DETERMINISTIC RELIABLE COMMUNICATION IN WIRELESS IIOT

A CHALLENGE ON ISM AND LICENSED BANDS

HANS-PETER BERNHARD
SILICON AUSTRIA LABS / JKU LINZ

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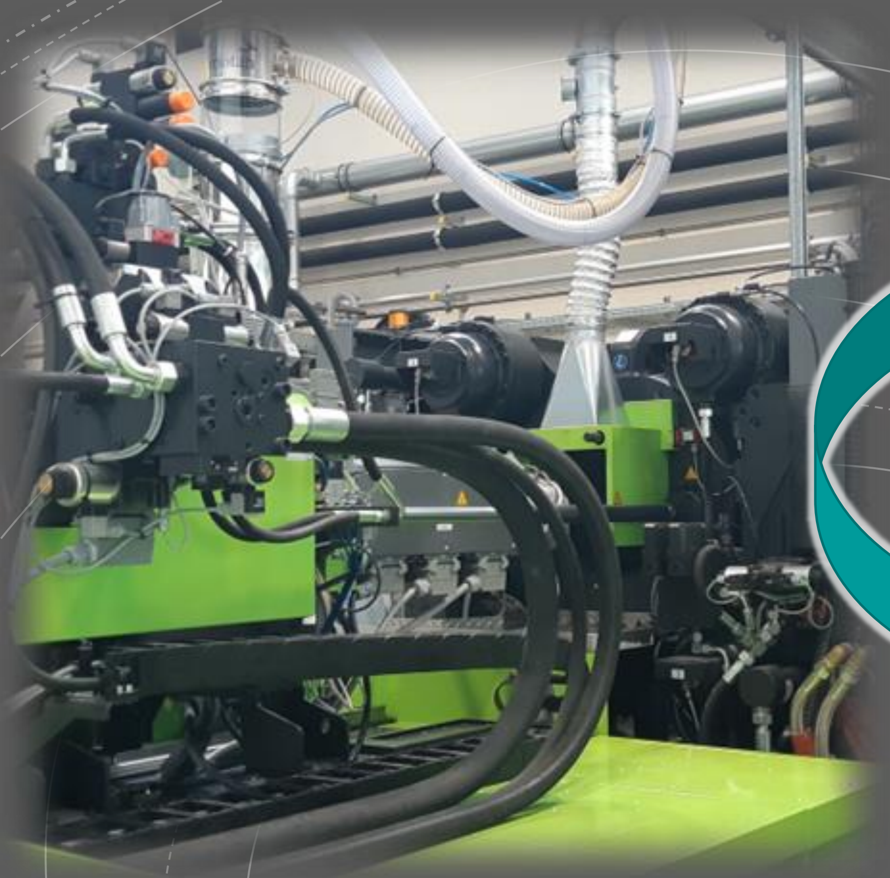
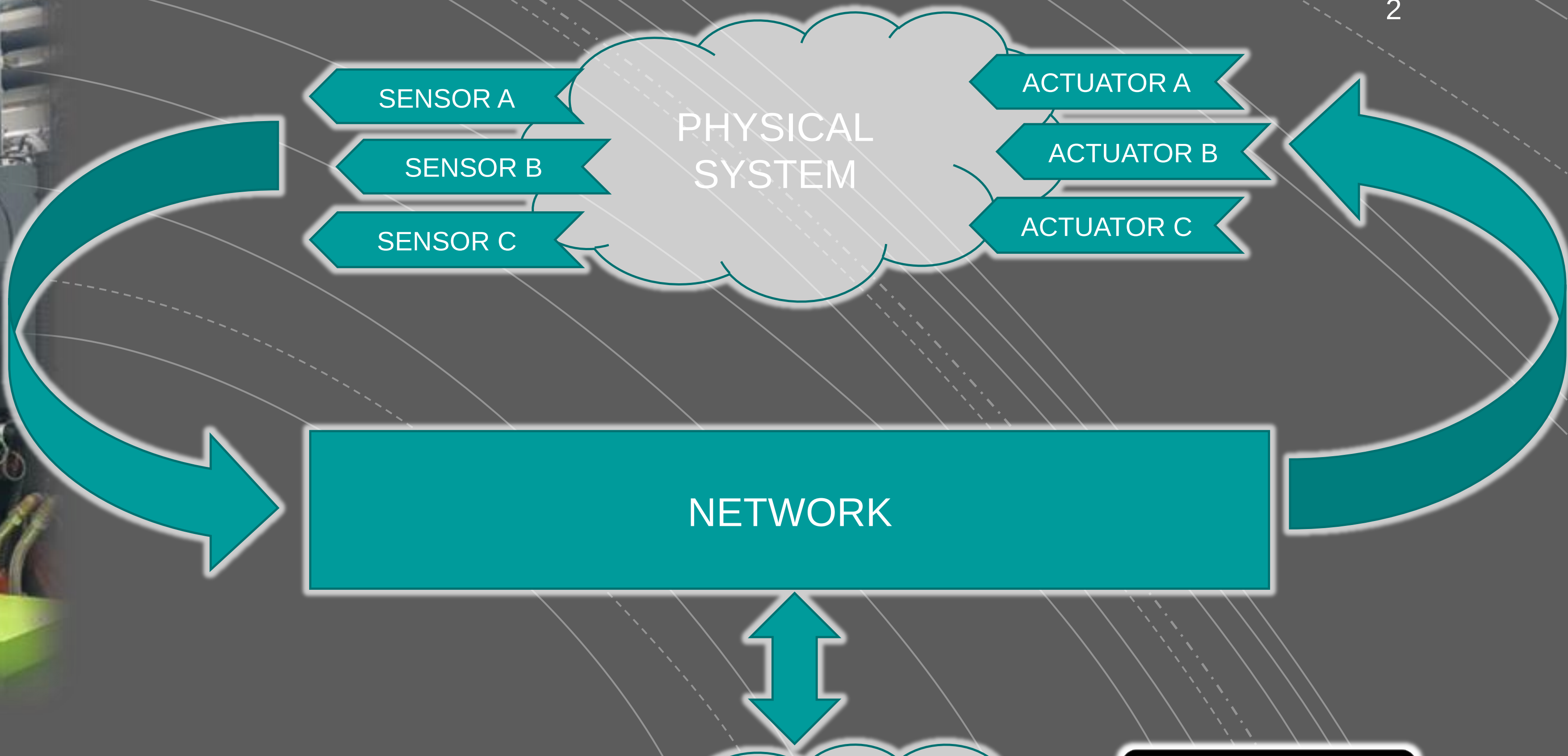
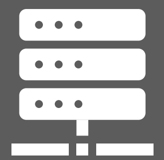




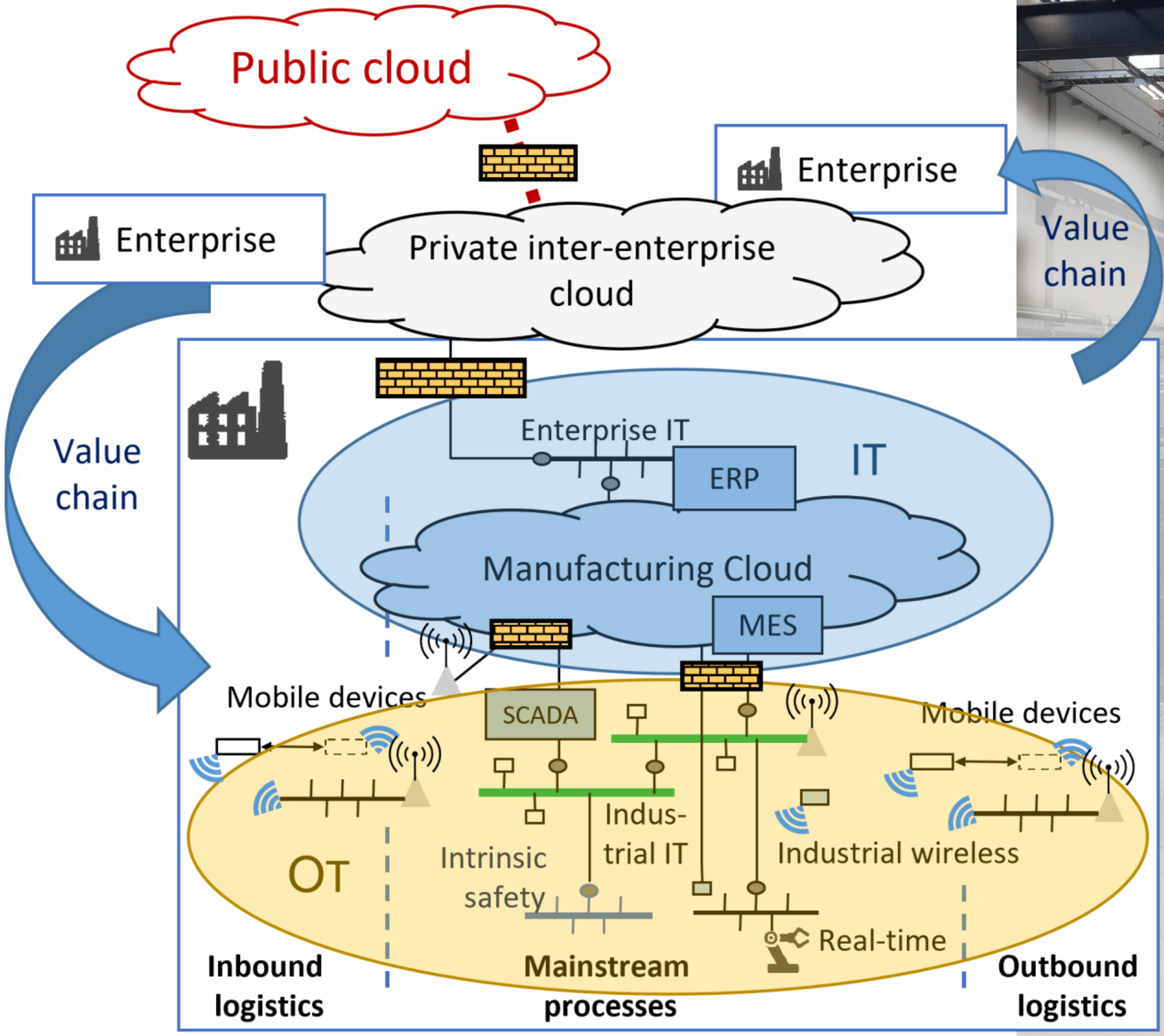
IOT IN INDUSTRY

------ IS MORE ------
ITS
CYBER PHYSICAL SYSTEMS



GENERAL NETWORK STRUCTURE IN I

- Industrial Cyber Physical Systems (CPS) systems
- CPS uses communication
- CPS changes to a service oriented connected system
- Usual ISM Band and IIoT as Wireless Fieldbus
- 5G/6G Allows a new perspective to IT and OT

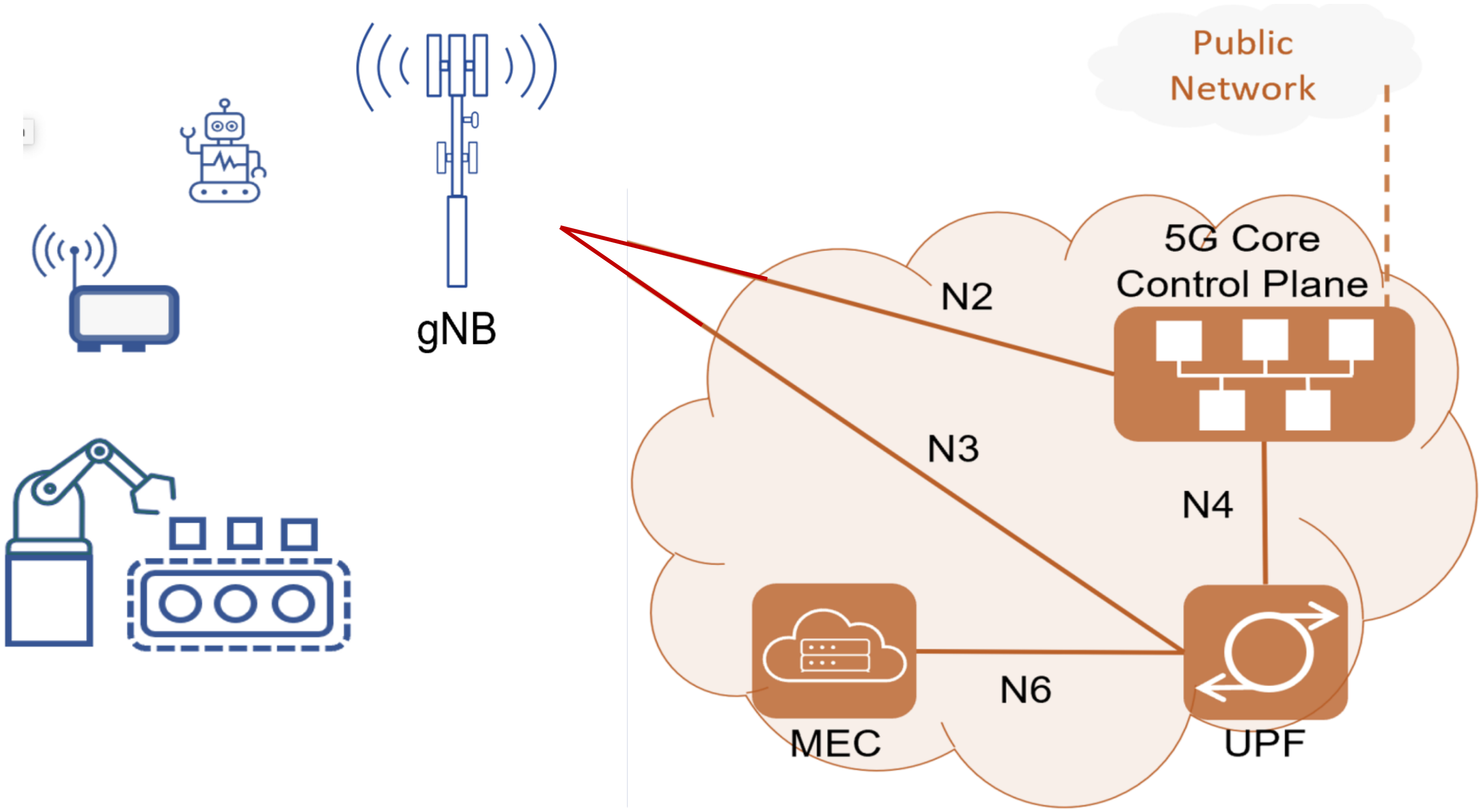


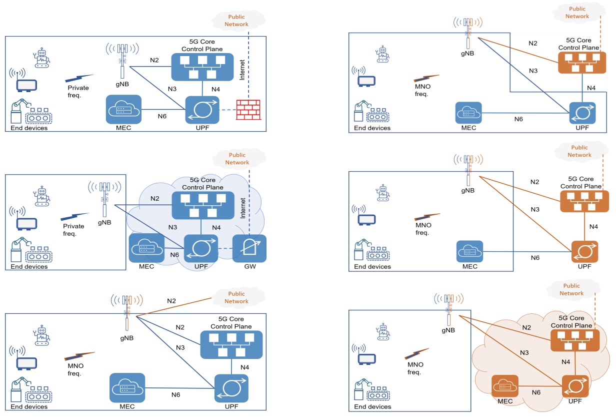
WIRELESS CONNECTIVITY 5G AND ISM BAND CONTENT OF THE TALK

