Highly Reliable Wireless-Edge Systems for Closed-Loop Control

ECC Workshop: Control and Networking in CPS

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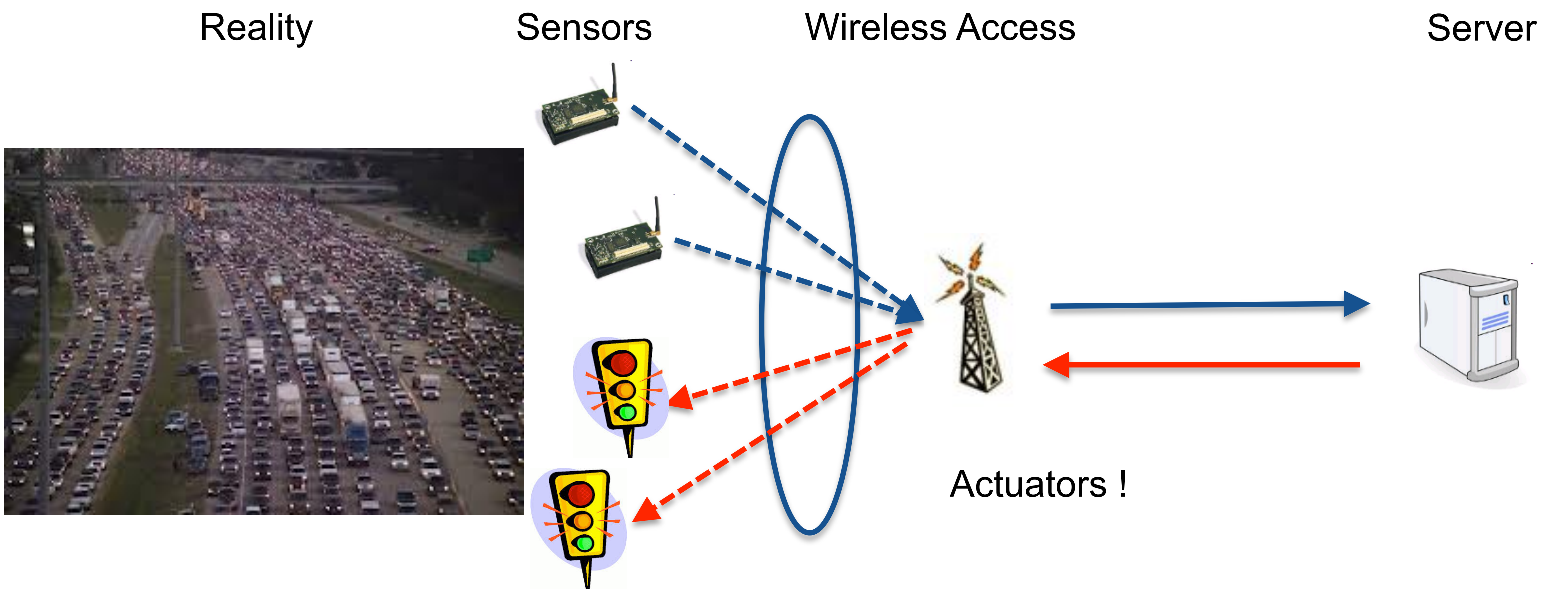
joint work with S. Schiessl, H. Al-Zubaidy, M. Skoglund

Outline

- Introduction to URLLC, edge computing and use cases
- Theoretical perspectives on URLLC
- Modeling and analysis of edge computing systems
- Conclusions and future work

URLLC Motivation



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

➔ URLLC: Ultra-reliable low latency communications!

URLLC: Application Fields

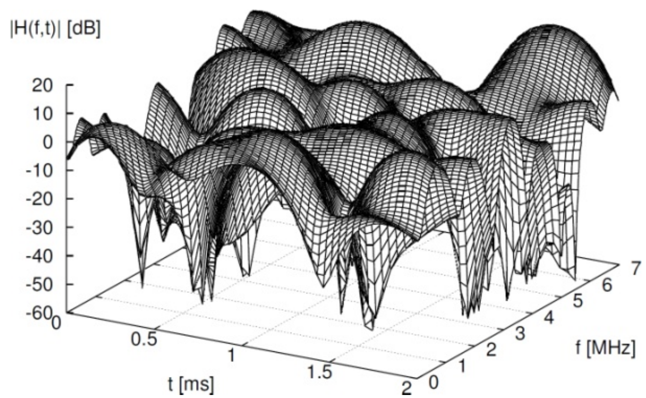
- Various application fields according to 3GPP:
  - Rail-bound mass transit
  - Building automation
  - Factory of the future / industrial automation
  - Smart living / smarty city
  - Electric power distribution & power generation

