Holistic Control and Management of Industrial Wireless Processes

Chenyang Lu, Humberto Gonzalez
Washington University in St. Louis

Motivation

- Wireless sensor-actuator networks (WSANs) establish a **symbiotic** relation between network resource allocation and physical system performance.
  - Stability, safety, and resilience of industrial plants can only be guaranteed if maximum information loss bounds are assumed.
  - Network schedules and energy efficiency can only be computed if maximum latency and sampling rates bounds for each flow are provided.
- We need **holistic** control algorithms that evaluate current physical and network conditions, adapt network and control configurations at run-time, and deploy the new configurations without downtime or performance loss.

Holistic Control

We are developing a new class of **holistic plant and network controllers** capable of:
(1) closing the loop between control and network;
(2) computing physical inputs and network configurations in real-time that guarantee cyber-physical safety;
(3) observing and predicting physical and network conditions and their impacts.

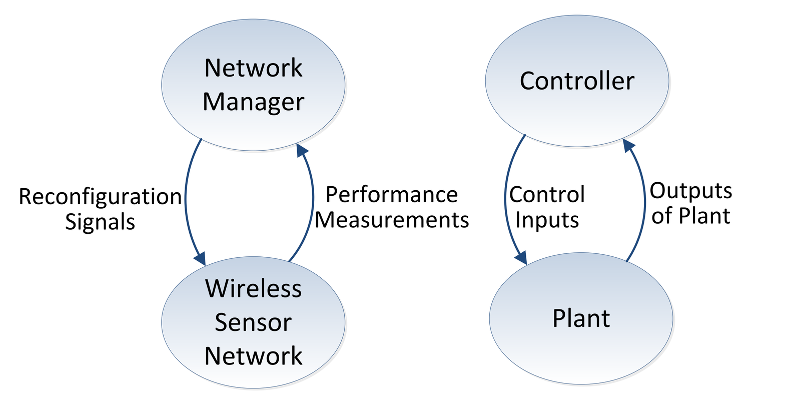


Figure 1: Current industrial process control separates control and network management.

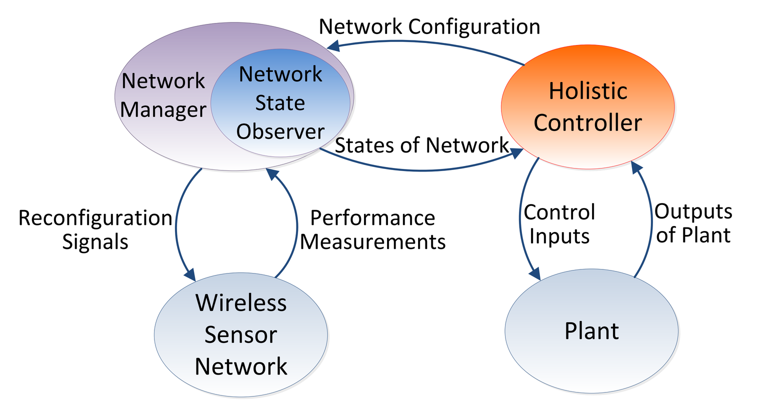


Figure 2: Next generation of holistic industrial process control.

Wireless Cyber-Physical Simulator

The Wireless Cyber-Physical Simulator (**WCPS**) provides a holistic simulation for wireless control systems:
- Open source: `http://wcps.cse.wustl.edu`;
- Integrate TOSSIM and Simulink;
- Support WirelessHART network adaptation;
- Provide Dockerized (container-based) installation.

WCPS Real-time (**WCPS-RT**)
- Integrate a **real** wireless network, and **simulated** physical plants and controllers;
- Capture wireless dynamics that are hard to simulate accurately;
- Leverage simulation support for physical plants.

Asymmetric Routing and Scheduling

Information flows in wireless networks should be asymmetrically routed and scheduled, providing extra redundancy for flows that have the highest impact in the response of the plant:
- Lost sensing information can be reliably estimated using intermittent observation state estimators. Thus, we use single-path **source routing** and reserve **fewer retransmissions** since it has low latency and demands less resources.
- Lost actuation information cannot be estimated, particularly on transient responses and unstable systems. Thus, we use multi-path **graph routing** or reserve **more retransmissions** since it has high reliability with strict delivery deadlines.

