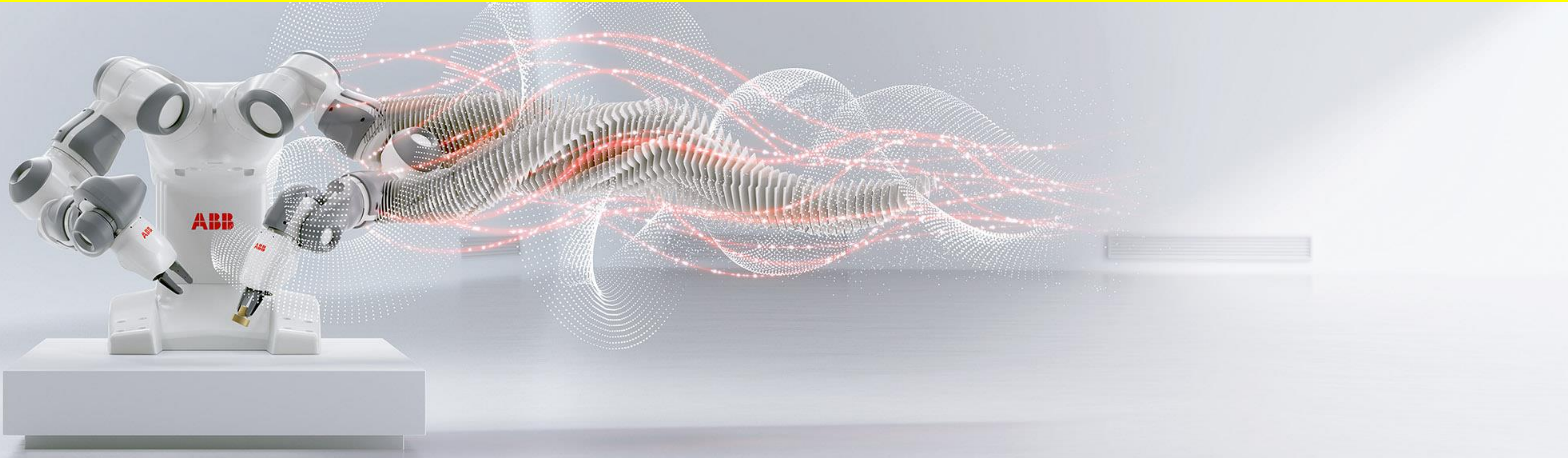
DISCLAIMER: this presentation is just my research findings and personal opinions as a researcher for academic discussions. It doesn't intend to present ABB's official roadmap or strategy in these areas.



2023-11-23

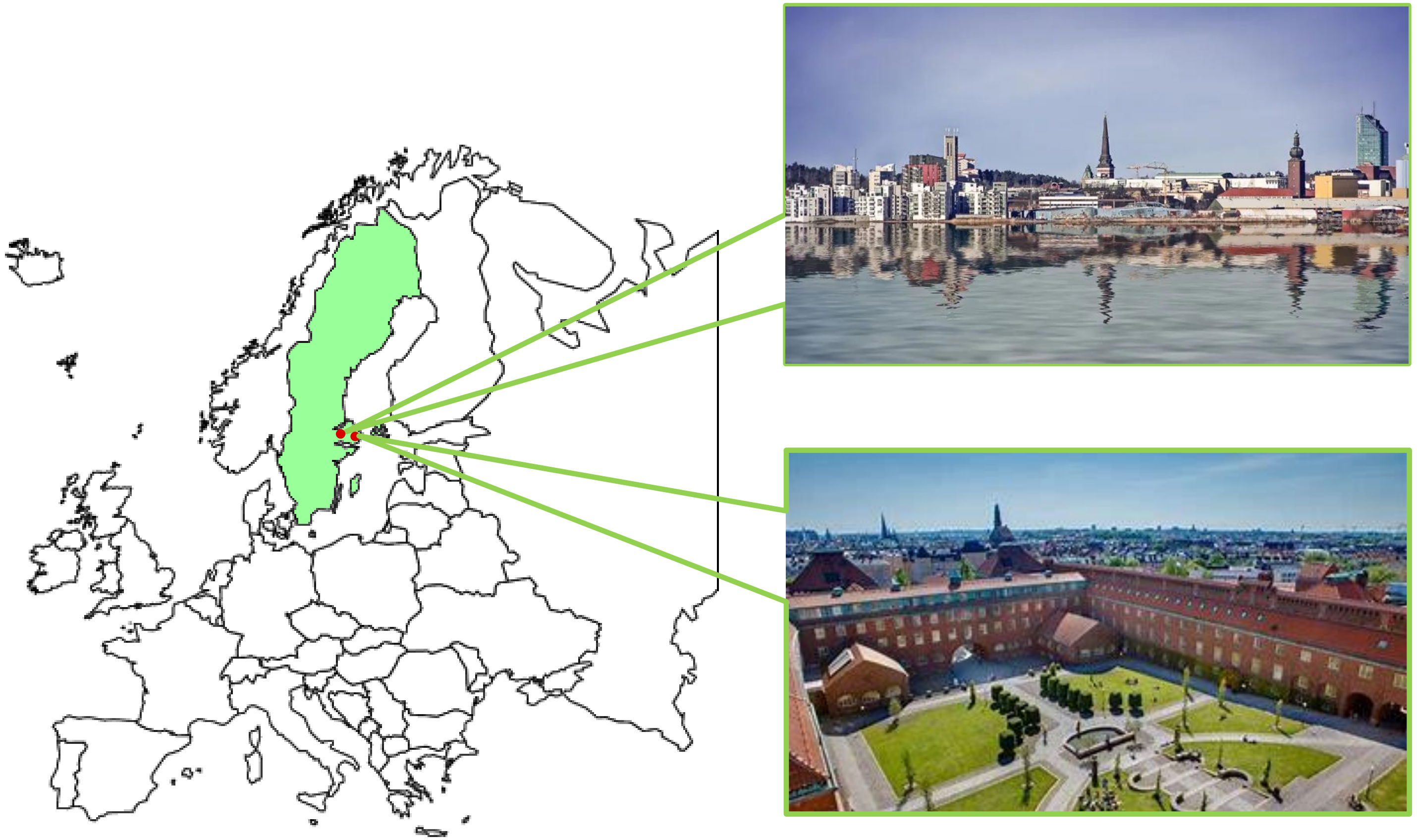
# Communication-Computing-Control Co-Design for the Cloud Fog Automation

## A New Paradigm of Realizing Industrial Automation Systems

Zhibo Pang, ABB Corporate Research Sweden and KTH Royal Institute of Technology, zhibo@kth.se

# About Sweden

SKANSKA SKF SCANIA SANDVIK ICA
preem Nordea NORDSTJERNAN H&M
Electrolux AstraZeneca Atlas Copco ABB
ERICSSON IKEA VATTENFALL VOLVO
SAAB TeliaSonera



Västerås

Stockholm

# Sweden’s largest technical university

**17 000**
students

**4 000**
staff (FTE)

**100 000**
alumni in 100 countries

**35%**
women

**2 300**
international

**339**
professors

**2 800**
staff within research

**1 700**
doctoral students

**20**
international alumni associations

# KTH’s schools and departments

| Architecture and the Built Environment | Electrical Engineering and Computer Science | Industrial Engineering and Management | Engineering Sciences in Chemistry, Biotechnology and Health | Engineering Sciences |
|---|---|---|---|---|
| Architecture<br>Civil and Architectural Engineering<br>Philosophy and History<br>Real Estate and Construction Management<br>Sustainable Development, Environmental Science and Engineering<br>Urban Planning and Environment | Computer Science<br>Electrical Engineering<br>Human Centered Technology<br>Intelligent Systems | Energy Technology<br>Industrial Economics and Management<br>Learning<br>Machine Design<br>Materials Science and Engineering<br>Production Engineering<br>Sustainable Production Development | Biomedical Engineering and Health Systems<br>Chemistry<br>Chemical Engineering<br>Engineering Pedagogics<br>Fibre and Polymer Technology<br>Gene Technology<br>Industrial Biotechnology<br>Protein Science<br>Theoretical Chemistry and Biology | Applied Physics<br>Engineering Mechanics<br>Mathematics<br>Physics |

# The new ABB operates through four focused, leading businesses

**Electrification** — **Automation** — **Robotization**

Low/Medium Voltage

Buildings & infrastructure

Measurement & analytics

Process control (DCS)

