IEEE 6G SUMMIT

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5G/6G for industrial control systems: a new starting point

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Our business areas

Electrification

Motion

Process Automation

Robotics & Discrete Automation

Outline

Needs and opportunities

Gaps and recommendations

- Latency and reliability
- Compatibility with industrial ethernet protocols
- Industry-oriented user equipment
- Functional safety and resilience
- Wireless-aware control application

Future perspectives

- Cloud-Fog Automation
- Control-Communication-Computing Co-design

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Needs and opportunities

5G enables mobility and flexibility

Large height

Rural areas

Mobile machines

Mobile operation

Moving parts

Harsh or corrosive

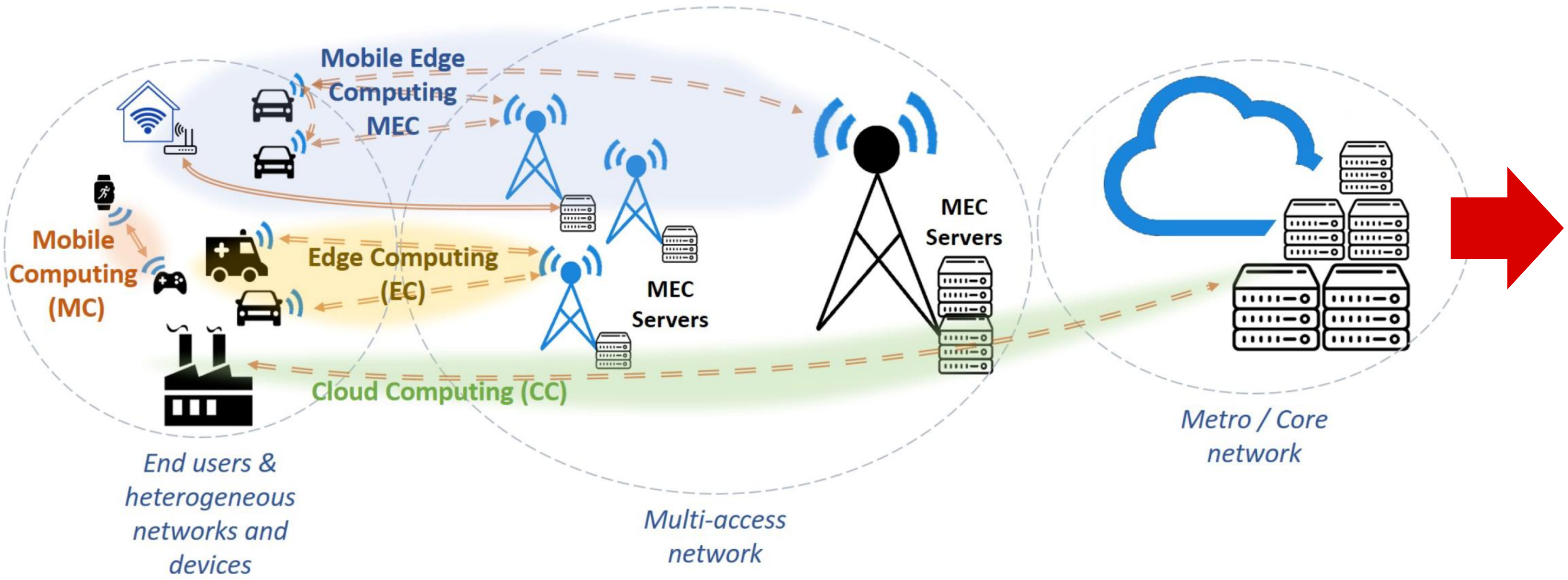
Access forbidden

Cabling forbidden

Temporary deployment

Needs and opportunities

5G brings computation to mobile edge



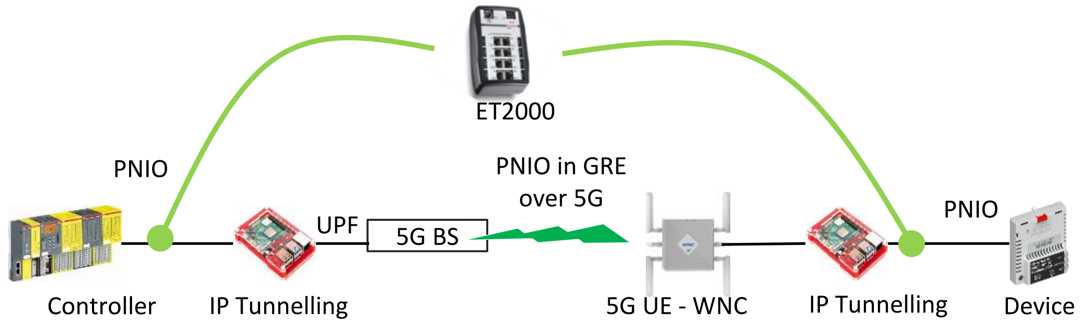
- Data ownership
- Security and privacy
- New BM, e.g., XaaS

