Radio Access for Internet of Things Traffic in Fifth-Generation Cellular Networks

MARCO CENTENARO

POSTDOCTORAL RESEARCH FELLOW

DEPARTMENT OF INFORMATION ENGINEERING

UNIVERSITY OF PADOVA, ITALY

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Marco Centenaro

PhD student from Nov. 2014 until Oct. 2017 @ UniPD

- Nokia Bell Labs Stuttgart intern (Sep.-Dec. 2016)
- Yokohama National University visiting researcher (Jan.-Jul. 2017)

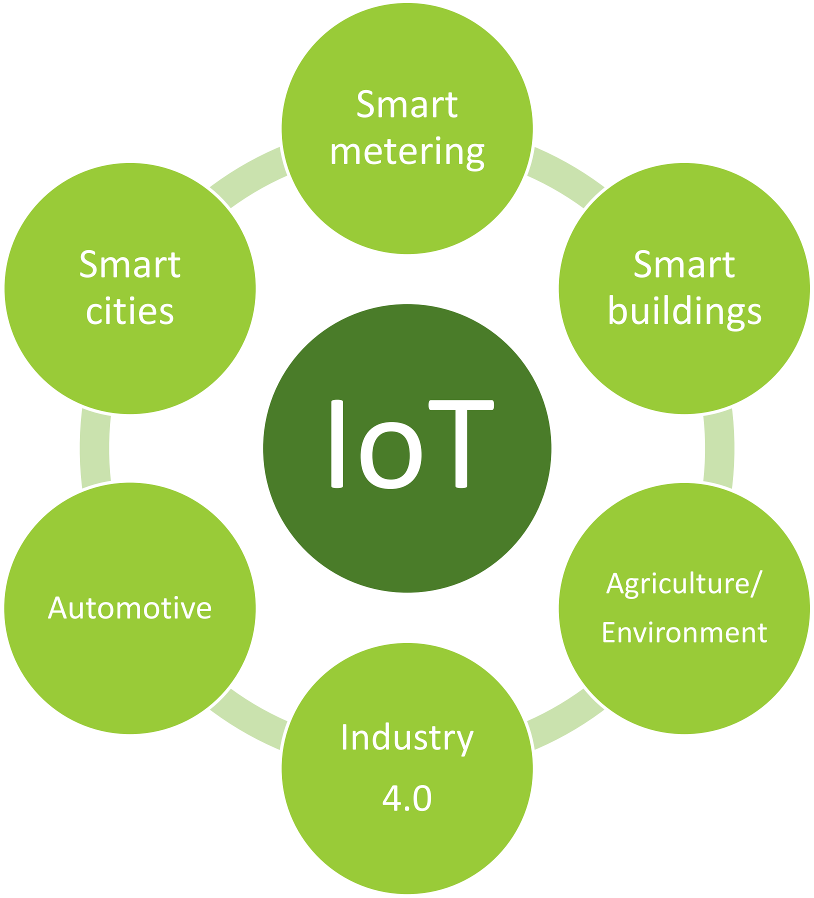
PhD defense passed in Mar. 2018

- Title of the PhD thesis: *On the Support of Massive Machine-to-Machine Traffic in Heterogeneous Networks and Fifth-Generation Cellular Networks*
- PhD supervisor: Prof. Lorenzo Vangelista
- Referees: Prof. C. Fischione (KTH) and Prof. C. Stefanovic (Aalborg University)

Since Nov. 2017, postdoctoral research fellow @ UniPD

- Channel-state information signaling reduction in FDD cellular systems (funded by Huawei)

IoT Use Cases



- Smart metering
  - Gas metering, water metering
- Smart buildings
  - Alarm systems, HVAC, access control, white goods
- Agricultural/Environment
  - Land/environment monitoring, pollution monitoring, animal tracking
- Industry 4.0
  - Remote control, asset tracking
- Automotive
  - Autonomous driving, remote diagnostics
- Smart cities
  - Streetlights, parking, waste management, ITS

