Queuing Analysis of Wireless Systems: No Waste of Time!

Dagstuhl Seminar “Predictable Systems”

March 2019

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joint work with S. Schiessl, H. Al-Zubaidy, J. Champati

Queuing Analysis of Wireless Systems: Waste of Time?

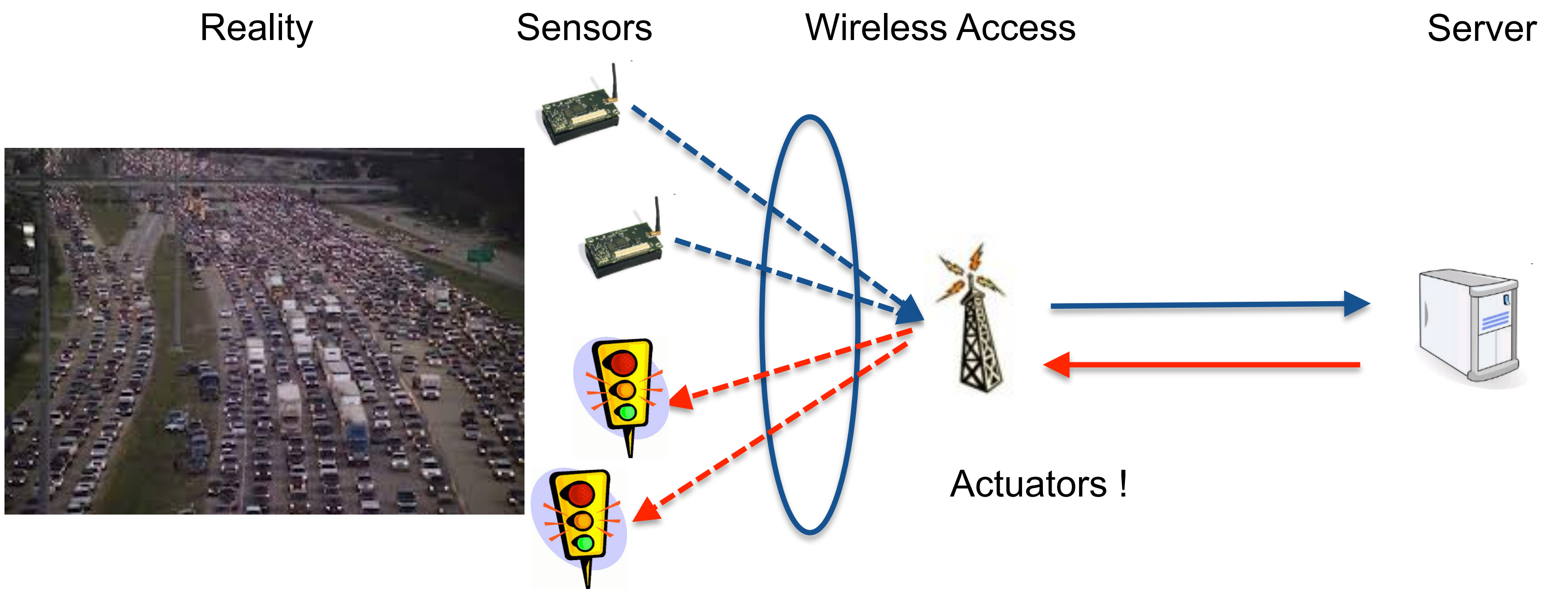
Dagstuhl Seminar “Network Calculus”
March 9th, 2015
James Gross

Take-home message 4 years ago

- Had worked with effective capacity, analyzed various wireless system set-ups (SISO, interference, relaying)
- Strived for accurate communication-theoretic modeling
- Results typically not easy to obtain
- Implications typically not very surprising
- Little attention in particular from industry

➔ Should this still be continued?

URLLC Motivation



- From sensing applications to closed-loop control
- Dependability becomes the focus (latency, reliability)

  ➔ URLLC: Ultra-reliable low latency communications!

