Dependable
Industrial Internet of Things

Chenyang Lu
Cyber-Physical Systems Laboratory
Department of Computer Science and Engineering
IoT for Industry 4.0

- 11.6+ billion hours operating experience
- 36,800+ wireless field networks
  [Emerson]

- $944.92 million by 2020
  [Market and Market]

NOT your best-effort IoT at home!

Courtesy: Emerson Process Management
WirelessHART

- Reliability and predictability
  - Multi-channel TDMA MAC
  - One transmission per channel
  - Redundant routes
  - Over IEEE 802.15.4 PHY

- Centralized network manager
  - Collect topology information
  - Generate routes and schedule
  - Change when devices/links break

Industrial wireless standard for process automation
Most of today’s industrial wireless networks are for **monitoring**.

Dependable **control** requires

- **real-time**
- **control performance**
- **resilience to loss**

Source: [https://www.automation.com](https://www.automation.com)
Towards Dependable Wireless Control

1. Real-time wireless networks and analysis

2. Optimizing control performance over wireless

3. Resilient yet efficient wireless control under loss.

Cannot be accomplished by wireless or control design alone →

Cyber-Physical Co-design of Wireless and Control
Towards Dependable Wireless Control

1. **Real-time wireless networks and analysis**

2. **Optimizing control performance over wireless**

3. **Resilient yet efficient wireless control under loss.**

*Cannot be accomplished by wireless or control design alone ➔ Cyber-Physical Co-design of Wireless and Control*
The Real-Time Problem

- A feedback control loop incurs a flow $F_i$
  - Route: sensor $\rightarrow$ ... $\rightarrow$ controller $\rightarrow$ ... $\rightarrow$ actuator
  - Generate packet every period $P_i$
  - Multiple control loops share a network

- Each flow must meet deadline $D_i \leq P_i$
  - Stability and predictable control performance

- Research problems
  - Real-time transmission scheduling $\rightarrow$ meet deadlines
  - Fast delay analysis $\rightarrow$ adapt to dynamics
Delays in WirelessHART

A transmission is delayed by

- **channel contention** when all channels are assigned to other transmissions
- **transmission conflict** over shared node

- 1 and 4 conflict
- 4 and 5 conflict
Fast Delay Analysis

- Compute upper bound of the delay for each flow
  - Sufficient condition for real-time guarantees
  - Enable fast adaptation to wireless dynamics

- Channel contention $\rightarrow$ multiprocessor task scheduling
  - A channel $\rightarrow$ a processor
  - Flow $F_i \rightarrow$ a task with period $P_i$, deadline $D_i$, execution time $C_i$
  - Leverage real-time scheduling theory!
    - Response time analysis for multiprocessors

- Account for delays due to transmission conflicts

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Delay due to Conflict

- Low-priority flow $F_l$ and high-priority flow $F_h$ conflict $\rightarrow$ 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

- Conflicts contribute significantly to delays
  - Delay analysis [TC 2015]
  - Scheduling [RTSS 2010, 2015]
  - Routing [IoTDI 2018]
Real-Time Wireless Networking

- **WirelessHART stack** [IoT-J 2017]
  - Implementation on a 69-node testbed
  - Network manager (scheduler + routing)

- **Real-time and efficiency for industrial IoT**
  - Emergency communication [ICCPS 2015]
  - Channel selection [INFOCOM 2017]
  - Channel reuse [ICDCS 2018]
  - Energy-efficient, real-time routing [IoTDI 2016, 2018]

- **Low-Power Wide-Area Networks**
  - **SNOW**: Sensor Network Over TV White Spaces [SenSys 2016, 2017]
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Cyber-Physical Co-design of Wireless and Control
Wireless-Control Co-Design

Observation

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

Cyber-Physical Co-Design

- Cojoin the design of wireless and control

Examples

- Rate selection for wireless control [TECS 2014]
- Scheduling-control co-design [ICCPS 2013]
- Routing-control co-design [ICCPS 2015]
Rate Selection for Wireless Control

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

- Rate selection must balance control and communication.
  - Low sampling rate $\rightarrow$ poor control performance
  - High sampling rate $\rightarrow$ long delay $\rightarrow$ poor control performance
  - Rate selection must balance control and communication.

Co-Design: incorporate the impacts of rates on both control and communication
Cyber-Physical Design Interface

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

**Interface between cyber and physical designs!**

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

\[
delay_i \leq 1 / f_i
\]

\[
f_{i}^{\text{min}} \leq f_i \leq f_{i}^{\text{max}}
\]
A Challenging Optimization Problem!

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

- non-linear
- non-convex
- non-differentiable

![Graph showing Lagrange dual of objective versus rates of control loops 5 and 6.](image)
Relax delay bound $\rightarrow$ simplify control optimization

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

Optimize control performance efficiently at run time!

Towards Dependable Wireless Control

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3. Resilient yet efficient control under data loss.

This cannot be accomplished by wireless or control design alone →

Cyber-Physical Co-design of Wireless and Control
Resilient Control under Data Loss

- Data loss causes instability and degrades control performance.

