



Hexa-X-II

D4.5: Final design of 6G radio solutions and promising radio innovations

Ahmad Nimr, Nurul Huda
Mahmood

hexa-x-ii.eu



WP4 Overview



Objectives	Tasks	Quantified targets
Objective 3: Enhanced connectivity for 6G services	T4.1: Sustainable, trustworthy and inclusive holistic radio design T4.2: Towards THz communications T4.4: Intelligent radio air interface design T4.5: Flexible spectrum access solutions	<ul style="list-style-type: none"> Data rate: (> 0.1 Tbps) access links Low-latency: (< 1 ms E2E and <0.1 ms in critical subnetworks), Service coverage: (> 99 %) of global population and (> 99 %) of world area with at EMF compliance: with international and EU recommended limits <p>A least one basic 6G use case at sustainable cost levels.</p>
Objective 4: Network sensing, compute, and AI for novel digital services	T4.3: Joint Communications and Sensing	<ul style="list-style-type: none"> Sensing precision: (< 1 m at 90th percentile) in mid-band, (< 10 cm at 90th percentile) at 100 GHz Detect a moving human-sized object at 10 m distance



		Milestones																													
		MS1					MS2					MS3					MS4					MS5					MS6				
HEXA-X II workplan		M01	M02	M03	M04	M05	M06	M07	M08	M09	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26				
WP4	Radio Evolution & Innovation																														
T4.1	Sustainable, trustworthy and inclusive holistic radio design						D				D							D									D				
T4.2	Towards THz communications						D				D							D									D				
T4.3	Joint Communications and Sensing						D				D							D									D				
T4.4	Intelligent radio air-interface design						D				D							D									D				
T4.5	Flexible spectrum access solutions						D				D							D									D				
Deliverables							D4.1				D4.2						D4.3								D4.4	D4.5					

- D4.1: **Presentation** on identified **key enablers** for 6G radio design and spectrum access [Jun 2023] (Internal)
- D4.2: Radio design and spectrum access requirements and **key enablers** for 6G Evolution [Oct 2023] (Public)

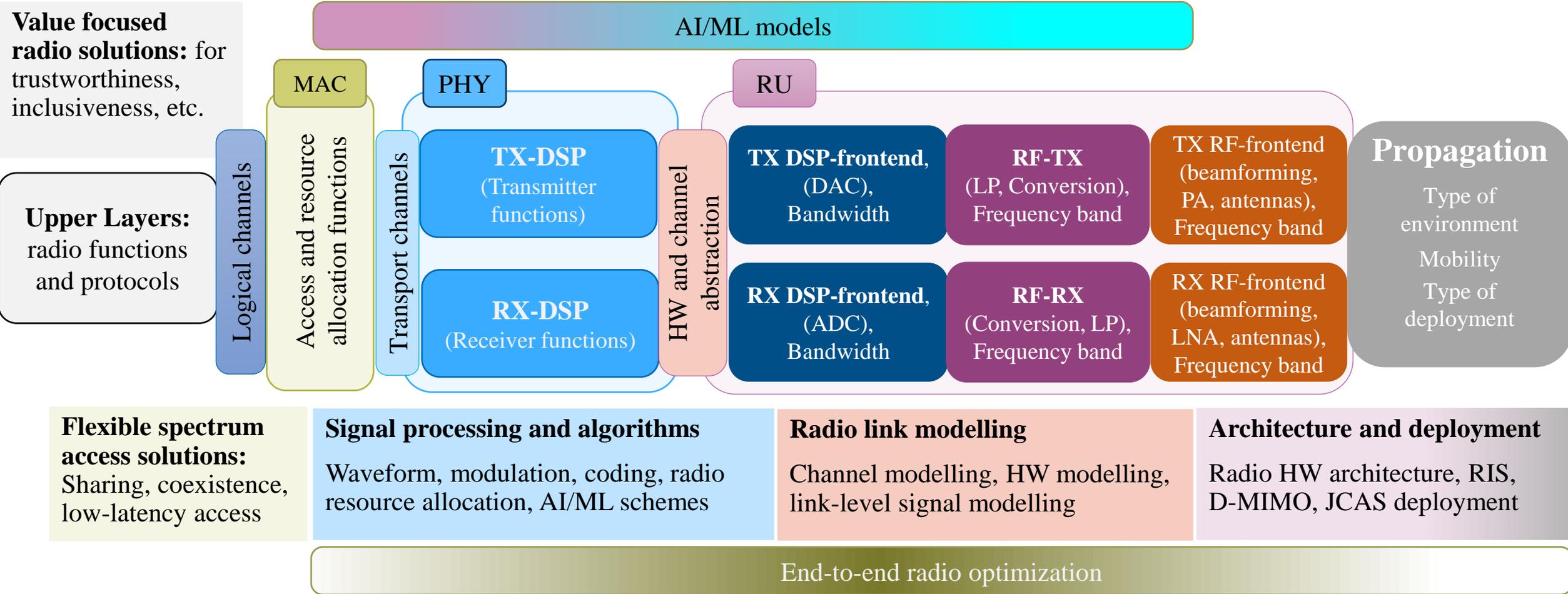
- D4.3: **Early results of 6G Radio Key Enablers** [Apr 2024] (Public)
- D4.4: **Preview of the final design** of 6G Radio solutions and Promising Radio Innovations [Dec 2024] (Internal)