Motors & generators

Drives

Machine & factory

Robotics

**Electrification**

**#2**

**Industrial Automation**

**#2**

**Motion**

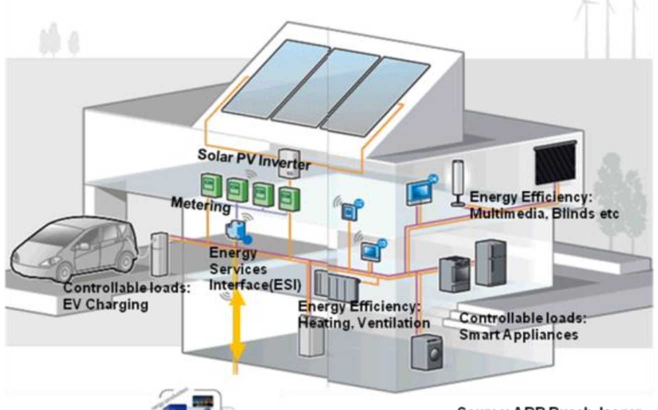
**#1**

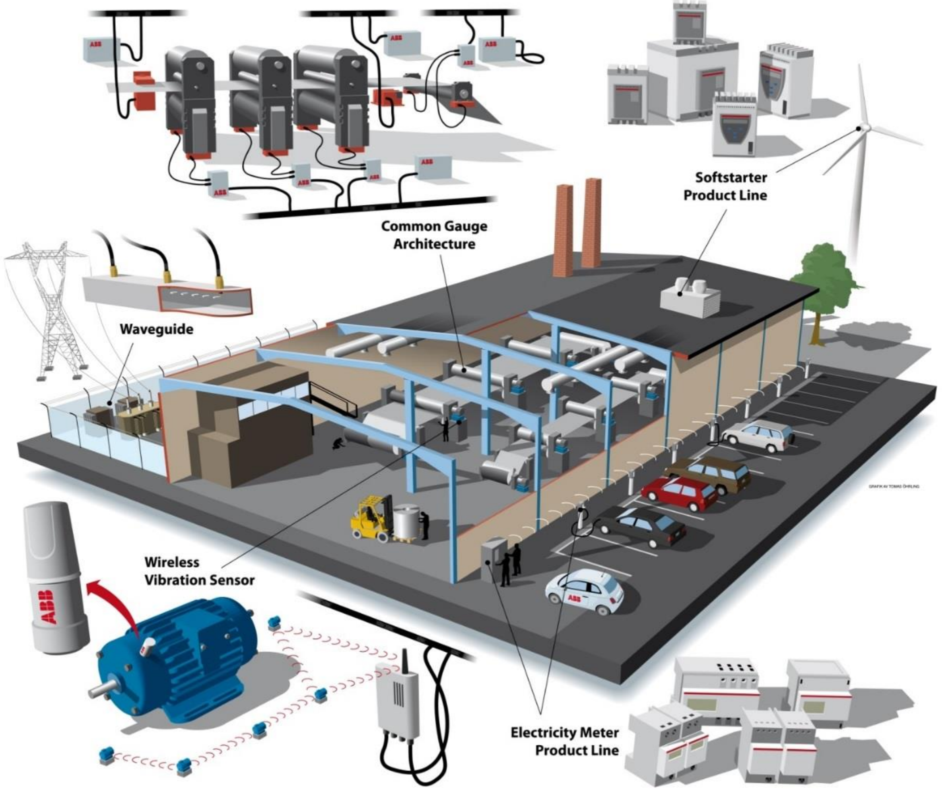
**Robotics & Discrete Automation**

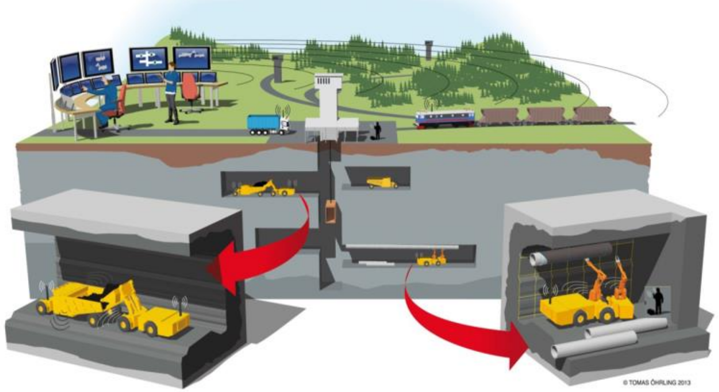
**#2**

**Digitalization: ABB Ability™**

# Research contexts at ABB SECRC/Industrial Networks and Control Group







# Agenda

Vision of Cloud Fog Automation

Software defined wireless wireless for Cloud Fog Automation

5G for Cloud Fog Automation

Communication-Computing-Control Co-Design

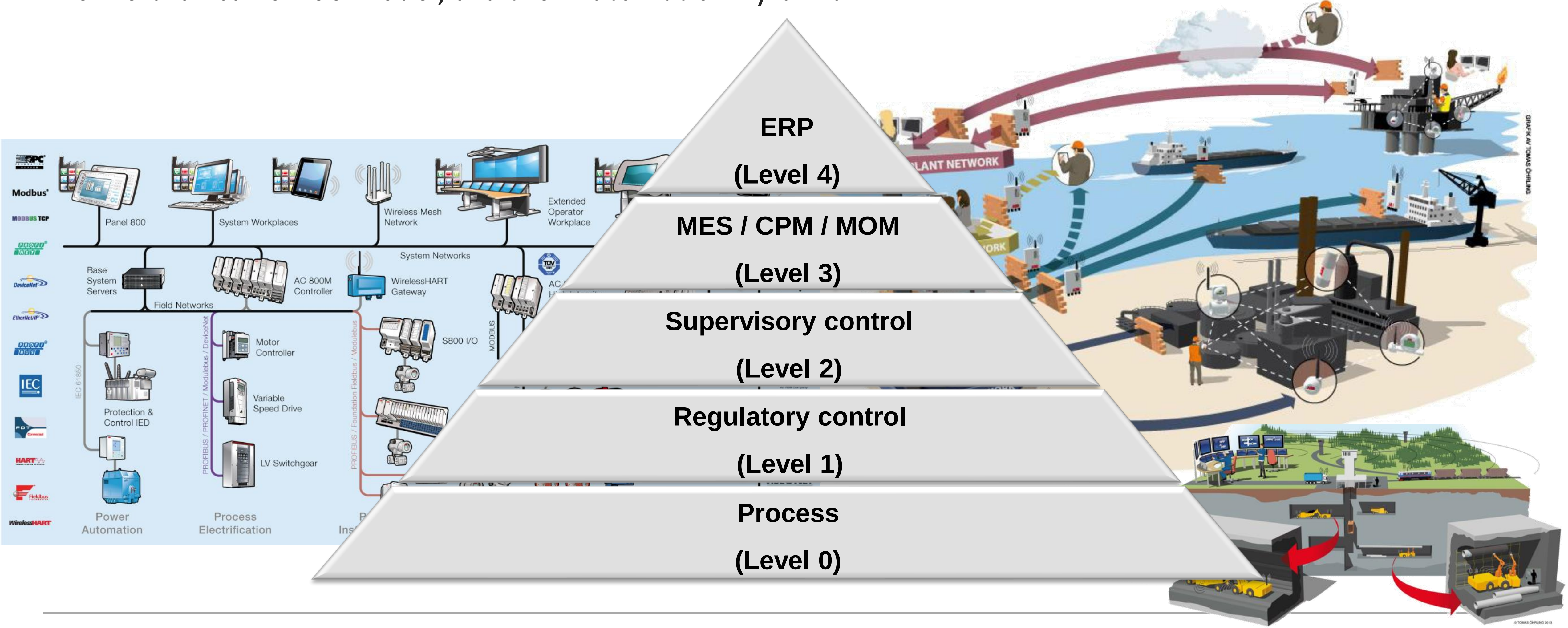
Future perspectives

*This presentation is based on the contributions from many of my current and former colleagues, collaborators, and students, including Alf Isaksson, Ognjen Dobrijevic, Krister Landernas, Pawel Wiatr, Koushik Bhimavarapu, Honghao Lyu, Jialin Zhang, Anna Bengtsson, Sofie Nilsson, Jing Yan, Johannes Deivard, Valentin Johansson, Fangbo Shi, Maxx Wallberg, Emil Lindahl (an incomplete list).*

# The vision of Cloud Fog Automation

# Today’s automation systems since the Industry 3.0

## The hierarchical ISA-95 model, aka the “Automation Pyramid”



**ERP**
**(Level 4)**

**MES / CPM / MOM**
**(Level 3)**

**Supervisory control**
**(Level 2)**

**Regulatory control**
**(Level 1)**

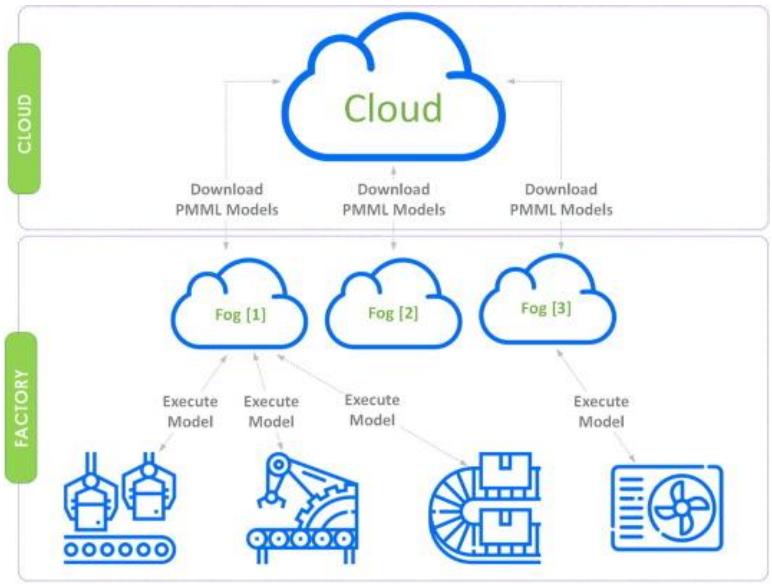
**Process**
**(Level 0)**

International standard, “ANSI/ISA-95.00.01-2010 (IEC 62264-1 Mod) Enterprise-Control System Integration - Part 1: Models and Terminology”, International Society of Automation, 2010
MES: Manufacturing Execution System, CPM: Collaborative Production Management, MOM: Manufacturing Operations Management

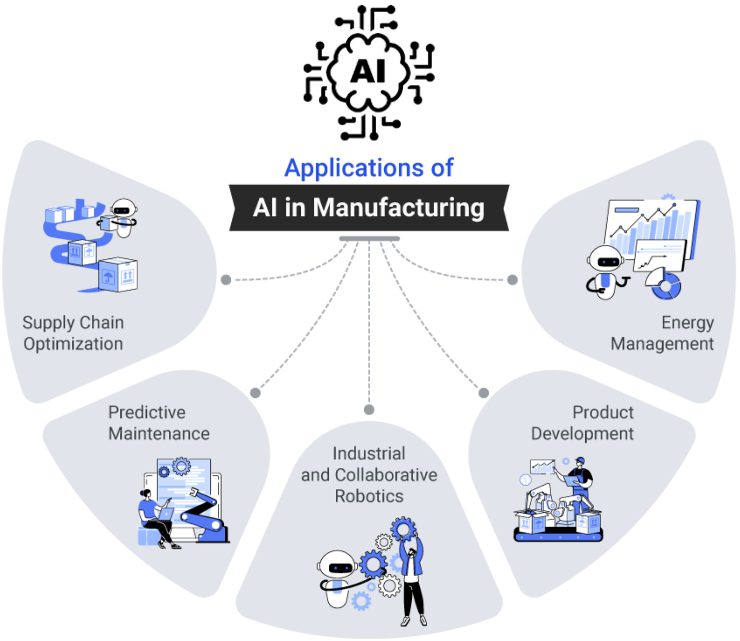
# The new game changers since the Industry 4.0

