Critical Machine-to-Machine Communications: Performance Models vs. Reality

WoNeCa 2016, Muenster, Germany

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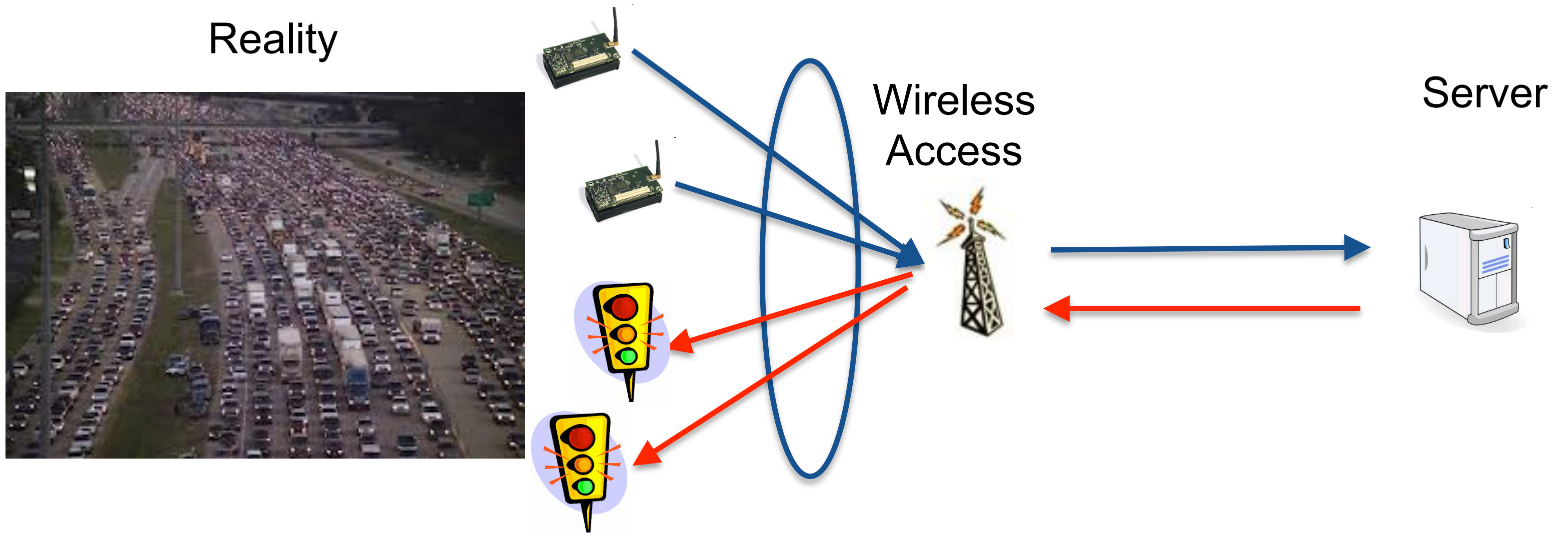
Closing the Loop …



Closed-loop control: Very wide range of requirements !

But very powerful in terms of application range …

Low Latency Wireless - Requirements

- Smart grid: Synchronization of generators
  - $T_{max} < 5$ ms & $P_{out} < 10^{-5}$
- Industrial automation: Factory control
  - $T_{max} < 1$ ms & $P_{out} < 10^{-7}$ (SIL 1)
- Traffic safety: Brake indication in platoons
  - $T_{max} < 10$ ms & $P_{out} < 10^{-5}$
- Tactile interaction over a network
  - $T_{max} < 10$ ms & $P_{out} < 10^{-6}$

Open Issues

- Are such communication systems feasible at all ?
- How to realize such systems efficiently ?

