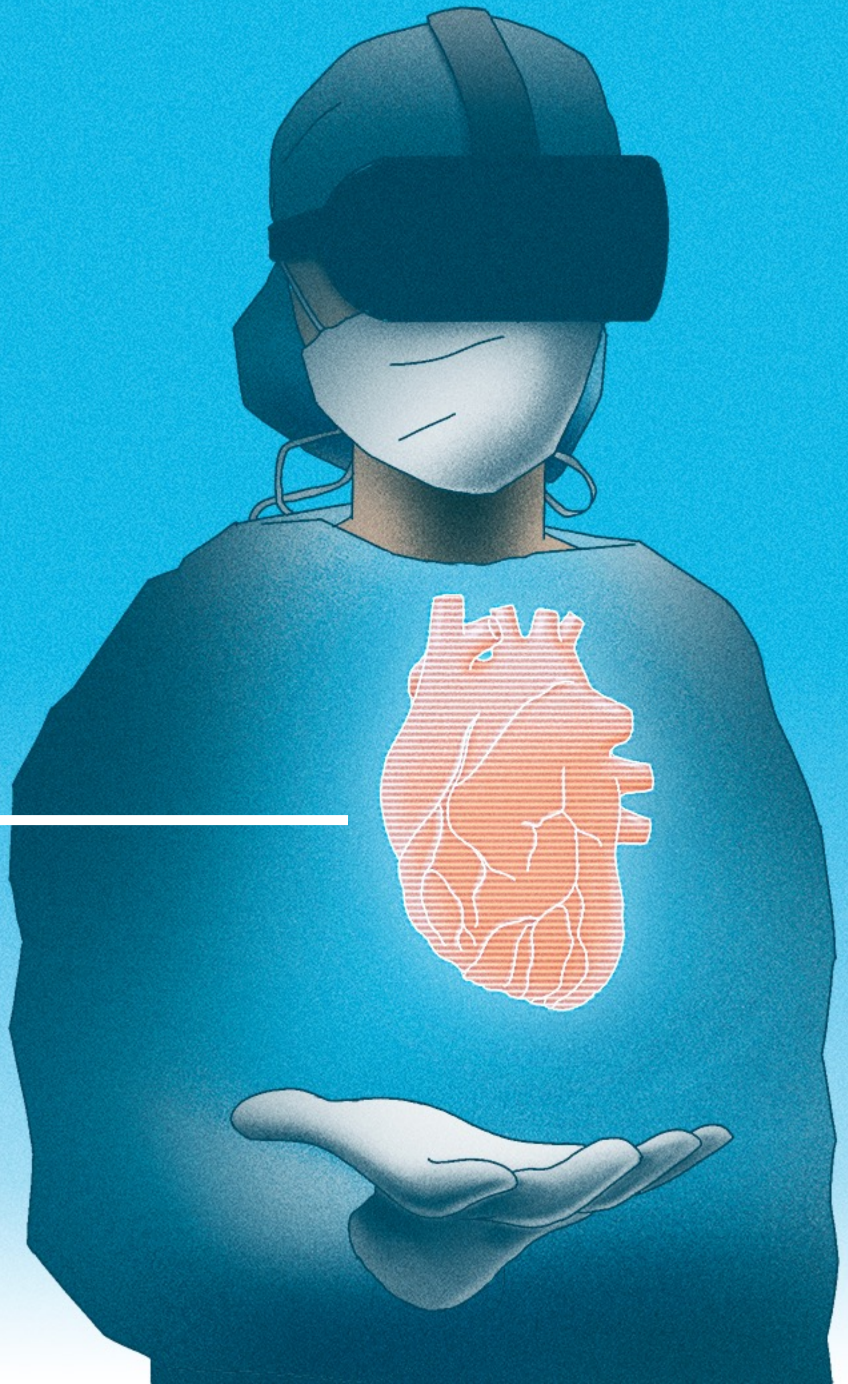
ACADEMIC KEYNOTE

6G is just around the corner. The Promise and Potential of 6G in the Next Decade

SLAWOMIR STANCZAK

6G-RIC
Research and Innovation Cluster



Prof. Dr.-Ing. habil. Slawomir Stanczak
Fraunhofer Heinrich Hertz Institute
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Bundesministerium für Bildung und Forschung

6G-RIC
Research and Innovation Cluster

Research and Innovation for Sustainable and Secure 6G Technologies

CAU Christian-Albrechts-Universität zu Kiel

Technische Universität Braunschweig

RWTH AACHEN UNIVERSITY

UR Universität Regensburg

mpii max planck institut informatik

Eberhard Karls Universität Tübingen

Fraunhofer IAF

Humboldt-Universität zu Berlin

Technische Universität Berlin

Freie Universität Berlin

Fraunhofer HHI

Fraunhofer FOKUS

Fraunhofer IZM

FBH Leibniz Ferdinand Braun Institut

ihp innovations for high performance microelectronics

Technische Universität Chemnitz

Fraunhofer IIS

FAU Friedrich-Alexander Universität Erlangen-Nürnberg

Universität Passau

DLR

- Development of Key 6G Technologies
- Demonstration of the Technologies‘ Application to selected Use Cases
- Open Test-/Development Infrastructure
- Contribution to the Development of an Open 6G Ecosystem
- Support and Promotion of Young Researchers

Coordination :

