CPSL
Cyber-Physical Systems Laboratory

Exploring Edge Computing for Multi-Tier Industrial Control

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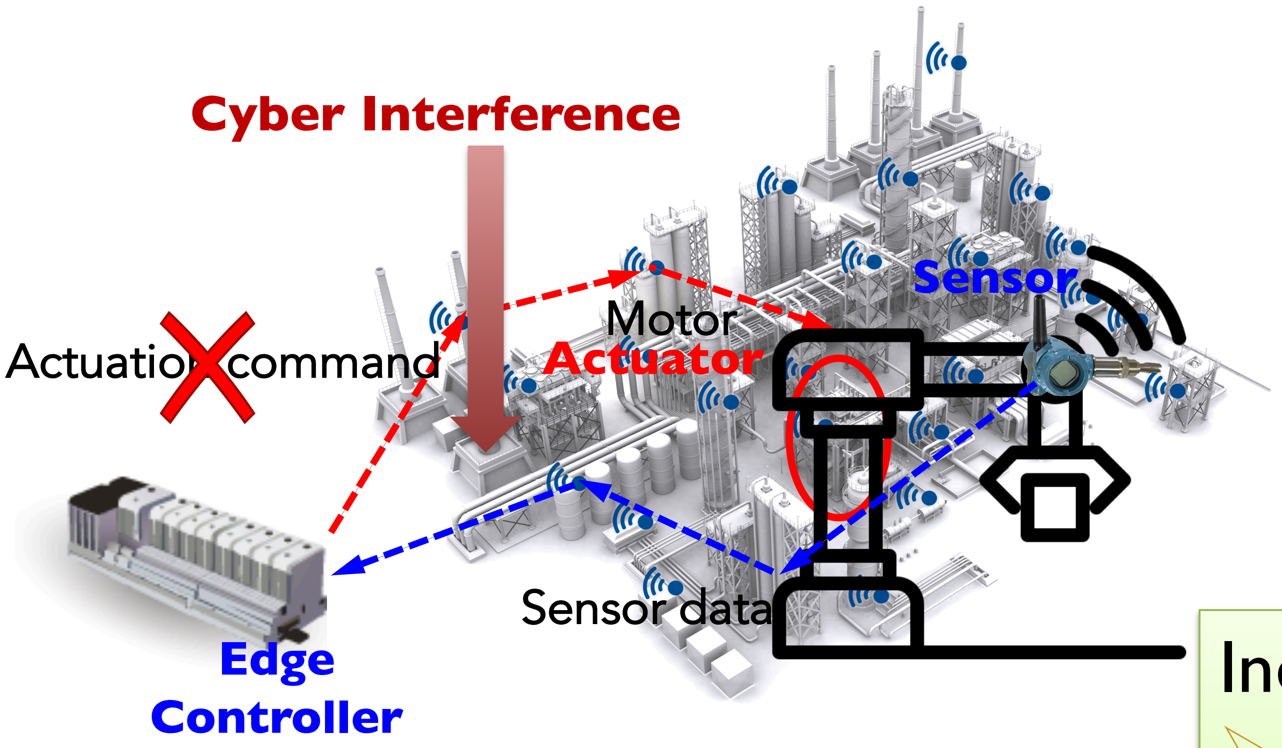
Edge Computing for Industrial Control

Edge computing and wireless networks are not ready for control!



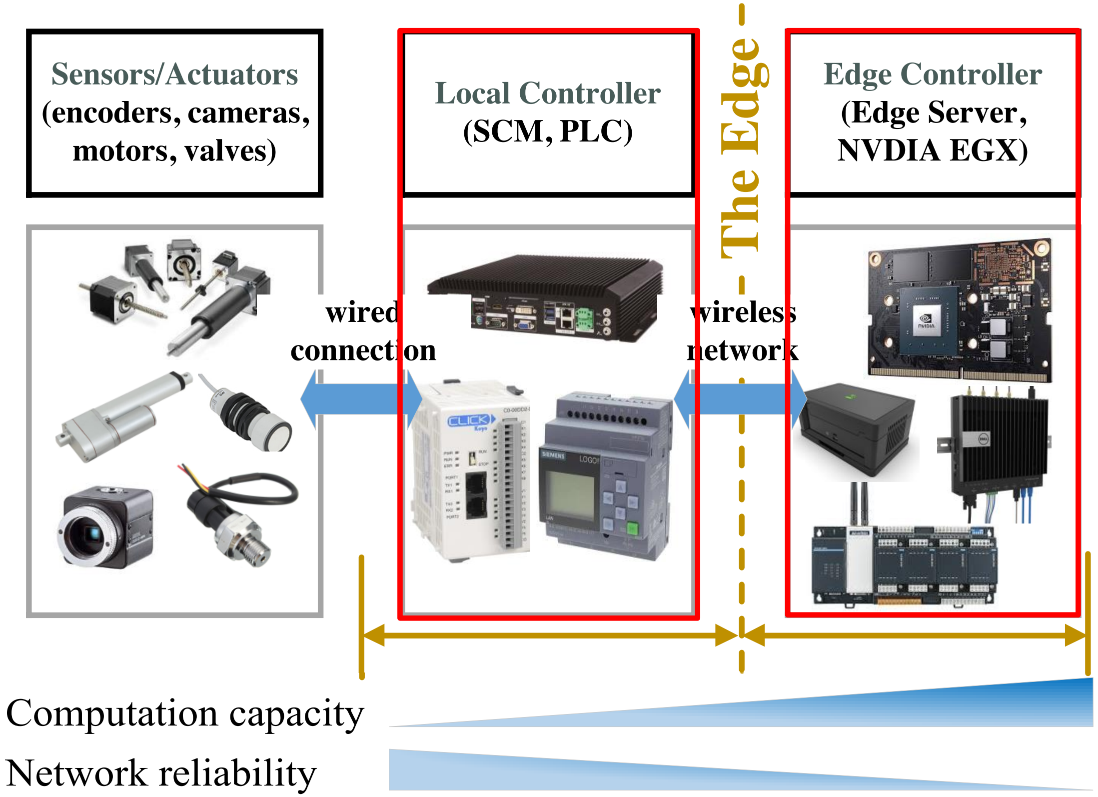
Industrial control requires
- ***Control performance***
- ***Stability***
- ***Resiliency***