- 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

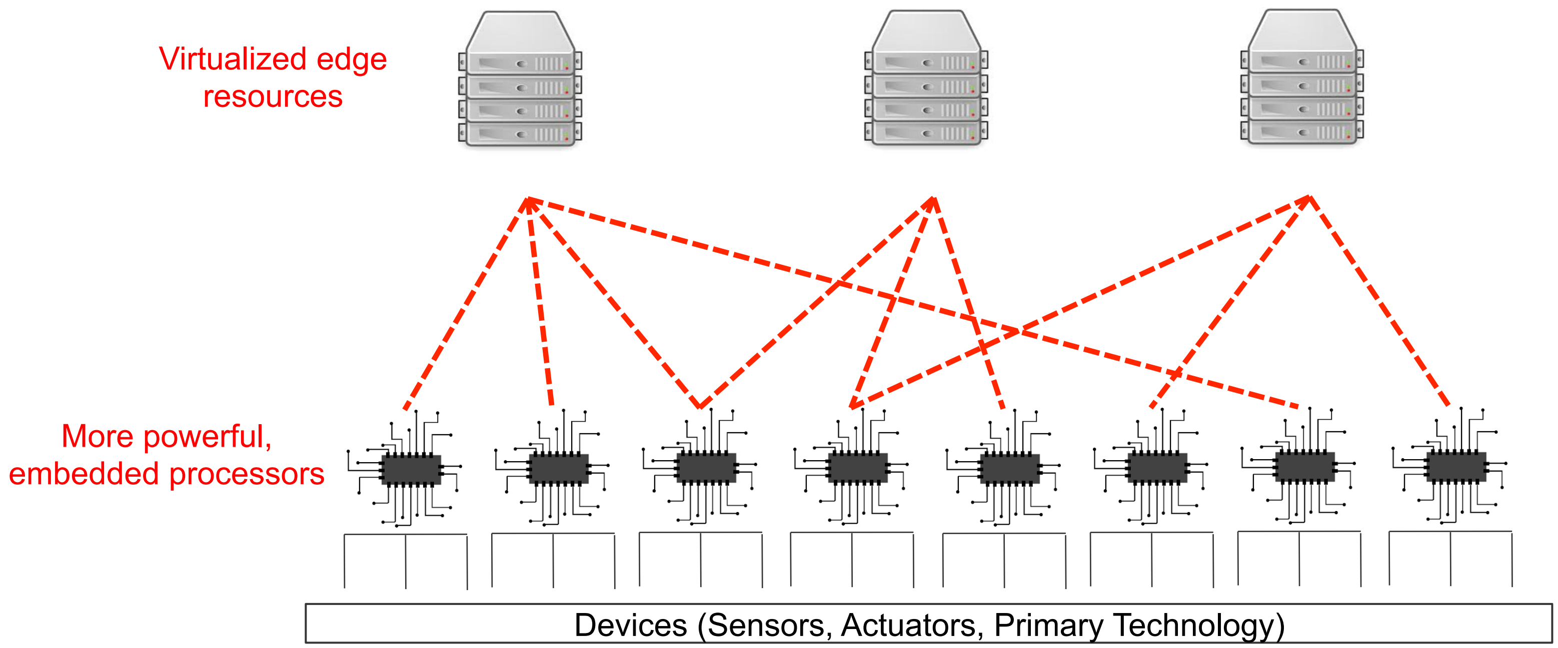
Range of Factory Automation Requirements

- 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}

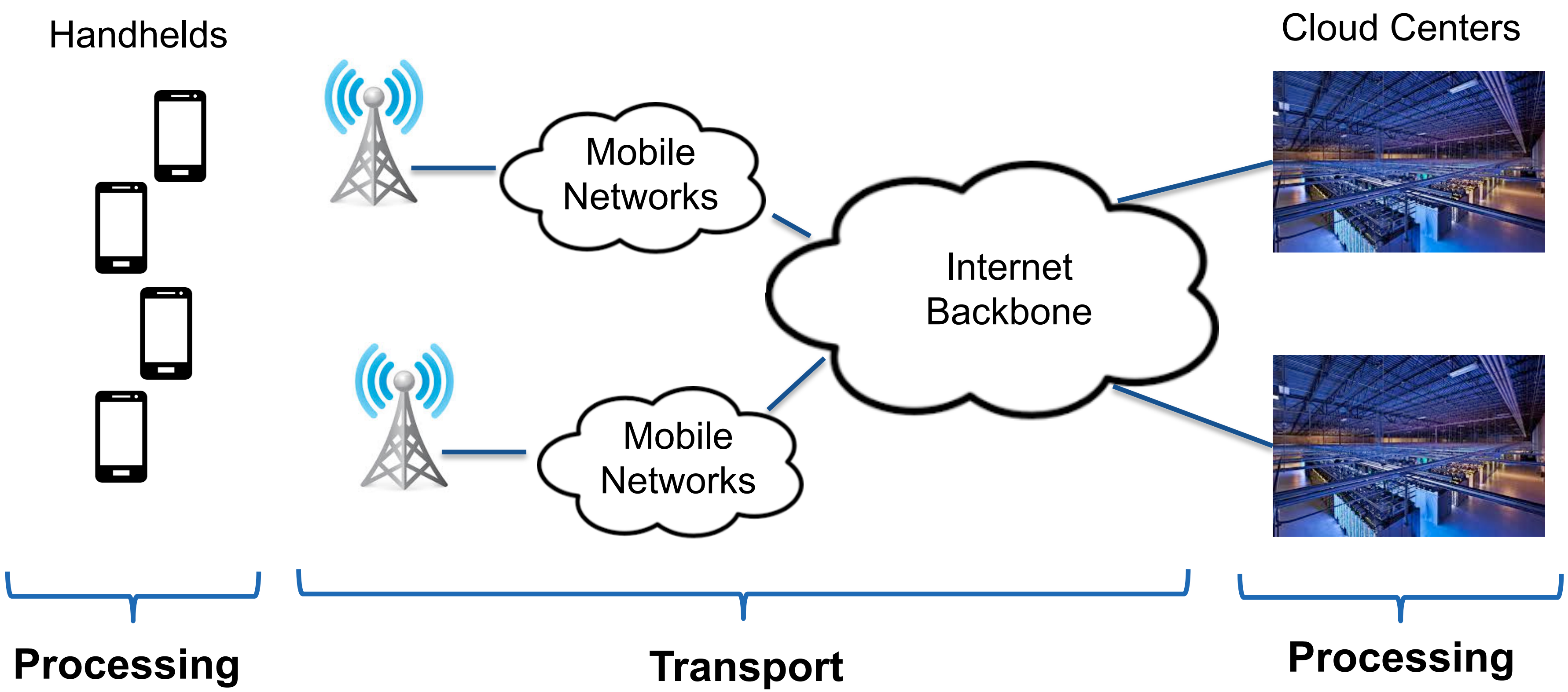


Why turn to wireless?