D4.5: Final design of 6G Radio solutions and Promising Radio Innovations [Feb 2025] (Public)

Sustainable, trustworthy and inclusive holistic radio design framework



Holistic radio design considers the entire radio system as a whole, and the interdependencies between different elements.



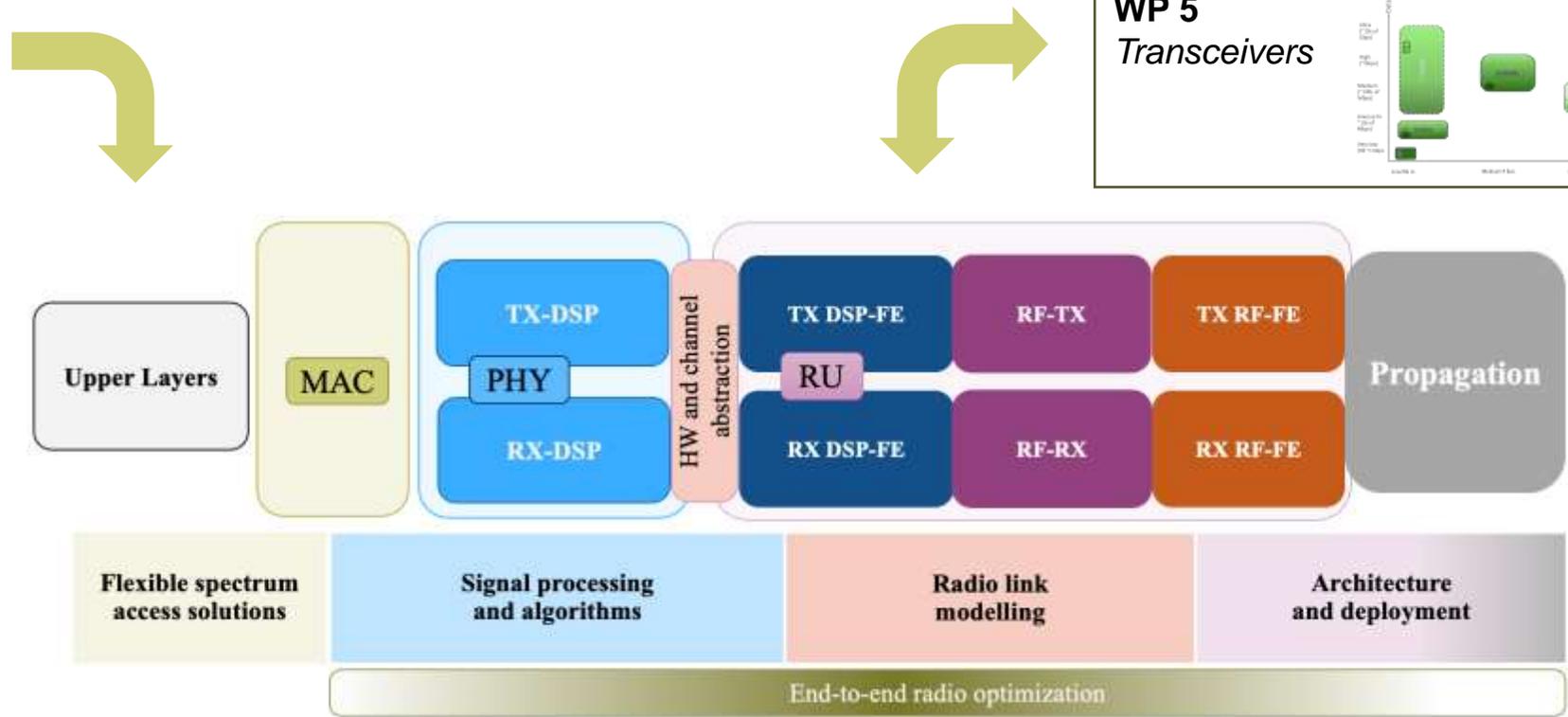
View of Hexa-X-II from WP4



WP 1
Use cases, sustainability, spectrum regulations

	FR 1	7-12 GHz	FR 2	82-300 GHz
Typically licensed				License-free or license-assisted
bandwidth	500 kHz	10 MHz	100 MHz	Multiple GHz
TM coverage	Wide area	Local	Local	Local
positioning	10m	10 cm	10 cm	10 cm