Holistic Control Framework

Holistic control framework for wireless control system:
(1) closing the loop between network and control;
(2) run-time network reconfiguration based on physical states;
(3) offering wireless control systems with **enhanced resiliency and efficiency!**

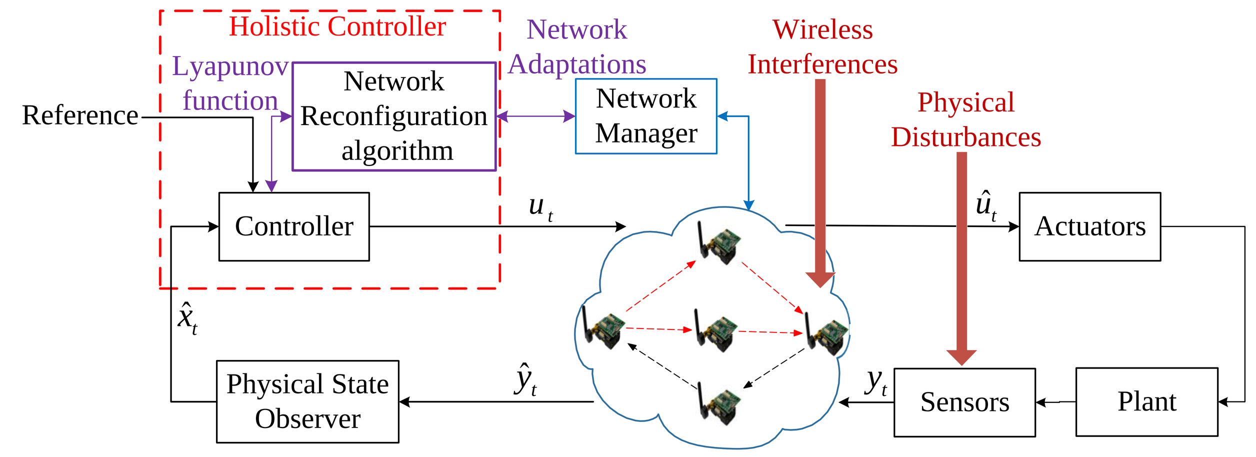


Figure 3: Holistic Control Architecture. It comprises (1) holistic controllers: monitor control performance, and compute network configurations and control commands; (2) network: transmits control commands and re-configures itself when needed.

We developed three holistic control strategies:
- adapting **number of retransmissions**;
- adapting **sampling rates**;
- adapting **transmission schedules** (self-triggered control).

