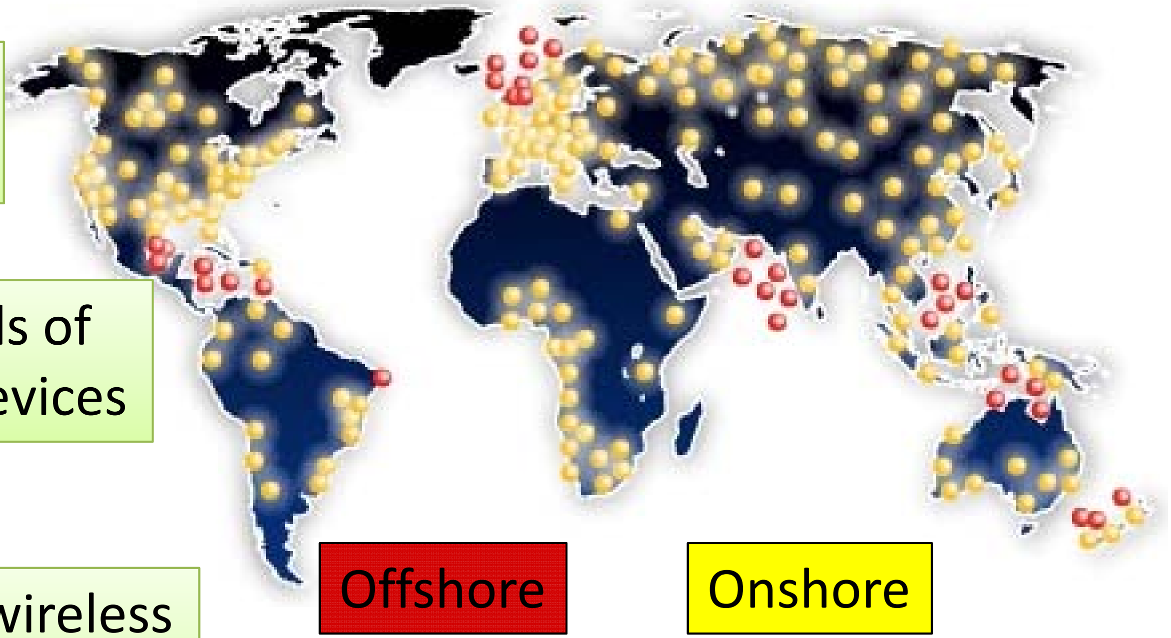
Wireless for Process Automation

- World-wide adoption of wireless in process industries

1.5+ billion hours operating experience

Hundreds of thousands of smart wireless field devices

Tens of thousands of wireless field networks



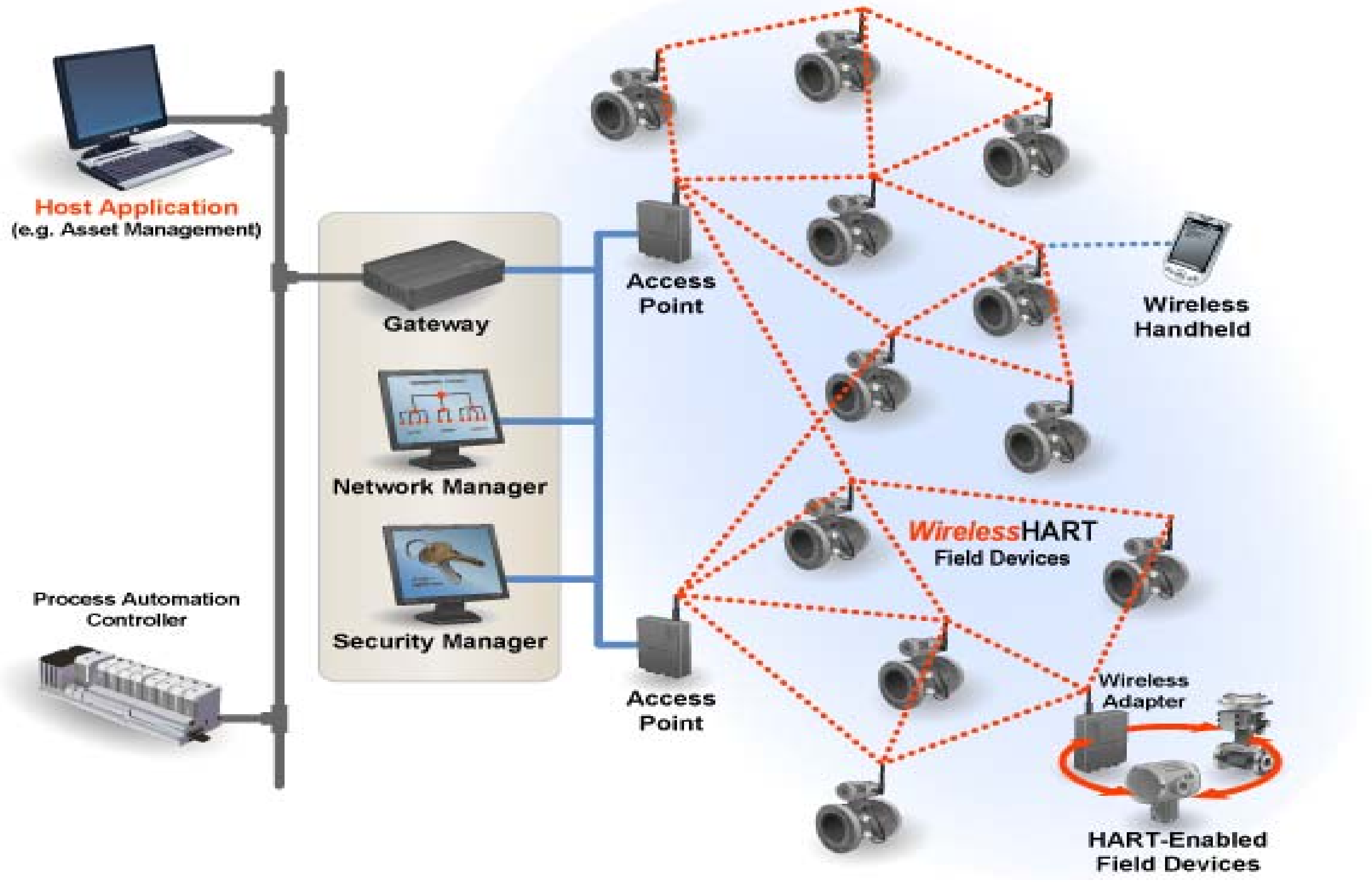
Courtesy: Emerson Process Management

Outline

- WirelessHART: real-time wireless in industry
- Real-time scheduling theory for wireless
- Wireless-control co-design
- Case study: wireless structural control

WirelessHART

Industrial wireless standard for monitoring and control



Characteristics

- Reliable in hash industrial environments
  - ❑ Time Division Multiple Access
  - ❑ Multi-channel
  - ❑ No concurrent transmission in a same channel
  - ❑ Route diversity

- Centralized network manager
  - ❑ Collects topology information from the network
  - ❑ Generates routes and global transmission schedule
  - ❑ Reconfigures when devices/links break

Real-Time Scheduling for Wireless

Goals

- Real-time transmission scheduling → meet end-to-end deadlines
- Fast schedulability analysis → online admission control and adaptation

Approach

- Leverage real-time scheduling theory for processors
- Incorporate wireless characteristics

Results

- Dynamic priority scheduling [RTSS 2010]
- Fixed priority scheduling