Fraunhofer Heinrich Hertz Institute
Prof. Slawomir Stanczak

Funding: BMBF

€ 70 Million

Investments approx. € 12 Million

Subcontracts approx. € 11 Million

Duration

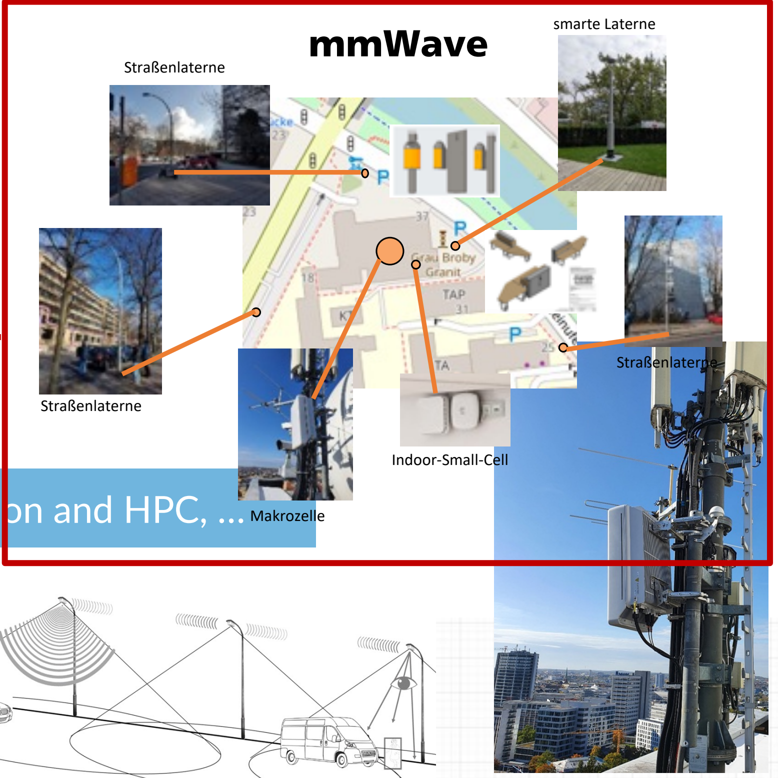
2021	2022	2023	2024	2025

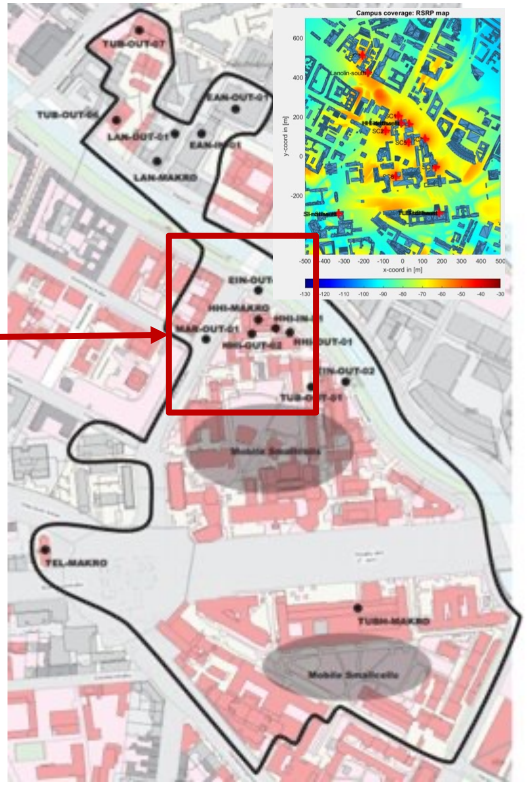
6G-RIC

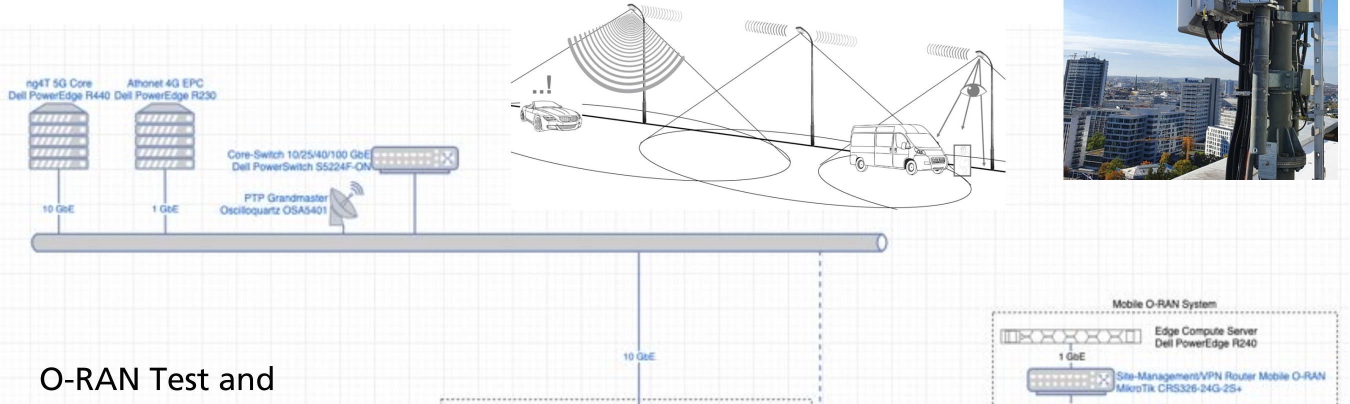
Testbeds and Infrastructure

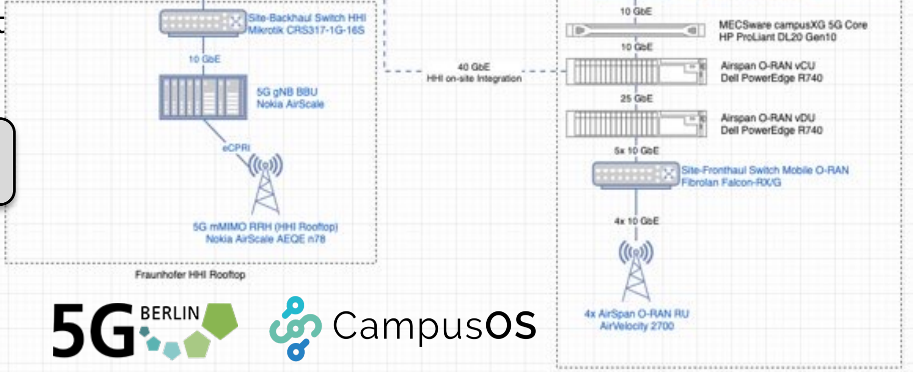
HHI Open Source Testbed

O-RAN Framework, RAN/Core Software Frameworks, Virtualisation and HPC, ...

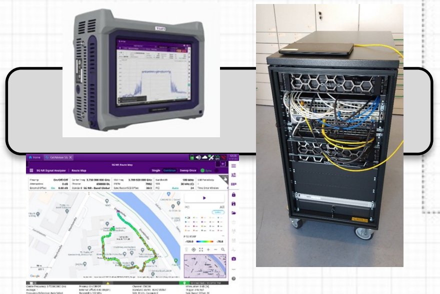






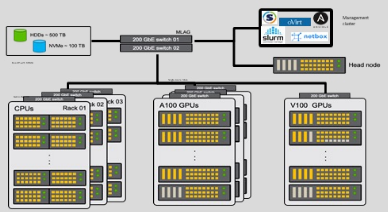


O-RAN Test and Development Environment



5G BERLIN CampusOS

Virtualization and HPC



Indoor and Outdoor Radio Deployments

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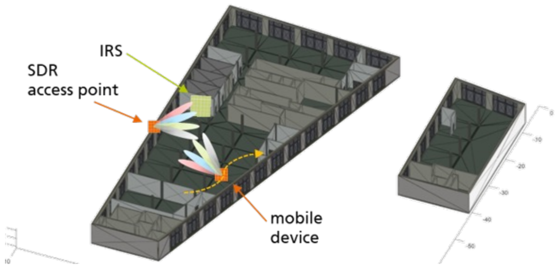
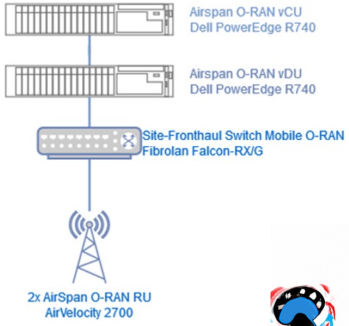
6G-RIC

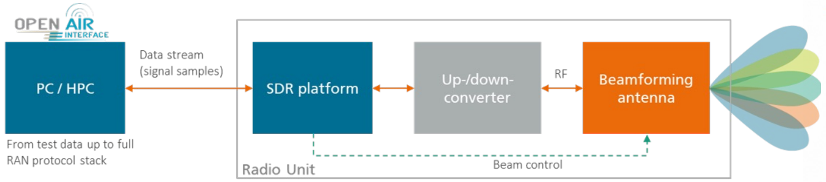
Testbeds and Infrastructure

Labs, Test Environments, and 6G-RIC Showroom

Open Interfaces (OAI, O-RAN) for Test and Demonstration

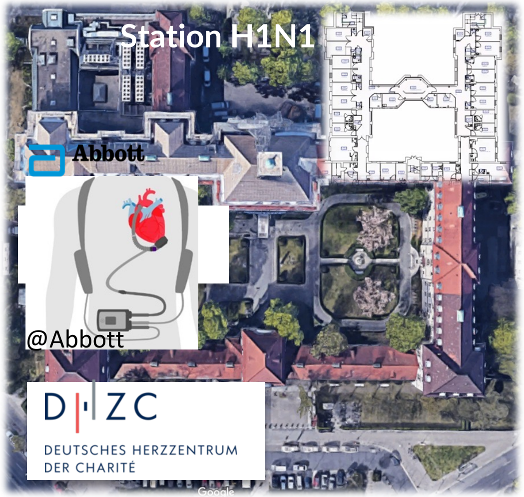




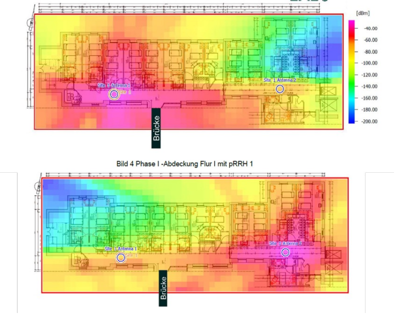


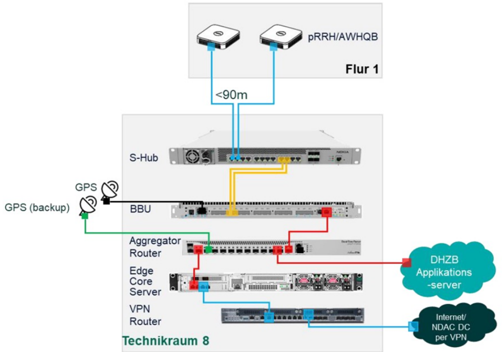
Applied Research in Medicine

5G Campus Network: German Heart Center at Charité



In Kooperation mit 5GMedCamp (BMWK)





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Throughput Increase: Potential Energy Crunch

Bits per kWh!