In Order to Deploy an IoT…

Performance metrics

- ❑ Network capacity
- ❑ Packet delivery delay
- ❑ Packet error rate (PER)
- ❑ Outage probability
- ❑ Battery lifetime
- ❑ Localization accuracy

Non-cellular-based technologies

1. Short-range systems (e.g., NFC)
2. Passive/active RFID
3. IEEE 802.15.4 (ZigBee)
4. Bluetooth Low-Energy
5. IEEE 802.11 (Wi-Fi)

Cellular-based solutions

1. Extended-Coverage GSM
2. LTE-M
3. NB-IoT

Each use case requires a specific combination of performance metrics!

Short-range, mesh technologies are suitable for small-size, localized IoT!

To support **massive machine-type communication (mMTC)** effectively, we must **maximize flexibility** and **minimize complexity**!

A New Trend: Long-Range IoT

IoT ON CELLULAR NETWORKS

PROS

1. Universal coverage
2. Quality of Service (QoS)

- Massive number of arrivals may overload the access network
- Excessive signaling and delay to establish a connection

IoT ON LoRa

PROS

1. Ready for the market
2. Extremely cheap end devices

- Basic radio access protocol

2. Constrained in terms of duty cycle and transmit power

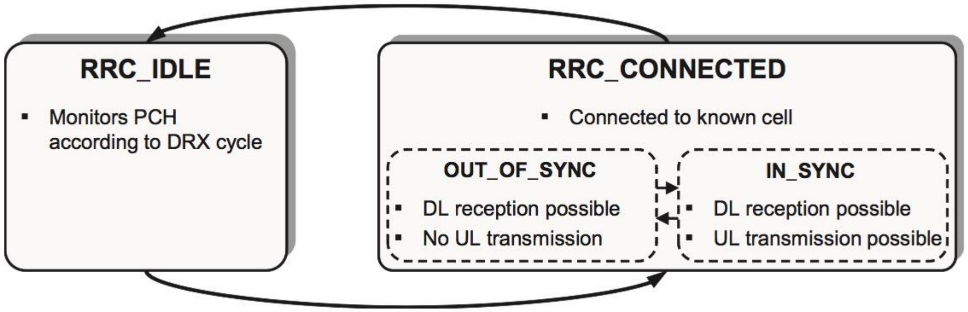
In this presentation, we will

1. focus on **cellular networks**
2. analyze the **performance** of various radio access protocols
3. propose **enhancements** to boost capacity