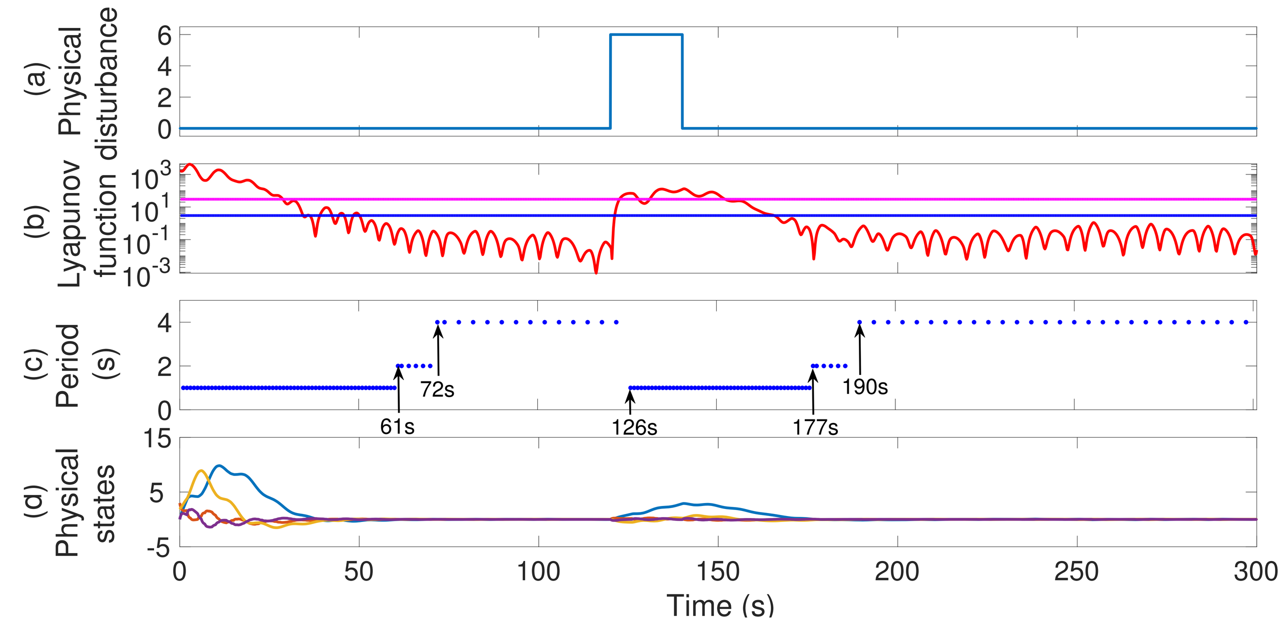
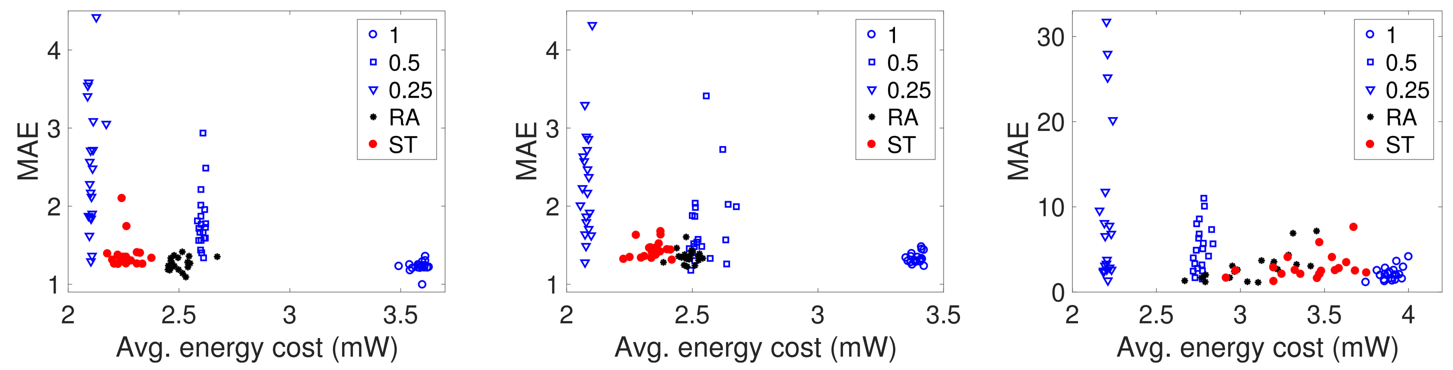


Figure 4: Wireless network adapts the **sampling rate** in face of physical disturbance. Disturbance begins at $t = 120$ s and ends at $t = 140$ s. The sampling rate of WSAN dynamically responds to the disturbance, which is increased when Lyapunov function violates the worst-case bound.

Cyber-Physical Case Study

Our hybrid simulation setup:
- Physical plant: up to 5 load positioning plants.
- Wireless network: 70-node WSAN testbed.
- Network interference: generated by Wi-Fi.
- Physical disturbance: constant bias of actuators.



(a) Under normal condition. (b) Under physical disturbance. (c) Under network disturbance.

Figure 5: Relationship between control performance (mean absolute error) and network energy cost. Fixed rate: 1, 0.5 and 0.25 Hz (blue), RA: rate adaptation (black), and ST: self-triggered control (red). (1) RA and ST have comparative control performance to fixed 1Hz sampling (2) while consuming less energy in the network! (3) ST is more aggressive in energy saving than RA under normal and physical disturbance. (4) ST consumes more energy than RA under network disturbance, due to packet loss recovery.

Edge Computing for Control Systems (On-Going)

- Multi-tier control architecture: (1) local control, (2) edge control, and (3) cloud control.
- The key differences among those tiers are the **computation capacities** and **communication latencies**, which increase as the platforms are located progressively further away.
- The advantage of the multi-tier computing architecture:
  - the flexibility in controller placements;
  - the choice of corresponding control policies.
- Real-time edge computing platform provides real-time and fault-tolerance control services.

New Simulation Tool! WCPS Edge-Computing (**WCPS-EC**) (Fig.6)
- Multi-tier control architecture integrating local/edge/cloud computation platforms;
- Explore the impacts and trade-off of computation and communication of different control tiers.

