Wireless Control Networks

- Real-time
- Reliability
- Control performance
Wireless for Process Automation

World-wide adoption of wireless in process industries

1.5+ billion hours operating experience

100,000s of smart wireless field devices

10,000s of wireless field networks

Offshore

Onshore

Courtesy: Emerson Process Management

Killer App of Sensor Networks!
WirelessHART

- Industrial-grade reliability
  - Multi-channel TDMA MAC
  - One transmission per channel
  - Redundant routes
  - Over IEEE 802.15.4 PHY

- Centralized network manager
  - collects topology information
  - generates routes and transmission schedule
  - changes when devices/links break

*Industrial wireless standard for process monitoring and control*
Outline

1. Real-time scheduling theory for wireless
2. Implementation and empirical evaluation
3. Wireless-control co-design
4. Case study: wireless structural control
Real-Time Scheduling for Wireless

Goals
- Real-time transmission scheduling \(\rightarrow\) meet end-to-end deadlines
- Fast schedulability analysis \(\rightarrow\) online admission control and adaptation

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

Results
- Fixed priority scheduling
  - Delay analysis [RTAS 2011]
  - Priority assignment [ECRTS 2011]
- Dynamic priority scheduling
  - Conflict-aware Least Laxity First [RTSS 2010]
  - Delay analysis for Earliest Deadline First [IWQoS 2014]
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
- Fixed priority scheduling
  - Delay analysis [RTAS 2011]
  - Priority assignment [ECRTS 2011]
- Dynamic priority scheduling
  - Conflict-aware Least Laxity First [RTSS 2010]
  - Delay analysis for Earliest Deadline First [IWQoS 2014]
Real-Time Flows

- Flow: sensor $\rightarrow$ controller $\rightarrow$ actuator over multi-hops

- A set of flows $F=\{F_1, F_2, \ldots, F_N\}$ 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 $D_i \ (\leq P_i)$
  - 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.

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

- 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: transmissions involve a same node

- Analyze each type of delay separately

- Combine both delays \(\rightarrow\) 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
  - $Q(l,h) = 5 \rightarrow F_h$ can delay $F_l$ by 5 slots
Acceptance Ratio

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

- Simulation (1 route)
- Our analysis (1 route)
- Simulation (2 routes)
- Our analysis (2 routes)
Outline

1. Real-time scheduling theory for wireless

2. Implementation and empirical evaluation

3. Wireless-control co-design

4. Case study: wireless structural control
Need for Experimentation

Abundant theoretical results on industrial WSANs

- ...

Scarce experimental research on industrial WSANs.

Few open-source implementation of industrial WSANs.
Protocol Implementation

- **TinyOS 2.1.2** on **CC2420X** radio stack
- **Multi-channel TDMA MAC**
  - 10 ms time slot
    - 2 ms at the beginning for time sync error and channel switching.
  - Dedicated slot - one transmission per channel
  - Shared slot - multiple transmissions contend for a channel
Protocol Implementation

- Field devices are synchronized using FTSP during Sync period
  - >95% of devices can be synchronized with errors less than 2ms
  - 60-node testbed with network diameter = 4

- Source routing: single-path
- Graph routing: multi-path

- ~19 KB ROM and ~1.6 KB RAM
Experimental Routing Study

- Evaluated on a 60-node testbed.
- Graph routing is more resilient to noise at the cost of latency and energy.
Industrial WSAN is an important area of research.

- Killer app of sensor networks.
- Yet scarce experimental research!

We implemented WirelessHART protocols in TinyOS.

- Enabler of experimental research on industrial WSANs.

Experimental routing study on a 60-node testbed.

Source code will be released soon!

http://cps.cse.wustl.edu
Outline

1. Real-time scheduling theory for wireless
2. Implementation and empirical evaluation
3. Wireless-control co-design
4. Case study: wireless structural control
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 $\alpha_i, \beta_i$

- Overall control cost of $n$ loops: $\sum_{i=1}^{n} \alpha_i e^{-\beta_i f_i}$
The Rate Selection Problem

- Constrained non-linear optimization

- Determine sampling rates \( f = \{ f_1, f_2, \cdots, f_n \} \)

minimize control cost \( \sum_{i=1}^{n} \alpha_i e^{-\beta_i f_i} \)

subject to \( \text{delay}_i \leq 1 / f_i \) \( \text{Delay bound} \)

\( f_i^{\text{min}} \leq f_i \leq f_i^{\text{max}} \)
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.
Relax delay bound to simplify optimization

- Derive a **convex** and **smooth**, but less precise delay bound.
- Rate selection becomes a convex optimization problem.
Greedy heuristic is fast but incurs high control cost.

Subgradient method is neither efficient nor effective.

Simulated annealing incurs lowest control cost, but is slow.

Convex approximation balances control cost and execution time.
Outline

1. Real-time scheduling theory for wireless

2. Implementation and empirical evaluation

3. Wireless-control co-design

4. **Case study: wireless structural control**
Case Study: Wireless Structural Control

- Structural control systems protect civil infrastructure.
- Wired control systems are costly and fragile.
- Wireless structural control achieves 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](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

- Main span: 1,150 ft.
- Carries up to 14,000 cars a day over Mississippi.
- 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

- Theory and practice of real-time wireless
  - Leverage real-time processor scheduling
  - Incorporate unique wireless properties
  - Open-source implementation of WirelessHART stack

- 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

- **Real-Time Scheduling for Wireless**

- **Open-Source Implementation**

- **Wireless-Control Co-Design**

- **Wireless Structural Control**
  - CPS Project on Wireless Structural Monitoring and Control: [http://bridge.cse.wustl.edu](http://bridge.cse.wustl.edu)

- **Wireless Cyber-Physical Simulator**
  - [http://wcps.cse.wustl.edu](http://wcps.cse.wustl.edu)

- **Open-Source Implementation**

- **Wireless-Control Co-Design**

- **Wireless Structural Control**
  - CPS Project on Wireless Structural Monitoring and Control: [http://bridge.cse.wustl.edu](http://bridge.cse.wustl.edu)

- **Wireless Cyber-Physical Simulator**
  - [http://wcps.cse.wustl.edu](http://wcps.cse.wustl.edu)