Theory and Practise of Ultra-Reliable Low-Latency Wireless Networking

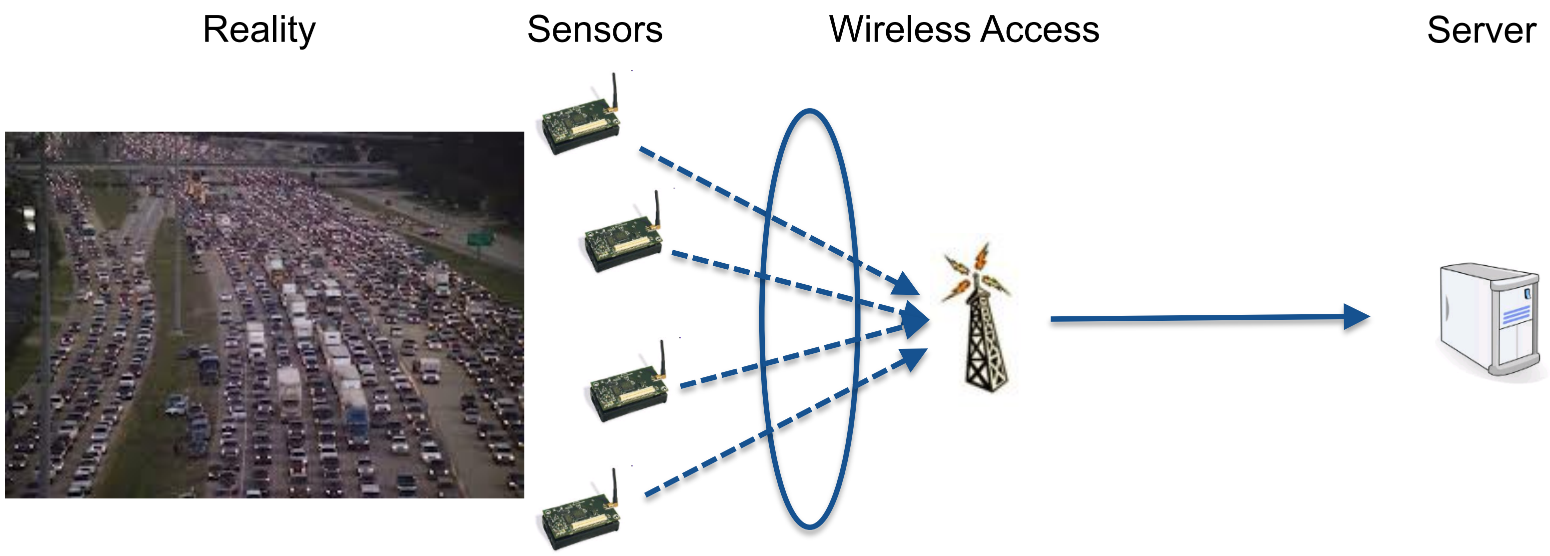
ISWCS URLLC Workshop 2018

joint work with M. Serror, C. Dombrowski, and Y. Hu

Outline

- URLLC: Motivation and Requirements
- Theoretical Perspective: FBL Analysis of Cooperation
- Practical Perspective: EchoRing Protocol
- Discussion and Outlook

Machine-Type Communications: Origins

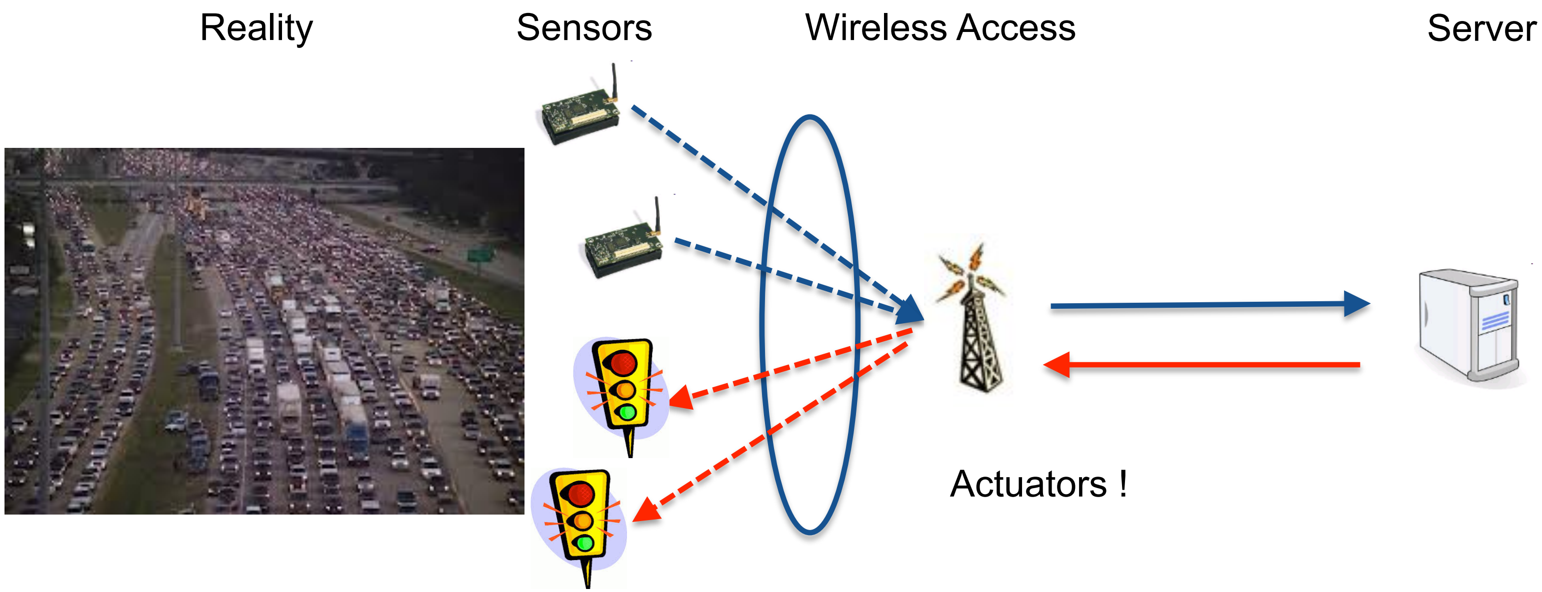


Autonomous monitoring & metering purpose

- End of 90s: First research on “sensor networks”
- Mid 2000: First standards (802.15.4, 6LowPAN)
- ~2010: Picked up by cellular networking industry (M2M business)

➔ Massive machine-type communications

Closing the Loop …



- Closed-loop control (driven by autonomy trend)
- Dependability becomes the focus

➔ Critical machine-type communications!