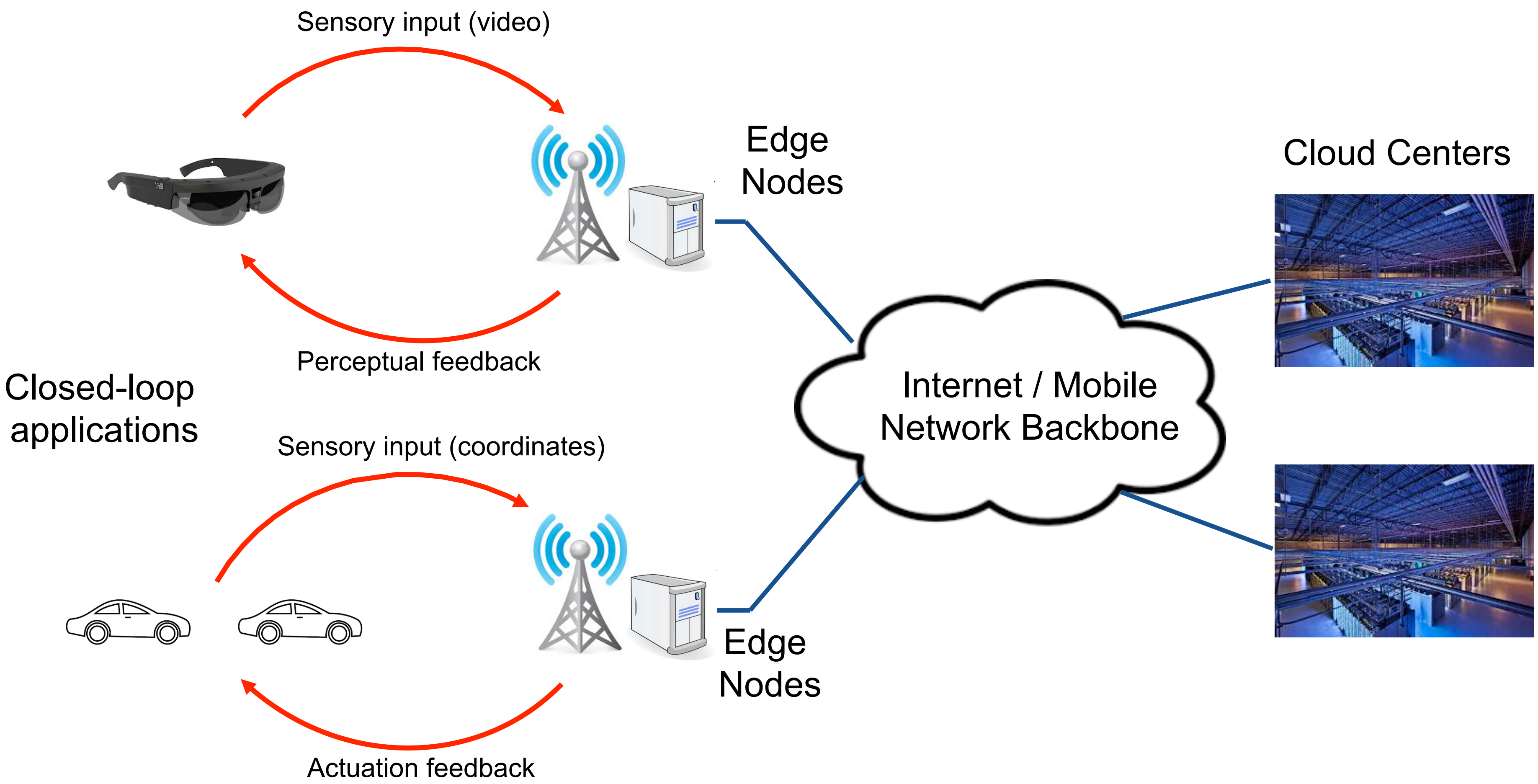
Visionary Reasoning: Flexibility



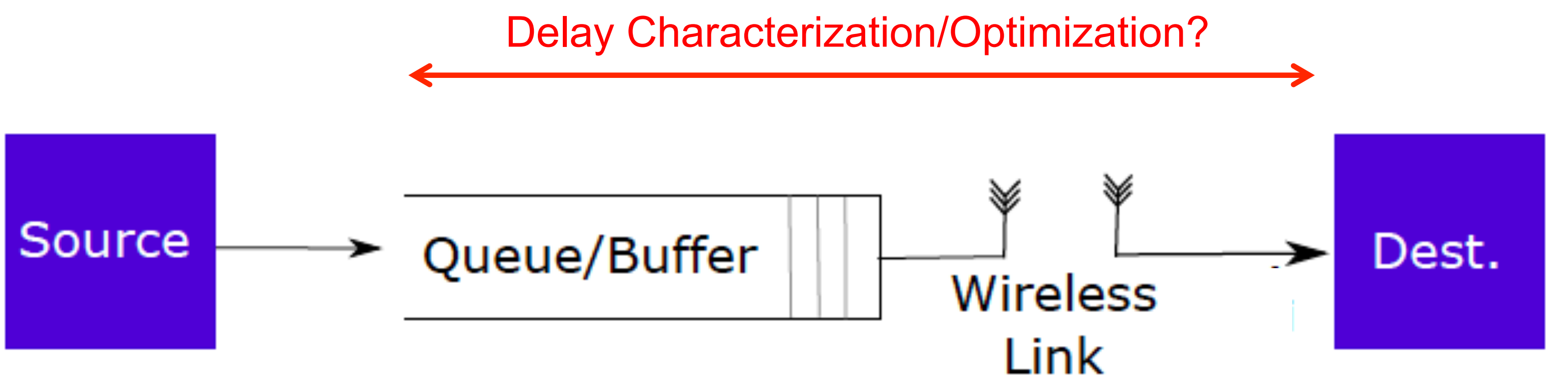
Contemporary Network Architectures



Edge Computing – Application Drivers

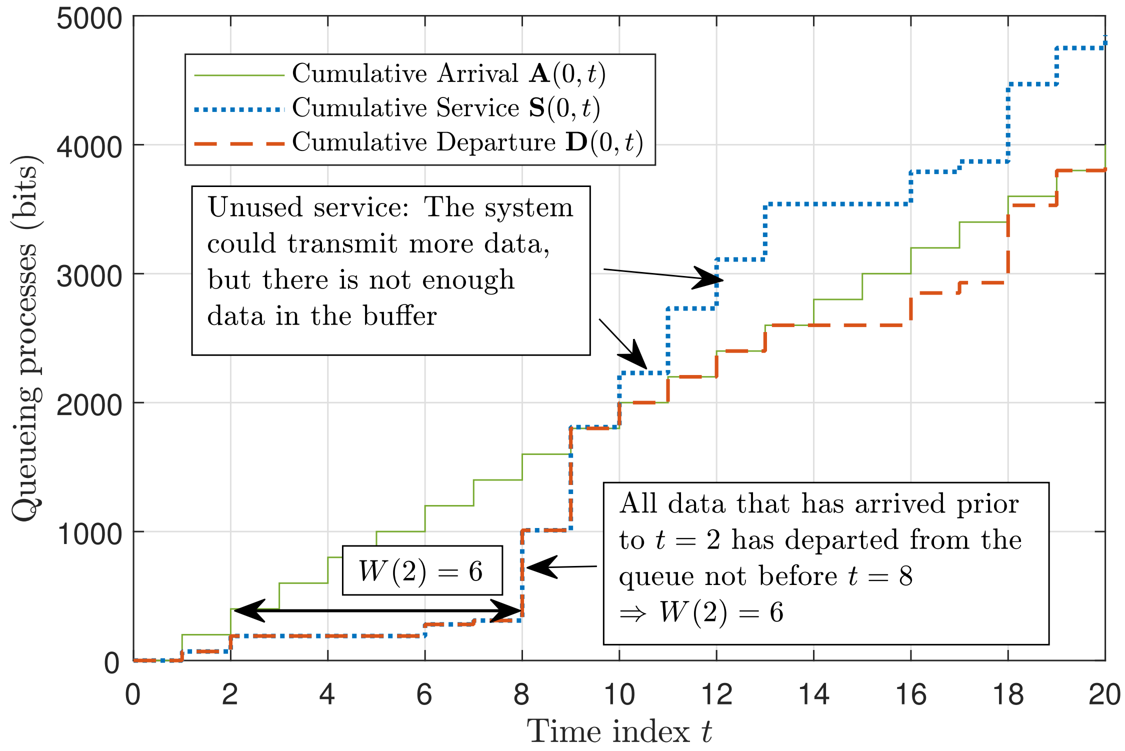


Queuing-Theoretic Problem Formulation



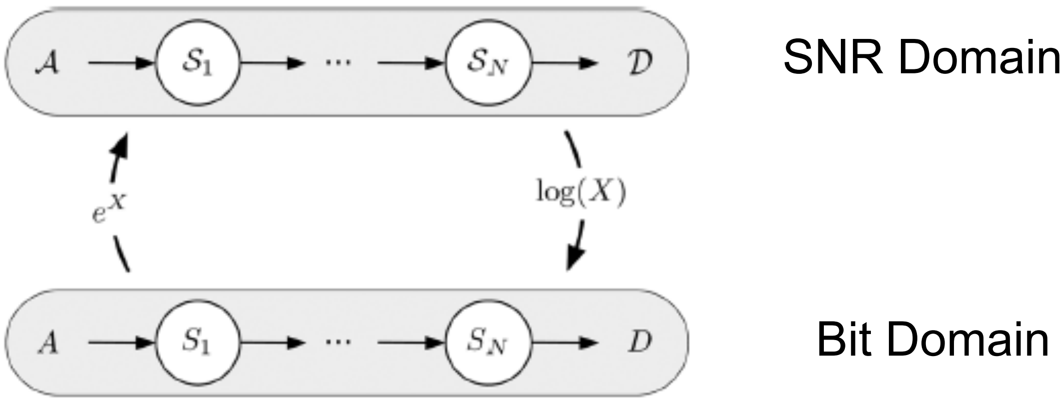
- Deterministic arrivals
- Random service: Fading, interference, cross-traffic

Basics of Stochastic Network Calculus



Basics of Stochastic Network Calculus

- Novel approach for wireless queuing analysis



H. Al-Zubaidy, J. Liebeherr, and A. Burchard, “A (min,x) Network Calculus for Multi-Hop Fading Channels,” *Proc. IEEE Infocom 2014*.

