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Cyber-Physical Systems Laboratory

Efficient Holistic Control over Industrial Wireless Sensor-Actuator Networks

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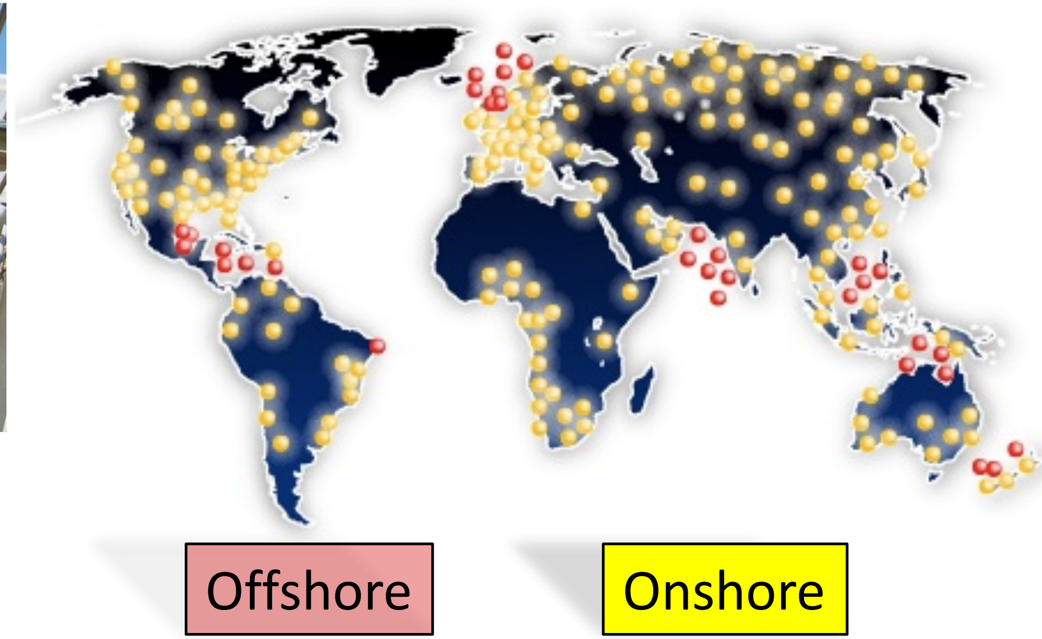
Industrial IoT for Industrial Internet



- 12.9+ billion hours operating experience
- 41,040+ wireless field networks

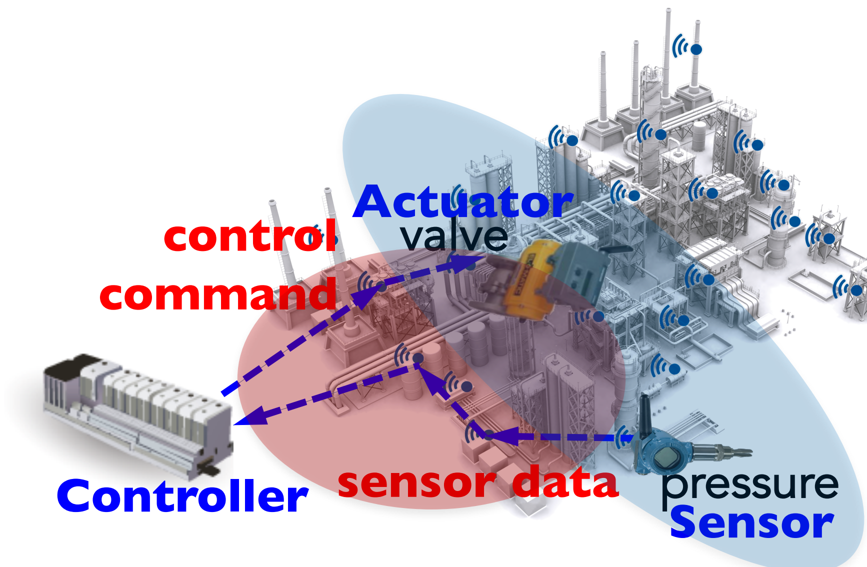
[Emerson]

Courtesy: Emerson Process Management

- $123 billion by 2021

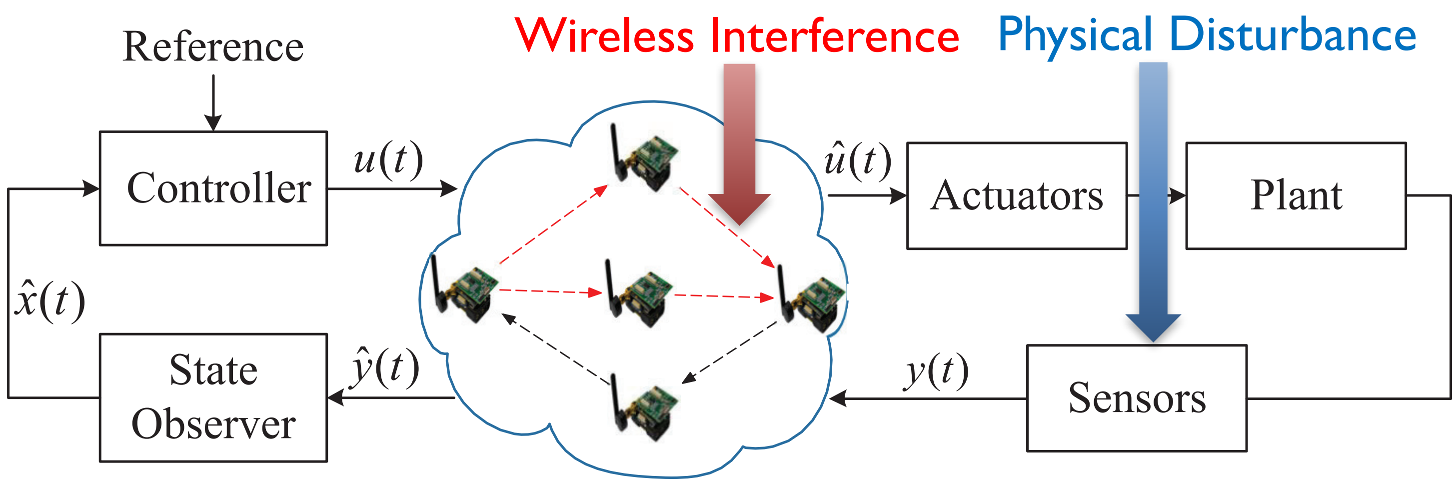
[Forbes]