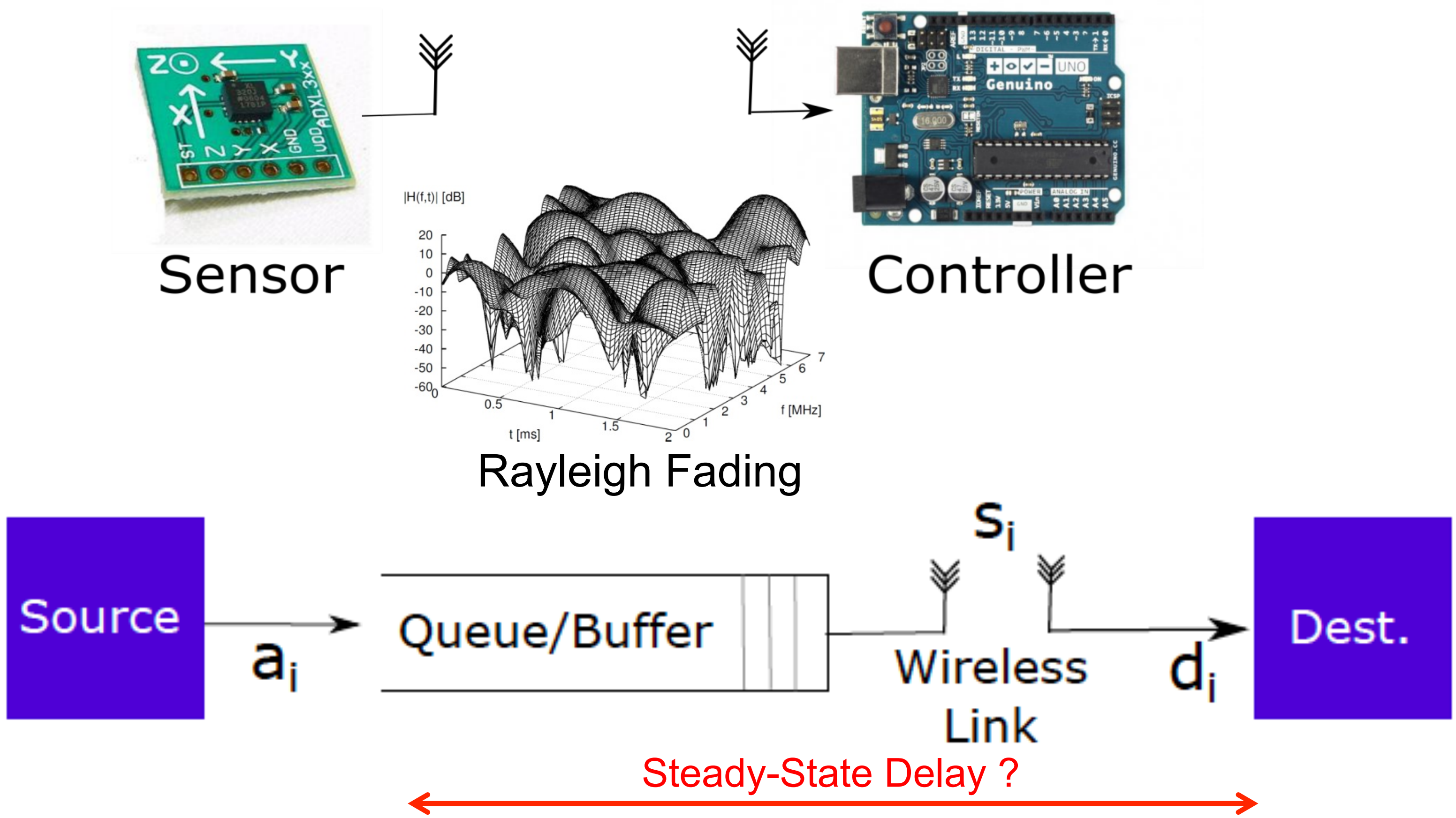
  ➔ Information / Communication Theory

- How to develop such systems ?
- How to guarantee system properties at run-time ?

  ➔ Validation / Verification

Credibility of model assumptions at 10^{-9} outage probability?