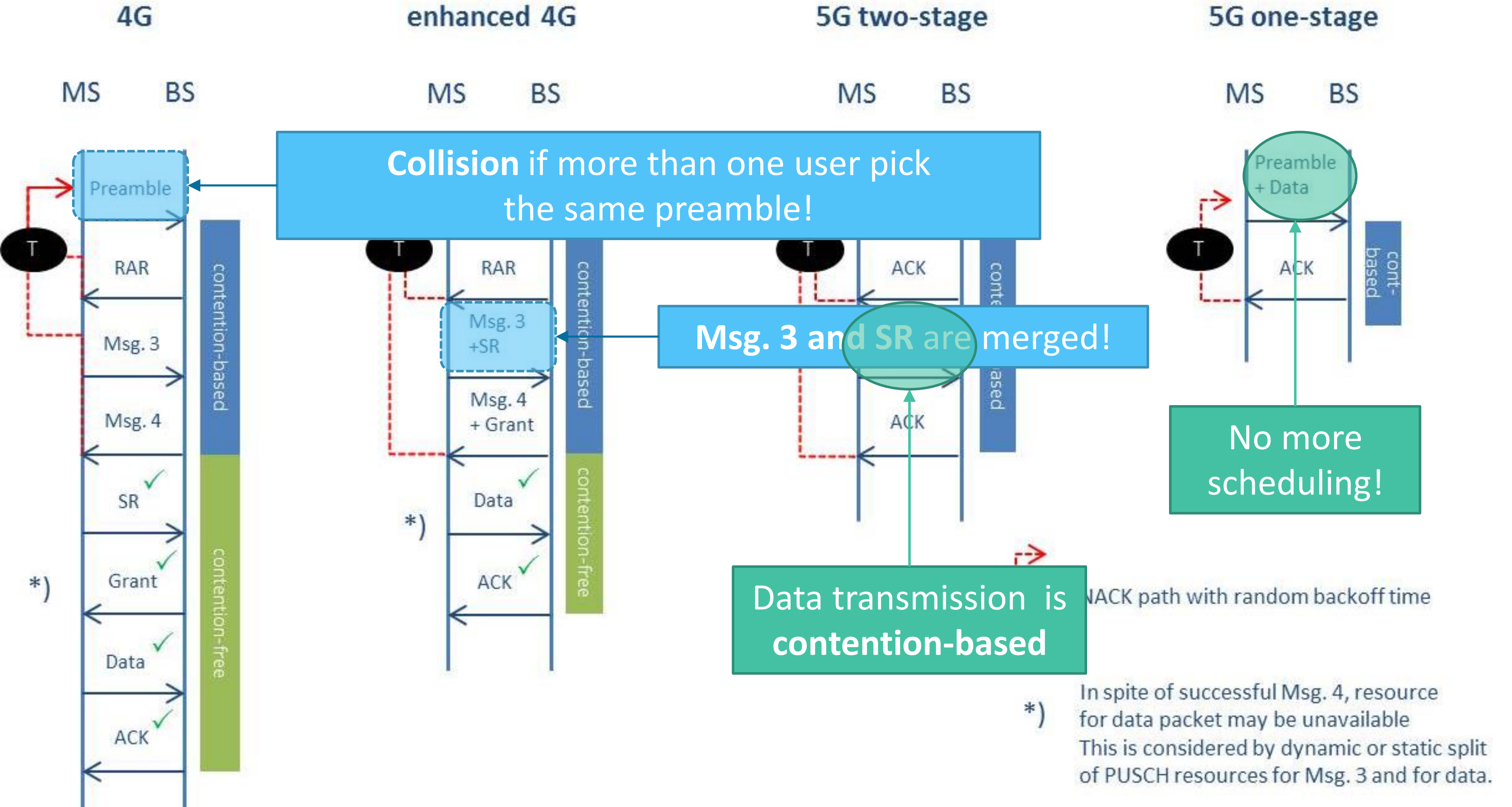
Problem Statement

The **4G radio access protocol** is not suited for IoT, because this kind of traffic is

- *infrequent* (focusing on the single terminal)
- *uplink-dominant*
- involves a *huge amount of terminals*



After transmitting a packet in uplink, the IoT terminal switches from `RRC_CONNECTED` to `RRC_IDLE`, losing the synchronization with the eNB and generating a lot of signaling to re-establish the connection.



Comparison of radio access protocols for IoT on cellular networks

The *stair* must be reduced, trading collision-free data transmission with lower delay and reduced control overhead