Dependable Wireless Control System



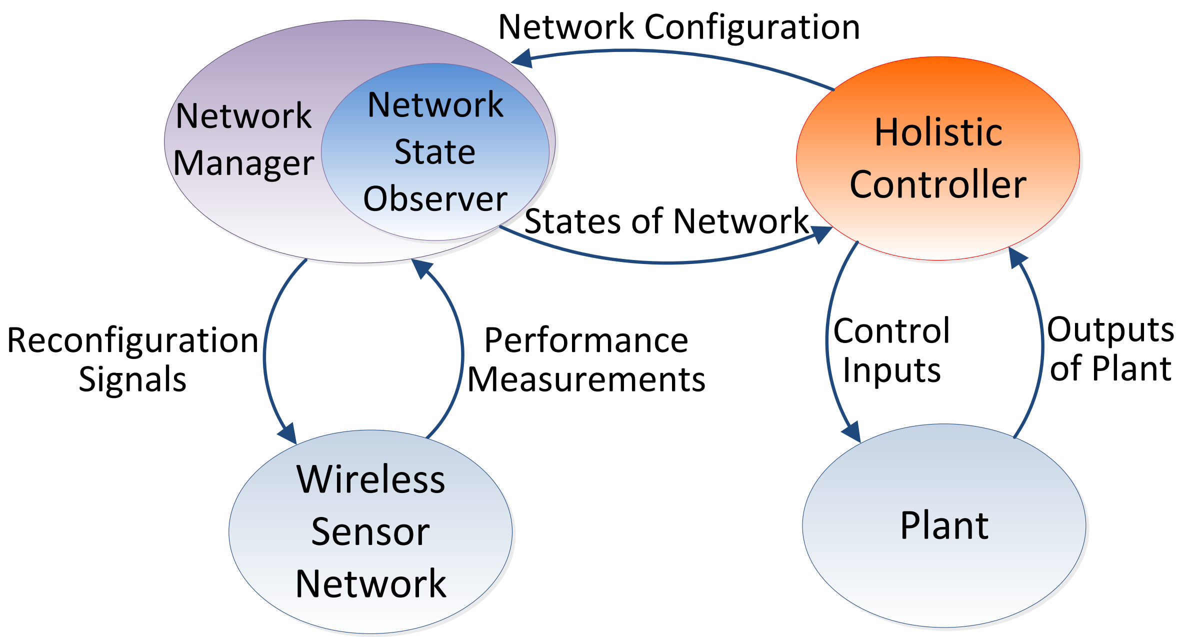
Most of today's industrial wireless networks are for monitoring

Dependable wireless control requires
- Control performance
- Resiliency
- Energy efficiency



Holistic Control

- Close the loop between control and network
- Holistic controller manages both the physical plant and network based on states of plants and the network



Ma, Y., Gunatilaka, D., Li, B., Gonzalez, H., & Lu, C. (2018). Holistic cyber-physical management for dependable wireless control systems. ACM Transactions on Cyber-Physical Systems, 3(1), 3.

Motivation

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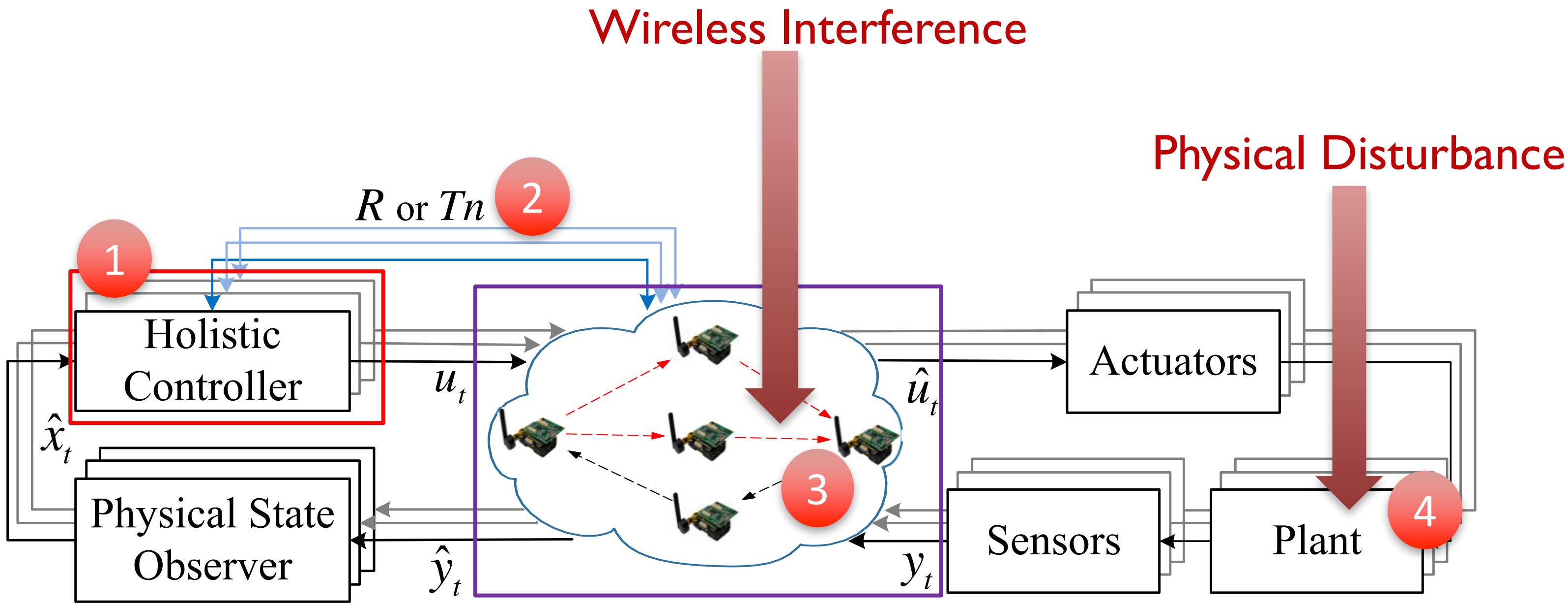
- Traditional periodic control
  - Low rate→ Low resiliency to interference
  - High rate→ Unnecessary energy cost
  - → Efficient rate-adaptation/event-triggered control
- Time-slotted multi-hop mesh WSAN
  - Lack of mechanism tailored for efficient control strategies
  - Run-time reconfiguration is challenging
- Simulation tools are of vital importance for wireless control
  - Real WSAN dynamics are hard to simulate
  - Running real industrial physical plant is extremely challenging