## Internet of Things

## Cloud/fog computing



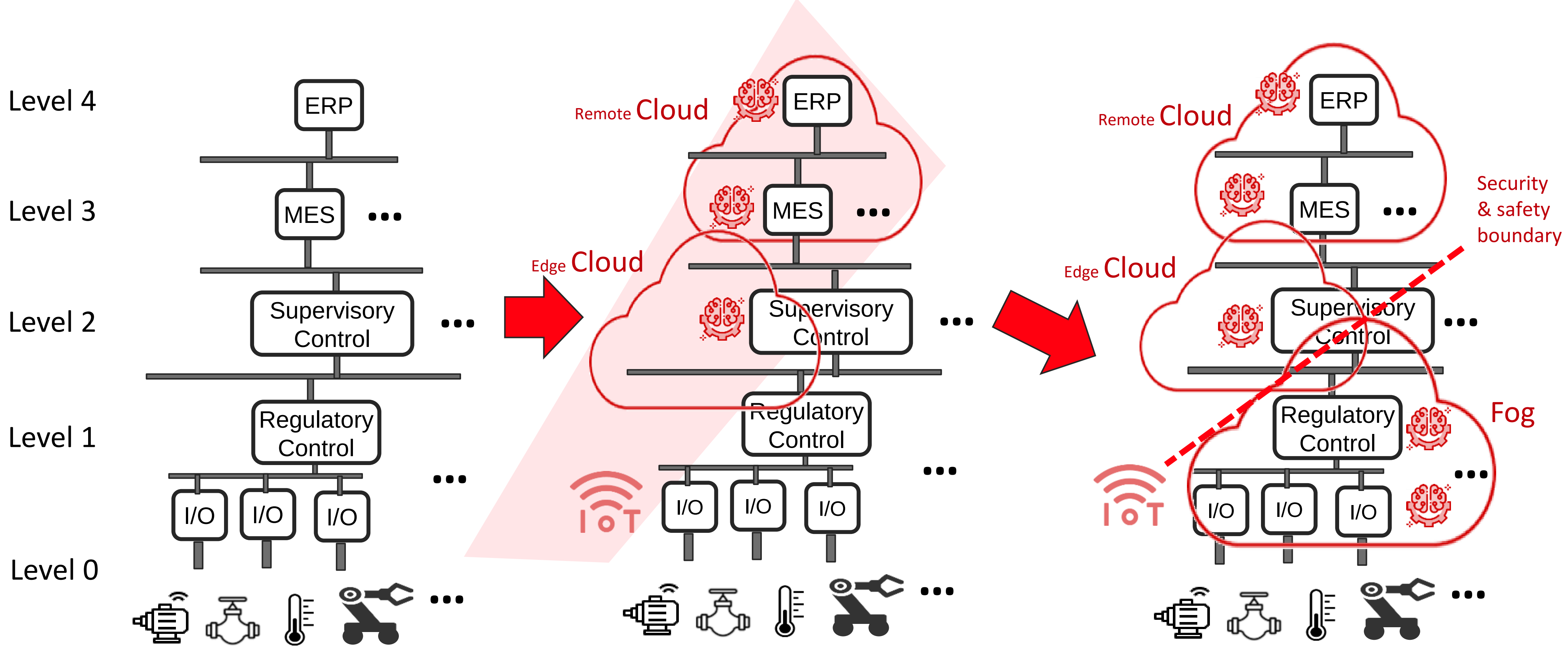
## Artificial intelligence



**The strong aggregation of talent and capital in these areas is making them “self-fulfilling”.**

# The vision of Could/Fog Automation

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



**Pyramid Automation**
**(ISA-95)**

**Cloud Automation**
**(after e.g., NOA, OPC UA, Cloud Robotics)**

**Cloud/Fog Automation**
**(after e.g., O-PAS, OPC UA FX, Fog Robotics)**

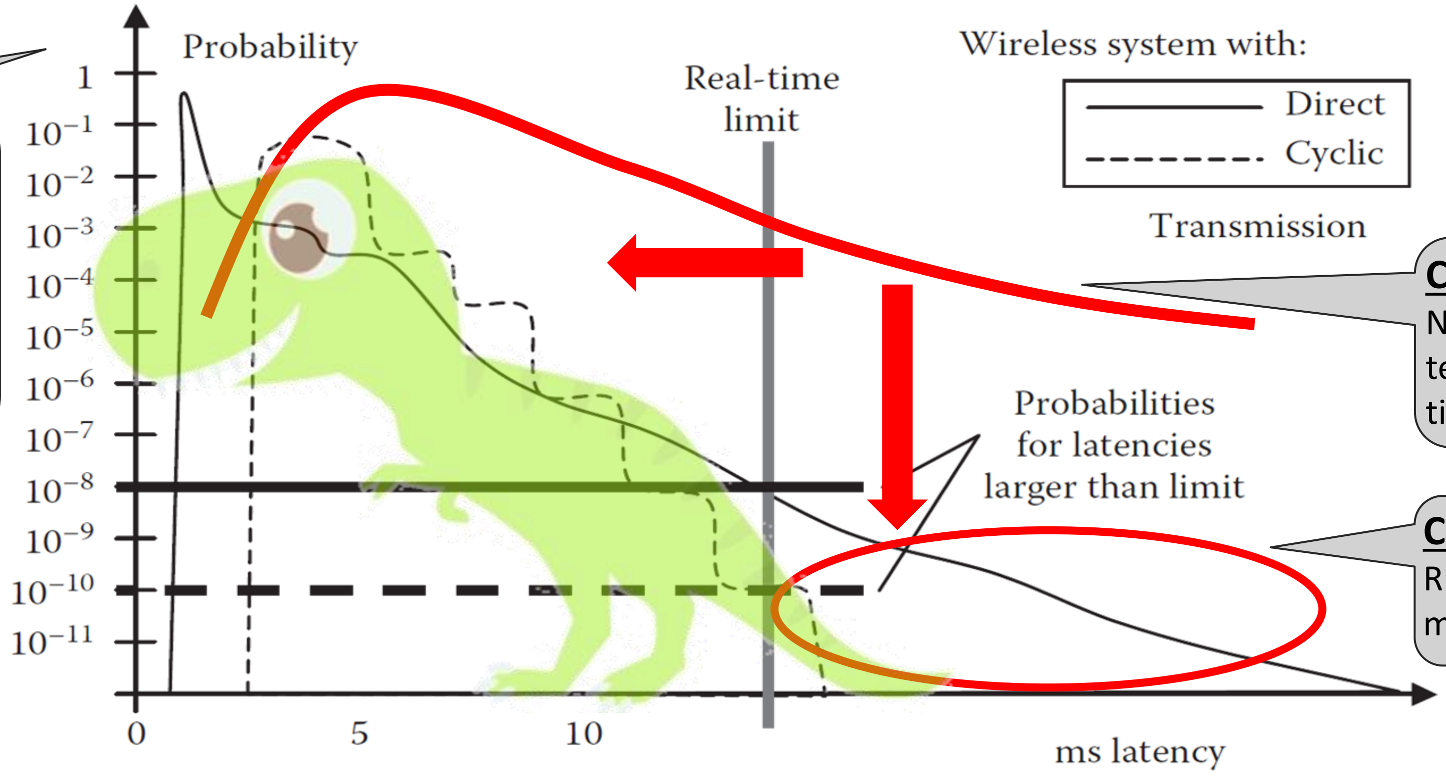
NAMUR
THE OPEN GROUP OPEN PROCESS AUTOMATION™ FORUM
OPC UA
open robotics
fora

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,

# Closed-loop control requires determinism of communication and computing

The “Dinosaur Curve” – an insightful view of latency and reliability

**Latency @ Probability:**
For mission critical applications, Packet Error Rate (PER) and Bound of Latency must be defined together. Otherwise, meaningless!



**Compress the body:**
New generation communication technology usually reduces by 10 times..

**Cut the tail:**
Rule-of-thumb: one more “9” means 10 times higher cost.

**FIGURE 28.2** Typical distribution of latency measurements in wireless automation devices.

An example of the WISA technology developed by ABB in early 2000s

Guntram Scheible, Dacfey Dzung, Jan Endresen, Jan-Erik Frey, “Design and Implementation of a Truly-Wireless Real-Time Sensor/Actuator Interface for Discrete Manufacturing Automation”, Networked Embedded Systems, Edited by Richard Zurawski, CRC Press 2009, Pages 28-1–28-28

# Software defined wireless communication for CFA

# Needs and opportunities

## Wireless enables mobility and flexibility

Large height

Rural areas

Mobile machines

Mobile operation

Moving parts

Harsh or corrosive

Access forbidden

Cabling forbidden

Temporary deployment

- ~10 times better than state-of-the-art WiFi-based solutions
- ~x1000 times better than 5G 50ms@sub-6GHz, 20ms@mmW (24-53GHz), 2022 results

# WirelessHP (v2 in 2018)

New physical layer targeted for critical control applications

Minimize the overhead by new physical layer

WirelessHP targets:

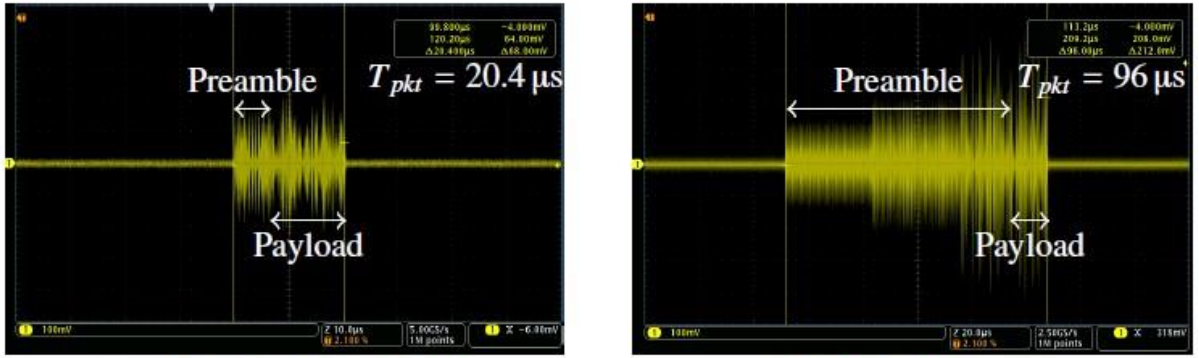
- High determinism (preferably 0 retransmissions)
- High reliability (PER 10e-6~10^-9)
- Low latency (1~10µs)

What are we sacrificing?

