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

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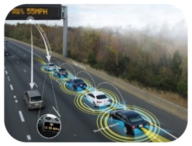
Wireless Autonomous Applications for IoT/5G

Industrial automation



Connected vehicles

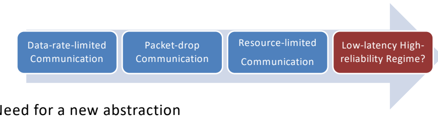
Safety-critical applications

Robotics

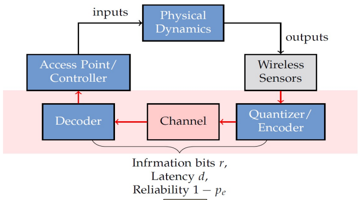
- Next generation wireless networks target time-sensitive autonomous systems:
- Ultra-low latency (<1ms), ultra-high reliability (99.999%), large-scale deployments
- Need for fast and reliable information transfer beyond capabilities of current networks

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

Problem Formulation

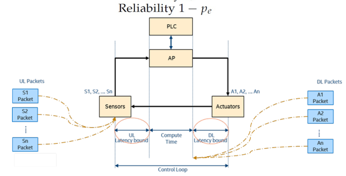


- Need for a new abstraction
- ➢ Latency: important in order to respond to physical disturbances timely
- ➢ Reliability: important in order to ensure overall system safety and stability
- ➢ Rate: important in order to convey high fidelity control information
- ➢ Uncertainty: adapt to unknown channel 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

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



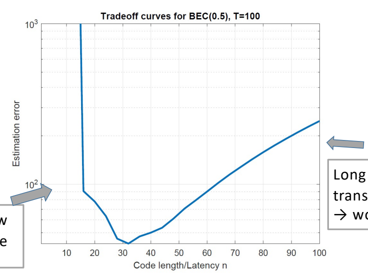
Optimal Code Length Selection for Low-Latency State Estimation

- 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. IEEE TAC 2020
Gatsis, Pappas, Statistical learning of network control systems, Automatica 2021

Scheduling for Low-Latency Control in IEEE 802.11ax

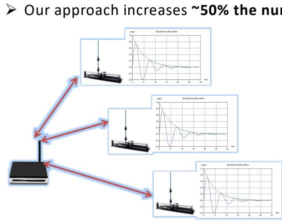
- Develop co-design scheduling method for low-latency wireless control systems
- Control systems can often afford lower packet error rates than traditional high reliability goals
- Results are leveraged to service larger number of users under tight low-latency constraints

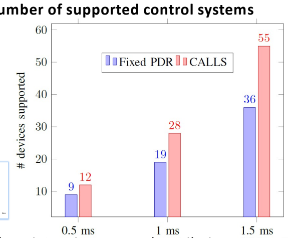
$$q(\mathbf{h}_{i,k}, \mu_i, \varsigma_i) \geq \frac{1}{\Delta_i}\left[\left\|(\mathbf{A}_i^c - \rho\mathbf{I})\hat{\mathbf{x}}_{i,k}^{(l_i)}\right\|^2_{\mathbf{P}^{\frac{1}{2}}} + (1-\rho)\sum_{j=0}^{l_i-1}\omega_i^j + \omega_i^{l_i} - c_i\right],$$

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 '19
D. Kalogerias et at, Almost Zero Duality Gaps in Model-Free Wireless, 2021

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:
- Development of new courses on the topics of the project

i) Reinforcement Learning: including topics relevant to Learning for Large Scale Wireless Control
ii) Graph Neural Networks for Distributed Systems and wireless communications
ii) Learning and Control focusing on the interface between machine learning and control systems

Future Directions

- **Low-latency channel coding:** Novel short channel-coding to meet low-latency requirements with efficient decoding
- **Federated Learning and Control over IoT data:** Optimal joint communication, learning, and controller design over latency-sensitive IoT devices
- **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.

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