Contributions

- Holistic control with efficient control strategies
  - Rate adaptation
  - Self-triggered control
- WSAN reconfiguration mechanisms
  - Support run-time adaptation for efficient holistic control
  - Target multi-hop mesh network
- Real-time network-in-the-loop simulator
  - Real WSAN testbed
  - Simulated physical plants and controllers
- Compare rate adaptation and self-triggered control

Efficient Holistic Control Framework

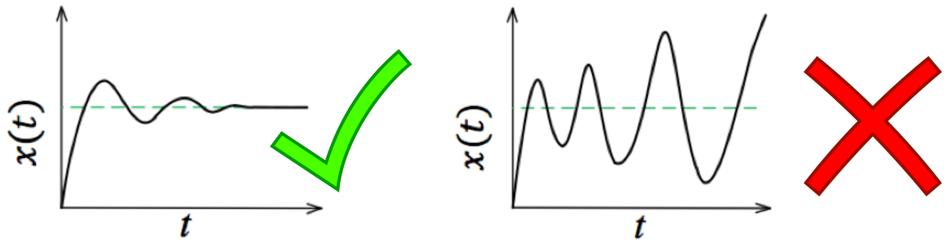


- Control performance monitoring
- Efficient control strategy→ Rate/Inter-transmission time

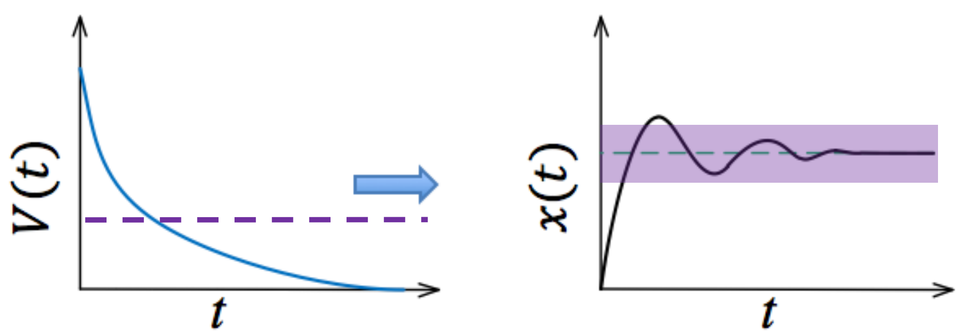
- Network reconfiguration mechanism

Control Performance Monitoring

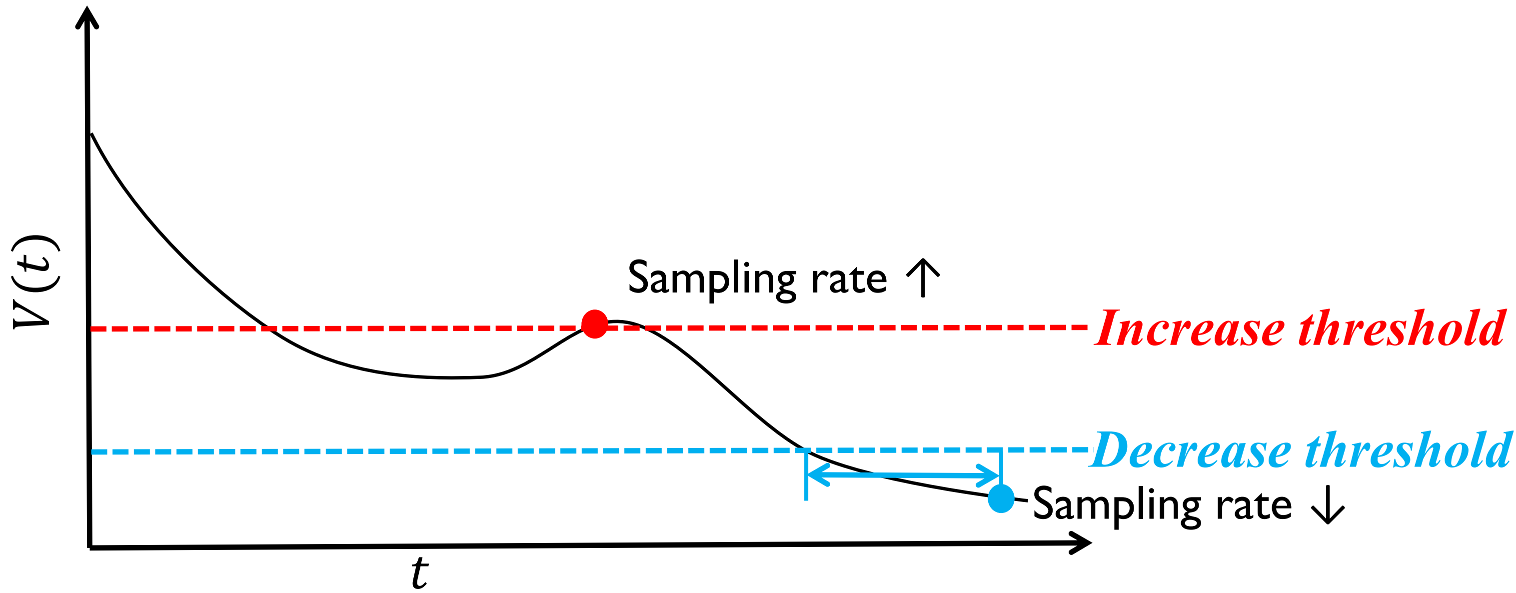
- Stability



- State error
  - $||x(t) - \text{reference state}||$
- Control performance index: Lyapunov function $V(x(t))$
  - $V(x(t))$ keeps decreasing → System is stable
  - Value of $V(x(t))$ → upper bound of physical state error