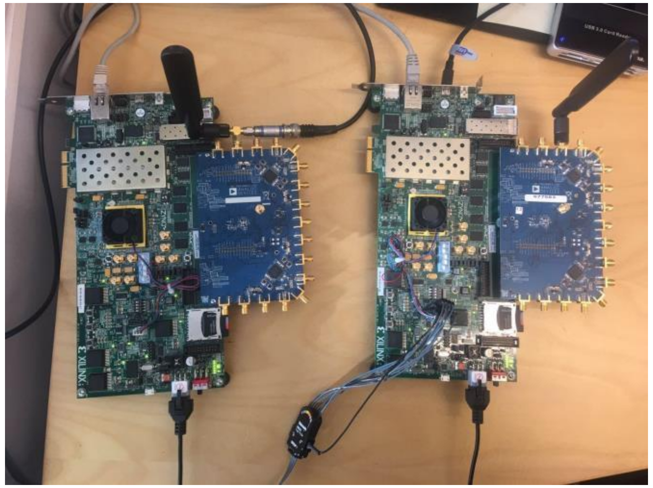
- Short packets (~10 bytes)
- Short range (~10 m)
- Static channel → low mobility

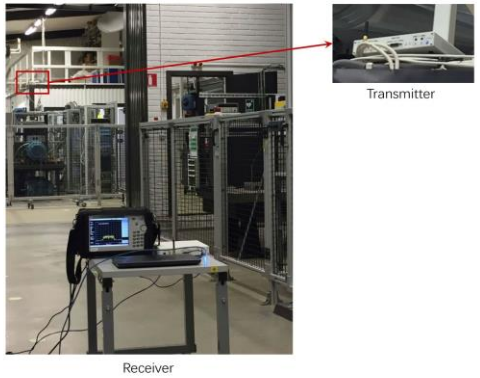
Progresses (2019)

- Fully-functional WiHP PHY (TX and RX) implemented in FPGA
- Fs=100MHz and BW=50MHz, **minimal slot= 6.72us**



(c) WirelessHP 8-PSK (d) WLAN 8-PSK

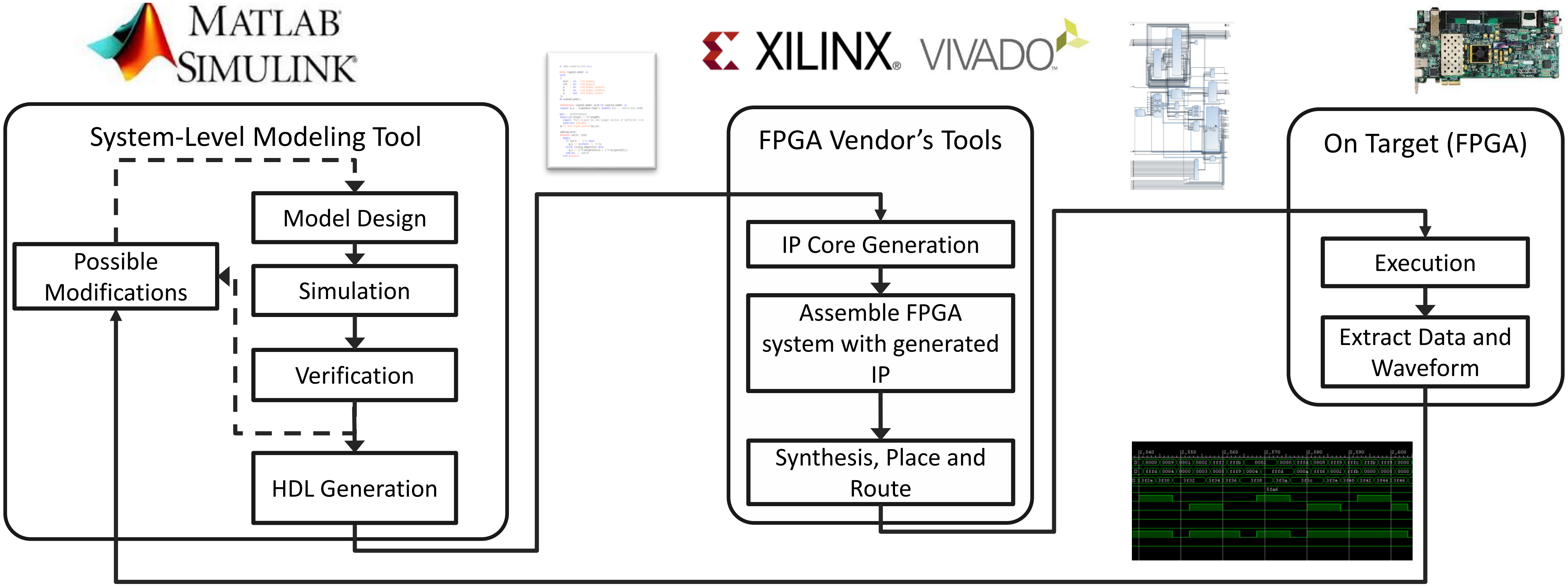




[1] Ming Zhan, **Zhibo Pang**, Dacfey Dzung, Michele Luvisotto, Kan Yu, Ming Xiao, "Towards High-performance Wireless Control: $10e^{-7}$ Packet Error Rate in Real Factory Environments", *IEEE Transactions on Industrial Informatics,* 2019.

[2] Michele Luvisotto, **Zhibo Pang**, Dacfey Dzung, "High-Performance Wireless Networks for Industrial Control Applications: New Targets and Feasibility", *Proceedings of the IEEE,* Vol 107, Iss 6, Page(s): 1074-1093, 2019

# WirelessHP methodology -- model-based development of FPGA-based SDR



- Reduced engineering efforts: from x 10 man-years ➔ x 10 man-months
- Enabling the shift of exploration: from communication company ➔ automation company

[1] Henrik Hellström, Michele Luvisotto; Roger N. Jansson, **Zhibo Pang**; "Software-Defined Wireless Communication for Industrial Control: A Realistic Approach", *IEEE Industrial Electronics Magazine*, 2019

[2] Michele Luvisotto; Zhibo Pang; Roger N. Jansson, "Fast prototyping of industrial wireless communications", *ABB Review*, Issue 2, 2020

# WirelessHP physical layer – error correction coding

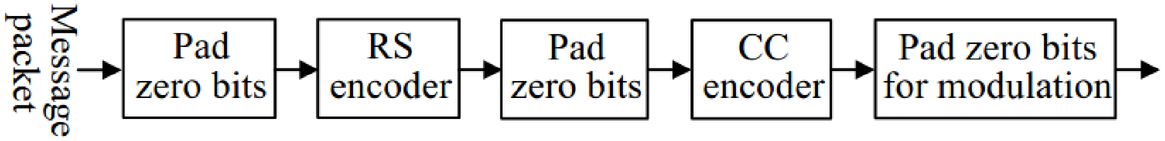
Stressing the limits of PER in realistic environments before retransmissions are applied in higher layers

## Design principles:

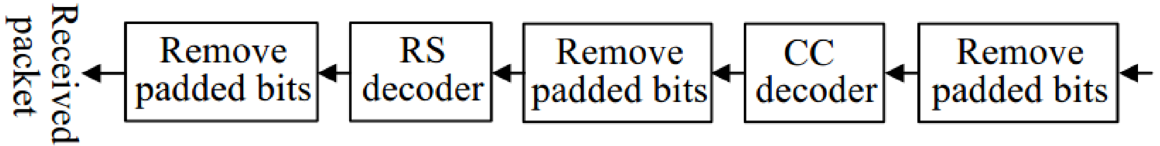
- The modern iterative decoding-based codes are suboptimal for short packets and low latency
- The classic block codes look more promising
- Retransmissions e.g. HARQ in higher layers can be applied, at the expense of latency

## Implementation:

- Coding: Reed Solomon (RS) combined with convolutional codes (CC) codes
- Decoding: Viterbi and Berlekamp-Massey (BM) algorithms
- Various coding parameters are compared