URLLC: Application Fields

- Various application fields according to 3GPP:
  - Rail-bound mass transit
  - Building automation
  - Factory of the future / industrial automation
  - Smart living / smarty city
  - Electric power distribution & power generation

- In addition:
  - Support for autonomous devices (cars, drones, robots)
  - Human-in-the-loop applications (AR / cognitive assistance)

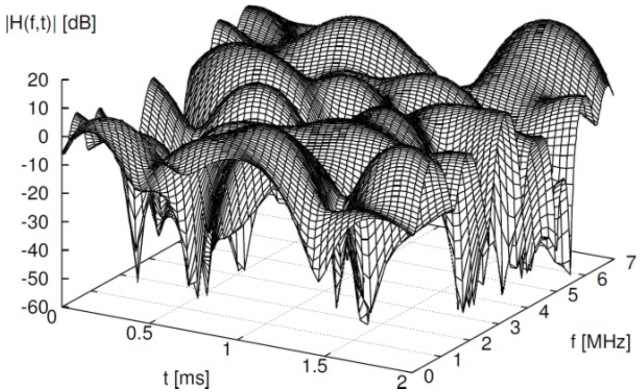
3GPP, TR22.804 v1.0.0, December 2017

Range of Factory Automation Requirements

- Dependability: Availability + Reliability + Security

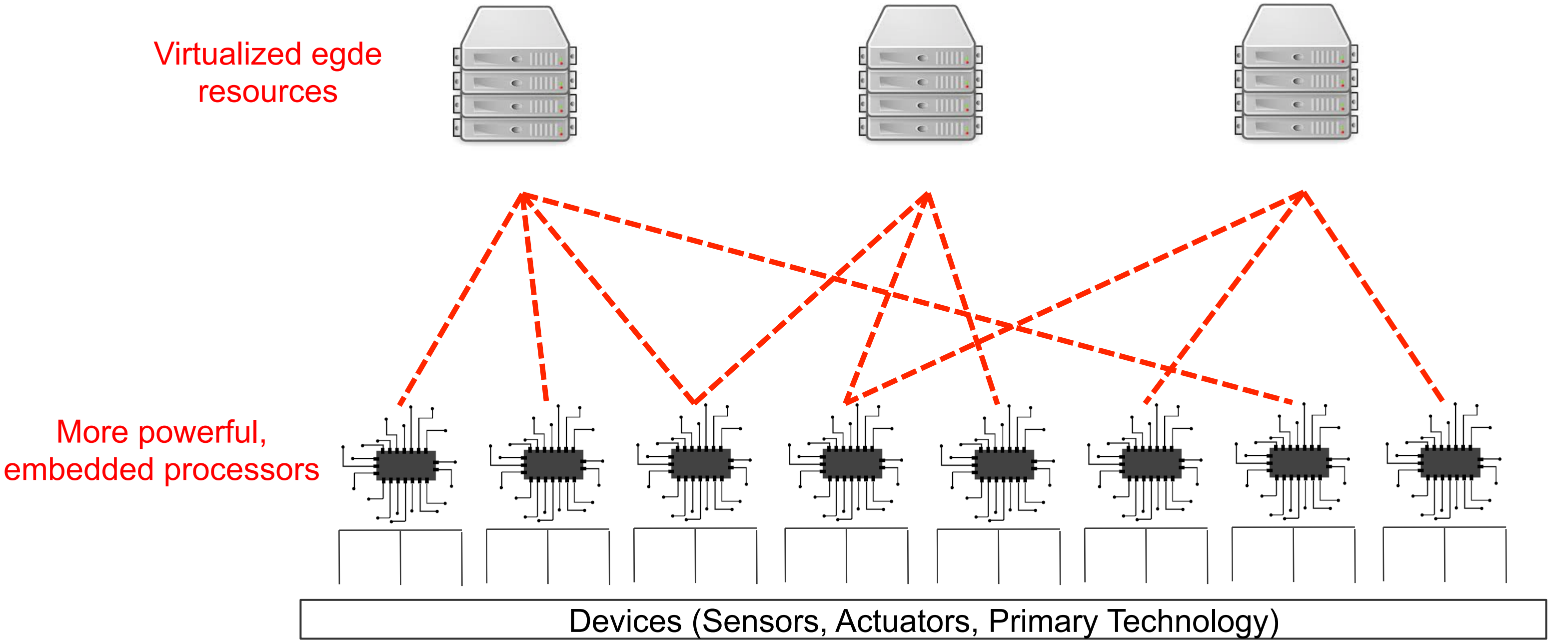
- Field-Level Control
  - Cycle time: <10 ms
  - Packet sizes: < 10 byte
  - Reliability: > $1 - 10^{-6}$

- Inter-PLC Communication:
  - Cycle time: < 50 ms
  - Packet sizes: < 500 byte
  - Reliability: > $1 - 10^{-6}$