ETSI, “Mobile Edge Computing A key technology towards 5G”, 2015, link

McClellan, M.; Cervelló-Pastor, C.; Sallent, S. Deep Learning at the Mobile Edge: Opportunities for 5G Networks. *Appl. Sci.* **2020**, *10*, 4735. https://doi.org/10.3390/app10144735

Gaps and recommendations: latency and reliability (1/2)

Use the “Unobtrusive Layer2 Tester” and “Dinosaur Curve” to evaluate the latency and reliability



Unobtrusive to control loop

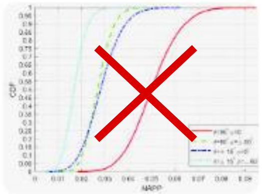
Insertion delay: <1us

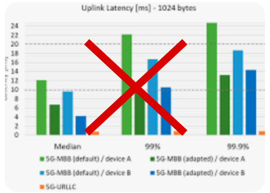
Latency error: < 40ns

Verified reliability: < 10e-8

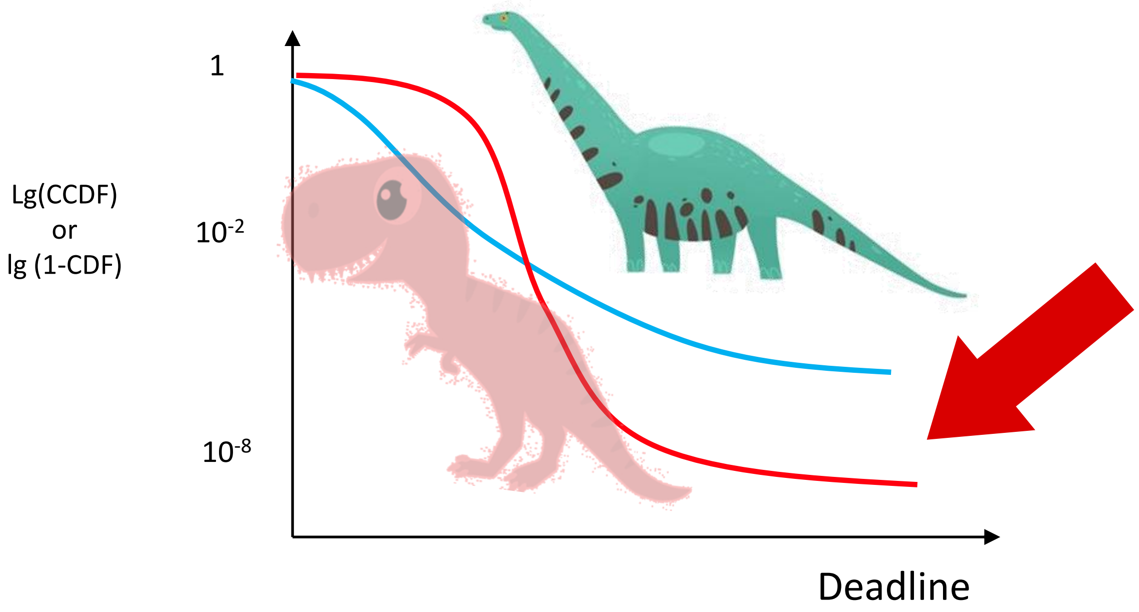
Verified protocols: PROFINET, PROFIsafe, Modbus TCP, EtherNet/IP, TCP, UDP, DDS, OPC UA

Limitation: Distance between probes: <100m (a)





Probability of missing the deadline



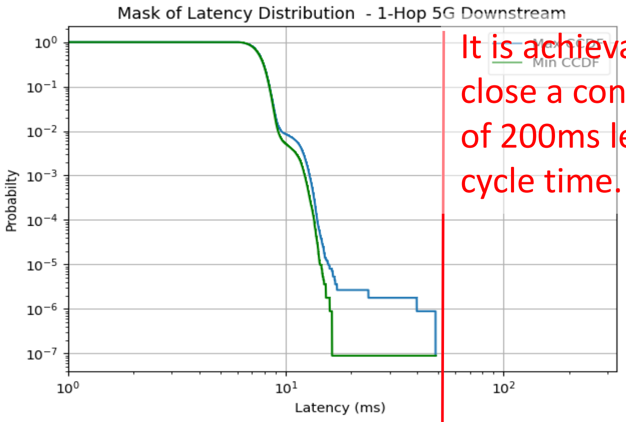
K. Bhimavarapu, Z. Pang*, O. Dobrijevic and P. Wiatr, "Unobtrusive, Accurate, and Live Measurements of Network Latency and Reliability for Time-Critical Internet of Things," in IEEE Internet of Things Magazine, vol. 5, no. 3, pp. 38-43, September 2022, doi: 10.1109/IOTM.001.2200068.

Gaps and recommendations: latency and reliability (2/2)

The promised 1ms RTT of URLLC is 100x away to reach, and field survivability and scalability need to be studied.