System Model

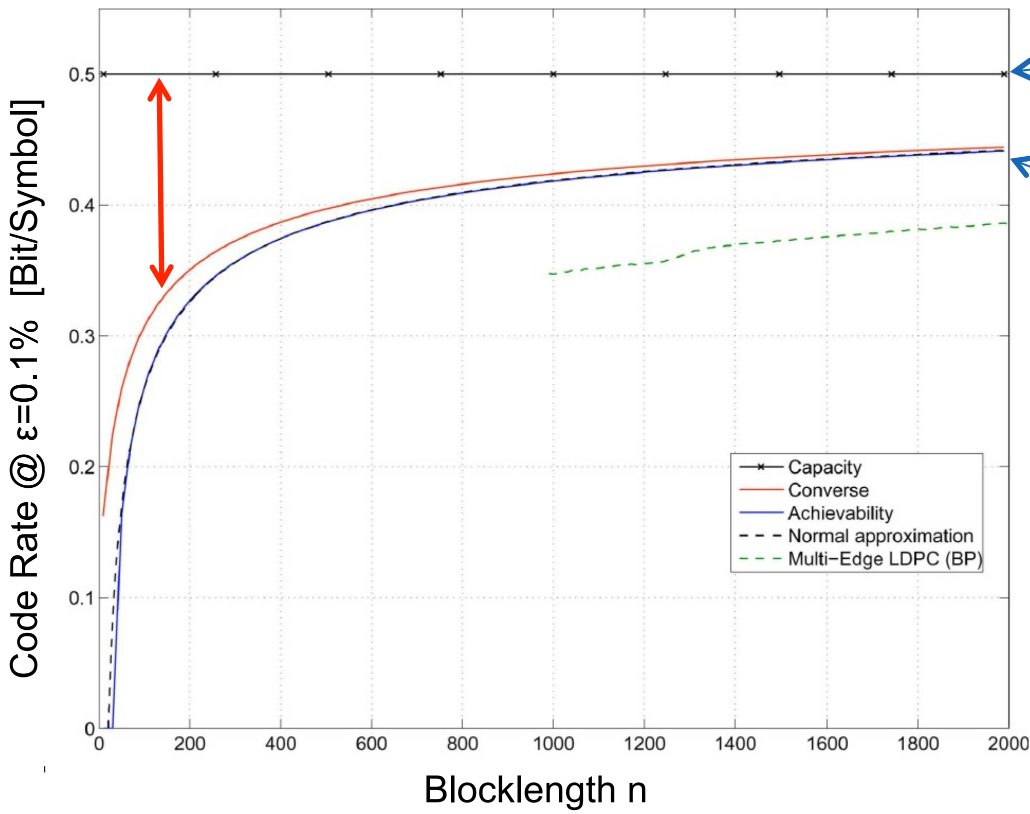


Link Modeling

- Given a link SNR, what is the capacity of the link ?
- Standard model (Shannon): $s_i = \log(1 + SNR)$
    - Assumes noise process averages out ➔many symbols/slot !
- Finite blocklength model [1] : $s_i \approx \log(1 + SNR) - \sqrt{\frac{V}{n}} Q^{-1}(\varepsilon)$
    - Accounts for finite (low) number of symbols n
    - Error floor ε needs to be specified

[1] 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.

Finite Blocklength Penalty



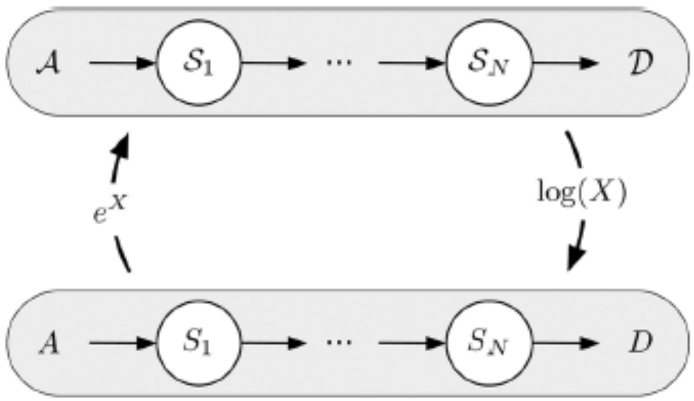
$\log(1 + SNR)$

$\log(1 + SNR) - \sqrt{\frac{V}{n}}Q^{-1}(\varepsilon)$

Makes queuing analysis more difficult !

Mellin Transform-Based Network Calculus

- Novel approach for wireless queuing analysis [2]



SNR Domain

Bit Domain

- Performance analysis by Mellin transform (Shannon cap.)

$$\mathbb{E}\left[\left(e^{S_i}\right)^{\theta}\right] = \mathbb{E}\left[(1+\mathrm{SNR})^{n\theta}\right]$$