Basics of Stochastic Network Calculus

$$p_{\mathrm{v}}(w) \leq \inf_{\theta>0} \{K(\theta, w)\}$$

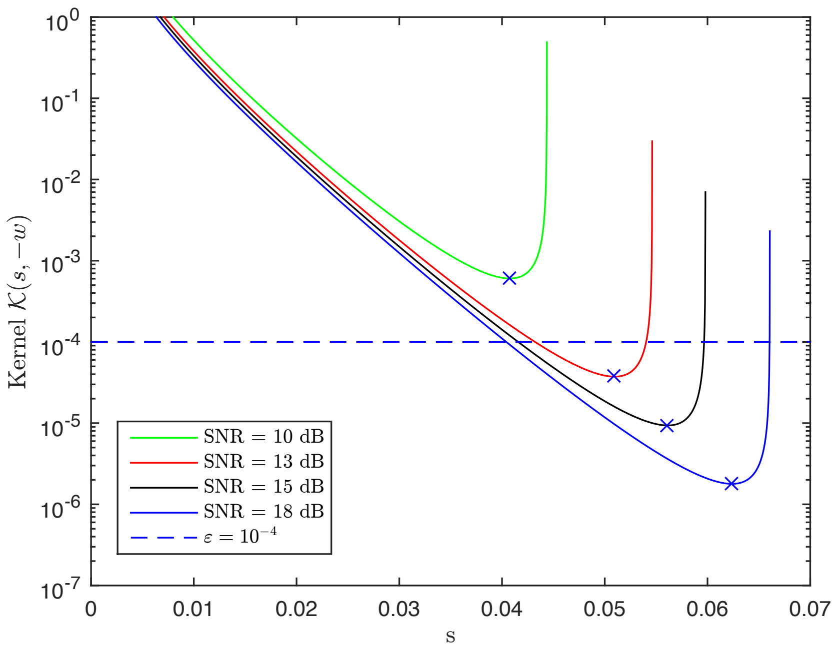
with

$$K(\theta, w) = \frac{\mathcal{M}_{\mathcal{S}}(1-\theta)^{w}}{1-\mathcal{M}_{\mathcal{A}}(1+\theta)\mathcal{M}_{\mathcal{S}}(1-\theta)},$$

where $\mathcal{M}_{\mathcal{A}}(\theta)$ and $\mathcal{M}_{\mathcal{S}}(\theta)$ are the Mellin transforms of the SNR-domain arrival and service processes $\mathcal{A}$ and $\mathcal{S}$.
The Mellin transform of a random process $\mathcal{X}$ is defined as:

$$\mathcal{M}_{X}(s,\tau,t) = \mathcal{M}_{X(\tau,t)}(s) = \mathrm{E}\left[X^{s-1}(\tau,t)\right]$$