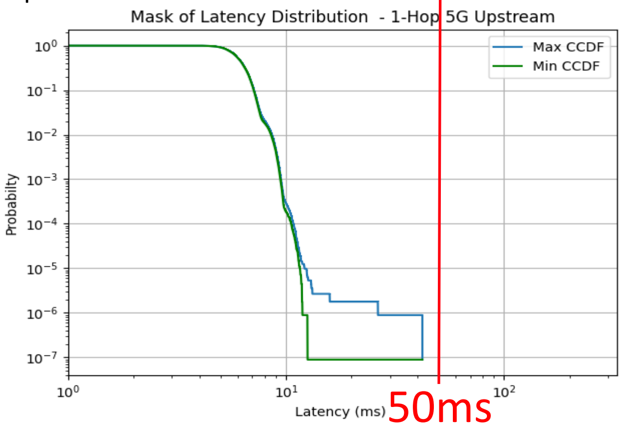
Latency and reliability of COTS 5G tested in Feb 2022

Downstream



It is achievable to close a control loop of 200ms level cycle time.

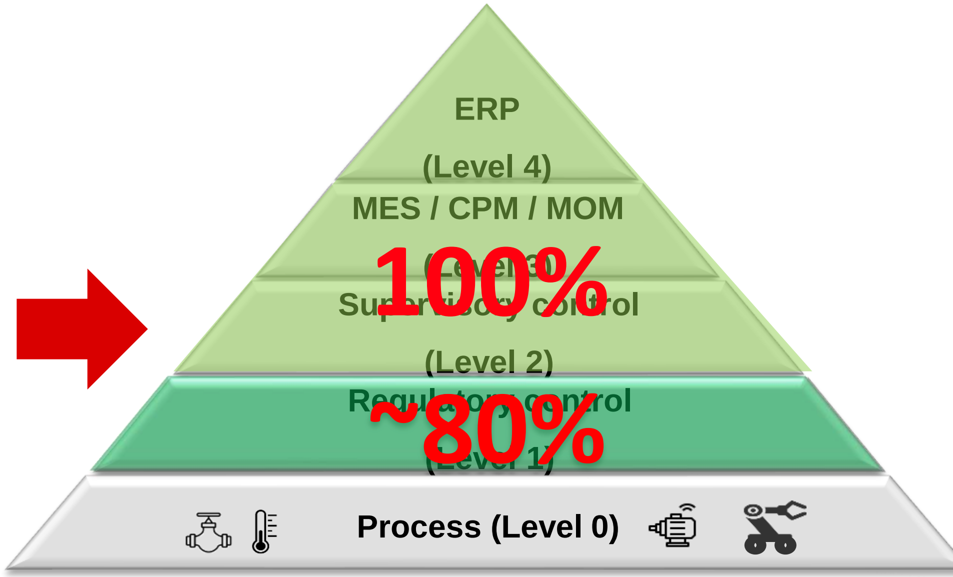
Upstream



Conditions: in lab, 1-hop 5G, 2m distance, no obstacle, no competing traffics, 16ms cycle time, 60B Ethernet frame (PNIO in GRE in Eth), when 5G system is stable, tested for 3 days, statistic window is 5-hour

5GACIA
5G Alliance for Connected Industries and Automation

"For URLLC, the first release of **5G (Release 15)** already has the capability to achieve a latency of **1 ms** with a reliability of **99.999%** over the 5G radio interface."
-- the position White Paper[2]



5G **was promised and expected** to be generic communication infrastructure for "nearly all" industrial control systems.

[1]K. Bhimavarapu, Z. Pang*, O. Dobrijevic and P. Wiatr, "Unobtrusive, Accurate, and Live Measurements of Network Latency and Reliability for Time-Critical Internet of Things," in IEEE Internet of Things Magazine, vol. 5, no. 3, pp. 38-43, September 2022, doi: 10.1109/IOTM.001.2200068.
[2] 5G-ACIA White Paper 5G for Connected Industries and Automation, Second Edition, 28.02.2019. link

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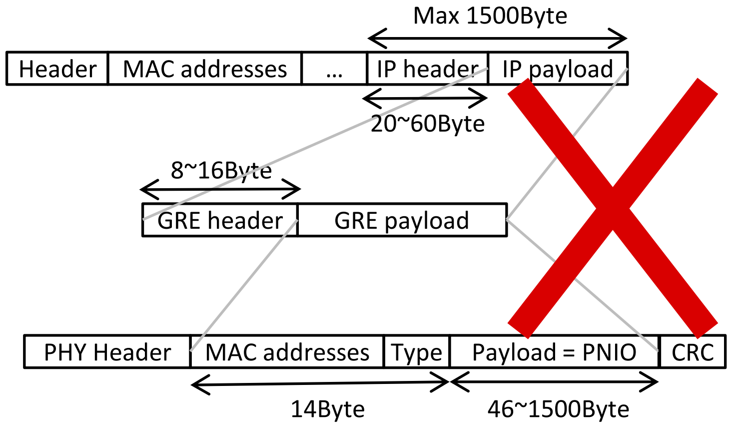
Gaps and recommendations: compatibility with industrial ethernet protocols

Depending on the decision of automation users, make ether the layer-2 or the layer-3 deterministic and multicast.

