Rethinking Communication and Control for Low-Latency, High-Reliability IoT Devices

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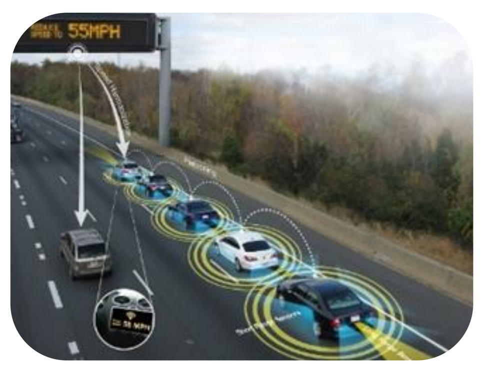
Wireless Autonomous Applications for IoT/5G

Industrial automation



Connected vehicles

Safety-critical applications

Robotics

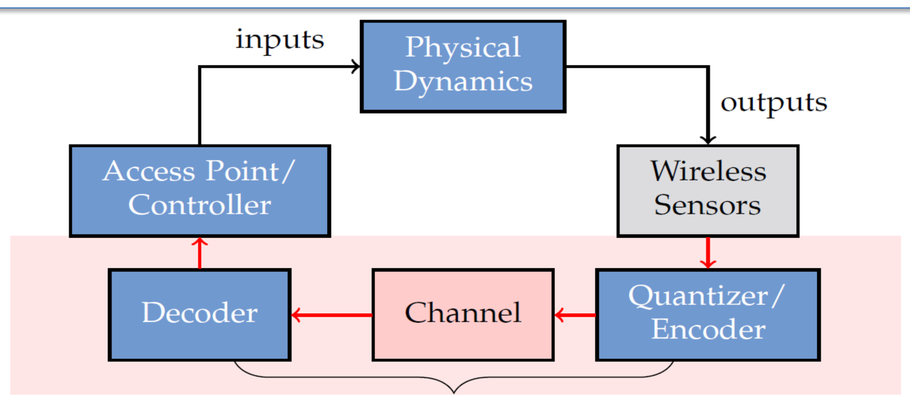
- Next generation wireless networks target time-sensitive autonomous systems:
- Ultra-low latency (<1ms), ultra-high reliability (99.999%), large-scale deployments
- Need for fast and reliable information transfer beyond capabilities of current networks

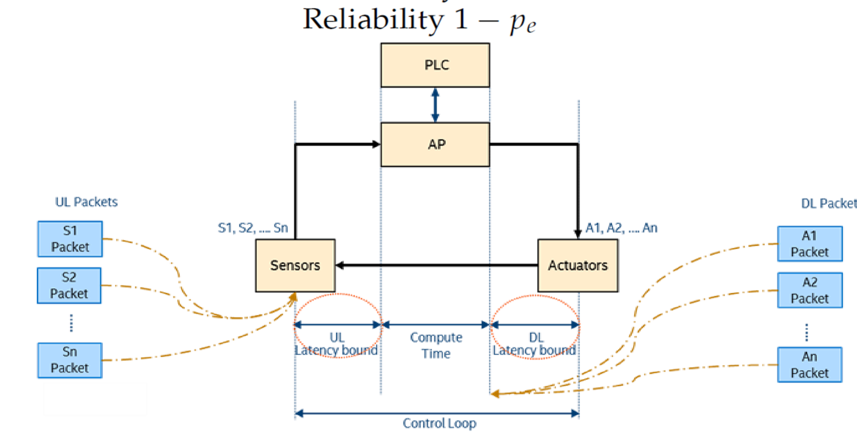
Project Goals:
- Design low-latency short packet codes and fundamental latency-reliability-rate tradeoffs over channels
- Rethink estimation and control designs based on novel rate-latency-reliability abstractions
- Enable large scale wireless control networks by reformulating as learning problems with tools such as GNNs

New Abstractions for Low-Latency High-Reliability Wireless Control

- Need for a new abstraction
  - Latency: important in order to respond to physical disturbances timely
  - Reliability: important in order to ensure overall system safety and stability
  - Rate: important in order to convey high fidelity control information
  - Uncertainty: adapt to unknown channel conditions and system dynamics
- Wireless control model features closing loop over error-prone channel
  - UL transmission given small latency threshold
  - Packet containing state info otherwise dropped