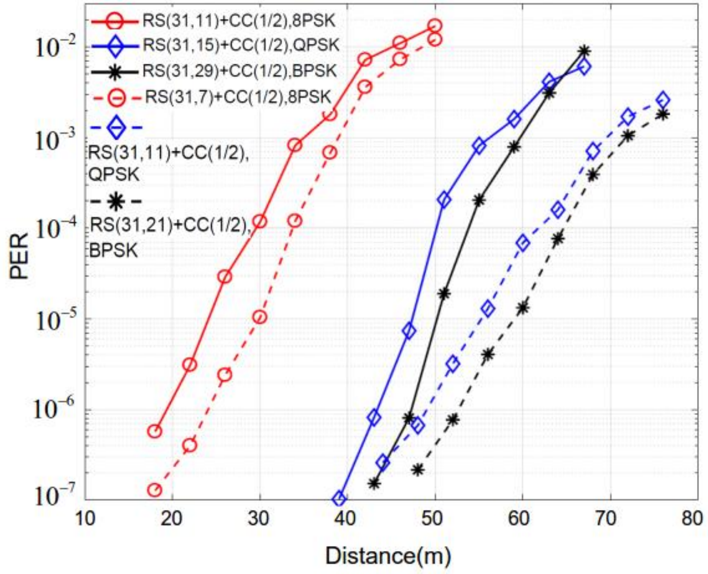
(a) Encoding at the transmitter side

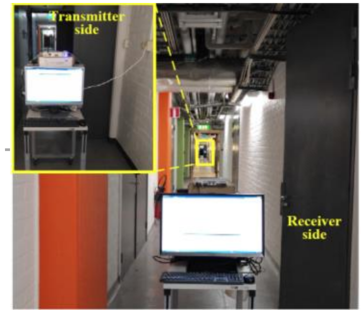


(b) Decoding at the receiver side

## Results:

- **PER < 10e-7 in realistic industrial environments (BW 5MHz, 100bits)**





[1] Ming Zhan, **Zhibo Pang**, Dacfey Dzung, Ming Xiao, "Channel Coding for High Performance Wireless Control in Critical Applications: Survey and Analysis", *IEEE Access*, Vol. 6, 2018

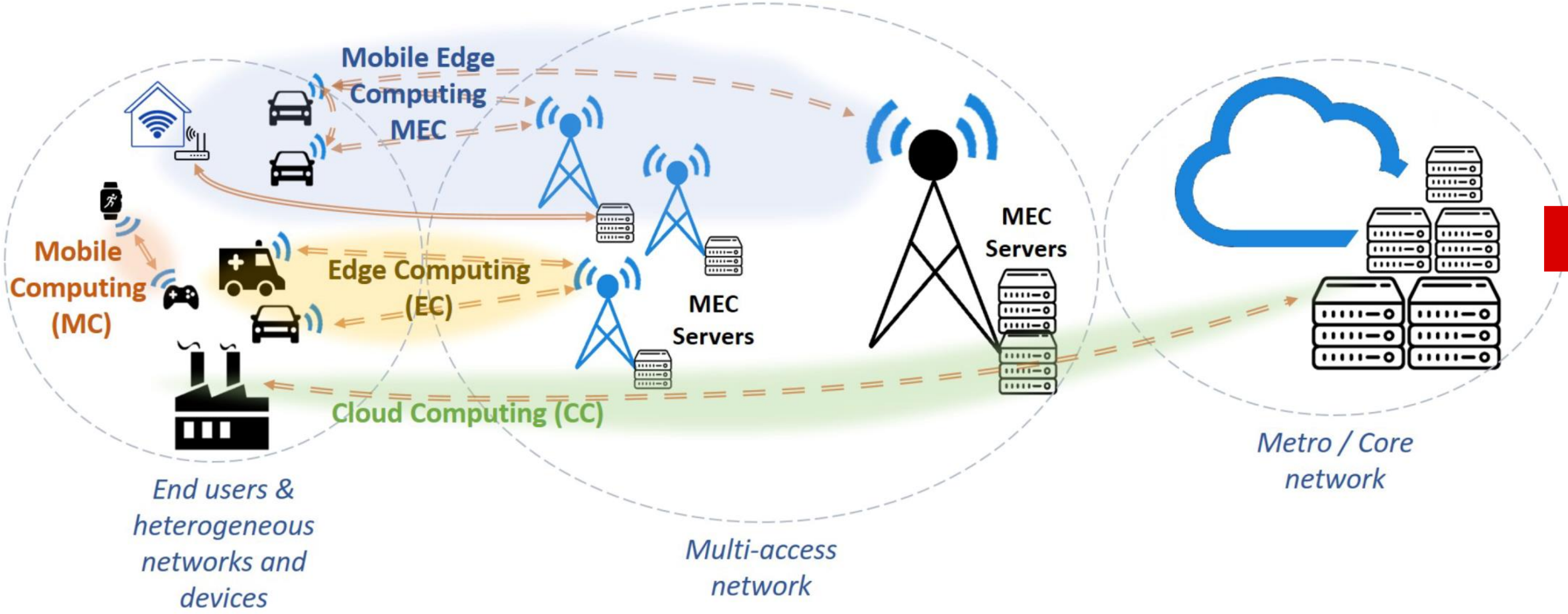
[2] Ming Zhan, **Zhibo Pang**, Ming Xiao, Michele Luvisotto, Dacfey Dzung, "Wireless High Performance Communications: Improving Effectiveness and Creating Ultrahigh Reliability with Channel Coding", *IEEE Industrial Electronics Magazine*, Vol 12, Iss 3, 2018

[3] Ming Zhan, **Zhibo Pang**, Dacfey Dzung, Michele Luvisotto, Kan Yu, Ming Xiao, "Towards High-performance Wireless Control: $10e^{-7}$ Packet Error Rate in Real Factory Environments", *IEEE Transactions on Industrial Informatics,* 2019

# 5G for Cloud/Fog Automation

# Needs and opportunities

5G brings computation to mobile edge



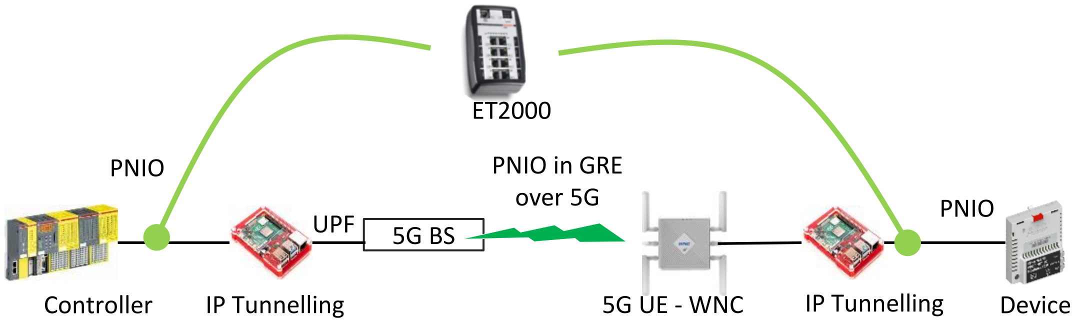
- Data ownership
- Security and privacy
- New BM, e.g., XaaS

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

# Experimental test of COTS 5G in Level-1 control loop

## Mid-band, eMBB, NSA, line-of-sight, lab condition (tested in Feb 2022)



**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

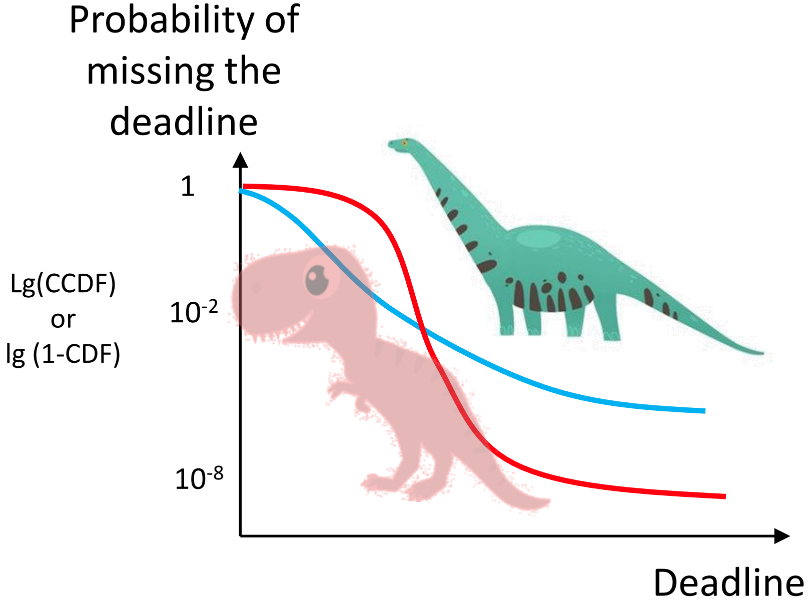
**Limitation**: Distance between probes: <100m (a)