If non-IP (more popular):

We need deterministic layer-2 (Ethernet PDU session). The IP tunneling is **not** a solution!



If IP:

We need deterministic IP layer-3 with multicast!

The **DetNet-over-5G** is more meaningful than the **TSN-over-5G**. But none of them looks serous enough (to me personally)!

[1]K. Bhimavarapu, Z. Pang*, O. Dobrijevic and P. Wiatr, "Unobtrusive, Accurate, and Live Measurements of Network Latency and Reliability for Time-Critical Internet of Things," in IEEE Internet of Things Magazine, vol. 5, no. 3, pp. 38-43, September 2022, doi: 10.1109/IOTM.001.2200068.

Gaps and recommendations: industry-oriented user equipment

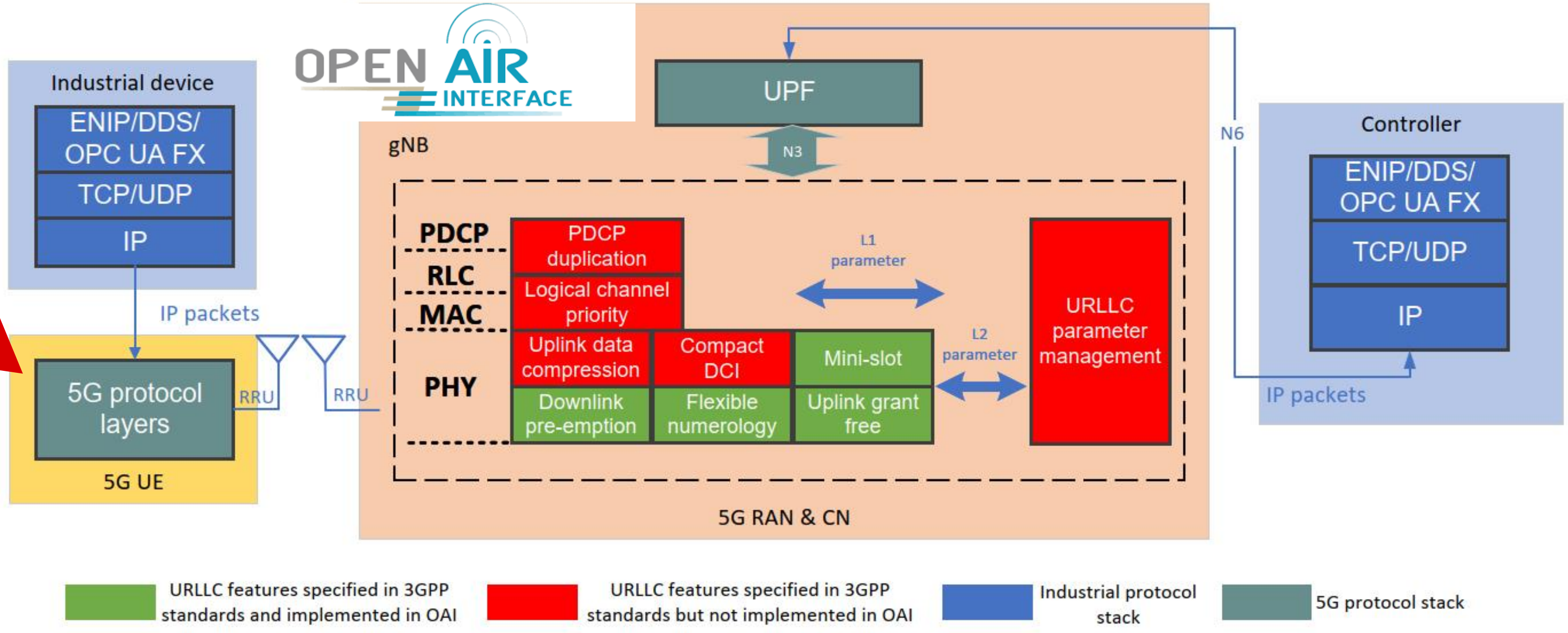
We need open implementation of 5G UE (“Open 5G UE”), like the open standards of automation domain.

OPC UA

open62541

OSADL
Open Source Automation Development Lab eG

OT market is value-sensitive rather than cost-sensitive



Gaps and recommendations: functional safety and resilience (1/2)

Guarantee safety and resilience against e.g., jamming without the expense of availability.

Gaps and recommendations: functional safety and resilience (2/2)

Guarantee safety and resilience against e.g., jamming without the expense of availability.