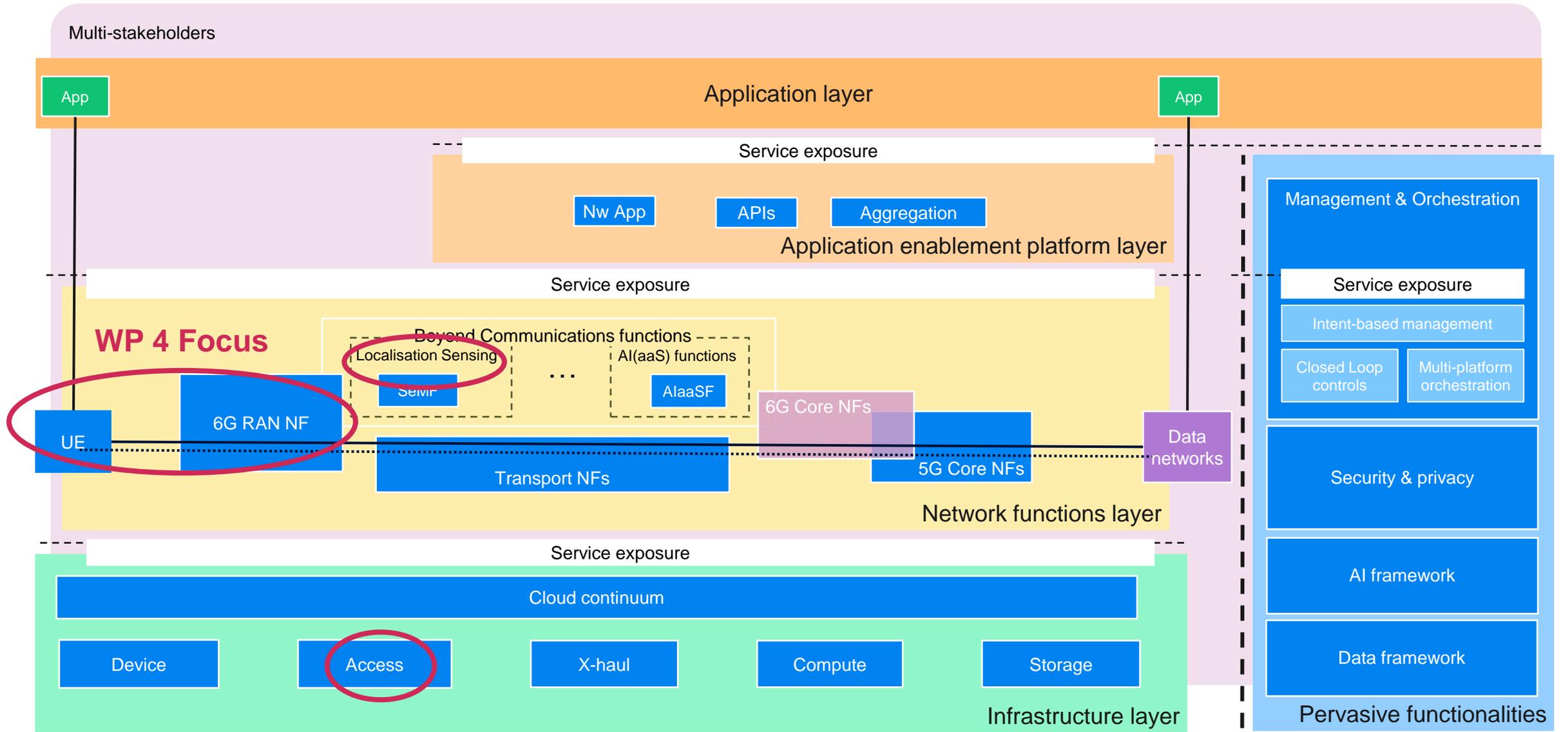
WP 5
Transceivers



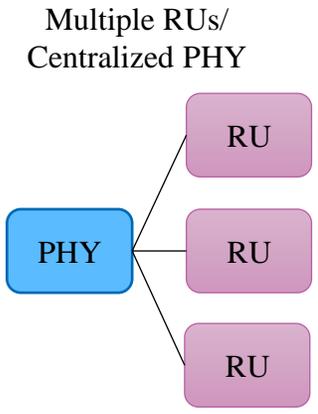
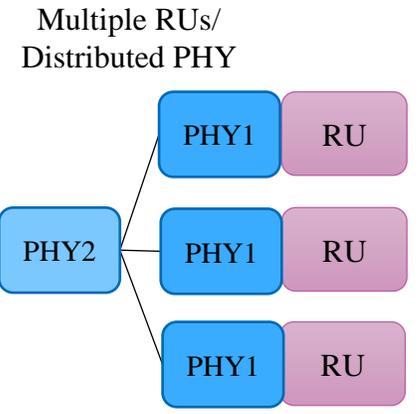
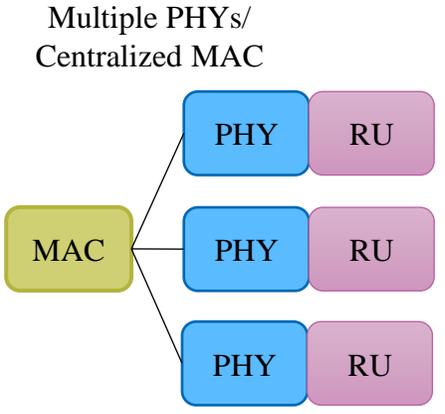