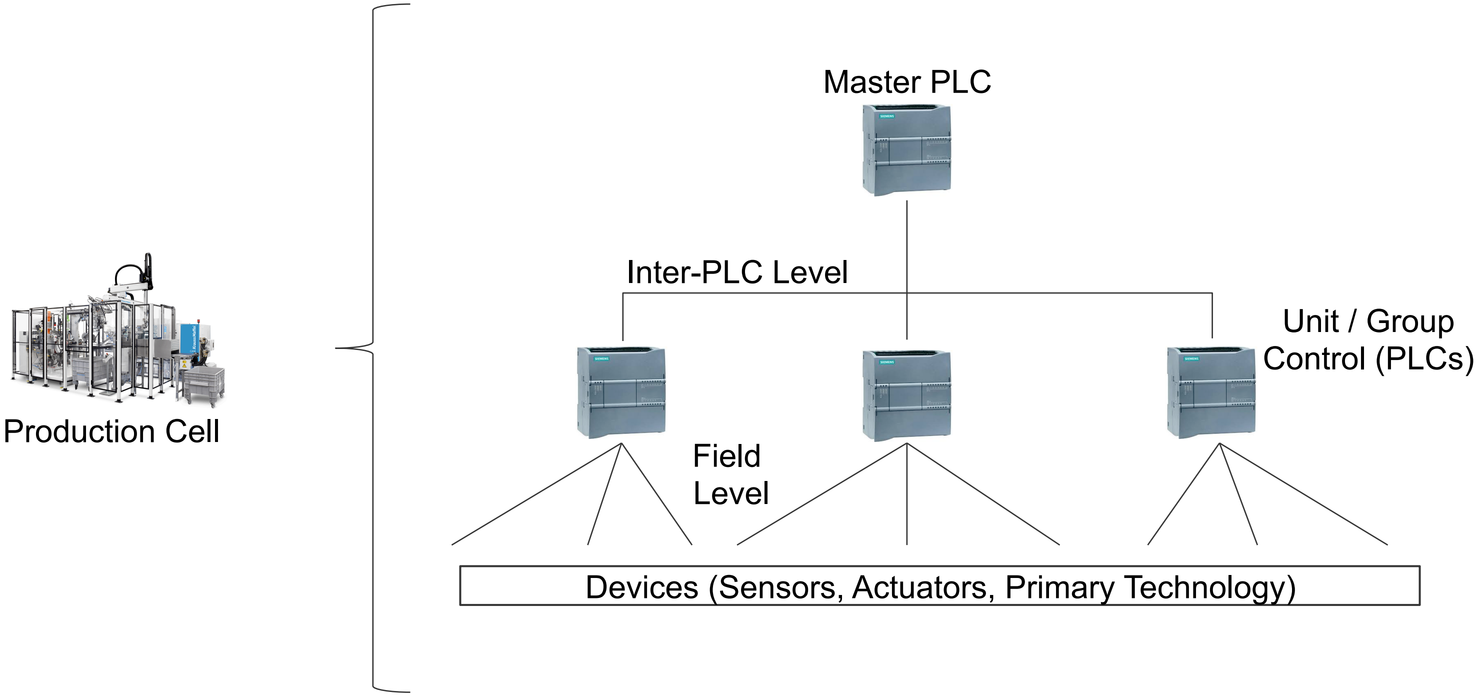
Critical MTC: Application Fields

- Various application fields according to 3GPP [1]:
  - 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)

[1] 3GPP, TR22.804 v1.0.0, December 2017

Critical MTC: Factory Automation

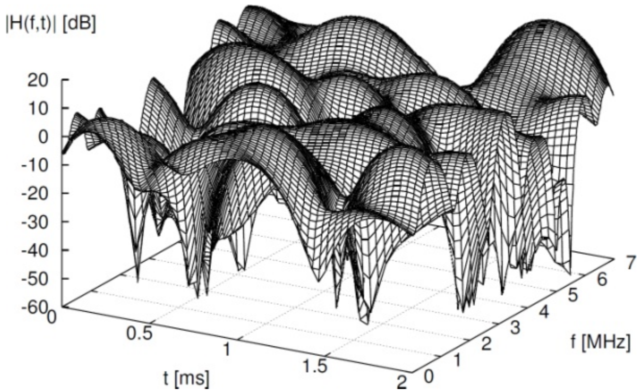


Range of Factory Automation Requirements

- Dependability: Availability + Reliability + Security

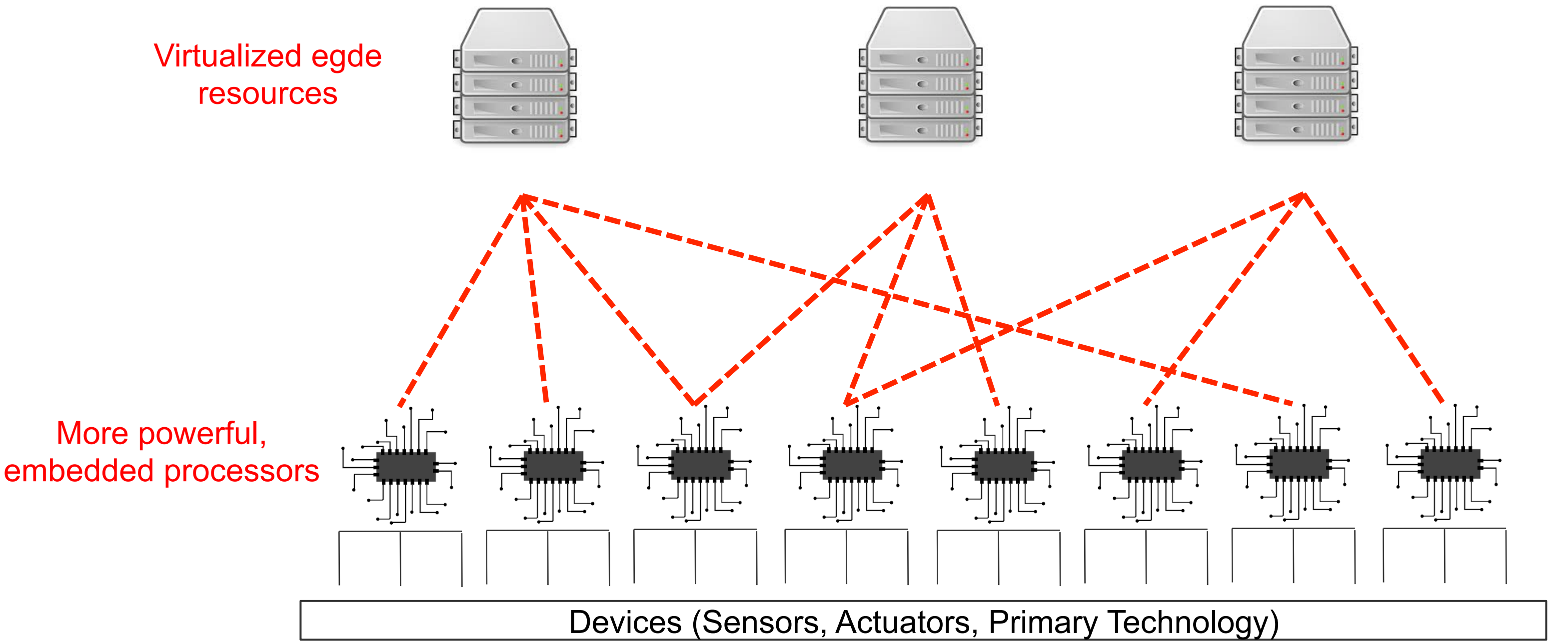
- Field-Level Control
  - Cycle time: <10 ms
  - Packet sizes: < 10 byte
  - Reliability: > $1 - 10^{-6}$