From the Black Channel to Gray Channel

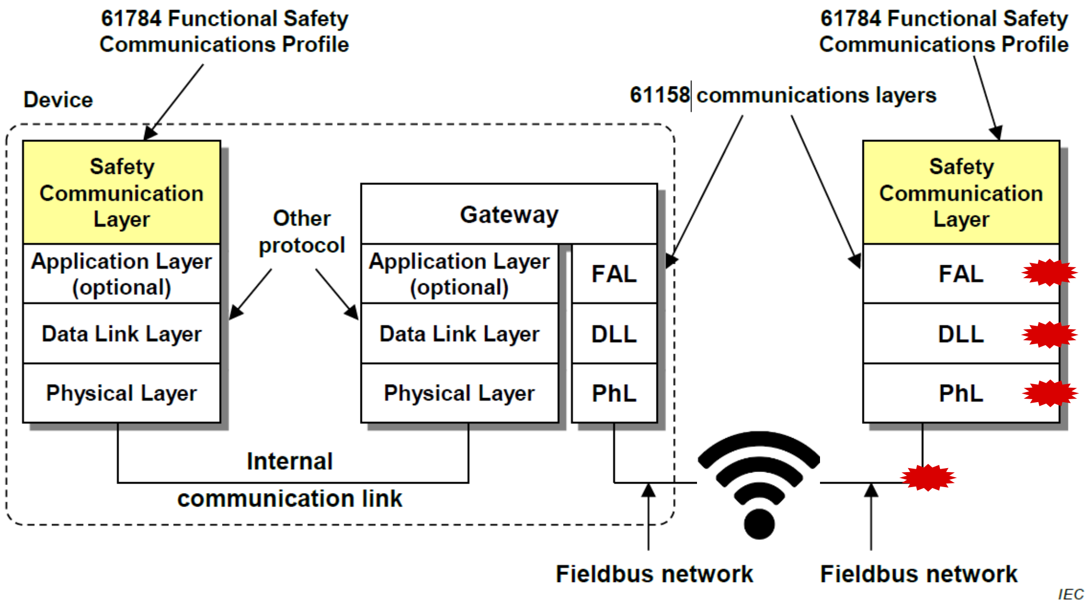


Figure 5 – Example model of a functional safety communication system

Wireless-aware safety

e.g., safety semantic communication.

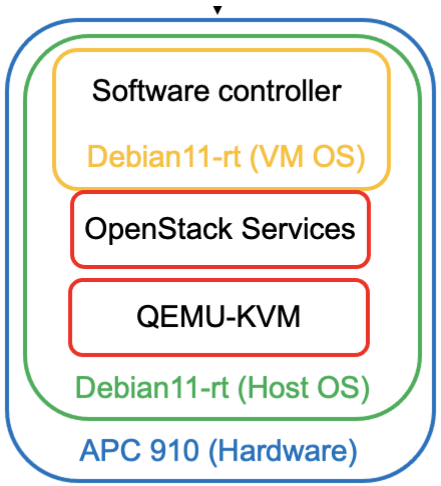
Safety-aware wireless

e.g., joint error detection and correction by cyclic redundancy check (CRC) code [1-3].

[1] M. Zhan et al., "High Throughput Joint Error Detection and Correction Based On GRAND-MO and CRC," in IEEE Transactions on Consumer Electronics, 2024
[2] Zhou, Q., Zhan, M., Zhang, J. et al. Energy efficient noise error pattern generator for guessing decoding in bursty channels. Peer-to-Peer Netw. Appl. (2024).
[2] M. Zhan, et al., "Noise Error Pattern Generation Based on Successive Addition-Subtraction for GRAND-MO," in IEEE Communications Letters, vol. 26, no. 4, pp. 743-747, April 2022

Gaps and recommendations: wireless-aware control application

Making the control applications more “prepared” for the wireless can avoid over-provisioning the 5G/6G system.



Inner Loop (P Controller):

$$G_{sm}(s) = \frac{K_{sm}e^{-sL}}{s(\tau s+1)}, \quad F_{inner}(s) = \frac{1}{\lambda s+1} \rightarrow C_{inner}(s) = \frac{1}{K_{sm}(\lambda + L)}$$