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

Mellin Transform of FBL Capacity I

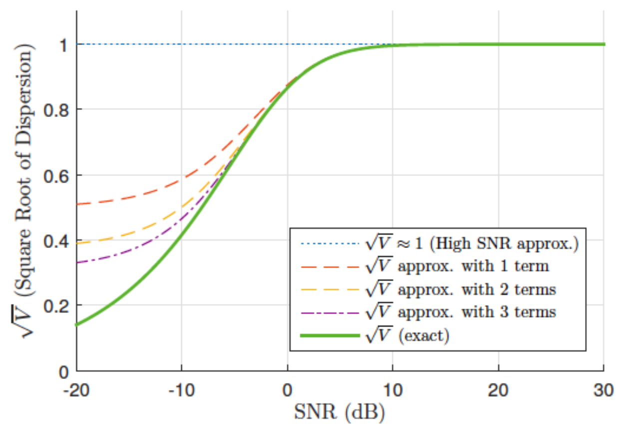
- Assume a fixed choice of ε

  ➔ FBL rate penalty is proportional to V !

- However, we have:

$$\sqrt{V} = \sqrt{1-x} = 1 + \sum_{j=1}^{\infty} \binom{1/2}{j} (-x)^j \qquad \left[x = \frac{1}{(1+\text{SNR})^2} \right]$$

$$= 1 - \frac{x}{2} - \frac{x^2}{8} - \frac{x^3}{16} \ldots$$



Mellin Transform of FBL Capacity II

- Computing the Mellin transform $\mathbb{E}\left[\left(e^{s_i}\right)^{\theta}\right]$
  requires integration over :

$$e^{-c\sqrt{V}} = e^{-c} \cdot e^{c\frac{x}{2}} \cdot e^{c\frac{x^2}{8}} \cdot e^{c\frac{x^3}{16}} \dots$$

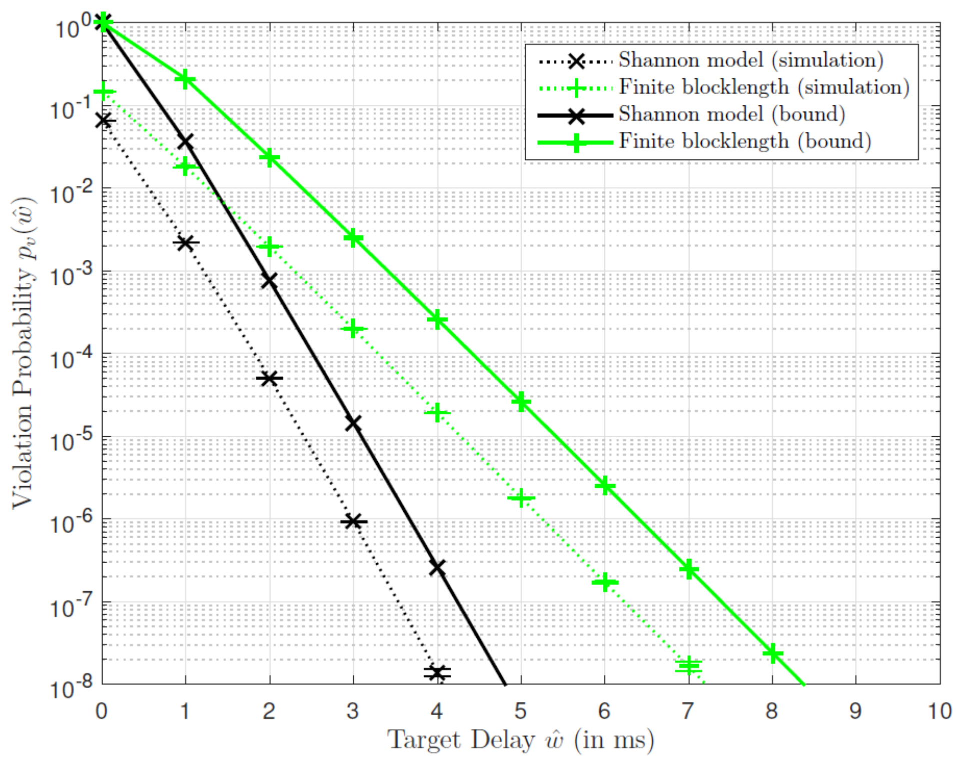
- Apply power series for exponential functions

$$e^x = \sum_{k=0}^{\infty} \frac{x^k}{k!}$$

  leads finally to infinite sums of infinite sums !
- [3] shows that a finite number of elements is sufficient.

[3] S. Schiessl, H. Al-Zubaidy and J. Gross, “Delay Analysis of Wireless Fading Channels with Finite Blocklength,” *Proc. ACM/IEEE MSWIM 2015*.

