6G Projects at TUM

Gerhard Kramer
Chair of Communications Engineering
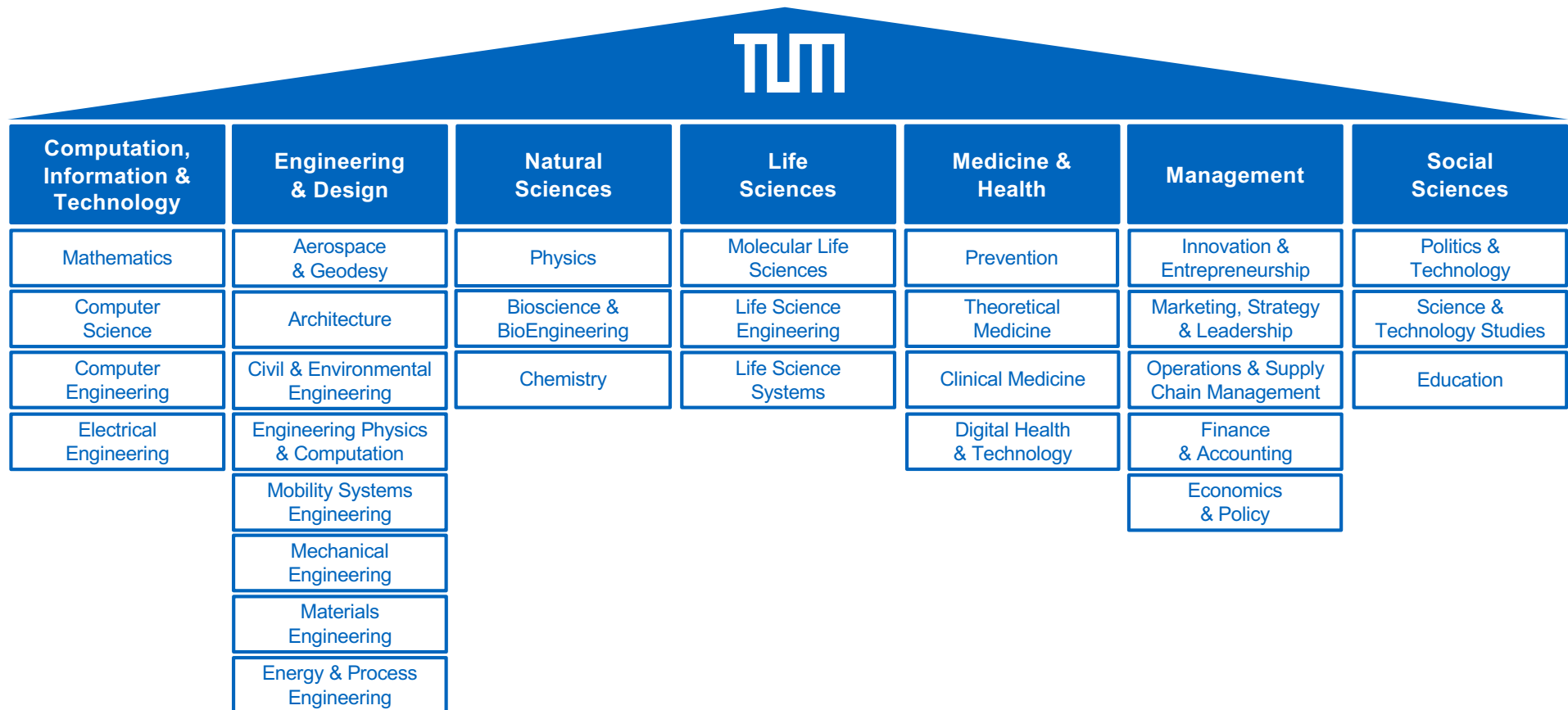SVP Research and Innovation
Technical University of Munich

TUM

Outline

1) Introduction to TUM and Communications Groups

2) 5G and Application Groups

3) 6G Future Lab Bavaria at TUM

4) 6G-life Hub at TUM

5) Other 6G Hubs in Germany

1) Introduction
to TUM and Communications Groups

TUM Schools. Departments

Computation, Information & Technology	Engineering & Design	Natural Sciences	Life Sciences	Medicine & Health	Management	Social Sciences
Mathematics	Aerospace & Geodesy	Physics	Molecular Life Sciences	Prevention	Innovation & Entrepreneurship	Politics & Technology
Computer Science	Architecture	Bioscience & BioEngineering	Life Science Engineering	Theoretical Medicine	Marketing, Strategy & Leadership	Science & Technology Studies
Computer Engineering	Civil & Environmental Engineering	Chemistry	Life Science Systems	Clinical Medicine	Operations & Supply Chain Management	Education
Electrical Engineering	Engineering Physics & Computation			Digital Health & Technology	Finance & Accounting	
	Mobility Systems Engineering				Economics & Policy	
	Mechanical Engineering					
	Materials Engineering					
	Energy & Process Engineering					

TUM Institute for Communications Engineering

Norbert Hanik	**Gerhard Kramer**	**Antonia Wachter-Zeh**
Line Transmission Technology	Communications Engineering	Coding and Cryptography
• Optical Communications • Signal Transmission over Copper Wires (DSL and Power Line) • Implementation in FPGAs • 7 Researchers	• Coding & Modulation • Optical & Wireless Communications • Security & Stealth • Quantum & Identification • 23 Researchers	• Coding Theory • Coding for Storage • Network Coding • PUFs • Post-Q Cryptography • 21 Researchers

Coding and Modulation

1) **Constellation shaping**: architectures and algorithms
   2019 IEEE/OSA Journal of Lightwave Technology Paper Award

2) **LDPC codes**: non-binary LDPC codes & convolutional codes for URLLC, quantized message passing, high throughput decoders

3) **Polar codes**: parallel & fading & noncoherent channels, PUFs

4) **Multi-access and Broadcast Channels**: code structures via polarization

Optical and Wireless Communications

1) **Lightwave communications:** Capacity & nonlinear Fourier Transform
   2018 IEEE Information Theory Society Paper Award

2) **Joint sensing & communications**: V2V radar & communications

3) **Network/massive MIMO**: MAGIQ precoding for multi-carrier (OFDM) signals and network/massive MIMO
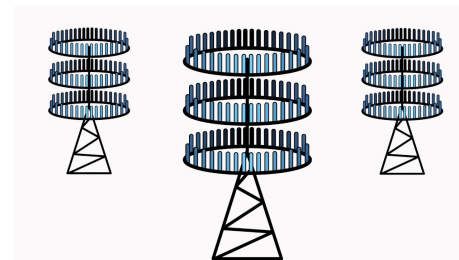
Security and Stealth, Quantum and Identification

1) Quantum & identification theory: focus on IT and codes

2) Key agreement, PUFs, covert/stealth: information theory and codes

3) Distributed compressed sensing with quantization: theory and approximate message passing (AMP) algorithms

TUM Center of Competence Communications (CoC COM)

What is the TUM CoC COM?

