

Real-Time Wireless Control Networks for Cyber-Physical Systems

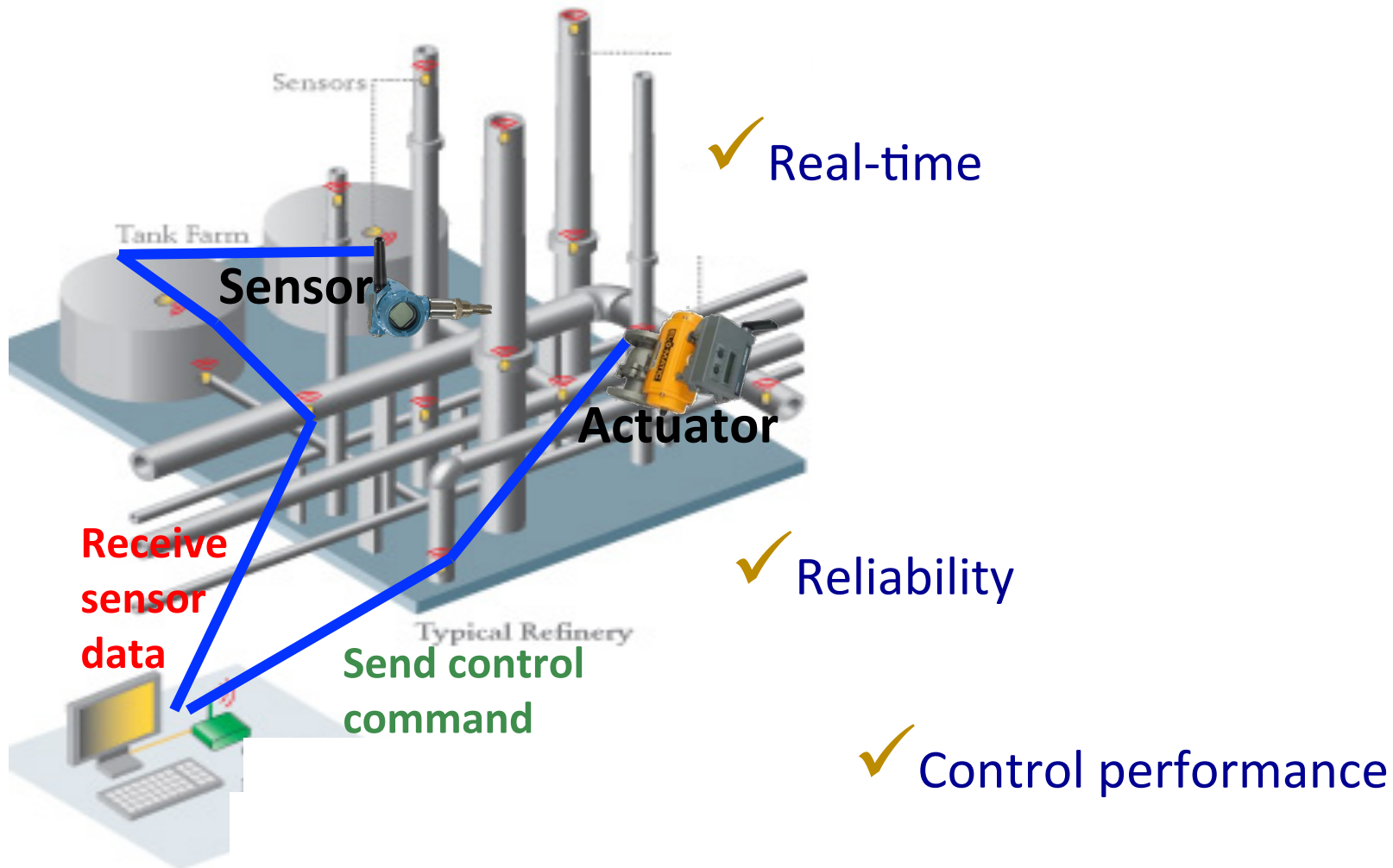
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