Example Kernel Function



Single-hop system,
Rayleigh fading,
CBR arrival of 50
Bit / slot

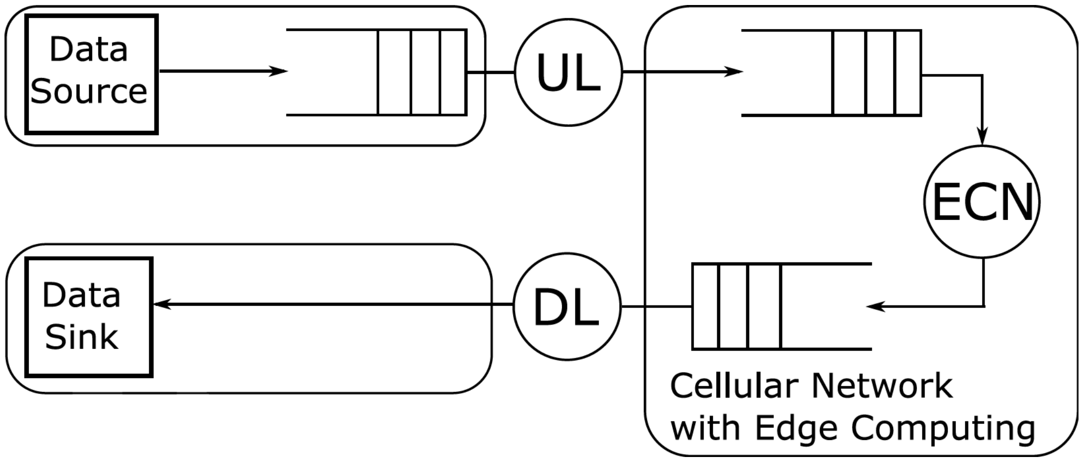
N. Petreska et al. “Bound-Based Power Optimization for Multi-Hop Heterogeneous Wireless Networks,” *Computer Networks,* 2019.

Wireless Queuing 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]

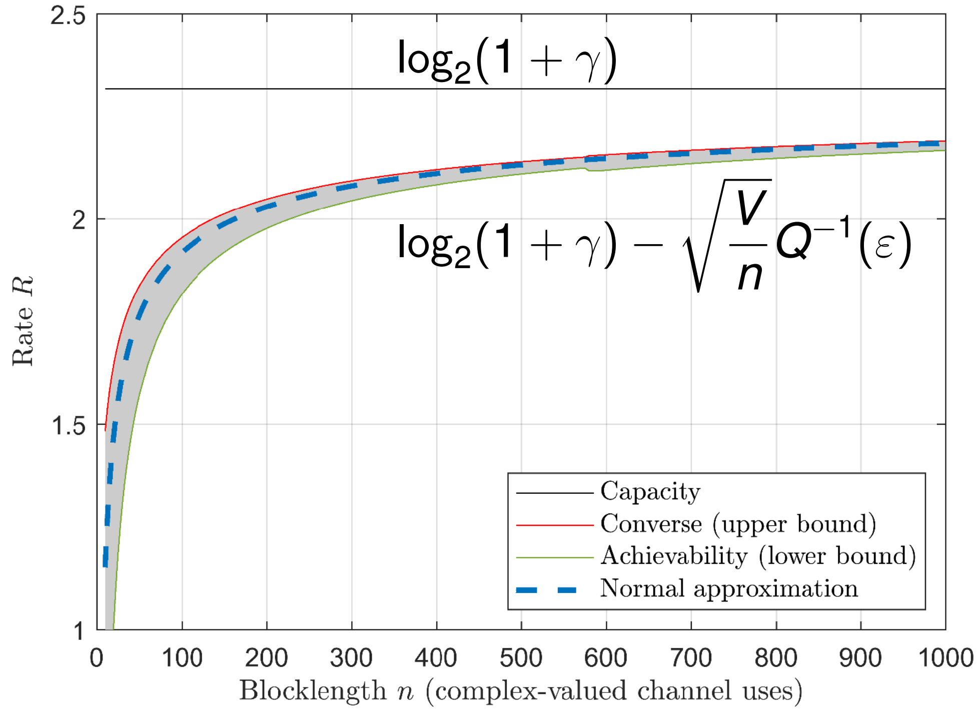
- Qualitative results rather than quantitative!

Edge Computing: System Model



- Independent fading in the uplink and downlink
- Constant rate edge processing
- Rate adaptation based on perfect CSI
- Small packets, finite length coding

Finite Blocklength Rate Model



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.

Central Performance Trade-off

How to split resources between uplink and downlink?