Two-Tier Control Architecture

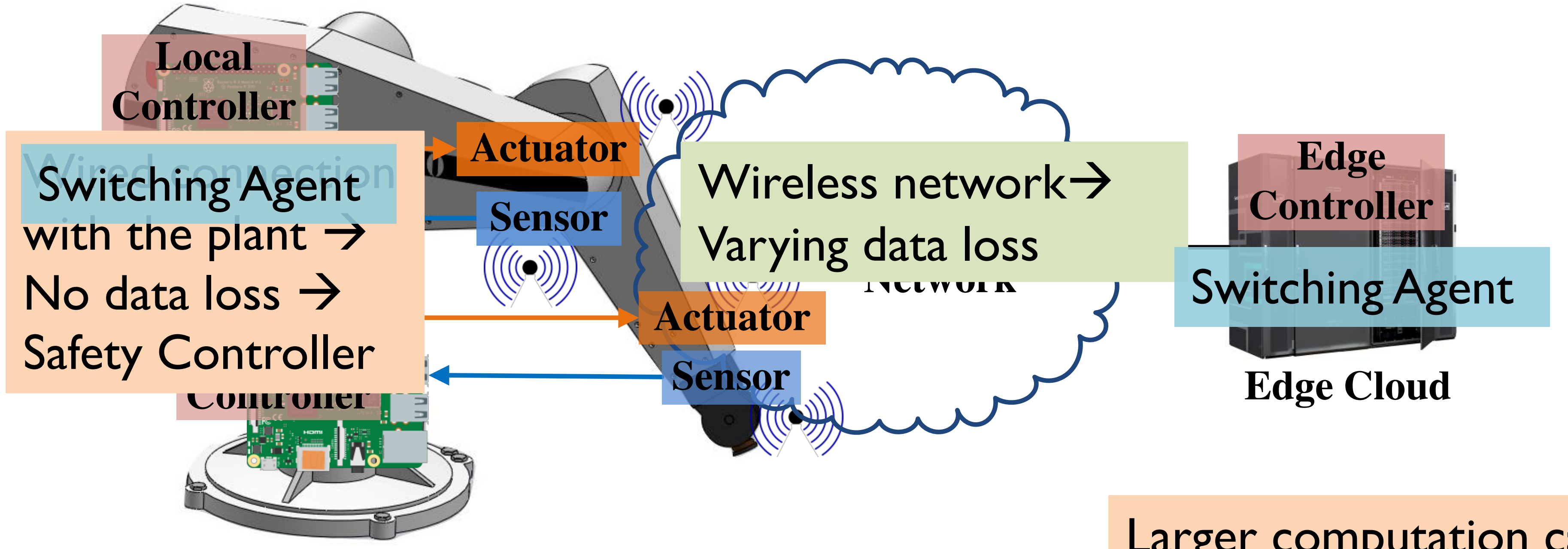
- Tradeoff between computing tiers
  - Local control: network reliability
  - Edge control: computation capacity

- Control performance depends on wireless reliability at run time

- Local control guarantees stability



System Model



Larger computation capacity →
Sophisticated control algorithm

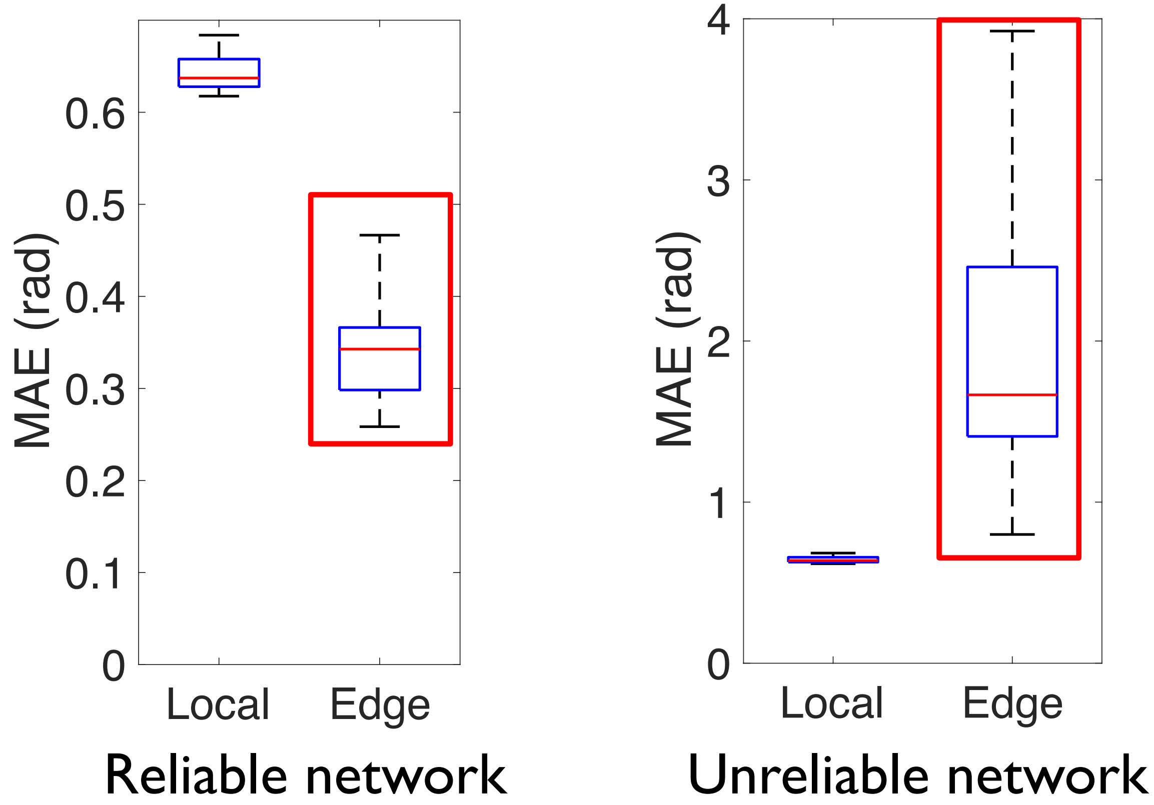
Platforms	Local	Edge
Computation	Raspberry Pi 3 (4 ARMv7 CPUs@ 900 MHz, 1G RAM)	Intel Server (4 Intel Core i5-4590 CPUs@ 3.3 GHz, 16 G RAM)
Communication	I/O + Ethernet cable	I/O + Wi-Fi + University network

