GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Wolfgang Kellerer
School of Computation, Information and Technology, TUM

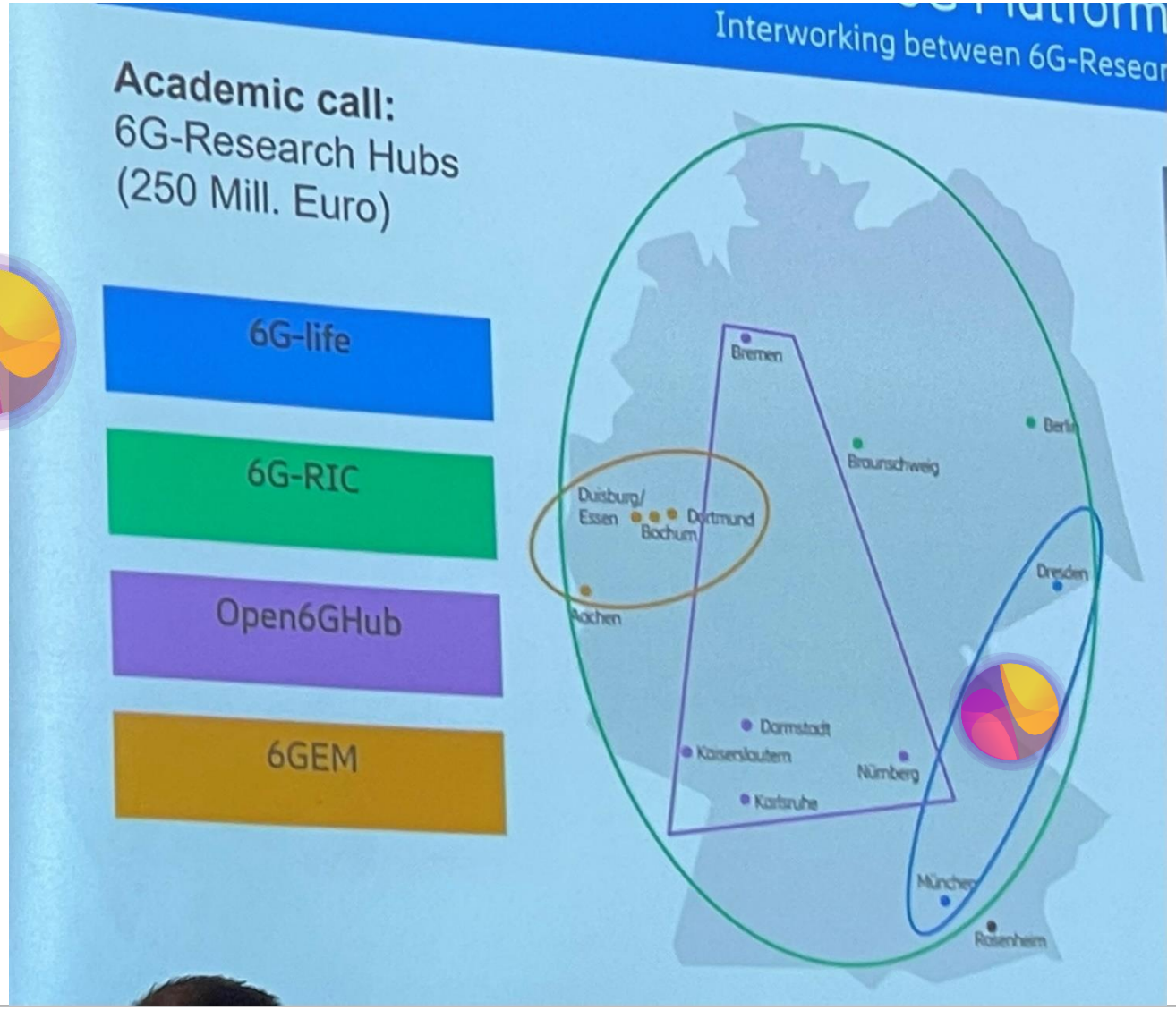
6G-life: Cutting-edge research for 6G communication networks with a focus on human-machine collaboration

ITG/GI NetSys 2023 - Zukunft der Netze (ZdN)

07.09.2023

Potsdam, HPI, Germany

4 BMBF Research Hubs

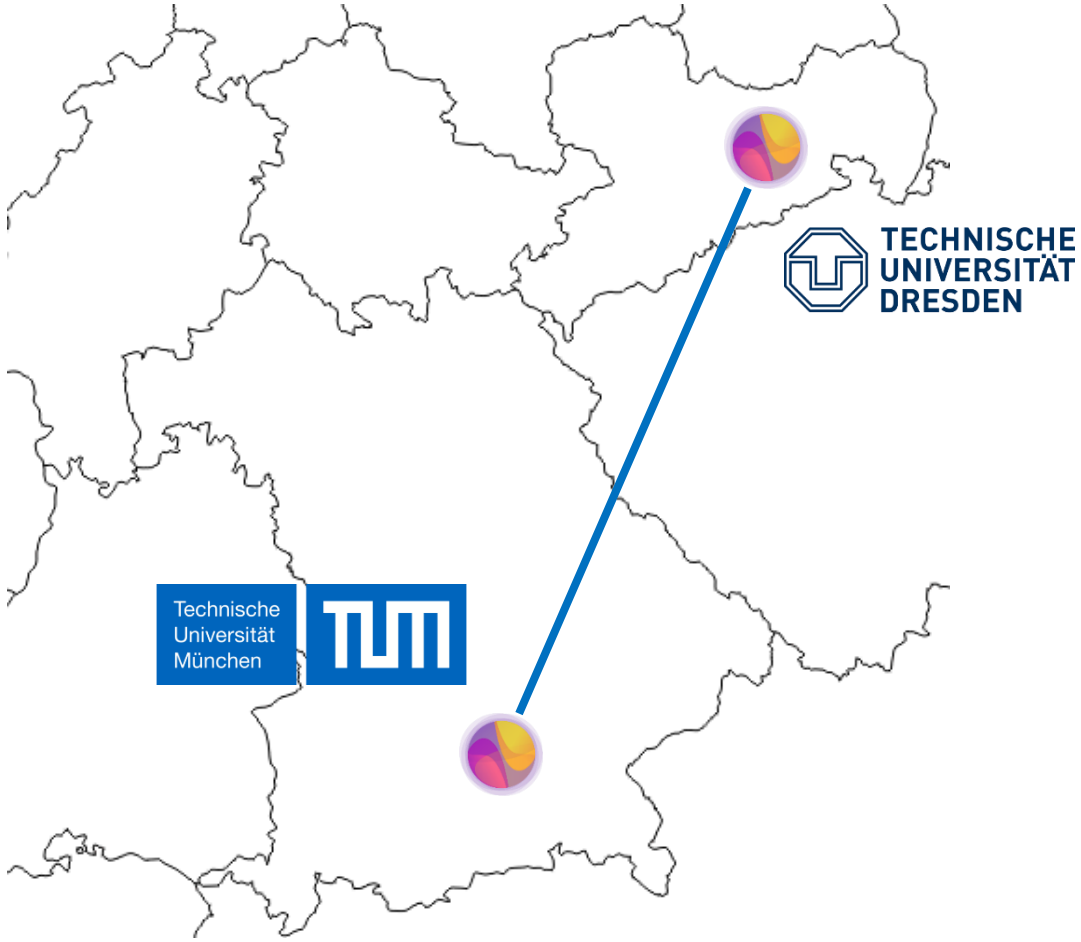


BMBF 6G Research Hub 6G-life

- Started August 15, 2021
- 70 Million € for 4 years
- 58 Principal Investigators + 156 researchers

- 6G: focus is on humans and their communication and interaction with machines and the virtual world → holistic research on innovative concepts for scalable communication, novel methods, flexible software concepts and adaptive hardware
- Four key performance indicators: Latency, Resilience, Security and Sustainability

- Digital Sovereignty and Digital Transfer
- 10 Million € for Start-ups



6G-life team

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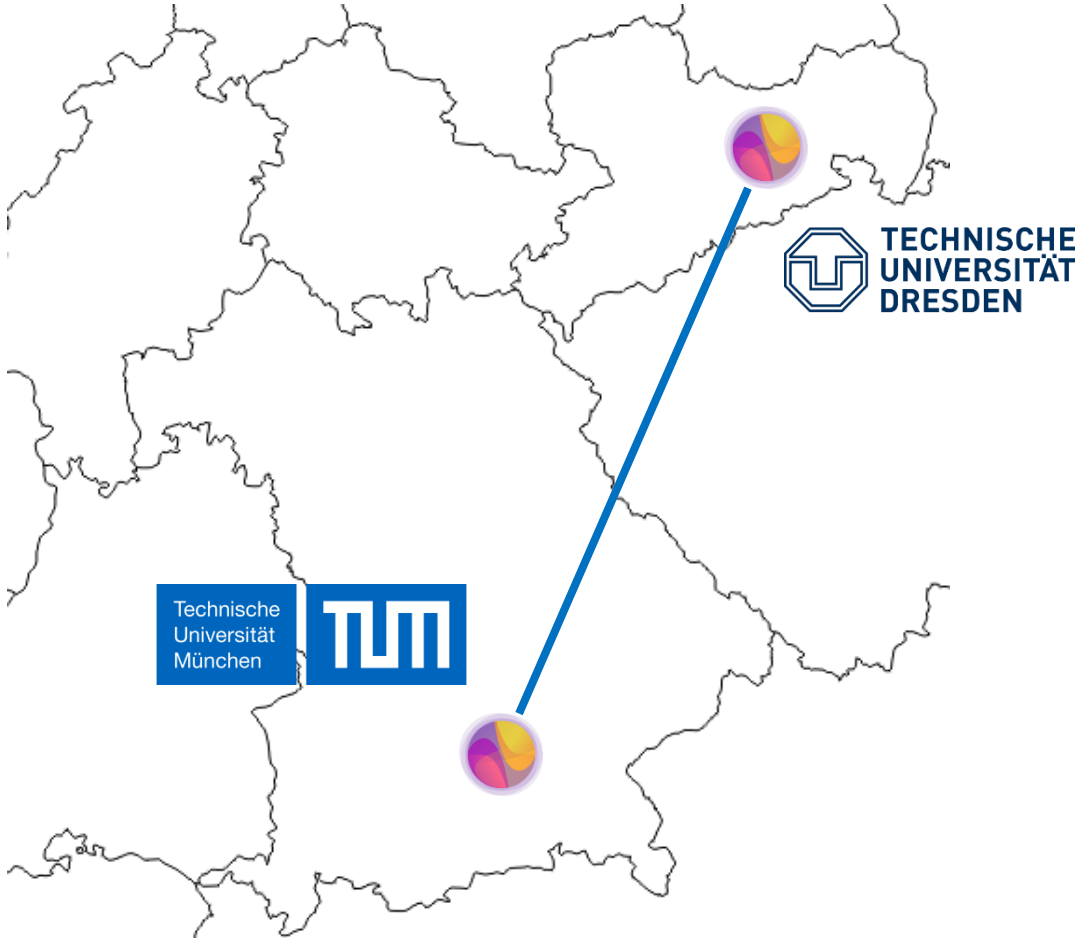


Startups - currently 20+ interactions

Sensors

blies tech

Haptic labs.io

PowerON Smart Elastic

HMI

Enari.

Mimetik

veiio

Robotics

HYDRABYTE

Olive Robotics

SMARTBIX

wandelbots

Communication

aeroLiFi

CADAMI

CAMPUS GENIUS

5 EINHALB

MESHMERIZE YOU MOVE. WE CONNECT.