More $\frac{\text{Throughput}}{\text{Area}}$ = **Higher spectral efficiency** × **Higher density** × **Larger bandwidth**

Higher spectral efficiency	Higher density	Larger bandwidth
More advanced signal processing	More hardware	Sub-THz communication
! Higher energy consumption	! Higher energy consumption	! Higher energy consumption

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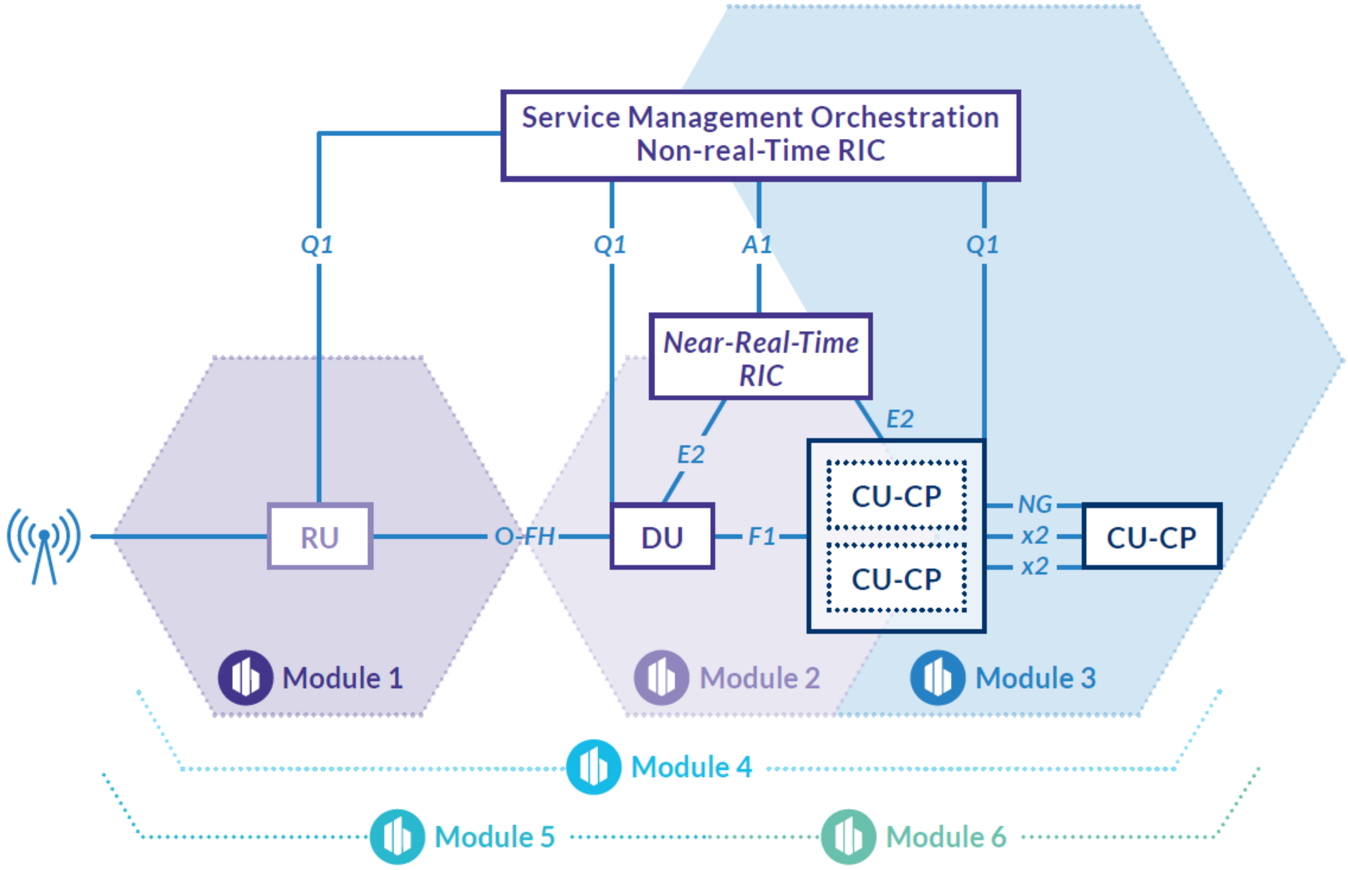
Network Computing: Virtualization and Cloudification

Intelligence per kWh!

- **Central Unit (CU) can be easily virtualized**
  - 5-10% of the processing requirements in the BBU
- **Distributed Unit (DU)**
  - provides the real-time functions of the lower layers
  - 90-95% of the processing requirements in the BBU
- **Virtualizing the DU is challenging!**



Energy efficient, real-time signal processing and network computing!

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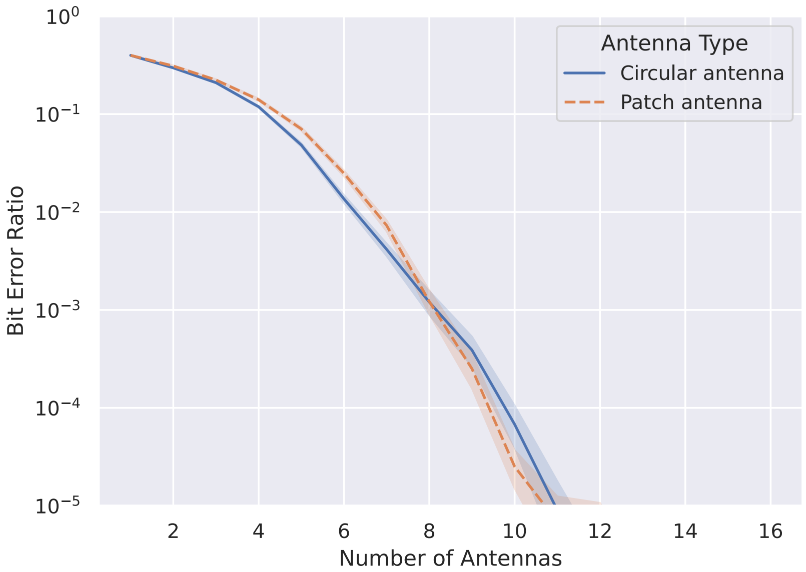
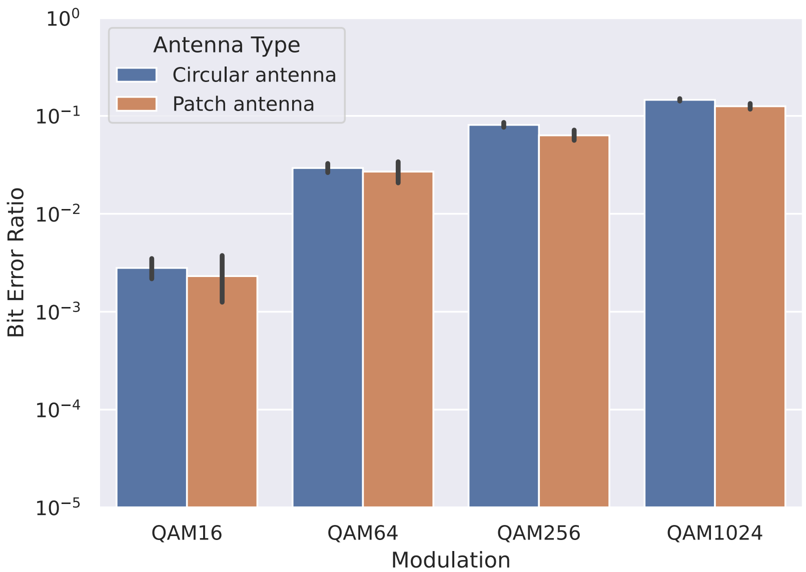
Example: Virtualized Real-Time Machine Learning-based NOMA

Use of Hardware Accelerators





Processing time (cf. MATLAB 40 seconds)

	RTX 2060 super	RTX 2080 Ti	Titan V
Baseline Implementation	7.82 ms	3.676 ms	2.23 ms
Multiple Vectors/Block	7.76 ms	2.180 ms	2.37 ms
Shared Memory	1.66 ms	1.615 ms	0.479 ms
Balanced	1.25 ms	0.906 ms	0.403 ms

Co-Design of Hardware and Software is essential

Matthias Mehlhose, et al.: Real-Time GPU-Accelerated Machine Learning Based Multiuser Detection for 5G and Beyond, IEEE Access, 2022