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



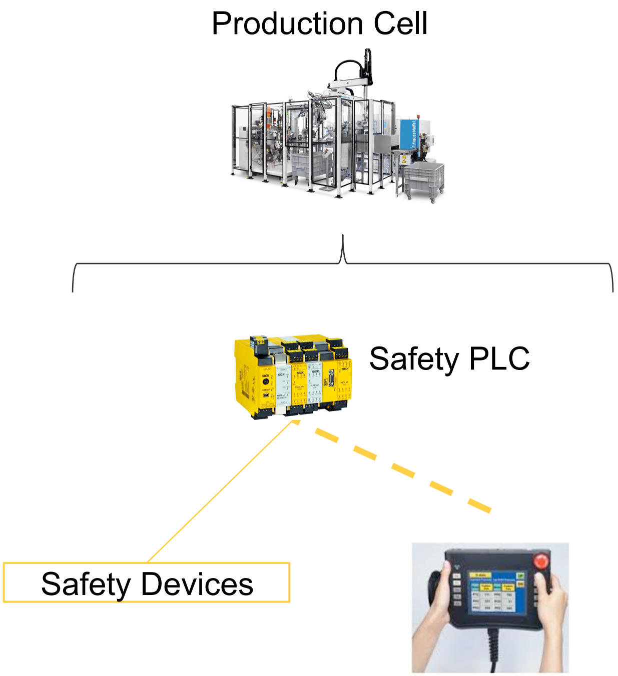
Why turn to wireless?

Visionary Reasoning: Flexibility

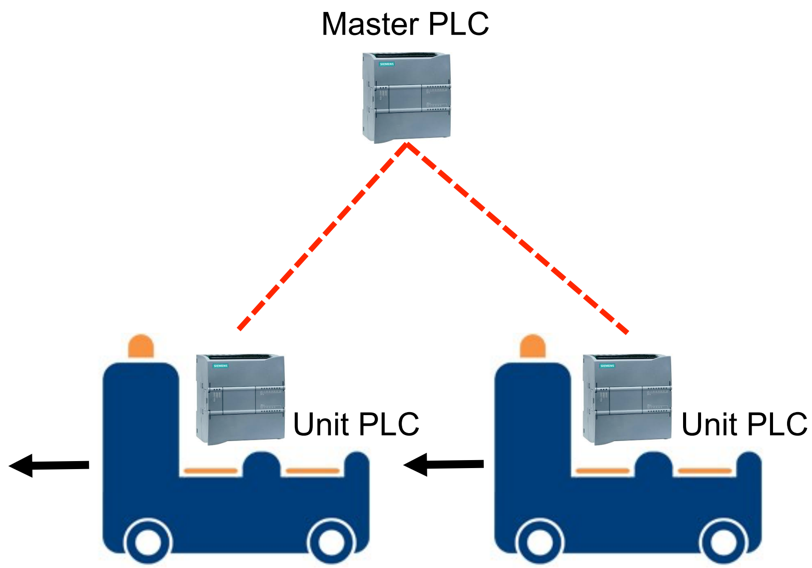


Realistic Use Cases: Mobility-Driven

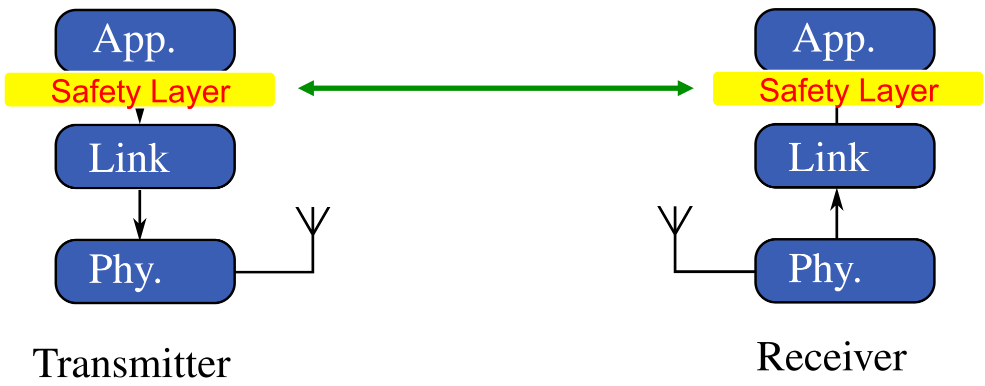
Safety Cases



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**

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Communication at Finite Blocklength

- 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:

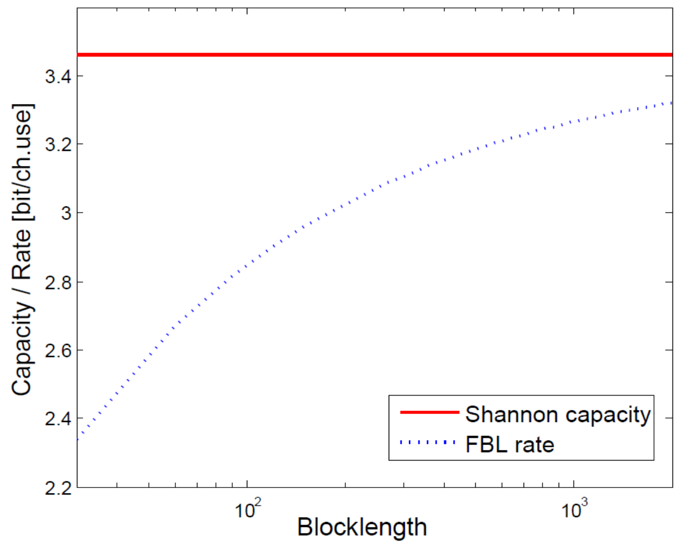
$$r_{\mathrm{FBL}} \approx C_{\mathrm{IBL}} - \sqrt{\frac{V}{n}} \cdot Q^{-1}(\epsilon) \;\; [\text{bits / channel use}]$$