QcomBIT

Cloud Computing

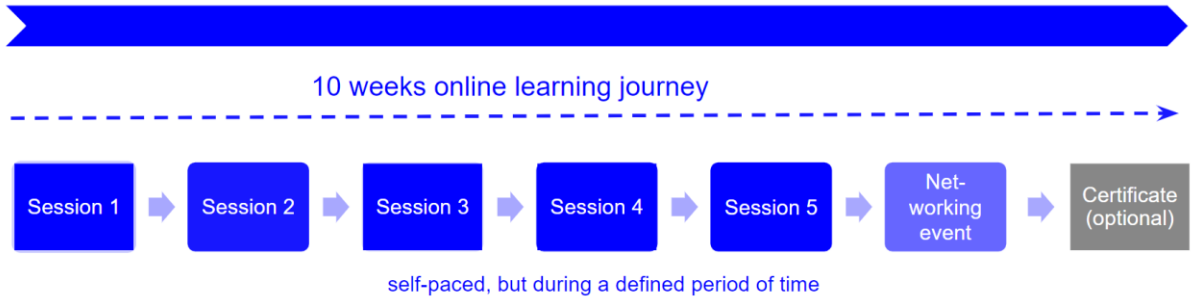
SpiNNcloud

bitteiler

Entrepreneurial Education and Startup Support

TUM with CDTM and TUM Venture Labs

- Trend Seminar
  „**The Future of Communication Technologies**“
  in Feb-April 2023
- Course
  „**Business Modeling & Prototyping**“ –
  Master students work on ideas of doctoral students/postdocs
- MOOC **Entrepreneurship in the era of 6G**
  open to all 6G-life researchers

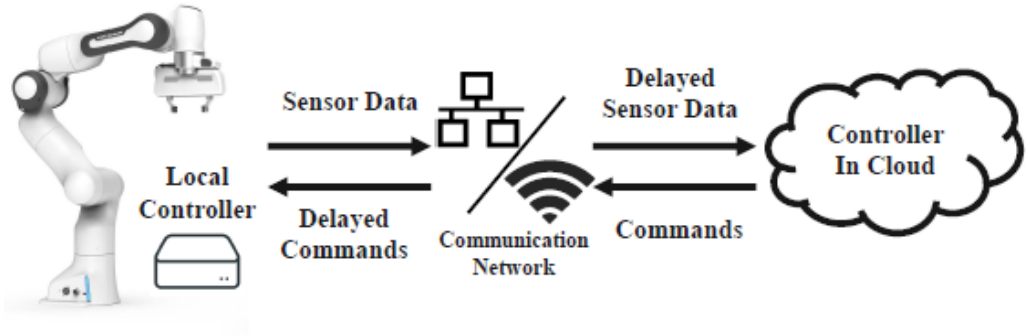


6G-life StartUp Contact Point

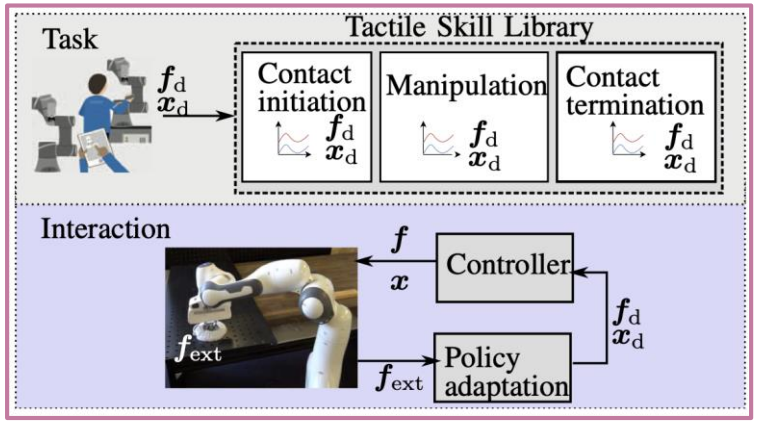
BMBF 6G Research Hub 6G-life

Image sources: TUM MRI, TUM LTI, TUM, TUD, 5G Campus, CeTI

6G-life use case examples: Industry

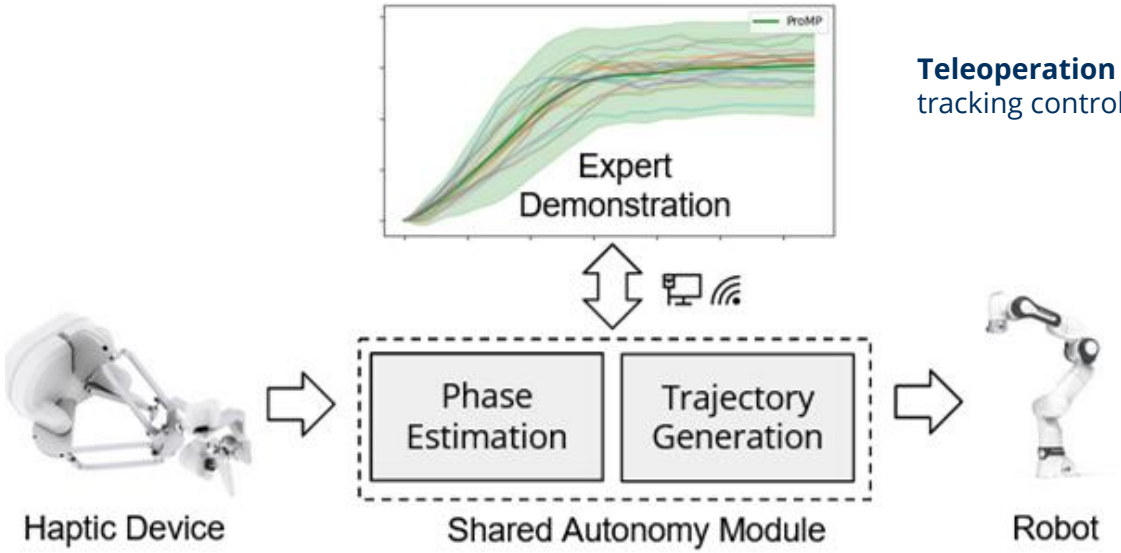


Framework of relocating the robot controller in the cloud



Passivity-Based Skill Motion Learning for robotic (dis)assembly

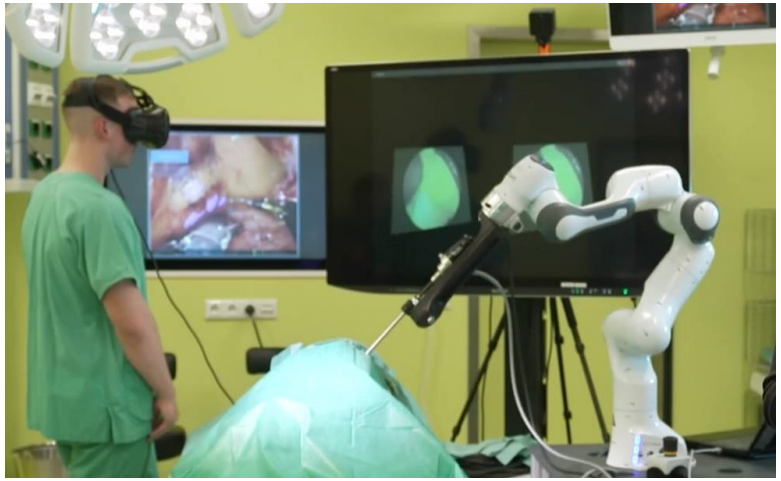
Teleoperation cell: GUI + moveme tracking controller /haptic controlle



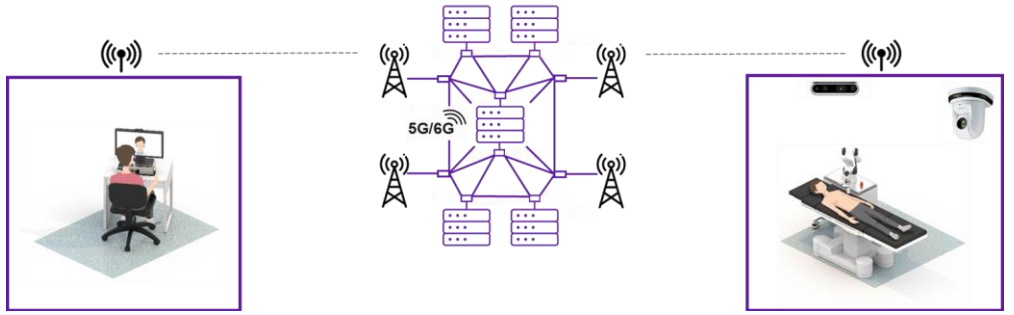
Shared autonomy in teleoperation

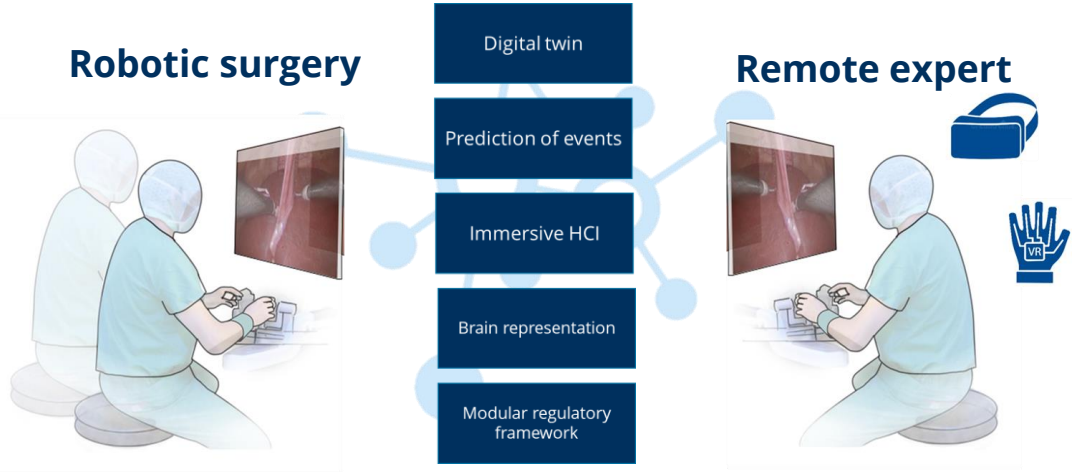
6G-life use case example: Healthcare

Testbed remote-surgery

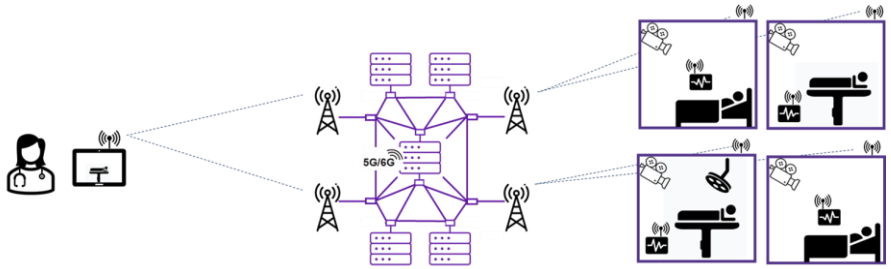


Testbed semiautonomous telerobotic examination suite





Testbed context-sensitive patient monitoring



BMBF 6G Research Hub 6G-life

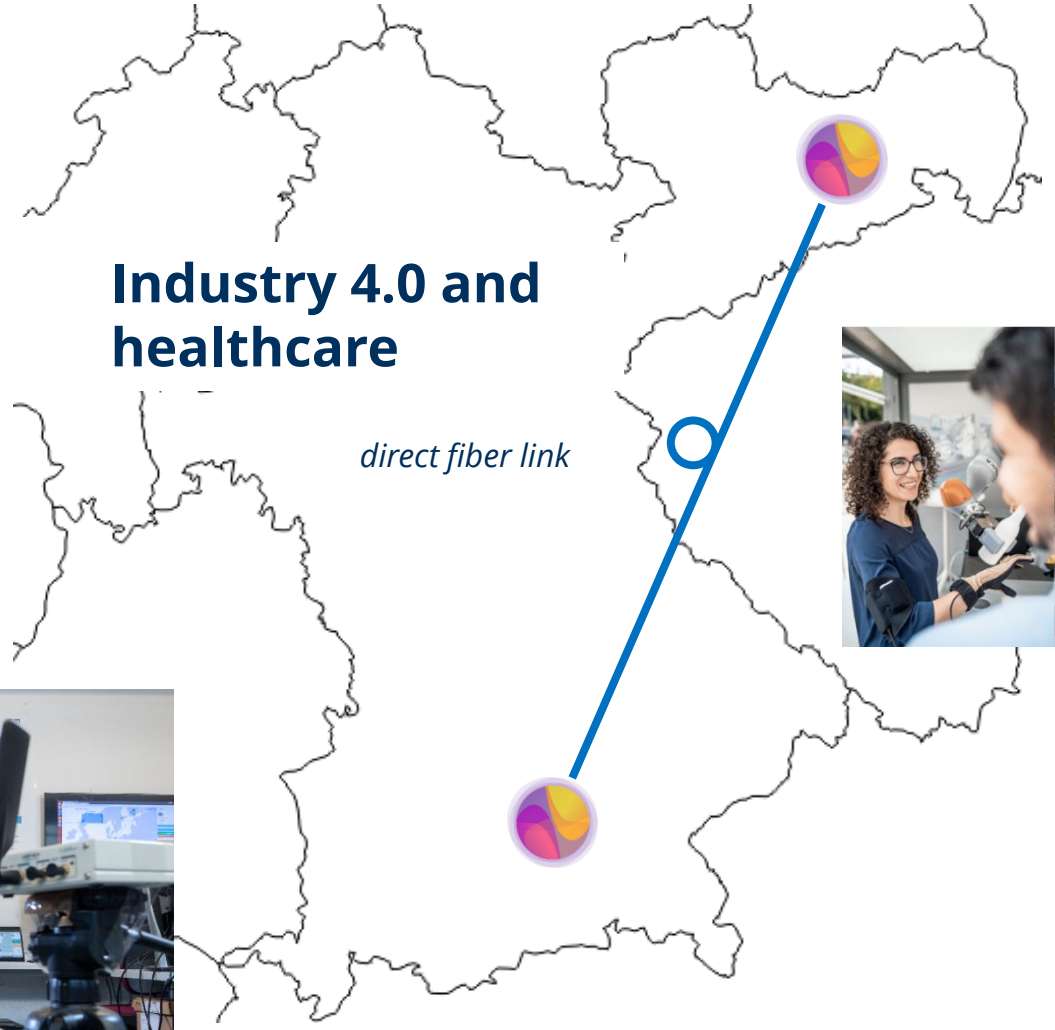
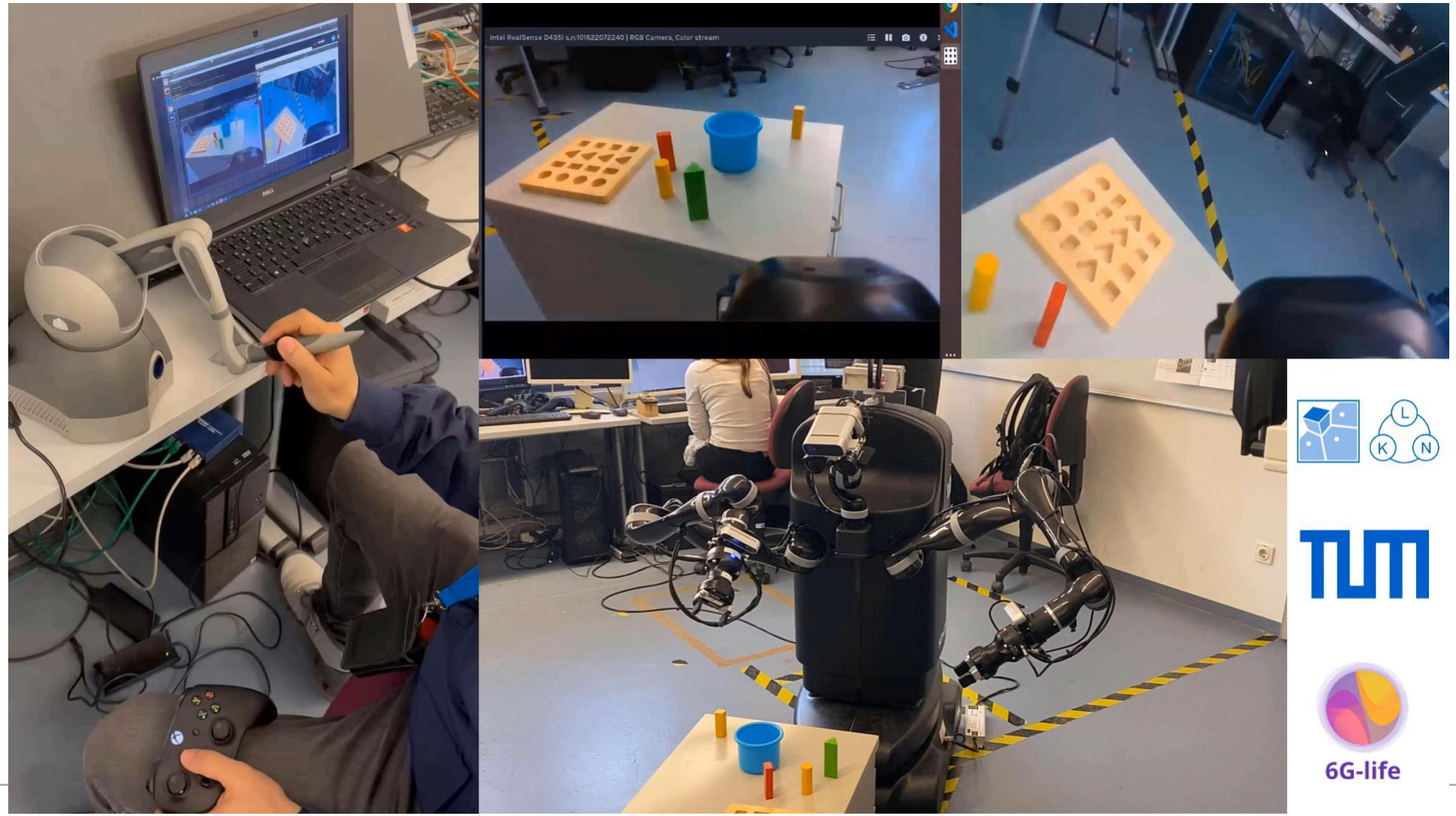