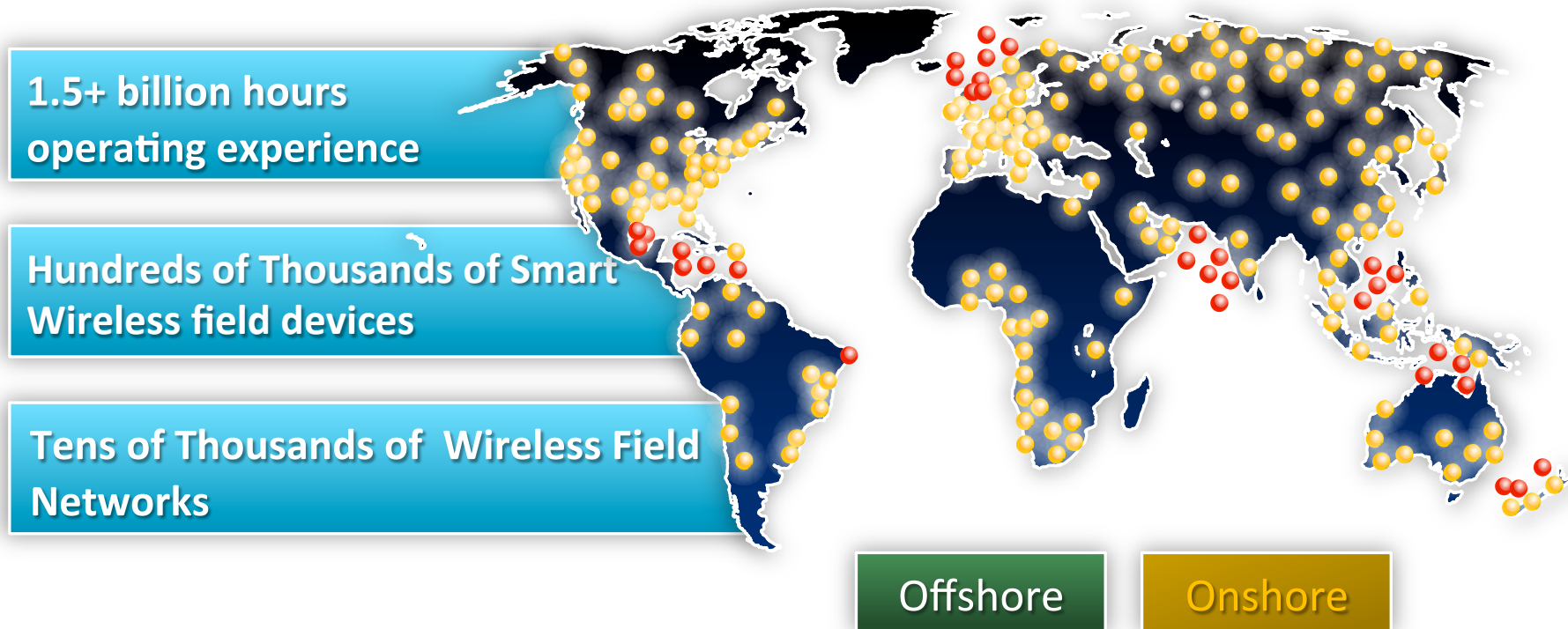
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Wireless Control Networks