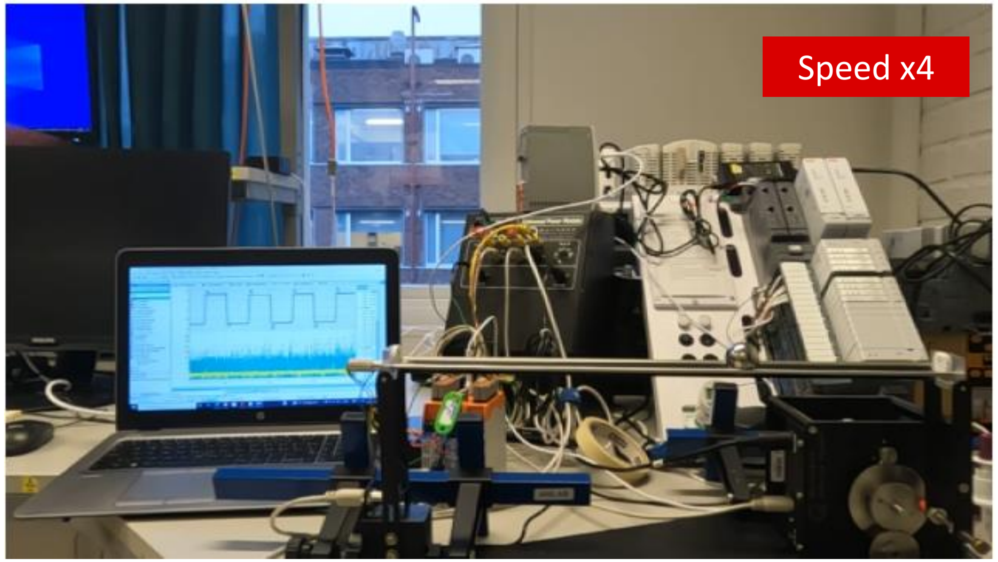
Outer Loop (PID Controller):

$$G_{bb}(s) = \frac{K_{bb}e^{-sL}}{s^2} \quad C_{outer}(s) = \frac{f_2^* s^2 + f_1^* s + 1}{K_{bb} t_0^* s} \cdot \frac{1}{\beta s + 1}$$

... [1]

$$F_{outer}(s) = \frac{1}{\beta s + 1}$$

Latency-aware Internal Model Control



openstack

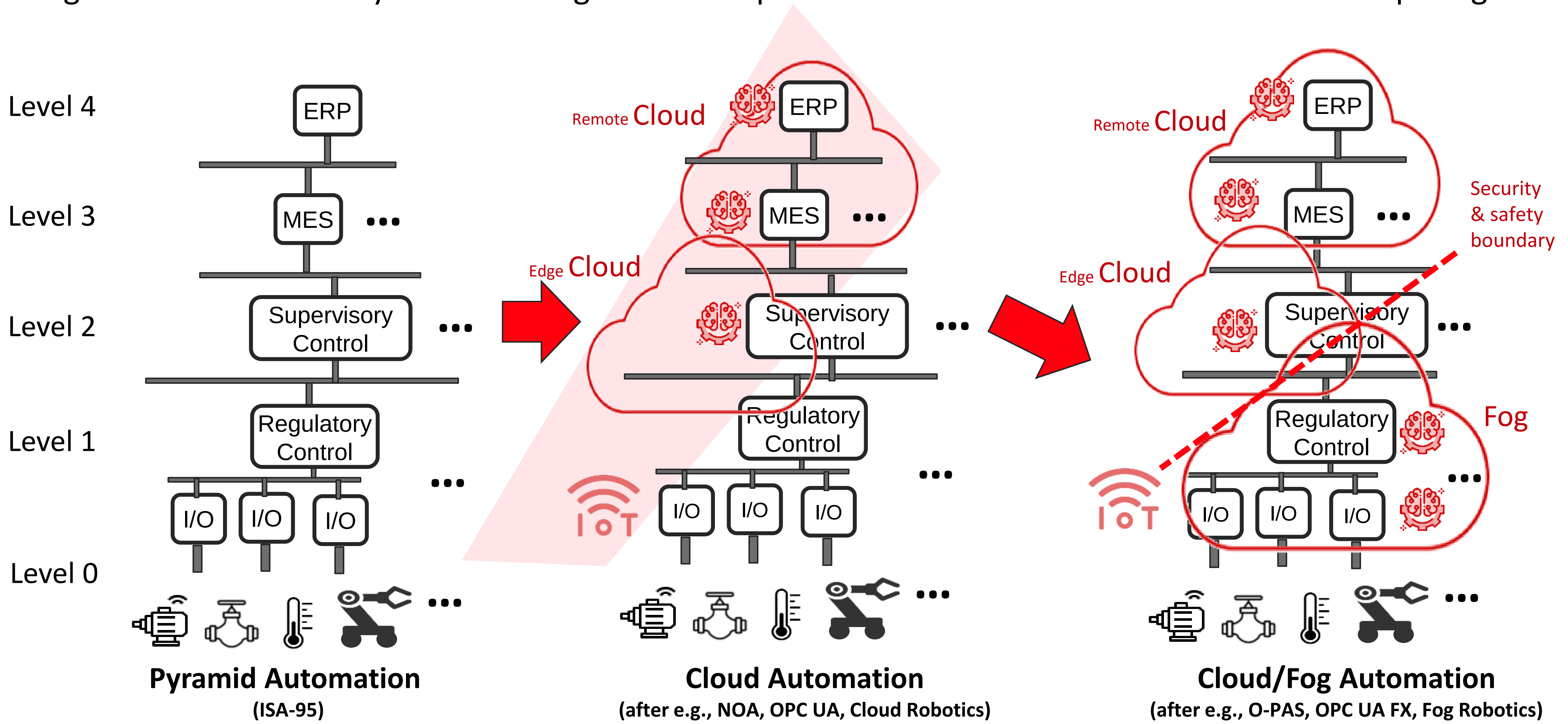
Final demo: OpenStack, private 5G R15 eMBB, Network Variables (UDP), Latency-aware Internal Model Control, 4ms cycle time

The Latency-Aware Control can tolerate more communication and computing latencies.
After this, Ball&Beam control accuracy looks same when Ethernet, 5G, or WiFi6 combined with OpenStack or not.