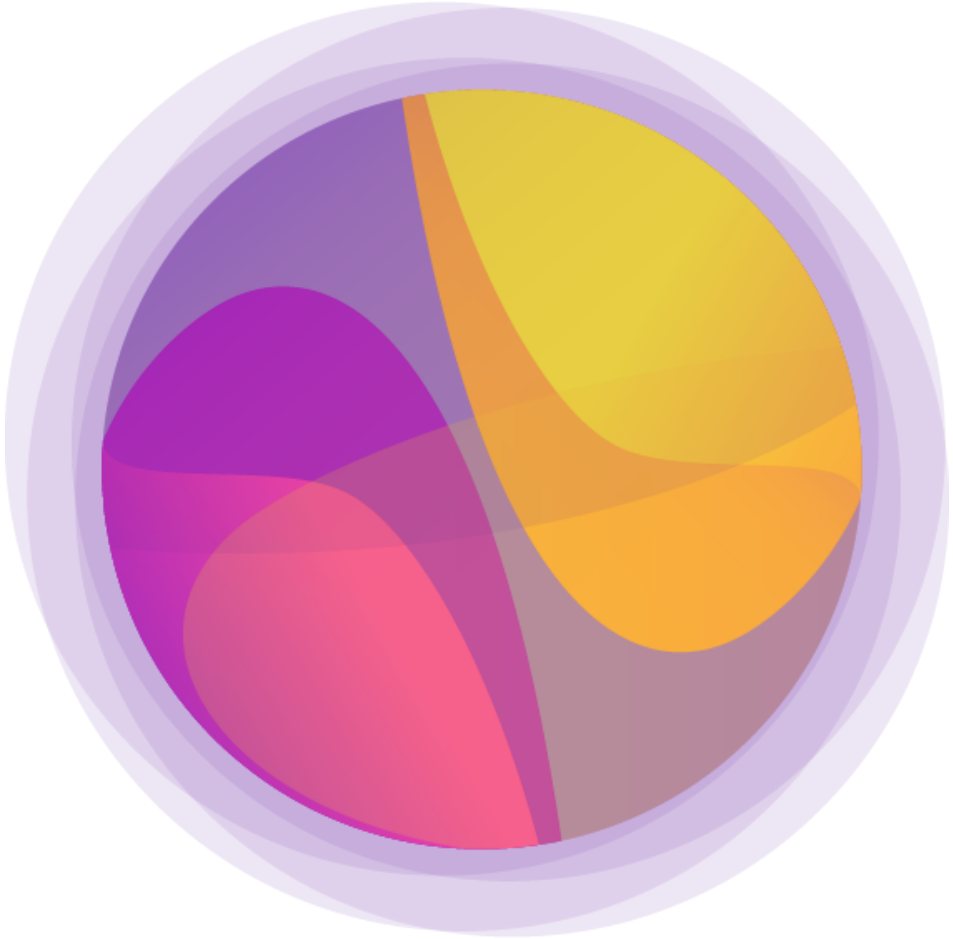
Image sources: TUM MRI, TUM LTI, TUM, TUD, 5G Campus, CeTI

Demonstration of haptic-based teleoperation between Dresden and Munich



Overview

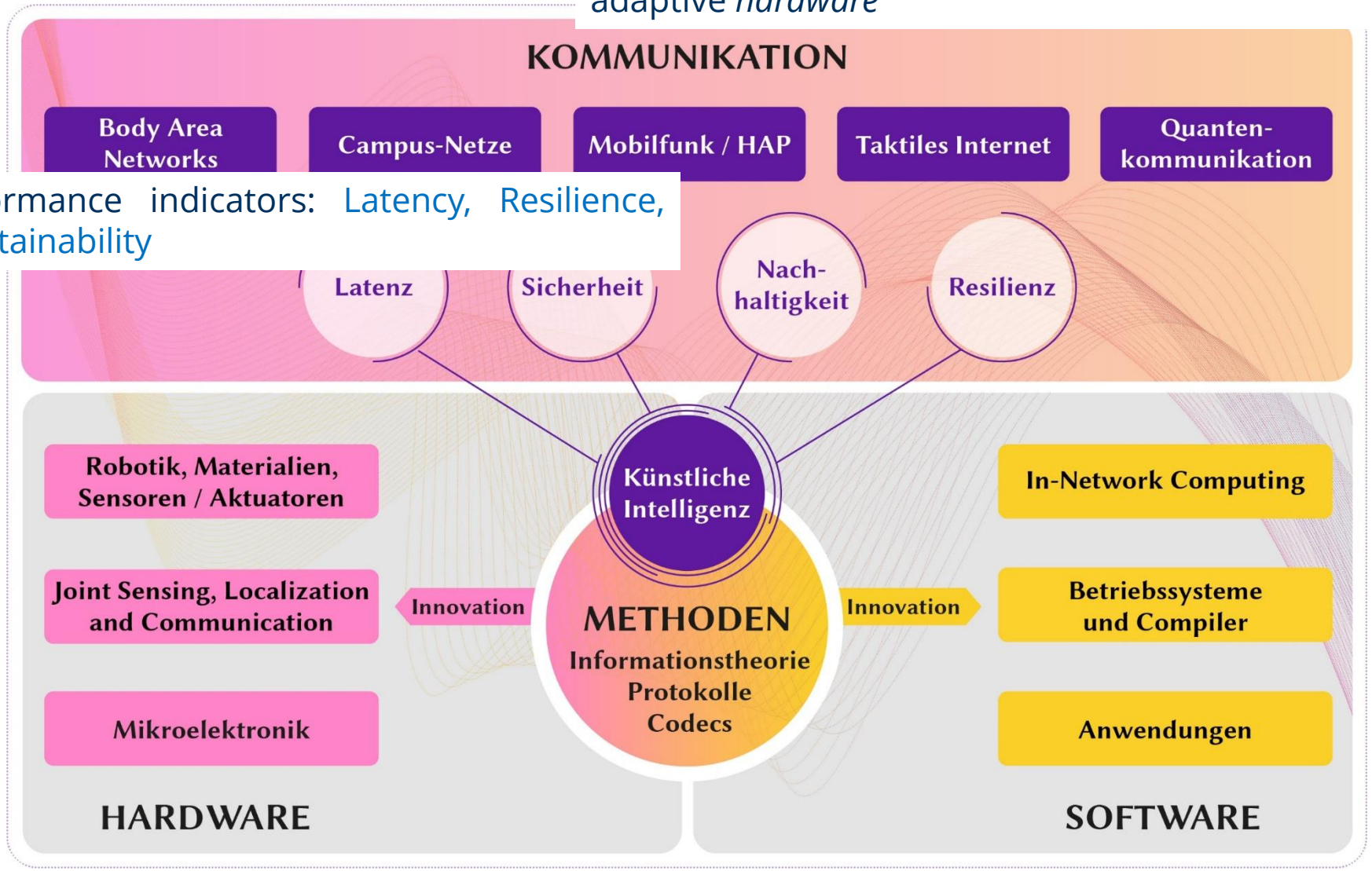
- 6G-life overview
- Use cases
- Research results (*some examples – not complete at all*)
  - Post Shannon
  - In-network computing
  - Digital Twin
  - Joint Communication & Sensing
  - Molecular communication



6G-life Overview

holistic research on innovative concepts for scalable *communication*, *novel methods*, flexible *software* concepts and adaptive *hardware*

- Four key performance indicators: Latency, Resilience, Security and Sustainability



6G-life Innovation Areas

Scalable Communication

communication network architectures including

- Cellular networks with Campus and HAP extensions
- Tactile Internet
- ***Quantum Communication***
- Body Area Networks
- **Molecular Communication**

Innovative Methods

novel methods for communication networks based on

- **Post Shannon Communication**
- AI for network control and new services
- **AI & Digital Twins**
- Protocol and codec design for Human-Machine Collaboration

Flexible Software

networks are dominated by SW

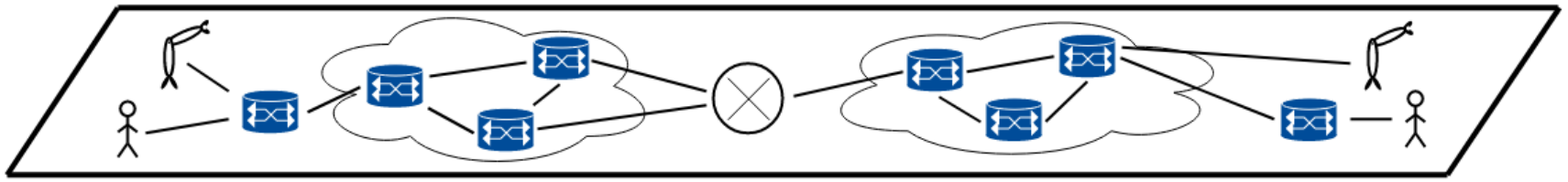
- **In-network computing and ORAN**
- 6G application in virtual worlds (digital twins and holograms)
- Low latency and energy efficient compiler/OS design