  - ☐ End-to-end delay analysis [RTAS 2011]
  - ☐ Priority assignment [ECRTS 2011]

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Real-Time Flows

- Flow: sensor → controller → actuator over multi-hops

- A set of flows $F=\{\overset{\substack{\text{highest}\\ \uparrow}}{F_1}, F_2, \ldots, \overset{\substack{\text{lowest priority}\\ \uparrow}}{F_N}\}$ ordered by priorities

- Each flow F_i is characterized by
  - A source (sensor), a destination (actuator)
  - A route through the controller
  - A period P_i
  - A deadline D_i ($\le P_i$)
  - Total number of transmissions C_i along the route

Scheduling Problem

- Fixed priority scheduling
  - ☐ Every flow has a fixed priority
  - ☐ Order transmissions based on the priorities of their flows.

end-to-end delay of F_i

$\uparrow$

- Flows are schedulable if $R_i \leq D_i$ for every flow F_i

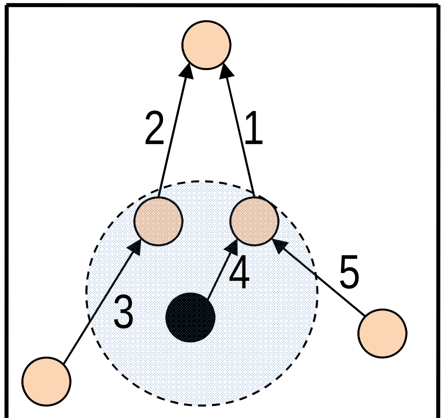
$\downarrow$

deadline of F_i

- Goal: efficient delay analysis
  - ☐ Gives an upper bound of the end-to-end delay for each flow
  - ☐ Used for online admission control and adaptation

End-to-End Delay Analysis

- A lower priority flow is delayed due to
  - ☐ channel contention: all channels in a slot are assigned to higher priority flows
  - ☐ transmission conflict: two transmissions involve a same node