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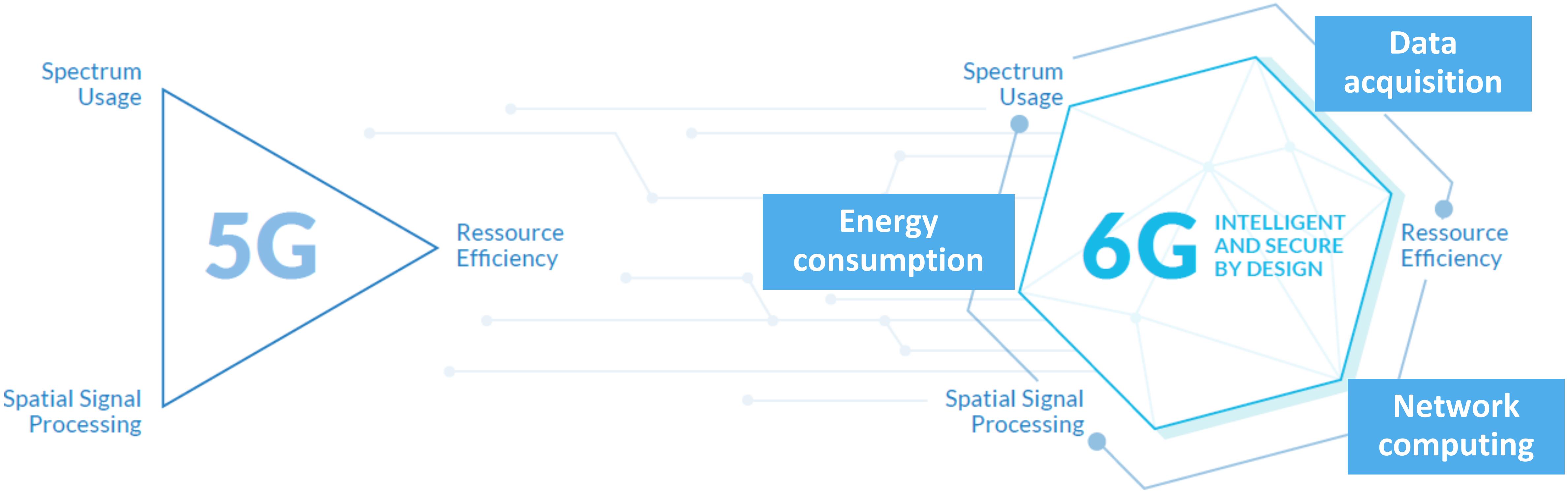
6G-RIC: Paradigm Shift in System Design

Transition towards 6G: Extended design dimensions



Energy efficiency as an integral part of the hardware and software design

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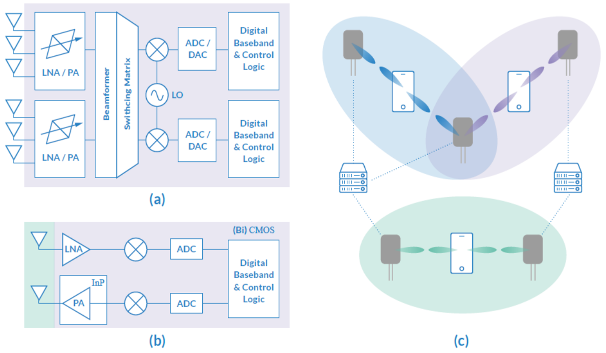
6G-RIC

Technology Innovation Areas (TIAs)

Sub-THz Mobile Access

How to achieve the throughput increase in an energy-efficient way?

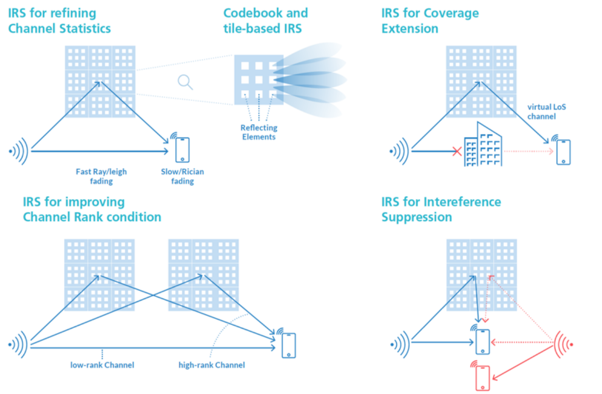
Energy-efficient transceiver architectures and radio access network design!



Steerable beamforming antennas: Key component of sub-THz and vital part of the 6G-RIC

Intelligent Reflecting Surfaces / Radio Environments

Key 6G technology or a hype?

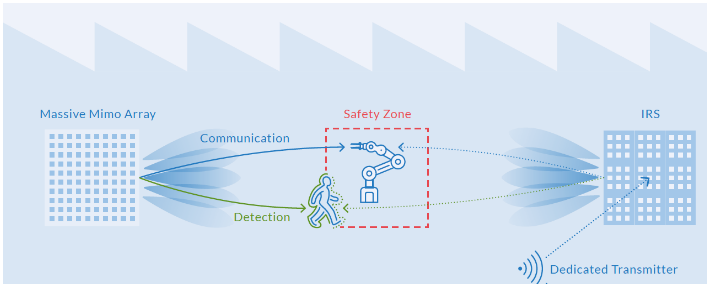


Advantages in selected scenarios, but low-complexity, real-time configuration is key!

Network as a Sensor

What level of integration of communication and sensing?

Beamspace processing for intrusion detection in industrial automation

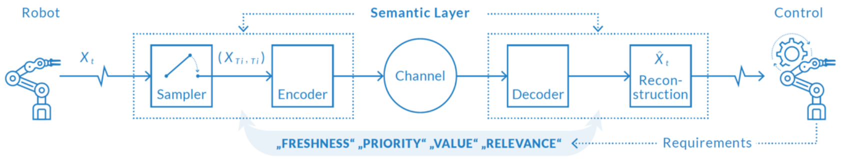


Tight integration of sensing and communication or coexistence?

Data Acquisition: Semantic Communication

Communication links are not bit pipes!

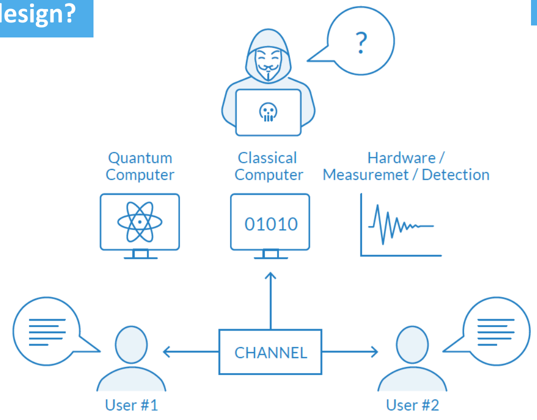
Semantic communication (6G-RIC viewpoint): *"The provisioning of the right and significant piece of information to the right point of computation (or actuation) at the right point in time."*



Goal-oriented unification of information generation, transmission and usage/control!

Embedded Security

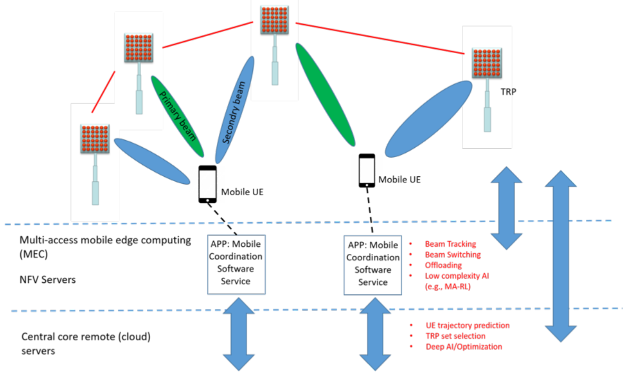
Security by design?



System security with open interfaces; Post-quantum security; PHYSEC

Autonomous Convergent Networks

Impact of 6G Technologies on Network Operation and Architecture

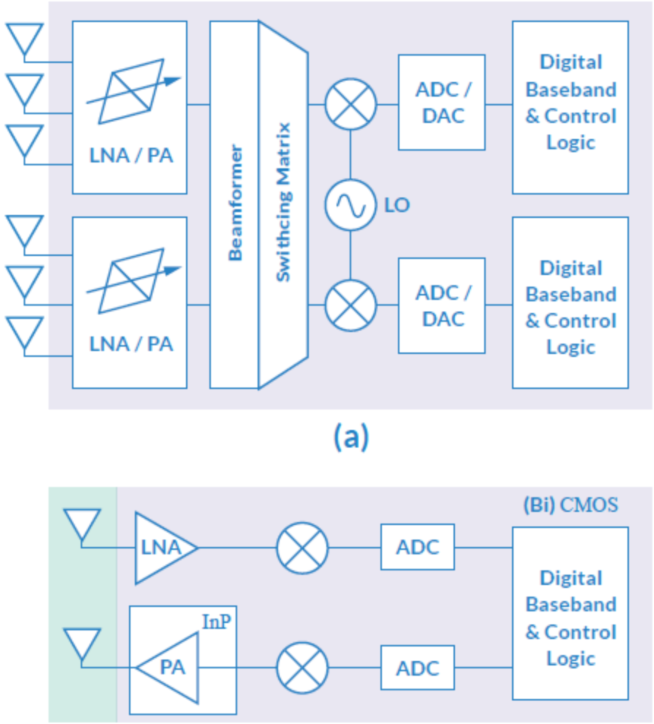


Enabling sub-THz Mobile Access via cell-free operation and distributed intelligence