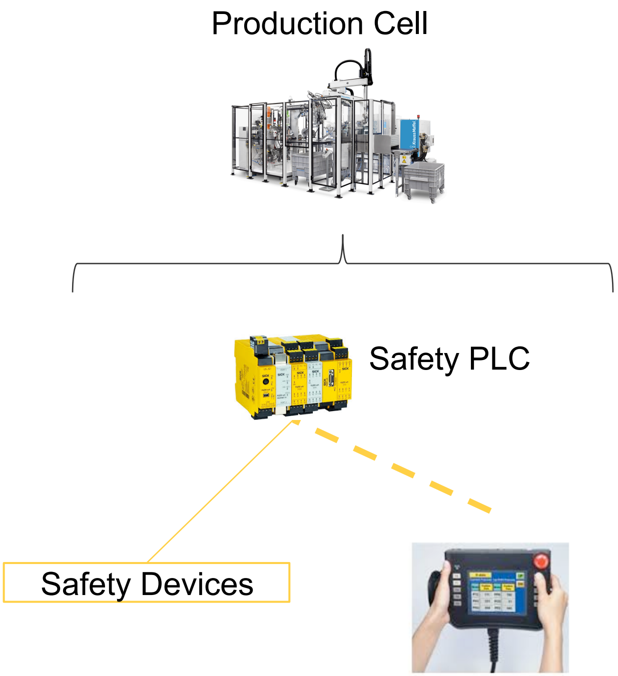
Why turn to wireless?