Case Study: Tradeoff between Local and Edge Control

- Robotic joint position control

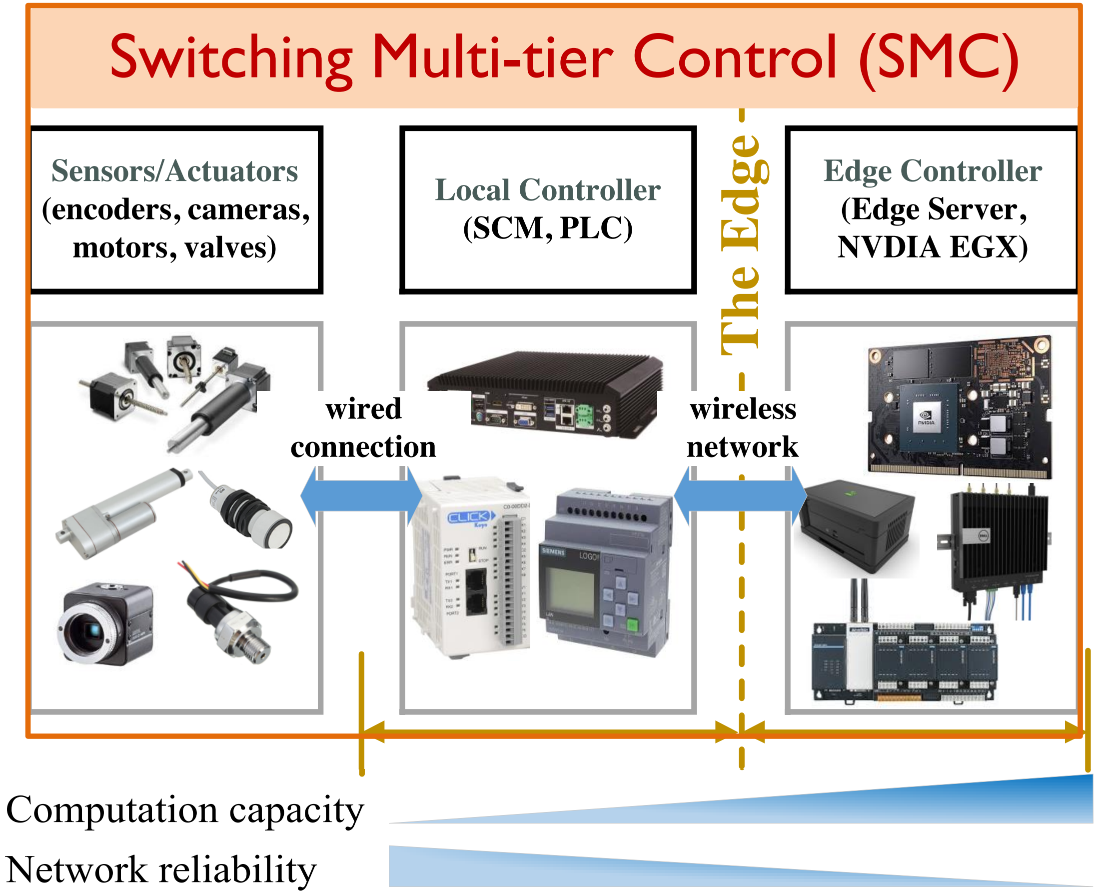
Control performance metric

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



- Edge may improve control performance
- Edge may also suffer from data loss
  - Lose performance
  - Lose stability
- Control performance depends on
  - control policy
  - network reliability
  - physical plant states

Switching Multi-tier Control: Objectives



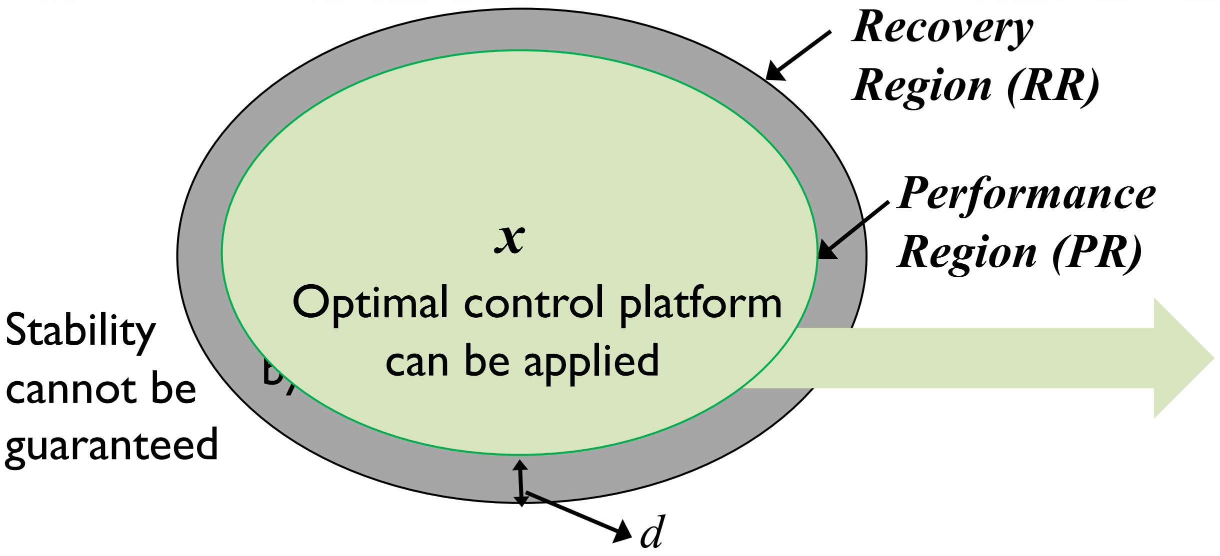
- Dynamically switch between local and edge controllers
  - to optimize control performance
  - while guaranteeing stability