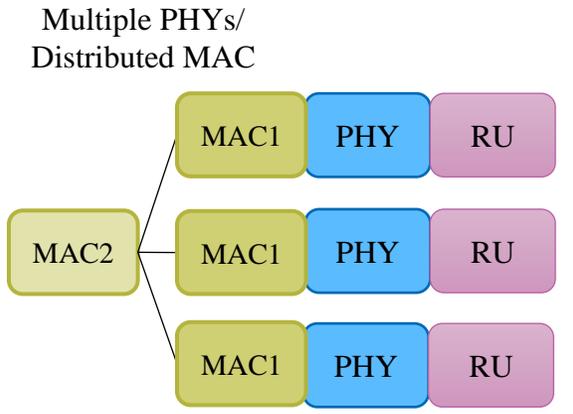
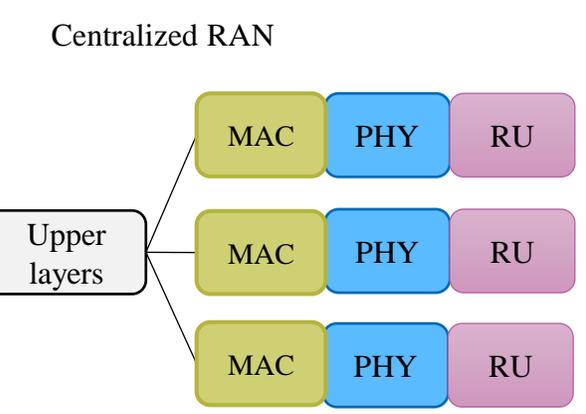
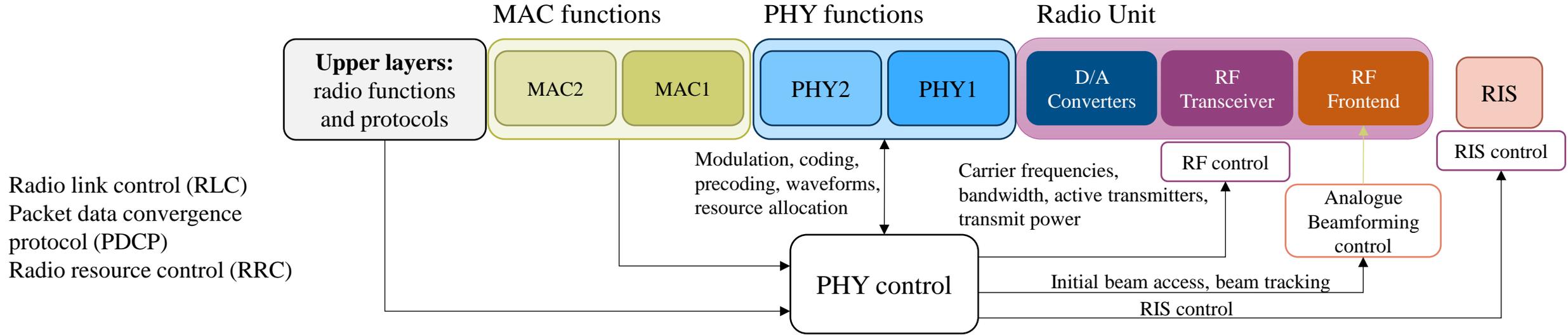
WP 2
System blueprint