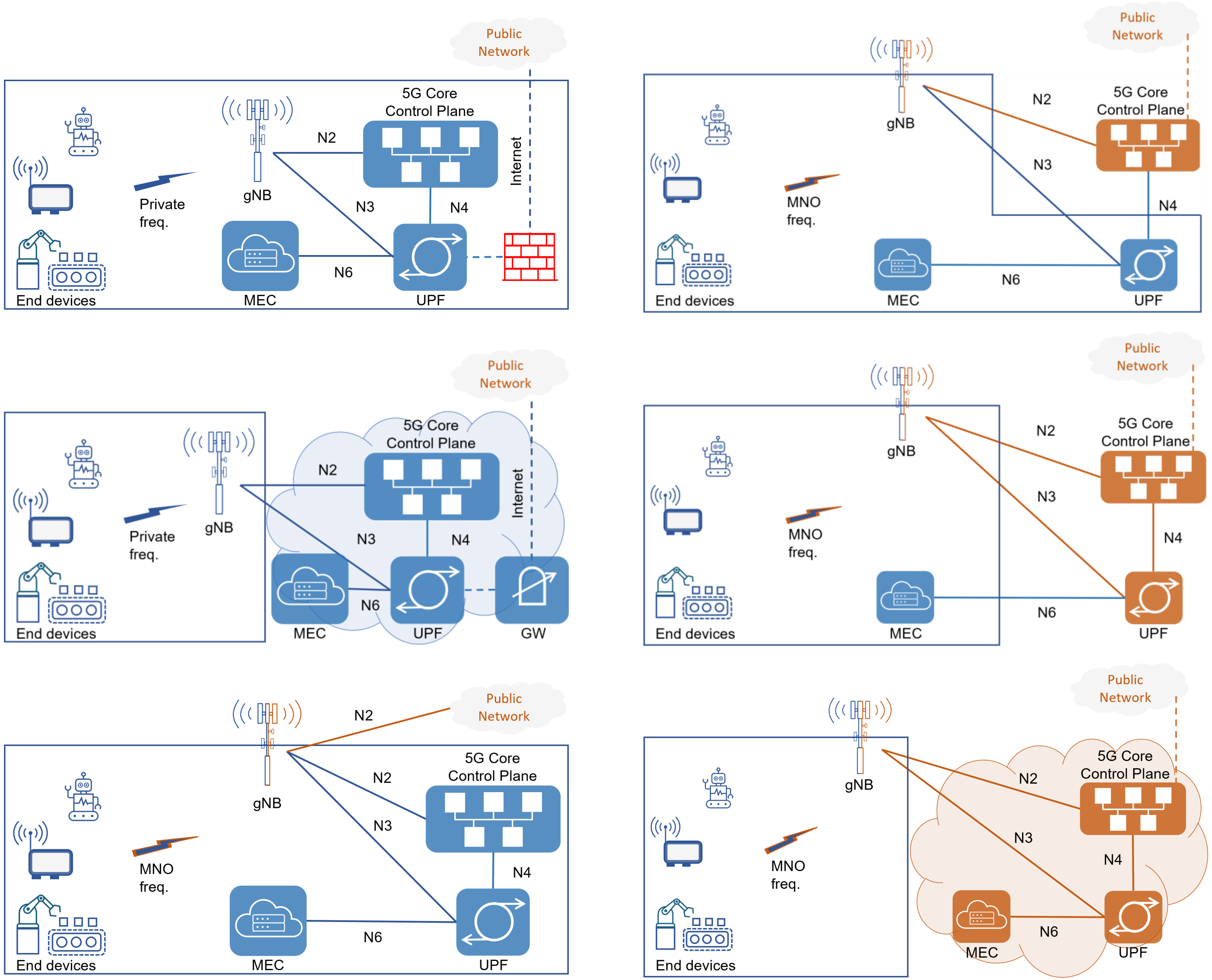
- 5G deployment
- 5G Modulation
- Similarities in ISM and 5G
- Jamming can be done in both
- Next Steps in a 6G future

STANDARD PUBLIC 5G NETWORKS

LTE release 15/16

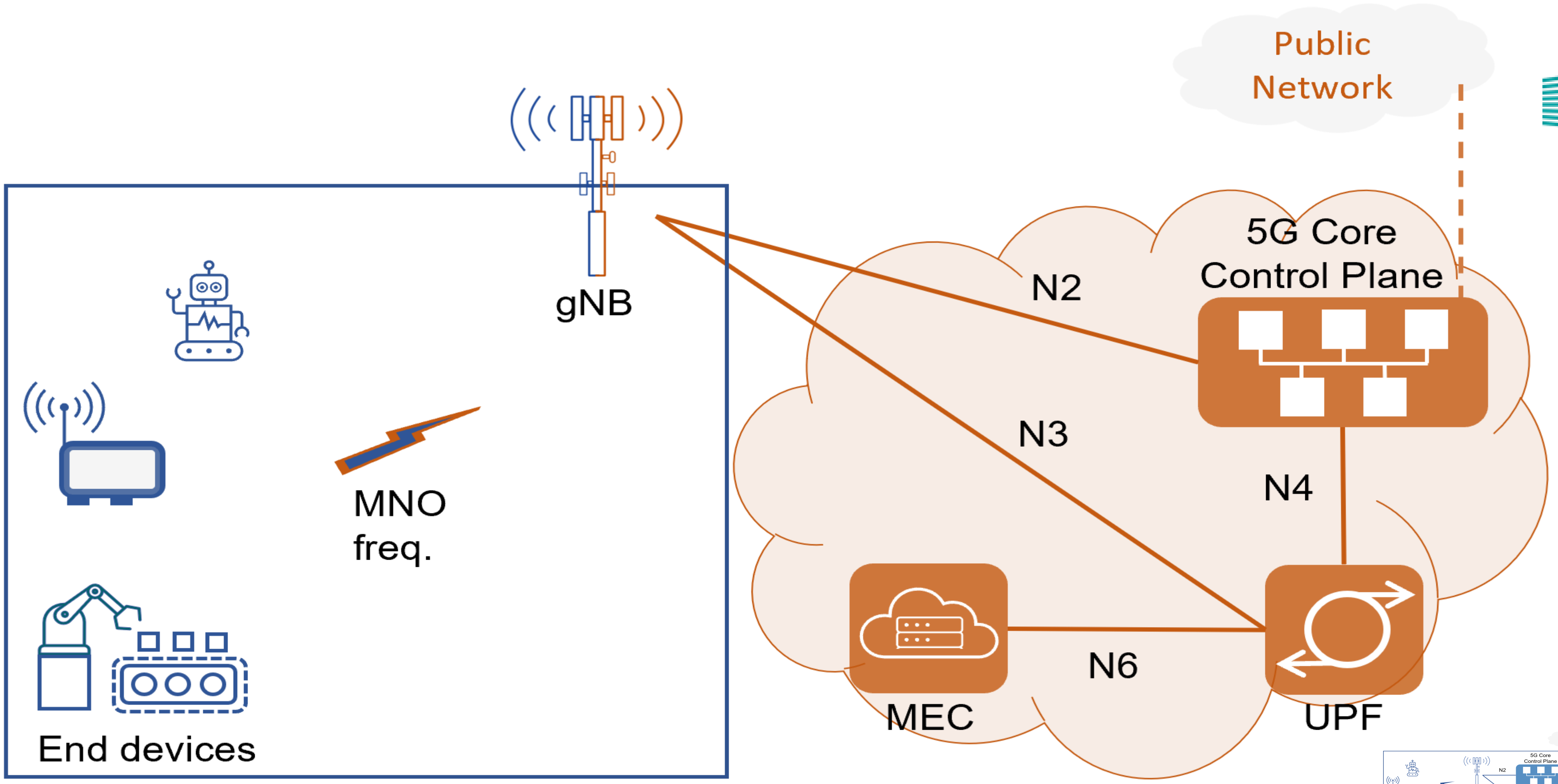


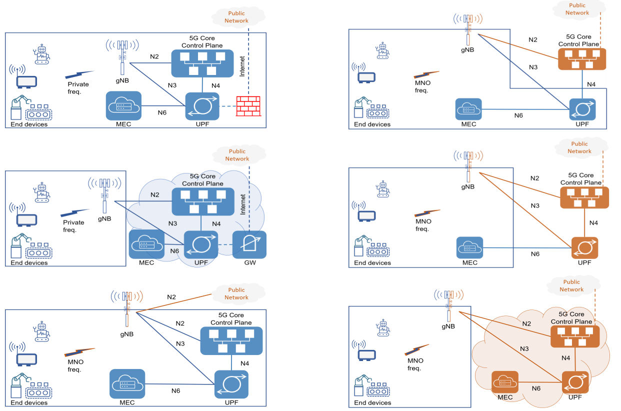




DEPLOYMENT OF (INDUSTRIAL) 5G SYSTEMS

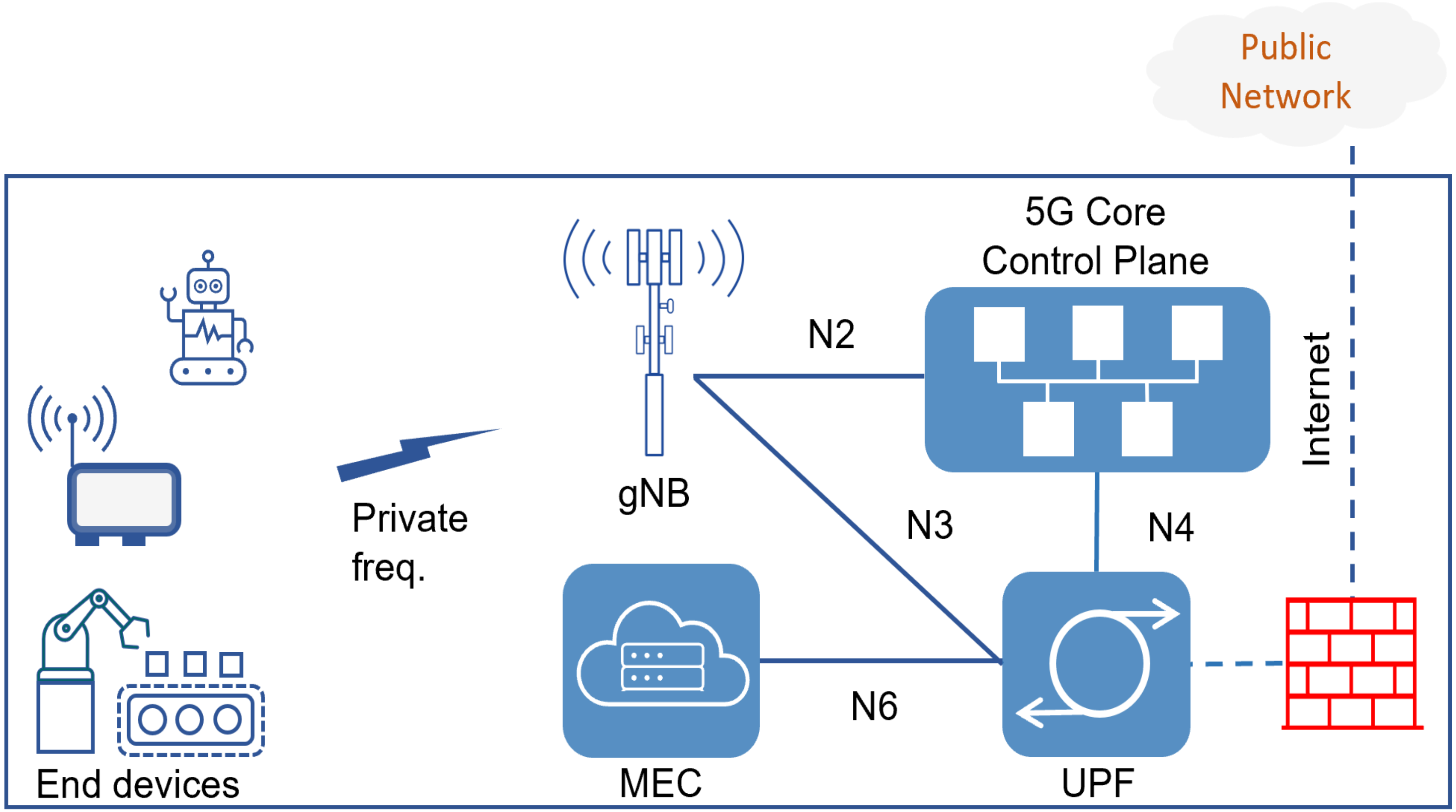
R. Muzaffar, M. Ahmed, E. Sisinni, T. Sauter, and H.-P. Bernhard „5G Deployment Models and Configuration Choices for Industrial Cyber-Physical Systems – a State of Art Overview“*IEEE Open Journal of the Cyber Physical Systems*, vol. Oct., in print, 2023.