1 and 5 are conflicting
4 and 5 are conflicting

3 and 4 are conflict-free

- Analyze each type of delay separately

- Combine both delays → end-to-end delay bound

Insights

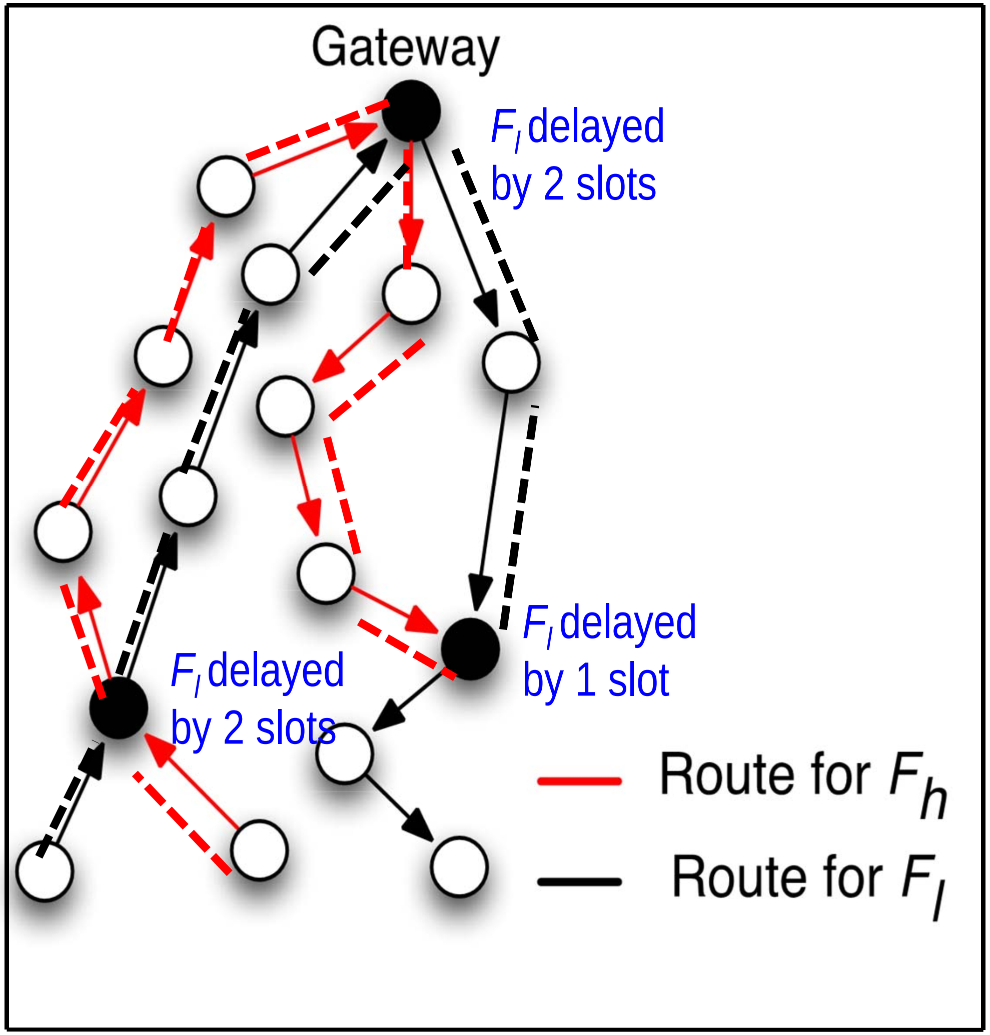
- Flows vs. Tasks
  - Similar: channel contention
  - Different: transmission conflict

- Channel contention → multiprocessor scheduling
  - A channel → a processor
  - Flow F_i → a task with period P_i, deadline D_i, execution time C_i
  - Leverage existing response time analysis for multiprocessors