Lyu, Honghao; Bengtsson, Anna; Nilsson, Sofie; Pang, Zhibo; Isaksson, Alf; Yang, Geng (2023): Latency-Aware Control for Wireless Cloud Fog Automation: Framework and Case Study. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.22586044.v2

A stronger driver for 5G/6G: the vision of Could/Fog Automation

Expanding entire automation system to new generation open and virtualized communication and computing infrastructure



1. Kang B. Lee, Richard Candell, Hans-Peter Bernhard, Dave Cavalcanti, Zhibo Pang, Inaki Val, "Reliable, High-Performance Wireless Systems for Factory Automation", *NIST Interagency/Internal Report (NISTIR)*, No. 8317, September 18, 2020
2. J. Jin, K. Yu, J. Kua, N. Zhang, Z. Pang* and Q. -L. Han*, "Cloud-Fog Automation: Vision, Enabling Technologies, and Future Research Directions," in IEEE Transactions on Industrial Informatics, 2023,

Future perspectives

Synergy of the “3C” is the key for success

IEEE JOURNAL ON

SELECTED AREAS IN COMMUNICATIONS

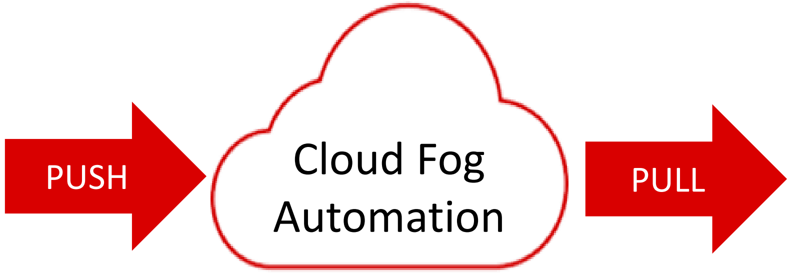
CFP: Co-Design of Communication, Computing, and Control in Industrial Cyber-Physical Systems

3C topics:

– “Grey-Channel” Functional Safety
– “Grey-Box” Cybersecurity

Communication & Computing topics:

– Determinism
  • Deterministic networking
  • Deterministic virtualization
– Orchestration
  • Redundancy
  • Failover
  • Self (at least easy) configuration
– Functional safety and cybersecurity



Control topics:

– Generalization
  • Generalizable Latency-Aware Control
  • Expand to Jitter-Aware ➔ QoS-Aware Control
– Value creation
  • Hybrid data-drive and model-based control
  • Optimization-based control (e.g., with respect to energy efficiency)
  • Camera-as-a-Sensor
  • Augmented Operator-in-the-Loop
  • Event-driven control
– Functional safety and cybersecurity

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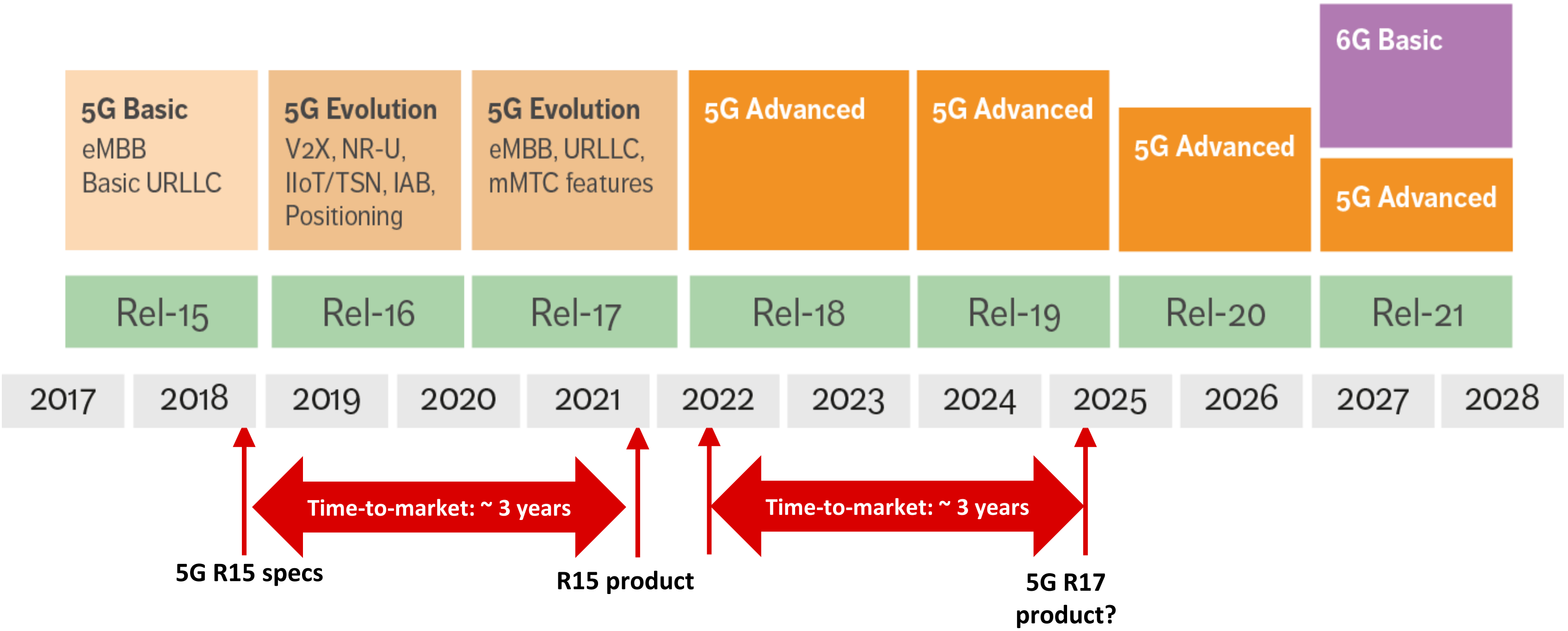
Gaps and recommendations: culture change (1/2)