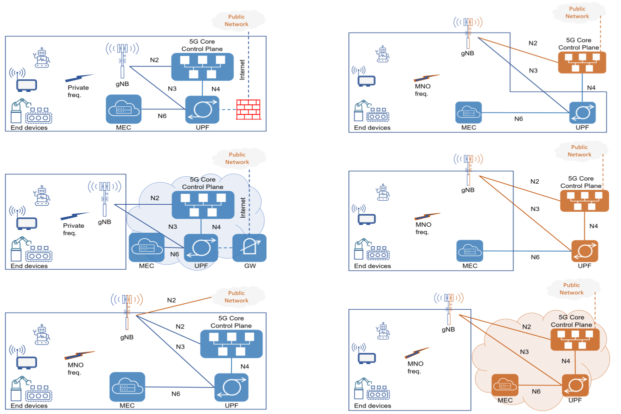




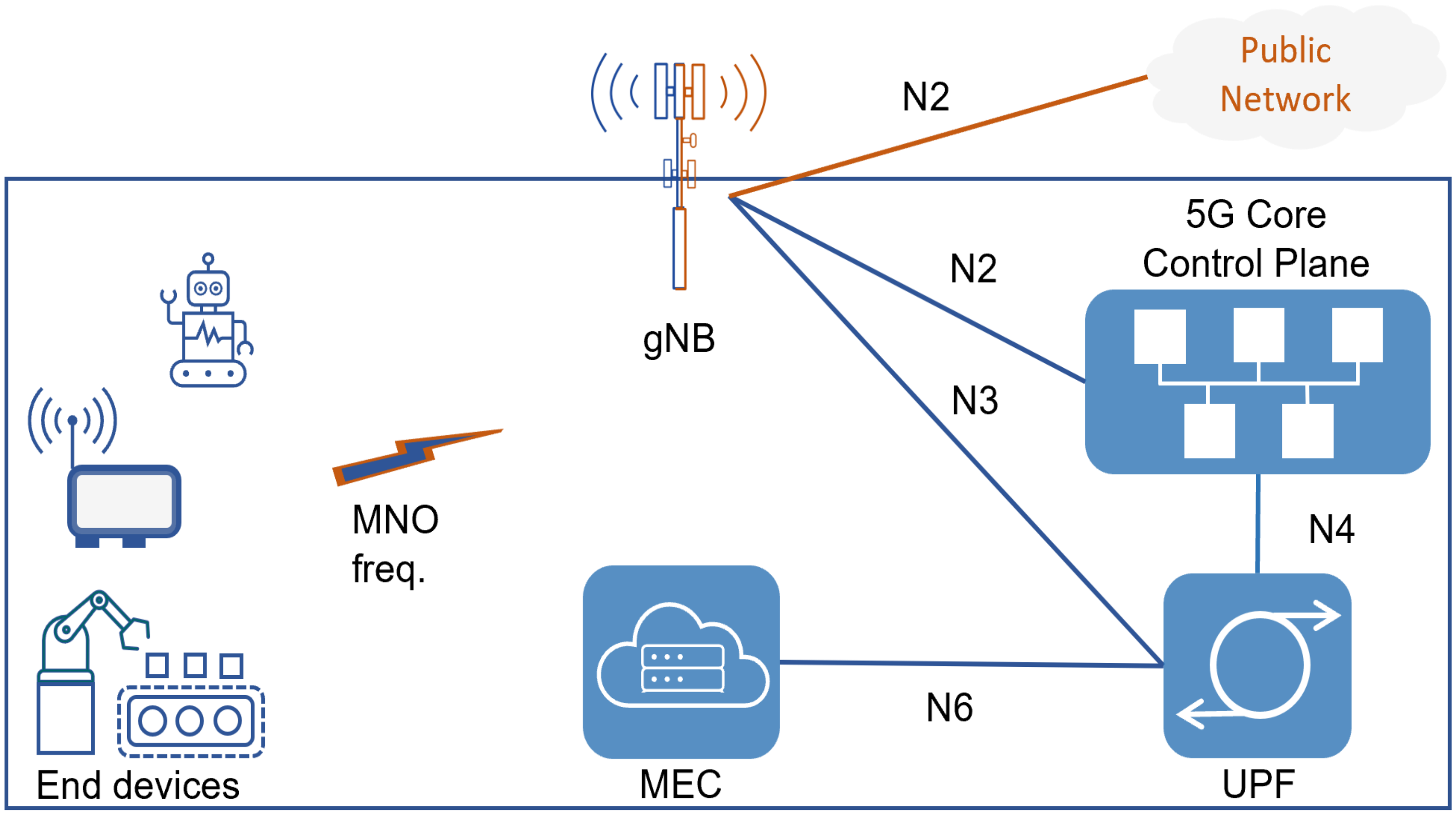
Cloud native PNI-NPN hosted by the public network operator

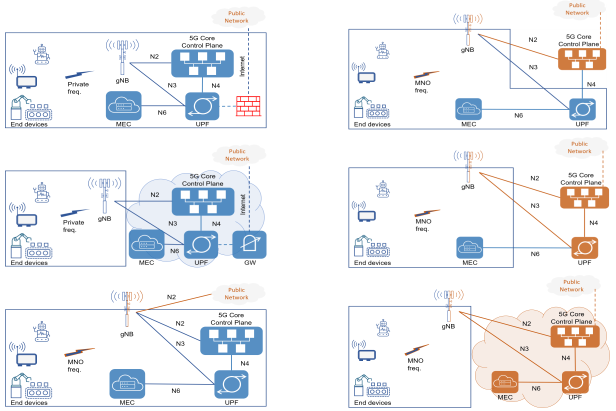
Public Network Integrated – Non Public Network





Isolated deployment





Shared access network (RAN Sharing)

5G ARCHITECTURE

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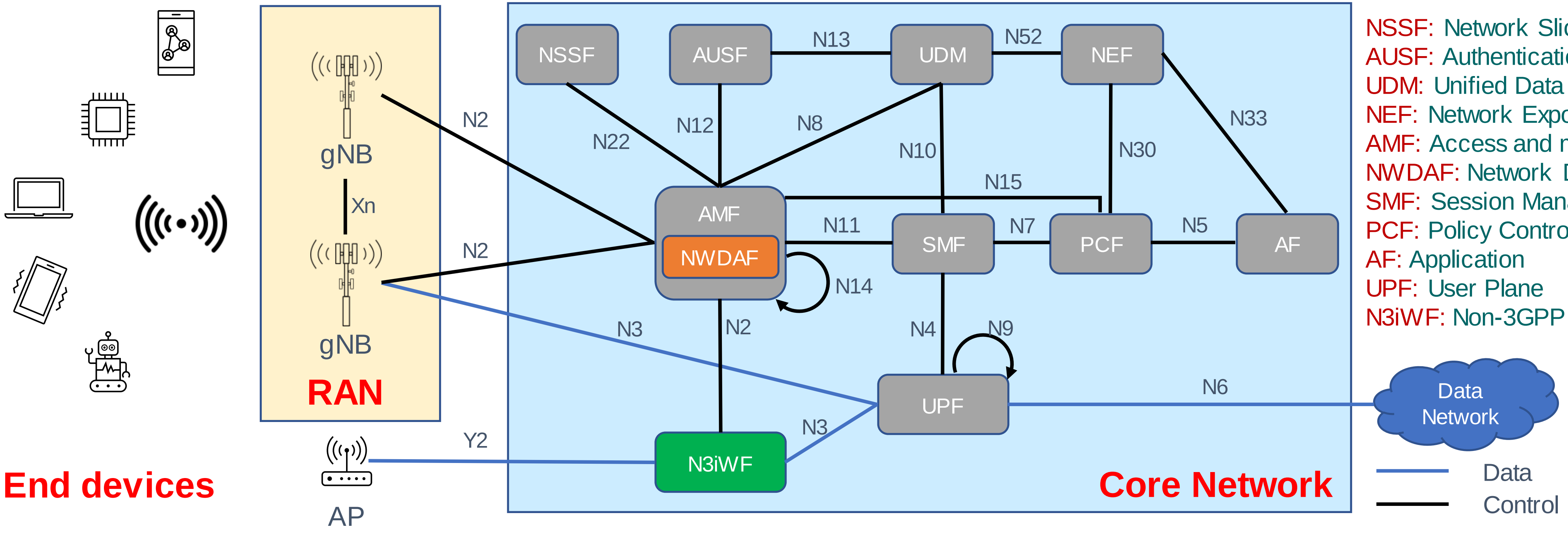
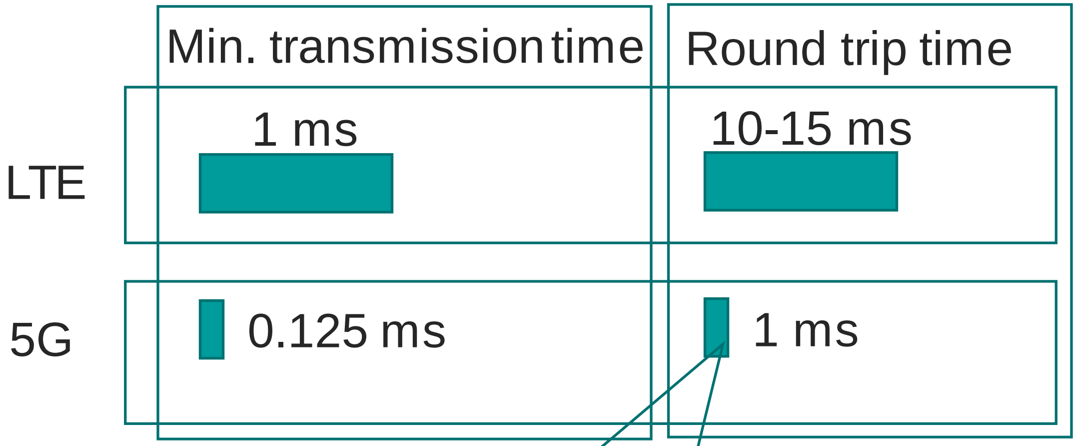


NSSF: Network Slice Selection
AUSF: Authentication Server
UDM: Unified Data Mngmt.
NEF: Network Exposure
AMF: Access and mobility Mngmt.
NWDAF: Network Data Analytics
SMF: Session Management
PCF: Policy Control
AF: Application
UPF: User Plane
N3iWF: Non-3GPP Interworking

- Multi-Access Edge Computing
- Network Function Virtualization
- Network Slicing
- Coordinated multipoint
- Access to network data analytics
- Non-3GPP network interfacing

5G FREQUENCY BANDS

Frequency	Capacity	Channel width
mmWave	20 Gbit/s	400 MHz
sub-6 GHz	2 Gbit/s	100 MHz
LTE 800 / 5G 700	200 Mbit/s	10 - 20 MHz

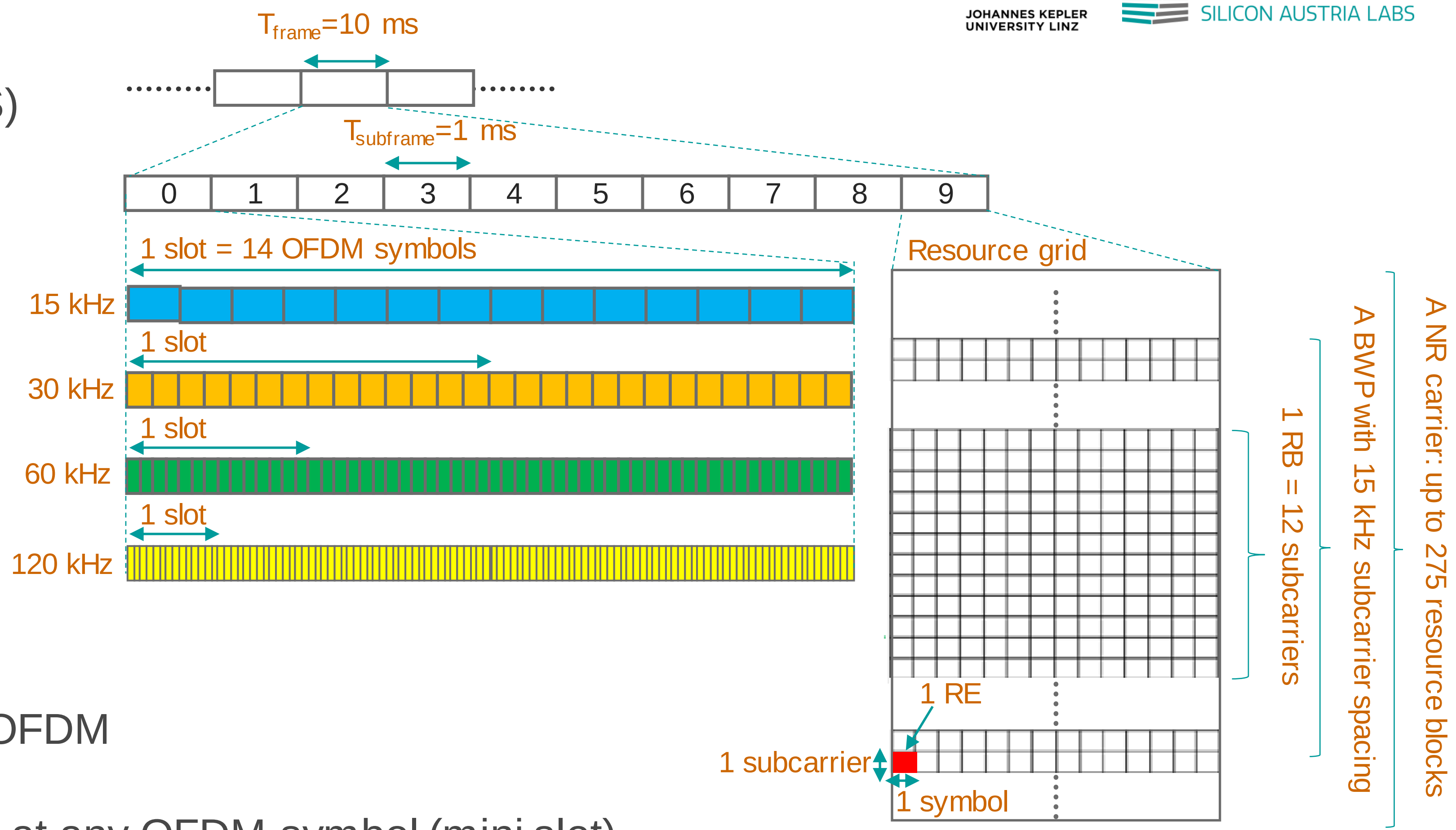


- Depends on
  - radio frame structure
  - application hosted at edge

- High bands for capacity
- Low bands for IoT and low latency critical communication

FRAME STRUCTURE

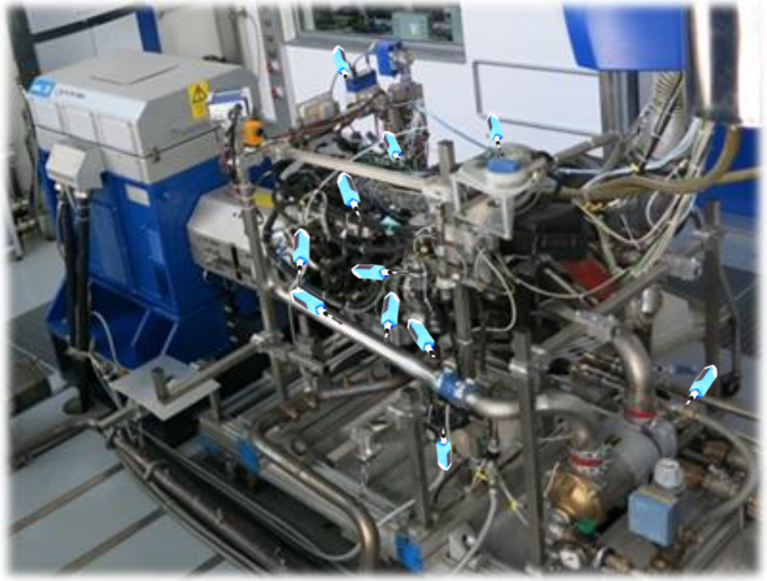
- Flexible subcarrier spacing (SCS)
  - $2^m \cdot 15$ kHz (m=0,1,…,4)
- sub-6 GHz
  - SCS of 15 and 30 kHz
- mmWave
  - 60 and 120 kHz for data channels
  - 120 kHz and 240 kHz for the SS/PBCH block
- Each subframe = 2^m slots of 14 OFDM
- NR enables transmission to start at any OFDM symbol (mini slot)
  - high priority transmission can start immediately
  - facilitate very low latency for critical data