Contribution

Analytical models to evaluate the various protocols in terms of

- Throughput
- Outage probability
- Average delivery delay

Ingredients for the analysis

- Probability theory
- Queueing theory

Publications

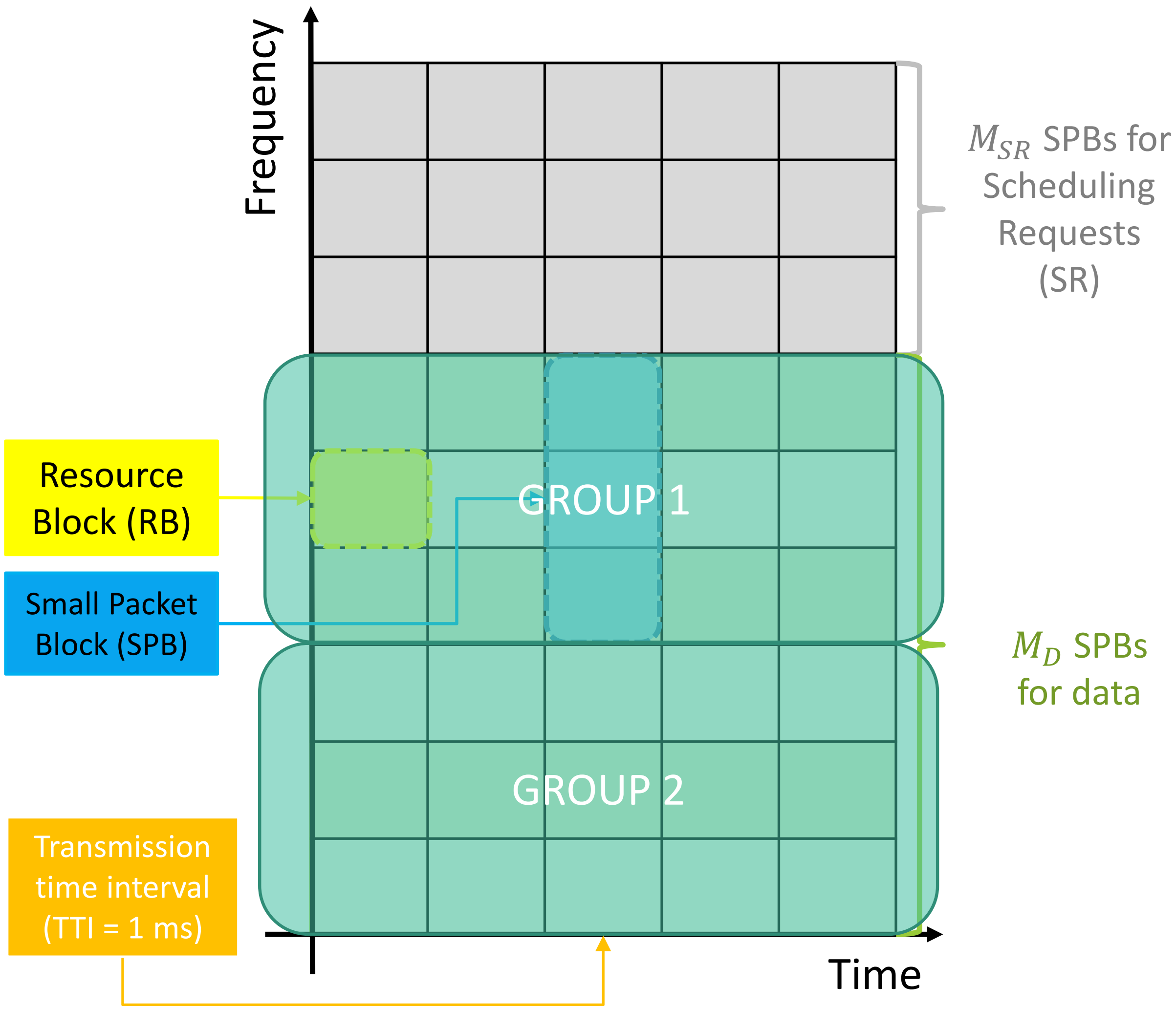
- M. Centenaro, L. Vangelista, S. Saur, A. Weber, and V. Braun, *Comparison of collision-free and contention-based radio access protocols for the Internet of Things*, IEEE Trans. on Commun., vol. 65, no. 9, pp. 3832-3846, Sept. 2017.
- M. Centenaro and L. Vangelista, *Analysis of small packet traffic support in LTE*, in Proc. Wireless Telecommun. Symp. (WTS), Chicago, IL, US, Apr. 2017, pp. 1-8.
- S. Saur and M. Centenaro, *Radio access protocols with multi-user detection for URLLC in 5G*, in Proc. European Wireless Conf., Dresden, Germany, May 2017, pp. 1-6.