WP 3
JCAS, NTN, AI

Mapping to System Blueprint



Flexible radio architecture and deployment



Examples:

Dual connectivity at PDCP

Carrier aggregation in different ranges, e.g. (FR1, FR2)

Carrier aggregation

D-MIMO, distributed PHY processing

D-MIMO, centralized PHY processing

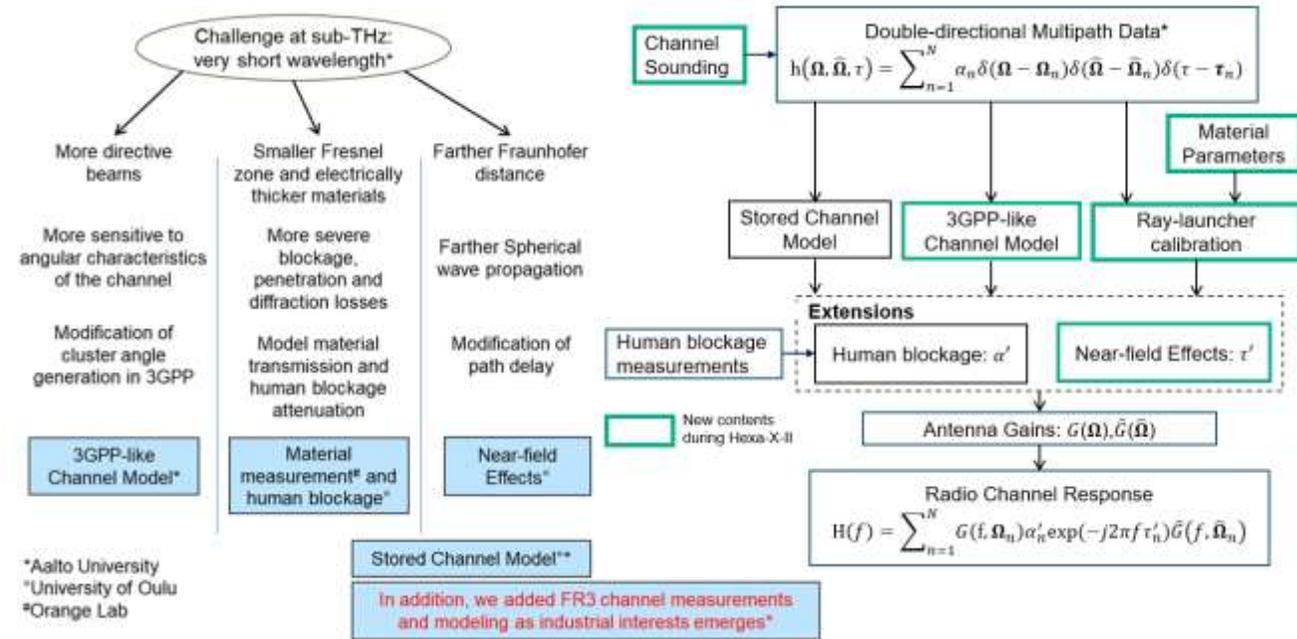
Channel Modelling



Channel modelling methodology

Chapter outline

- Impact of coated surfaces on reflection coefficients
- Simplified model for molecular absorption loss above 100 GHz
- Sub-THz dual-band channel characterization for IIoT
- Channel model components for near-field condition
- 3GPP-like channel model at 140 GHz
- Calibration of ray-launcher for coverage study at 140 GHz
- Implication of sub-THz link budget on EMF compliance
- FR-3 channel sounding at 15 GHz



Key findings

- New channel model components and parameters are introduced for channels at 6G operating frequencies (sub-THz ((100-300 GHz) and FR3 ((7-24 GHz)).
- This work supports some of identified needs of other work packages and enables their simulation studies.
- New propagation measurements at radio frequencies of interest are described.
- This task also studied the following items that were reported in D4.3
 - JCAS channel models at any frequencies
 - Coverage analysis at THz frequencies
 - Signal level analysis for RIS in a simplified scenario