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

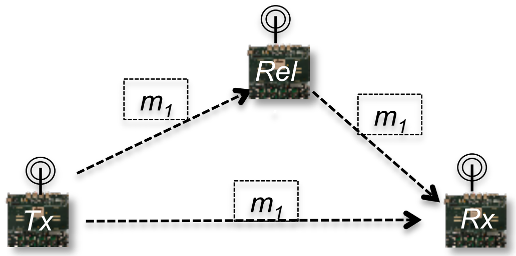
- No error-free communication possible due to “above-average” noise effects
  - The lower the blocklength, the higher the rate reduction

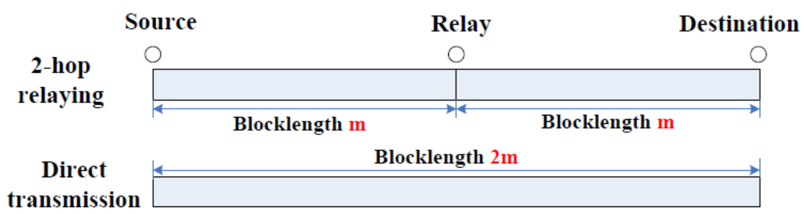


- AWGN Channel
- SNR 10dB
- Target error prob. 10^{-5}
- Perfect CSI

Design Options for Low-Latency Systems

- Maximize reliability ➔ Exploit diversity:
  - Space & Frequency: Complex transceivers, low diversity degree
  - Multi-terminals (relaying): Simple transceivers, potentially higher diversity degree, but impacts the time budget!





Relaying vs. Direct Transmission

- AWGN channel, blocklength $2m$,perfect CSI, MRC
- Assume always scheduling with fixed rate r^*
- Direct transmission:

$$\epsilon_{\mathrm{SD}}\left(h_{\mathrm{SD}}, r^*, 2m\right) \Rightarrow T_{\mathrm{DL}} = \left(1 - \epsilon_{\mathrm{SD}}\right) \cdot r^*$$

- Relaying:

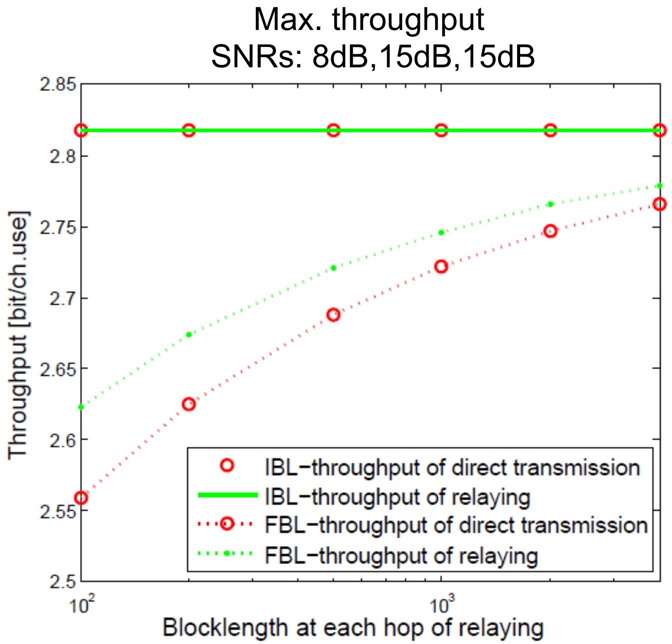
$$\epsilon_{\mathrm{R}} = \epsilon_{\mathrm{SD}} \cdot \epsilon_{\mathrm{SR}} + \left(1 - \epsilon_{\mathrm{SR}}\right) \cdot \epsilon_{\mathrm{MRC}}$$

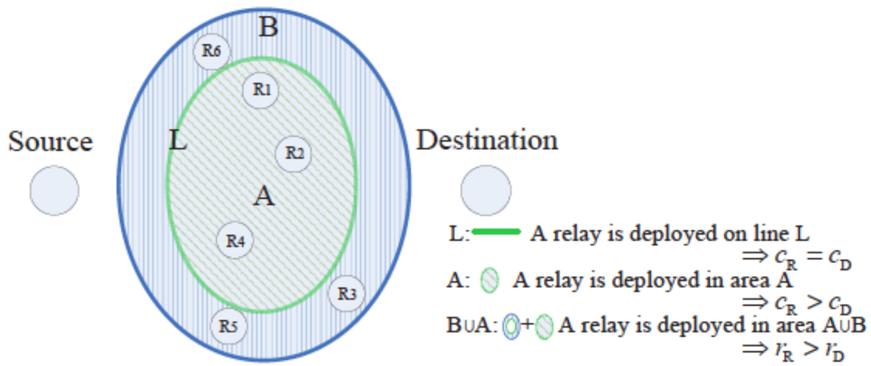
$$\epsilon_{\mathrm{SR}}\left(h_{\mathrm{SR}}, r^*, m\right) \quad \epsilon_{\mathrm{MRC}}\left(h_{\mathrm{SD}}, h_{\mathrm{RD}}, r^*, m\right)$$

$$\Rightarrow \quad T_{\mathrm{R}} = \left(1 - \epsilon_{\mathrm{R}}\right) \cdot r^*/2$$

Trade-off: Slot length vs. channel gain

AWGN Channel

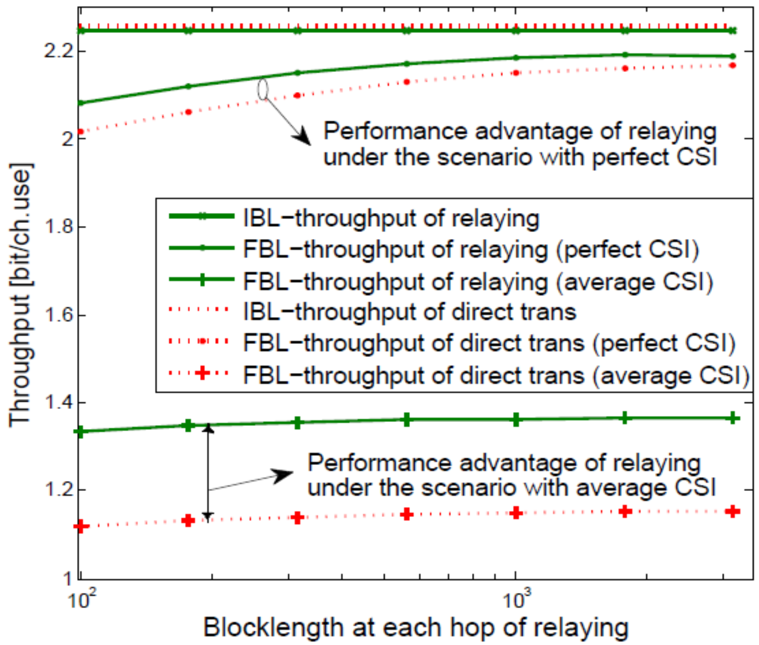




Y. Hu, J. Gross and A. Schmeink, “On the Capacity of Relaying with Finite Blocklength”,
IEEE Transactions on Vehicular Technology, vol. 65, no. 3, pp. 1790-1794, Mar. 2016.