Rate Adaptation



- Simplified of the rate adaptation algorithm

If *Increase threshold*

→ *Sampling rate* ↑

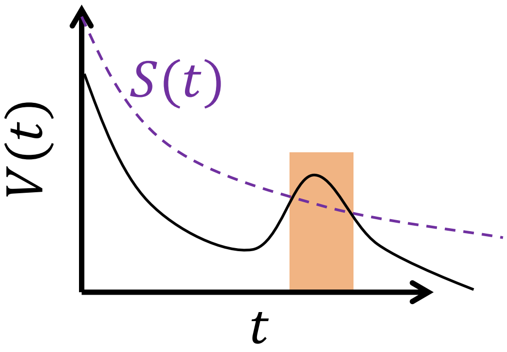
If *Decrease threshold for* ***a time interval***

→ *Sampling rate* ↓

Self-triggered Control

- Event trigger rule
  - Stability index is specified by: $S(t)$

$$S(x_t) = V(x_{t_{k-1}})e^{-\gamma V(x_{t_{k-1}})^{\delta}(t - t_{k-1})}$$

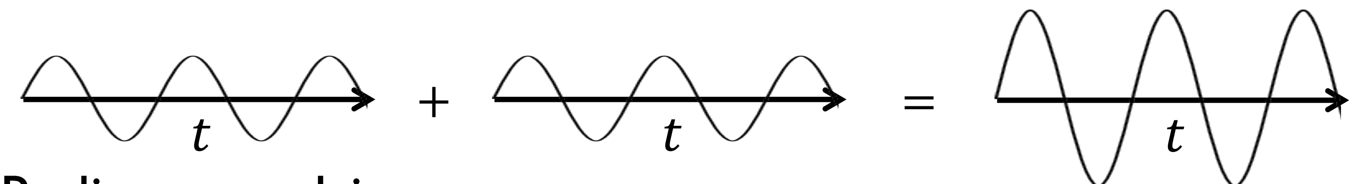


  - Ideal Lyapunov function $V(t) \leq S(t)$
  - Trigger when $V(t) \geq S(t)$

- Self triggered control
  - Predict when the trigger condition will be violated based on model

Low-power Wireless Bus (LWB)

- Glossy flooding
  - One to many
  - Constructive interference



  - Radio event driven
  - Fast (propagation delay < 10 ms in 100-node mesh network)
- Low power wireless bus (LWB) network protocol
  - Maps all communication on fast Glossy floods→ many to many

Ferrari, F., Zimmerling, M., Thiele, L., & Saukh, O. Efficient network flooding and time synchronization with glossy. *In IPSN*, 2011.
Ferrari, F., Zimmerling, M., Mottola, L., & Thiele, L. Low-power wireless bus. *In Sensys*, 2012.

Low-power Wireless Bus (LWB)

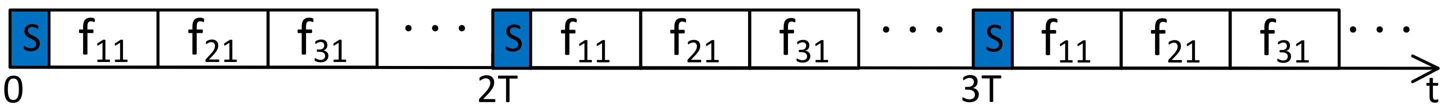
- Advantages of LWB
  - Fast
  - Topology independent
  - Suitable for network-wide adaptation

- Challenges of network design
  - Support reconfiguration of whole communication schedules
  - Recover from data loss during adaptation

Rate Adaptation: Network Design

- Network reconfiguration mechanism
  - All nodes store global static schedule (max rate)

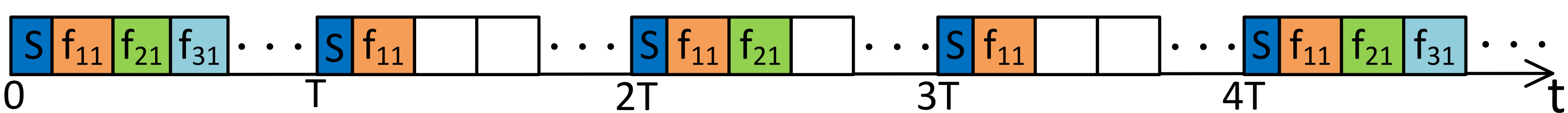
E.g.



  - Holistic controllers piggyback the updated rate with actuation packet, and flood them in their assigned slot

f_{11}: $\frac{1}{T}$ Hz f_{12}: $\frac{1}{2T}$ Hz f_{13}: $\frac{1}{4T}$ Hz

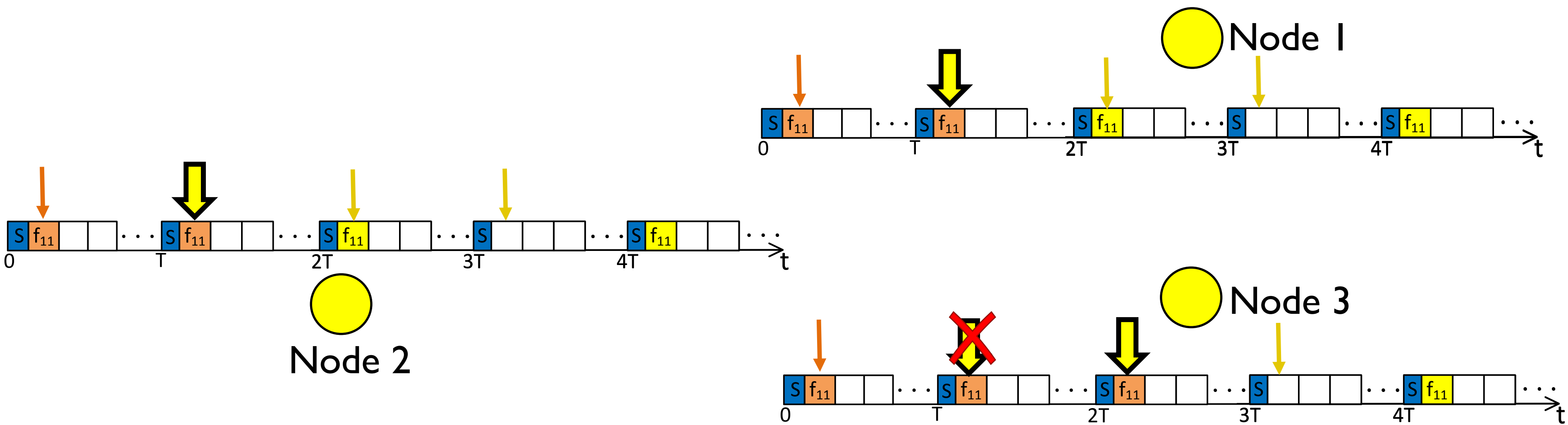
  - Every node receives updated rates and calculates its schedule locally using implicit scheduling (e.g., based on rate monotonic scheduling)