Adaptive Hardware

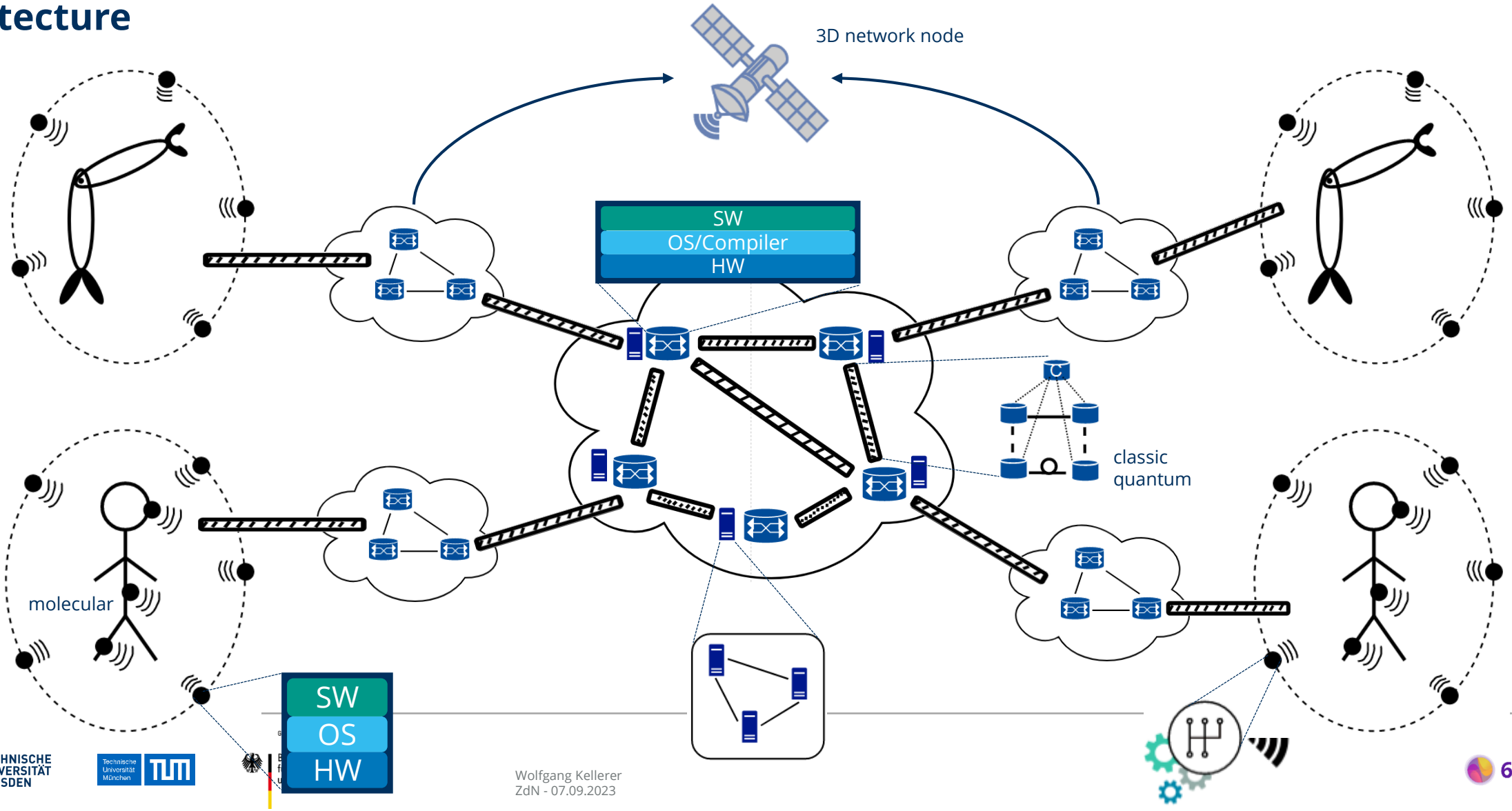
Novel hardware concepts for future needs and applications

- New materials for robotics and humans in virtual worlds
- **Joint sensing and communication**
- Flexible energy saving

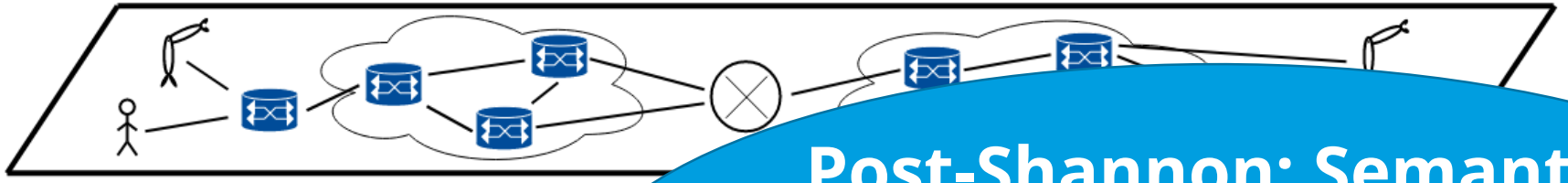
6G-life high-level system architecture



virtual network
„a 6G slice“

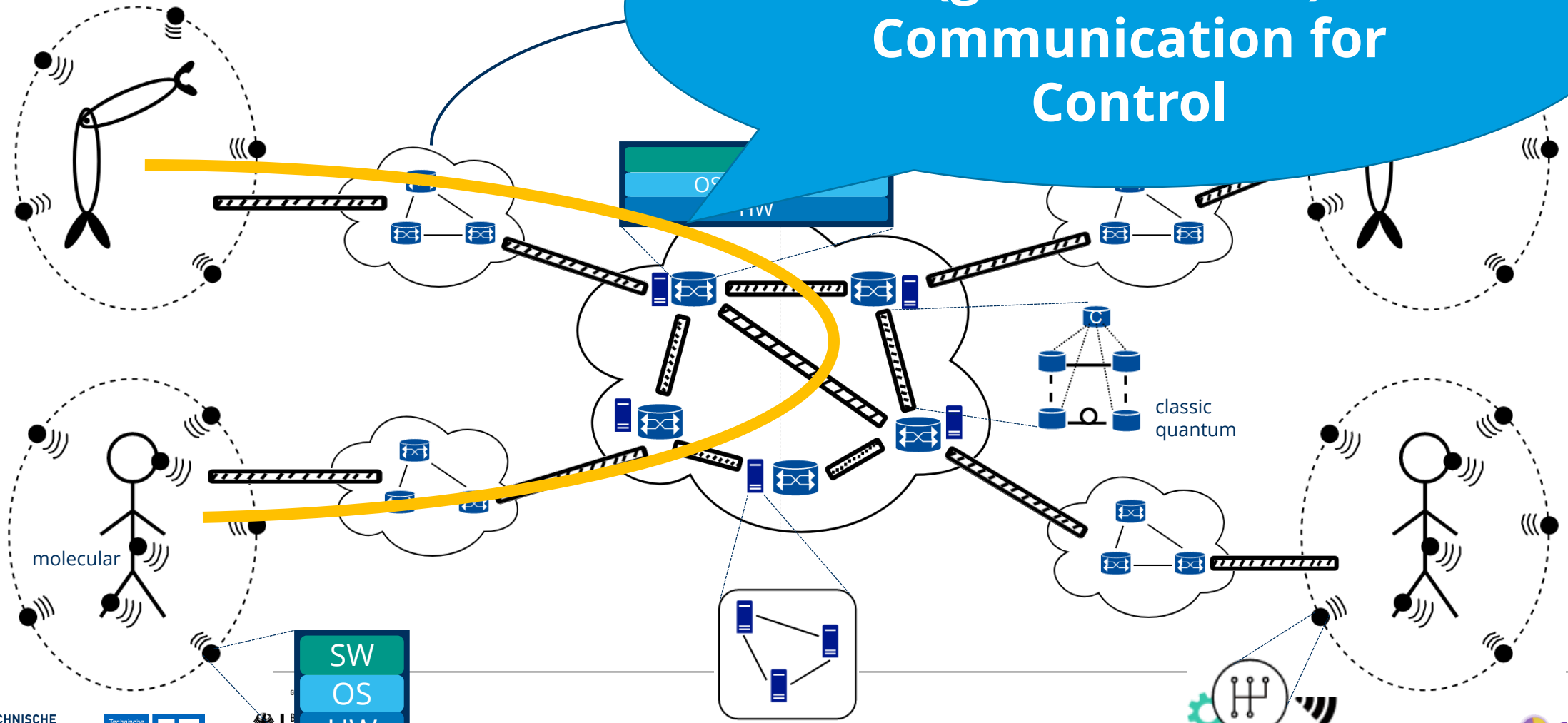


6G-life high-level system architecture

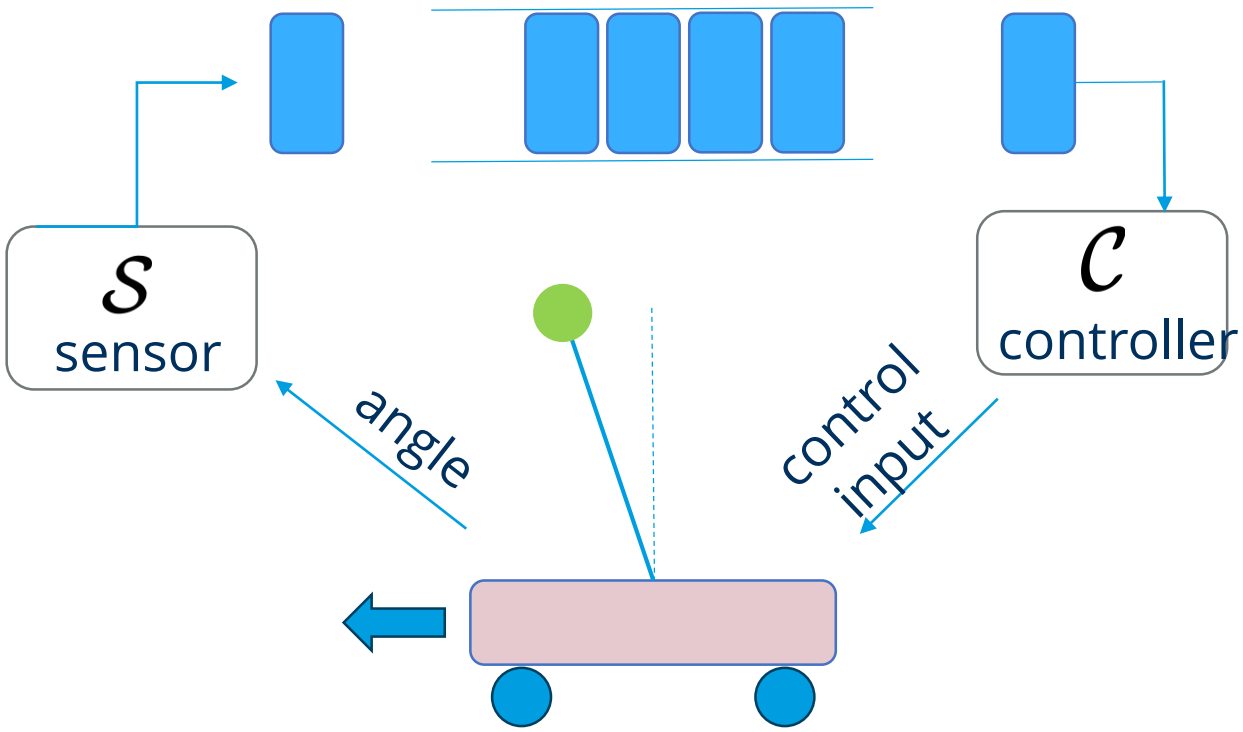


virtual network
6G slice“

Post-Shannon: Semantic (goal-oriented) Communication for Control



Goal-Orientation in Networking: Control Application



- Conventional transport layer (TL)– occupy bandwidth
- Network actually delivers a *transport service*
- Application performance can deteriorate due to inefficient network

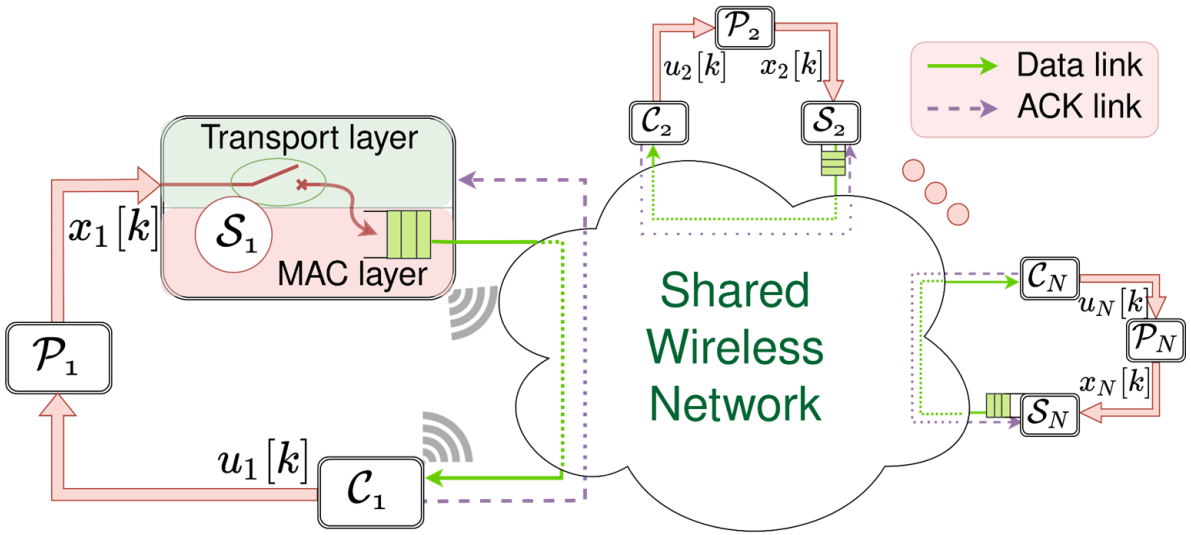
Semantic (goal-oriented) communications:
- design of network algorithms w.r.t. application goals
- effects of real network on the application performance