- Traditionally addressed in separation
  - Control: control design to tolerate data loss.
  - Wireless: redundancy reduces loss at high resource cost.
  - *But how much redundancy is sufficient?*

- Cyber-physical **co-design**
  - Incorporate robust control design.
  - Tailor wireless protocols for control needs.
  - *Resilient and efficient wireless control.*
Handle Data Loss from Sensors

- **State Observer** estimates system states based on a system model even if there is no new data from sensors.

Handle Data Loss from Controller

- **Model Predictive Control**
  - Controller computes control inputs in the next $w+1$ sampling periods: $u(k), u(k+1), ..., u(k+w)$.
  - Actuator applies $u(k)$.

- **Buffered actuation**
  - Actuator buffers previous control inputs $u(k+1), ..., u(k+h)$ ($h \leq w$).
  - Applies buffered control input if updated input is lost.
  - Buffer size of $h \rightarrow$ tolerate $h$ consecutive packet loss.
Case Study: Exothermic Reaction Plant

Plant: nonlinear chemical reaction
Control input: $u_1$ and $u_2$
Objective: Maintain temperature in Tank 2

Wireless Cyber-Physical Simulator (WCPS)

- Integrate TOSSIM and Simulink
- Capture dynamics of both wireless networks and physical plants
- Holistic simulations of wireless control
- Open source: wcps.cse.wustl.edu
Impact of Data Loss from Sensor

Extended Kalman filter under 60% loss from sensor

System is highly resilient to packet loss from sensors
Impact of Data Loss to Actuator

Actuation buffer (size 8) under 60% loss to actuator

Actuation is more sensitive to data loss than sensing.

⇒ Data losses are not equal!
Routing in WirelessHART

- **Existing approach to routing**
  - Source routing: single path routing $\rightarrow$ efficient but unreliable.
  - Graph routing: every node on the primary path has a backup path $\rightarrow$ reliable at cost of capacity and energy.
  - Entire network uses a **uniform** routing strategy.

- **But sensing and actuation need different levels of reliability!**

![Diagram](a) Source Routing

![Diagram](b) Graph Routing
Asymmetric Routing

- **Differentiated** routing for sensing and actuation

- State observer handles data loss from sensors

- **Source routing from sensors**
  - State observer compensates for lower reliability
  - Save network resource

- Actuation is more sensitive to data loss

- **Graph routing to actuators**
  - High reliability
  - High resource cost, but needed for control

**Tailor routing to control**

* Spend wireless resource where control needs it*
Source/Graph performs close to Graph/Graph at 3Hz sampling rate.

Efficiency allows higher sampling rate with Source/Graph \(\rightarrow\) further improve control performance!

Towards Dependable Wireless Control

- Real-time wireless networking
  - Protocols and delay analysis for latency guarantees

- Optimize control performance over wireless
  - Incorporate scheduling analysis in rate selection

- Resilient wireless control under data loss
  - Tailor routing strategies for control needs

Cannot be accomplished by wireless or control design alone

Cyber-Physical Co-design of Wireless and Control
Beyond Design: Holistic Cyber-Physical Control

- Today: network management and control operate in isolation
  - Controller controls physical plants
  - Network manager configures networks
  - Ignore interdependencies → vulnerable and inefficient industrial plants.
- Holistic control: close the loop between control and network
  - Holistic controller controls both physical plants and networks.

Beyond Design: Holistic Cyber-Physical Control

- Today: network management and control operate in isolation
  - Controller controls physical plants

**How to coordinate networks and control at run-time for resiliency?**

- Holistic controller controls both physical plants and networks.

Support real-time applications in the cloud.
- Latency guarantees.
- Real-time performance isolation.
- Resource sharing between real-time and non-real-time workloads.

Real-time cloud stack.
- RT-Xen → real-time virtual machine scheduling (*included in Xen*)
- VATC → real-time network I/O on a virtualized host.
- RT-OpenStack → real-time cloud resource management.

### Diagram
- **RT-Xen**
  - Real-Time Virtualization
- **VATC**
  - RT Network I/O
- **RT-OpenStack**
  - Real-time cloud resource management
- **Cyber-Physical Event Processing**
- **RT Cilk Plus**

**Latency guarantees**
Beyond Wireless: Real-Time Edge and Cloud

- Support real-time applications in the cloud.
  - Latency guarantees.
  - Real-time performance isolation.

**How to orchestrate edge and cloud for dependable control?**

- **VATC** → real-time network I/O on a virtualized host.
- **RT-OpenStack** → real-time cloud resource management.
The Dependability Challenges

- Industrial IoT have started!
  - Industrial drivers: standards, consortia, deployments
  - System building blocks: from wireless to edge and cloud
  - Holistic modeling, simulation and design tools

- We must address the dependability challenges
  - Real-time, resiliency, safely, security…
  - Cyber-physical co-design is a necessity!

**Application driver from Industry 4.0**

*CPS: Solving the Right Problem at the Right Time!*
For More Information


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


- RT-Xen: [https://sites.google.com/site/realtimexen/](https://sites.google.com/site/realtimexen/)