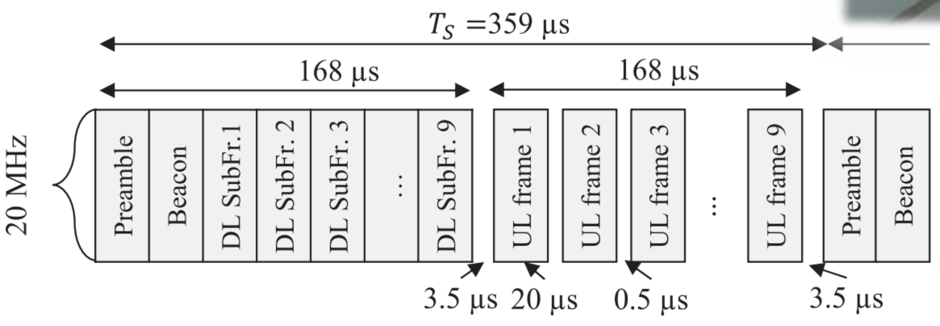
X. Lin, et al. "5G new radio: Unveiling the essentials of the next generation wireless access technology." IEEE Communications Standards Magazine, 2019

ISM-BASED COMMUNICATION

- ISM Deployment
  - Link/MAC layer protocols
  - No complexity in deployment
  - Network organization is not standardized
  - Access points and Nodes/STA



- Some ISM PHY
  - WiFi
  - BLE
  - Zigbee
  - 802.15x
  - Many more

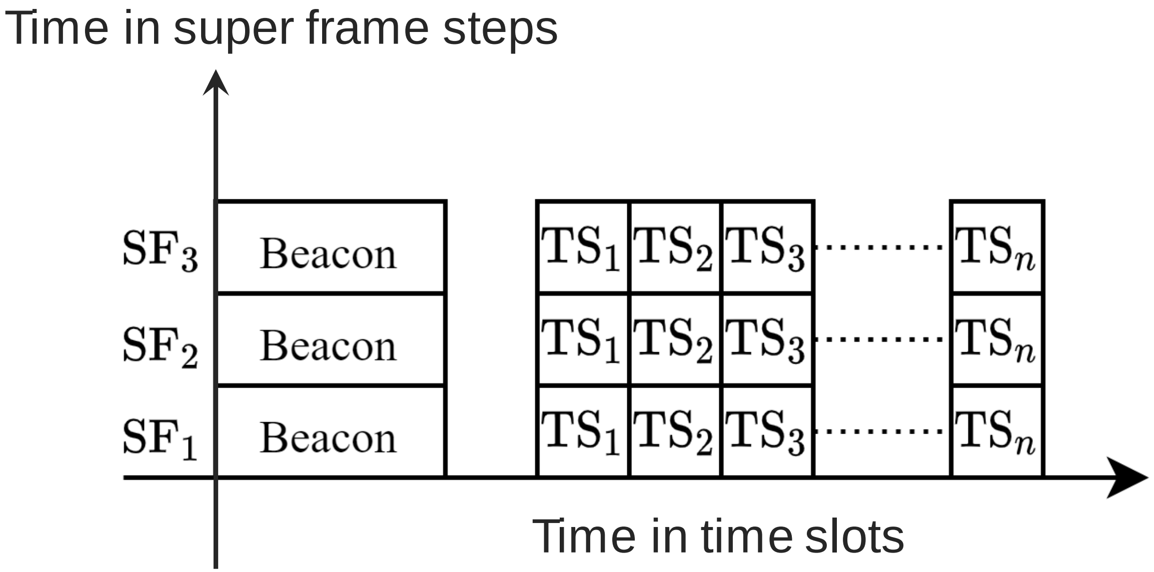


SHARP TDMA MAC on WiFi

TDMA-BASED COMMUNICATION & INTERFERENCE MEASUREMENT

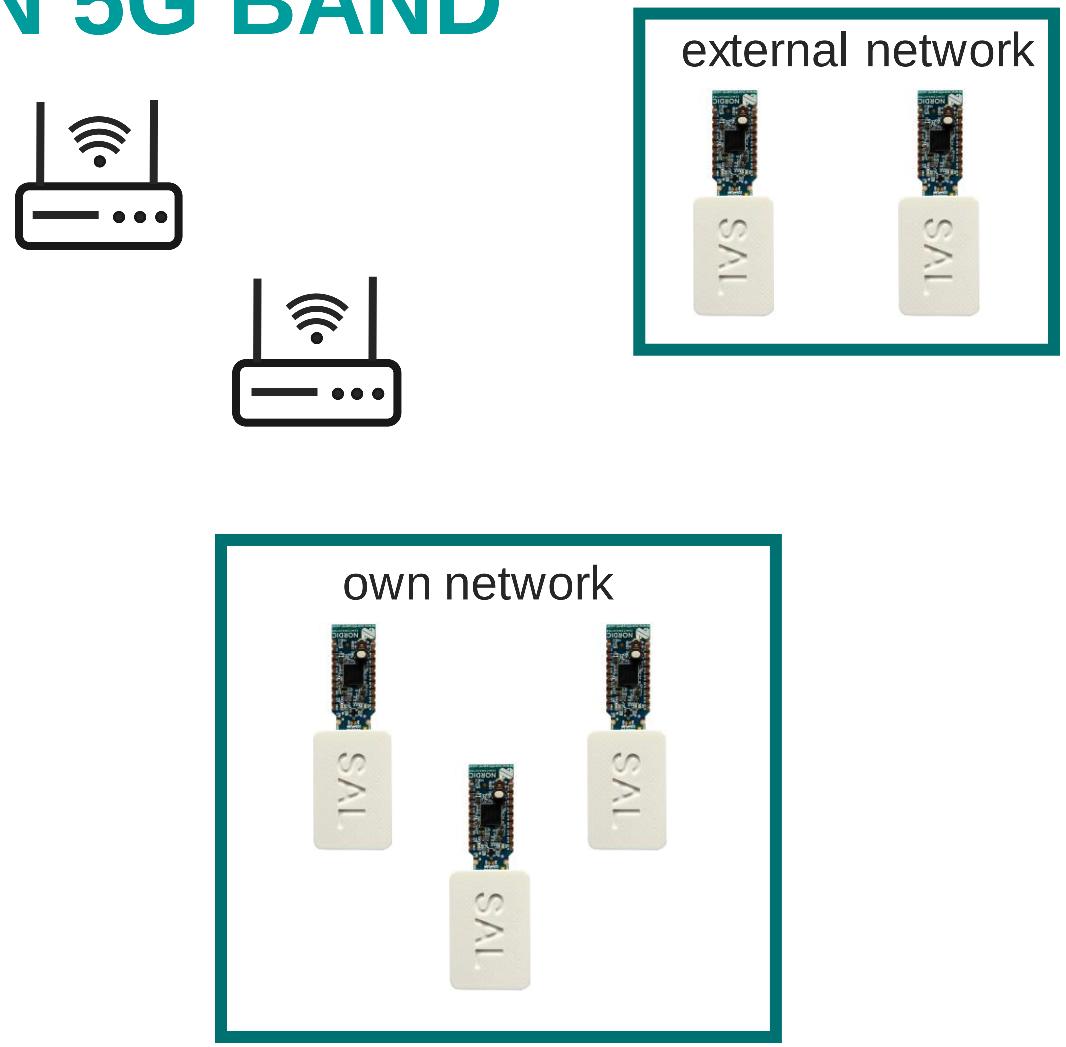
- TDMA-based IIoT
  - BLE PHY Layer,
  - Base-station, Controller
  - each node dedicated timeslot

- Sniffer node
  - Low-cost hardware
  - Measure average signal level of all timeslots
  - Data collected at base-station



YOU ARE NOT ALONE IN ISM BAND YOU HOPE TO BE ALONE IN 5G BAND

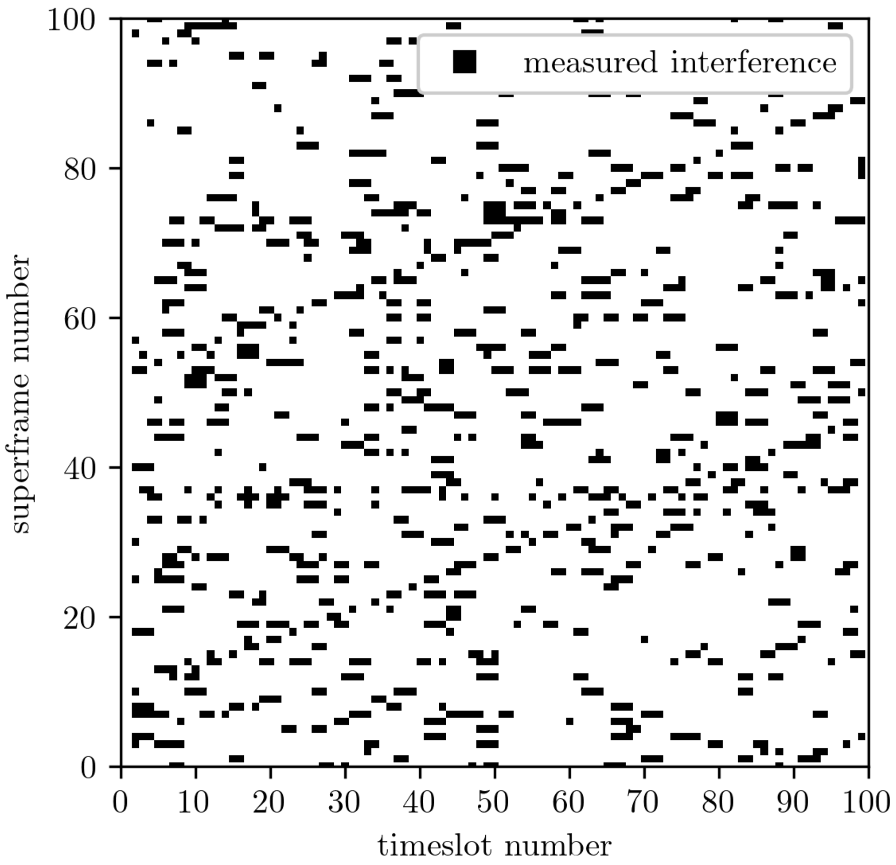
- A lot of networks rely on unlicensed frequency bands (e.g., 2.4 GHz Band)
- Everybody can use it (although you maybe don’t want to share)
- Coexistence and interference mitigation becomes very important especially in industry settings
- Goal
  - Find pattern in external channel access
  - Track over time
  - Identify interference
  - Predict and avoid future collisions



GENERAL IDEA

- Problem
  - A lot of measurements from one superframe to the other
  - Separate periodic interferer from each other and noise
- Multi Hypothesis Tracking proposed by Reid [1] solve data association problem

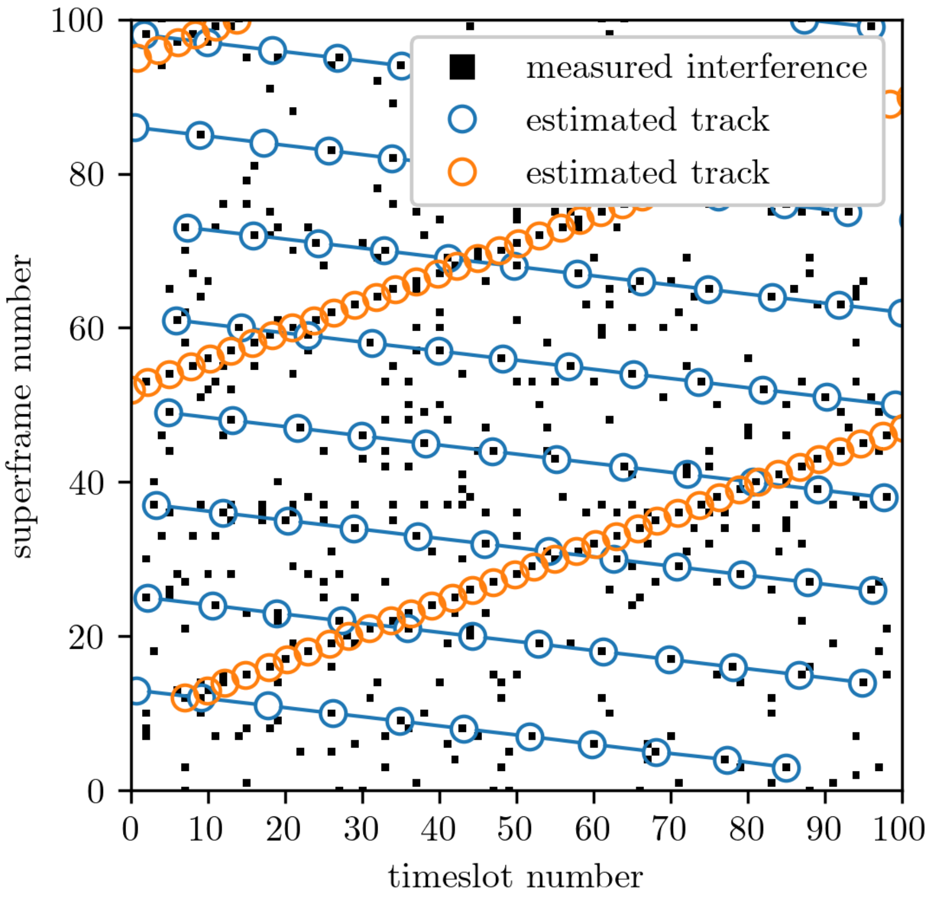
- Idea
  - Consider all combination of measurements from on superframe to the next
  - Use a separate tracking algorithm for every
  - Find best tracks and prune others



[1] D. Reid, “An algorithm for tracking multiple targets, ”IEEE Transactions on Automatic Control, vol. 24, no. 6, pp. 843–854, 1979.