- Need to account for delays due to transmission conflicts

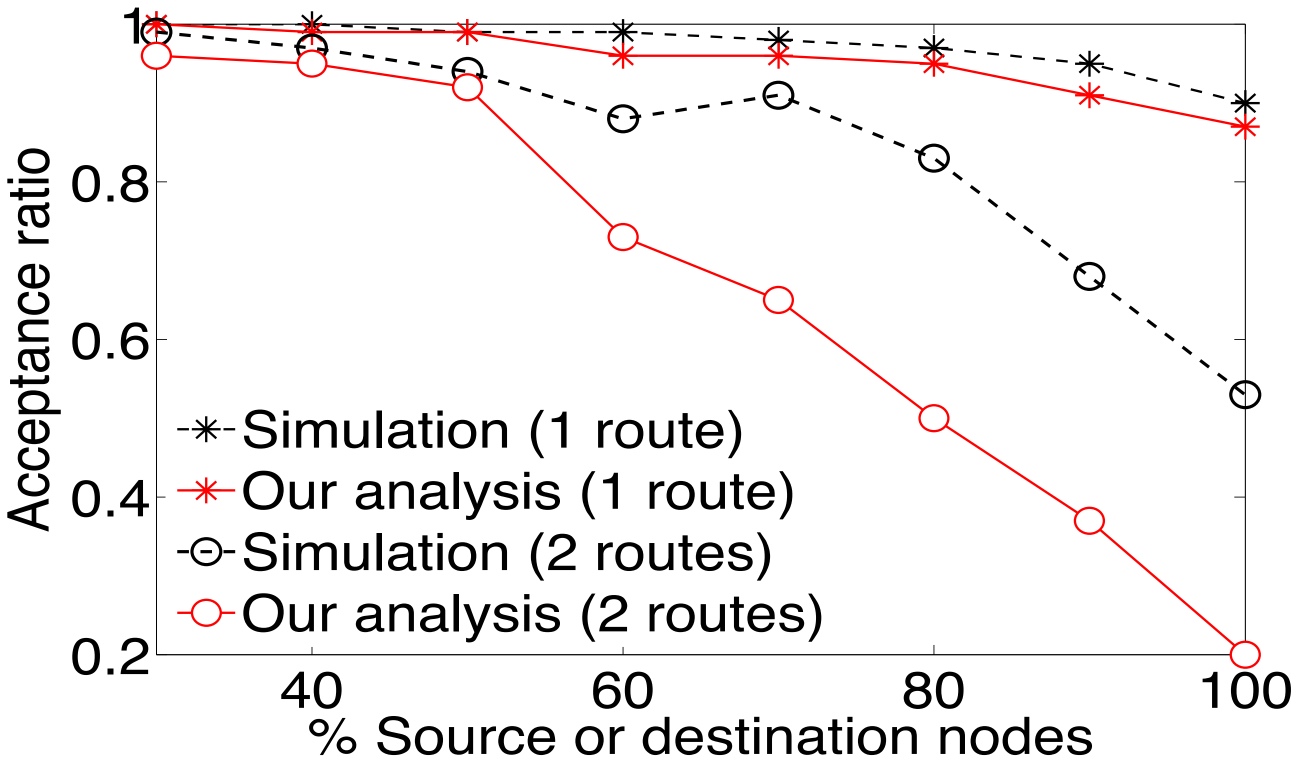
Delay due to Conflict

- Low-priority flow F_l and high-priority flow F_h, conflict → delay F_l
- $Q(l,h)$: #transmissions of F_h sharing nodes with F_l
  - In the worst case, F_h can delay F_l by $Q(l,h)$ slots
  - $Q(l,h) = 5$ → F_h can delay F_l by 5 slots



Acceptance Ratio

Fraction of test cases deemed schedulable based on analysis vs. simulations



Wireless-Control Co-Design

Goal: optimize control performance over wireless

Challenge

- Wireless resource is scarce and dynamic
- Cannot afford separating wireless and control designs

Cyber-Physical Systems Approach

- Holistic co-design of wireless and control

Examples

- Rate selection for wireless control [RTAS 2012, TECS]
- Wireless structural control [ICCPS 2013]

Rate Selection for Wireless Control

- Optimize the sampling rates of control loops sharing a WirelessHART network.

- Rate selection must balance control and network delay
  - ☐ Low sampling rate → poor control performance
  - ☐ High sampling rate → long delay → poor control performance

Control Performance Index

- Digital implementation of control loop i
  - ❑ Periodic sampling at rate f_i
  - ❑ Performance deviates from continuous counterpart
- Control cost of control loop i under rate f_i [Seto RTSS'96]
  - ❑ Approximated as $\alpha_i e^{-\beta_i f_i}$ with sensitivity coefficients α_i, β_i
- Overall control cost of n loops: $\sum_{i=1}^{n} \alpha_i e^{-\beta_i f_i}$

The Rate Selection Problem

- Formulated as a constrained non-linear optimization
- Determine sampling rates $f = \{f_1, f_2, \cdots, f_n\}$ to