    - All nodes sleep at unassigned slots

Rate Adaptation: Packet Loss Recovery

If a node loses updated rate of loop i, it will continue to use latest rate it receives until another updated rate of loop i is received

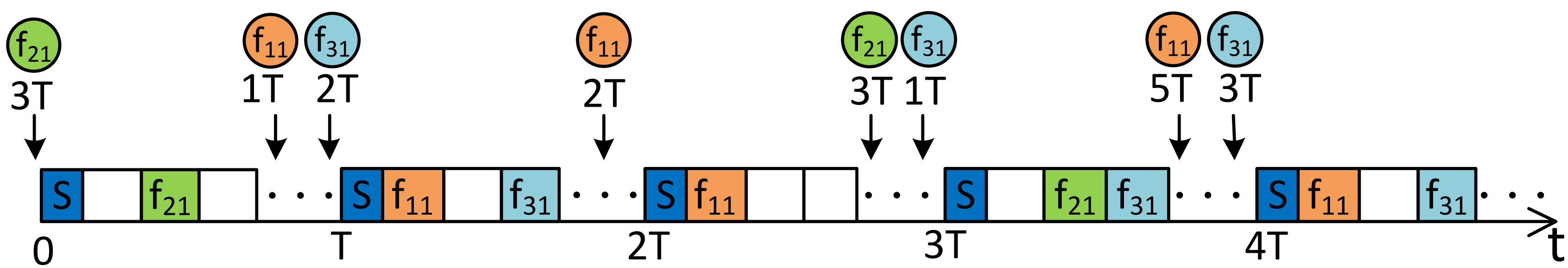


- The node recovers faster from packet loss if candidate rates share more common slots

- Candidate rate selection
  - Candidate rates should be harmonic

Self-triggered Control: Network Design

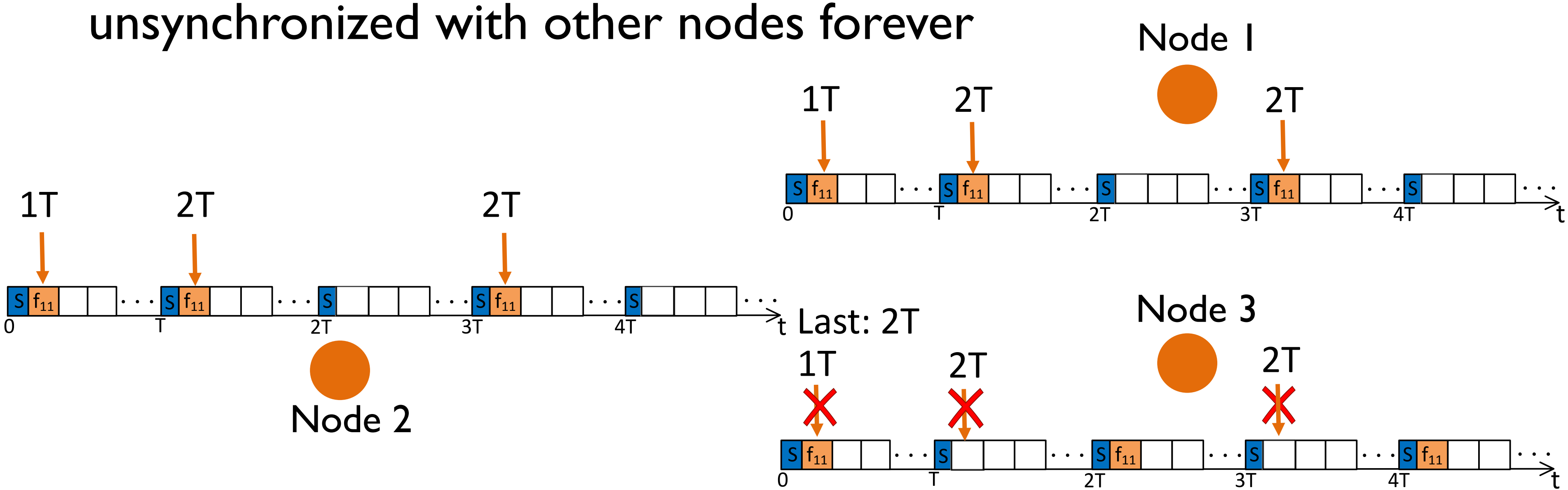
- Network reconfiguration mechanism
  - All nodes store global static schedule (max rate)
  - Holistic controllers piggyback the predicted time till the next transmission with actuation packet, and flood them in their assigned slots
  - Every node sets up timers for each flow