Block Fading Channel

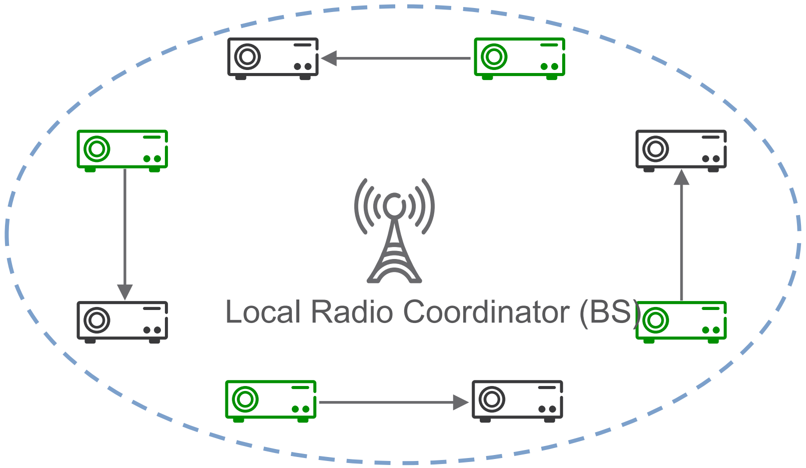
Max. throughput, IID Rayleigh channel, av. SNRs: 6dB,14dB,14dB



Y. Hu, A. Schmeink and J. Gross, "Blocklength-limited performance of relaying under quasi-static Rayleigh channels", IEEE Transactions on Wireless Communication, vol. 15, no. 7, pp. 4548 - 4558, July. 2016.

Multi-Terminal Setting

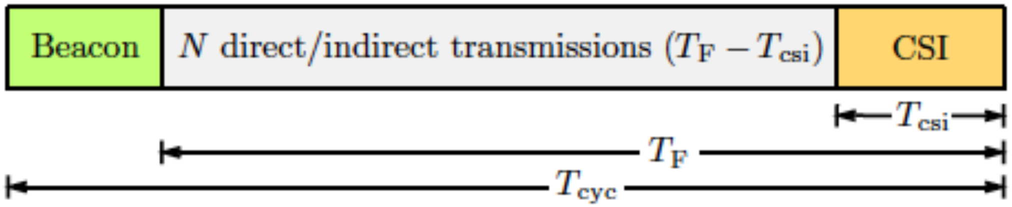
- So far: Relaying beneficial for low latency scenarios
  - FBL loss due to shorter slots overcompensated by better SNR

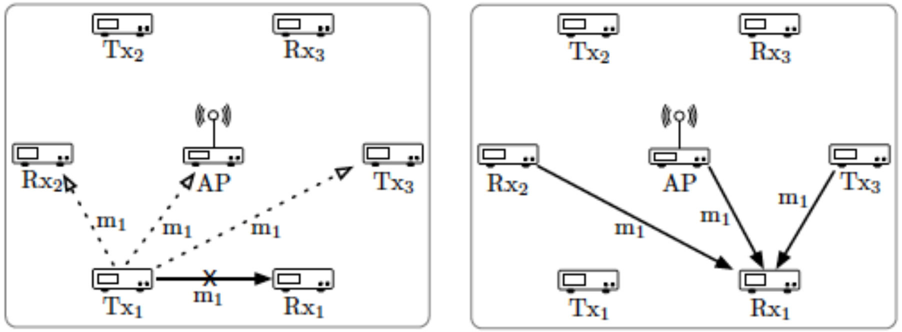


How does this affect multi-terminal scenarios?

Multi-terminal System Model

- Single cell TDMA system, N transmitters, Rayleigh fading



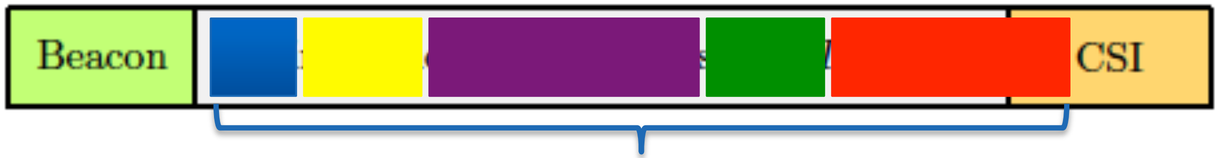


Cooperation via all terminals

System Analysis

- Scheduler selects most efficient path (direct or via relay)
- Consider IBL & FBL regime
- Metric: Packet error probability

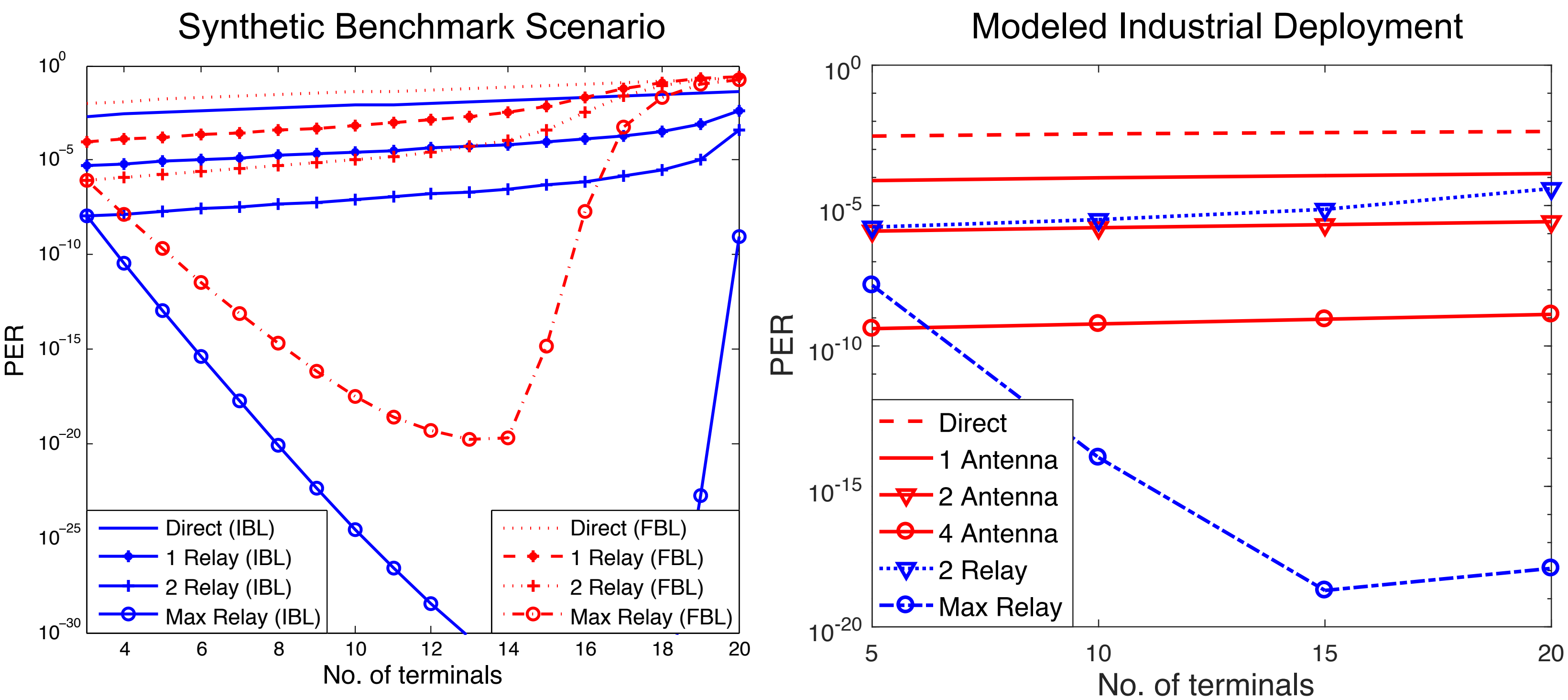
1. Frame length is not sufficient (IBL & FBL)