TRACKING ON REAL MEASUREMENT

- Two periodic interferer are present
  - 102.4 ms (same as IEEE 802.11 beacon)
  - 92.4 ms
- Simple peak estimation to get only one “point” per interference
- Able to estimate position with a RMSE of 0.146 ms (measurement resolution is 0.9 ms)
- Reconstruct missing measurements



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INFRASTRUCTURE

- Private 5G Campus Network with 5G Spectrum 80 MHz BW from local operator Liwest
- Open Source 5G Core from Fraunhofer FOKUS with latest 3GPP releases
- Off-the-shelf communication hardware (RAN from Huawei)
- Edge computing hardware for local use case implementation
- UE: 5G Quectel modules, 5G and TSN supported end-devices
- CISCO TSN Switch

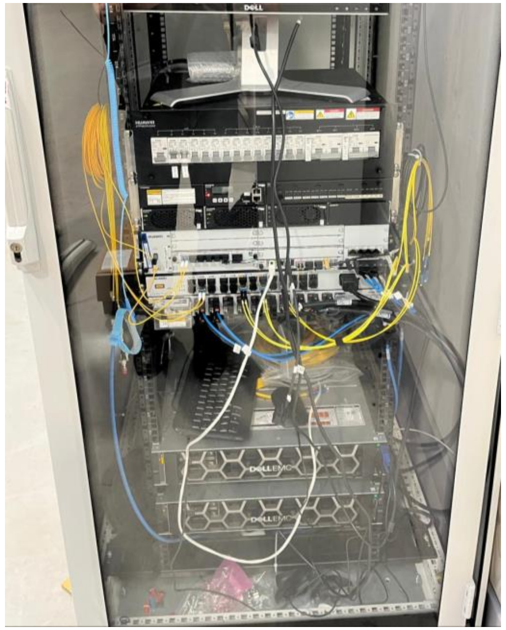
JKU LIT Factory

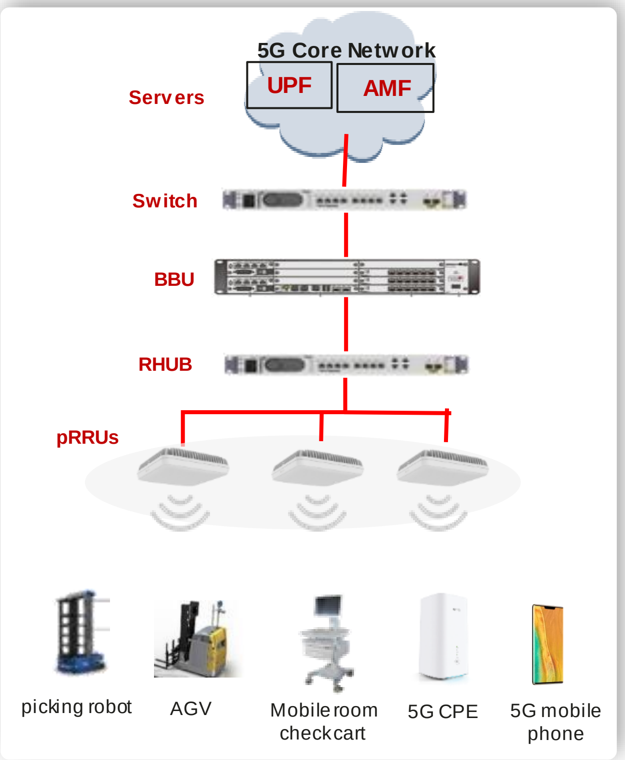
Member of international industry alliance

5G Infrastructure Association

5G Alliance for Connected Industries and Automation

LIT FACTORY - 5G TESTBED





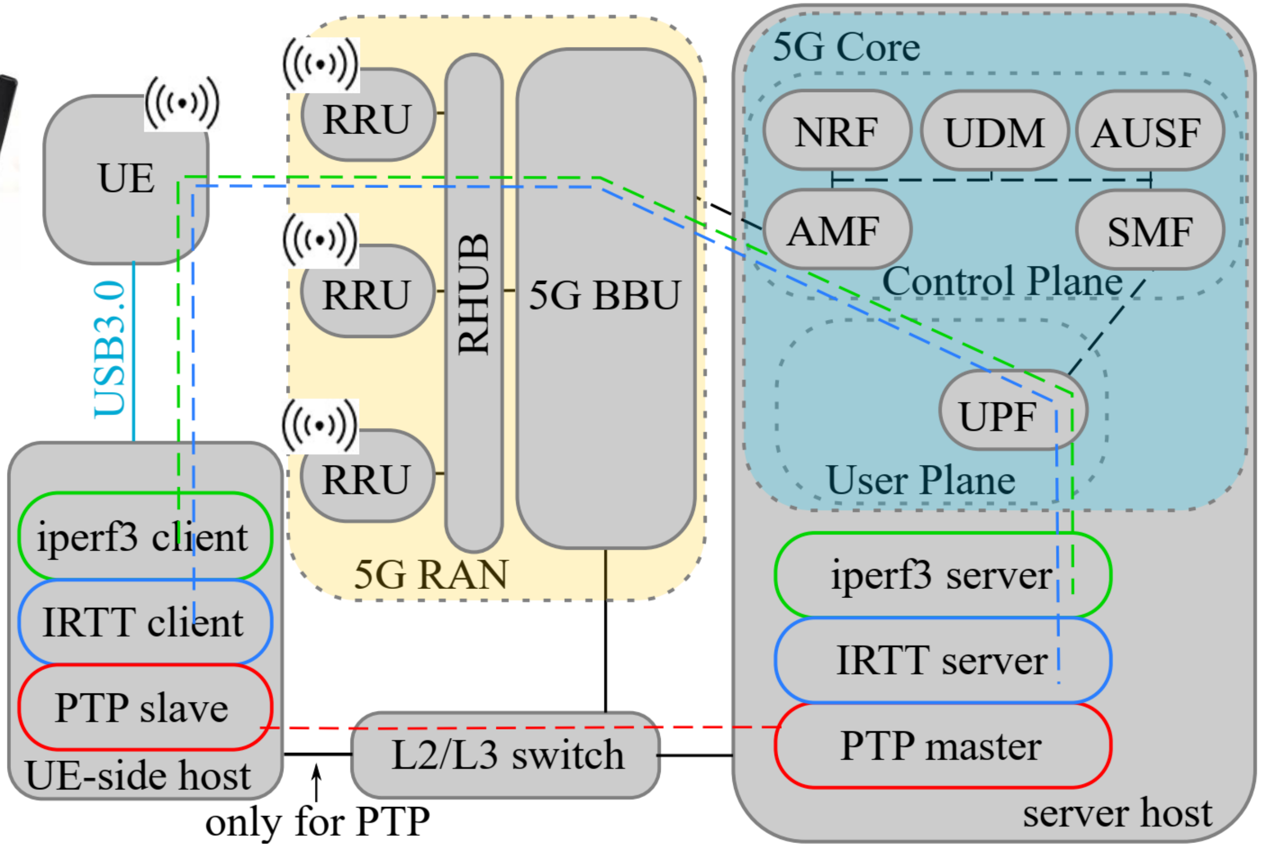
5G TESTBED SETUP

5G mobile phone

Quectel RM502Q-GL

Laptop

UP Squared Pro



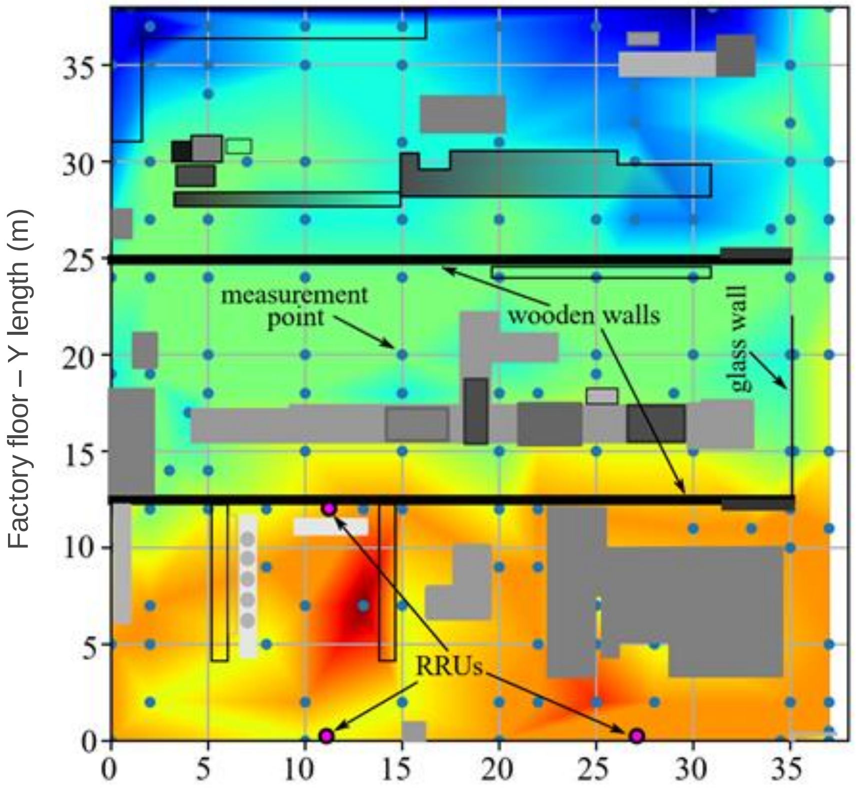
Measurement setup of the 5G testbed

- UE: User Equipment
- RRU: Remote Radio Unit
- RHUB: RRU HUB
- BBU: Baseband Unit
- PTP: precision Time Protocol
- RAN: Radio Access Network
- NRF: Network Repository Function
- UDM: Unified Data Management
- AUSF: Authentication server Function
- AMF: Access and Mobility Management Function
- SMF: Session Management Function
- UPF: User Plane Function
- IRTT – tool for latency testing
- Iperf3 – tool for throughput testing and traffic generation

FACTORY FLOOR
MEASUREMENTS

- Obstacles - height in grayscale (white 0m, black 10m)
- Obstacles are mostly steel machines
- Height of RRUs - 8m
- Most significant signal attenuators:
  - Distance – path loss
  - Height of steel obstacles
  - Glass wall
- Parameters measured at points highlighted in blue circles.
  - Interpolated values in-between

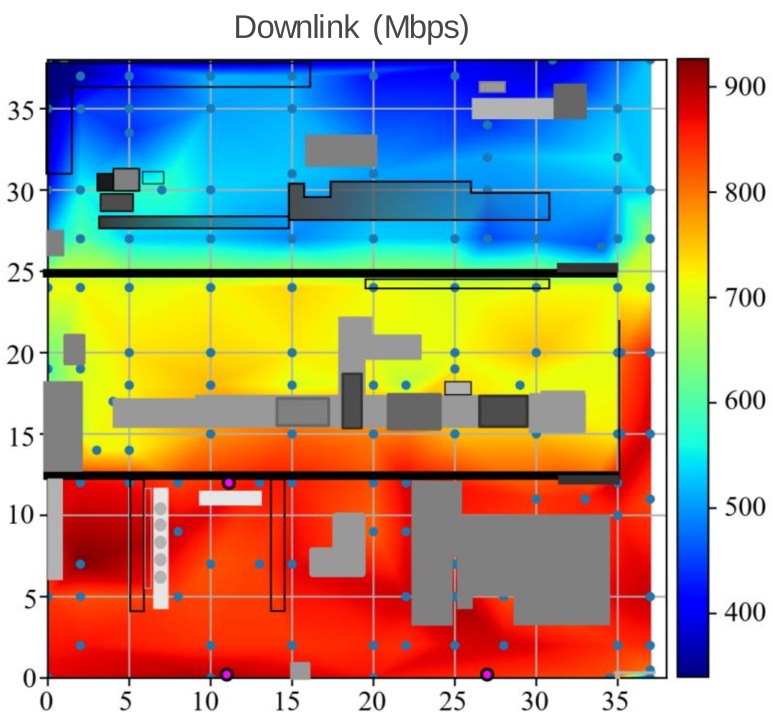
LIT Factory floor at JKU LINZ campus

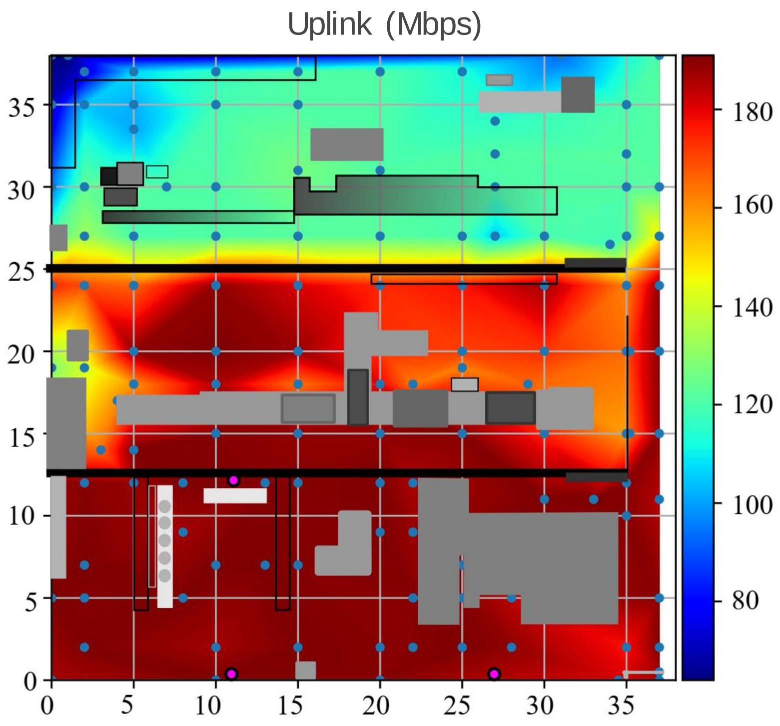


RRU: Remote Radio Unit

THROUGHPUT

- Throughput capacity measured with a single UE with *iperf3* test.
- *iperf3* set for maximum traffic load between server (5G core side) and client (UE side) applications.
- Results at every measurement point averaged over the duration of 5s.
- The reason for a bigger area with the maximum throughput in uplink is the adjustable TX power of the UE (uplink).