Mathematical Model: Preliminaries

Definitions

- SPB: a group of J RBs
- Number of SPBs
  $M = M_{SR} + M_D$
- *Overprovisioning*: for every data SPB, N preambles available for SRs
- Data SPBs *grouping* available

Let us consider the following OFDMA grid:



$$\lambda = \text{arrival rate} \left[\frac{\text{users}}{s}\right]$$

θ = # of available tx attempts

Mathematical Model: Sketch

ONE-STAGE

Data SPB collision probability

$$p_c = \mathbb{E}\left\{1-\left(1-\frac{1}{M_D}\right)^{J-1} \middle| J \text{ arrivals}\right\}$$

$$\cong 1-\left(1-\frac{1}{M_D}\right)^{\Delta-1},$$

where Δ is the average number of arrivals in a subframe.

Failure probability

$$p_f = p_c$$

TWO-STAGE

From theory of queues with *impatient* customers

Time flexibility for scheduling

P collision

$$p_c = \mathbb{E}\left\{1-\left(1-\frac{1}{\boldsymbol{N}M_D}\right)^{J-1} \middle| J \text{ arrivals}\right\}$$

SR drop probability

$$p_d = f(\lambda, M_D, W)$$

Failure probability

$$p_f = 1-(1-p_c)(1-p_d)$$

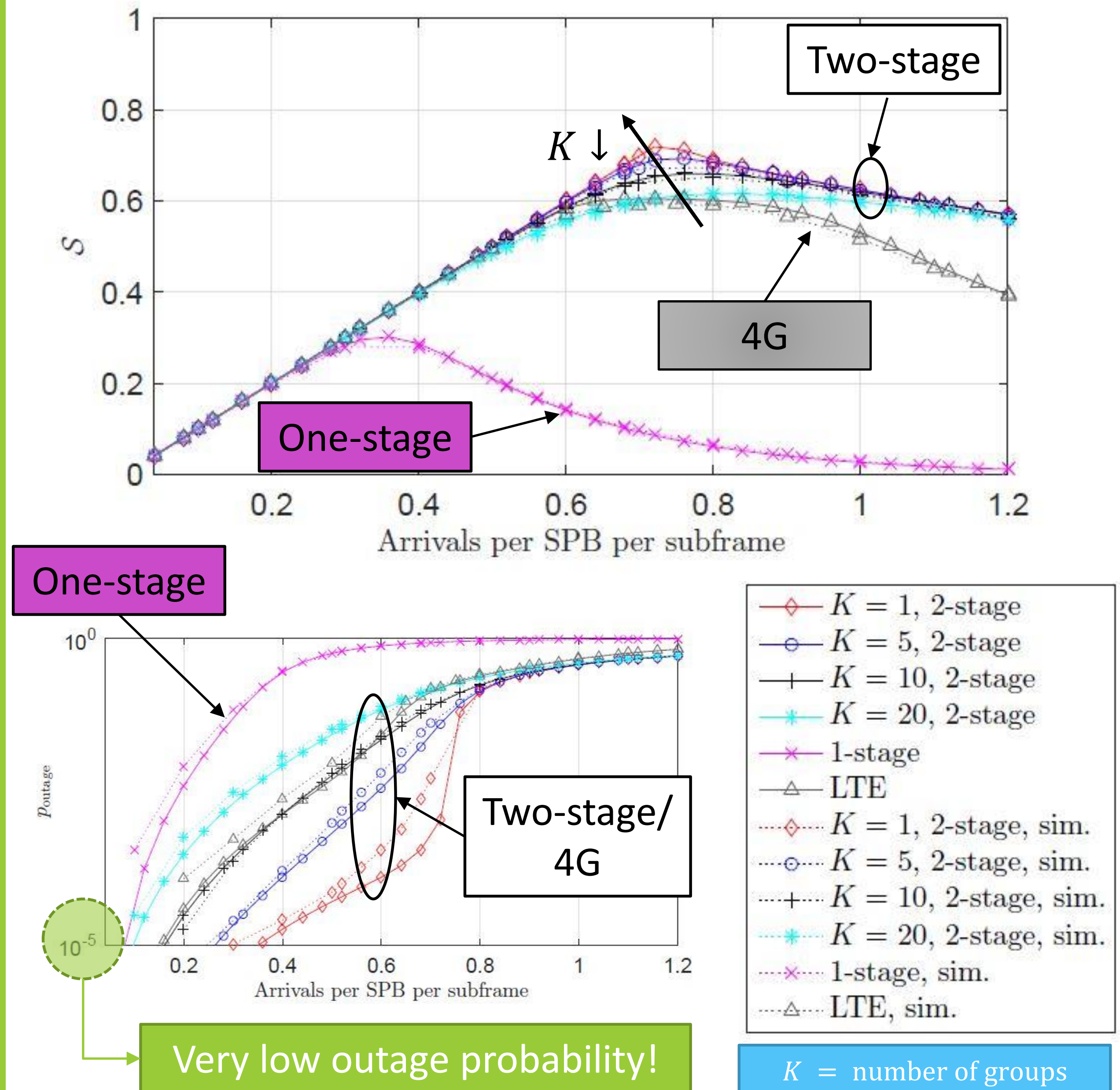
Performance metrics

$$p_{outage} = {p_f}^{\theta}$$

$$\mathcal{S} = \lambda(1-p_{outage})$$

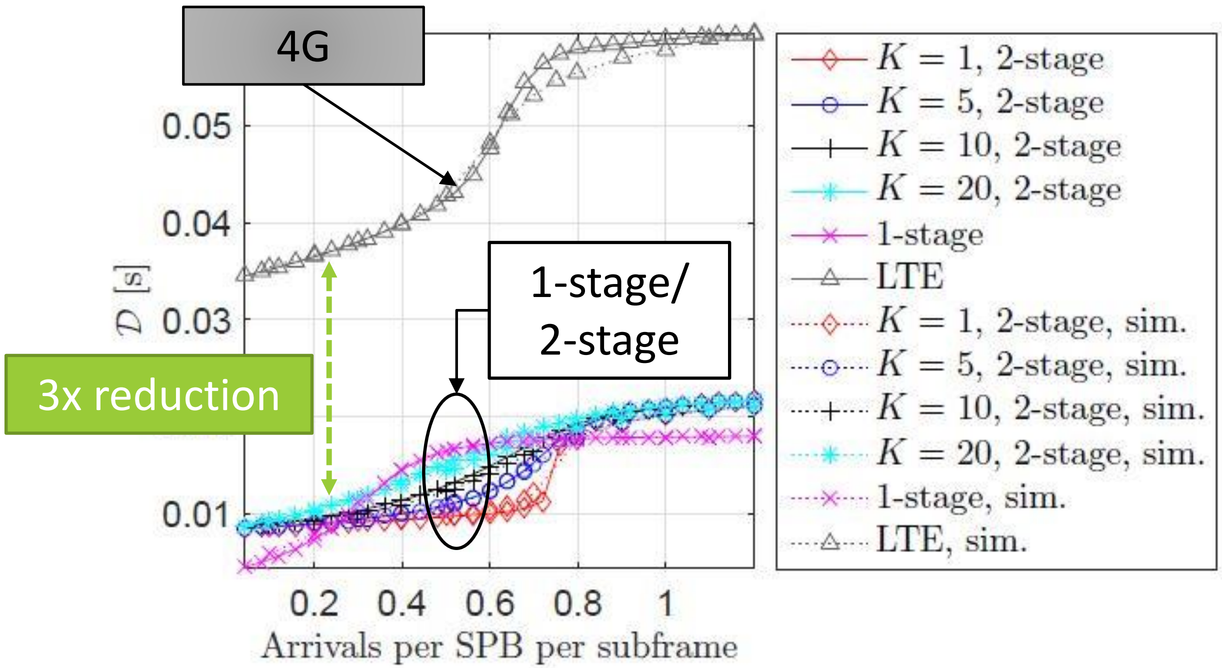
Performance Evaluation: Throughput and Outage