Industrial Wireless Networks



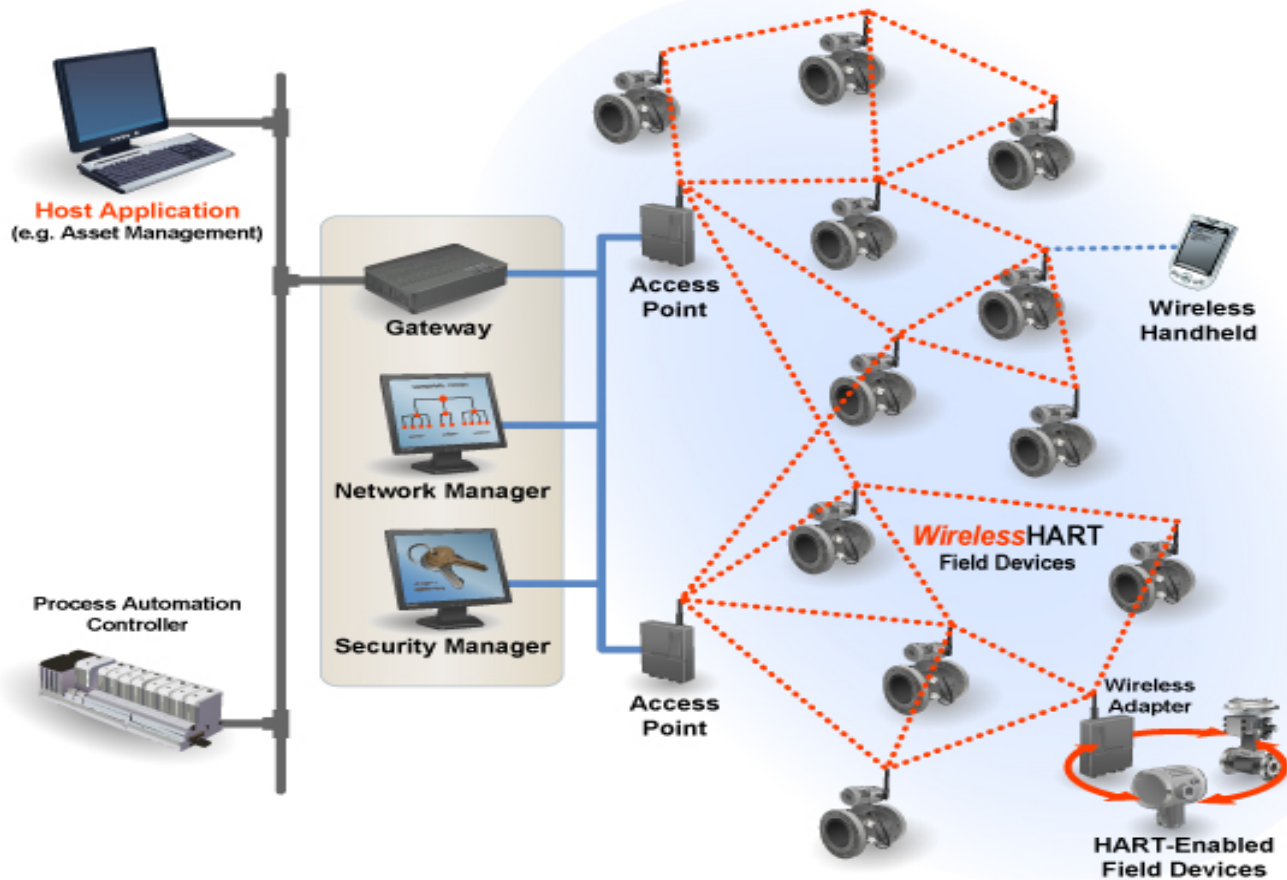
Courtesy: Eric Rotvold, Emerson

Outline

- WirelessHART: real-time wireless in real 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 harsh industrial environments
 - ❑ Time Division Multiple Access
 - ❑ Multi-channel
 - ❑ Route diversity
 - ❑ No concurrent transmission in a same channel

- 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'10]
- Fixed priority scheduling
 - ❑ End-to-end delay analysis [RTAS'11]
 - ❑ Priority assignment [ECRTS'11]

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Real-Time Flows

- Flow: sensor → controller → actuator over multi-hops
- A set of flows $F = \{F_1, F_2, \dots, F_N\}$ ordered by priorities
 - highest
 - lowest priority
- 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 ($\leq P_i$)
 - ❑ Total number of **transmissions** C_i along the route

Scheduling Problem

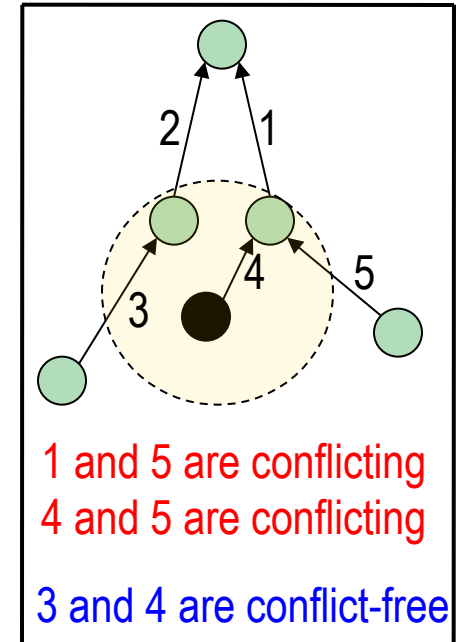
- Fixed priority scheduling: transmissions ordered by the priorities of their flows.

- Flows are **schedulable** if $R_i \leq D_i \quad \forall F_i \in F$
 - ↑ end-to-end delay of F_i
 - ↓ 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**: when all channels are assigned to higher priority flows in a slot
 - ❑ **transmission conflict**: two transmissions involve a same node
- Analyze each type of delay separately
- Combine both delays → end-to-end delay bound