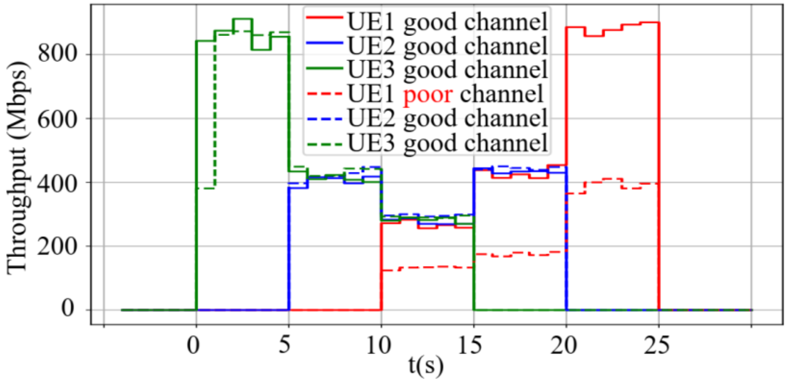




THROUGHPUT WITH 3 UES

VARYING CHANNEL CONDITIONS AND 5G QoS PARAMETERS

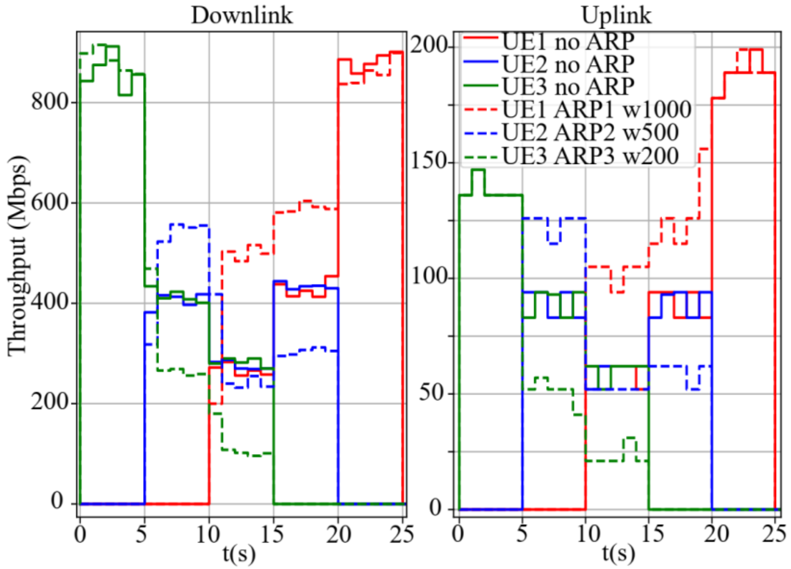
Impact of the channel conditions on the DL throughput, with equal QoS parameters.



- All three UEs share the equal amount of resources with equal QoS parameters.
- In case of poor channel conditions, UE1 achieves lower TP due to lower modulation scheme used (e.g., QAM16 vs QAM256)

ARP: Allocation and retention priority – 5G QoS parameter
TP: Throughput

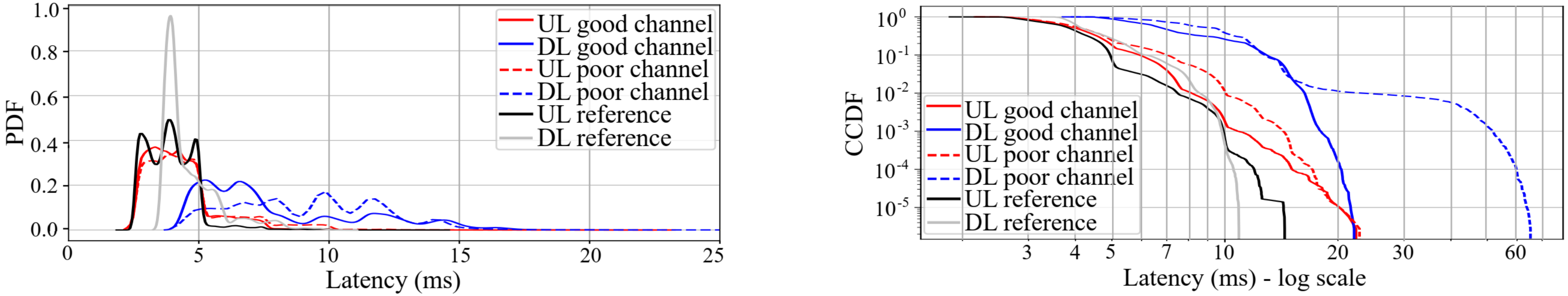
Impact of the QoS ARP parameter on the DL and UL throughput.



- With different QoS (ARP priority), resources among UEs are shared according to the weights *w*.
- Under the same channel conditions, different UEs achieve different TP due to different amount of resources allocated, proportional to the weights *w*.

LATENCY
VARYING CHANNEL CONDITIONS

Impact of the channel conditions on the UL and DL latency, where UE generates 450 Mbps of additional DL traffic load.

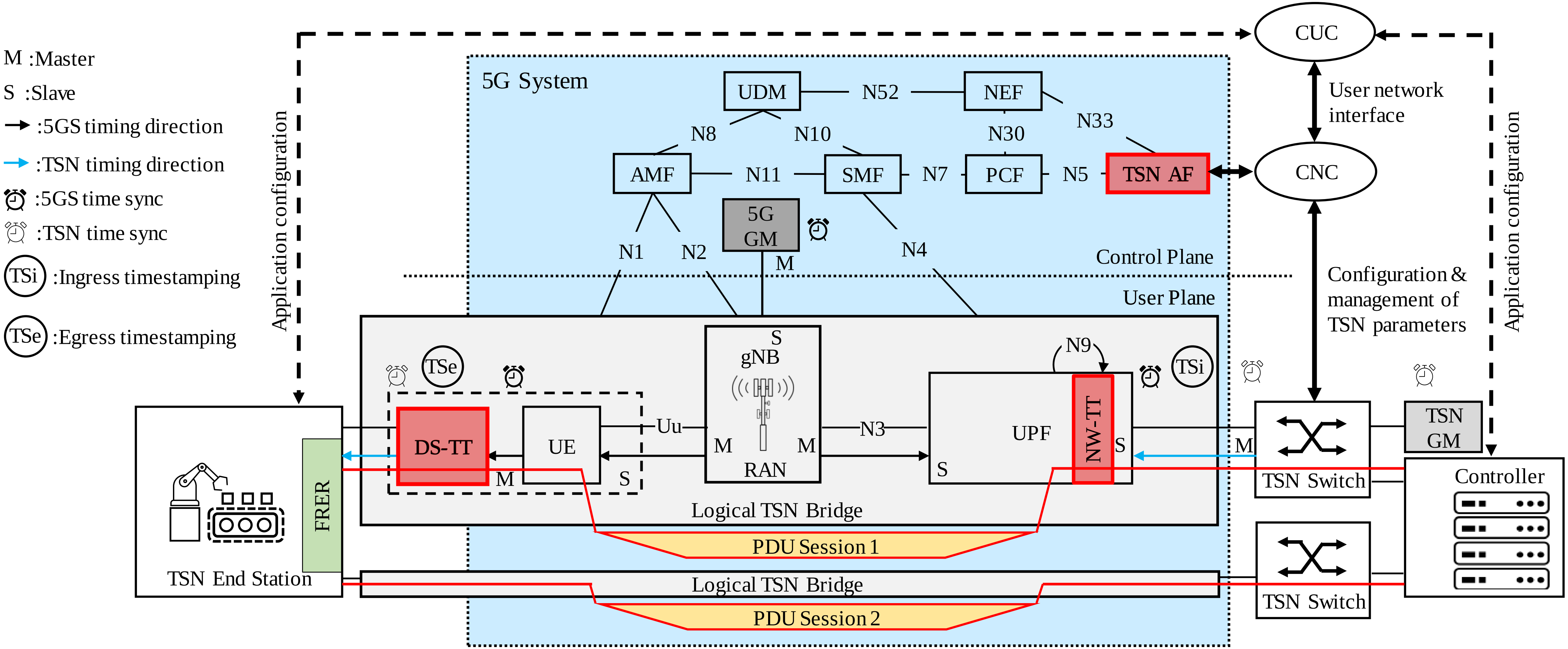


- The mean one-way latency is 4.6 ms in DL and 3.9 ms in UL in the reference case (no additional traffic).
- The DL latency is significantly more impacted by the additional traffic in DL in **poor** channel conditions:
  - Mean value is **6 ms, in good** channel conditions vs. **10 ms, in poor** channel conditions),
  - In poor channel conditions, the latency is significantly higher at the tail of the distribution curve
    - E.g., **20 ms in good** channel conditions vs. **60 ms in poor** channel conditions at 10^{-4} (see CCDF).
- The UL latency is only slightly impacted by the additional traffic in the DL.

5G AND TSN

M. K. Atiq, R. Muzaffar, O. Seijo, I. Val, and H.-P. Bernhard, "When IEEE 802.11 and 5G meet time-sensitive networking," *IEEE Open Journal of the Industrial Electronics Society*, vol. 3, pp. 14–36, 2022.

5G AS TSN LOGICAL BRIDGE



CUC: Centralized user Configuration
CNC: Centralized Network Configuration
TSN AF: TSN Application Function
NEF: Network Exposure Function
PCF: Policy Control Function

SMF: Session Management Function
UDM: Unified Data Management
AMF: Access and mobility Management
UPF: User Plane Function
RAN: Radio Access Network

NW-TT: Network-side TSN Translator
DS-TT: Device-side TSN Translator
PDU: Protocol Data Unit
FRER: Frame Replication and Elimination for Reliability
UE: User Equipment

DETERMINISTIC WIRELESS IIOT

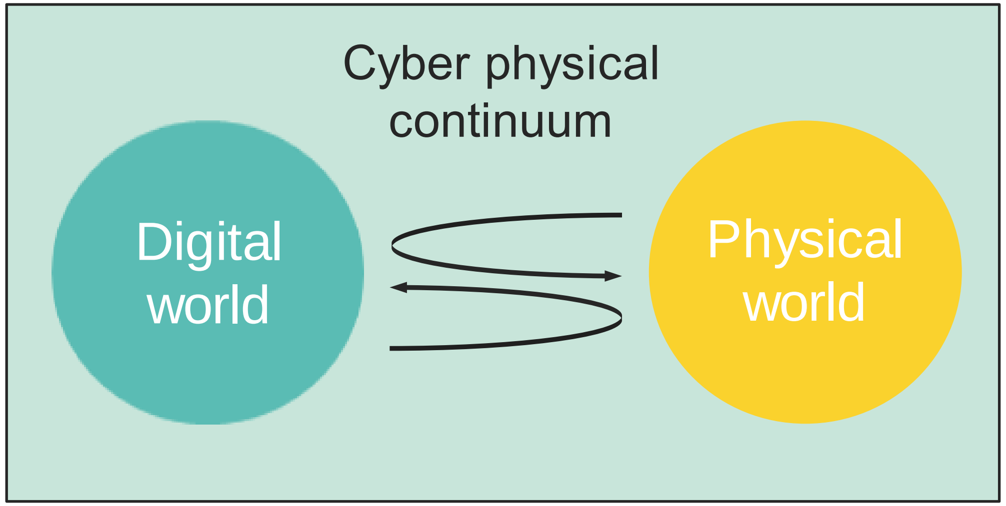
- Industrial CPS systems contain wireless IIoT
- Determinism is influenced by
  - Traffic
  - Channel quality
  - Messages
  - Number of users
- 5G is offering a standard for wireless communication usable for CPS
- Is 6G aiming to become a CPS

VISION

To set the foundation for future global communication standards enabling 6G deterministic communication for visionary use cases

- Cyber-physical continuum between the connected physical world of senses, actions, experiences, and its programmable digital representations

- Future 6G technology must ensure E2E deterministic communication flows to fulfill emerging requirements of visionary use cases

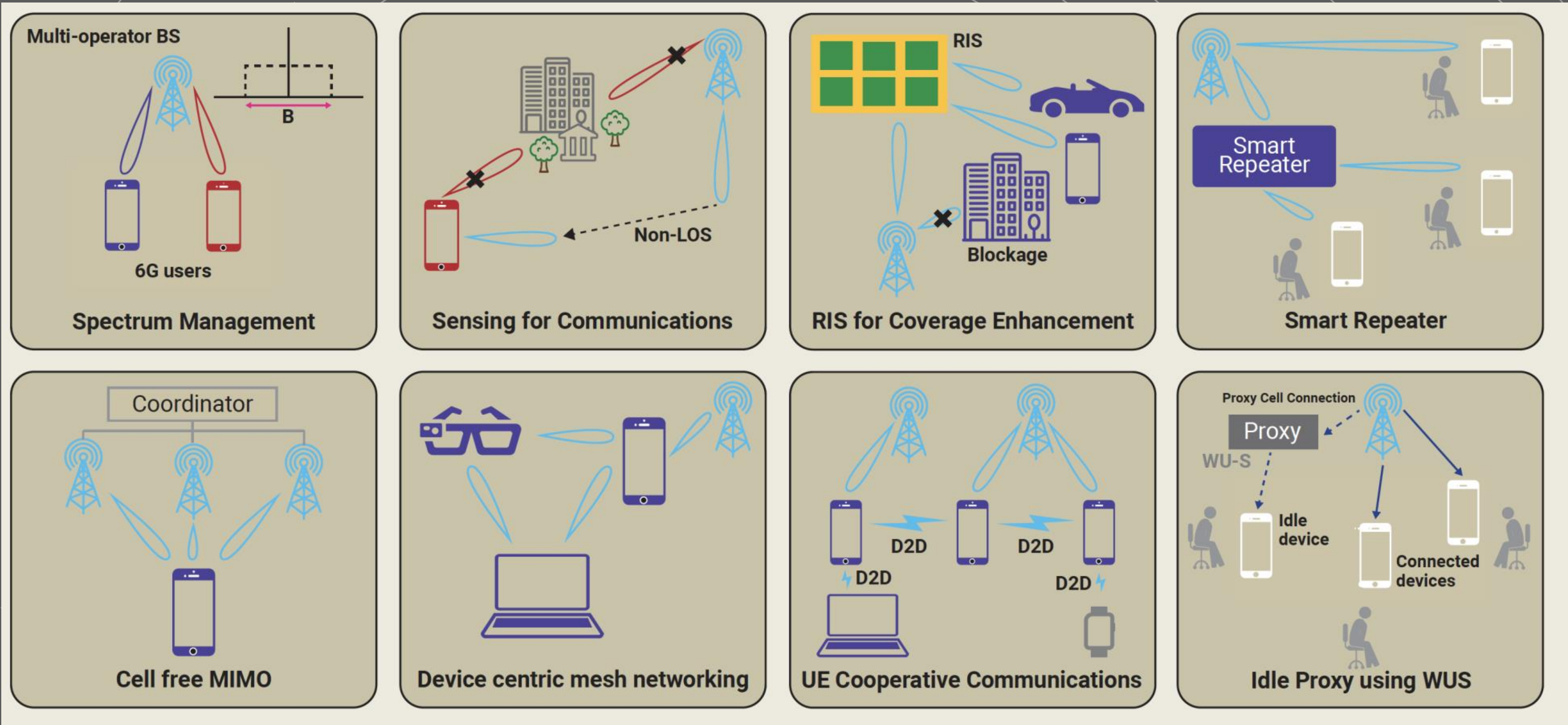


E2E deterministic communication infrastructure

NEXT G WILL BE

FASTER, HIGHER, BIGGER?

?