$$x_{k+1} = Ax_k + Bu_k + w_k, \ k \geq 0$$





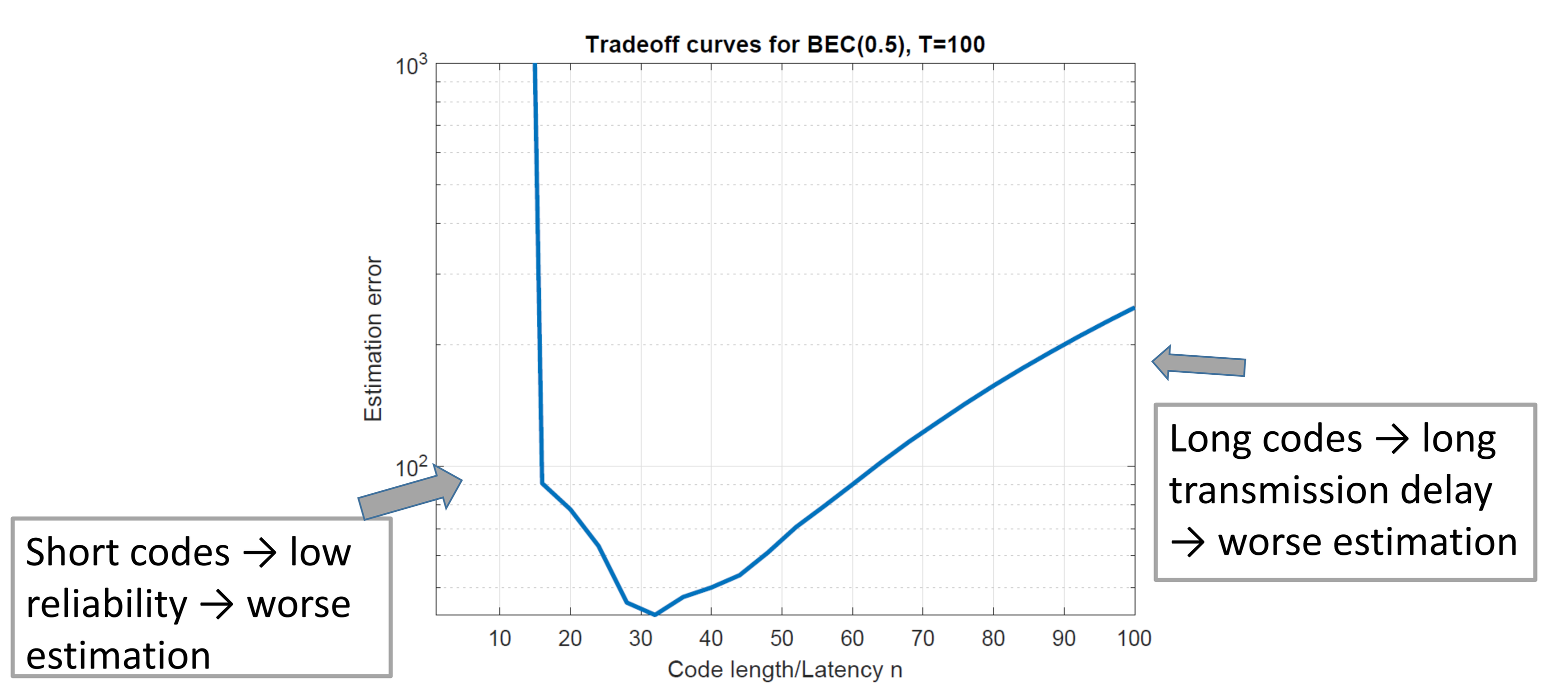
Optimal Code Length Selection for Low-Latency State Estimation

- Information theory describes how optimal error rate scales with code length (but decoding complexity is a challenge)

$$p_e = Q\left(\sqrt{\frac{n}{V}}(C-R) + O(\log n)\right)$$

- Co-design: select optimal code length and code error rate that optimizes estimation performance of dynamical process

$$\frac{A^d + (p_e + \frac{1-p_e}{2^r})(A^T - A^d) - 1}{1 - (p_e + \frac{1-p_e}{2^r})A^T} \frac{W}{A-1}$$



*Gatsis, Hassani, Pappas. "Latency-Reliability Tradeoffs for State Estimation". Submitted. Arxiv '19