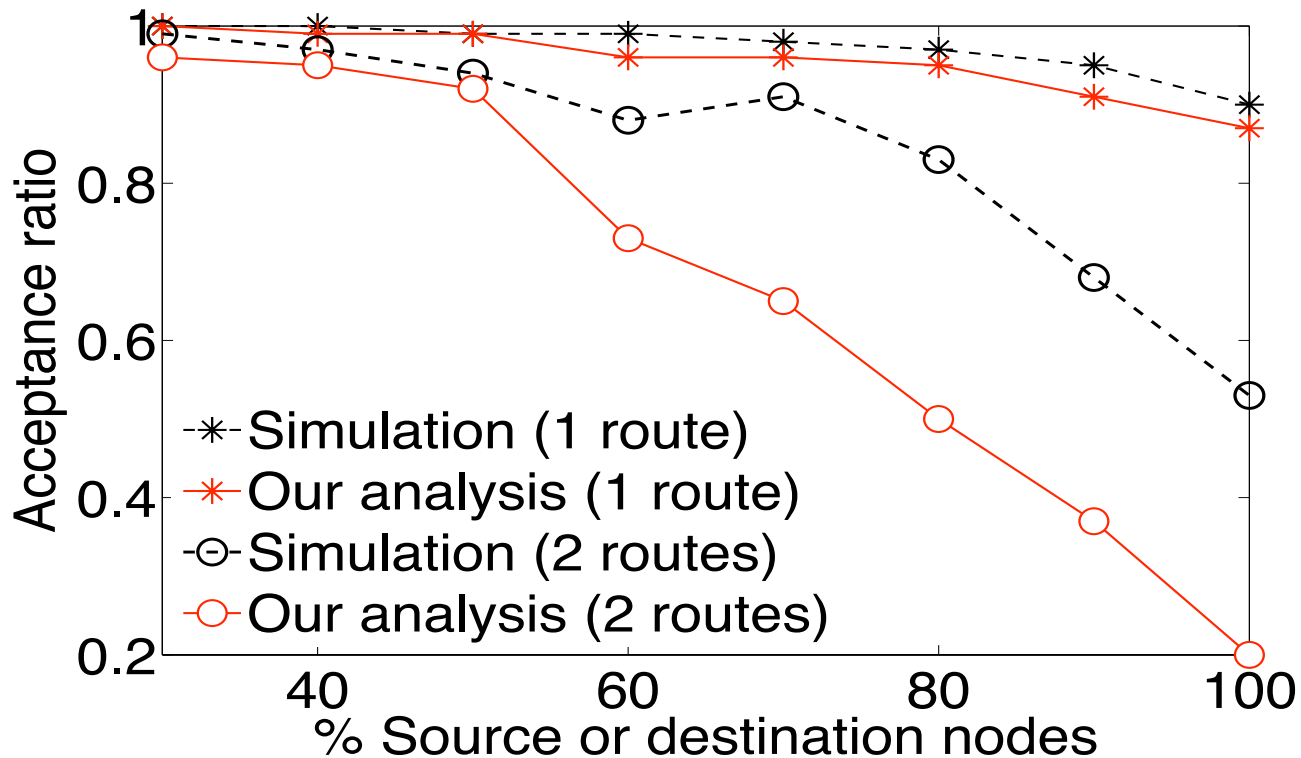


Insights

- **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

Acceptance Ratio

Fraction of test cases deemed schedulable based on analysis or 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'12, TECS]
- Wireless structural control [ICCPS'13]

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 $f = \{f_1, f_2, \dots, f_n\}$ to