Hub of experts on communications technology @TUM

- Establish and collaborate on joint **research strategies**
- Pursue joint **teaching activities**
  - Master of Science in Communications Engineering
    ~80 students/year, all-English, algorithms & electronics, since 1998
  - Center for Digital Technology and Management:
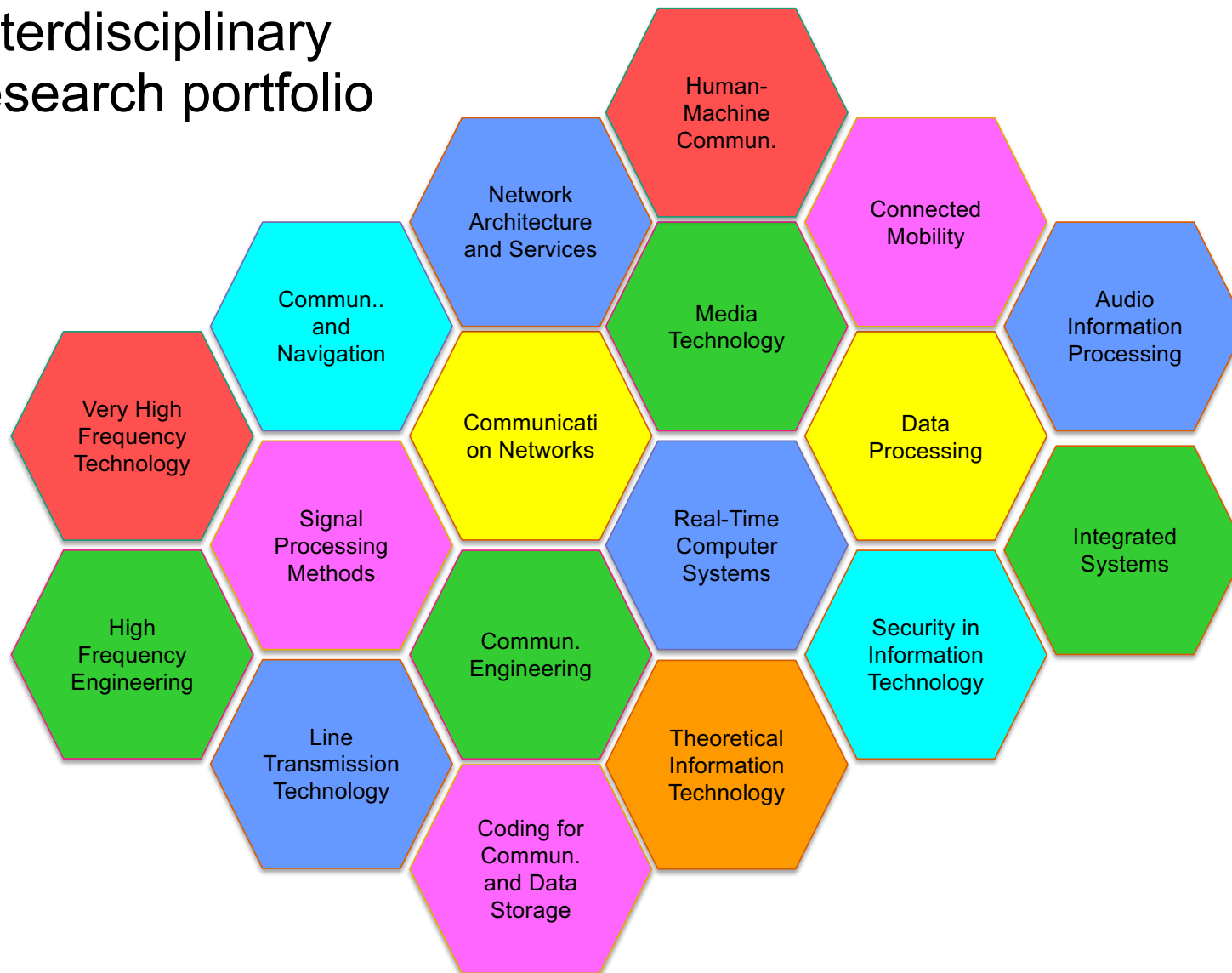   ~25 students/semester study 'Technology Management', since 1998
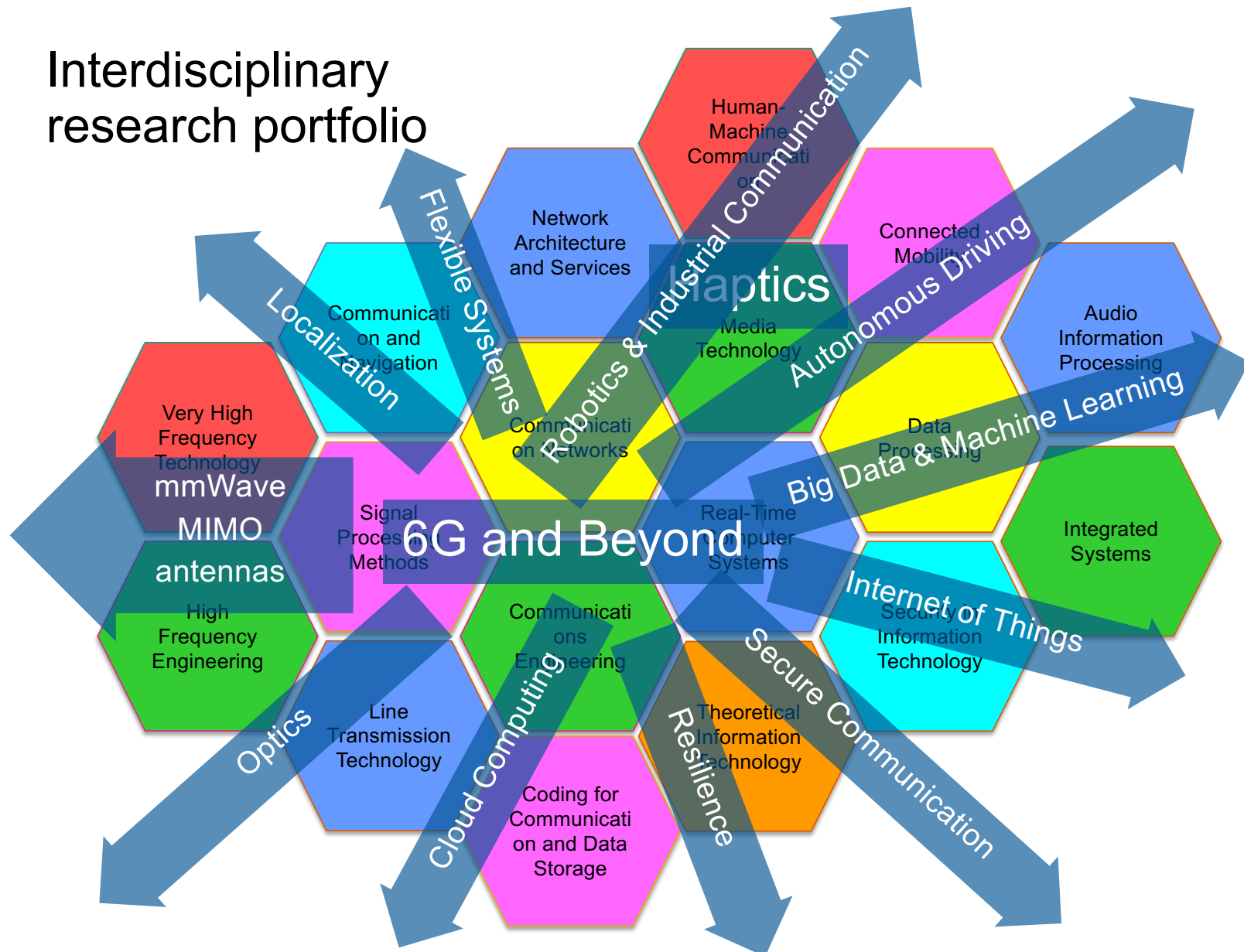
TUM Center of Competence Communications