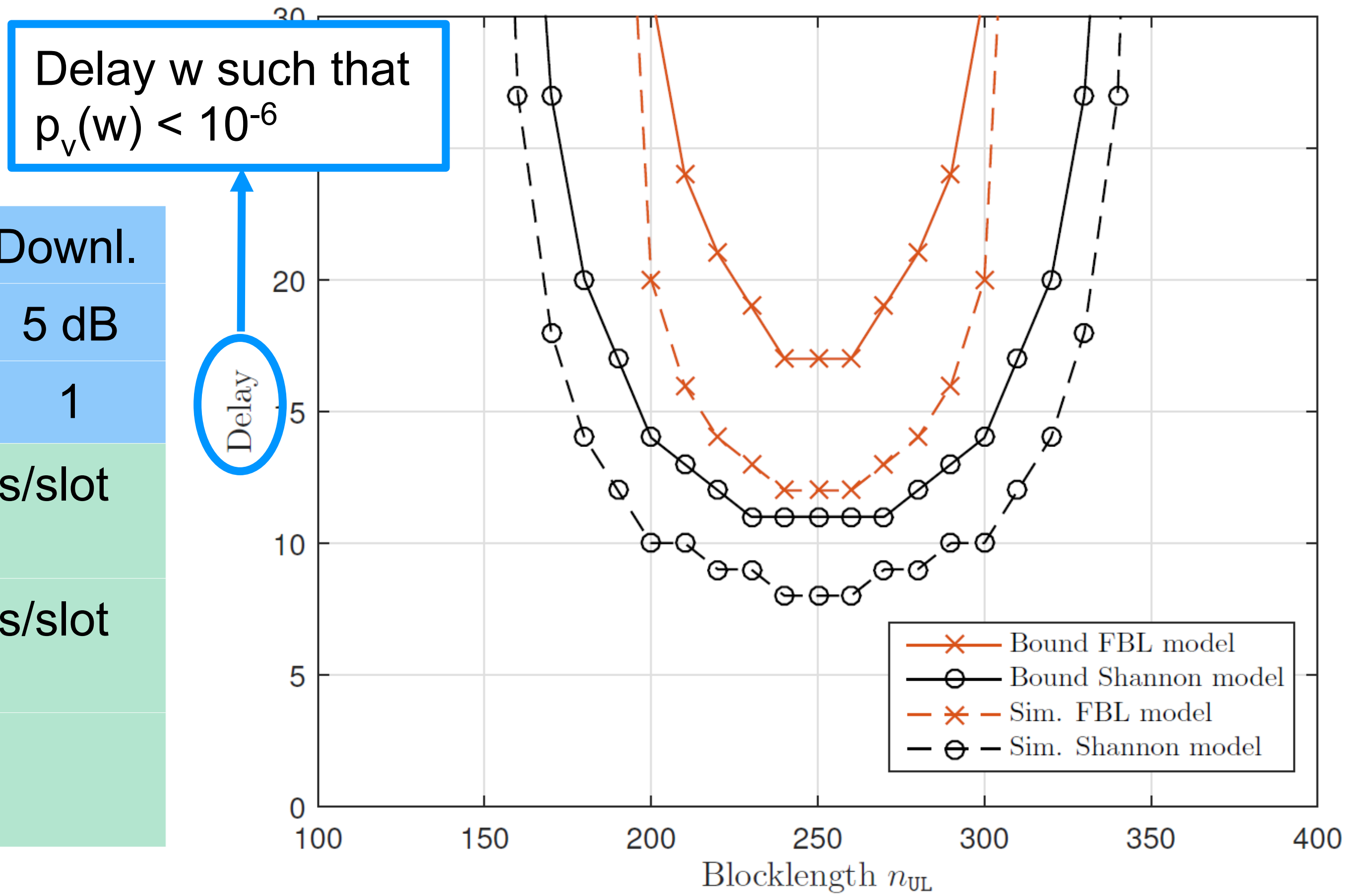
- Symmetric vs. asymmetric channels conditions
- Processing relationship channel / edge node

- How does the trade-off relate to normal, Shannon-like modeling of the links?
- How is FBL modeling impacting the trade-off?

S. Schiessl, J. Gross et al., “Finite Length Coding in Edge Computing Scenarios,” ITG Workshop on Smart Antennas, 2017.

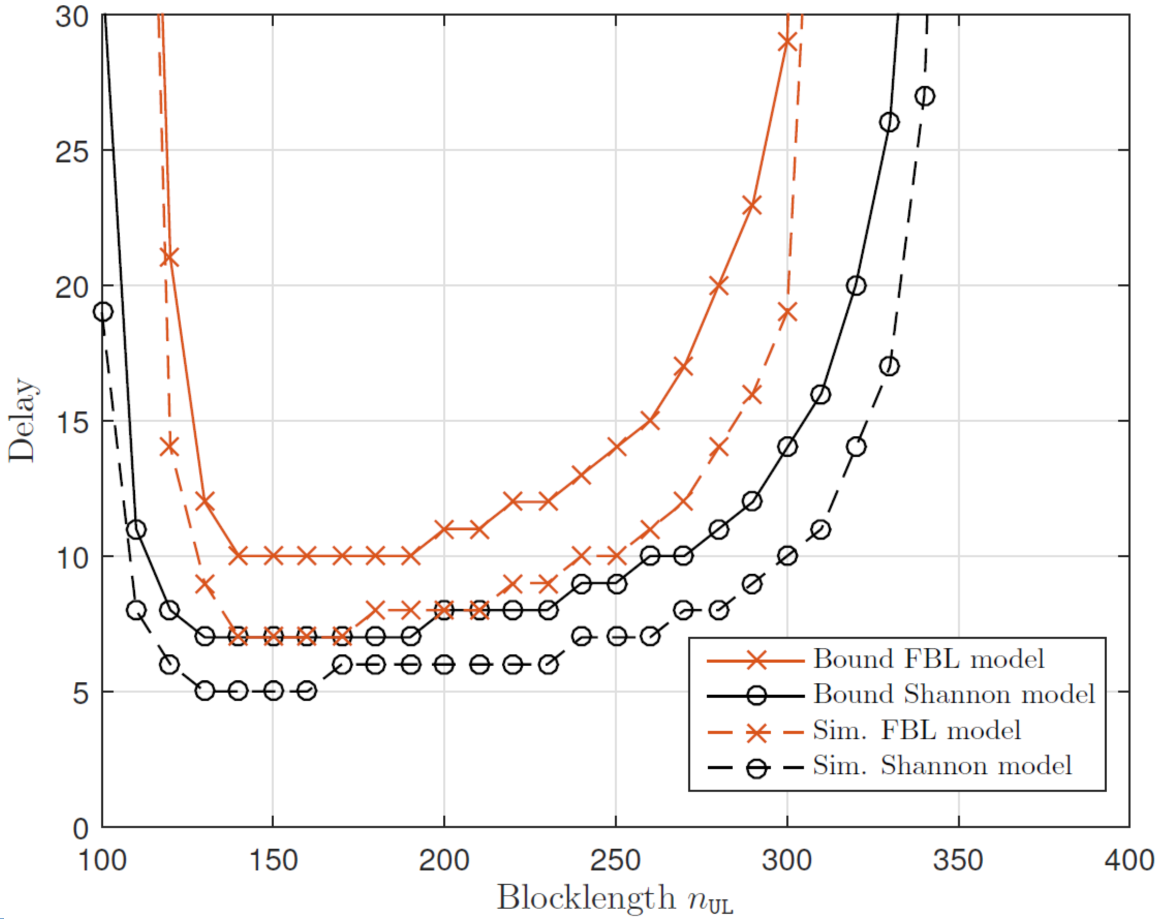
Results: Base Case

	Uplink	Downl.
SNR	5 dB	5 dB
Nak.-m	1	1
Arrivals	250 bits/slot	
ECN Speed	500 bits/slot	
ECN scaling	1	