- One approach sketched by Next G Alliance
  - Channel influence and spectrum sharing
  - Multihop & mesh like structures
  - Idle management by Wake up on signaling

COMMUNICATION PRARDIGM CHANGE

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Current approach:
Designing $s(t)$ and
processing $r(t)$

$$r(t) = (h(\tau, t) * s(\tau))(t) + n(t)$$

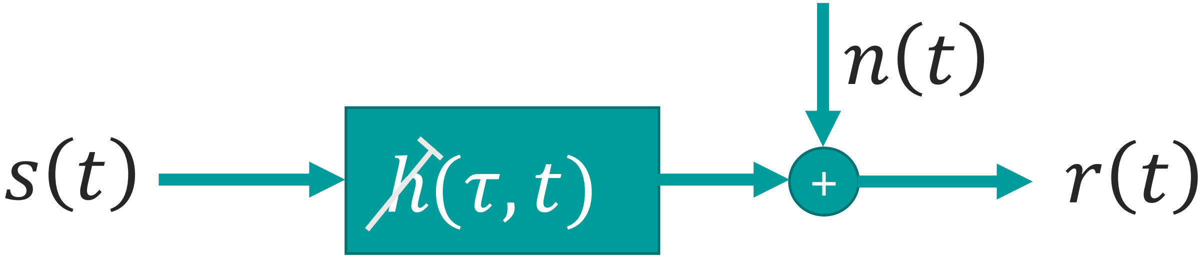
$$s(t) \longrightarrow \boxed{h(\tau, t)} \longrightarrow \overset{n(t)}{\oplus} \longrightarrow r(t)$$

COMMUNICATION PARADIGM CHANGE

Current approach:
Designing $s(t)$ and
processing $r(t)$

$$r(t) = (\cancel{h}(\tau, t) * s(\tau))(t) + n(t)$$

NEXT G proposition:
Designing $s(t)$ and
processing $r(t)$ and
controlling $h(\tau, t)$



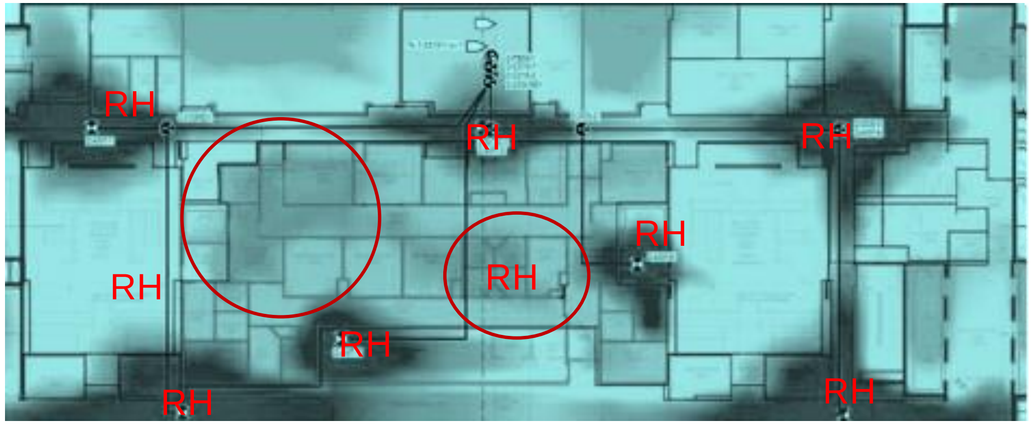
LEARN THE ENVIRONMENT

- Base stations are fixed and can adapt to their scenario
- Base stations can have outages
- UE can act as sensors in static or mobile scenarios
- Communicating parameters learned form other mobile devices used for this area

- Landscape of communication Dependability

COVERAGE MAP

- Radio heads (RH)
  - Dynamic
  - Blocked
  - Fail
  - Jammed
- Dynamic Map
  - Updated in core
  - Provide to device
  - Resource planning
- UE sense
  - Position
  - Signal strength
  - Variability
  - Density
- Predict
  - Dependability
  - Latency
  - Coverage
  - Localization



Dynamic environment

Missing radio head

Measurements in office space Oct. 2022 sub 6GHz SA

On the Performance of an Indoor Open-Source 5G Standalone Deployment, A. Sahbafard, R. Schmidt, F. Kaltenberger, A. Springer, H.-P. Bernhard, WCNC 2023

MULTIPATH SUPPORTS DEPENDABLE COMMUNICATION

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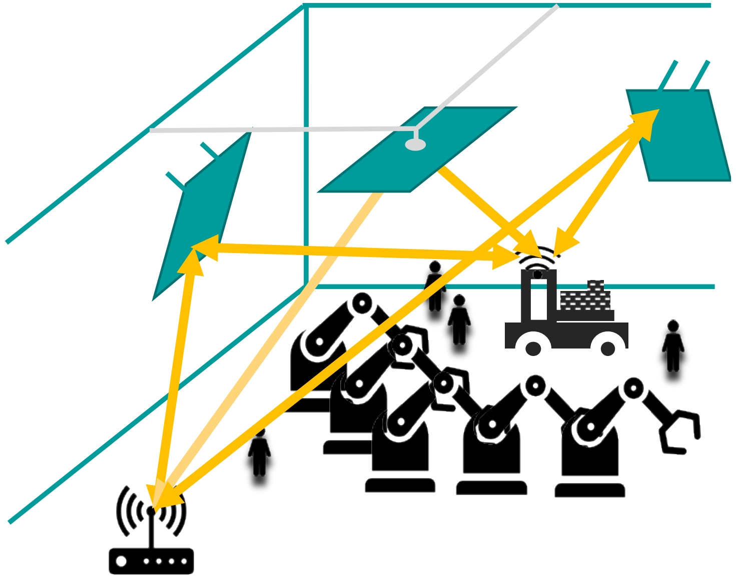
WITH STEERABLE BEAMS & RECONFIGURABLE INTELLIGENT SURFACES

- Single reflection
  - Achieve line of sight condition
  - Alternative path if temporarily unavailable

- Multiple reflections to one node
  - Multiple received packets from different directions
  - Single anchor localization
  - Localization based on TDOA
  - Direction and movement detection



J. Kulmer *et al*., "Using DecaWave UWB transceivers for high-accuracy multipath-assisted indoor positioning," *2017 IEEE International Conference on Communications Workshops*

RELAYING OPTIMAL FOR DEPENDABILITY

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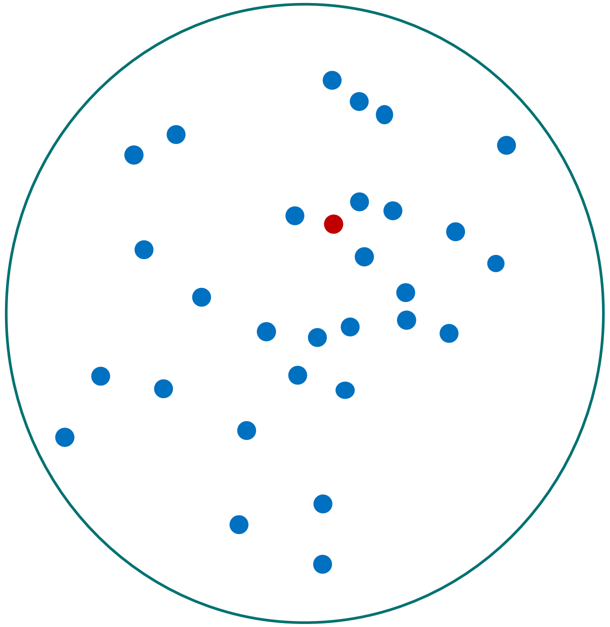
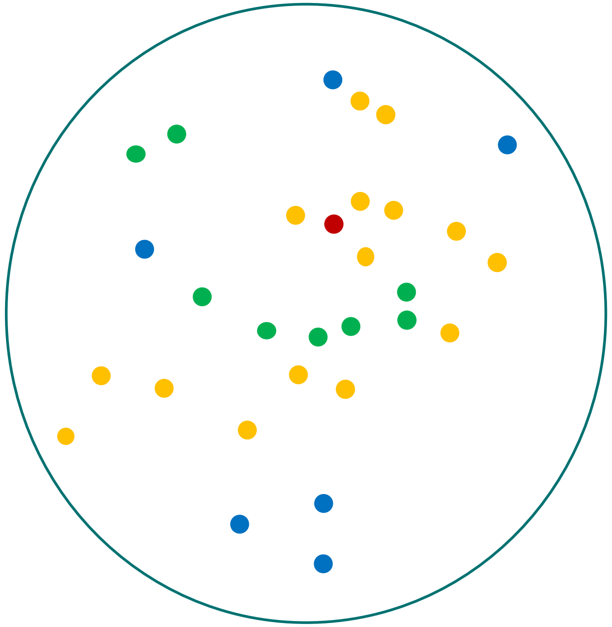
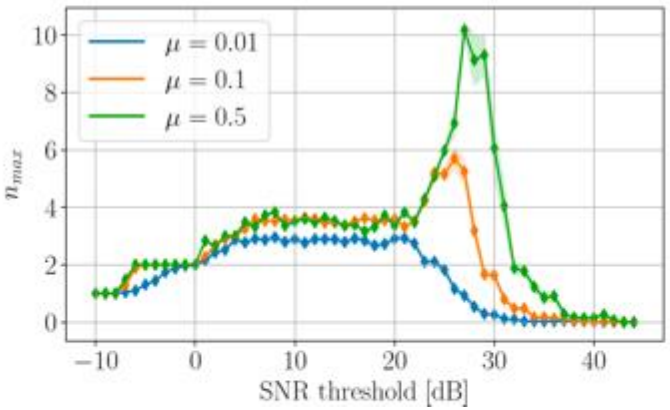
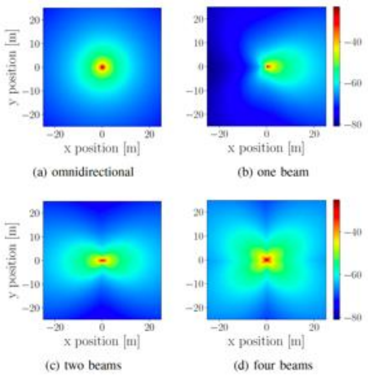








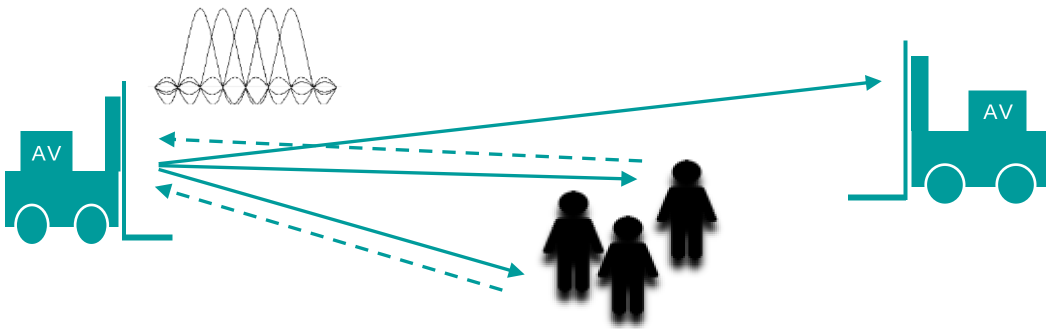
- Dependability Relaying
  - Latency minimizing
  - Energy minimizing
  - With a defined SNR
- Industrial environment
  - 2 section pathloss model
- Layered Structure
- Agorithm
  - Centralized
  - Directional antennas
  - Static environment

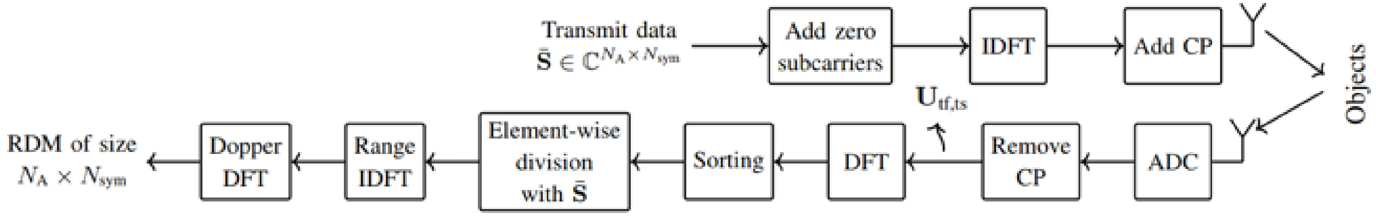
LEARN THE TIMING

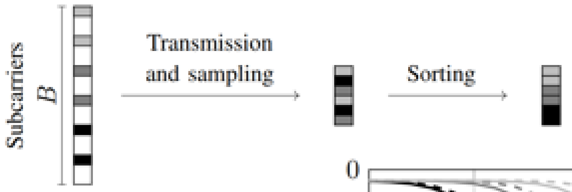
- Moving obstacles can be considered
- Dynamic parameters can be learned
- Blocking scenarios become deterministic
- Time and position variant prediction of the communication landscape
- Embedded intelligence to reduce prediction latency

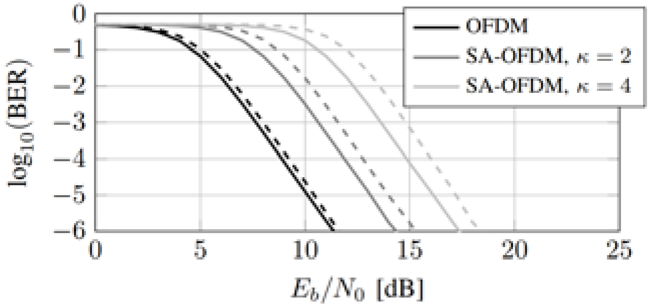
JOINT COMMUNICATION & SENSING

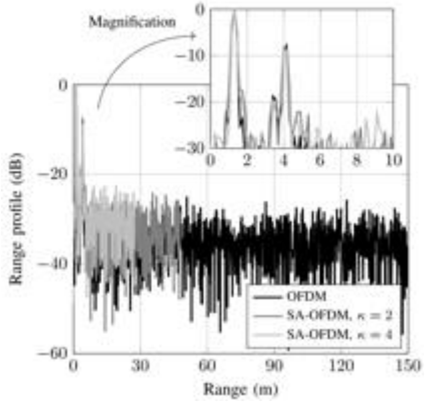
- OFDM joint communication and radar
  - Waveform design and receiver concepts
  - Analytical investigations, simulations, and measurements









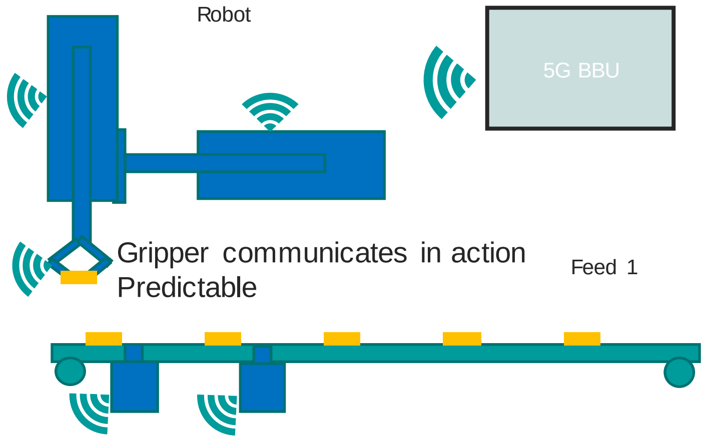


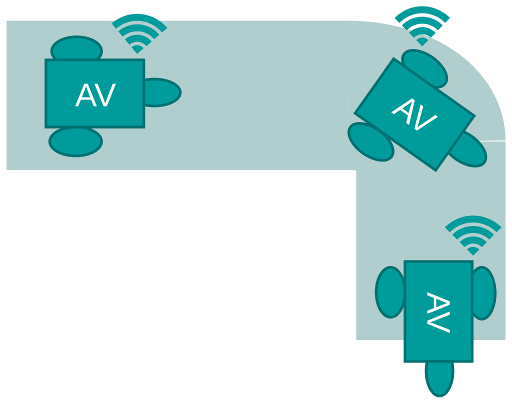
Lang, O., et al. OFDM Radar With Subcarrier Aliasing
IEEE Transactions on Vehicular Technology 2022.