➔ Analysis by convolution of PDFs

Y. Hu, M. Serror, K. Wehrle, and J. Gross "Finite blocklength performance of multi-terminal wireless industrial networks", IEEE Transactions on Vehicular Technology, accepted for publication

Numerical Analysis – Increasing Load



10 dB av. SNR, 1 ms frame length, 20 MHz bandwidth, perfect CSI at BS

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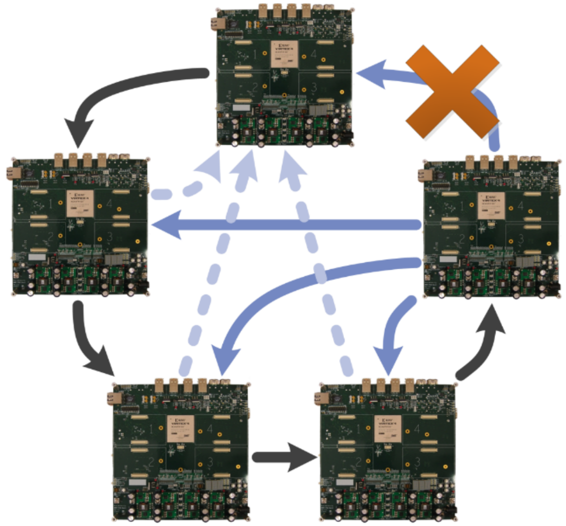
From Theory to Practice

- Cooperation boosts reliability especially for low latencies
- Can this result per confirmed in practice?
- Main challenges:
  - Design of efficient protocol
  - Extremely reliable implementation

Efficient Protocol: EchoRing

- Guarantee medium access
- Distributed cooperative system

} Token-passing protocol EchoRing



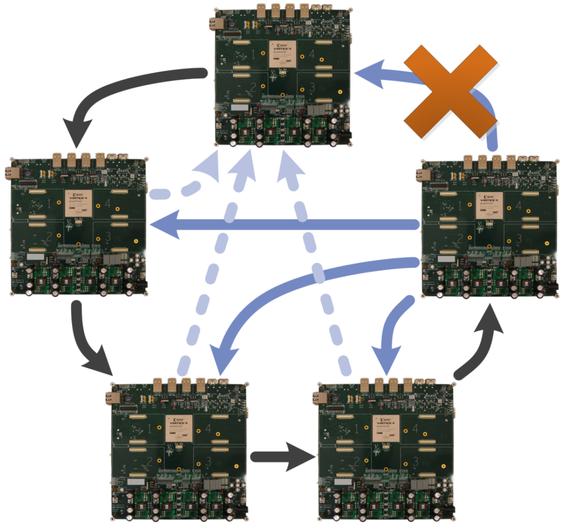
Distinct features:

- Fast exchange of CSI
- Cooperative ARQ
- Fault-tolerant link layer
- Reliability prediction

Related Work: Wireless token-passing does not work!

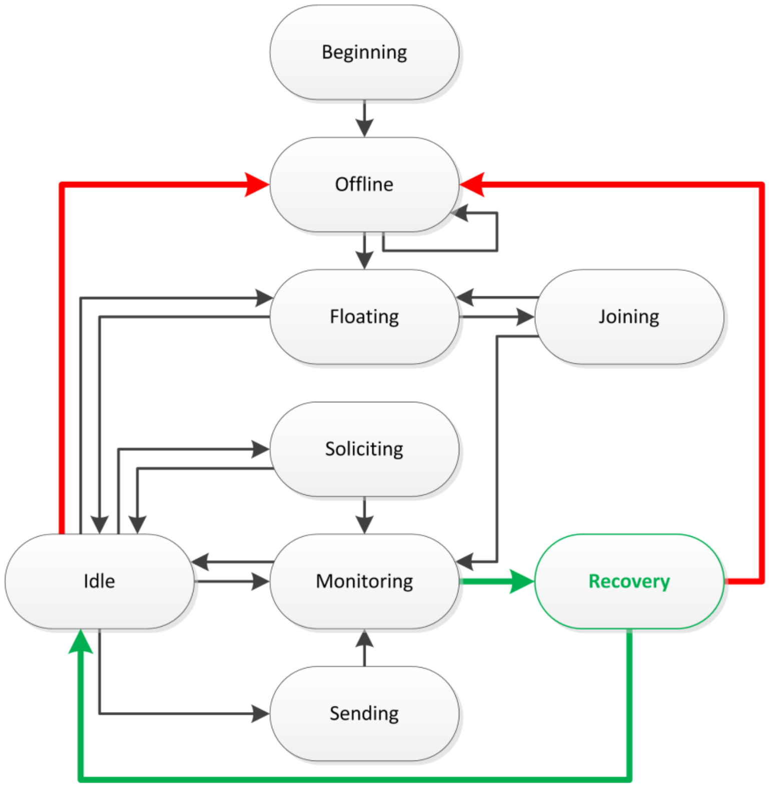
EchoRing – Cooperative ARQ

- Piggyback channel state information (CSI) with token
- Full CSI matrix at all stations after one rotation
- Dynamic relay selection primitive = “Echo”