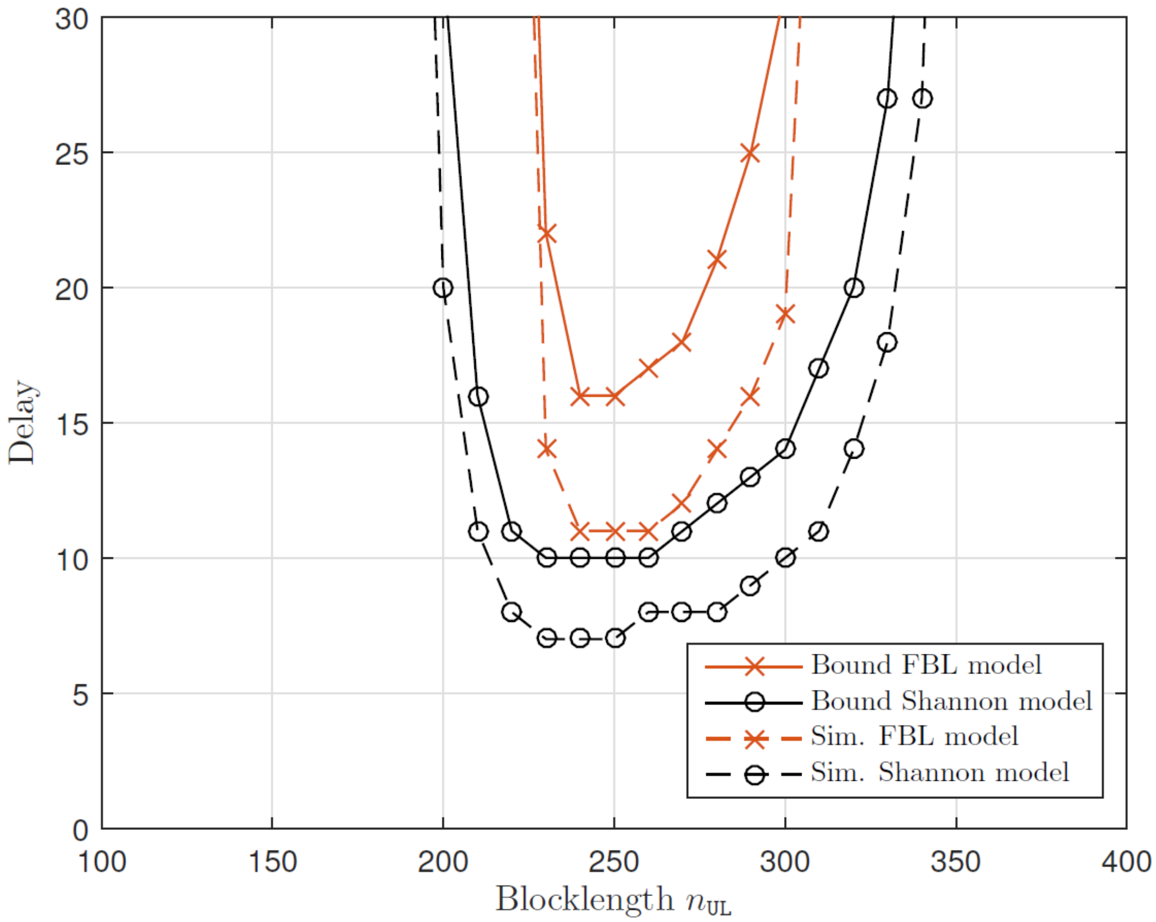
Results: More Uplink Antennas

	Uplink	Downl.
SNR	8 dB	5 dB
Nak.-m	2	1
Arrivals	250 bits/slot	
ECN Speed	500 bits/slot	
ECN scaling	1	



Results: Larger Packets / Faster Edge Node

	Uplink	Downl.
SNR	8 dB	5 dB
Nak.-m	2	1
Arrivals	500 bits/slot	
ECN Speed	1000 bits/slot	
ECN scaling	1/2	



Current Work: Transient Analysis

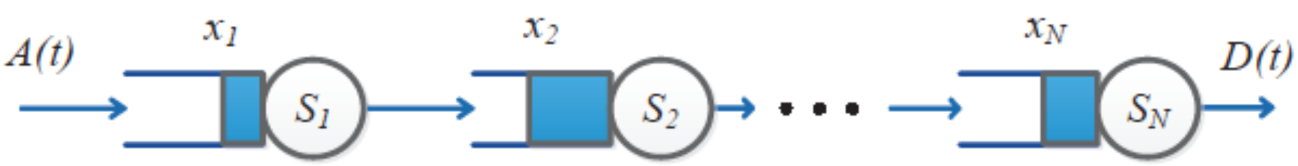


Figure: Multi-hop wireless network observed from time t_0.