DEPENDABILITY PREDICTION

SAL SILICON AUSTRIA LABS

- Dependability is needed
  - Trigger by messages
  - Trigger by position of devices
  - Trigger by communicated values
- Switching to short latency / high redundancy if needed
  - Planning ahead
  - Analyzing on-line
- Demand can be learned from message analyzing
  - Supported by unsupervised learning
  - Supported by labeled learning





APPLY THE SECURITY

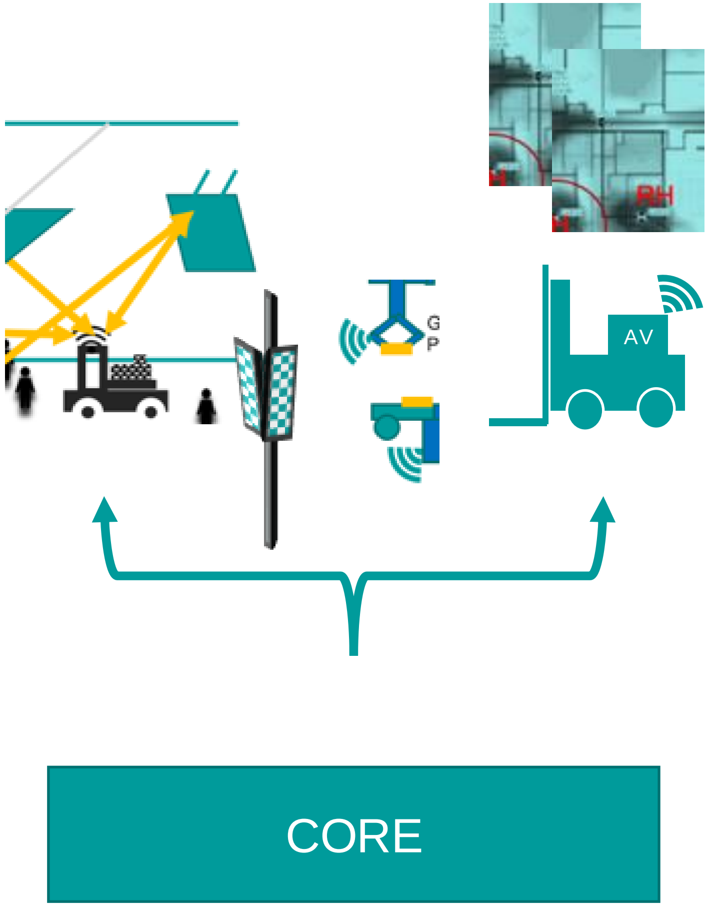
- PHY layer security
- Point to point privacy
- Point to many privacy
- Location based security
- Jamming detection
- Jamming mitigation
- Integrating network information

COMBINE FOR DEPENDABILITY

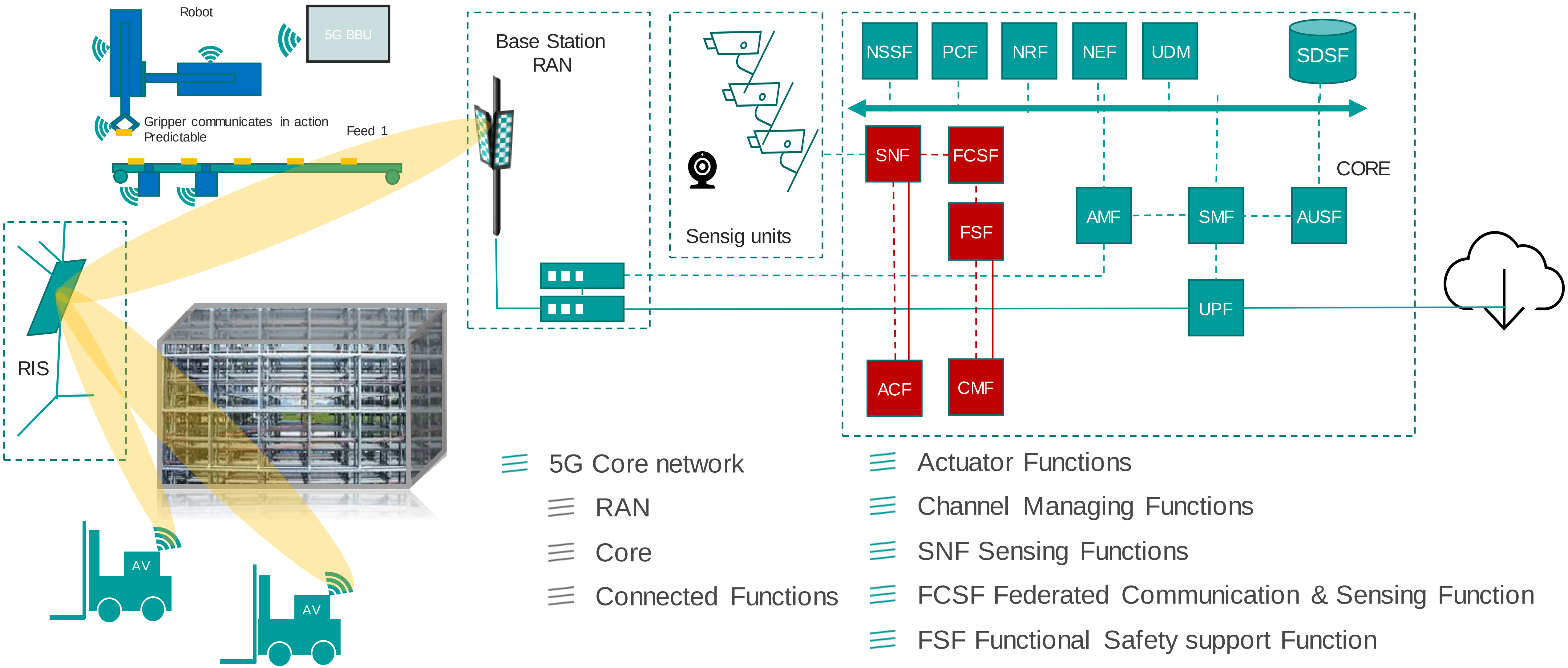
- Learning
  - Environment
  - Time behavior
  - Security
- Combine it to safety functions
- Provide in the 5G/6G core

FEDERATED COMMUNICATION & SENSING (FC&S)

- Federation
  - More than Joint Communication & Sensing JC&S
  - Includes JC&S
  - Pull all collected data together
  - Combine and interpret
  - Store and manage
  - Learn
  - Distribute



NETWORK STANDARD PERSPECTIVE



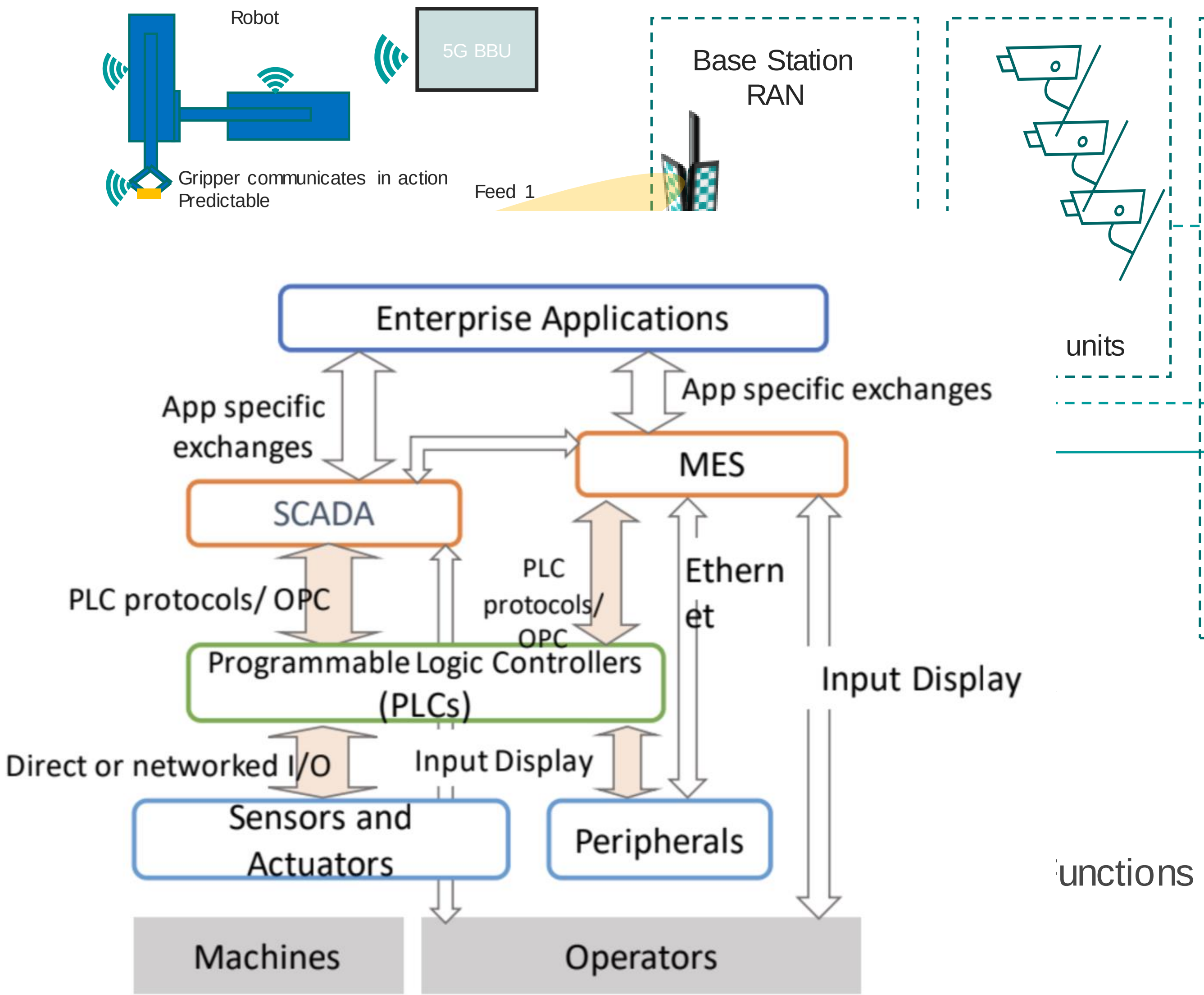
- 5G Core network
  - RAN
  - Core
  - Connected Functions

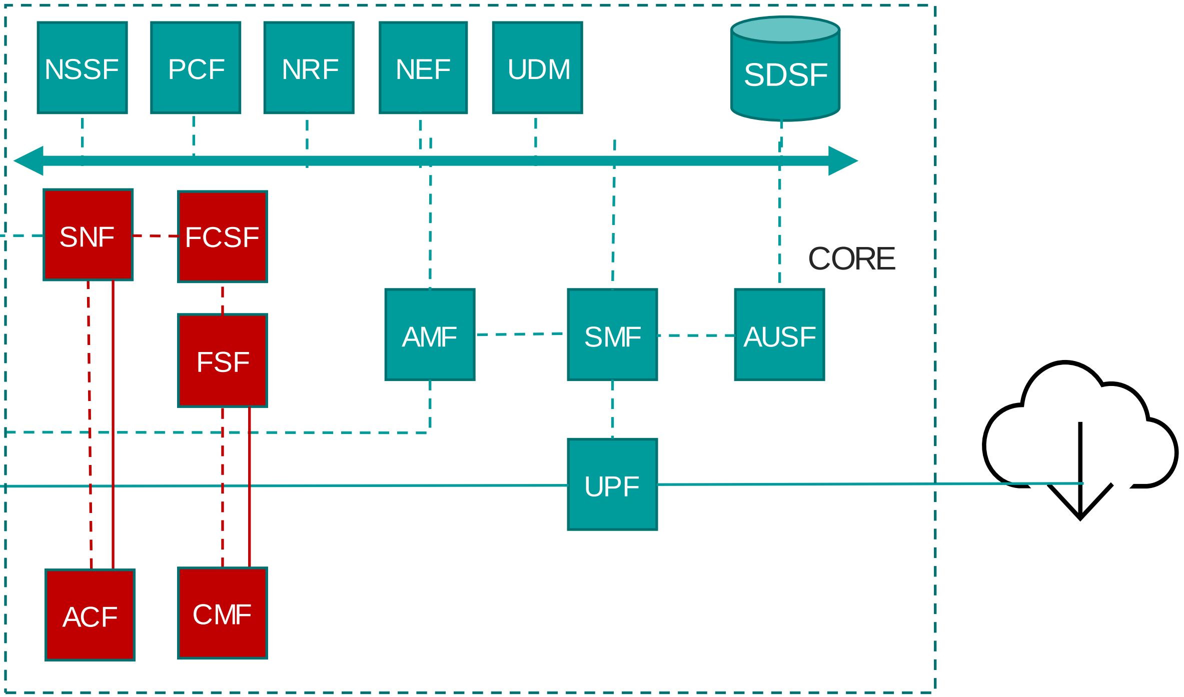
- Actuator Functions
- Channel Managing Functions
- SNF Sensing Functions
- FCSF Federated Communication & Sensing Function
- FSF Functional Safety support Function

NETWORK STANDARD PERSPECTIVE

JOHANNES KEPLER UNIVERSITY LINZ

SAL SILICON AUSTRIA LABS





- Actuator Functions
- Channel Managing Functions
- SNF Sensing Functions
- FCSF Federated Communication & Sensing Function
- FSF Functional Safety support Function

IIOT & CPS AS BUILDING BLOCK FOR DEPENDABILITY

- Stable standard and protected band
- Dependability relies on CPS to
  - Learn the environment
  - Learn the timing
  - Apply security