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

subject to

$$R_i \leq P_i$$

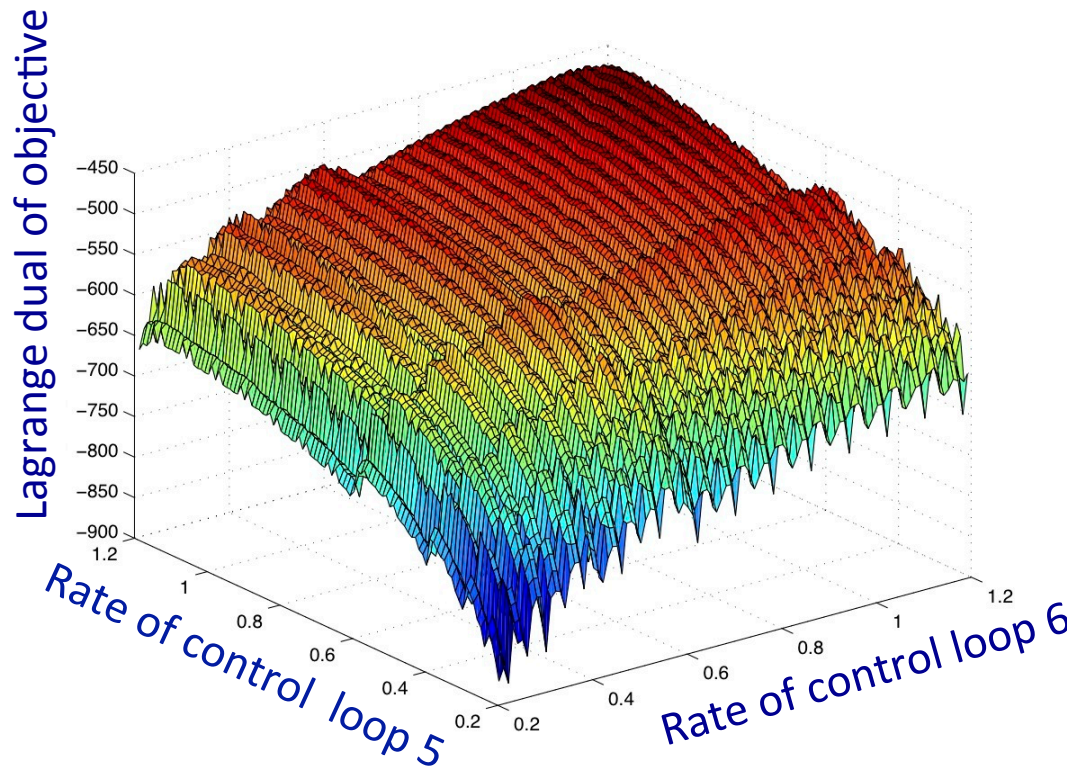
Delay bound

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

Polynomial Time Delay Bounds

➤ In terms of decision variables (rates), the delay bounds are

- ❑ Non-linear
- ❑ Non-convex
- ❑ Non-differentiable

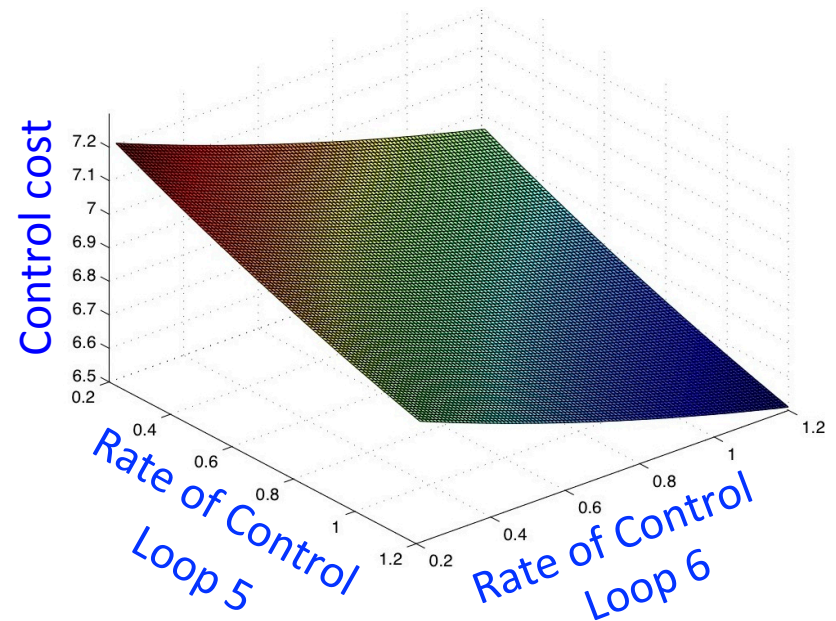
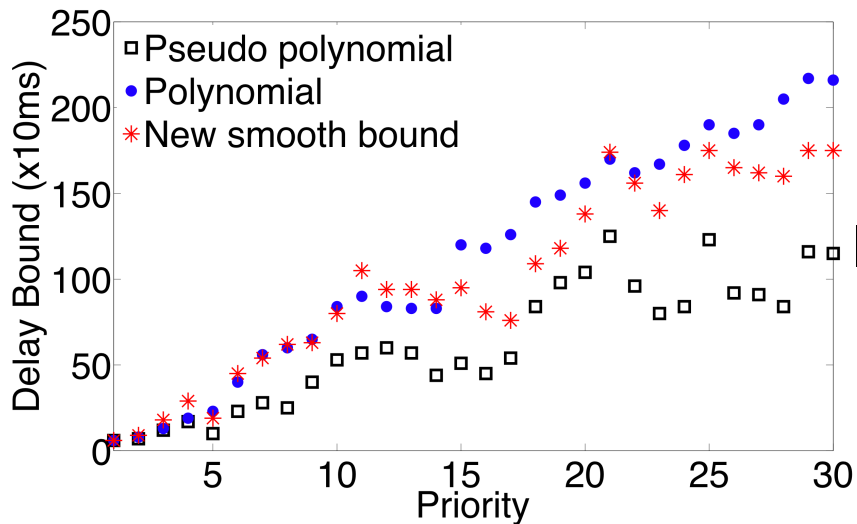