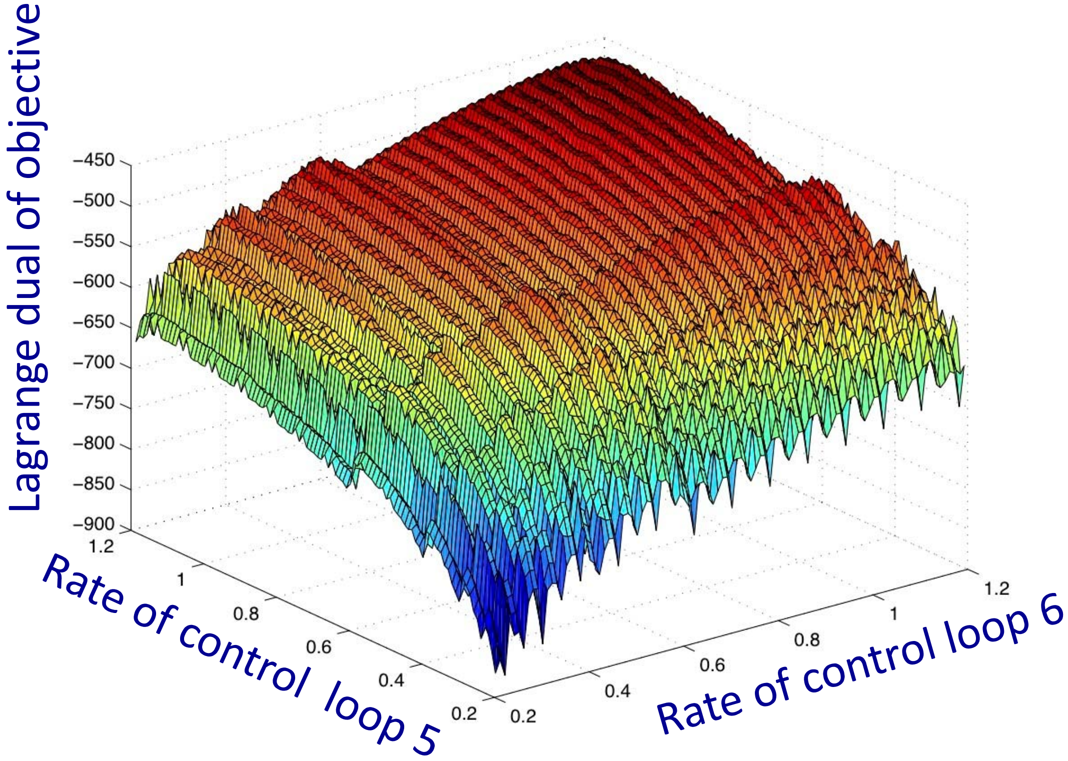
Minimize control cost $\sum_{i=1}^{n} \alpha_i e^{-\beta_i f_i}$

subject to $\boxed{R_i \le 1/f_i}$ *Delay bound*

$$f_i^{min} \le f_i \le f_i^{max}$$

Polynomial Time Delay Bounds

- In terms of decision variables (rates), the delay bounds are
  - ☐ Non-linear
  - ☐ Non-convex
  - ☐ Non-differentiable