Visionary Reasoning: Flexibility

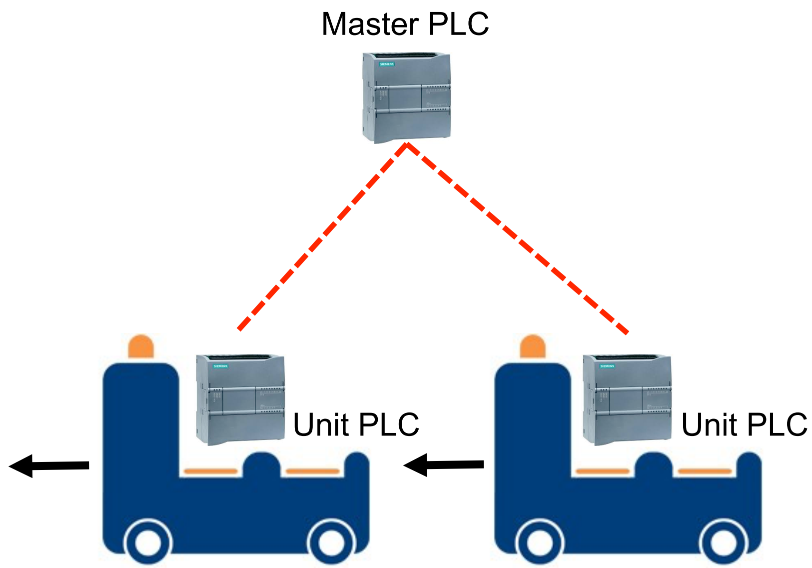


Realistic Use Cases: Mobility-Driven

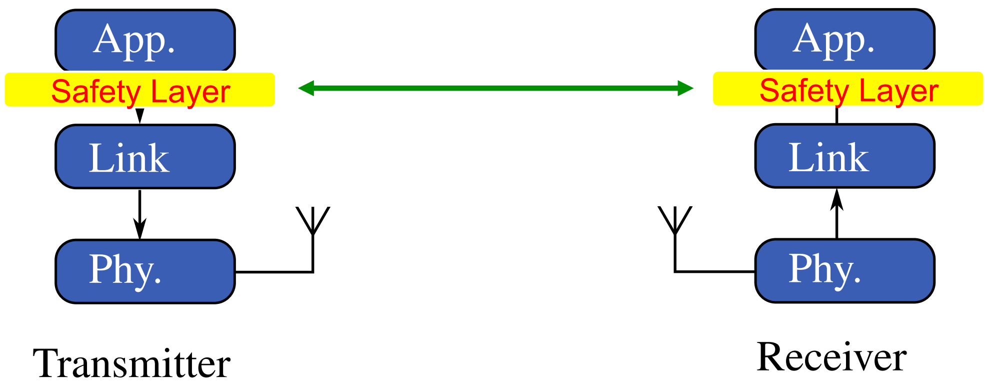
Safety Cases



Logistics Cases

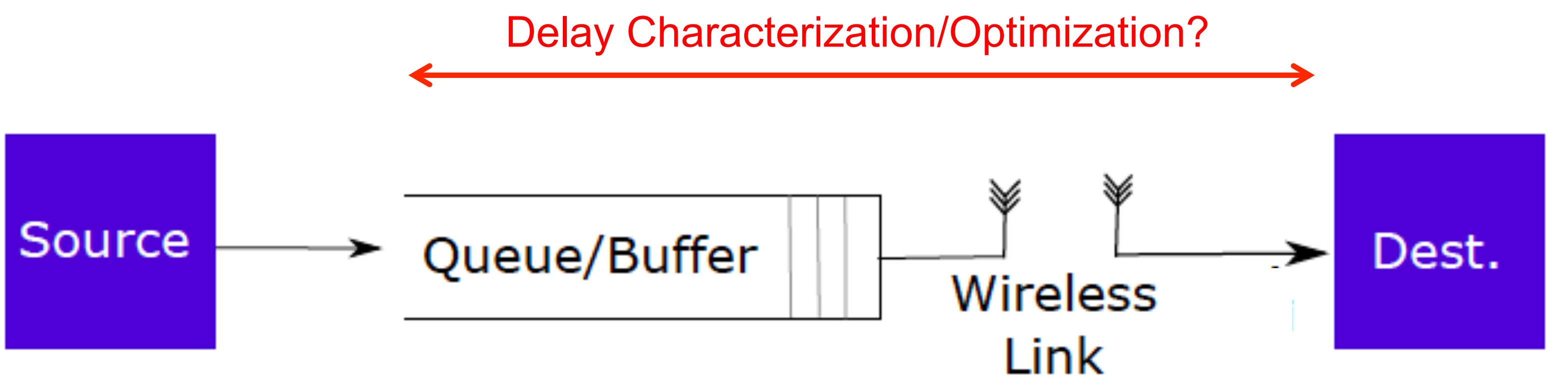


Systems & Safety Layers



- Black channel principle
- Periodic message exchange, >10 ms cycle time
- Small PDUs, about 10 byte
- **Turns link reliability issues into availability issues of the system**

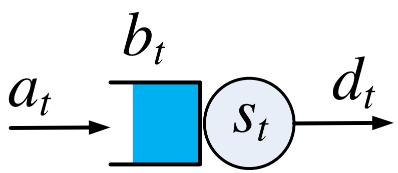
Queuing-Theoretic Problem Formulation



- Deterministic arrivals
- Random service: Fading, interference, cross-traffic

Modeling Assumptions

- Discrete time t
- Fluid-flow model
- FIFO Queue with infinite size
- Constant arrivals
- Work-conserving server
- Service increments are independent & stationary



Wireless Service Increments

- Shannon capacity used for principle design of networks

$$C_{\mathrm{IBL}} = \log_2 (1+\gamma) \;\; [\text{bits / channel use}]$$

- Low latencies ➔ Shannon capacity inappropriate
  - Assumes infinitely long code words

- Tight finite blocklength approximation:

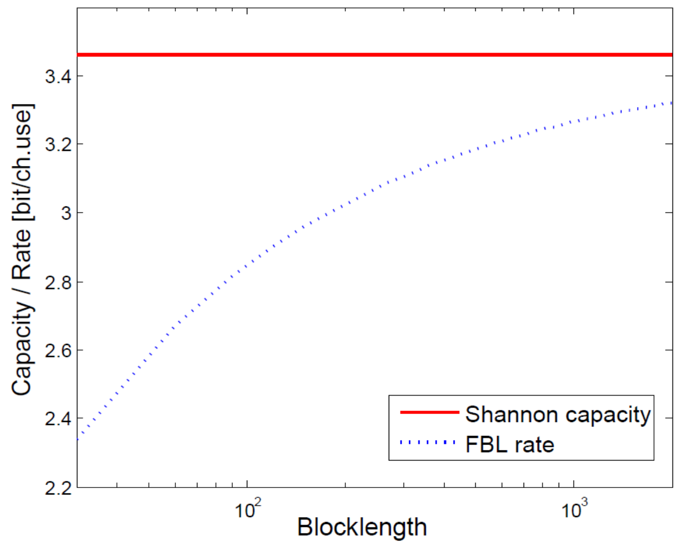
$$r_{\mathrm{FBL}} \approx C_{\mathrm{IBL}} - \sqrt{\frac{V}{n}} \cdot Q^{-1}(\epsilon) \;\; [\text{bits / channel use}]$$

V : Channel dispersion, n : blocklength, ε : block error rate

Y. Polyanskiy, H. Poor, and S. Verdu, "Channel coding rate in the finite blocklength regime," IEEE Trans. Inf. Theory, vol. 56, no. 5, pp. 2307– 2359, May 2010.