Design control- and congestion-aware transport layer scheme

Goal-Oriented Transport Layer for Control

$$x_{k+1} = Ax_k + Bu_k + w_k$$

$$u_k = -L\hat{x}_k$$

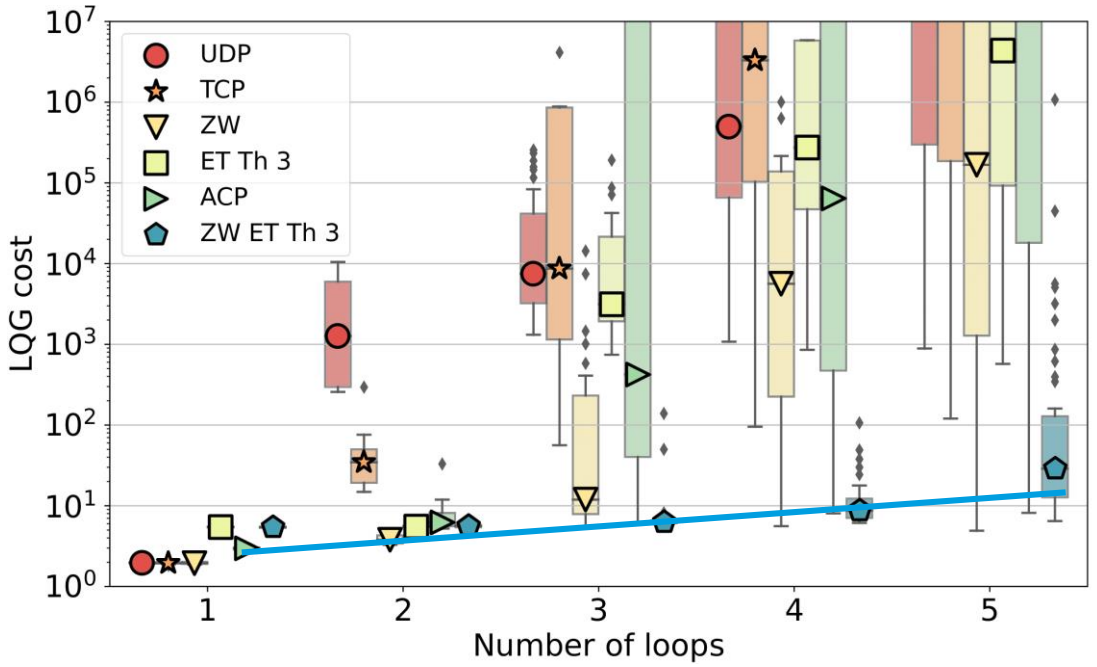


- Controller **estimates** plant state based on available delayed observations, applied control inputs minimize control cost
- **Control- and congestion-aware** transport layer (TL) at the sensor side admits/discards each sampled status update

Shape input traffic to the network to prioritize most relevant updates and minimize the adverse effects of the network congestion on application performance

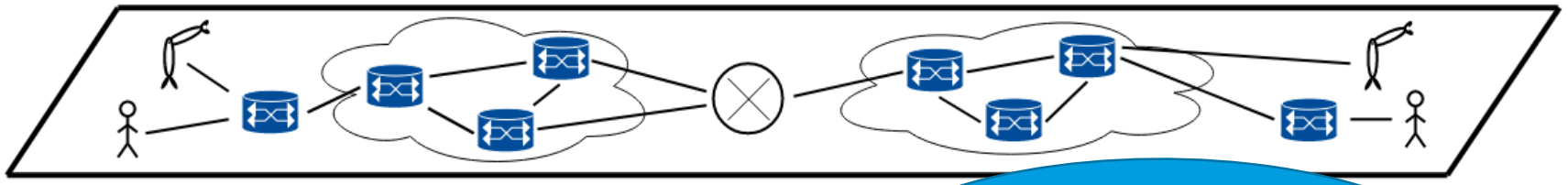
Goal-Oriented Transport Layer for Control: Experimental Study

- Extensive **experimental study** with industrial IoT Zolertia ReMotes (802.15.4 for MAC and PHY)
- **Zero-wait** policy combined with basic **event-triggering** outperforms conventional TL schemes
- Use **ACKs** to augment controller estimation and improve relevance assessment

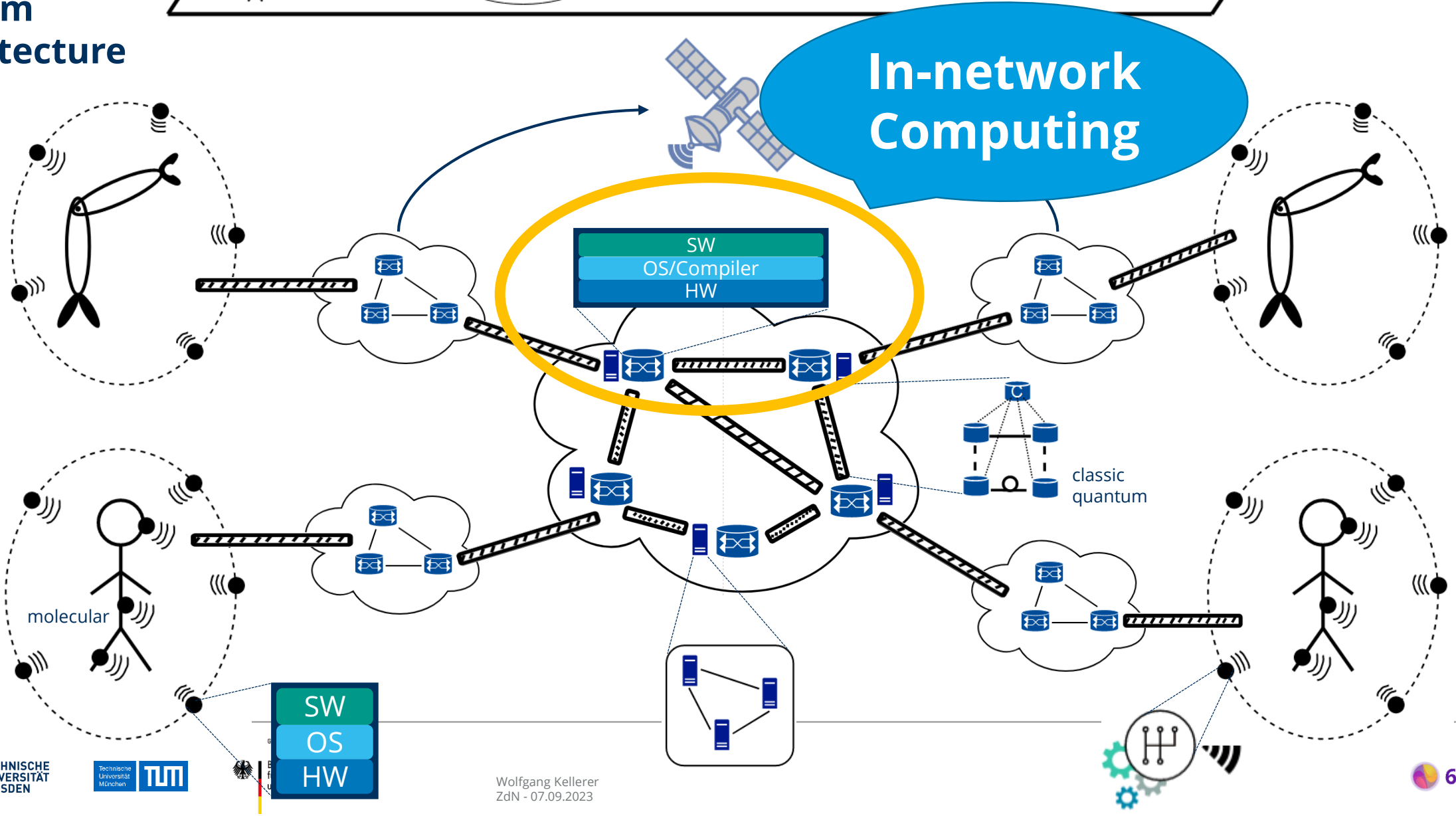


[SECON 2023 full paper and demo]