- Part of the Department of Electrical & Computer Engineering
- 19 Professors
  - **Audio- & High Frequency** (3): Biebl, Eibert, Seeber
  - **Data & Media Technology** (3): Diepold, Sigl, Steinbach
  - **Communication Theory & Coding** (4): Boche, Hanik, Kramer, Wachter-Zeh
  - **Machines, Signal Processing** (3) : Heckel, Rigoll, Utschick
  - **Navigation** (1): Günther
  - **Networks, Systems, IoT** (4): Carle, Herkersdorf, Kellerer, Ott, Steinhorst

# Interdisciplinary research portfolio

- Human-Machine Commun.
- Network Architecture and Services
- Connected Mobility
- Commun.. and Navigation
- Media Technology
- Audio Information Processing
- Very High Frequency Technology
- Communication Networks
- Data Processing
- Signal Processing Methods
- Real-Time Computer Systems
- Integrated Systems
- High Frequency Engineering
- Commun. Engineering
- Security in Information Technology
- Line Transmission Technology
- Theoretical Information Technology
- Coding for Commun. and Data Storage

Interdisciplinary research portfolio

6G and Beyond

Haptics

Flexible Systems

Localization

Robotics & Industrial Communication

Autonomous Driving

Big Data & Machine Learning

Internet of Things

Secure Communication

Cloud Computing

Optics

Resilience

mmWave MIMO antennas

Human-Machine Communication

Network Architecture and Services

Connected Mobility

Communication and Navigation

Media Technology

Audio Information Processing

Very High Frequency Technology

Communication Networks

Data Processing

Signal Processing Methods

Real-Time Computer Systems

Integrated Systems

High Frequency Engineering

Security of Information Technology

Communications Engineering

Line Transmission Technology

Theoretical Information Technology

Coding for Communication and Data Storage

Holistic end-to-end system portfolio

- Telecommunications
- Urban mobility and transport
- Industry 4.0
- Automobile systems and autonomous driving
- Robotics, automation and teleoperation
- Tactile Internet
- Internet of Things and cyber-physical networking

- Multimedia signal processing and –communication
- Perception oriented (incl. haptics) and user centered design
- Machine learning and data analytics
- Network and data security
- Cloud computing and data storage
- Localization and navigation
- Optimization, planning and TCO analysis
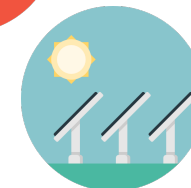
Selected Experimental Facilities
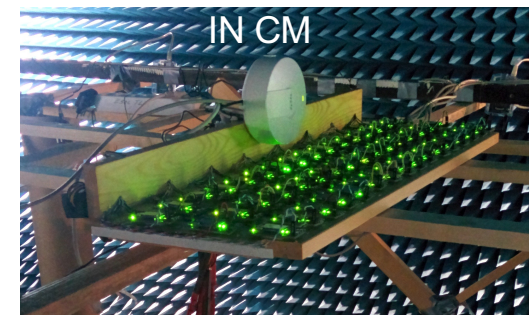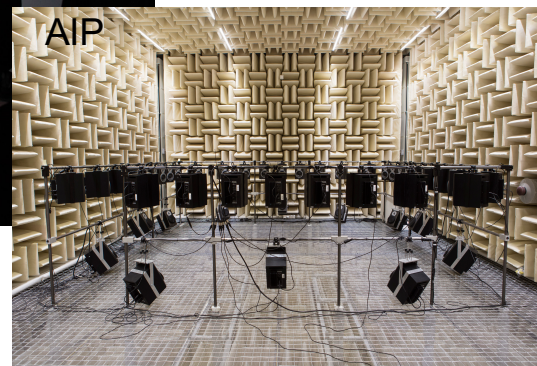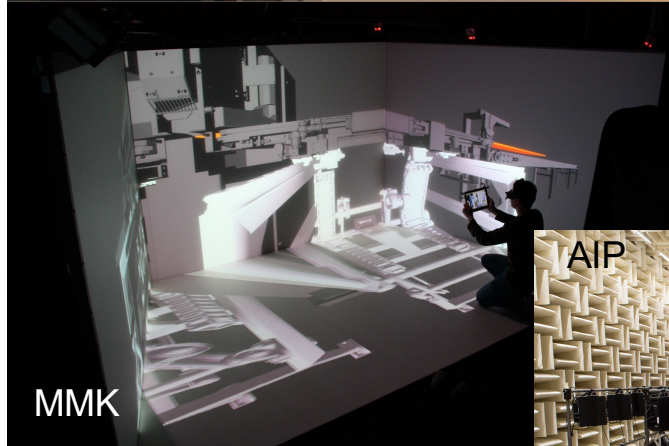
Spin Offs