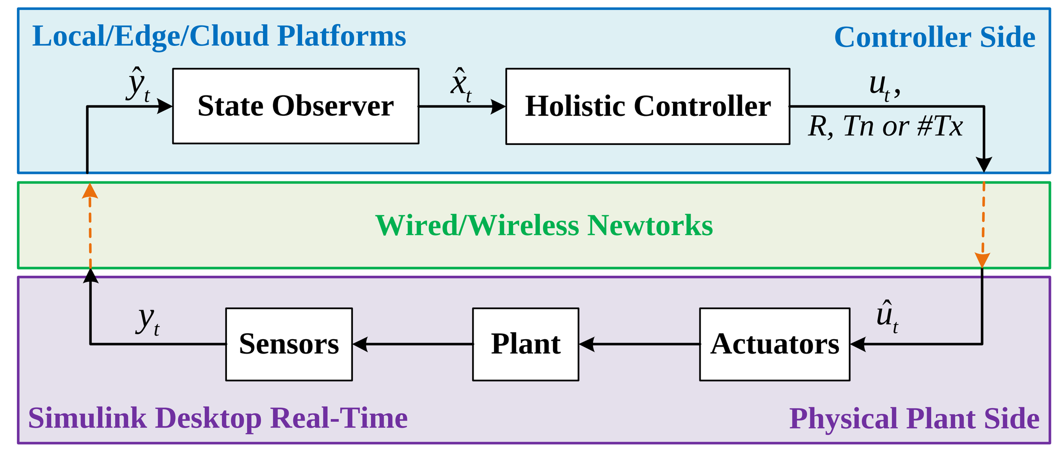


Figure 6: WCPS-EC Architecture. WCPS-EC is a real-time hybrid simulator that integrates a physical plant **simulated** in Simulink Desktop Real-Time, **real** wire/wireless networks, e.g., WirelessHART network, Wi-Fi, Internet, and **real** multi-tier computation platforms.

References

[1] H. Li, C. Lu and C. Gill, "Predicting Latency Distributions of Aperiodic Time-Critical Services." IEEE Real-Time Systems Symposium (RTSS), December 2019.

[2] A. Saifullah, S. Sankar, J. Liu, C. Lu, R. Chandra, and B. Priyantha, "Capnet: Exploiting wireless sensor networks for data center power capping." ACM Transactions on Sensor Networks, 15(1), Article No. 6, January 2019.

[3] Y. Ma and C. Lu, "Efficient Holistic Control over Industrial Wireless Sensor-Actuator Networks." IEEE International Conference on Industrial Internet (ICII), 2018.

[4] Y. Ma, D. Gunatilaka, B. Li, H. Gonzalez and C. Lu, "Holistic Cyber-Physical Management for Dependable Wireless Control Systems." ACM Transactions on Cyber-Physical Systems, Special Issue on Dependability in Cyber Physical Systems and Applications, 3(1), Article No. 3, 2018.

[5] A. Saifullah, M. Rahman, D. Ismail, C. Lu, J. Liu and R. Chandra, "Low-Power Wide-Area Network over White Spaces." IEEE/ACM Transactions on Networking, 28(4): 1893-1906, 2018.

[6] D. Gunatilaka and C. Lu, "Conservative Channel Reuse in Real-Time Industrial Wireless Sensor-Actuator Networks." IEEE International Conference on Distributed Computing Systems (ICDCS), 2018.

[7] P. Park, S.C. Ergen, C. Fischione, C. Lu and K.H. Johansson, "Wireless network design for control systems: A survey." IEEE Communications Surveys & Tutorials, 20(2):978-1013, 2018.

[8] C. Wu, D. Gunatilaka, M. Sha and C. Lu, "Real-Time Wireless Routing for Industrial Internet of Things." ACM/IEEE International Conference on Internet of Things Design and Implementation (IoTDI), 2018.

[9] B. Li, Y. Ma, T. Westenbroek, C. Wu, H. Gonzalez, and C. Lu. "Wireless Routing and Control: A Cyber-Physical Case Study." ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS), 2016.

[10] A. Saifullah, M. Rahman, D. Ismail, C. Lu et al. "Enabling Reliable, Asynchronous, and Bidirectional Communication in Sensor Networks over White Spaces." ACM Conference on Embedded Networked Sensor Systems (SenSys), 2017.

[11] M. Sha, D. Gunatilaka, C. Wu, and C. Lu. "Empirical Study and Enhancements of Industrial Wireless Sensor-Actuator Network Protocols." IEEE Internet of Things Journal, 4(3): 696-704, 2017.

[12] D. Gunatilaka, M. Sha, and C. Lu. "Impacts of Channel Selection on Industrial Wireless Sensor-Actuator Networks." IEEE International Conference on Computer Communications (INFOCOM), 2017.

NSF Grants #1646579