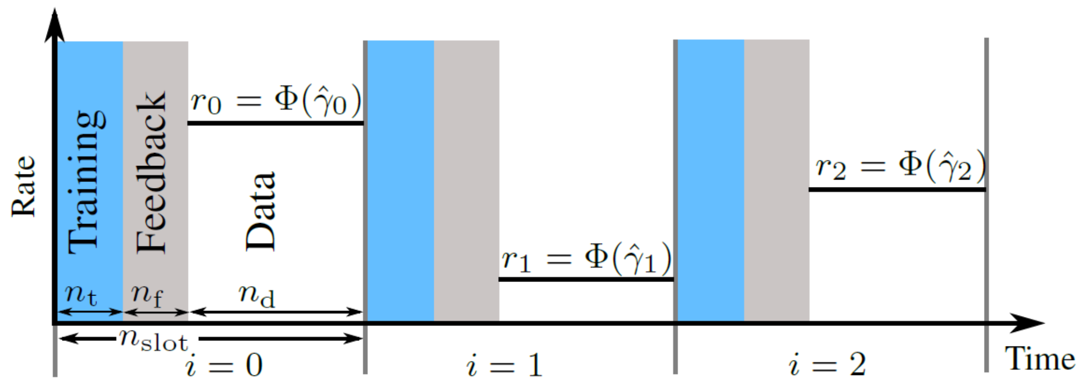
Communication at Finite Blocklength

- No error-free communication possible due to “above-average” noise effects
  - The lower the blocklength, the higher the rate reduction