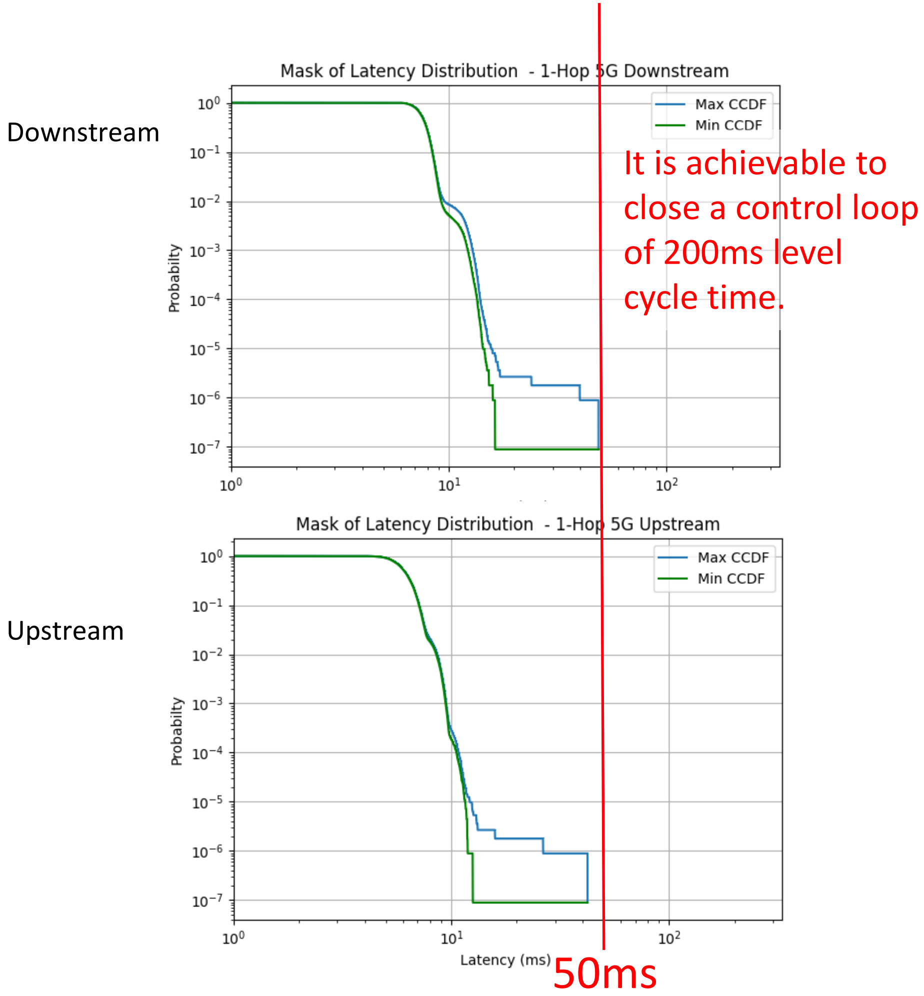
| Parameter | 5G |
|---|---|
| Generation of standard | 3GPP Release 15 (R15), eMBB profile |
| TC-IoT Controller | AC500 PLC |
| TC-IoT Device | ACS880 Drive |
| Deployment mode | Non-standalone (NSA) |
| TDD slot pattern | DDSU |
| User Equipment/ Access point | WNC SKM-5xE |
| Frequency band(s) | LTE: 1875-1880 MHz<br>5G: 3720-3800 MHz |
| Industrial Ethernet protocol | PROFINET RT |
| Distance of the wireless link | ≤ 10m |
| QoS at network and user equipment levels | No |
| Network type | Private network in office building |
| Application cycle time | 16ms |
| Packet rate | 62.5 packets/sec in each direction (from Controller to Drive and vice versa) |
| Packet length | 76 bytes |
| Timeout limit of packet matching | 300ms |
| Experiment duration | 112 hours |
| Other parameters | Line of sight (LoS) between UE and BS, radio resource pre-allocation enabled |

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.

# Latency and reliability of COTS 5G

The “Dinosaur Curve“ (tested in Feb 2022, settings in previous pages)





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

- 5G has achieved a lot
- URLLC not there yet
- Lab results are encouraging, but field tests are necessary:
  - ○ Field survivability
  - ○ Scalability

**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

# Known functional gaps of COTS 5G

to integrate 5G in Level 1 control network (tested in Feb 2022, settings in previous pages)

It lacks support to layer2 Ethernet PDU → Cannot fully support layer2 industrial ethernet e.g., PROFINET

It lacks time synchronization signaling for user devices → Difficult or infeasible to realize time-critical application

It lacks support to IP/UDP multicast → Difficult or infeasible to realize time-critical PubSub e.g., DDS, OPC UA PubSub

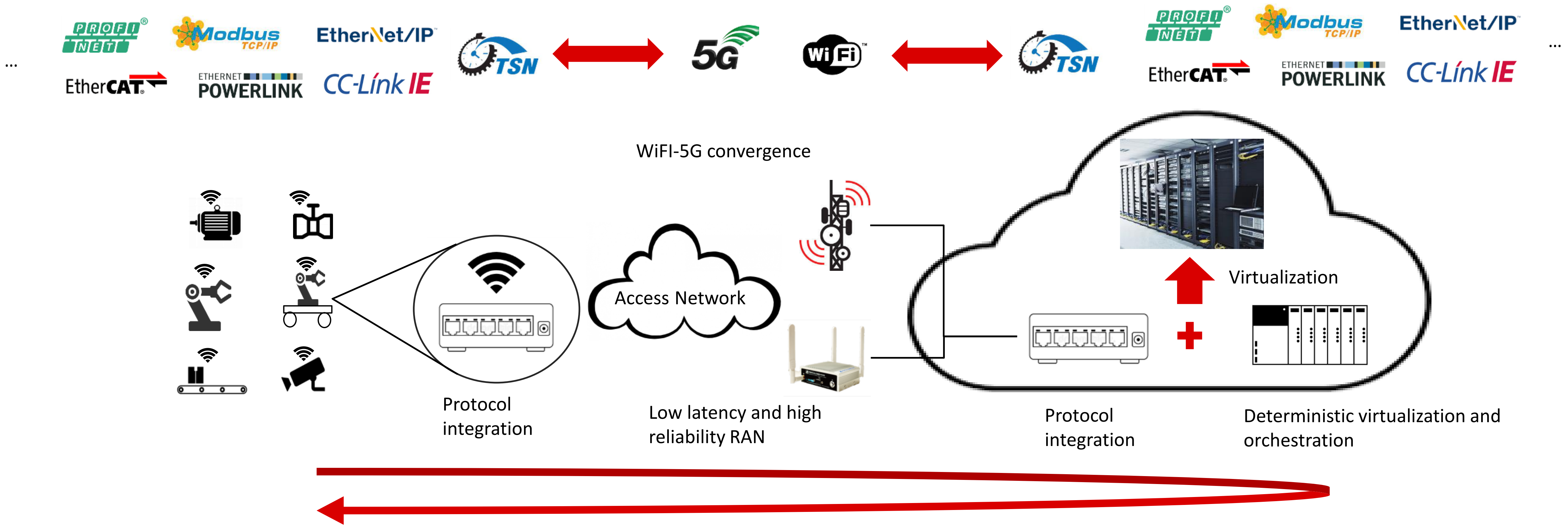
---

Ethernet PDU (protocol data unit) is the layer 2 Ethernet packet which is commonly used in main-stream industrial ethernet protocols.
UDP: user defined protocol, a common way of realizing industrial communication protocols on top of IP (internet protocol).

# Communication-Computing-Control Co-Design

# The CFA requires end-to-end determinism, not only the network itself

Protocol conversion, wired-wireless integration, virtualization, security, safety



WiFI-5G convergence

Access Network

Virtualization

Protocol integration

Low latency and high reliability RAN

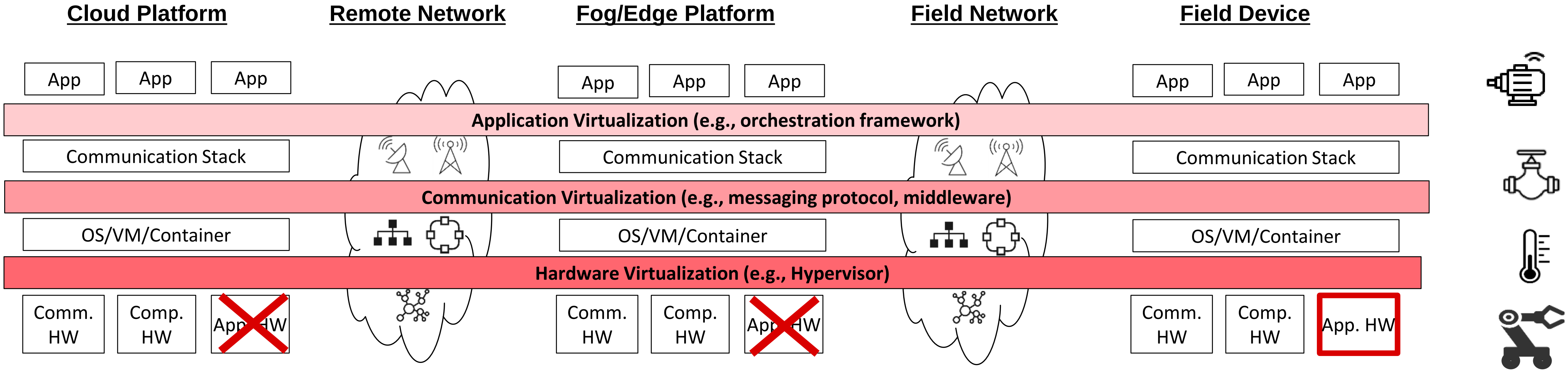
Protocol integration

Deterministic virtualization and orchestration

End-to-end latency <1~100ms, availability > 99.999%, depending on the equipment under control.
OT cybersecurity (e.g., IEC 62443), and functional safety (e.g., IEC61508, ISO 13849)

# The CFA requires deterministic virtualization, the full-stack!

What is new? 3 virtualization layers are inserted for executing control logics



**Cloud Platform** **Remote Network** **Fog/Edge Platform** **Field Network** **Field Device**

…

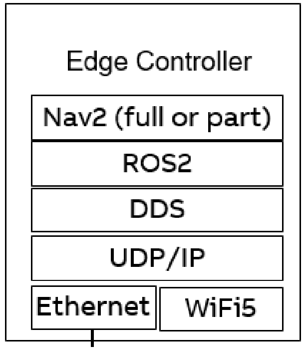
**The inserted virtualization layers enables the "Lower-Layer Independence", protects the business interests of vendors, but also brings in some "black holes" of overheads.**

Note: Edge Computing is not a 5G-specific thing, ETSI has expanded the definition of MEC from Mobile Edge Computing to Multi-Access Edge Computing.