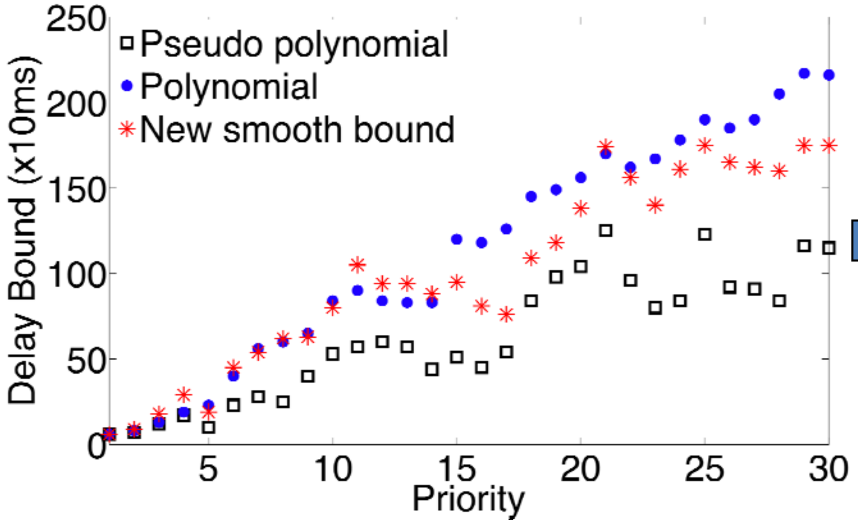


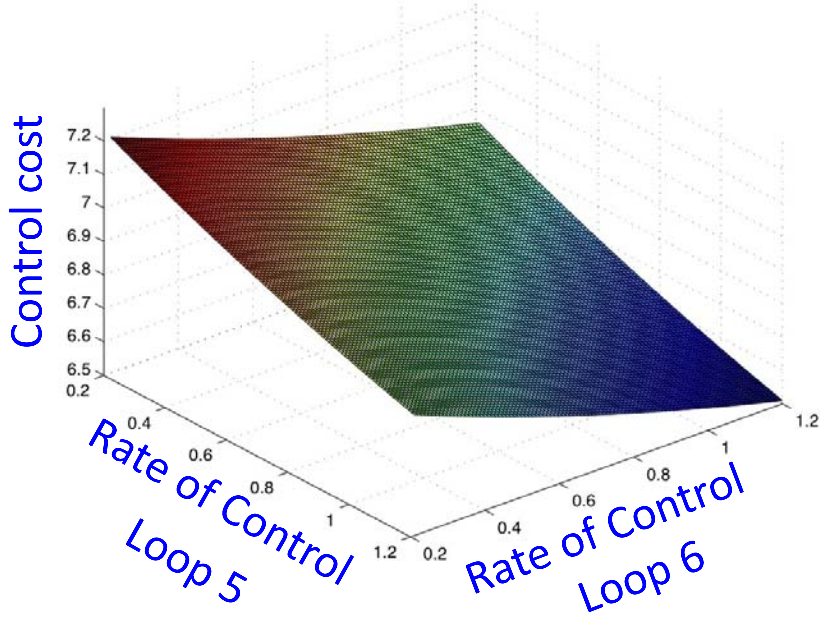
The optimization problem is thus non-convex, non-differentiable, not in closed form

Scheduling-Control Co-Design

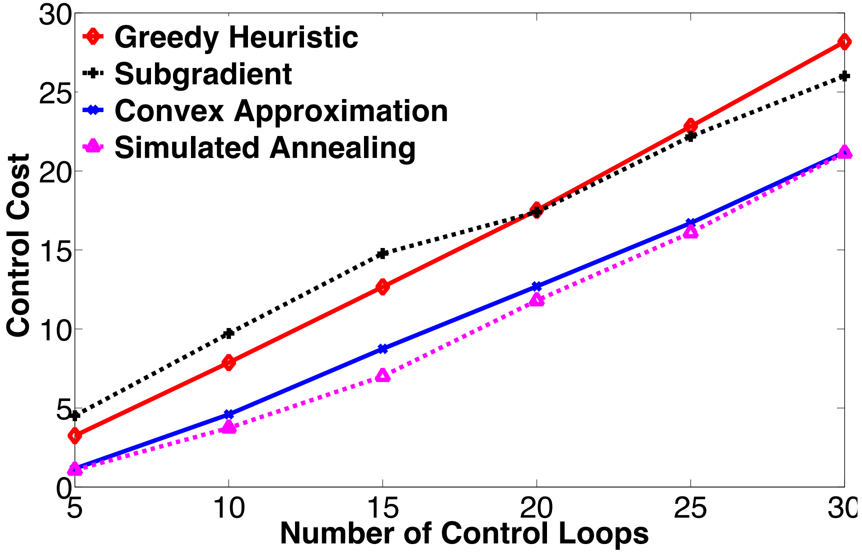
Relax delay bound to simplify optimization!

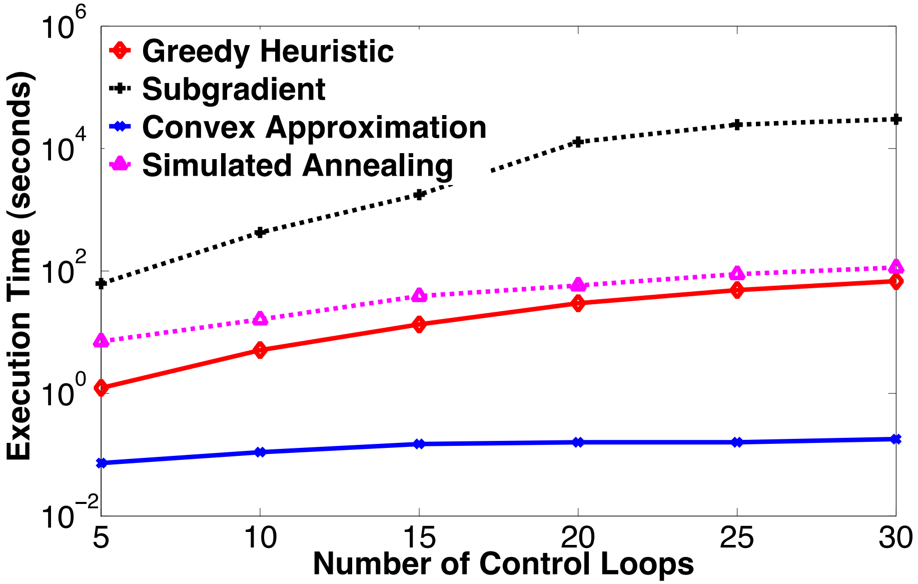
- Derive a convex and smooth, but less precise delay bounds.
- Rate selection becomes a convex optimization problem.





Evaluation





- ❑ Greedy heuristic is fast but incurs high control cost.
- ❑ Subgradient method is neither efficient nor effective.
- ❑ Simulated annealing incurs the lowest control cost, but takes a long time.
- ❑ Convex approximation balances control cost and execution time.