- All nodes sleep at inactive slots

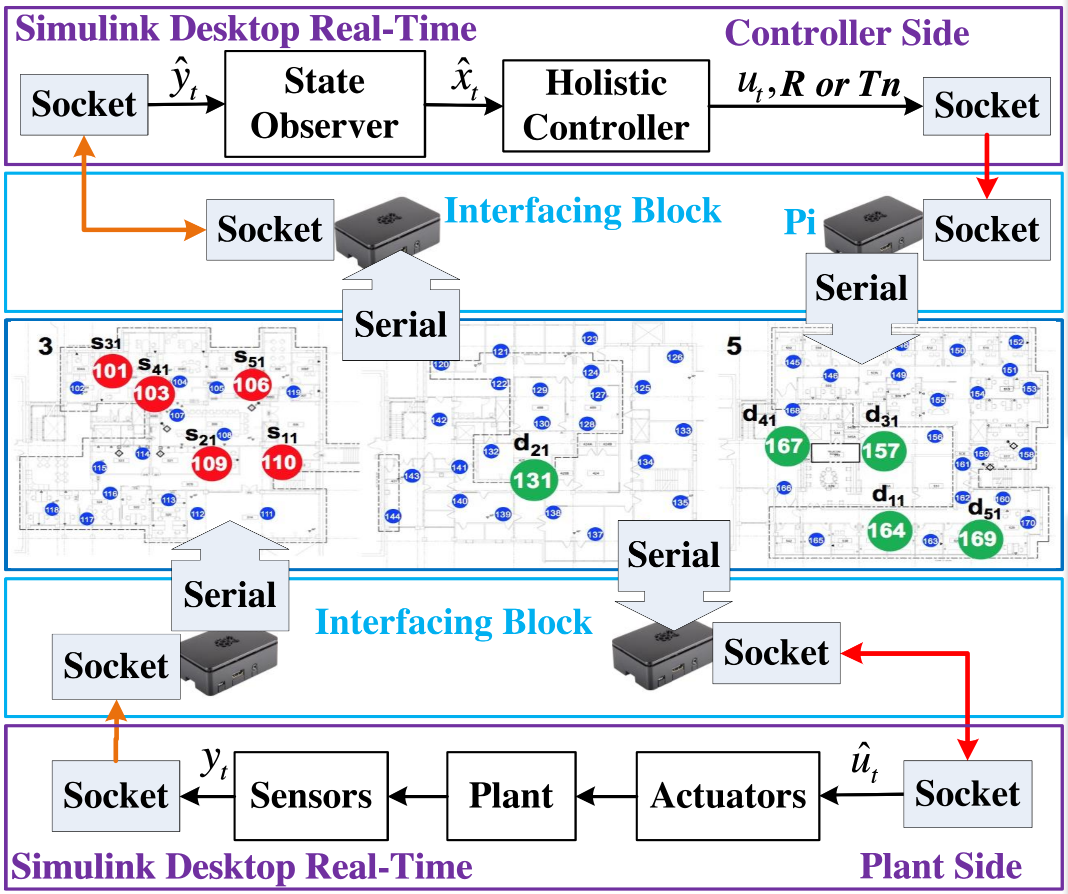
Self-Triggered Control: Packet Loss Recovery

Problem: If a node fails to receive the predicted time till the next transmission, it may wake up at the wrong time and become unsynchronized with other nodes forever



Solution: If a node loses inter-transmission time of a loop, it should re-awake at the highest rate until another actuation packet of this loop is received

WCPS-RT for Hybrid Simulation



Wireless Cyber-Physical Simulator (WCPS)

- MATLAB/Simulink
- TOSSIM
- wcps.cse.wustl.edu

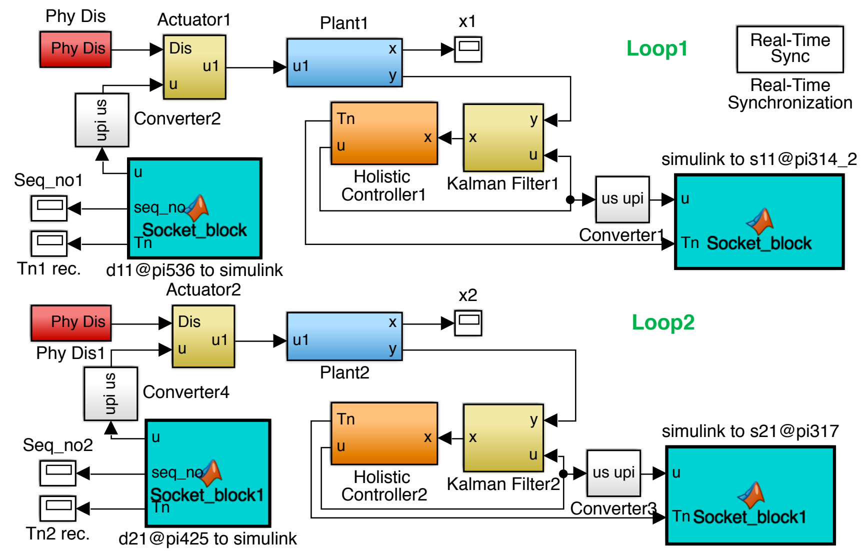
Li, B., et. al, realistic case studies of wireless structural control. In ICCPS, 2013

WCPS-RT: Hybrid Simulations

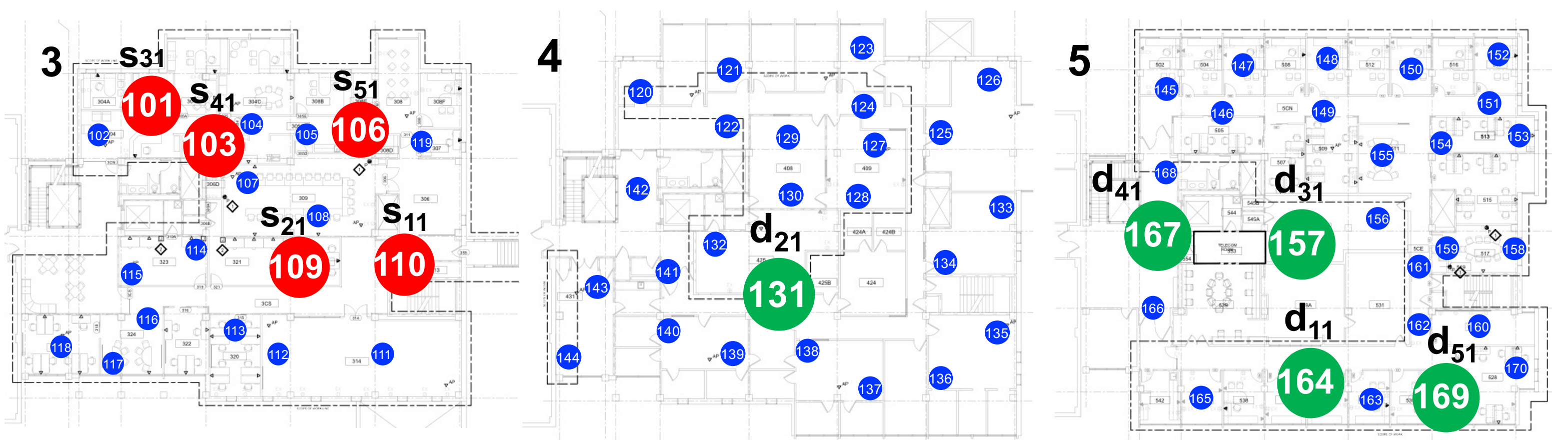
- real wireless networks + simulated physical plants
- capture wireless dynamics that are hard to simulate accurately
- leverage simulation support for controllers and plants.