# Converged Control Platform by the Cloud/Fog Automation

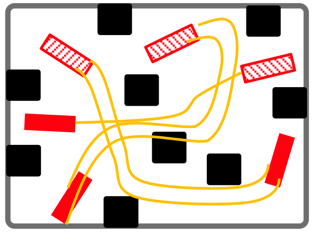
Heterogeneous control applications over unified infrastructure by virtualized computing and converged networks

Mobile navigation

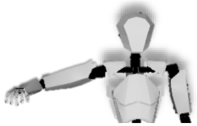


Edge Controller
- Nav2 (full or part)
- ROS2
- DDS
- UDP/IP
- Ethernet | WiFi5

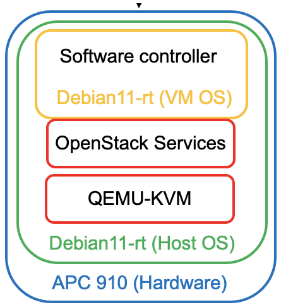
Safety coordination



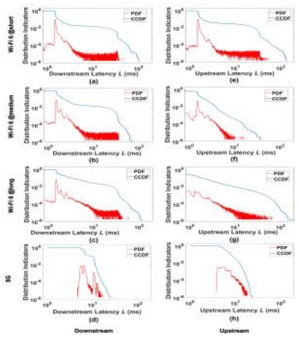
Teleoperation



Motion control

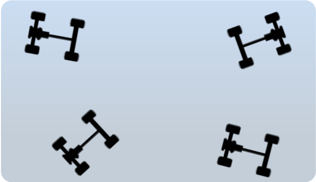


- Software controller
- Debian11-rt (VM OS)
- OpenStack Services
- QEMU-KVM
- Debian11-rt (Host OS)
- APC 910 (Hardware)

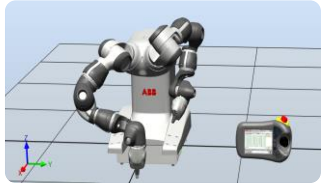


Mobile navigation

Safety coordination



Teleoperation



Motion control

**Virtualized Computing**

**Converged Networks**

**Heterogeneous Applications (control targets)**

**Value for end customers are flexibility, scalability, cost reduction, autonomy, open ecosystem, "digital life cycle", …**

# Experimental evaluation of computing latencies

The essence of computing latencies are the same as the communication latencies

**Real-Time hypervisor is mature for 10ms level applications:**

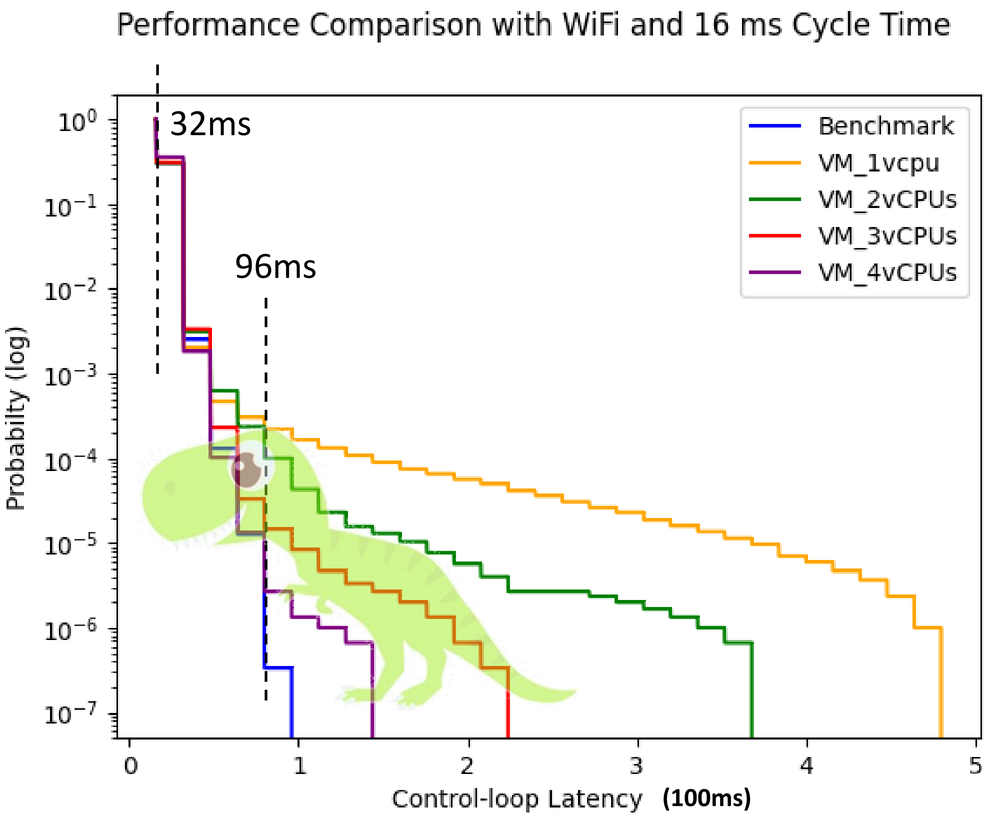
- 100us level OS delay by free Linux QEMU-KVM with RT patch (free equivalent of OpenShift)

**Computing and communication orchestration is key:**

- Network interface allocation
- CPU allocation
- Task and data routing

**Implementation of protocol stacks is crucial when using virtualization which is less deterministic :**

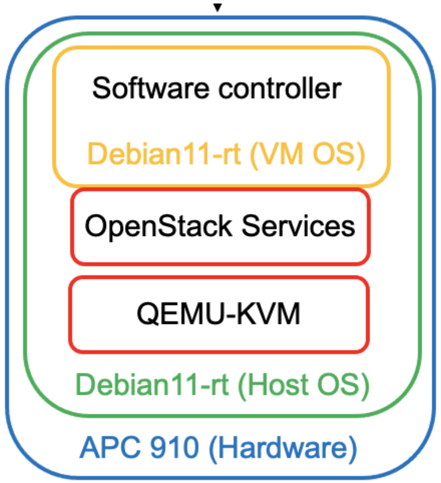
- If a task misses the deadline, end-to-end latency increases 1 cycle time, e.g., 1us more processing time causes 16ms more control latency.



Settings: WiFi 6, controller in OpenStack. no Latency-aware control

# Latency-aware control

Verified on SoftPLC + UDP + OpenStack



Software controller

Debian11-rt (VM OS)

OpenStack Services

QEMU-KVM

Debian11-rt (Host OS)

APC 910 (Hardware)

Inner Loop (P Controller):

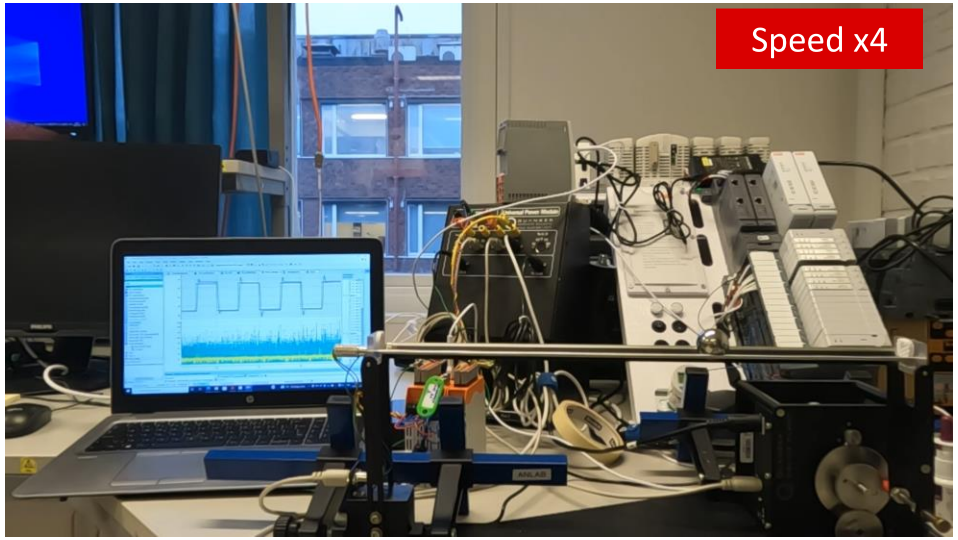
$$\begin{cases} G_{sm}(s) = \dfrac{K_{sm}e^{-sL}}{s(\tau s + 1)} \\ F_{inner}(s) = \dfrac{1}{\lambda s + 1} \end{cases} \longrightarrow C_{inner}(s) = \frac{1}{K_{sm}(\lambda + L)}$$

Outer Loop (PID Controller):

$$\begin{cases} G_{bb}(s) = \dfrac{K_{bb}e^{-sL}}{s^2} \quad C_{outer}(s) = \dfrac{f_2^* s^2 + f_1^* s + 1}{K_{bb}t_0^* s} \boxed{\dfrac{1}{\beta s + 1}} \\ \ldots [1] \end{cases}$$