- CADAMI
- NavVis
- Konux
- Kinexon
- NuvoLight
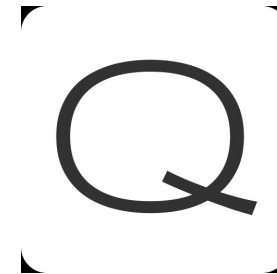- QoLWare
- ParkHere
- KliniSoft
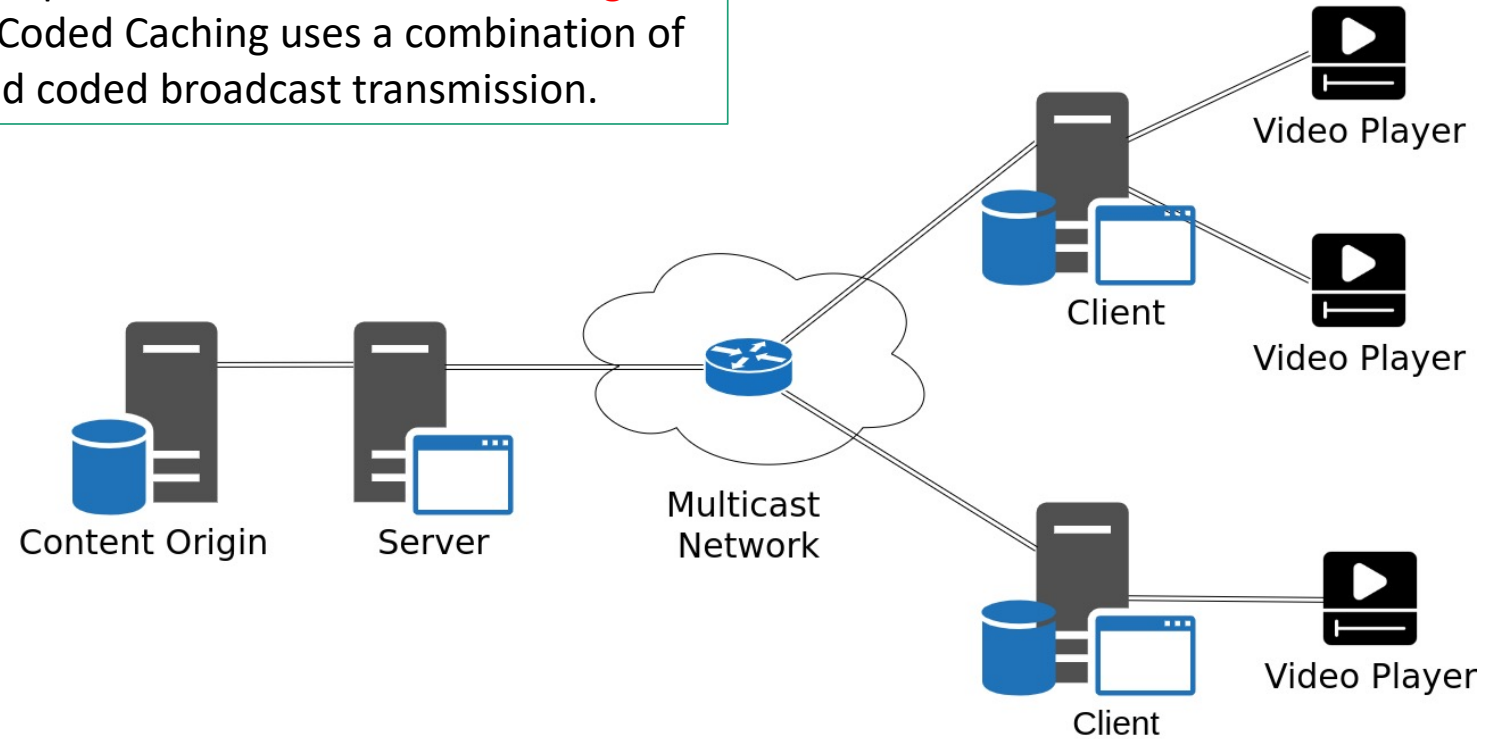
CADAMI

Cadami offers a software implementation of Coded Caching for commercial applications. Coded Caching uses a combination of caches at the receivers and coded broadcast transmission.

2) 5G and Application Groups

5G: Key Application Groups

Three groups for the many applications:

1) Enhanced Mobile Broadband (eMBB):

   ➢ High rates: 10-20 Gbit/s for high quality of service, video streaming
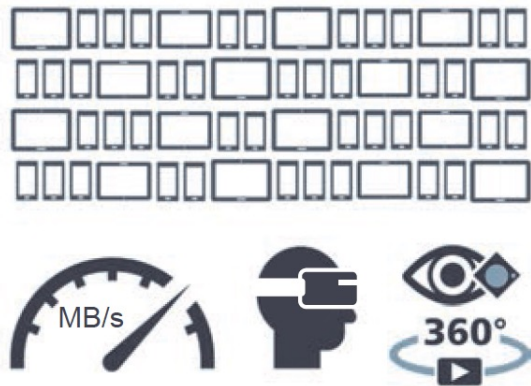
2) Massive Machine Type Communications (mMTC)

   ➢ Energy efficiency: Internet-of-Things (talk of 100 trillion devices)

3) Ultra-Reliable and Low-Latency Communications (URLLC)

➢Reliability and low latency: 1 msec

Enhanced Mobile Broadband

eMBB

MB/s 360°

- Improved user experience
- High device connectivity
- High mobile data rates
- Mobile virtual and augmented reality applications
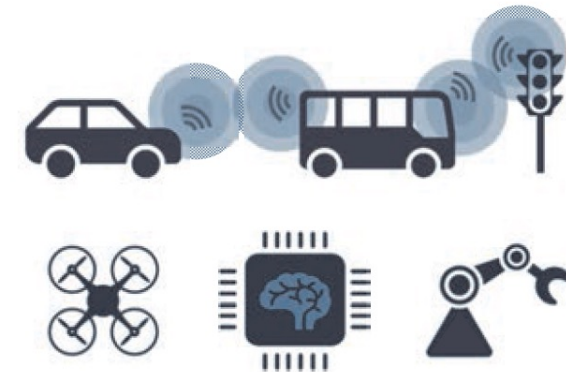
Massive Machine Type Communications

mMTC

- eHealth applications
- Industry 4.0 applications
- Intelligent logistics
- Environmental monitoring
- Smart grids
- Smart farming

Ultra-Reliable and Low-Latency Communications

URLLC

- Car-to-X communication
- Control of parcel drones
- Vital data monitoring
- Smart manufacturing

Figure 1 – Three key application groups for 5G: emBB, mMTC and URLLC
Source: Federal Government based on Ofcom 2017: update on 5G spectrum in the UK

*Source: "5G Strategy for Germany," Federal Ministry of Transport and Digital Infrastructure

Technical Challenges

eMBB: How do we get to 10-20 Gbit/s?

mMTC: How do we address 100 trillion devices with low energy?