Case Study: Wireless Structural Control

- Structural control systems protect civil infrastructure.
- Wired control systems are costly and fragile.
- Wireless structural control (WSC) offers flexibility and low cost.

Heritage tower crumbles down in earthquake of Finale Emilia, Italy, 2012.

Hanshin Expressway Bridge after Kobe earthquake, Japan, 1995.

Contributions [ICCPS 2013]

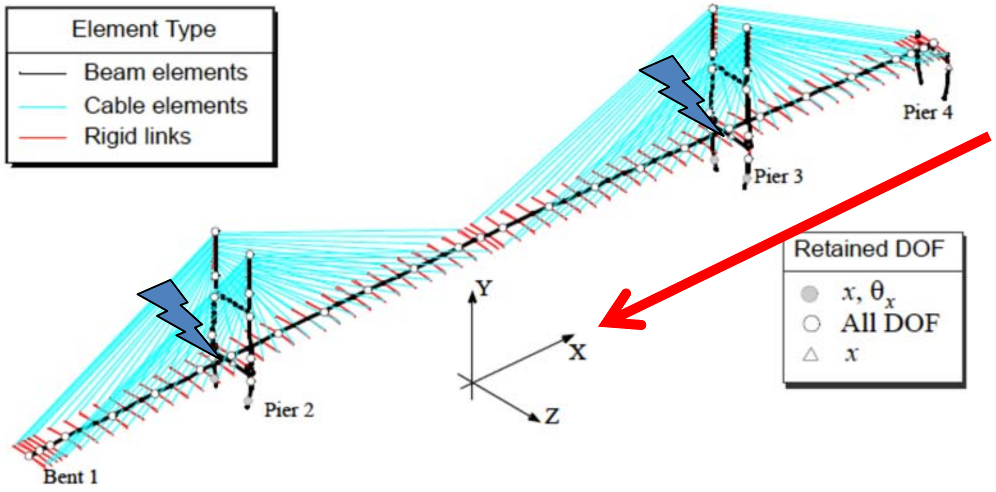
- Wireless Cyber-Physical Simulator (WCPS)
  - ☐ Capture dynamics of both physical plants and wireless networks
  - ☐ Enable holistic, high-fidelity simulation of wireless control systems
  - ☐ Integrate TOSSIM and Simulink/MATLAB
  - ☐ Open source: http://wcps.cse.wustl.edu

- Realistic case studies on wireless structural control
  - ☐ Wireless traces from real-world environments
  - ☐ Structural models of a building and a large bridge
  - ☐ Excited by real earthquake signal traces

- Cyber-physical co-design
  - ☐ End-to-end scheduling + control design
  - ☐ Improve control performance under wireless delay and loss

Bill Emerson Memorial Bridge: Physical Model

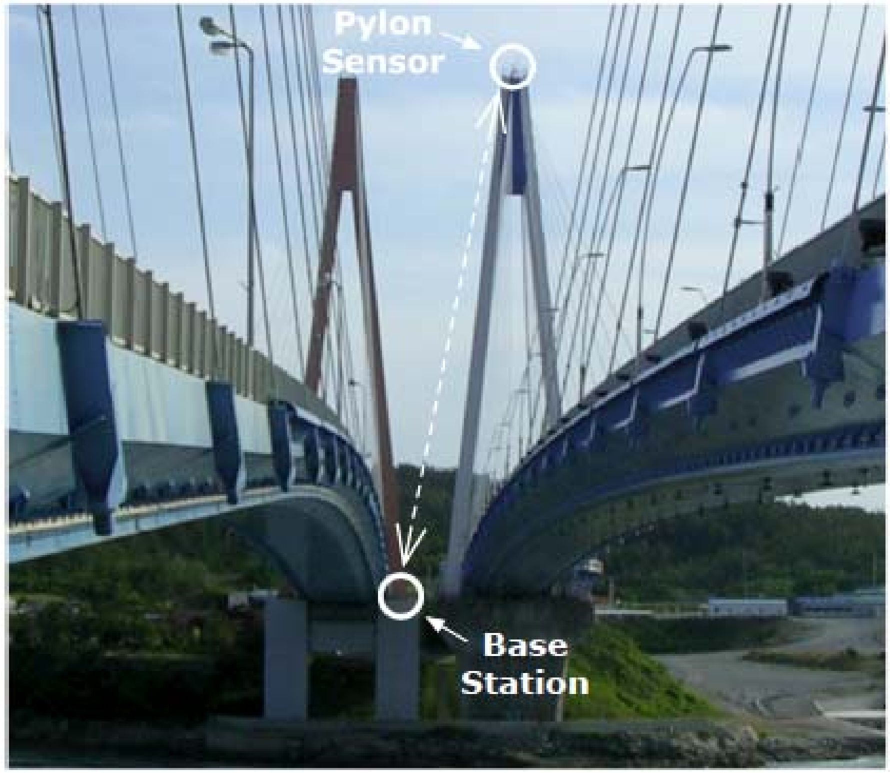
(a)