Experimental Settings

- Physical plant and controller
  - Up to five 4-state load positioning plants



- 3- floor WSAN@WUSTL
  - 70 TelosB motes

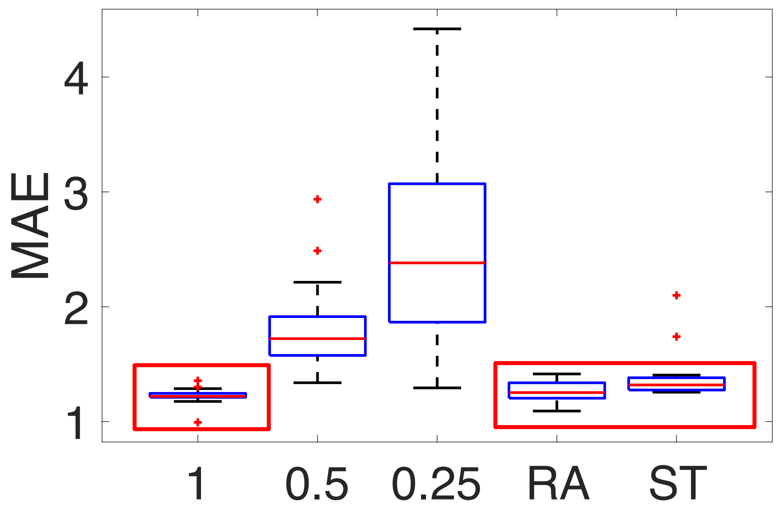


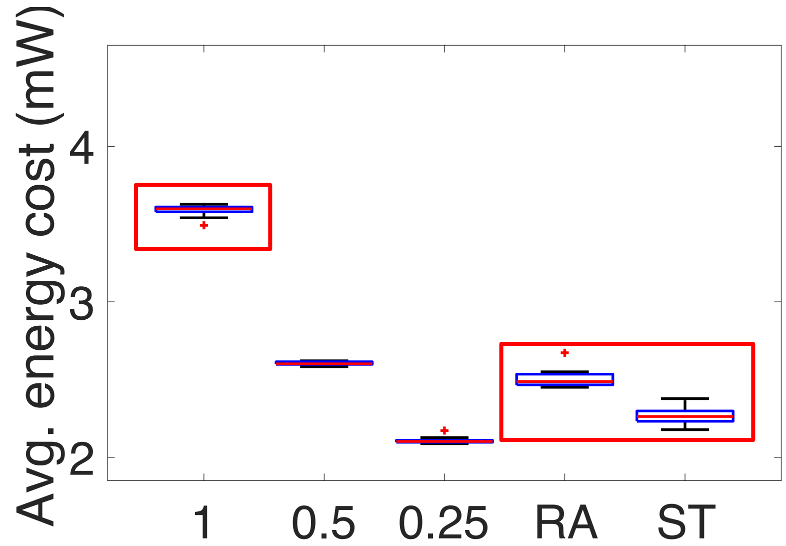
Normal Condition

Control performance metric:

$$MAE = \frac{1}{n+1} \sum_{k=0}^{n} |x(k) - x_{ref}(k)|,$$

- RA: Rate Adaptation
- ST: Self-Triggered control

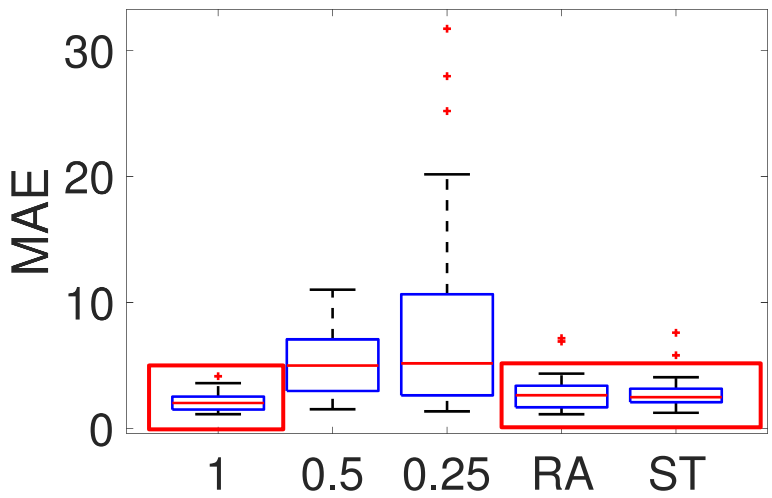


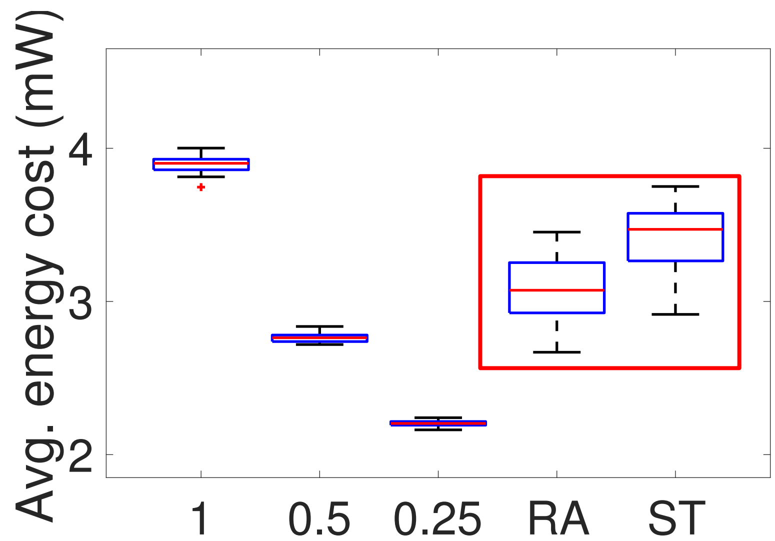


- RA and ST have similar control performance to fixed 1 Hz sampling
  - while incurring over 40% fewer energy consumption in the network!
- ST is more aggressive in energy saving than RA