URLLC: How do we combine reliability and low latency

Technical Solutions

1) New radio frequencies: go to 6 GHz or 24 GHz (eMBB)

2) Small cells: more base stations (mMTC)

3) Massive MIMO: massive number of antennas (eMBB, mMTC)

4) New algorithms: for networking and codes (URLLC)

3) 6G Future Lab Bavaria at TUM

https://www.6g-future-lab.de/

Thank you to Prof. Wolfgang Kellerer for the Slides!

In a nutshell

- German und Bavarian governments push for a leading role in 6G technology at an early stage

- Focus on universities and startups (in addition to industry funding)

- Push for an early ecosystem by establishing „platforms"

- Important objective is technology "sovereignty"

Bavarian 6G Initiative


- Launched on Sept. 14, 2020
- Three pillars

1. 6G-Pilot: „6G Zukunftslabor Bayern – 6G Future Lab Bavaria" @ TUM

2. Networking platform for academia and industry: „Thinknet 6G" @BI

3. Call for 6G Collaboration Projects (1st round in Spring 2021)

Digitale Transformation gemeinsam gestalten – innovativ, intelligent, vernetzt

CYBERSECURITY | 6G | DIGITAL PRODUCTION & ENGINEERING | DIGITALISIERUNG IM ENERGIEBEREICH | DIGITALES PLANEN UND BAUEN | SMART CITIES & REGIONS | VERNETZTE MOBILITÄT

My view on 6G?

- 5G: machine-to-machine communication
- 6G: *extensions of the human intelligence and human abilities (AI)*

- *Network adaptation (commun. + processing + storage)*
- *Network-as-a-Sensor*
- *AI/ML-native communication*
- *Sustainability: end-to-end energy efficiency*
- *Resilience, security, privacy and trust by design*
- *Exploratory topics: "post Shannon" communication, quantum communication*
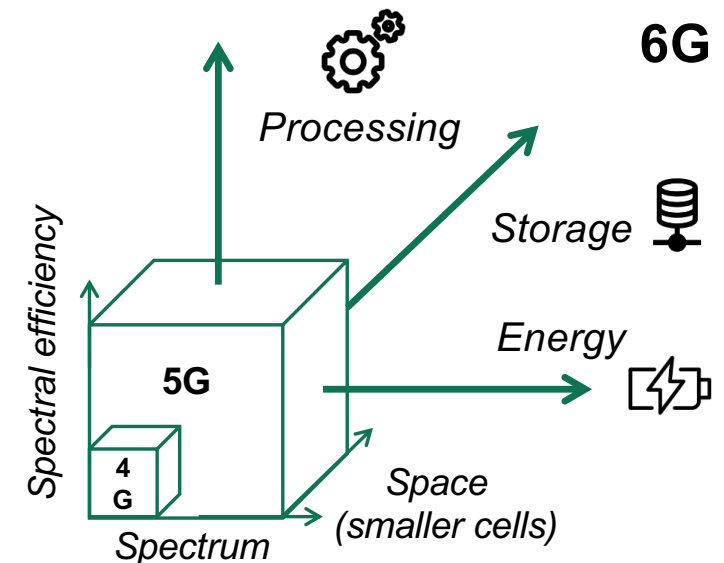
6G Future Lab Bavaria

- Started on May 1, 2021
- 4 Million € for 3 years
- 13 Principal Investigators in 8 subprojects

- The TUM lighthouse project studies fundamentals of 6G and develops them for further investigation and standardization.
- Research focus is on coupling the digital and physical worlds („digital twins"), on flexible network management, sustainability, resilience and security.

6G fundamental research - 6G experimental platform - 6G roadmap

Fundamental, interdisciplinary research

- Prof. Eckehard Steinbach, Media Technology
- Prof. Reinhard Heckel, Machine Learning
- Prof. Klaus Diepold, Data Processing

application, AI, digital twin

- Prof. Wolfgang Kellerer, PD Carmen Mas Machuca, Communication Networks
- Prof. Georg Carle, Network Architectures and Services, Informatics
- Prof. Jörg Ott, Chair of Connected Mobility, Informatics

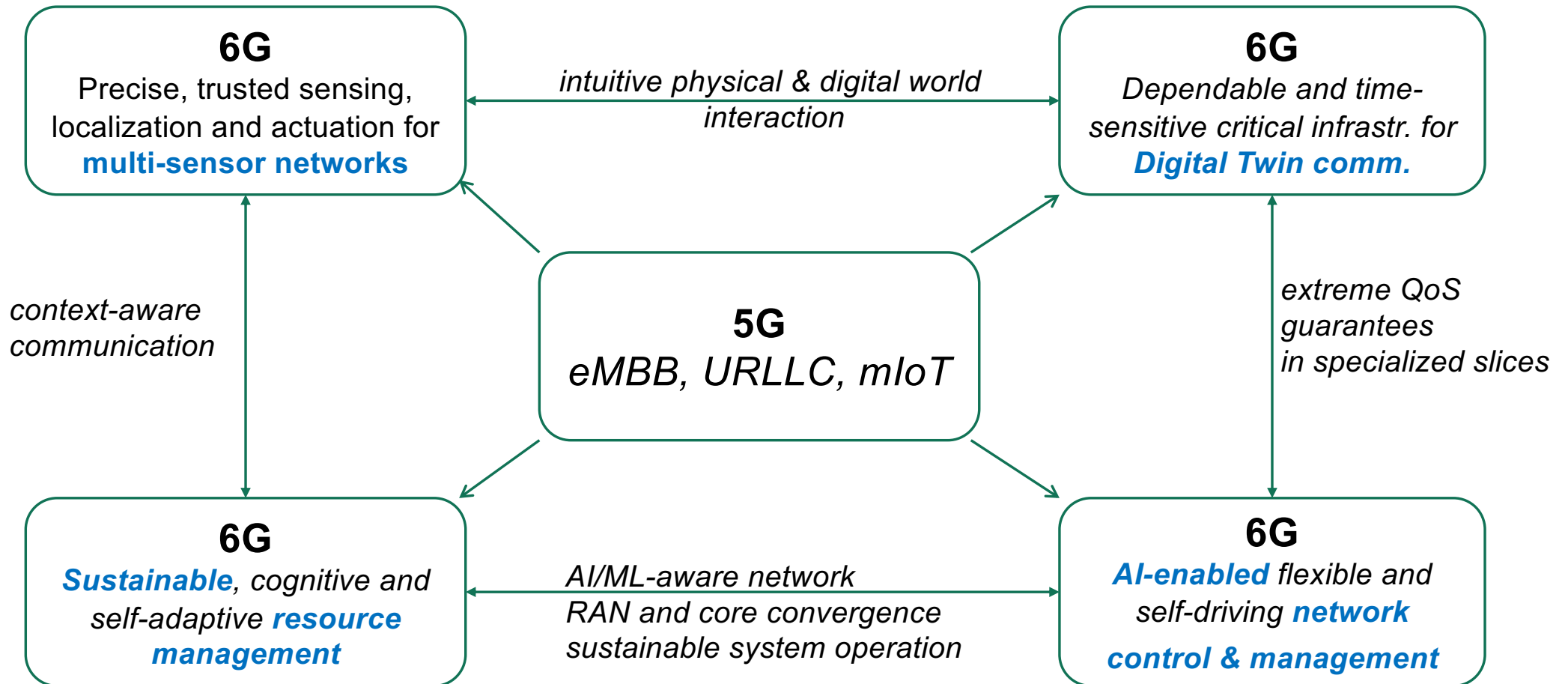*flexible, resilient and sustainable end-to-end network*