- AWGN Channel
- SNR 10dB
- Target error prob. 10^{-5}
- Perfect CSI

Finite Blocklength and Imperfect CSI

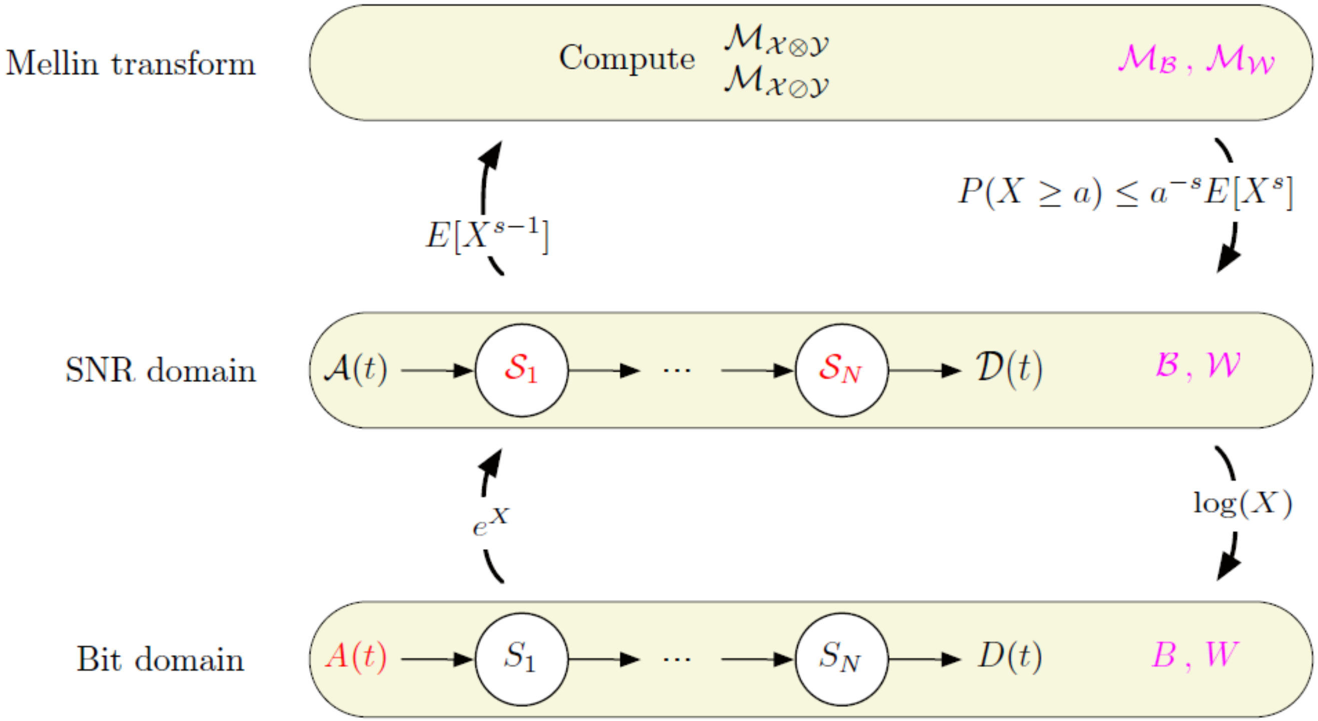


- SISO set-up, focus on impact of CSI at transmitter:
  - Trade-off 1: Training symbols n_t ⇔ Data symbols n_d
  - Trade-off 2: Rate r ⇔ Error probability ε

➔ Errors are bad, but low r and small n_d can also increase the queueing delay!

S. Schiessl et al. "Delay Performance of Wireless Communications with Imperfect CSI and Finite Blocklength," IEEE TCOM, 2018.

From Bit-Domain SNC to SNR-Domain SNC



H. Al-Zubaidy et al. "Network-layer Performance Analysis of Multi-hop Fading Channels," IEEE/ACM TON, 2016

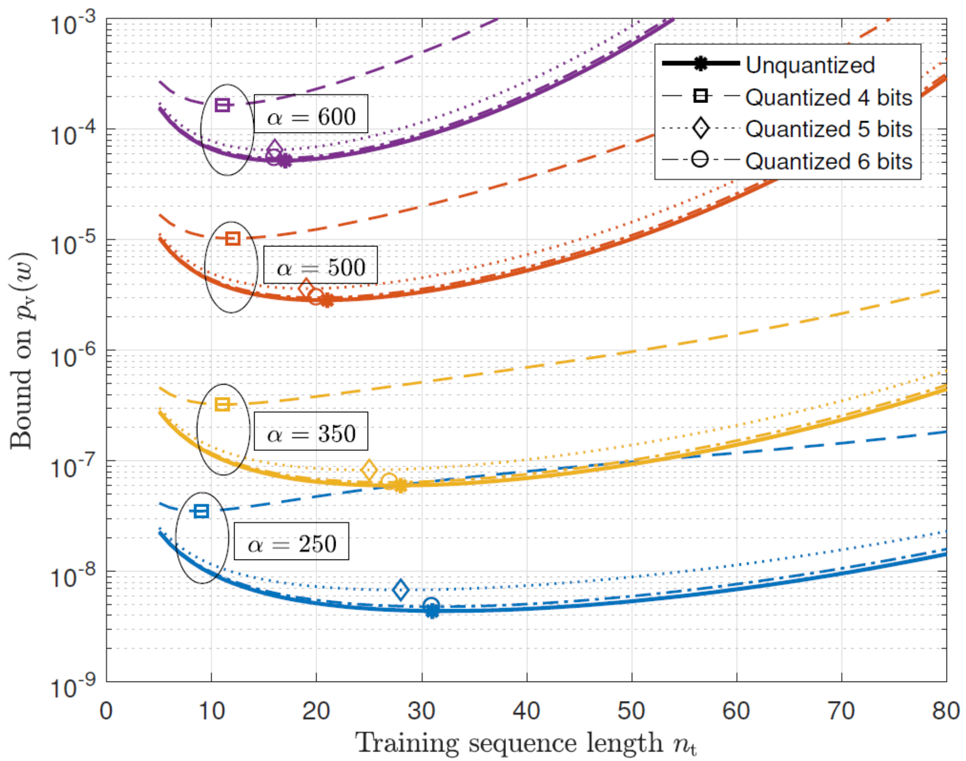
Finite Blocklength and Imperfect CSI

To minimize the delay violation probability, minimize

$$\mathcal{M}_{\mathcal{S}}(\theta) = \mathbb{E}\left[\mathcal{S}^{\theta-1}\right] = \int_0^\infty (1+\gamma)^{\theta-1} f(\gamma) d\gamma$$

- For each estimated SNR $\hat{\gamma}$: need to solve trade-off $r \Leftrightarrow \varepsilon$
- Can be solved quickly, as the expression is convex in the error ε