Sub-THz Mobile Access

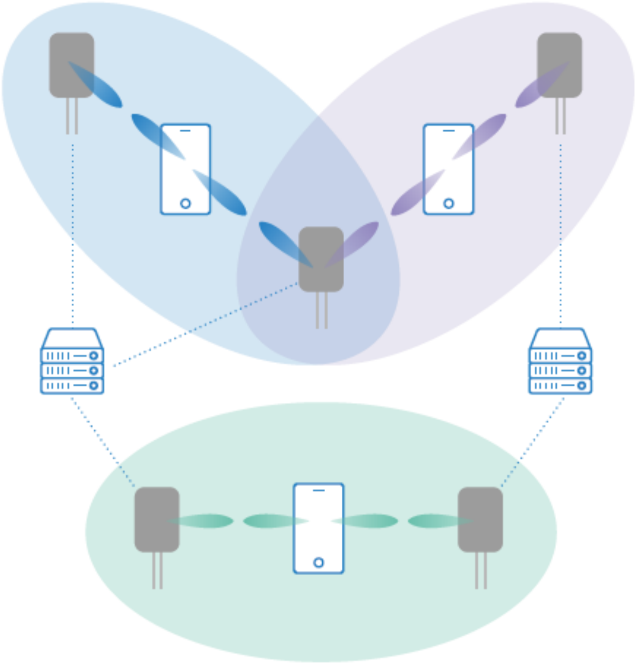
How to achieve the throughput increase in an energy-efficient way?

Energy-efficient transceiver architectures and radio access network design!



(a)

(b)



(c)

Steerable beamforming antennas: Key component of sub-THz and vital part of the 6G-RIC

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Why Sub-THz mobile access?

Achieving a 100x increase in capacity

$$C = B \cdot M \cdot \mathrm{SE} \quad [\mathrm{bit/s/km^2}]$$

Sub-6GHz 5G NR

- $B \approx 100$ MHz
- $M \approx 16$ streams/km²
- SE $\approx 4 - 6$ b/s/Hz

100x capacity?

Sub-6GHz 6G

- $B \approx 100$ MHz
- $M \approx 800$ streams/km²
- SE $\approx 8 - 12$ b/s/Hz

Sub-THz 6G

- $B \approx 30$ GHz
- $M \approx 16$ streams/km²
- SE $\approx 1 - 3$ b/s/Hz

- Sub-6GHz: very challenging
  - SE close to practical limit caused by hardware imperfections
  - Problematic interaction between M and SE caused by interference
  - In practice, capacity must be split among many low rate users
- Sub-THz key issue: energy consumption
  - Low SE sufficient for 100x capacity (and 100x single-user rates)
  - Low SE very useful for energy efficiency

Spectral efficiency (SE) is neither needed nor welcome

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How to avoid excessive energy consumption?

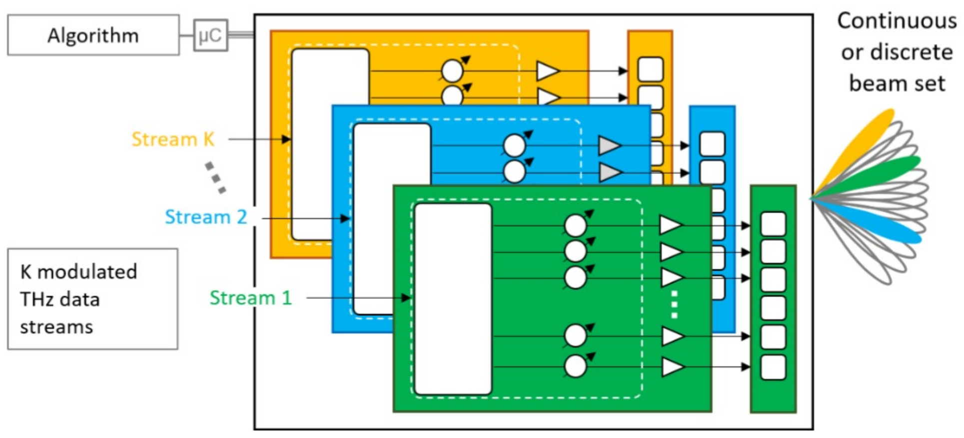
The 6G-RIC way

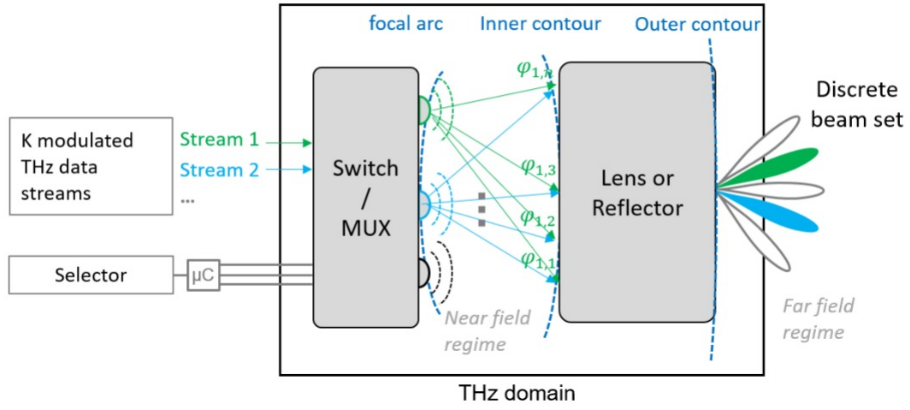
Energy efficiency (EE) is key

Cross-domain approaches enable synergetic gains

- Heterointegration of semiconductor technologies
- Modular ("partially connected") hybrid phased arrays
- Alternative analog technologies (e.g., lens, IRS)
- Low SE simplifies hardware components (PA, A/DC, etc.)
  - Constant envelope modulation (QPSK)
- Measurement/validation of sparse beam-space channel
  - Single-carrier waveform + simple EQ likely enough