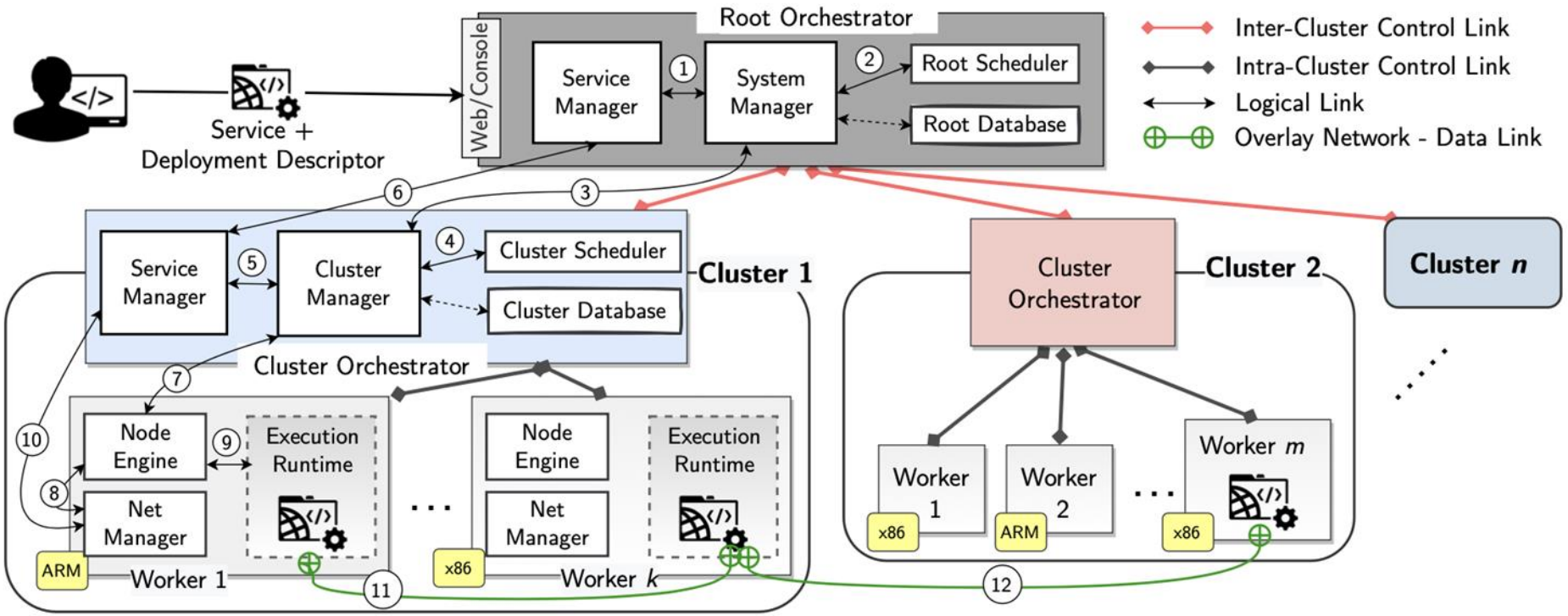
6G-life high-level system architecture



virtual network
„a 6G slice“

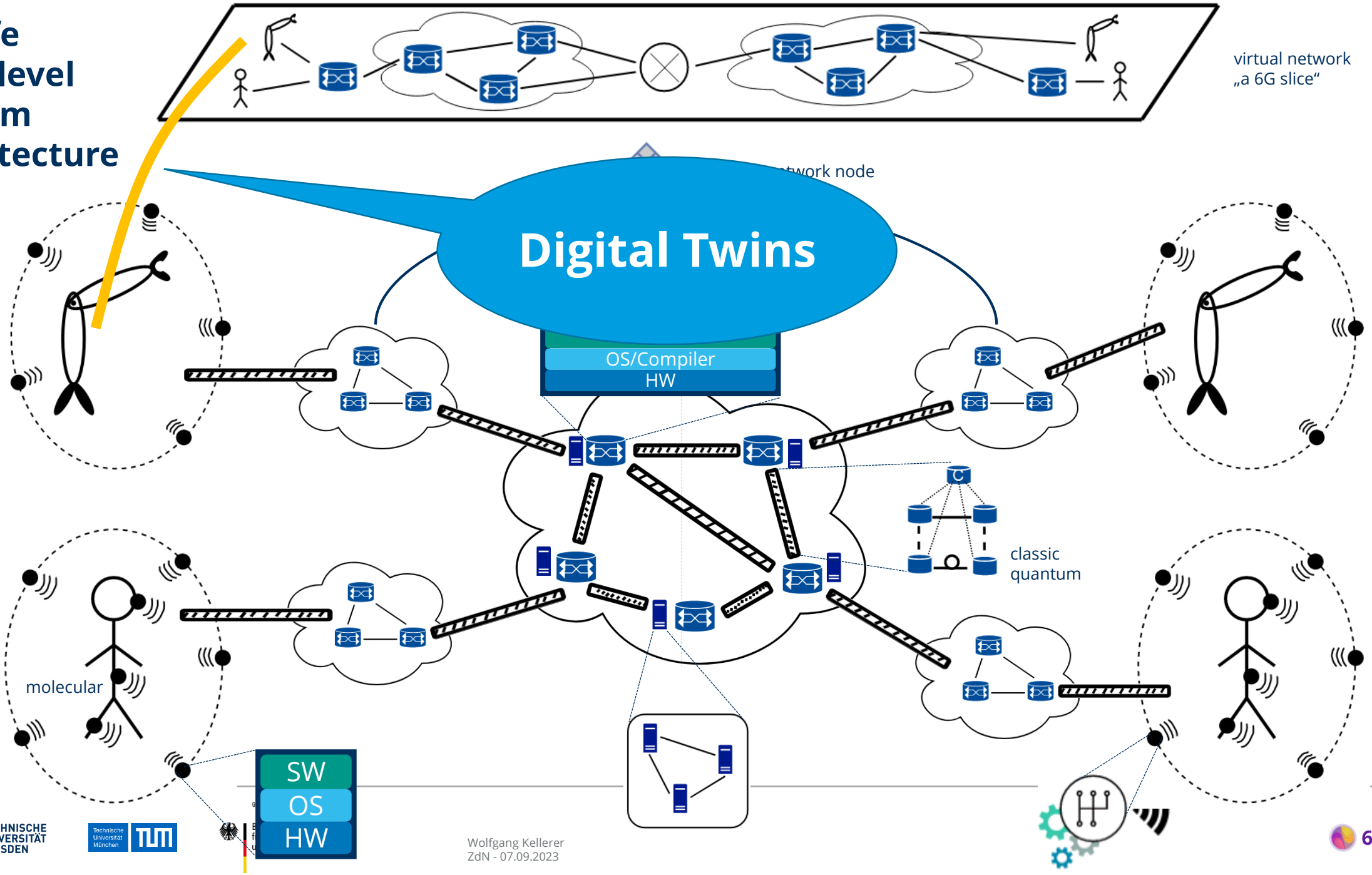


In-Network Computing example: Oakestra



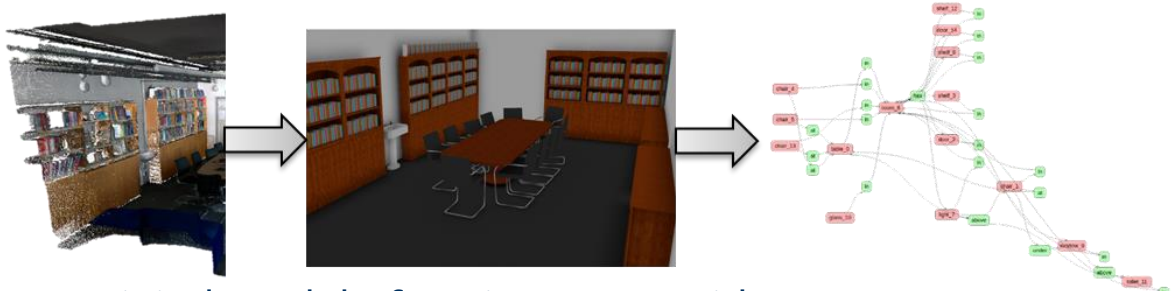
Oakestra provides (open-source) lightweight orchestration of containers/unikernel virtualization services in multi-tenant edge infrastructures
[USENIX ATC 2023]

6G-life high-level system architecture

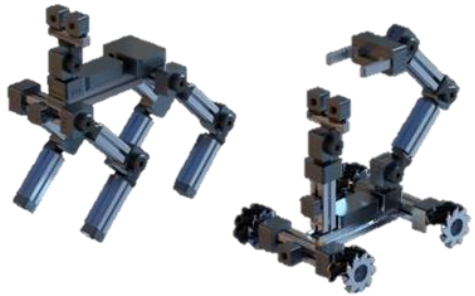


AI and Digital Twins

3D-Scanning



Digital Model of Environment with Structure Extraction and Dynamic Updates



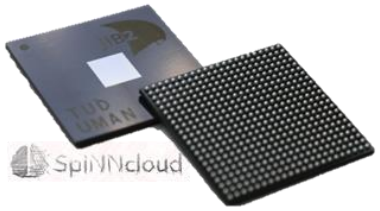
Petri nets and motion grammars for robotic frameworks

Foundations & ML Approaches
representation learning for scenes, motion spaces, humans
prior-based tracking and prediction
speech recognition, reservoir computing
feature and structure extraction, CAD retrieval

Capturing of Body, Hand and Tongue Motion, Speech with age variability

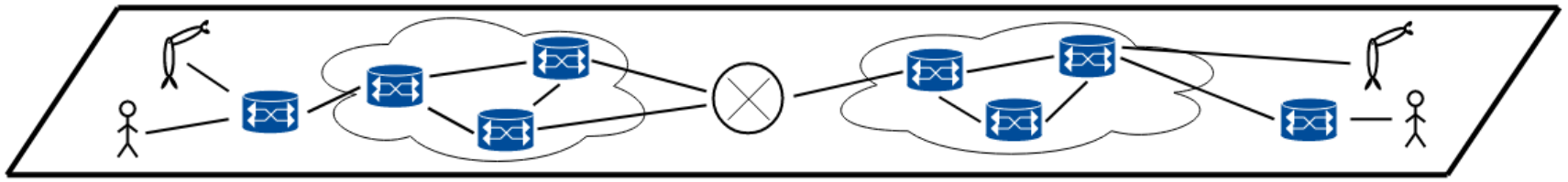
Avatars and Parametric Models for Digital Twins of Humans with Cloths and real-time tracking

frameworks for immersive AR/VR environments



exploit dedicated hardware

6G-life high-level system architecture



virtual network
„a 6G slice“

3D network node

Sensors and Actuators

Joint Communication and Sensing

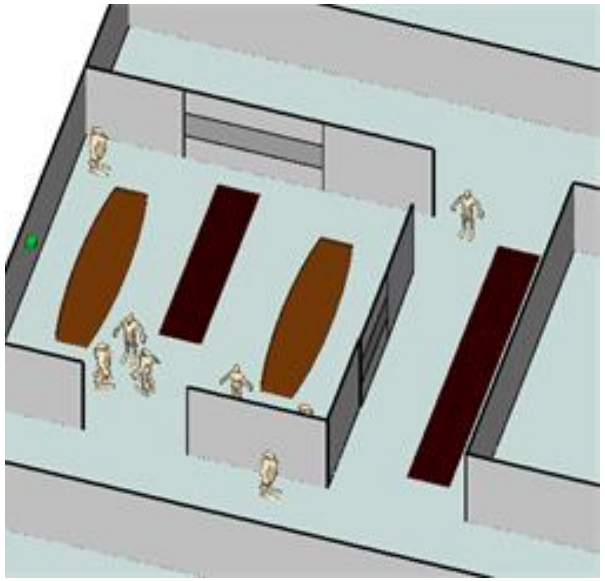
SW
OS/Compil

classic
quantum

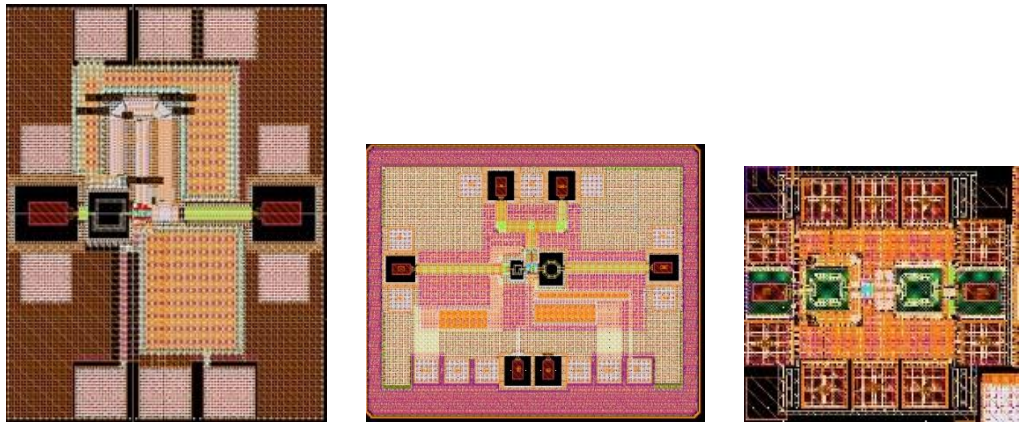
molecular

SW
OS
HW

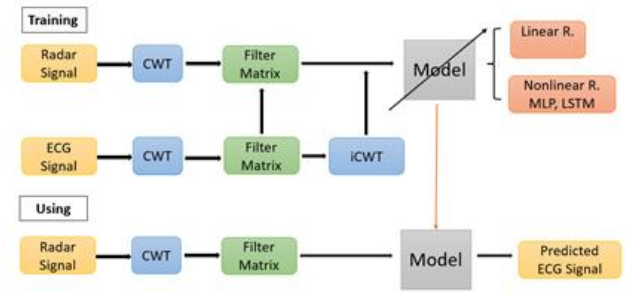
Joint Communications and Sensing



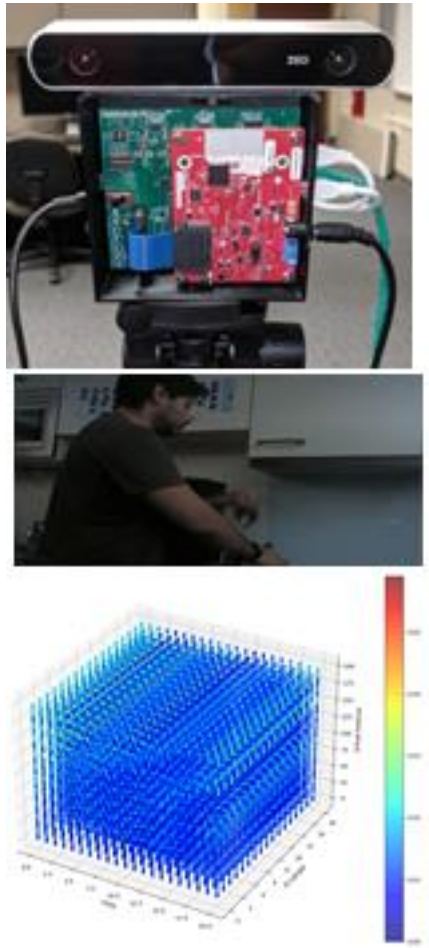
JCAS python library: simple and scalable interface for simulation of complex RF channels