The optimization problem is thus non-convex, non-differentiable, not in closed form

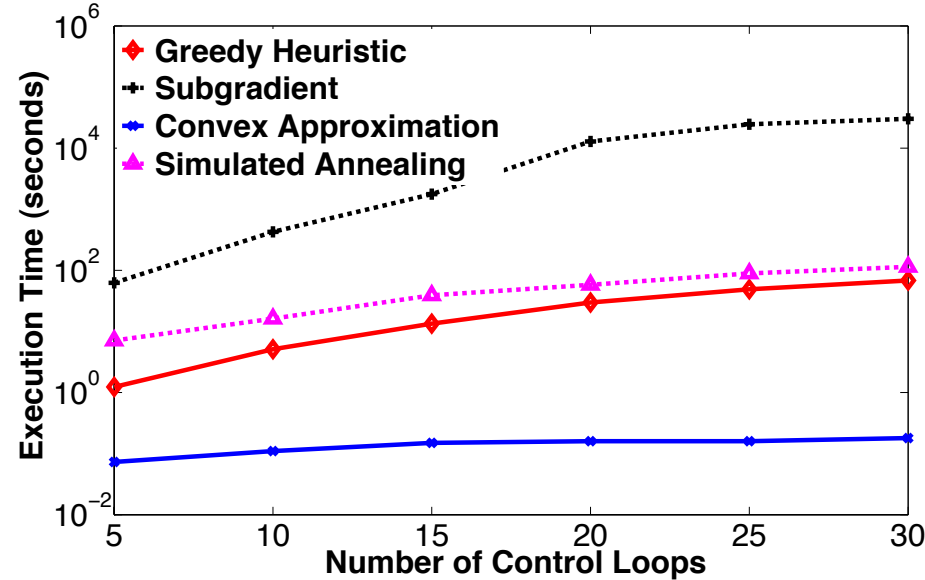
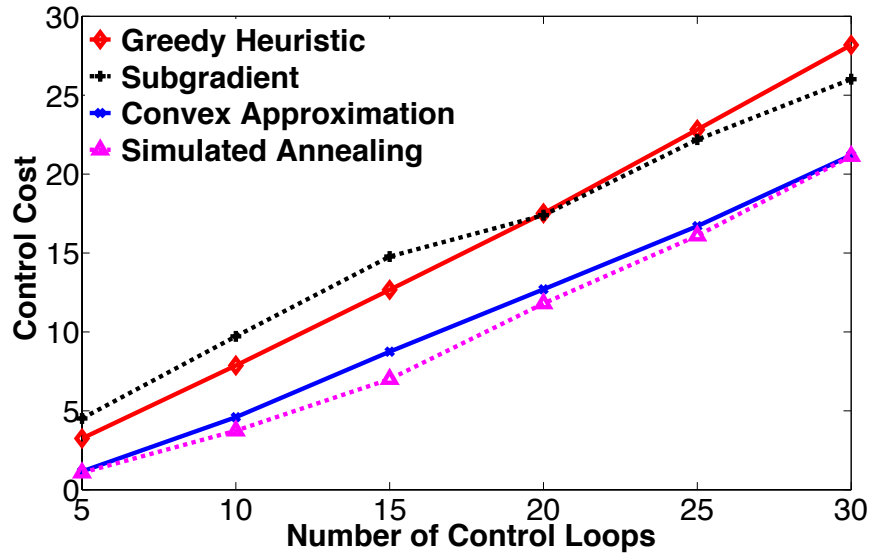
Scheduling-Control Co-Design

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 higher control cost.
- ❑ Subgradient method is neither efficient nor effective.
- ❑ Simulated annealing incurs least 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'13]