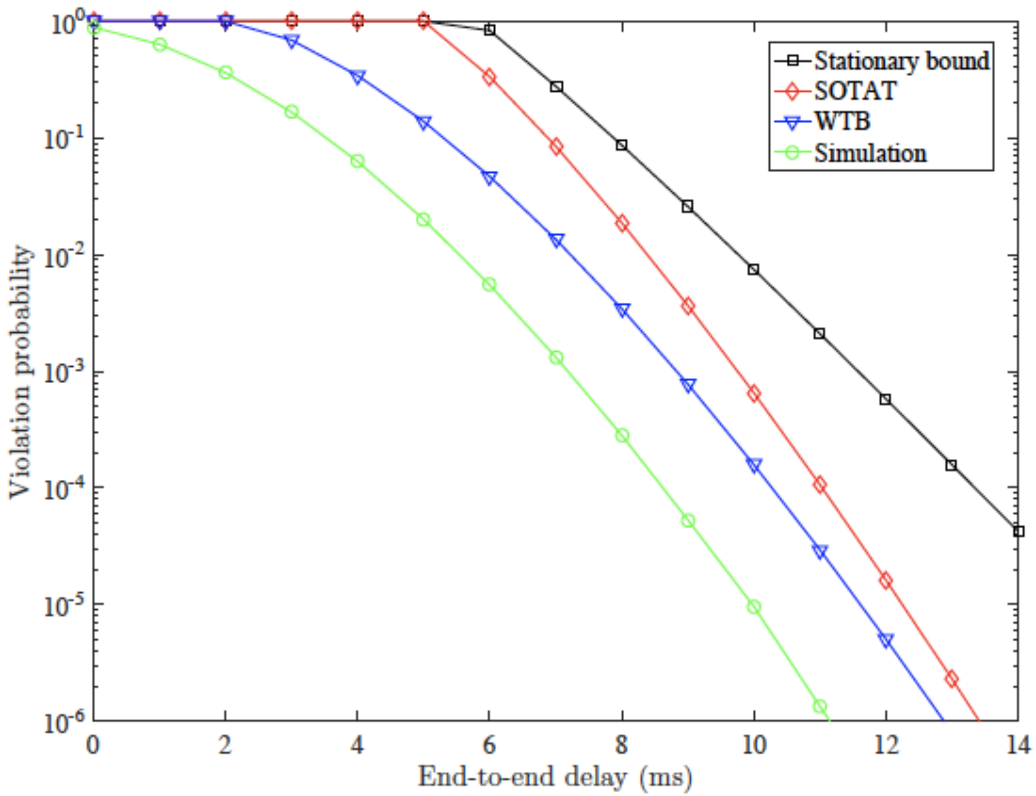
- x_n: backlog of wireless link n at t_0
- Service at each link is given by capacity of fading channel
- $A(t)$: finite sequence of time-critical data bits/packets arrive in $[t_0, t_0 + T]$, where $t_0 \leq T < \infty$

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

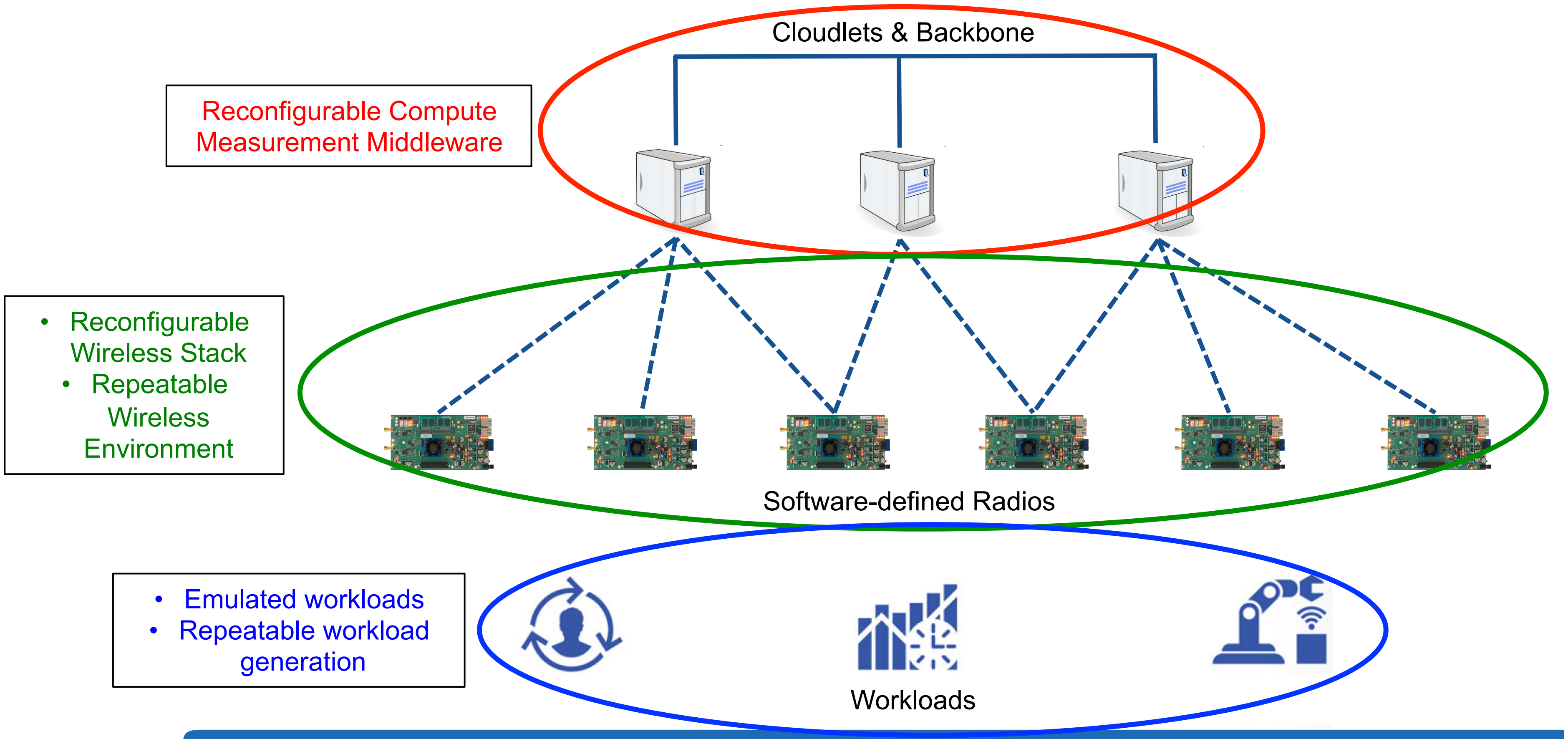


Parameters:

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

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

Upcoming Work: Experimental Testbed



Please approach me if:

- You are interested in a benchmarking testbed
- If you have applications that you would like to benchmark
- If you are looking for a benchmarking environment for protocols, compute approaches or middleware

Conclusions

- Main contribution from SNC: System design guide
  - Bounds used for comparison of different system approaches
  - Bound behavior carries over to simulated systems
  - Still, lots of assumptions and simplifications

- Future work:
  - Stochastic behavior of the compute node
  - Models and analysis of looped applications (feedback)
  - Experimental validation