We need a single timeline committed by not the marketing/standardization team, but the product team!



eMBB feature	
IAB	• Addition of (limited) support for network topology changes • Improved duplexing of access and backhaul links (simultaneous operation on child and parent link, for example) • Routing enhancements
MIMO	• Improvements based on experience from commercial networks focusing on multi-beam operation mainly for frequency range 2 (FR2), support for multi-TRP deployment, SRSs, and CSI measurement and reporting
DSS	• Cross-carrier scheduling enhancements • Other scheduling enhancements
Coverage	• Enhanced wide-area coverage for both FR1 and FR2 (to be studied) • Focus on mobile broadband and voice services use cases, with the exception of the low-power wide area use case
Multi-radio dual connectivity	[illegible]
UE power saving	[illegible]
Data collection	• Simplified deployment and enhancements to support self-organizing networks (SON) with improved data-collection mechanisms for SON and minimization of drive tests
QoE management and optimizations for diverse services	[illegible]
URLLC feature	
IIoT and URLLC support	• Improved support for … feedback enhanceme… • Identification of enha… environments on unli…
Positioning	• Higher accuracy (hori… IIoT use cases
Sidelink	• Focus on V2X, public … • Resource allocation e… • Sidelink discontinuou…
RAN slicing (also relevant for the mMTC use case)	• Mechanisms to enabl… • Mechanisms to suppo… handover service inte…
mMTC feature	
Small data transmissions in inactive state	• Reduced overhead fr… • Use cases: keep-alive …

Table 1, Summary of release 17 enhancements to existing features

Which features are you asking about??

eMBB feature	
[illegible]	[illegible] requirements applicable to unlicensed spectrum
Multicast and broadcast services	• Primarily targeted at V2X, public safety, IP multicast, software delivery and Internet of Things (IoT) applications
Support for multi-SIM devices	• Paging collision avoidance • Network notification when a UE switches networks
Support for non-terrestrial networks	• Support for satellites (especially Low Earth orbit and geostationary satellites) and high-altitude platforms as an additional means to provide coverage in rural areas
Sidelink relaying	• L2 versus L3 relaying (study and compare) • Scenarios include single-hop, UE-to-UE and UE-to-network relaying
URLLC feature	
Anything reality (XR) evaluations	• Evaluate needs in terms of simultaneously providing very high data rates and low latency in a resource-efficient manner • Intended to support various forms of augmented reality and virtual reality, collectively referred to as XR
mMTC feature	
Support of reduced-capability NR devices	• Targeted at mid-tier applications such as machine-type communications for industrial sensors, video surveillance, and wearables with data rates between Narrowband IoT/LTE-M data rates and "full" NR data rates • Addresses issues including complexity reduction, UE power saving and battery lifetime enhancement

Table 2, Summary of new functionality added in release 17

Toward 5G Advanced: overview of 3GPP releases 17 & 18 – Ericsson
3GPP releases 16 & 17 overview – 5G NR evolution - Ericsson

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Gaps and recommendations: culture change (2/2)

Revisit the 5G use cases and gaps before rush into 6G, change from over-promise to over-delivery.

Victor K. L. Huang; Zhibo Pang; Cheng-Jen Allen Chen; Kim Fung Tsang "New Trends in the Practical Deployment of Industrial Wireless: From Noncritical to Critical Use Cases", *IEEE Industrial Electronics Magazine*, Volume: 12, Issue 2, 2018, Pages: 50 – 58, 2018.

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