Under Wireless Interference

Interference generated by WiFi

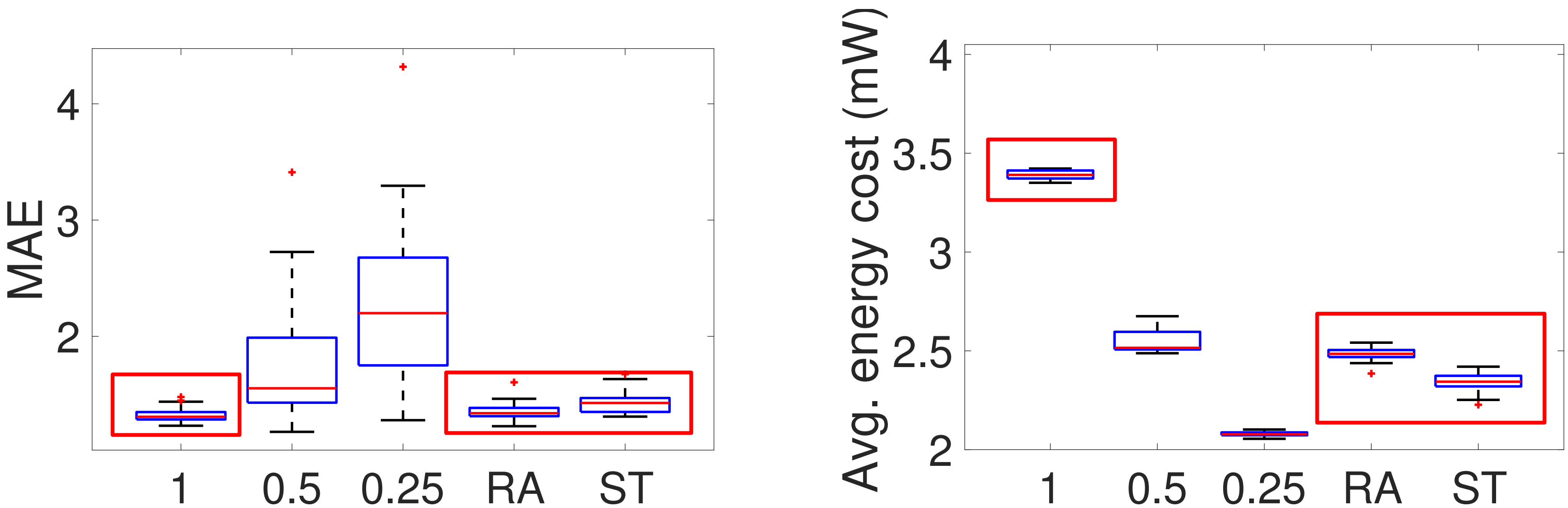




- RA and ST have similar control performance to fixed 1Hz sampling
  - Higher energy cost due to recovery, but still lower than 1 Hz sampling
- ST consumes more energy than RA, due to packet loss recovery

Under Physical Disturbance

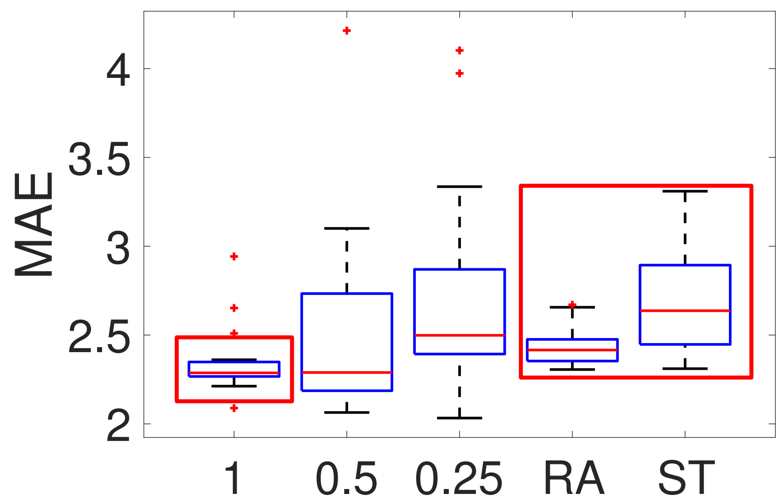
- Disturbance: constant bias of actuators
- Performance over the entire experiments

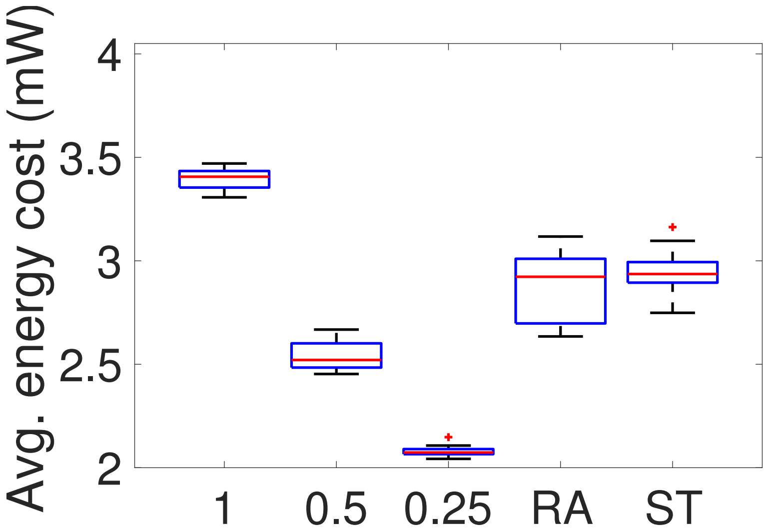


- RA and ST have similar control performance to fixed 1Hz sampling
  - Energy consumption reduction of more than 30%

Under Physical Disturbance

- During the disturbance (120s – 180s)





- ST performs worse than RA under disturbance
- Longer inter-transmission interval → slow responsive to disturbance

Conclusion

- Holistic control enhances efficiency and resiliency of wireless control systems
- Incorporate two efficient holistic control designs
  - Rate Adaptation (RA)
  - Self-Triggered control (ST)
- Novel network reconfiguration mechanisms based on LWB
- Hybrid wireless control experiments based on WCPS-RT
  - RA and ST offer advantages in control performance and efficiency
  - ST is less efficient than RA under network interference due to loss recovery
  - ST can be less responsive to physical disturbances due to predicted transmission time