- Prof. Holger Boche, Theoretical Information Technology
- Prof. Gerhard Kramer, Communications Engineering
- Prof. Wolfgang Utschick, Signal Processing Methods
- Prof. Antonia Wachter-Zeh, Coding for Communication and Data Storage

resilient, sustainable cognitive radio

- Prof. Andreas Herkersdorf, Integrated Systems
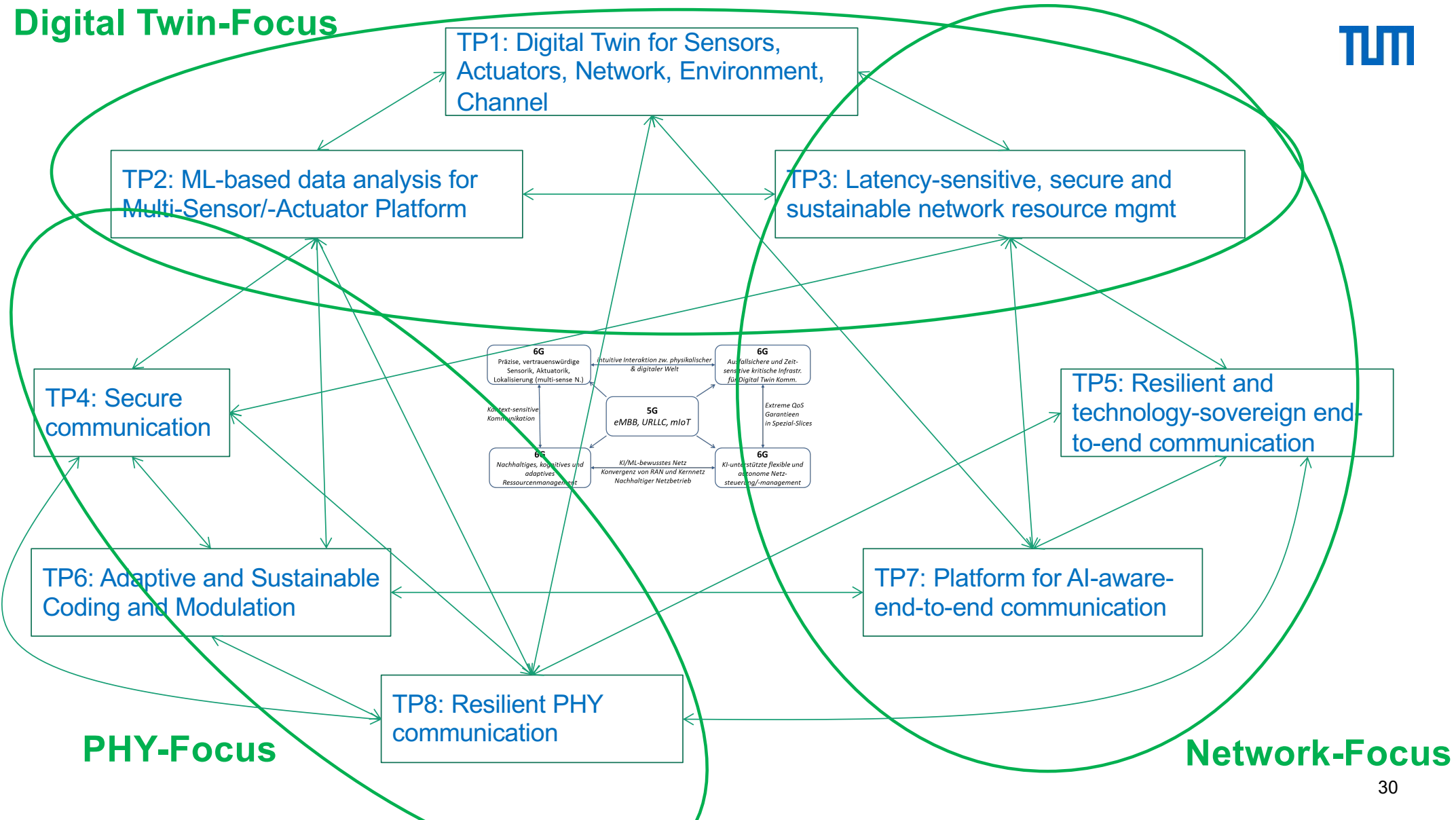- Prof. Georg Sigl, Security in Information Technology