JCAS hardware: 75% blocks taped-out



Positioning and health monitoring using mm-wave radar

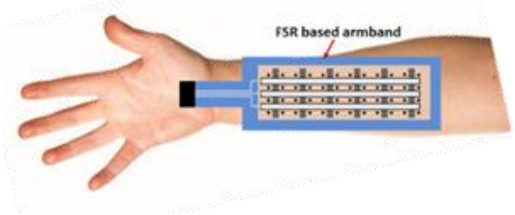


Radar-camera activity sensing

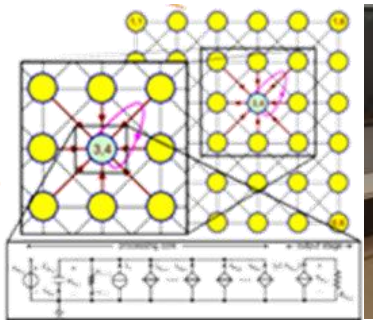
Sensors & Actuators

6G-life Enabled Remote Affective Touch Transmission Hardware and System

Haptic Sensing on Flexible Wearable



Memristor CNN Processing

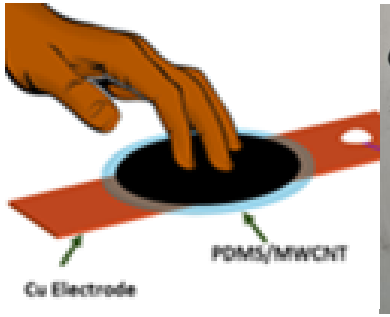


Digital Avatar Interaction

Haptic Rendering on Actuator Wearable

Novel Sensors and Actuators

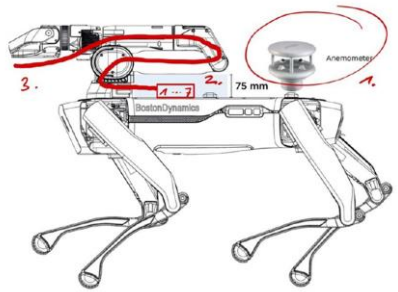
Nano Generator



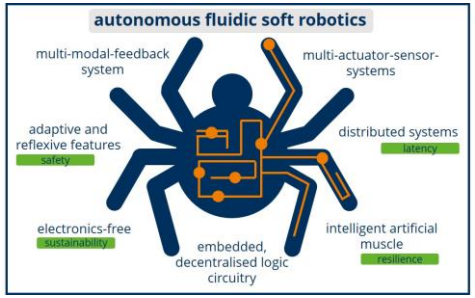
Haptic Drum Stick

Olfactive Sensor

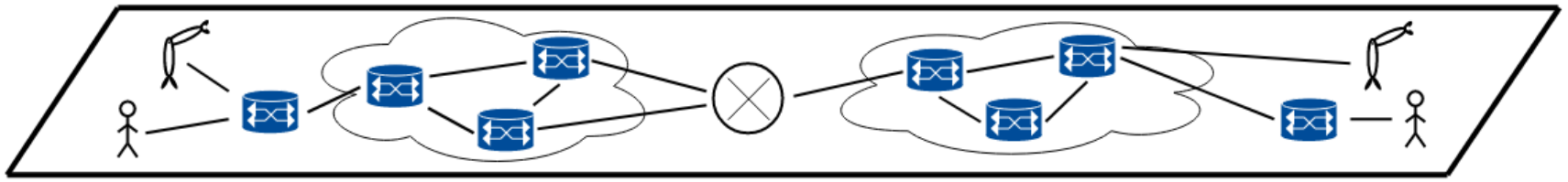
Robot Integration



Fluidic Soft Robot



6G-life high-level system architecture



virtual network
„a 6G slice“

3D network node

SW
OS/Compiler
HW

Molecular Communication

molecular

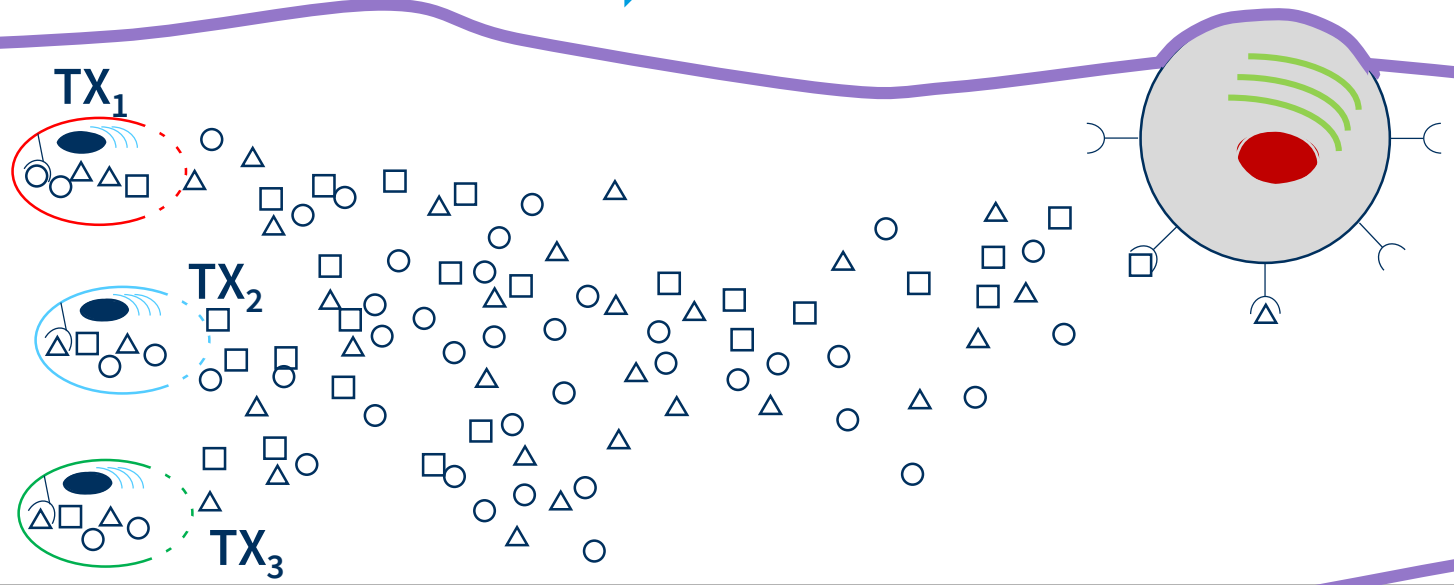
classic
quantum

SW
OS
HW

Internet of Bio-Nano-Things for future medical use cases

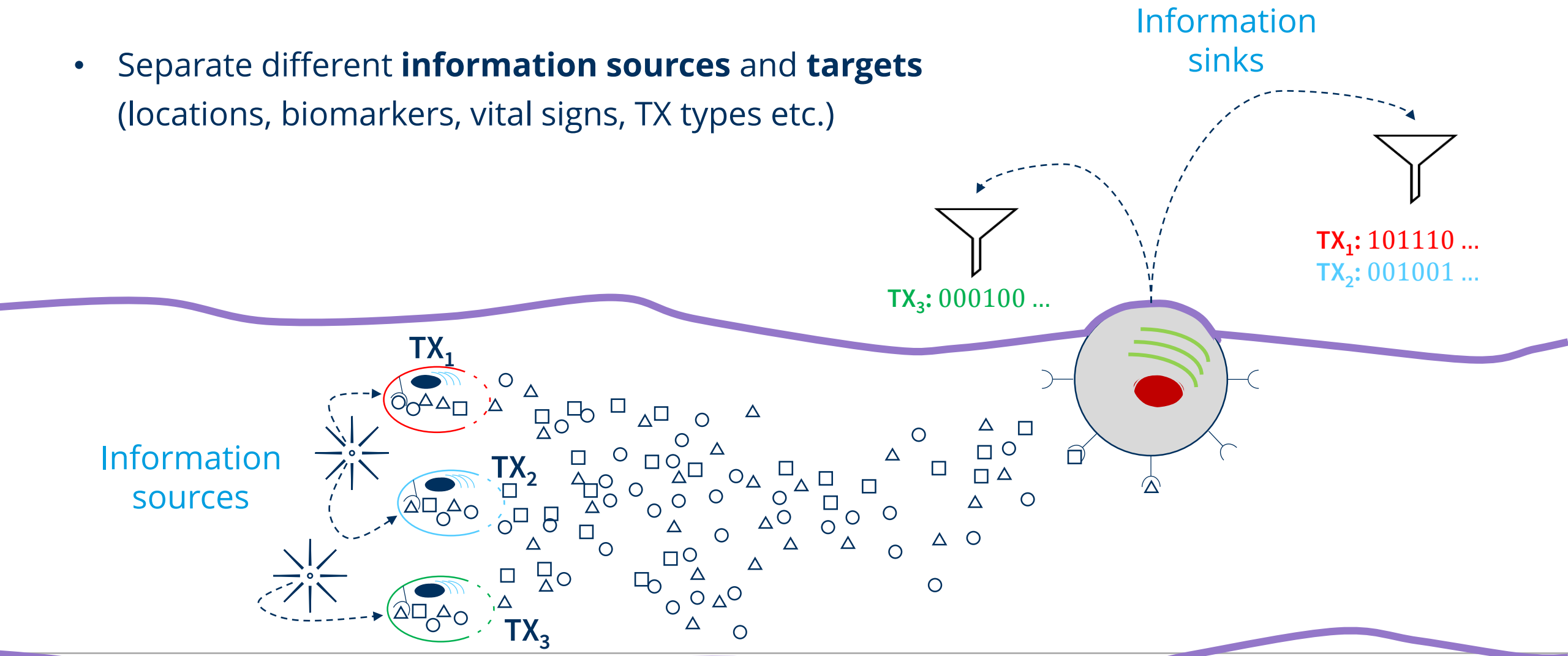
- **Bio-nano-machines** (BNMs) need to **communicate** to achieve **complex tasks**
- **Controlled** and **efficient** information exchange
- Large number of **different types** of BNMs

MC Networks



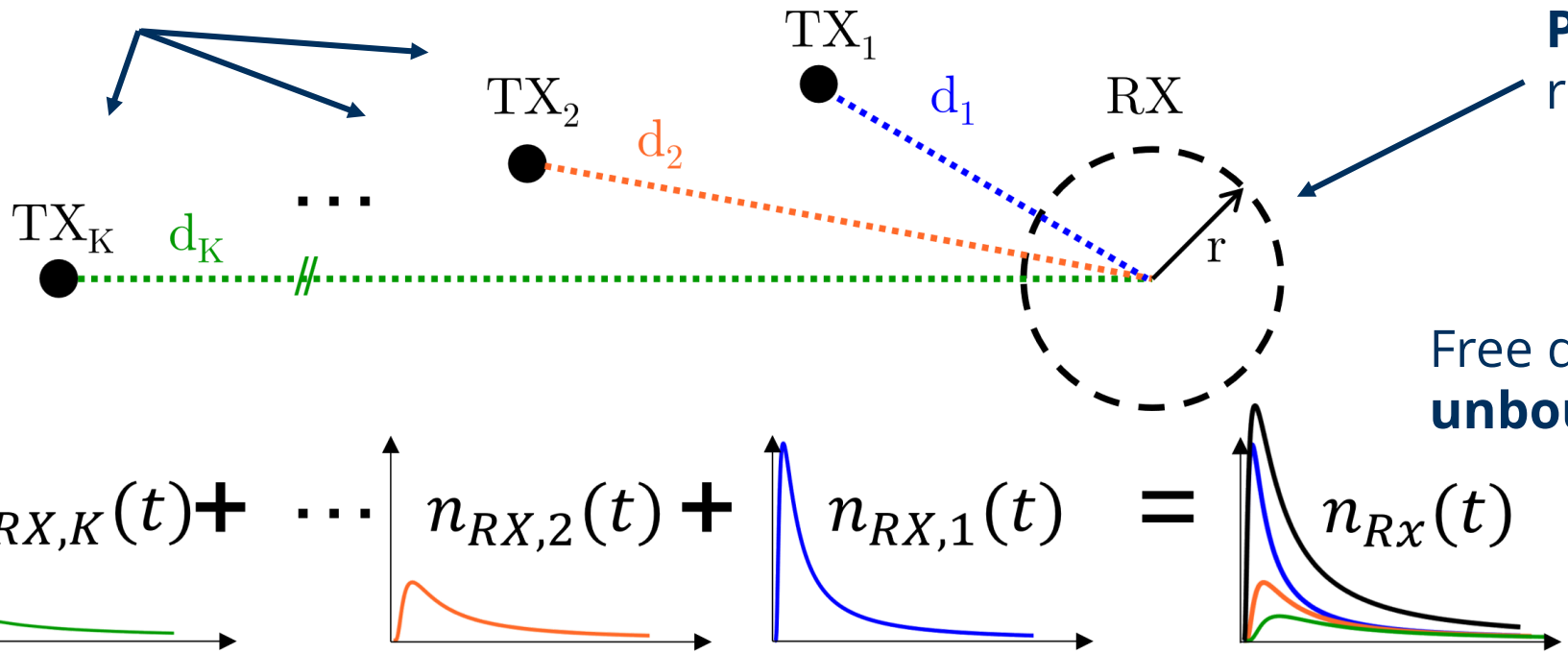
MC Networks need Multiple Access

- Separate different **information sources** and **targets** (locations, biomarkers, vital signs, TX types etc.)



Simplified Communication Scenario: NOMA

Point transmitters (TXs)

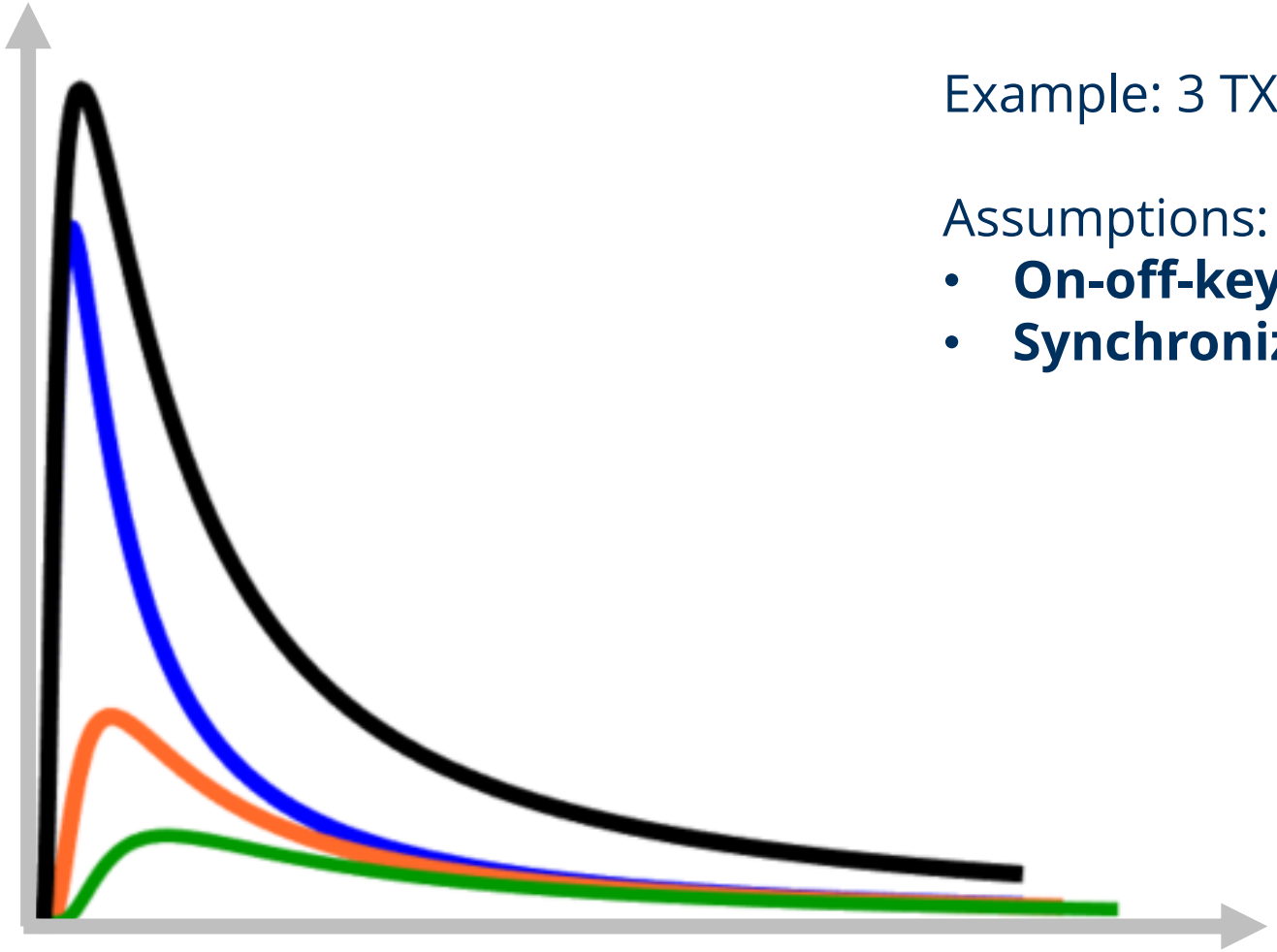


Passive spherical receiver (RX)