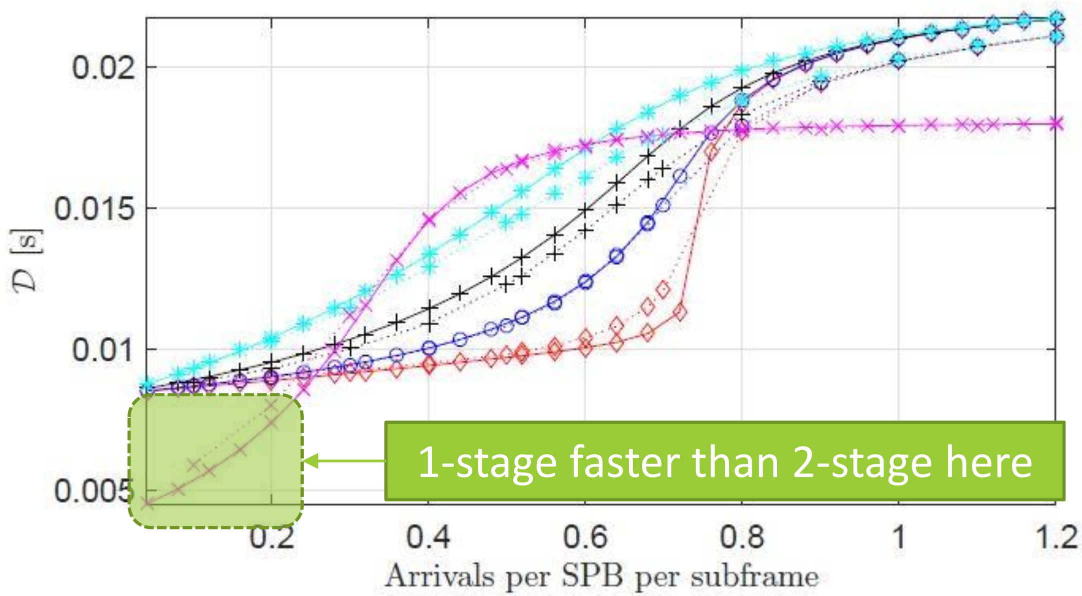
- 2-stage yields a throughput increase with respect to 4G
- 1-stage becomes unstable soon
- Low outage probability can be obtained!
- Mathematical model and simulations are cross-validated
- No grouping ($K = 1$) provides the highest throughput



Delay

- Huge delay reduction
- For low arrival rates, one-stage provides the fastest delivery





Observations

ONE-STAGE VS 4G

PROS

- Very fast packet delivery

CONS

- High collision probability
- Difficult coexistence with scheduled transmissions