hardware platform and security
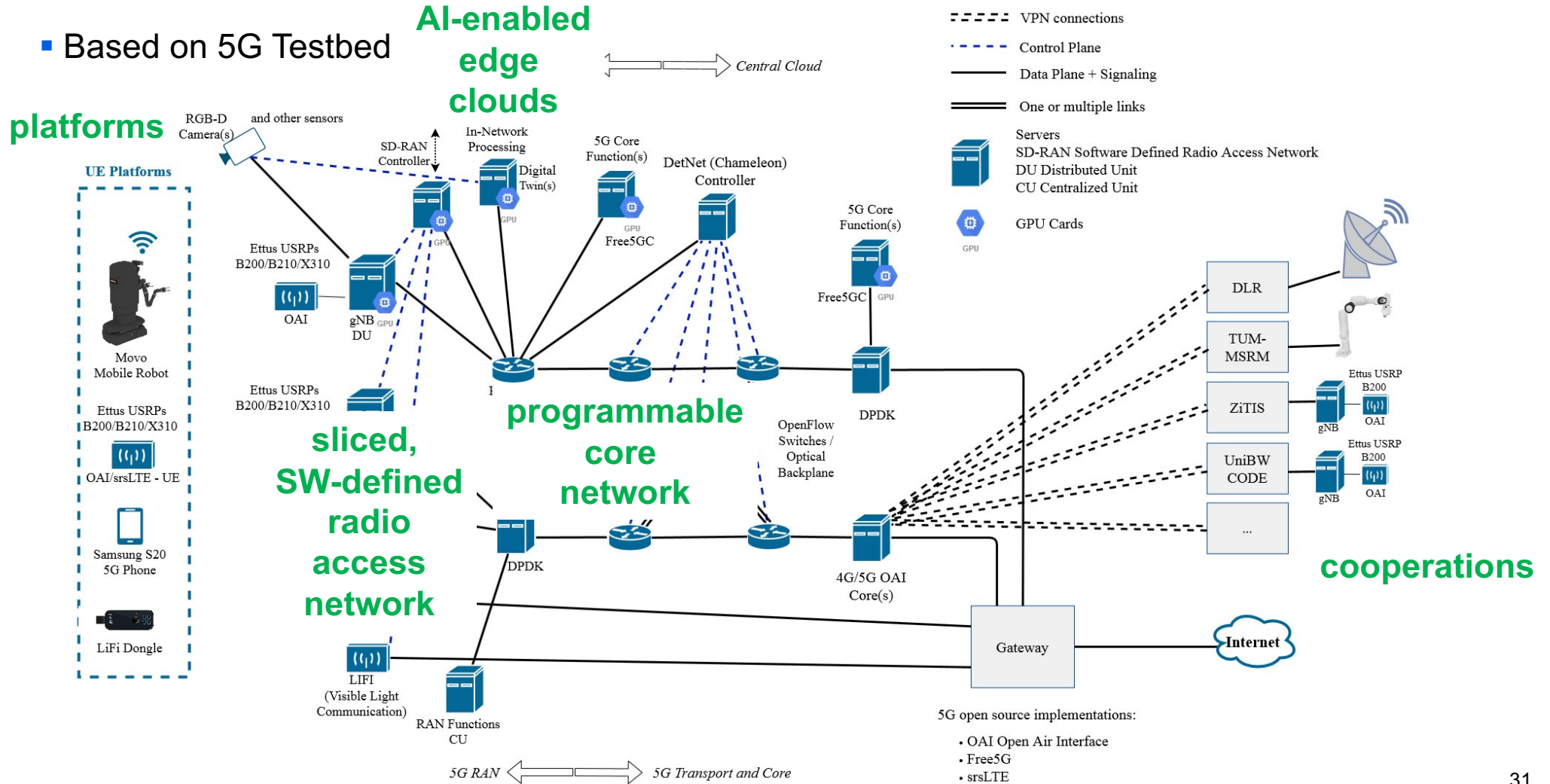
6G Future Lab core research areas

6G
Precise, trusted sensing, localization and actuation for **multi-sensor networks**

intuitive physical & digital world interaction

6G
Dependable and time-sensitive critical infrastr. for **Digital Twin comm.**

context-aware communication

5G
eMBB, URLLC, mIoT

extreme QoS guarantees in specialized slices

6G
Sustainable, *cognitive and self-adaptive* **resource management**

AI/ML-aware network RAN and core convergence sustainable system operation

6G
AI-enabled *flexible and self-driving* **network control & management**

Example: Video Image information for 6G resource management

Concept:

- Channel estimation based on video image processing
- AI-based estimation is performed in edge cloud
- Significant increase in throughput and reliability

Packet Error Rate

Serkut Ayvaşık, H. Murat Gürsu, and Wolfgang Kellerer. 2019. Veni Vidi Dixi: reliable wireless communication with depth images.
In Proceedings of the 15th International Conference on Emerging Networking Experiments And Technologies (CoNEXT '19).

6G Experimental Platform

- Based on 5G Testbed

platforms

AI-enabled edge clouds

sliced, SW-defined radio access network

programmable core network

cooperations

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6G Experimental Platform

https://www.5g-munich.de/html/demo.html

TUM

4) 6G-life Hub at TUM

6g-life.de

6G-life

- Started August 2021
- 70 Million € for 4 years
- > 40 Principal Investigators
- Cooperation between TUM and TU Dresden
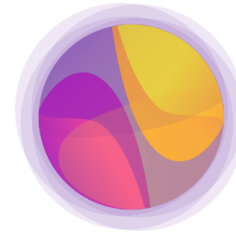
- Focus on humans and their communication and interaction with machines and the virtual world.
- Innovative concepts for scalable communication, flexible software and adaptive hardware
- Focus fields of application: Industry 4.0 and Healthcare.
- Four key points: Latency, Resilience, Security and Sustainability
- Key words: Digital Sovereignty
- 10 Million € for Start-ups

6G-life Research Areas
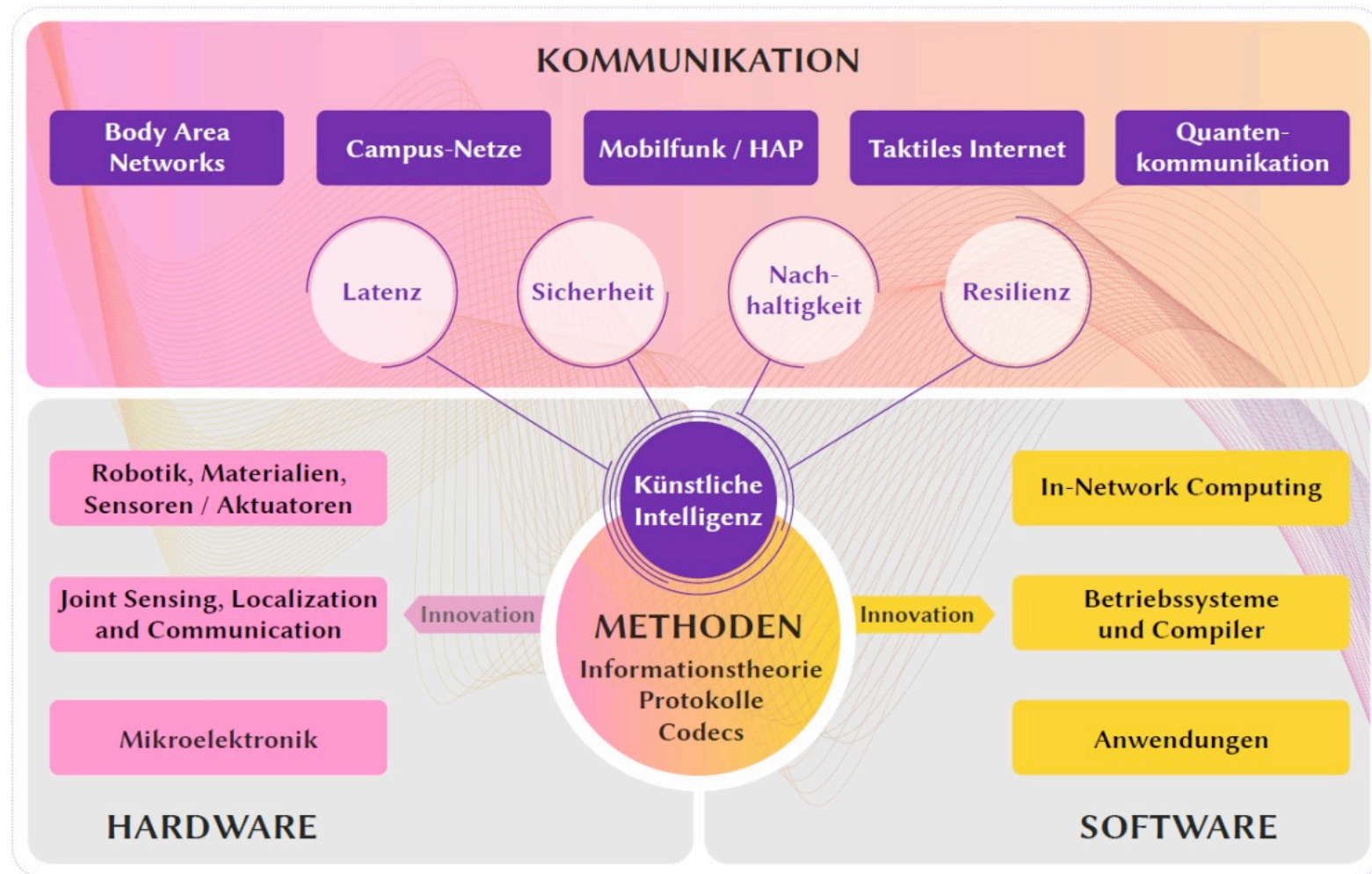
6G-life Innovation Areas