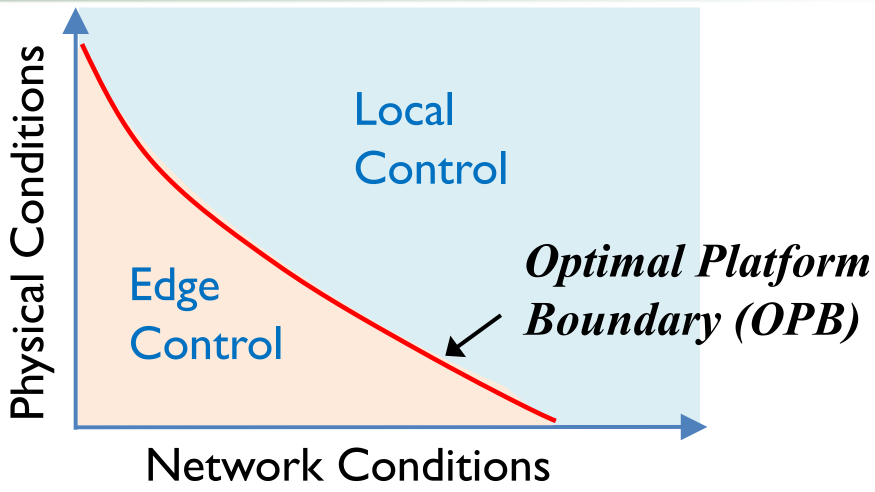
based on physical states and network reliability

Contributions

- Switching Multi-tier Control (SMC): edge computing for control
- Switching architecture
  - Optimal Platform Classifier: data-driven approaches to select optimal computing tiers
  - Stability Switch: extend Simplex to multi-tier architecture
- Hybrid simulator: WCPS-EC
  - real computing platforms + real/simulated wireless networks+ simulated plants
- Robotic control case study

Switching Logic of SMC





- The Stability Switch guarantees stability

Simplex Framework
Sha, L., Using simplicity to control complexity. IEEE Software, (4),2001

- The Optimal Platform Classifier (OPC) selects the optimal control platform

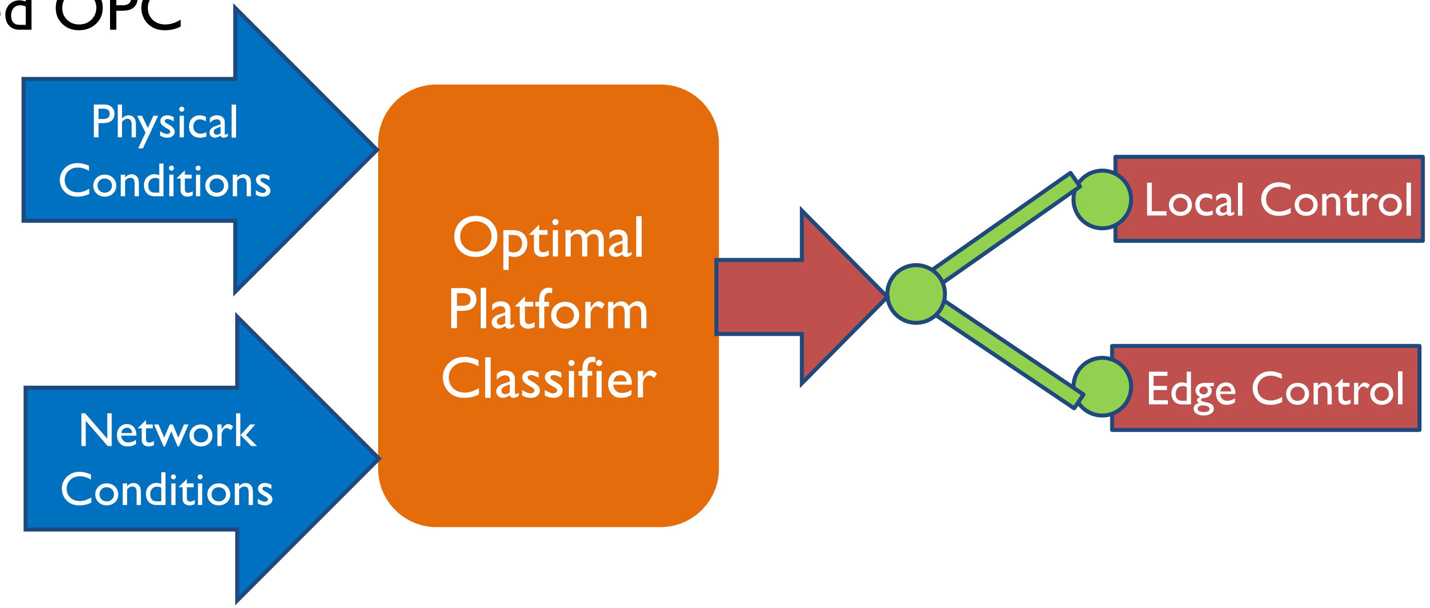
Switching Logic:

- $x \in PR$: OPC selects the optimal controller based on network conditions and physical states
- $x \notin PR$: switch to local controller to guarantee stability

Select Optimal Controller through Data-driven Approach

- Theoretical analyses of control performance over various control systems and network characteristics are challenging

- Learning-based OPC

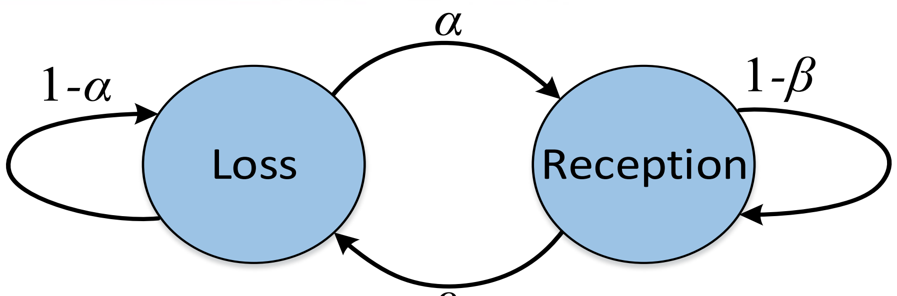


✓ Overcome restrictions of analytical modeling

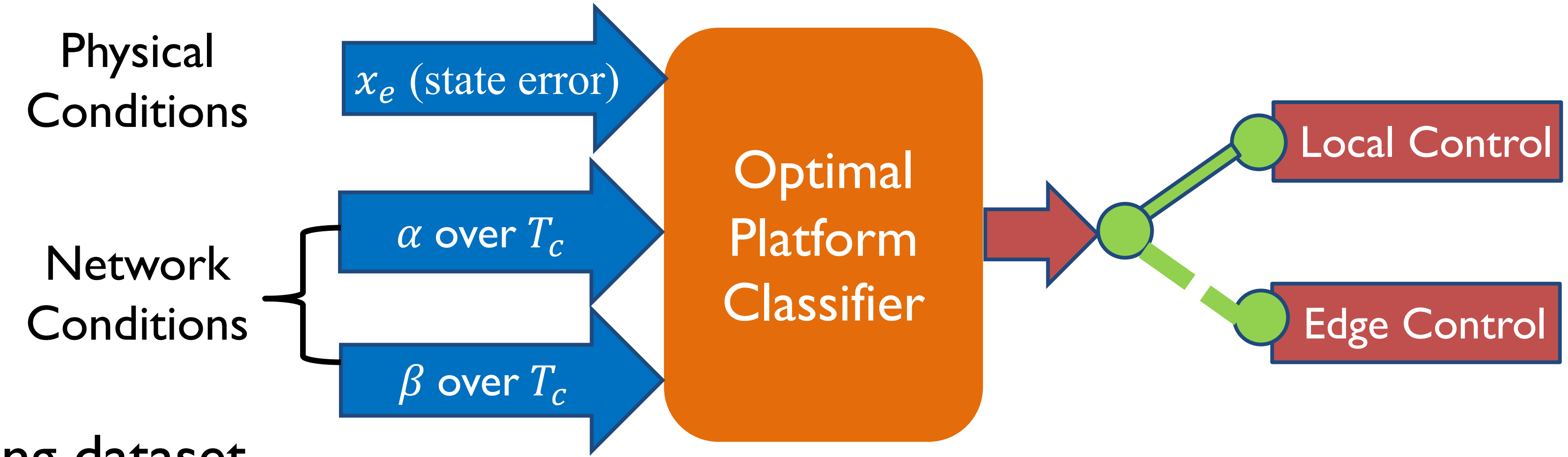
✓ Applicable to wide range of control techniques

Training Data for Optimal Platform Classifier

- Physical plant: PUMA 560
- Local: state feedback controller
- Edge: model predictive controller
- Wireless network: two-state Markov chain loss model