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

Latency-aware Internal Model Control



**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.**

# Future perspectives

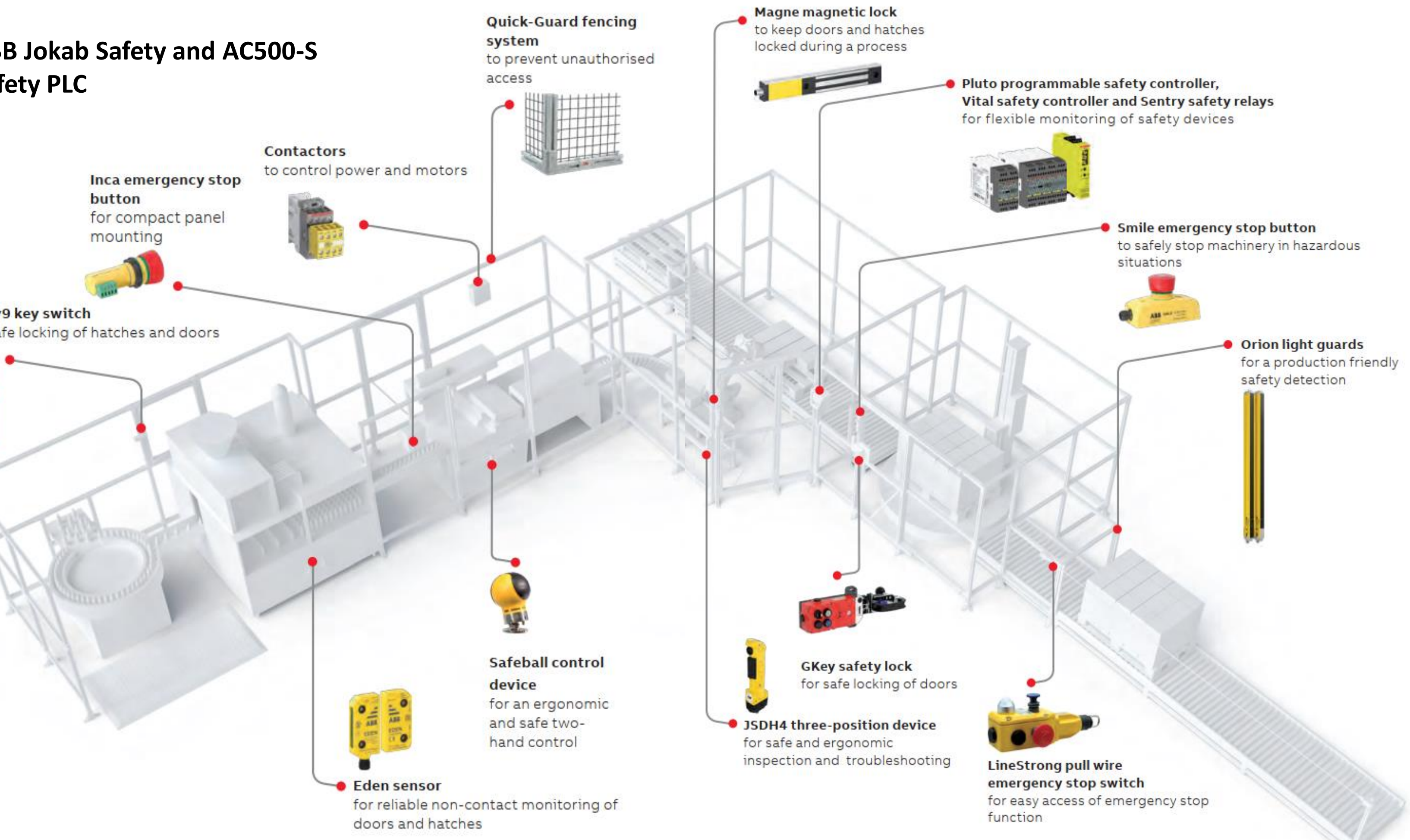
# Functional safety is a MUST in automation systems

## Complete coverage

Functional safety system is a large set of hardware and software which are tightly integrated as an indispensable part of any production systems.

It covers the entire production facility and process.

**ABB Jokab Safety and AC500-S Safety PLC**



**Quick-Guard fencing system**
to prevent unauthorised access

**Magne magnetic lock**
to keep doors and hatches locked during a process

**Pluto programmable safety controller, Vital safety controller and Sentry safety relays**
for flexible monitoring of safety devices

**Contactors**
to control power and motors

**Inca emergency stop button**
for compact panel mounting

**Smile emergency stop button**
to safely stop machinery in hazardous situations

**MKey9 key switch**
for safe locking of hatches and doors

**Orion light guards**
for a production friendly safety detection

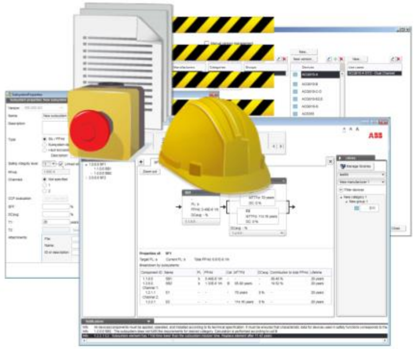
**Safeball control device**
for an ergonomic and safe two-hand control

**GKey safety lock**
for safe locking of doors

**JSDH4 three-position device**
for safe and ergonomic inspection and troubleshooting

**LineStrong pull wire emergency stop switch**
for easy access of emergency stop function

**Eden sensor**
for reliable non-contact monitoring of doors and hatches



**Functional Safety Design Tool**

**AC500-S Safety PLC**

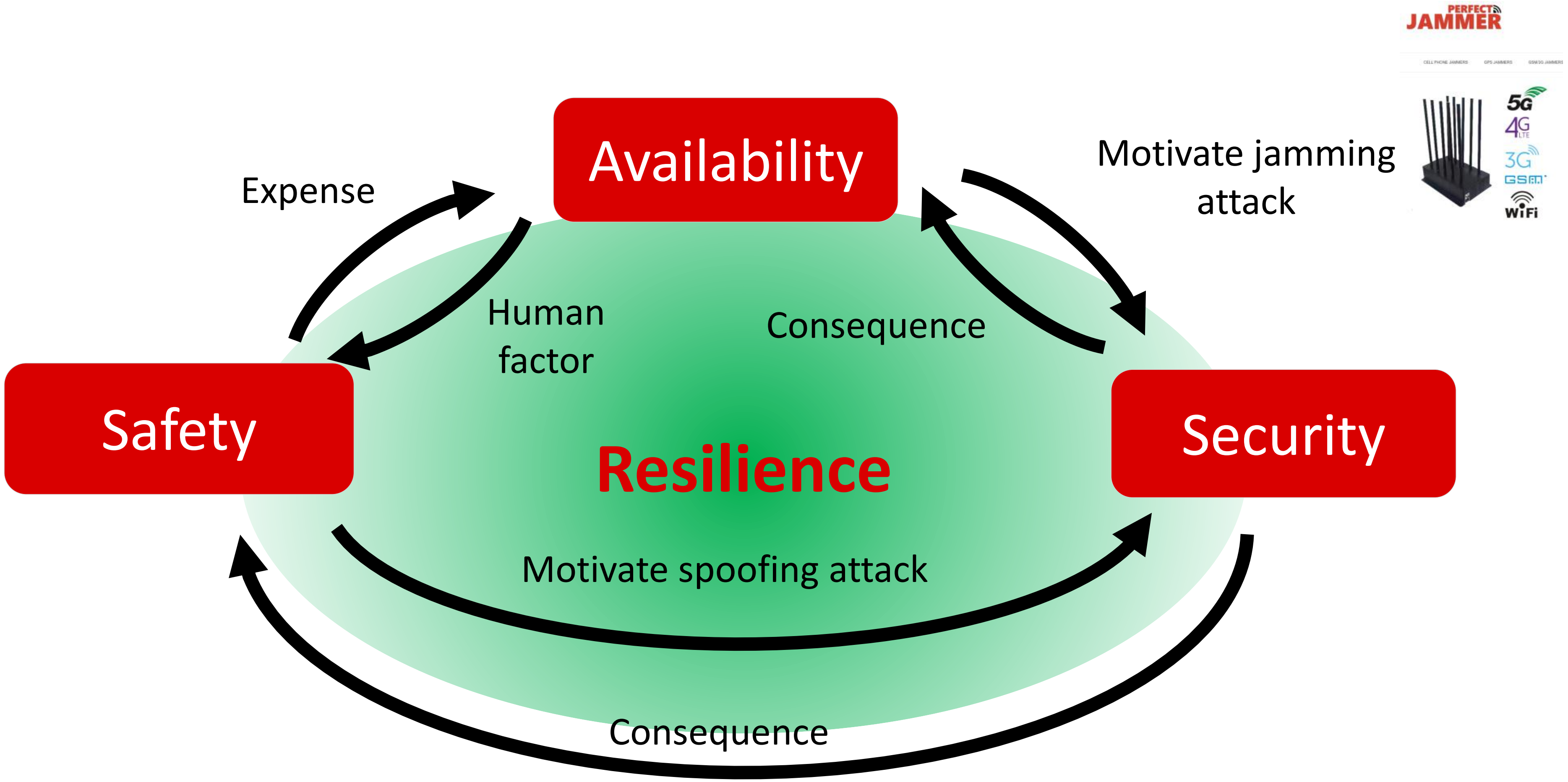
Safety Product Handbook ABB Jokab Safety, https://library.e.abb.com/public/ac78ec67405e42889f1a4003dd111af3/ABB%20Jokab%20Safety_LR.pdf
https://new.abb.com/plc/programmable-logic-controllers-plcs/ac500-s
https://new.abb.com/drives/functional-safety/functional-safety-design-tool

# Grand challenge: safety over open infrastructures in open environments

Safety is a must for mobile robots, and in general, CFA for industrial cyber physical systems

# Extra complexity and challenges

## Relations between the 3 major concerns



Availability

Safety

Security

Resilience

Expense

Human factor

Consequence

Motivate jamming attack

Motivate spoofing attack

Consequence

# Future perspectives

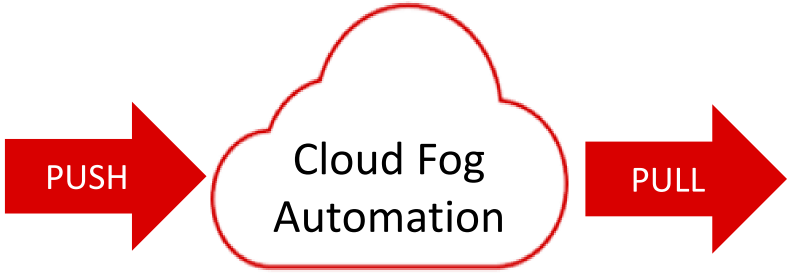
Synergy of the “3C” is the key for success

**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

# Swedish Wireless Innovation Network (SweWIN)

A competence center where sustainability and energy efficiency in both wireless communication and in the use of sustainable materials are in focus. (Advanced digitalization)

VINNOVA

- Hosted KTH Royal Institute of Technology
- Funded by Vinnova, companies, and academia
- Total budget: 90MSEK (~8,2MUSD)
- 5 years: 2024-2028 (+ 5 years possible)

| **Research institutes** | **Large enterprises** | **Start-ups** |
|---|---|---|
| KTH VETENSKAP OCH KONST | ERICSSON | BeammWave |
| RISE Research Institutes of Sweden | ABB | CellMax |
| | SAAB | NW Northern Waves |

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