Efficient beam-alignment / tracking is key





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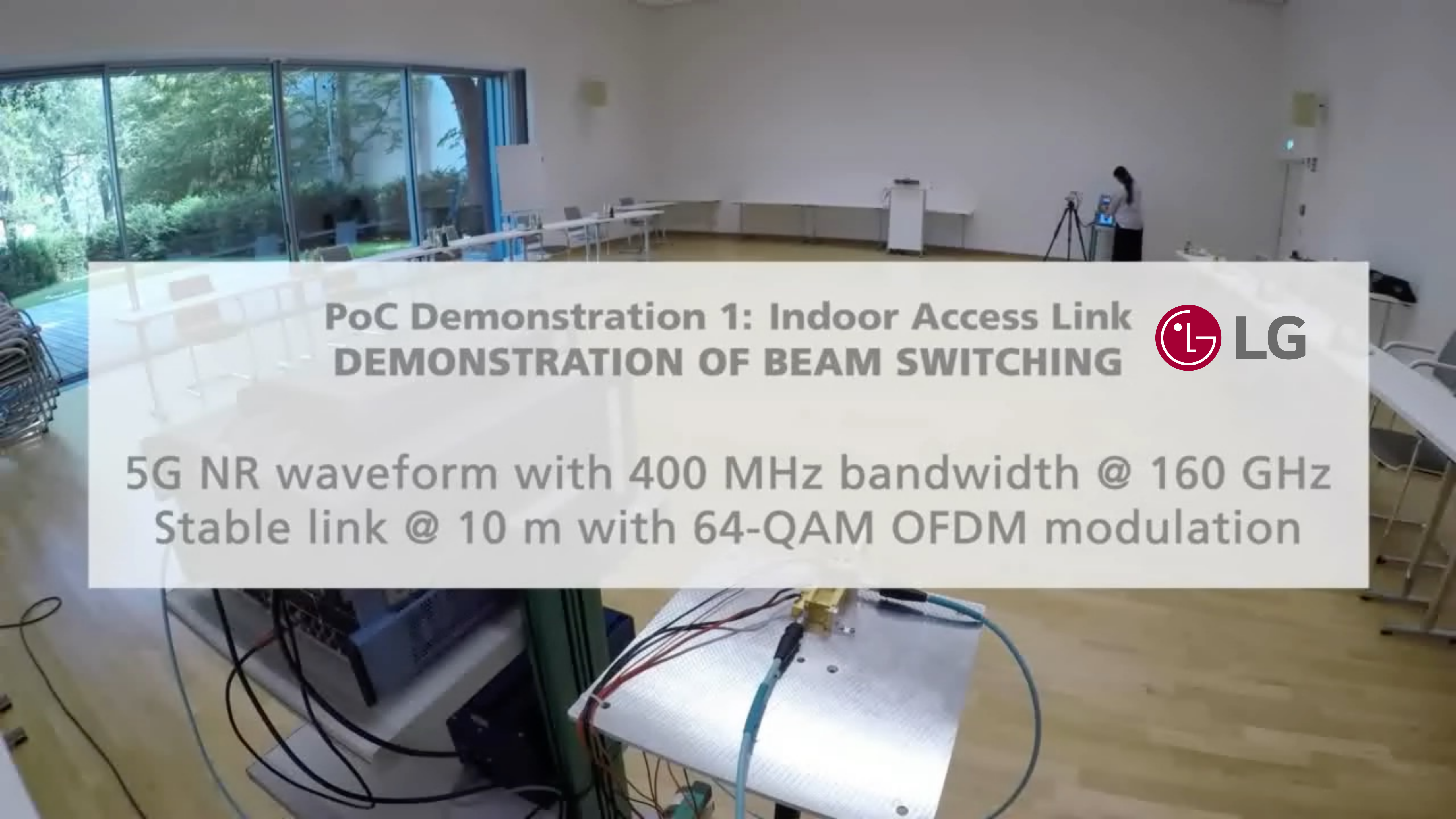
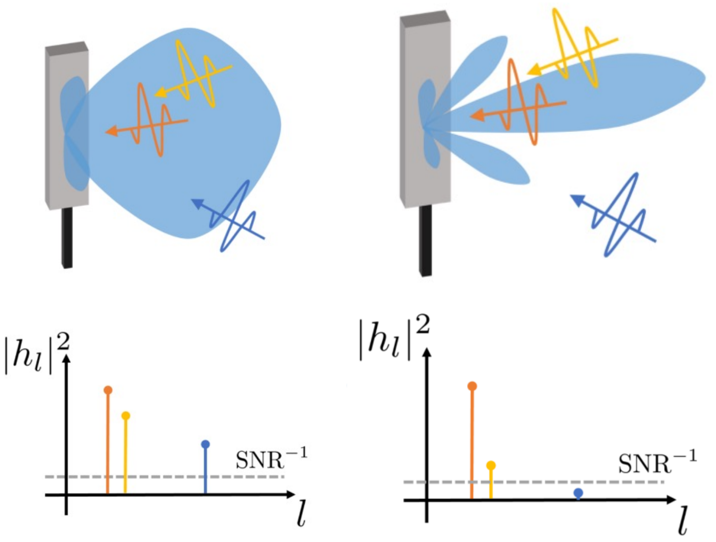

PoC Demonstration 1: Indoor Access Link
DEMONSTRATION OF BEAM SWITCHING
LG
5G NR waveform with 400 MHz bandwidth @ 160 GHz
Stable link @ 10 m with 64-QAM OFDM modulation

Sub-THz Mobile Access

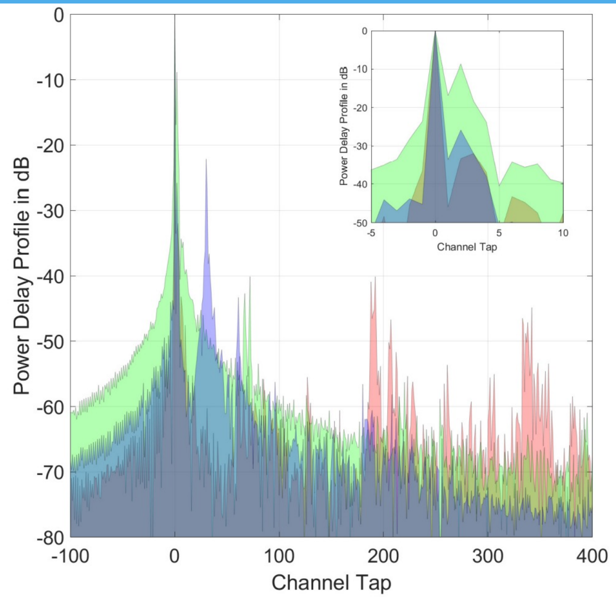
Flat effective channel and validation using measurements

Basic Idea

- ○ Low target spectral efficiency
- ○ Directivity decreases delay spread
  - channel becomes essentially flat
  - simple equalization possible



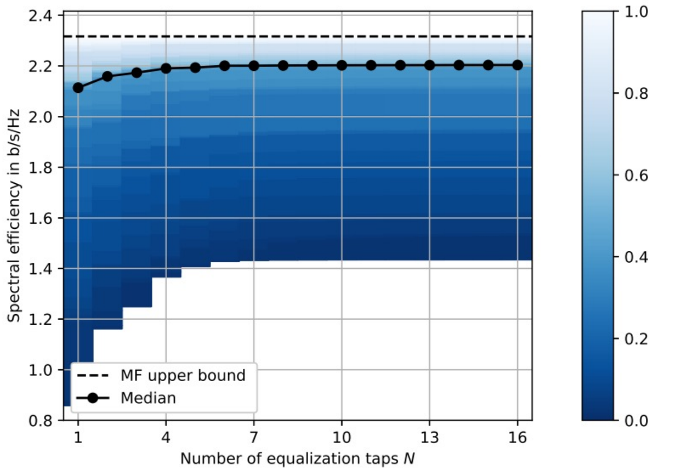
Indoor measurements at 160 GHz/4GHz



- ○ Measurements approximate real sub-THz radio channels after:
  - Two-sided beam alignment (LoS)
  - Sinc-like Nyquist pulses
  - Phase and freq. offset compensation
  - Timing synchronization

Validation

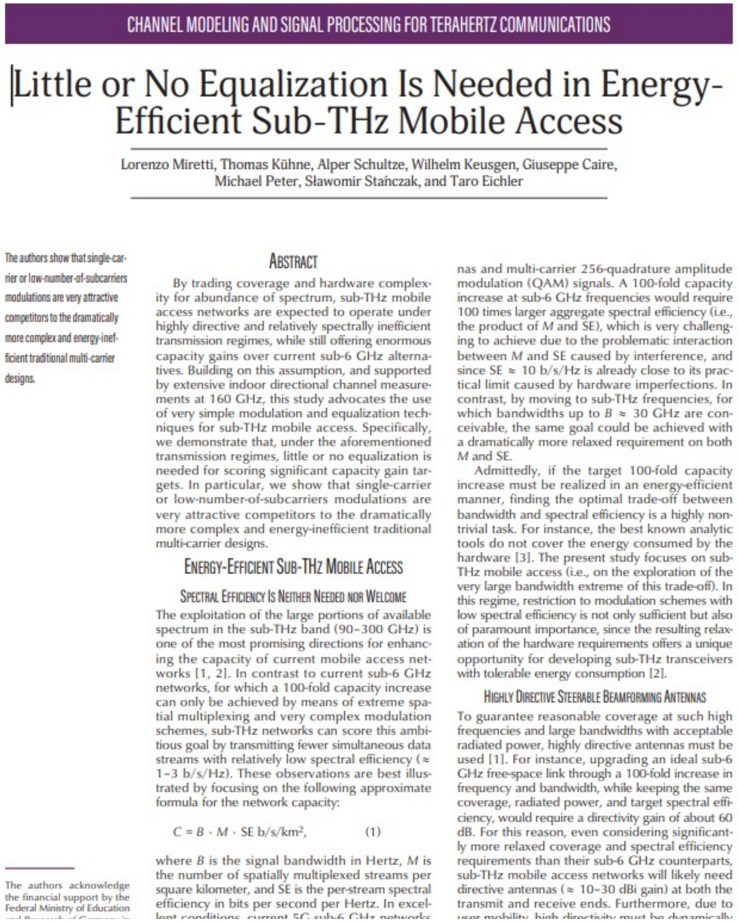
- ○ Single-carrier, N-taps linear MMSE equalizer
  - Mostly no equalization needed
  - Worst-case channels: 5-6 taps are sufficient to mitigate most inter-symbol interference



Sub-THz Mobile Access

The first demonstrator at ICC in Rome

Publication



CHANNEL MODELING AND SIGNAL PROCESSING FOR TERAHERTZ COMMUNICATIONS

Little or No Equalization Is Needed in Energy-Efficient Sub-THz Mobile Access

Lorenzo Miretti, Thomas Kühne, Alper Schultze, Wilhelm Keusgen, Giuseppe Caire, Michael Peter, Sławomir Stańczak, and Taro Eichler

The authors show that single-carrier or low-number-of-subcarriers modulations are very attractive competitors to the dramatically more complex and energy-inefficient traditional multi-carrier designs.

