Real-Time Wireless Control Networks for Cyber-Physical Systems

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Wireless Control Networks

- Real-time
- Reliability
- Control performance

Diagram showing the flow of sensor data and control commands in a wireless control network.
Industrials Wireless Networks

1.5+ billion hours operating experience

Hundreds of Thousands of Smart Wireless field devices

Tens of Thousands of Wireless Field Networks

Courtesy: Eric Rotvold, Emerson
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 $\rightarrow$ 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: transmissions ordered by the priorities of their flows.

- Flows are schedulable if \( R_i \leq D_i \quad \forall F_i \in F \)

- 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 $\rightarrow$ end-to-end delay bound
Insights

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

- Channel contention $\rightarrow$ multiprocessor scheduling
  - A channel $\rightarrow$ a processor
  - Flow $F_i$ $\rightarrow$ 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

- When low priority flow $F_l$ and high priority flow $F_h$, conflict, $F_l$ is delayed

- $Q(l,h)$: #transmissions of $F_h$ sharing nodes with $F_l$
  - In the worst case, $F_h$ can delay $F_l$ by $Q(l,h)$ slots
  - e.g., $Q(l,h) = 5 \rightarrow F_h$ can delay $F_l$ by 5 slots
Acceptance Ratio

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

![Graph showing acceptance ratio vs. % source or destination nodes.](image)
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 $\rightarrow$ poor control performance
  - High sampling rate $\rightarrow$ long delay $\rightarrow$ 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

- Formulated as a constrained non-linear optimization

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

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

  subject to
  \[
  R_i \leq P_i \quad \textit{Delay bound}
  \]

  \[
  f_i^{\min} \leq f_i \leq f_i^{\max}
  \]
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 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](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

- 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 $\rightarrow$ 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
  - 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 $\rightarrow$ 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 $\rightarrow$ robust implementation $\rightarrow$ deployment
For More Information

- **Real-Time Scheduling for Wireless**

- **Wireless-Control Co-Design**

- **Case Study on 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)

- **Cyber-Physical Systems Laboratory**: [http://cps.cse.wustl.edu](http://cps.cse.wustl.edu)
- **Home Page**: [http://www.cse.wustl.edu/~lu](http://www.cse.wustl.edu/~lu)