EchoRing – Fault-tolerant Link Layer

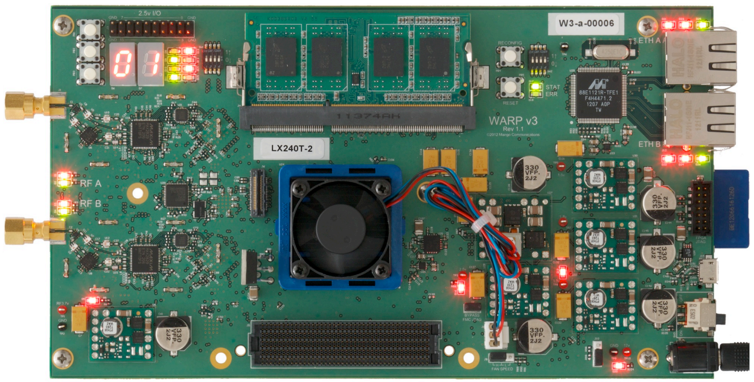
- Token-passing protocols susceptible to channel errors
- Introduce *Recovery* state, observe further operation:
  - Recover to *Idle* under certain conditions (link error types)
  - Go *Offline* only if node appears to be permanently down



Prototyping Environment

FPGA-based WARP board

- 2 integrated radios
- 2 & 5 GHz carrier
- .11g compliant stack

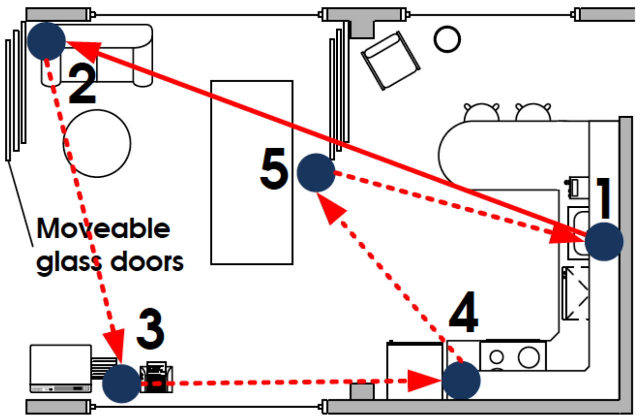


- Programming:
  - PHY in Xilinx System Generator
  - Link layer in C

Experimental Evaluation - Settings

Scenario:

- 5 stations
- Indoor, low mobility
- 5 GHz band, no interference
- 100 Byte packet size
- ~10^8 transmitted packets



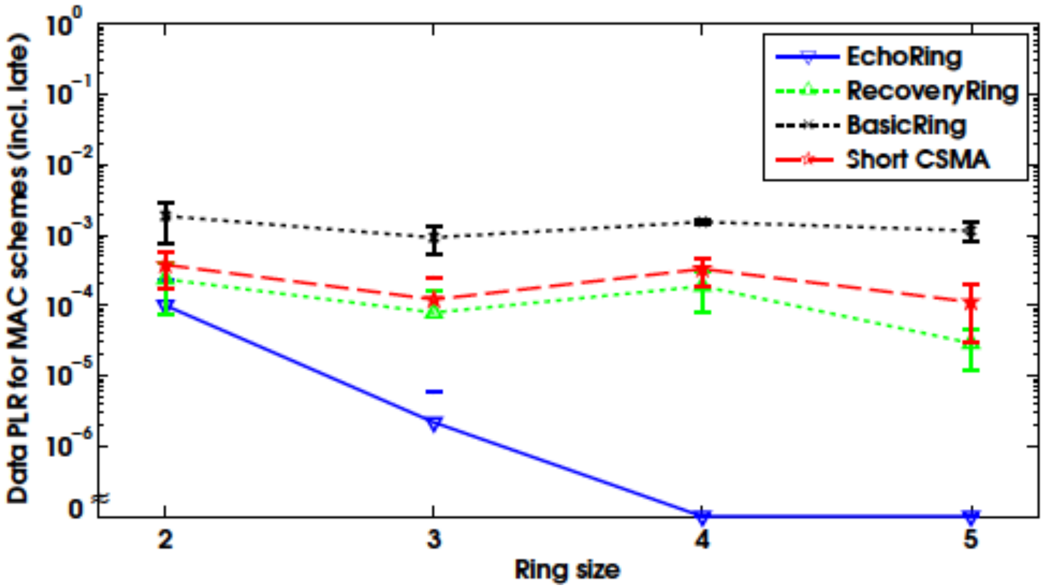
~10 x 20 meters

Schemes:

- Basic ring
- CSMA
- Recovery ring
- EchoRing

Experimental Evaluation I

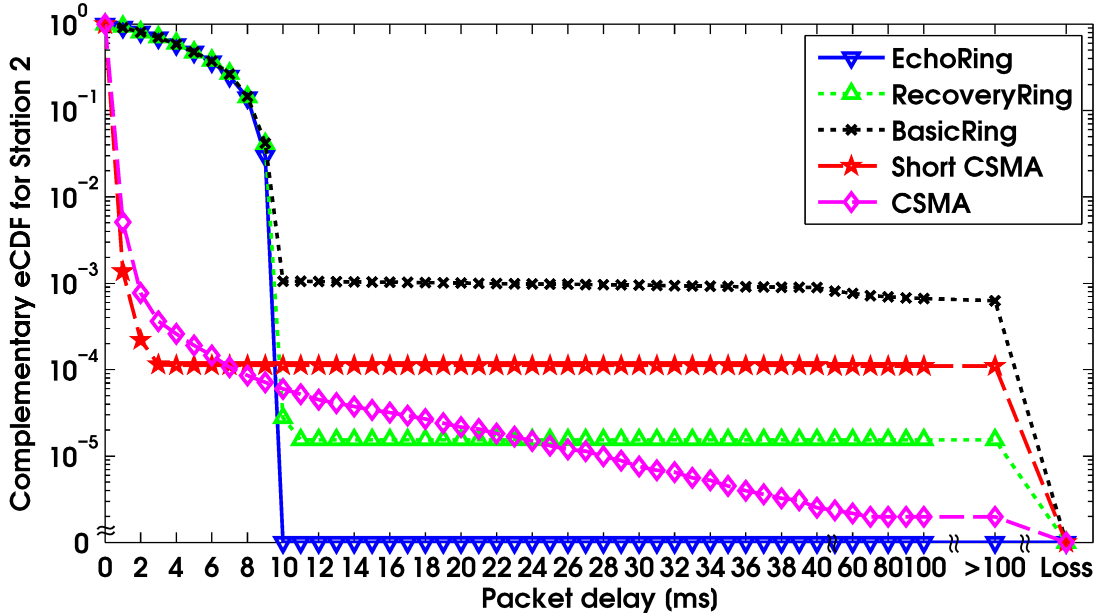
Payload PER for Increasing Number of Stations