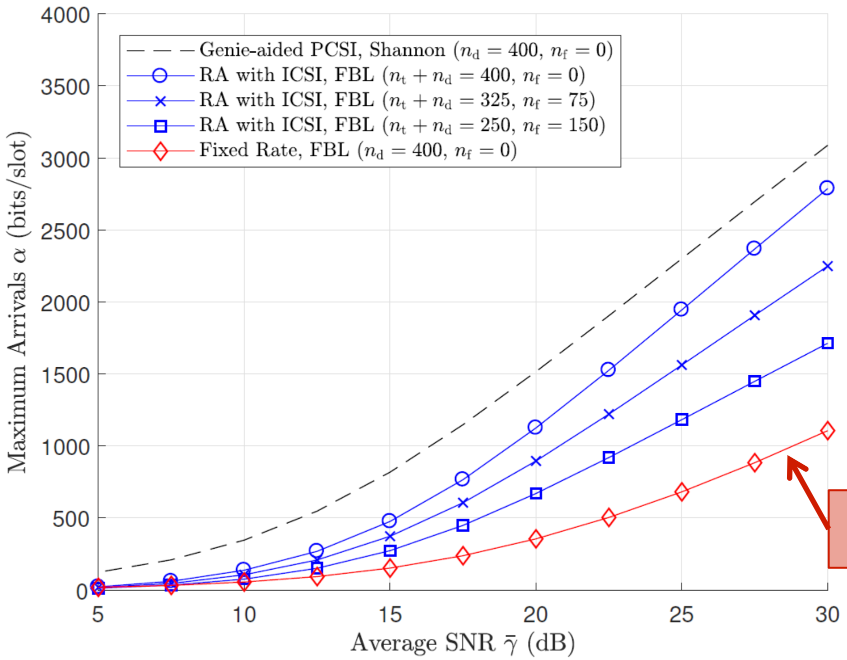
Main Result 1: Optimal n_t



Parameters:

- n_{slot} = 250,
- $n_d = n_{slot} - n_t$,
- w = 5 slots,
- Avg. SNR 15 dB

Result 2: Rate Adaptation is Superior



Adaptive rate, n_d=370 – 390
$n_{feedback}$=0

Adaptive rate, n_d=220 - 240,
$n_{feedback}$=150

Fixed rate, n_d=400

- n_{slot} = 400,
- n_d = n_{slot} - n_t,
- w = 5 slots

- These results consider queueing constraints: $p_v(w=5) < 10^{-8}$
- Ignoring the queueing constraints would lead to wrong conclusions.

More Results

- Interference channel [1]
- MISO downlink [2]
- Non-orthogonal multiple access [3]
- Physical layer secrecy [4]
- Millimeter-wave multi-hop [5]
- WirelessHART multi-hop [6]
- Physical layer authentication [7]

- Most of the results are understood as qualitative results rather than quantitative.

[1] S. Schiessl et al., “On the Delay Performance of Interference Channels,” *IFIP Networking*, 2016.

[2] S. Schiessl et al., “Delay Performance of the Multiuser MISO Downlink under Imperfect CSI and Finite Length Coding,” IEEE JSAC, 2019.

[3] S. Schiessl et al., “NOMA Uplink: Delay Analysis with Imperfect CSI and Finite-Length Coding,” *in preparation, available upon request*, 2019

[4] F. Naghibi et al, “Performance of Wiretap Rayleigh Fading Channels under Statistical Delay Constraints,” *IEEE ICC*, 2017.

[5] G. Yang et al., “Analysis of Millimeter-Wave Multi-Hop Networks with Full-Duplex Buffered Relays,” *IEEE/ACM TON*, 2018.

[6] N. Petreska et al., “Bound-Based Power Optimization for Multi-Hop Heterogeneous Wireless Industrial Networks Under Statistical Delay Constraints,” *Computer Networks*, 2018.

[7] H. Forsell et al., “Physical Layer Authentication in Mission-Critical MTC Networks: A Security and Delay Performance Analysis,” *IEEE JSAC*, 2019.