Scheduling for Low-Latency Control in IEEE 802.11ax

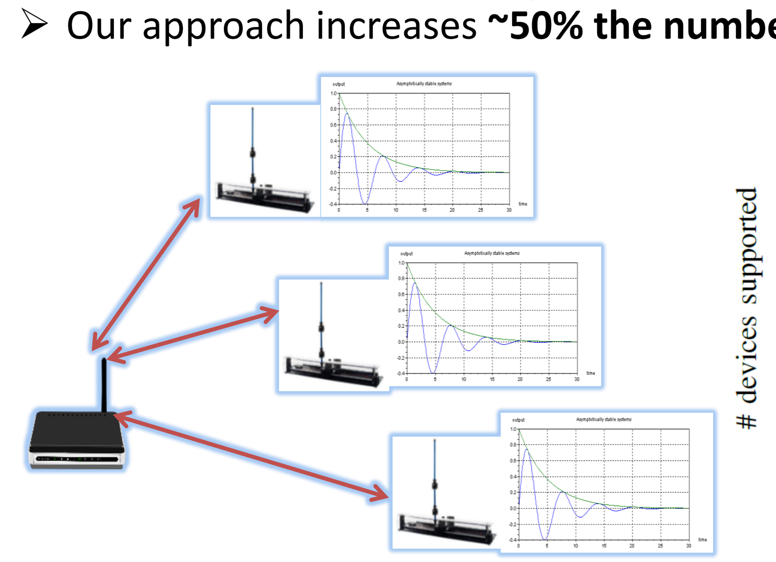
- Develop co-design scheduling method for low-latency wireless control systems
- Control systems can often afford lower packet error rates than traditional high reliability goals
- Results are leveraged to service larger number of users under tight low-latency constraints

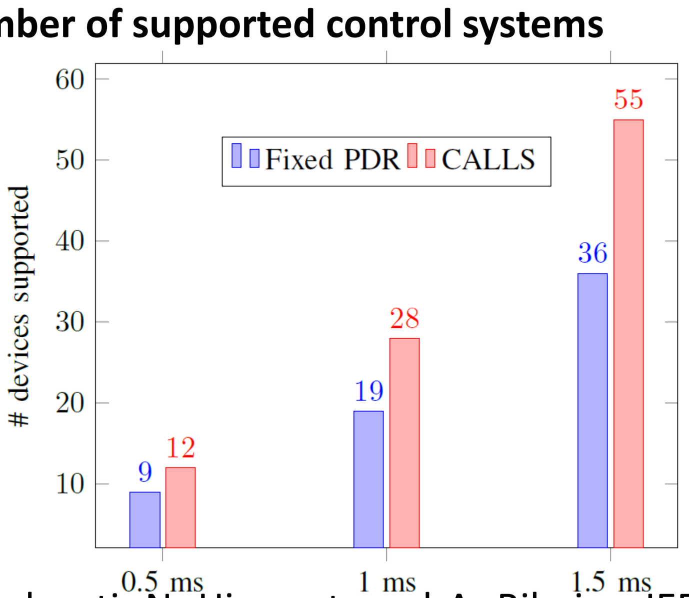
$$q(\mathbf{h}_{i,k}, \mu_i, \varsigma_i) \geq \frac{1}{\Delta_i}\left[\left\|(\mathbf{A}_i^c - \rho\mathbf{I})\hat{\mathbf{x}}_{i,k}^{(l_i)}\right\|_{\mathbf{P}^{\frac{1}{2}}}^2 + (1-\rho)\sum_{j=0}^{l_i-1}\omega_i^j + \omega_i^{l_i} - c_i\right],$$

where we have further defined the constant

$$\Delta_i := \sum_{j=0}^{l_i-1}[\omega_i^{j+1} - Tr(\mathbf{A}_i^{cT}(\mathbf{A}_i^T\mathbf{P}^{1/j}\mathbf{A}_i)^j\mathbf{A}_i^c\mathbf{W}_i)].$$

- Our approach increases **~50% the number of supported control systems**





*M. Eisen, M. M. Rashid, K. Gatsis, D. Cavalcanti, N. Himayat, and A. Ribeiro, IEEE IoT Journal '19

Broader Impact

Industrial Impact:
- Leveraging existing collaboration in Intel Science and Technology Center (ISTC) on Wireless Autonomous Systems
- Integrating our results on Next Generation WiFi Protocol (802.11ax) for industrial control processes with improved latency and scalability

Educational impact:
- Planning a Micro-Masters program in Internet of Things (IoT) on the edX MOOC platform
- Development of new courses on the topics of the project

i) Reinforcement Learning: including topics relevant to Learning for Large Scale Wireless Control

ii) Coding For IoT: including both practical and fundamentals of information theory from the perspective of IoT devices

Future Directions

- **Low-latency channel coding:** Novel short channel-coding to meet low-latency requirements with efficient decoding
- **Control over low latency-aware communication channels:** Optimal joint coding and controller design over latency-reliability curves
- **Learning for large scale wireless control networks:** Data-driven optimization for large scale wireless control networks with competing latency/reliability requirements using Graph Neural Networks
- **Evaluation:** Implementation in future wireless protocols (IEEE 802.11ax) and experimental demonstration in high-speed formation control with ground vehicles and aerial swarms.

Penn

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