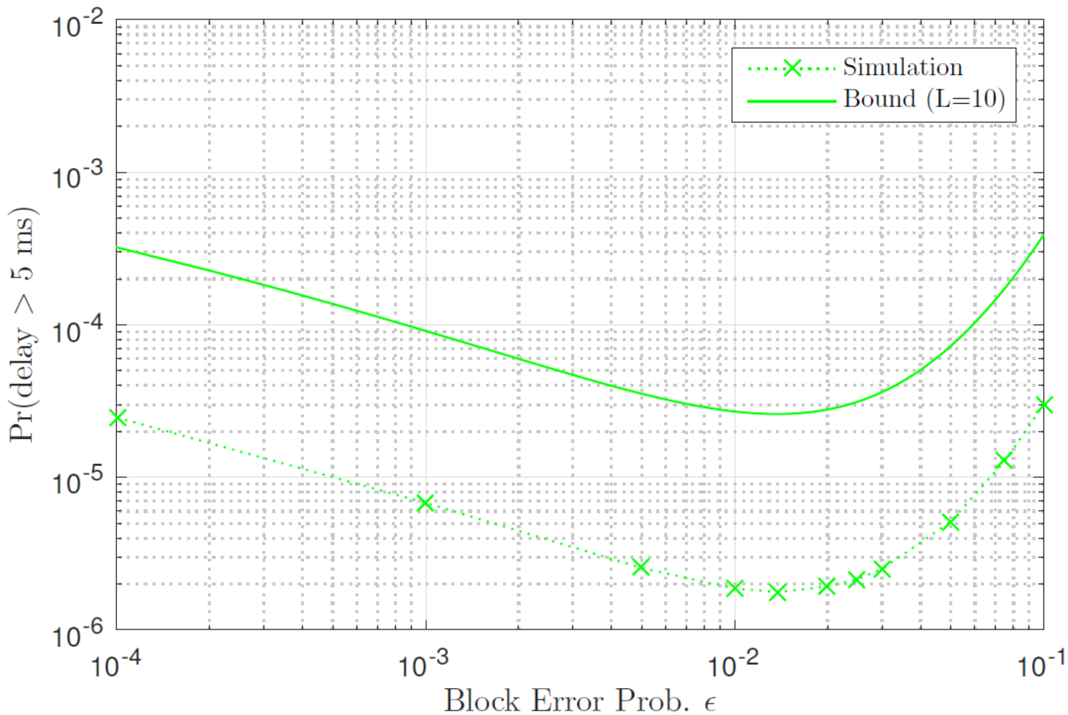
Numerical Analysis



- n ~ 150
- Average SNR 5 dB
- Arrival of 25 Bit/slot
- Perfect CSI
- $\varepsilon = 0.1\%$

Finite blocklength effects have significant performance impact !

Numerical Analysis II

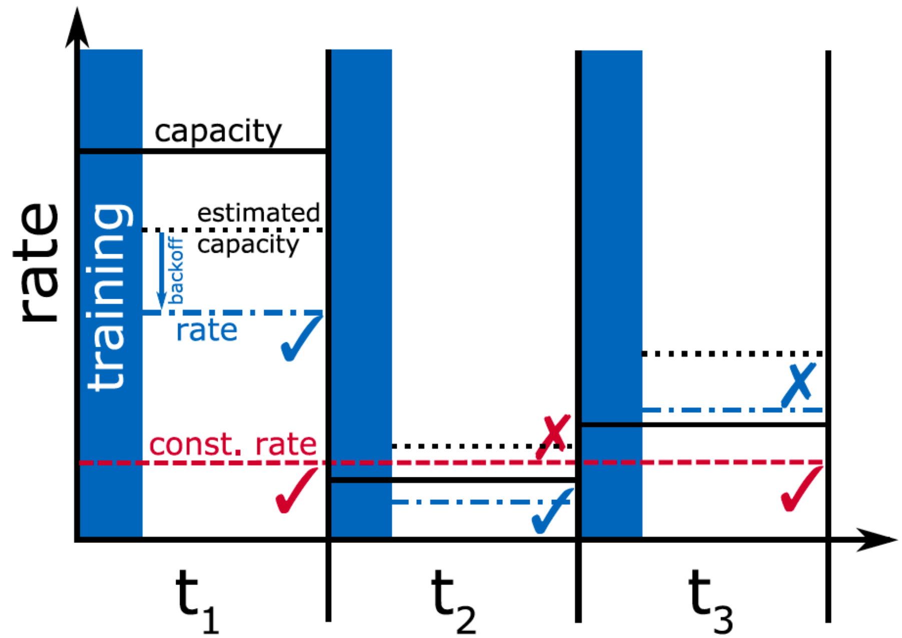


- n ~ 150
- Average SNR 5 dB
- Arrival of 25 Bit/slot
- Perfect CSI

New degrees of freedom available under FBL regime !