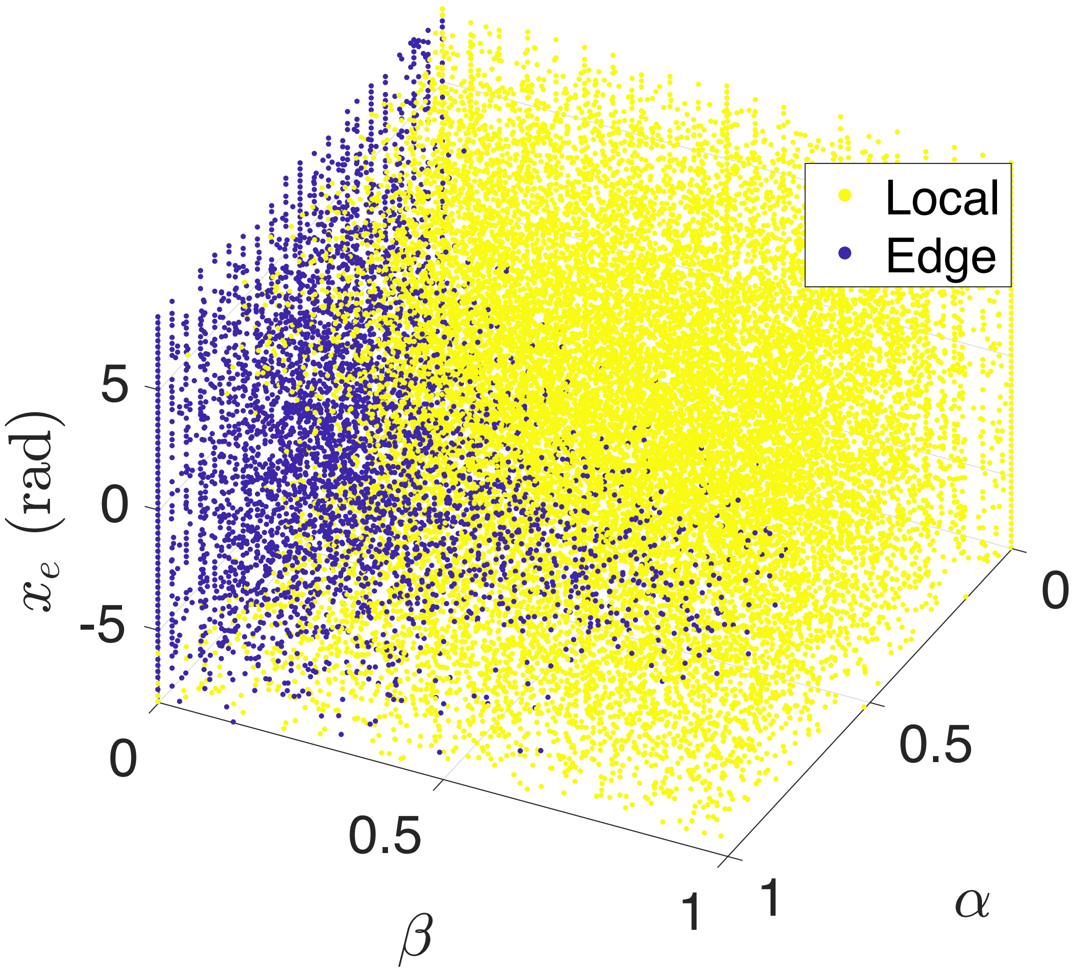


The Gilbert-Elliott loss link model



- Training dataset
  - 26,000 simulations, 40 GB data
  - Simulation interval (coordination period, prediction horizon): $T_c = 15$ s

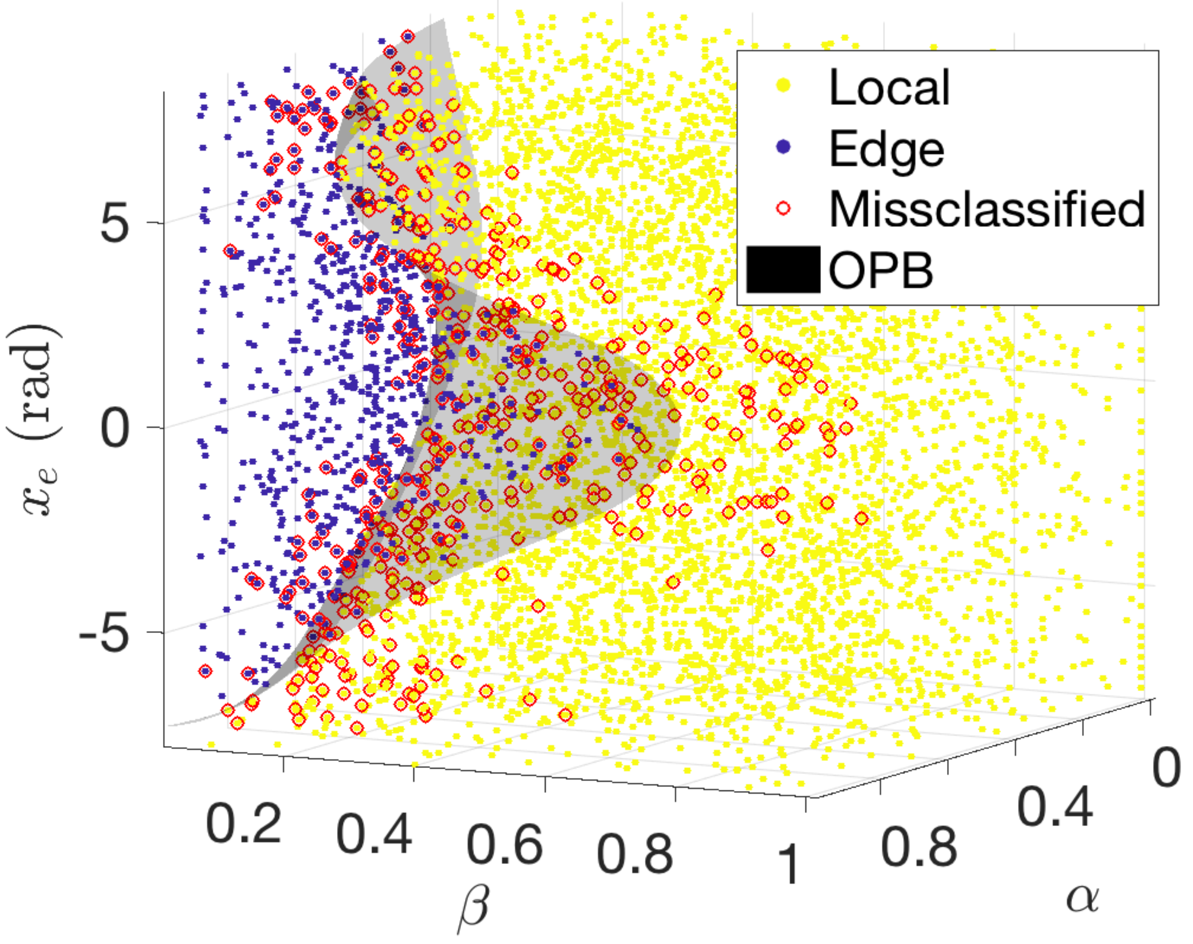
Training Data



Optimal platform labeling

- Each data point represents a simulation run
- Label each data point with the optimal controller
  - When x_e and β are low, and α is high, edge control has smaller MAE
- Training a model to classify optimal controller