(b)

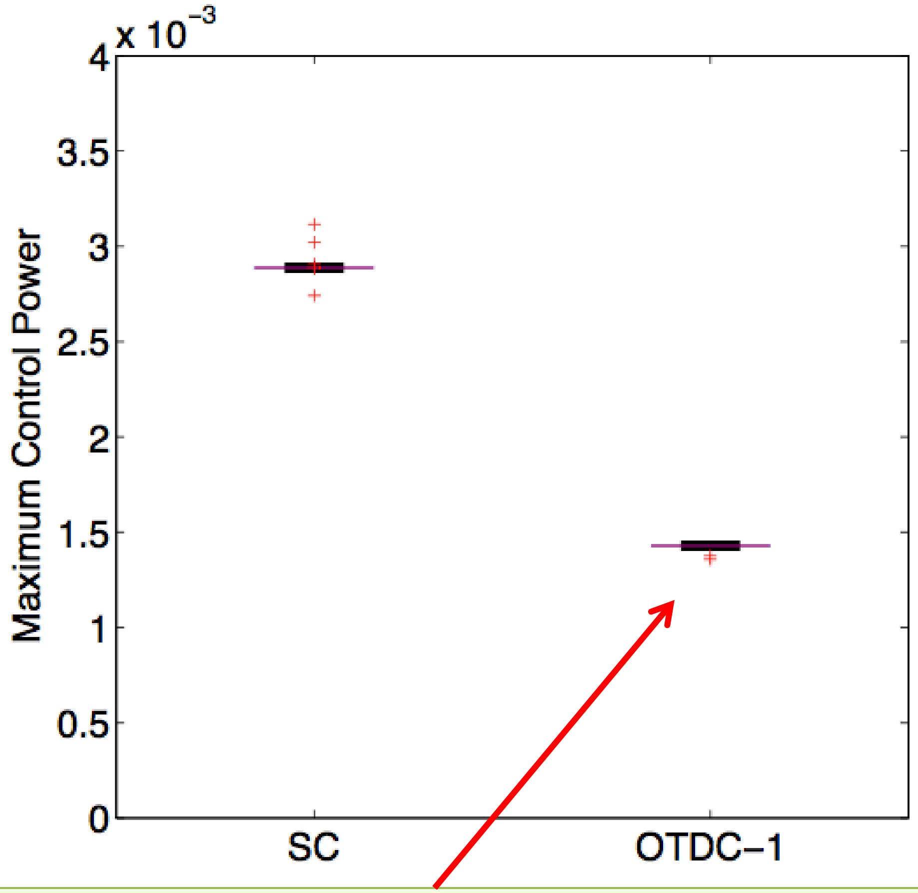
- ➢ Main span: 1,150 ft.
- ➢ Carries up to 14,000 cars a day over the Mississippi River.
- ➢ In the New Madrid Seismic Zone
- ➢ Replaced joints of the bridge by actuators
  - ❑ 24 hydraulic actuators
- ➢ Vibration mode:
  - ❑ 0.1618 Hz for 1st mode
  - ❑ 0.2666 Hz for 2nd mode
  - ❑ 0.3723 Hz for 3rd mode

Jindo Bridge: Wireless Traces



- Largest wireless bride deployment [Jang 2010]
  - ❑ 113 Imote2 units; Peak acceleration sensitivity of 5mg – 30mg
- RSSI/noise traces from 58-node deck-network for this study

Reduction in Max Control Power



Cyber-physical co-design → 50% reduction in control power.

Conclusion

- Real-time wireless is a reality today
  - Industrial standards: WirelessHART, ISA100
  - Field deployments world wide
- Real-time scheduling theory for wireless
  - Leverage real-time processor scheduling
  - Incorporate unique wireless properties
- Cyber-physical co-design of wireless control systems
  - Rate selection for wireless control systems
  - Scheduling-control co-design for wireless structural control
- WCPS: Wireless Cyber-Physical Simulator
  - Enable holistic simulations of wireless control systems
  - Realistic case studies of wireless structural control

Future Directions

- Scaling up wireless control networks
  - ❑ From 100 nodes → 10,000 nodes
  - ❑ Dealing with dynamics locally
  - ❑ Hierarchical or decentralized architecture

- A theory and practice for wireless control
  - ❑ From case studies to unified theory and methodology
  - ❑ Bridge the gap between theory and systems
  - ❑ Theory → robust implementation → deployment

For More Information

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  - Wireless Cyber-Physical Simulator: http://wcps.cse.wustl.edu