Communication

Several communication network architectures in 6G-life, e.g.,

- Cellular networks with Campus and High Altitude Platform (HAP) extensions
- Tactile Internet including Quantum Communication
- Body Area Networks

Methods

6G-life investigates novel methods for communication networks based on:

- AI for network control and services
- Protocol & codec design for Human-Machine Collaboration
- Post Shannon Theory

Software

Commun. networks and equipment are dominated by software. 6G-life works on:

- In-network computing and ORAN
- 6G applications in virtual worlds (digital twins & holograms)
- Low latency and energy efficient compilers and OS

Hardware

Novel hardware concepts for future needs and applications will be introduced:

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

Selected 6G technology focus fields in 6G-life

- Ultra-scalable 6G architecture, from Body Area Networks (BAN) to WAN
- Tactile Internet
- AI for network control and AI support in-network
- In-network computing and ORAN
- Digital Twins
- Joint sensing and communication
- New materials, e.g. for robotics

- Post Shannon Theory
- Quantum communication
- Post-quantum security

6G-life Participants

The network of partners is continuously extended.
In particular, startups are in the focus.

5) Other 6G Hubs in Germany

Bundesministerium
für Bildung
und Forschung

Federal Ministry of Education and Research

6GEM: 6gem.de

- Cooperation between RWTH Aachen, Ruhr-University Bochum, Dortmund University of Technology, University of Duisburg-Essen, Fraunhofer Institute for Material Flow and Logistics, Fraunhofer Institute for Microelectronic Circuits and Systems, Fraunhofer Institute for High Frequency Physics and Radar Technology, Max Planck Institute for Security and Privacy.

- Focus on the network, material, component/microchip and module levels
- 7 test sites will be integrated and equipped with 6G systems:
  1) a digital operating room at University of Düsseldorf
  2) a smart hospital at University Hospital Essen
  3) the German Rescue Robotics Center in Dortmund
  4) the high-speed intralogistics of the Fraunhofer Institute for Material Flow and Logistics in Dortmund
  5) the highly automated production environments of the Fraunhofer Institute for Production Technology in Aachen
  6) a large-scale port logistics in Duisburg
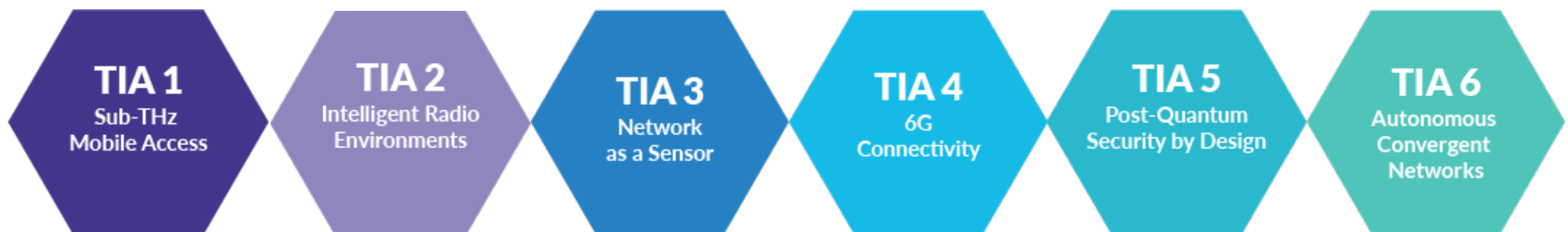 7) road traffic scenarios from the city center to the highway in Aldenhoven.

6G-RIC: 6g-ric.de

- TU Berlin, FU Berlin, Humboldt-University Berlin, FhG Heinrich-Hertz-Institut, FhG Institute for Open Communication Systems, FhG Institute for Reliability and Microintegration, Leibniz Institute for High Frequency Technology, RWTH Aachen, Kiel University, TU Darmstadt, Tübingen University, Fraunhofer Institute for Applied Solid State Physics, German Aerospace (DLR), University of Passau, FAU Erlangen, TU Chemnitz, Institute for Microelectronics

- 6 Technological Innovation Areas:

TIA 1	TIA 2	TIA 3	TIA 4	TIA 5	TIA 6
Sub-THz Mobile Access	Intelligent Radio Environments	Network as a Sensor	6G Connectivity	Post-Quantum Security by Design	Autonomous Convergent Networks

OPEN6GHUB: www.dfki.de/web/news/open6ghub-foerderung-bmbf/

- Deutsches Forschungszentrum für Künstliche Intelligenz (DFKI), FAU Erlangen, FhG FOKUS, FhG IAF, FhG SIT, Leibniz Institute for Microelectronics, KIT, Hasso-Plattner-Institut Potsdam, RWTH Aachen, TU Berlin, TU Darmstadt, TU Ilmenau, TU Kaiserslautern, University Bremen, University Duisburg-Essen, University Freiburg, University Stuttgart

- Focus on security, networked production, future mobility, new worlds of learning, personalized medicine, human interaction with autonomous vehicles and devices
- accelerated digitization for sustainability and achieving climate policy goals
- equal coverage of rural areas via 6G satellite connections
- AI to increase network efficiency and resilience, and to support for mobile services
- Protection of private data, and automated support of changing network topologies

Conclusion

- Bavaria and the German BMBF are investing in 6G @ universities and research institutions

- Are there opportunities for collaborations with IMT?