- **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>

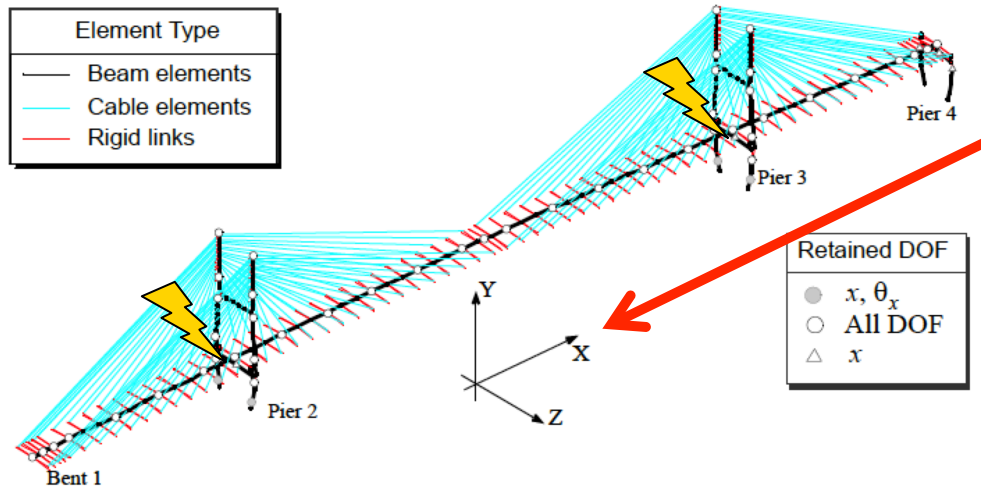
- **Realistic case studies on wireless structural control**
 - ❑ Wireless traces from real-world environments
 - ❑ Structural models of a building and a large bridge
 - ❑ Excited by real earthquake signal traces

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

Bill Emerson Memorial Bridge: Physical Model



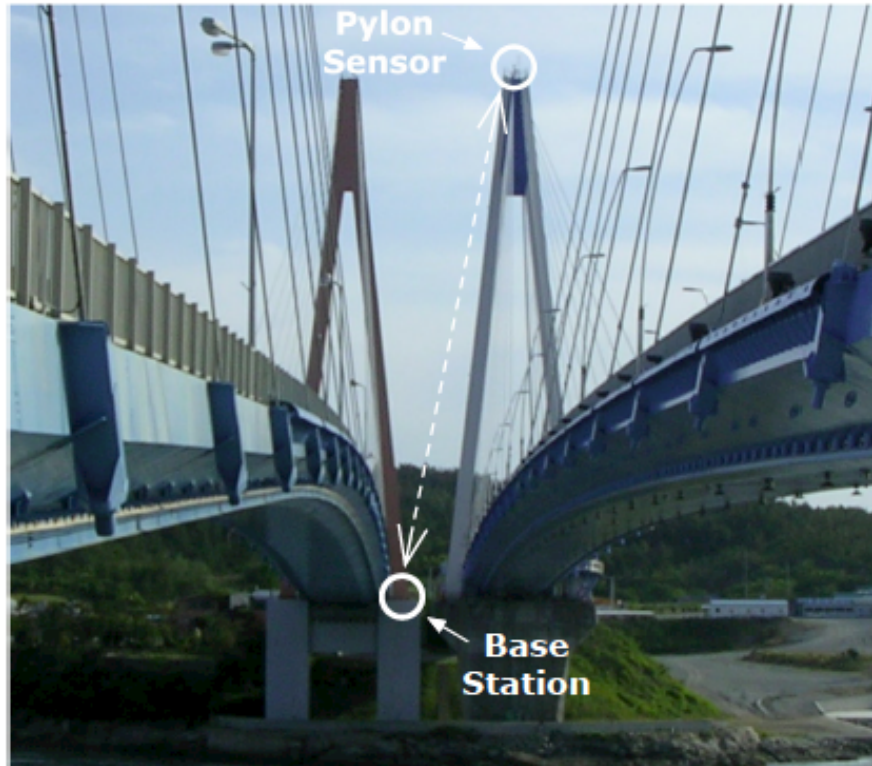
(a)



(b)