Abstract

By trading coverage and hardware complexity for abundance of spectrum, sub-THz mobile access networks are expected to operate under highly directive and relatively spectrally inefficient transmission regimes, while still offering enormous capacity gains over current sub-6 GHz alternatives. Building on this assumption, and supported by extensive indoor directional channel measurements at 160 GHz, this study advocates the use of very simple modulation and equalization techniques for sub-THz mobile access. Specifically, we demonstrate that, under the aforementioned transmission regimes, little or no equalization is needed for scoring significant capacity gain targets. In particular, we show that single-carrier or low-number-of-subcarriers modulations are very attractive competitors to the dramatically more complex and energy-inefficient traditional multi-carrier designs.

Energy-Efficient Sub-THz Mobile Access

Spectral Efficiency Is Neither Needed nor Welcome

The exploitation of the large portions of available spectrum in the sub-THz band (90–300 GHz) is one of the most promising directions for enhancing the capacity of current mobile access networks [1, 2]. In contrast to current sub-6 GHz networks, for which a 100-fold capacity increase can only be achieved by means of extreme spatial multiplexing and very complex modulation schemes, sub-THz networks can score this ambitious goal by transmitting fewer simultaneous data streams with relatively low spectral efficiency (≈ 1–3 b/s/Hz). These observations are best illustrated by focusing on the following approximate formula for the network capacity:

$$C = B \cdot M \cdot \text{SE b/s/km}^2, \qquad (1)$$

where B is the signal bandwidth in Hertz, M is the number of spatially multiplexed streams per square kilometer, and SE is the per-stream spectral efficiency in bits per second per Hertz. In excellent conditions, current 5G sub-6 GHz networks

nas and multi-carrier 256-quadrature amplitude modulation (QAM) signals. A 100-fold capacity increase at sub-6 GHz frequencies would require 100 times larger aggregate spectral efficiency (i.e., the product of M and SE), which is very challenging to achieve due to the problematic interaction between M and SE caused by interference, and since SE ≈ 10 b/s/Hz is already close to its practical limit caused by hardware imperfections. In contrast, by moving to sub-THz frequencies, for which bandwidths up to B ≈ 30 GHz are conceivable, the same goal could be achieved with a dramatically more relaxed requirement on both M and SE.

Admittedly, if the target 100-fold capacity increase must be realized in an energy-efficient manner, finding the optimal trade-off between bandwidth and spectral efficiency is a highly non-trivial task. For instance, the best known analytic tools do not cover the energy consumed by the hardware [3]. The present study focuses on sub-THz mobile access (i.e., on the exploration of the very large bandwidth extreme of this trade-off). In this regime, restriction to modulation schemes with low spectral efficiency is not only sufficient but also of paramount importance, since the resulting relaxation of the hardware requirements offers a unique opportunity for developing sub-THz transceivers with tolerable energy consumption [2].

Highly Directive Steerable Beamforming Antennas

To guarantee reasonable coverage at such high frequencies and large bandwidths with acceptable radiated power, highly directive antennas must be used [1]. For instance, upgrading an ideal sub-6 GHz free-space link through a 100-fold increase in frequency and bandwidth, while keeping the same coverage, radiated power, and target spectral efficiency, would require a directivity gain of about 60 dB. For this reason, even considering significantly more relaxed coverage and spectral efficiency requirements than their sub-6 GHz counterparts, sub-THz mobile access networks will likely need directive antennas (≈ 10–30 dBi gain) at both the transmit and receive ends. Furthermore, due to

The authors acknowledge the financial support by the Federal Ministry of Education

Demonstration: World's first long-range D-Band system with analog beamforming

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Semantic Communication

The search for meaning

C. E. Shannon and W. Weaver, 1949:

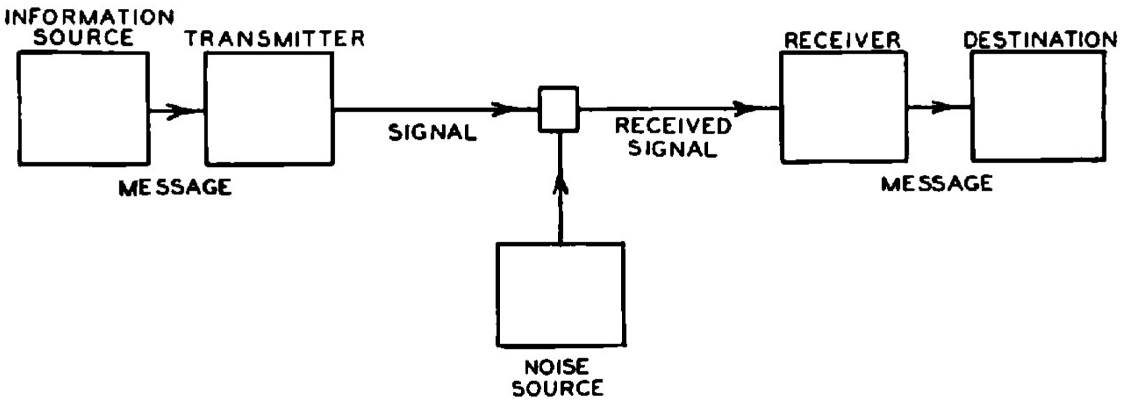
The technical problem:
- symbols conveying information should be reliably transmitted to the recipient;

The semantic problem:
- the meaning conveyed by the transmitted symbols should accurately reflect the intentions of the sender;

The effectiveness problem:
- The conduct of the system in response to communications should be effective in accomplishing a desired task.

Historically, focus on the „technical problem“

Communication model as considered by C. Shannon, 1948



It fails to meet the needs of new networked intelligent systems

Beyond the technical problem of communication: escaping the „Shannon Trap“! [Popovski et al.]

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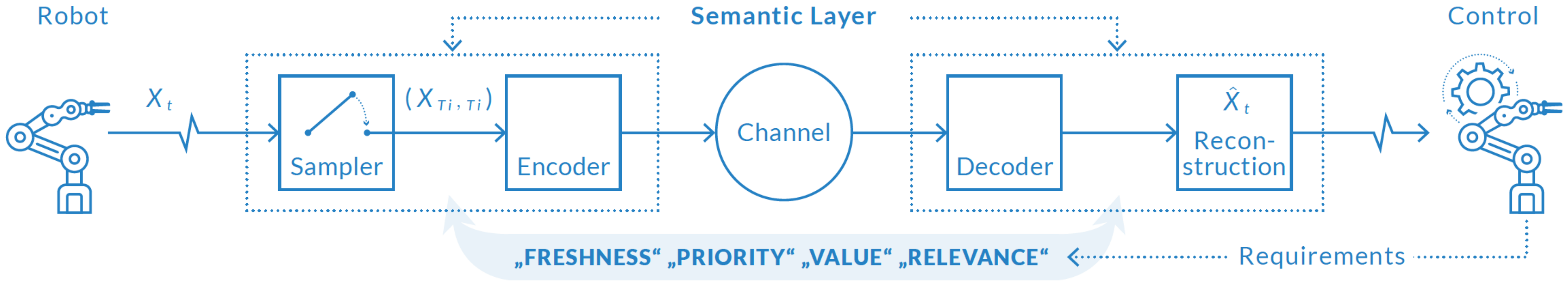
Data Acquisition: Semantic Communication

Communication links are not bit pipes!

Semantic communication (6G-RIC viewpoint):
“The provisioning of the right and significant piece of information to the right point of computation (or actuation) at the right point in time.”