Recent Attempt: Transient Analysis

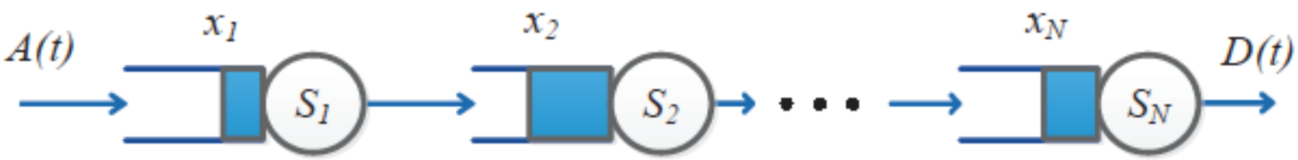


Figure: Multi-hop wireless network observed from time t_0.

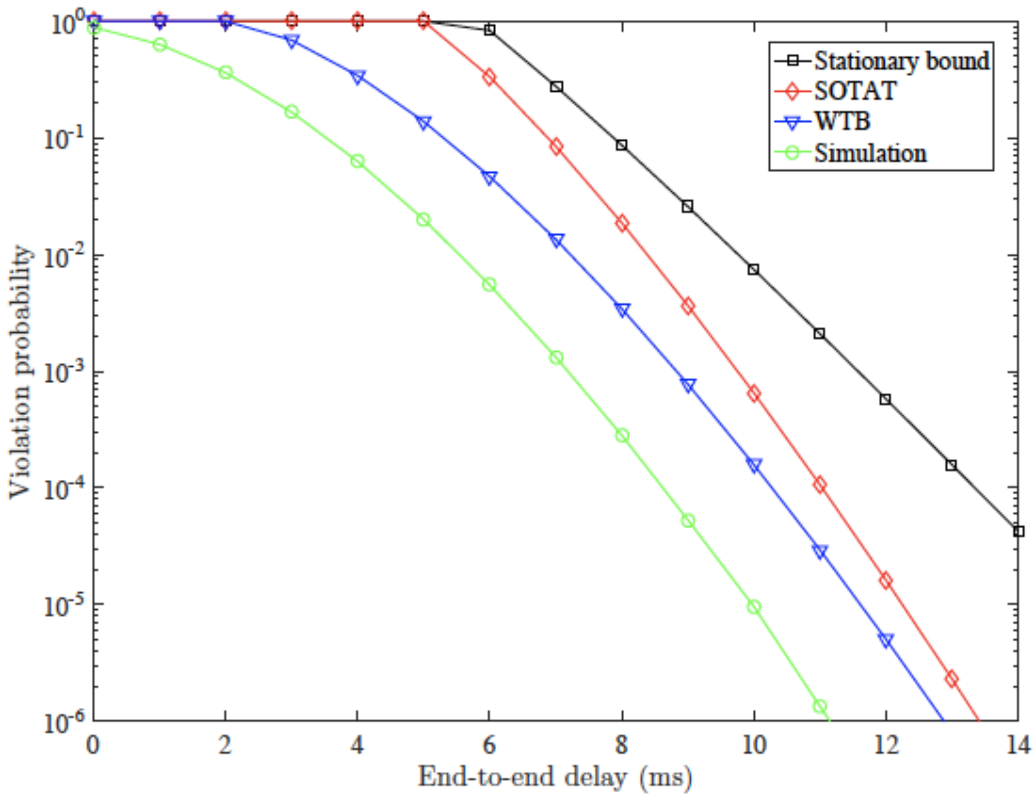
- x_n: backlog of wireless link n at t_0
- Service at each link is given by capacity of fading channel
- $A(t)$: finite sequence of time-critical data bits/packets arrive in $[t_0, t_0 + T]$, where $t_0 \leq T < \infty$

Three Approaches

- Model initial backlog as cross-traffic, invoke SNC
- Naïve approach: Consider stationary delay bound by assuming constant arrivals, and some cross-traffic
- Apply SNC bound by considering finite time horizon with some cross-traffic (SOTAT)
- Own contribution WTB: Start from SNC and tailor bound towards the backlog of interest.

J. Champati et al. “Transient Delay Bounds for Multi-Hop Wireless Networks,” ArXiv Draft, 2018

Somewhat Surprising Results



Parameters:

- Slot duration: 1 ms
- W = 20 kHz
- Backlog: 100 bits
- Arrival of 25 bits
- Avg. SNR 5 dB

Conclusions

- Main contribution from SNC: URLLC design guide
  - Bounds used for comparison of different system approaches
  - Significantly different conclusions than capacity analysis
  - Still, lots of assumptions and simplifications
- Attempt towards application of SNC bounds for real systems:
  - Experimentation with wirelessHART
  - Transient bounds
- No waste of time anymore!