Free diffusion in **unbounded** space

↳ Modelled as mean and variance $\lambda(t)$ of a time-varying **Poisson** distribution

Successive Interference Cancellation for the MC Channel



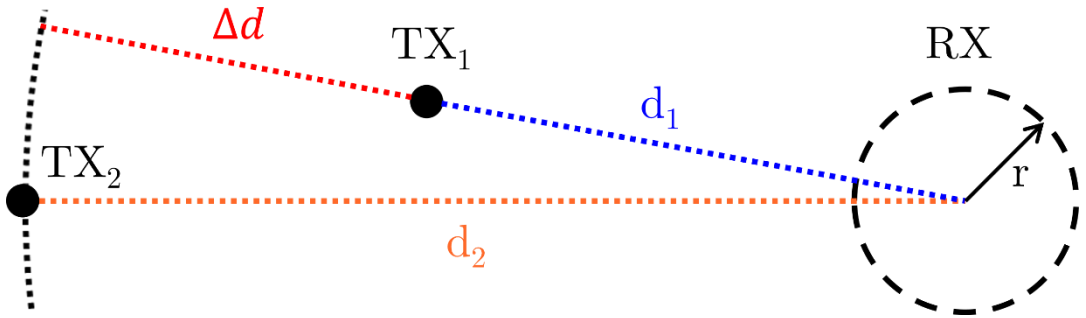
Example: 3 TXs have sent a 1 over the channel

Assumptions:

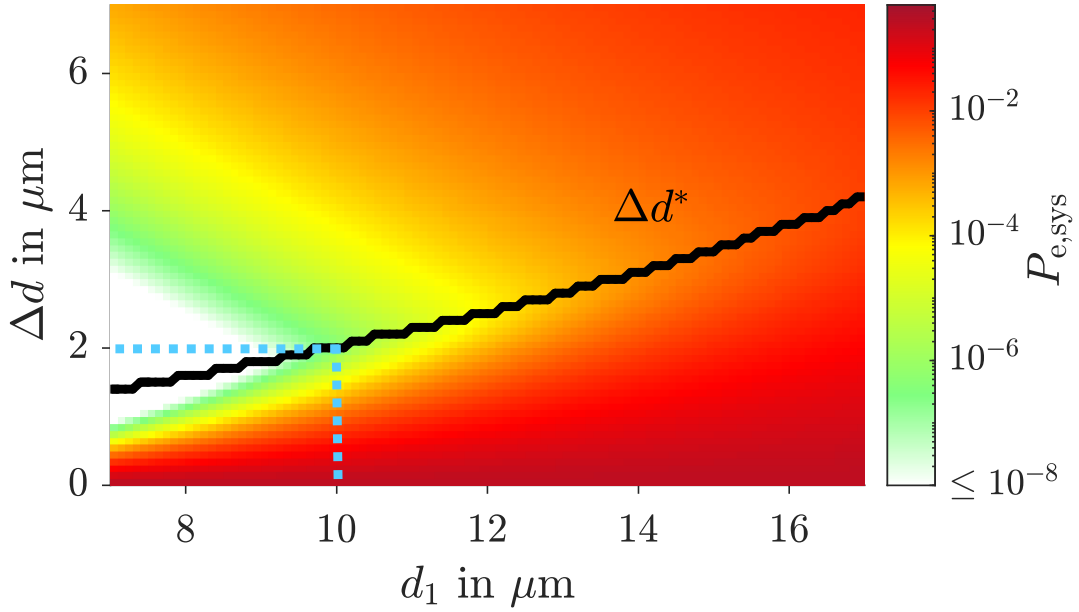
- **On-off-keying** with predefined pulse magnitude
- **Synchronization**, i.e. all TXs send at the same time

Preliminary Results – Performance Analysis

- Influence of distance constellation



Bit Error Probability



Preliminary Results – Performance Analysis

- Influence of distance constellation

Effect 1

TXs **closer to the RX**

Lower BEP

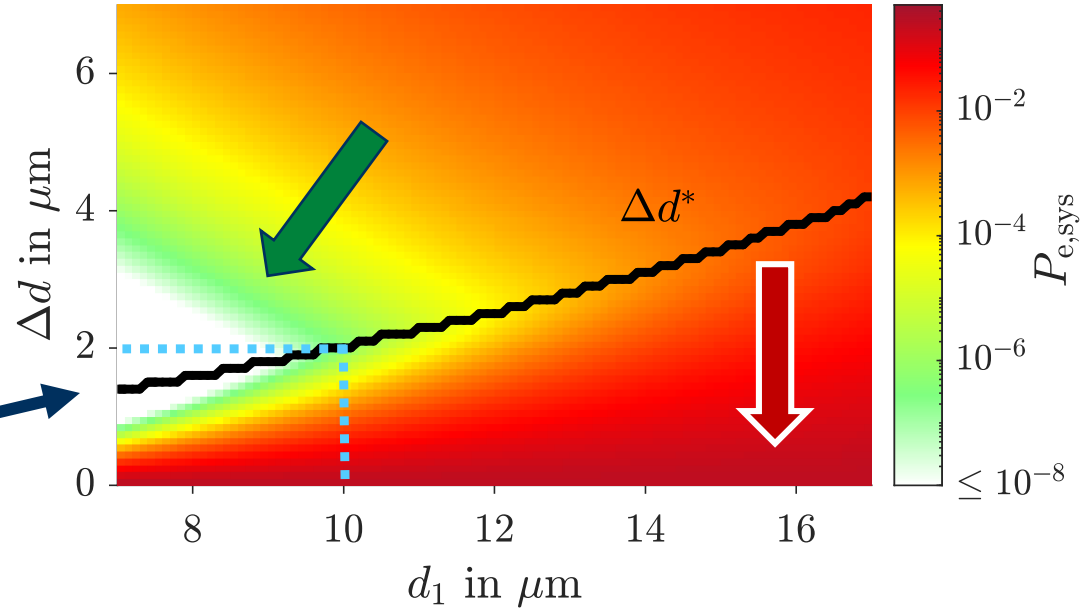
Effect 2

TXs **closer to each other**

Higher BEP

Equilibrium point

Bit Error Probability



TX-RX distance ⟹ Emitted molecules → Optimization parameter?

NOMA ⟺ **TDMA, MDMA, ...**

6G Perspective of Mobile Network Operators, Manufacturers, and Verticals

6G Perspective of Mobile Network Operators, Manufacturers, and Verticals

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***Abstract*—The first release of 5G technology is being rolled out worldwide. In parallel, 3GPP is constantly adding new features to upcoming releases covering well-known use cases. This raises the questions i.) when will 6G be introduced?, ii.) how can 6G be motivated for the stakeholders, and iii.) what are the 6G use cases? In this work, we present the perspective of these stakeholders, namely the network operators, manufacturers, and verticals, identifying potential 5G shortcomings and the remaining 6G solution space. We will highlight the Metaverse as the enabler for 6G addressing omnipresent daily challenges and the upcoming energy problem.**

***Index Terms*—6G Use cases, Metaverse, AI, Quantum Communication, Molecular Communication, Pandemic, Aging Society, Climate Change, Skill Shortage**

I. Introduction

Public 5G mobile communication systems are currently being rolled out. Most of the 5G communication systems in operation are based on Release 15 non-standalone (NSA) and are nowadays converted into standalone (SA) systems. While NSA is still based on a 4G core system, the SA embeds a 5G core and can therefore be considered the first natural 5G system. While 4G and its predecessors still had the consumer market in mind, 5G aims to open up entirely new markets. Even though 5G is advertised with high data rates to attract the old consumer customer front, the absolute novelty in 5G is the support of low latency communication for the Industrial Internet, health care, mobility, etc., mainly machine-to-machine communication. This led to a new customer base, namely the verticals. In addition to latency, 5G has brought two other groundbreaking changes.

Firstly, new communication architectures such as non-public or 3D networks are supported parallel to the public cellular networks. Secondly, in-network concepts from the Internet Engineering Task Force (IETF), mainly for the Internet, have been intensively incorporated into mobile communication systems. The latter increased the importance of software in communication systems. First, only the backbone's communication components have been realized by software rather than proprietary hardware boxes. Nowadays, even Radio Access Networks (RAN) technologies are candidates for softwarization. Even though most people or industry sectors have yet to experience the full 5G technology, researchers are starting to think about 6G technologies [1]. Unfortunately, a clear definition of 6G communication networks has not been defined yet. European flagship research projects such as HEXA-X [2] or the 6G Platform Germany [3] have gathered leading industry players and research institutions to develop such as definition.

Often, researchers advertise 6G technologies without considering the upcoming releases of the 3rd Generation Partnership Project (3GPP). This often leads to a misunderstanding in the community about what 6G is. Release 16 and 17 will complete Release 15, initializing the first wave of *lifelike* 5G technology enabling most of the envisioned use cases, especially those addressing low latency requirements such as machine-to-machine communication, e.g., with mobile robotics. The second wave starts with Release 18 (5G advanced starting standardizations in 2022). Currently, Release 19 is looking for new topics to be discussed in standardization.

Therefore, in this paper, we will first briefly list in Section II the features that will be available in the upcoming 5G releases. Then, in Section III, we will look at the current needs of the verticals and whether the current releases meet these. From the shortcomings of the current releases and the new needs of the verticals and consumers due to the recent results, we present possible use cases of 6G in Section IV. 6G can only succeed if we build a communications system that serves the needs of people or people-owned machines. Along the way, we will examine what new opportunities are available to the manufacturers and what role the network operators play in this.

II. What Will 5G Give Us?

To understand what 6G should focus on, a short description of the feature and study list in 3GPP for ongoing 5G activities is given. It is assumed that 6G will be introduced with Release 21 or higher. However, an earlier version can also be called 6G if the marketing departments of the companies want to outbid each other.

- **3GPP Feature and Study Item list: Rel-15-17**: Study on Communication for Automation in Vertical Domains; New radio, Non-Orthogonal Multiple Access; Satellite; TLS; Edge computing; network slicing;
- **3GPP Feature and Study Item list: Rel-18**: Satellite; IoT; UAV; Sidelink; Proximity; Location and Positioning;

- **3GPP Feature and Study Item list: Rel-15-17**: Study on Communication for Automation in Vertical Domains; New radio, Non-Orthogonal Multiple Access; Satellite; TLS; Edge computing; network slicing;
- **3GPP Feature and Study Item list: Rel-18**: Satellite; IoT; UAV; Sidelink; Proximity; Location and Positioning; Smart Energy; Ad hoc Group communication; Enhanced Network Slicing; eXtended, augmented, and virtual reality; Railways; Tactile and multi modality communication services; Self-organising Networks;
- **3GPP Feature and Study Item list: Rel-19**: Integrated Sensing and Communication; Metaverse; Network Sharing; AI/ML Model Transfer; Robots; Energy considerations

TABLE I: Overview of different technologies for 6G with respect to costs, energy consumption, latency, and security. ↑↑ / ↓↓ - tremendous impact, ↑ / ↓ - great impact, ↗ / ↘ - small impact, → - no impact

Technology	Costs	Energy	Latency	Security	5G/6G
In-Network Computing and OpenRAN	↘	→	↓↓	↑	Not 3GPP, started now
Joint Communication and Sensing	↓	↓	→	→	Release 18
Post-Shannon Theorie	→	↓↓	↘	↑	6G
Quantum Communication	↑↑	↑	↓	↑↑	6G
Molecular Communication	↓	↓↓	↑↑	→	6G

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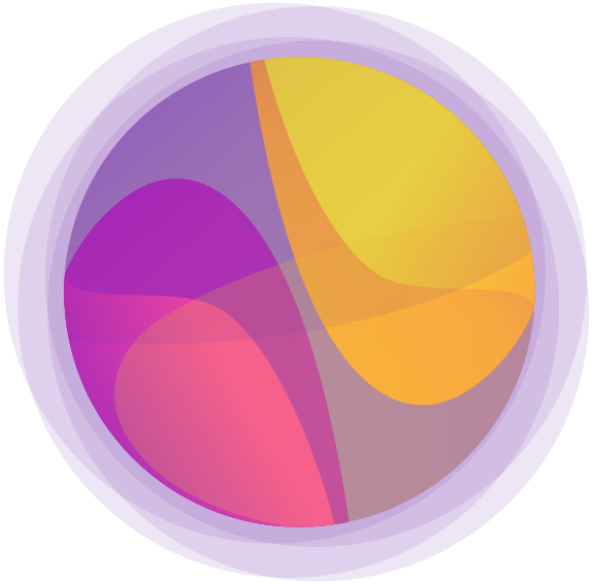
Thank You!



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