TWO-STAGE VS 4G

PROS

- Higher throughput
- Reduction of downlink feedback

CONS

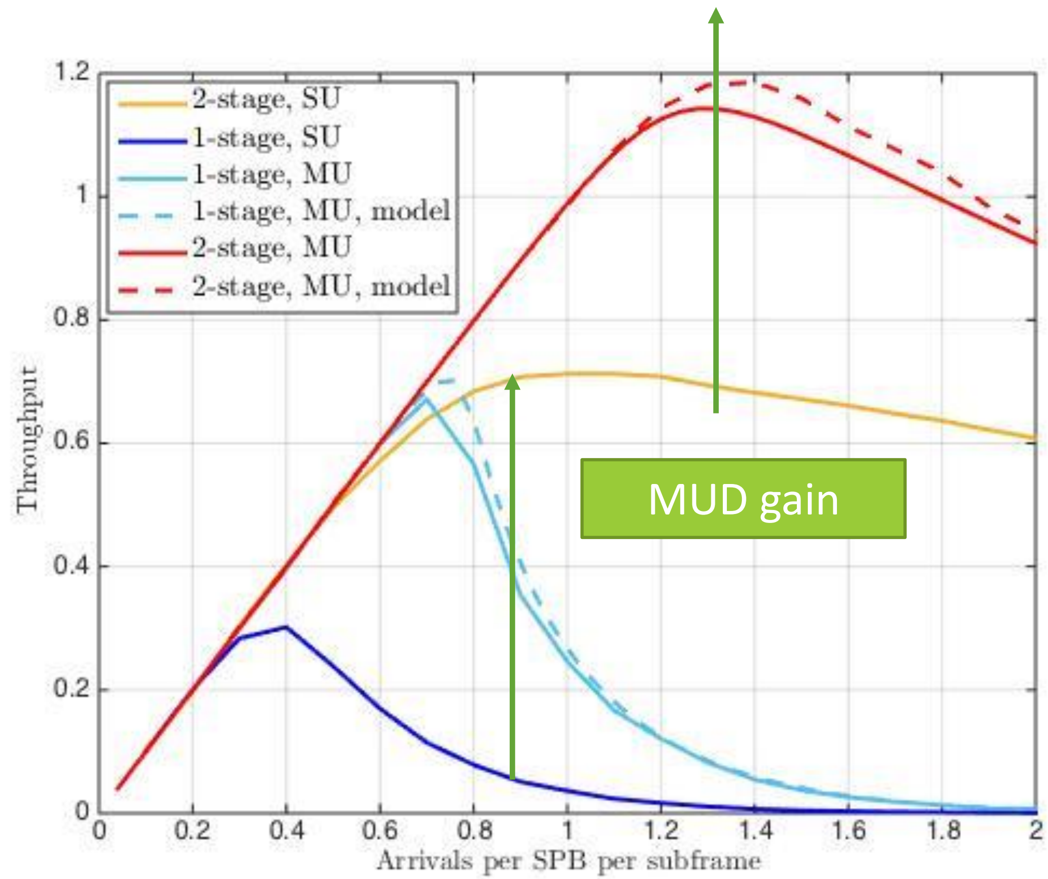
- Longer latency than 1-stage

Impact of Multi-User Detection

Exploiting *multi-user detection* algorithms at the eNB yields a massive performance improvement, that is, a network capacity increase.

MUD is based on successive interference cancelation, thus it is computationally demanding, however, it is performed at the eNB side: **no further burden at the mobile terminals**.

The design of the extended mathematical models is a work in progress.



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BACKUP

Queueing Theory

Queues With Impatient Customers

The data transmission phase is modeled as a queueing system in which the *customers* (the SRs) are *impatient*: the maximum waiting time is τ. The long-term fraction of customers that leave the queue is

$$p_d = \frac{(1-\rho)\rho\Omega}{1-\rho^2\Omega}$$

where

$\Omega = e^{-\mu(1-\rho)\tau}$

$\mu = \frac{M_D}{\delta_{RAO}}$ is the service rate, δ_{RAO} is the time interval between two SR SBPs

$\rho = \frac{\lambda_A}{\mu}$ is the load factor, $\lambda_A = \text{rate of activated SRs } [\text{SR}/s]$

$\tau = W\delta_{RAO}$ is the maximum waiting time

4G Model

Preamble collision probability

$$p_c = \mathbb{E}\left\{1 - \left(1 - \frac{1}{54}\right)^{J-1} \middle| J \text{ arrivals}\right\}$$

Preambles in 4G

Connection request (Msg.3) drop probability

$$p_d^{CR} = f(\lambda, n_{CR}, W_{RAR})$$

RAR window

RBs for connection requests

SR drop probability

$$p_d = f(\lambda, p_d^{CR}, M_D, T_{SR})$$

SR periodicity

Failure probability

$$p_f = 1 - (1 - p_c)(1 - p_d^{CR})(1 - p_d)$$