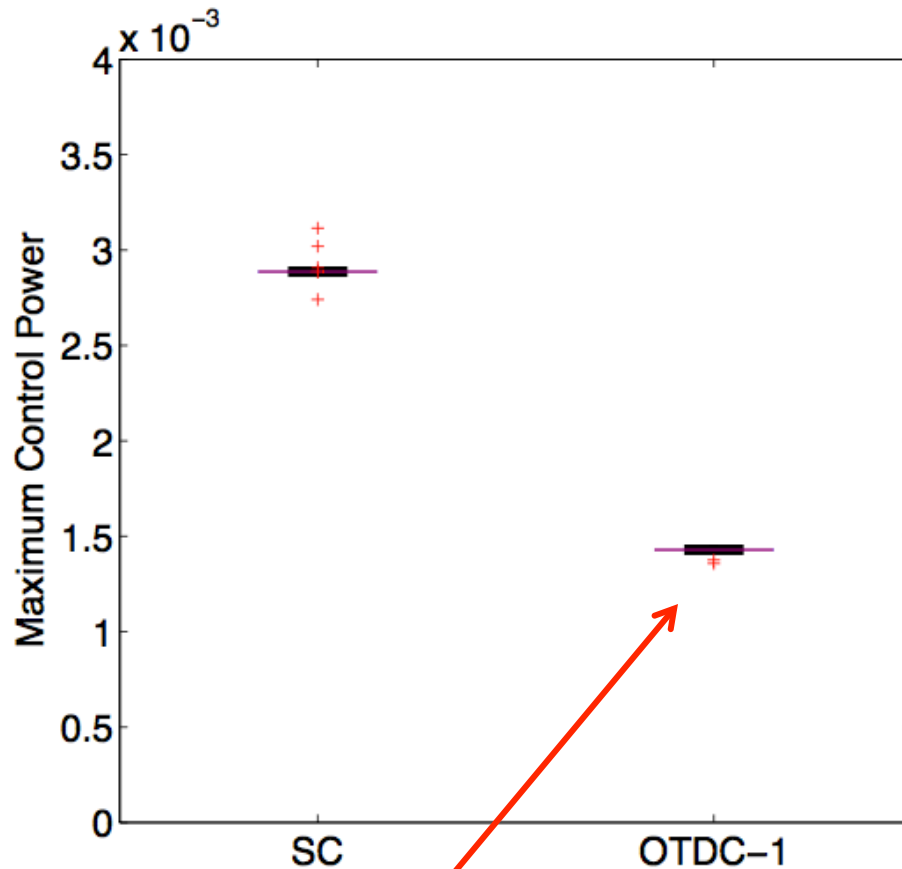
- Main span: 1,150 ft.
- Carries up to 14,000 cars a day over the Mississippi River.
- In the New Madrid Seismic Zone
- Replaced joints of the bridge by actuators ⚡
- 24 Hydraulic actuators
- Vibration mode:
 - ❑ 0.1618 Hz for 1st mode
 - ❑ 0.2666 Hz for 2nd mode
 - ❑ 0.3723 Hz for 3rd mode

Jindo Bridge: Wireless Traces



- Largest wireless bridge 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 \rightarrow 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**
 - ❑ Near 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 & methodology
 - ❑ Bridge the gap between theory and systems
 - ❑ From theory → robust implementation → deployment

For More Information

- **Real-Time Scheduling for Wireless**
 - ❑ A. Saifullah, Y. Xu, C. Lu and Y. Chen, End-to-End Delay Analysis for Fixed Priority Scheduling in WirelessHART Networks, IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS'11), April 2011.
 - ❑ A. Saifullah, Y. Xu, C. Lu and Y. Chen, Priority Assignment for Real-time Flows in WirelessHART Networks, Euromicro Conference on Real-Time Systems (ECRTS'11), July 2011.
 - ❑ A. Saifullah, Y. Xu, C. Lu, and Y. Chen, Real-time Scheduling for WirelessHART Networks, IEEE Real-Time Systems Symposium (RTSS'10), December 2010.
 - ❑ http://cps.cse.wustl.edu/index.php/Real-Time_Wireless_Control_Networks
- **Wireless-Control Co-Design**
 - ❑ A. Saifullah, C. Wu, P. Tiwari, Y. Xu, Y. Fu, C. Lu and Y. Chen, Near Optimal Rate Selection for Wireless Control Systems, ACM Transactions on Embedded Computing Systems, Special Issue on Real-Time and Embedded Systems, accepted.
 - ❑ A. Saifullah, C. Wu, P. Tiwari, Y. Xu, Y. Fu, C. Lu and Y. Chen, Near Optimal Rate Selection for Wireless Control Systems, IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS'12), April 2012.
- **Case Study on Wireless Structural Control**
 - ❑ B. Li, Z. Sun, K. Mechitov, G. Hackmann, C. Lu, S. Dyke, G. Agha and B. Spencer, Realistic Case Studies of Wireless Structural Control, ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS'13), April 2013.
 - ❑ CPS Project on Wireless Structural Monitoring and Control: <http://bridge.cse.wustl.edu>
 - ❑ Wireless Cyber-Physical Simulator: <http://wcps.cse.wustl.edu>
- **Cyber-Physical Systems Laboratory:** <http://cps.cse.wustl.edu>
- **Home Page:** <http://www.cse.wustl.edu/~lu>