Optimal Platform Classifier

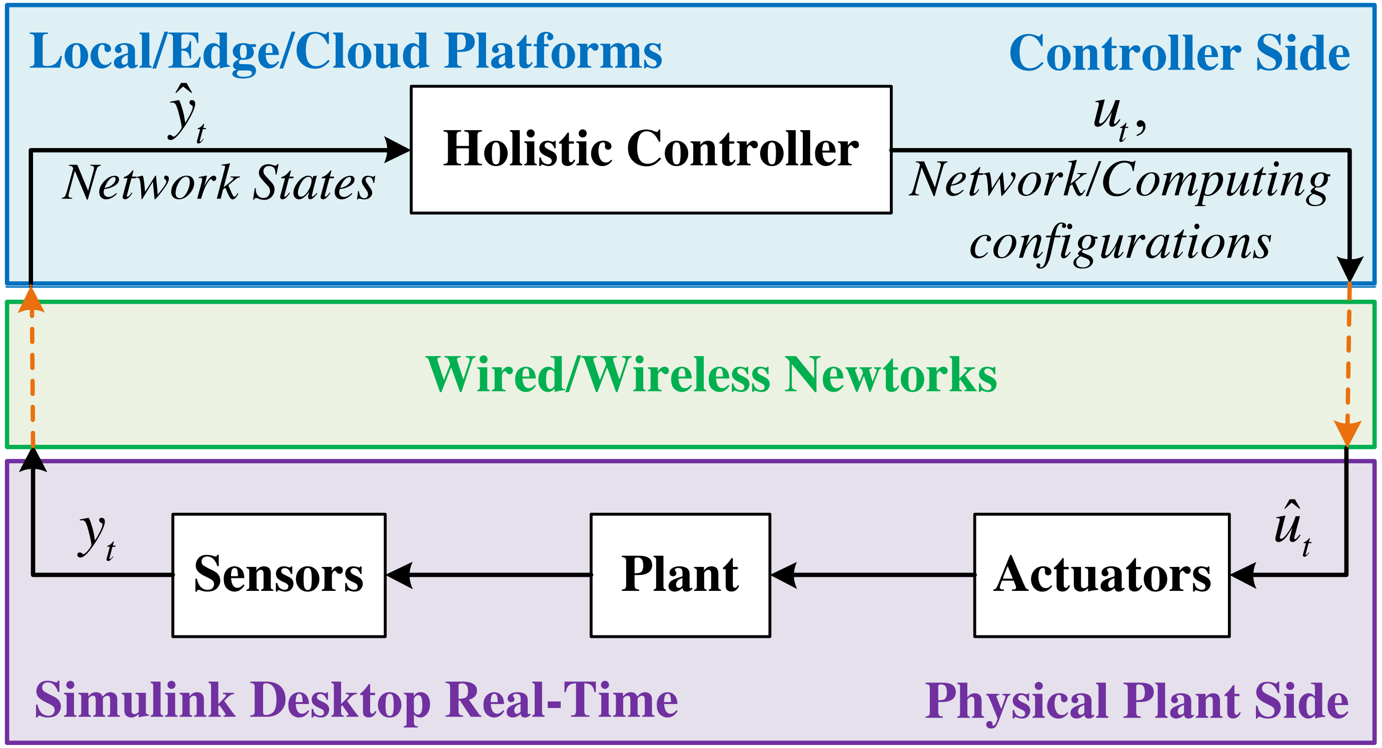


SVM OPC

- When x_e and β are low, and α is high, OPC chooses edge control
- SVM model learns the non-linear boundary between the controllers
  - Training accuracy in 10-fold cross validation: 91.72%
  - Testing accuracy: 90.98%

WCPS-EC

Wireless Cyber-Physical Simulator – Edge Computing



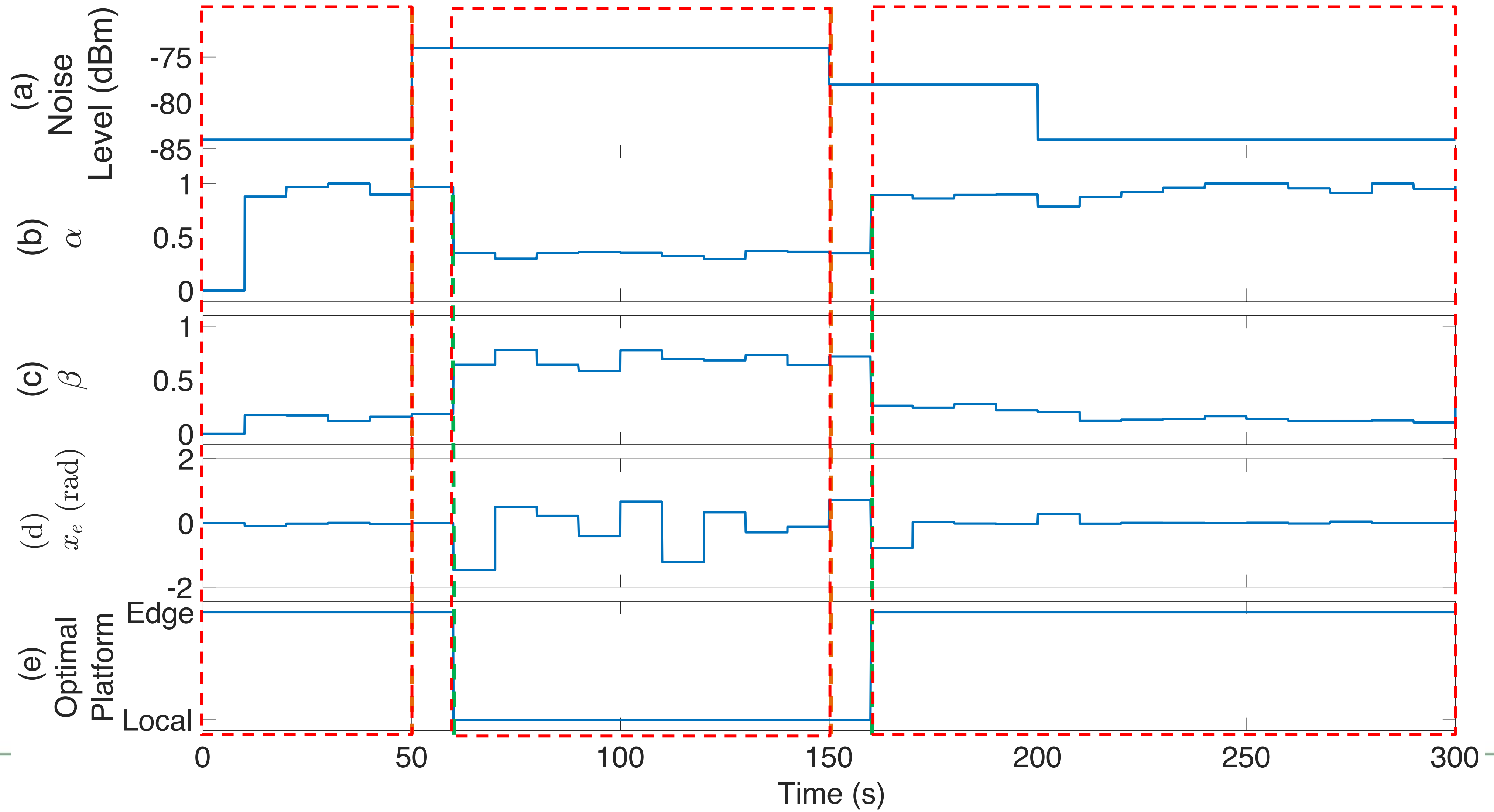
Hybrid simulations of multi-tier control