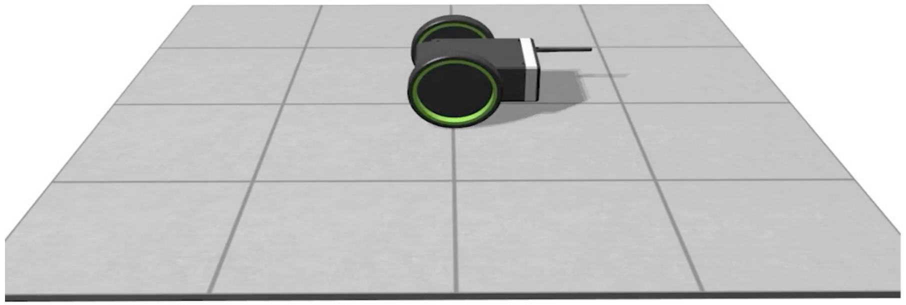


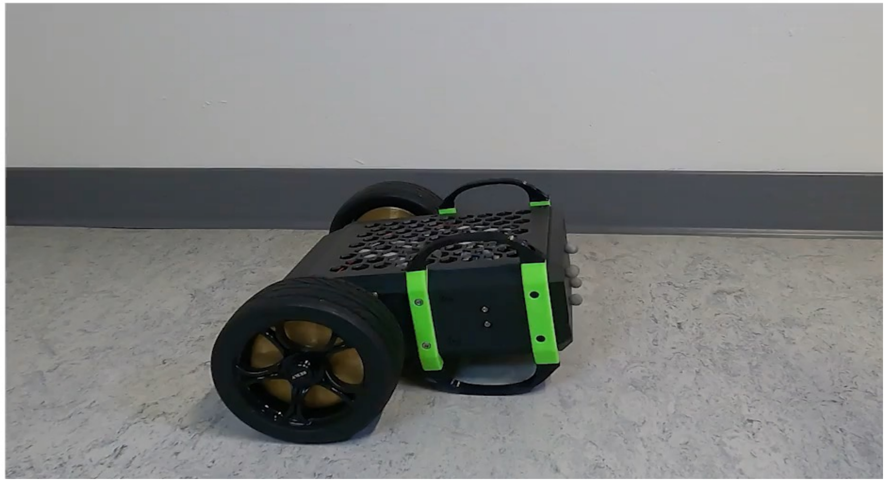
Goal-oriented unification of information generation, transmission and usage/control!

Example of Goal-Oriented Communication

Connected Robotics and Autonomous Systems (CRAS)

EXPERIMENTS





Chair Prof. Jörg Raisch

Technische Universität Berlin

science of intelligence

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Neuromorphic Processing for Energy-efficient Edge Intelligence

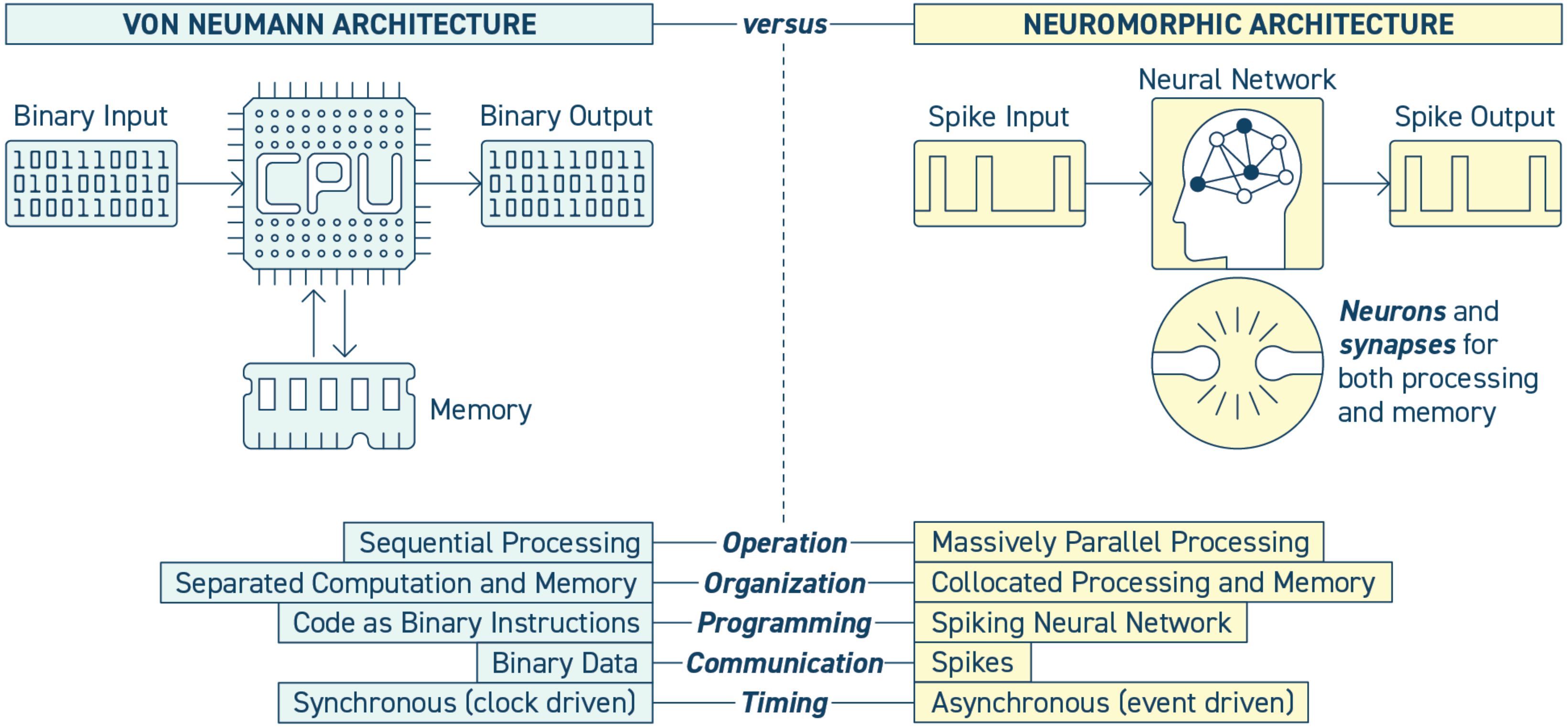
Spiking Neural Networks (SNNs) for Edge Intelligence: A Perfect Match?

Why Neuromorph. Processing?

- energy-efficiency (**~ pJ per spike**)
- low latency, event-based processing

Interest from Industry:

- Intel (LOIHI)
- IBM (TrueNorth)
- Prophesee & Sony (Neuromorphic Vision)
- Brainchip (AKIDA)
- Spinnaker (EU Brain Project)
- SynSense



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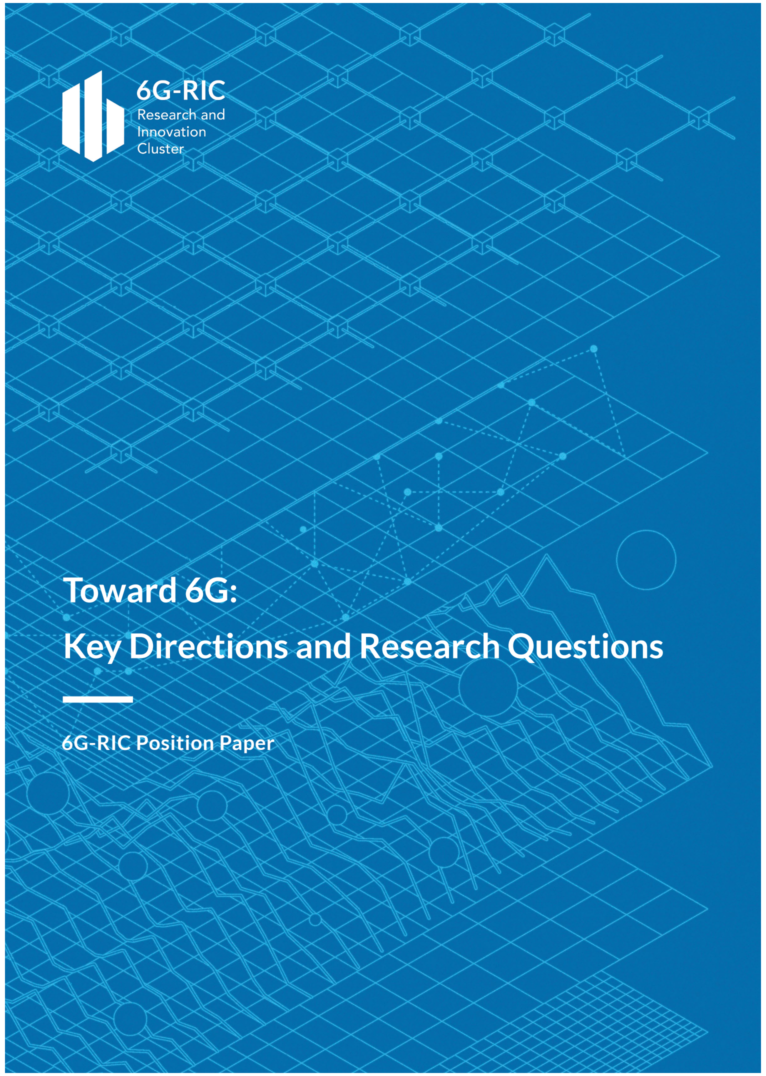
6G-RIC Position Paper

Published in Nov. 2022

- poses key research questions
- defines the research scope of the 6G-RIC
- basis for whitepapers and magazine papers



Thank You!