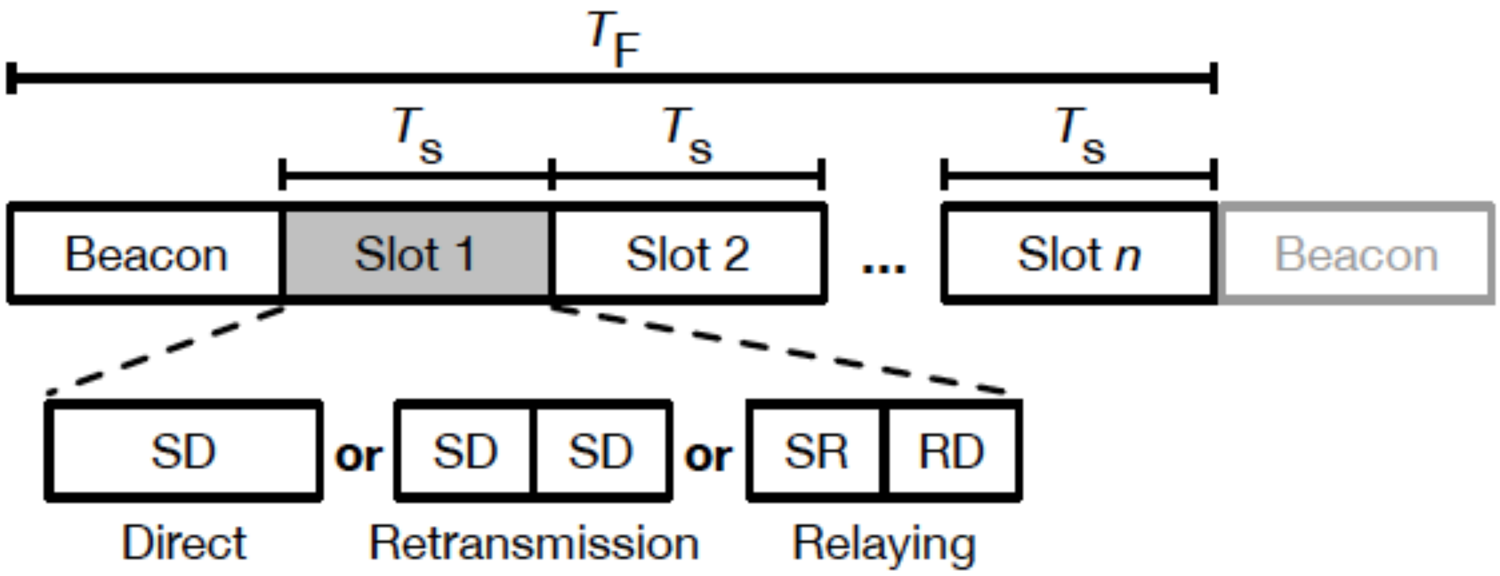
C. Dombrowski, J. Gross, "EchoRing: A Low-Latency, Reliable Token-Passing MAC Protocol for Wireless Industrial Networks", European Wireless, 2015

Experimental Evaluation II

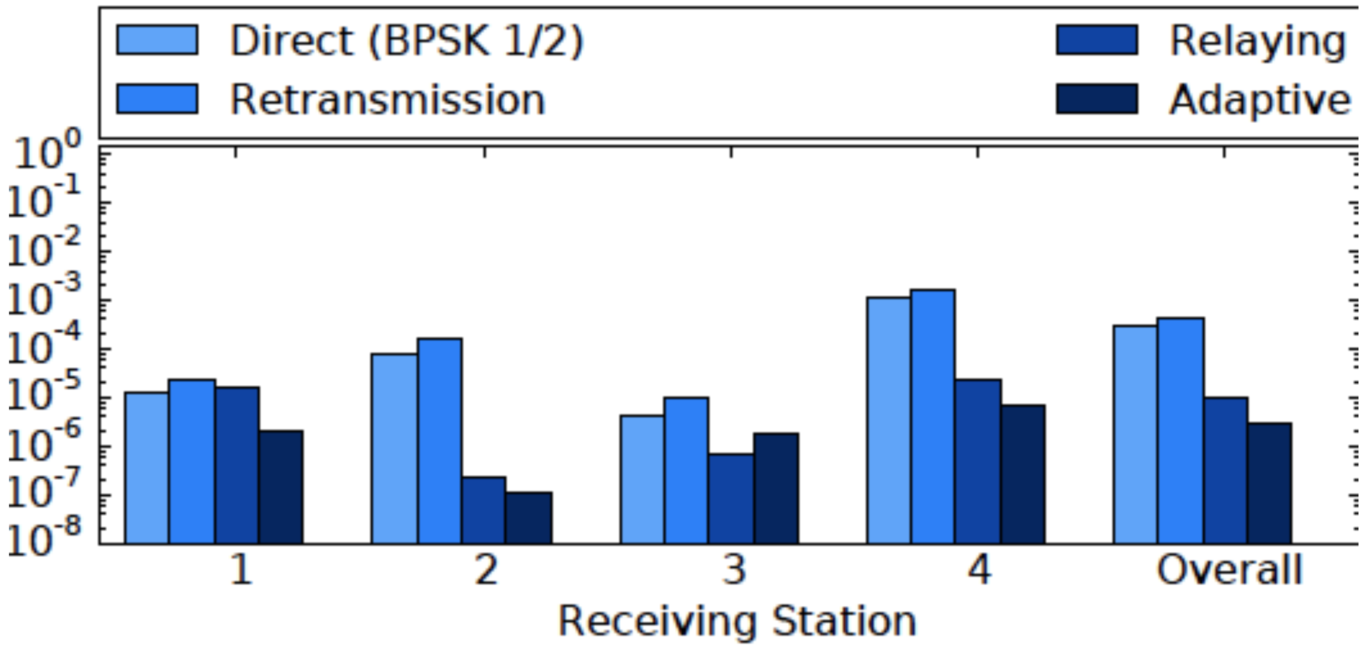
Close-up latency behavior



Recent Sub 1 ms Results - Approach



Recent Sub 1 ms Results - Results



M. Serror, J. Gross et al. “Practical Evaluation of Cooperative Communication for Ultra-Reliability and Low Latency”, IEEE WoWMoM, 2018

Conclusions

How to build a critical MTC system?

- FBL analysis principle tool for system design
- Relaying/cooperation are promising candidates
- Rigorous development process required!
- Practical experiments validate theoretical analysis
- Not mentioned: Model vs. experimental performance

Interesting other areas:

- Interference
- Security for low-latency wireless networks
- Co-design of control loop and communication system