- Local/edge/cloud computing platforms
- Real/simulated networks
  - WiFi
  - IEEE 802.15.4 (TOSSIM)
- Simulated physical plants (Simulink)

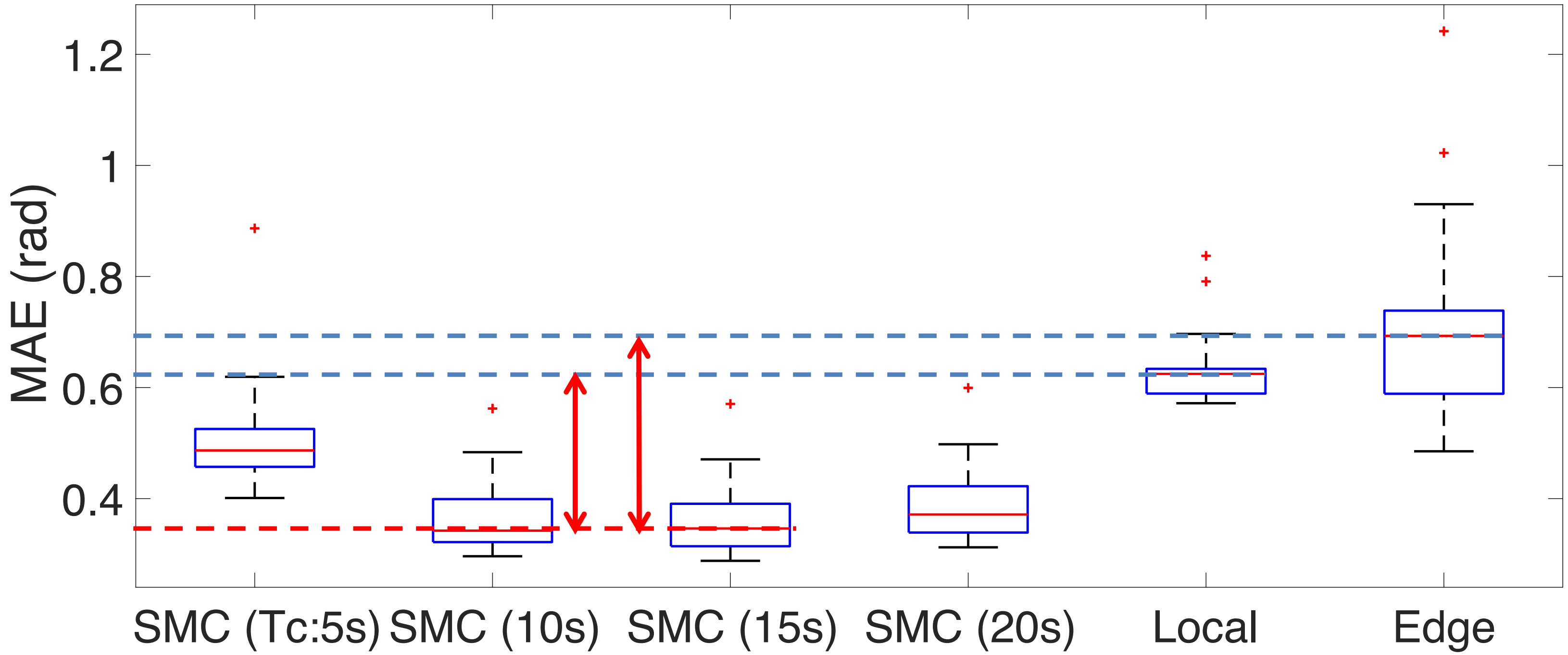
Evaluation of SMC

- Joint position control facing network loss

Coordination period (Tc): 10s



Evaluation of SMC



- SMC provides over 30% and 40% control performance improvements compared with fixed local and edge control, respectively
- When T_c is short, OPC is trained based on data in transient states only
- When T_c is long, OPC cannot react to frequently changing network conditions in time

Conclusions

- Edge computing leads to a two-tier control architecture
  - Platforms with different computation capacities and communication reliability
- Switching Multi-tier Control (SMC) optimizes performance with stability guarantees
  - Data-driven Optimal Performance Classifier → optimize control performance
  - Stability Switch → guarantee system stability
- Case study: robotic control implemented in WCPS-EC
  - SMC outperforms local and edge control
  - while maintaining stability

  under changing network reliability

Thanks. Questions?