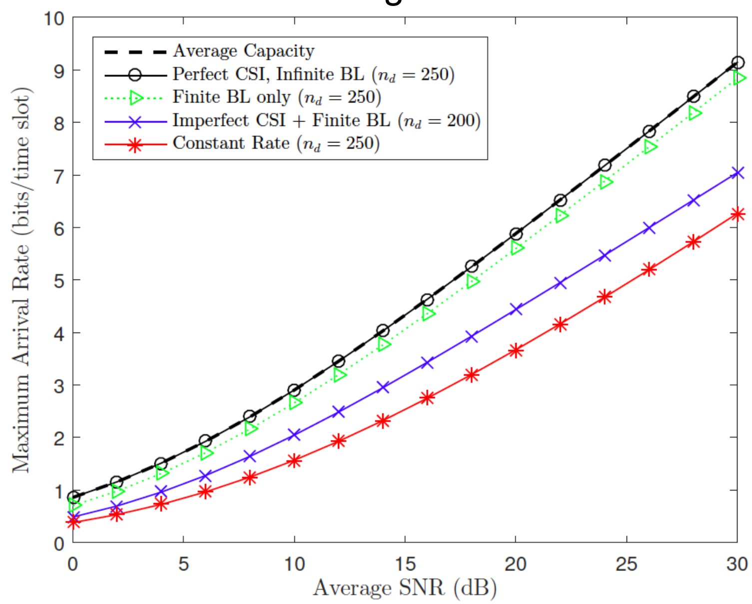
Extension: CSI Knowledge

- Slot split into channel acquisition and payload phase
- Longer training phase ➔ Better channel knowledge!

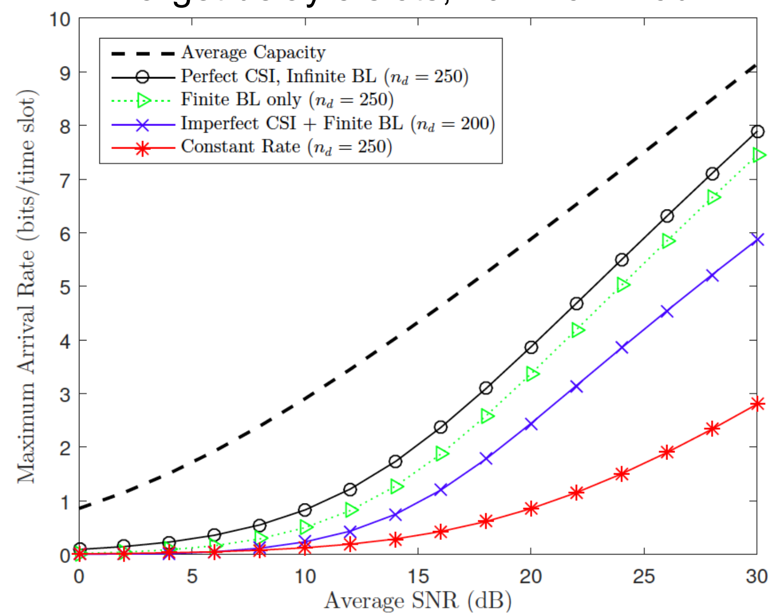


Numerical Results

Average Rate



Target delay 5 slots, 10^{-9} viol. Prob.



Channel adaptation pays off only at higher SNRs

S. Schiessl, H. Al-Zubaidy and J. Gross, "Queueing Performance under Finite Blocklength Channel Coding and Imperfect Channel Knowledge," *in preparation.*

Conclusions

- Current focus: low-latency, ultra-reliable wireless networks
- Many open theoretical and practical problems
- Today: How to build such systems ?
  - FBL regime and CSI acquisition play very important role
  - Channel adaptation only at higher SNRs

- Holy grail of critical M2M: Which models predict reality ?