MIMO Transmission



Chapter outline

- D-MIMO transmission schemes
 - Coherent joint transmission
 - Non-coherent space-time coded transmission
 - Distributed OTA cooperative beamforming design
- D-MIMO architectures
 - D-MIMO with rotary ULAs
 - D-MIMO with analogue fronthaul
 - D-MIMO for JCAS
- Massive MIMO
 - Energy efficient beamforming for sub-THz
 - Hybrid analogue-digital architectures
 - MU-MIMO optimization in diverse device scenarios
- Low-complexity optimization for MIMO
 - One-bit ADC for multicell setup
 - Enhanced data detection with 1-bit ADCs
 - Massive MIMO with 1-bit DAC/ADCs

Key findings

- Coherent and non-coherent beamforming strategies can address varying CSI availability and fronthaul signalling limitations, ensuring robust system performance.
- Rotary and movable antennas in D-MIMO scenarios have demonstrated significant performance improvements.
- Analogue fronthaul integration enhances EVM performance by improving synchronization and signal quality.
- The optimization of JCAS beamforming within D-MIMO systems showed promising gains.
- Energy-efficient hybrid beamforming architectures and deployment strategies can minimize power consumption while maintaining high performance in massive MIMO systems.
- In the context of MU-MIMO, low-complexity, data-driven channel estimation techniques have been introduced to handle scenarios where pilot-based CSI is unavailable.
- Lastly, techniques to enhance the performance of 1-bit ADCs have been proposed for both single-cell and multi-cell scenarios, showcasing their potential for low-complexity, energy-efficient massive MIMO implementations.

RIS-Assisted Transmission



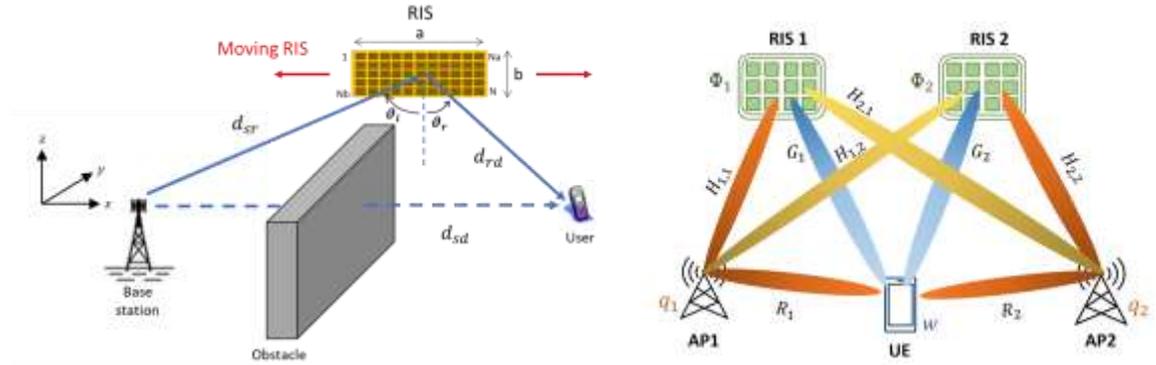
Chapter outline

- Signal level analysis for RIS in a simplified scenario
- D-MIMO assisted with RIS
- RIS assisted integrated access and backhaul (IAB)
- Reflection modulation via RIS with jointly active and passive beamforming

Key findings

- RIS can provide a substantial coverage enhancement when the direct propagation path is strongly attenuated or fully blocked.
- RISs can improve the performance of D-MIMO or lower deployment costs by trading off APs and RISs.
- Advanced techniques such as multi-RIS UE assistance and active RIS can enhance the performance of D-MIMO systems.
- Service coverage probability in IAB networks is improved in certain scenarios.
- Reflection modulation methods via RIS shows promising performance gains compared with beamforming approaches without RIS.

Examples of RIS deployment scenarios



Open Challenges

- RIS control is a complex challenge that needs further investigations towards standardization.
- Tunable elements in passive RIS are difficult to design and manufacture.
- Aggregated CSI via RIS is difficult to acquire in dynamic environments.
- Power consumption of RIS surface and control unit adds to the overall power energy cost.
- Uncontrolled interference is a challenge due to broadband nature of RIS, requiring complex interference management techniques.
- Dynamically configuring the RIS efficiently in real time is challenging.
- Multi-RIS deployment requires efficient algorithms and network protocols.

Waveform and Modulation



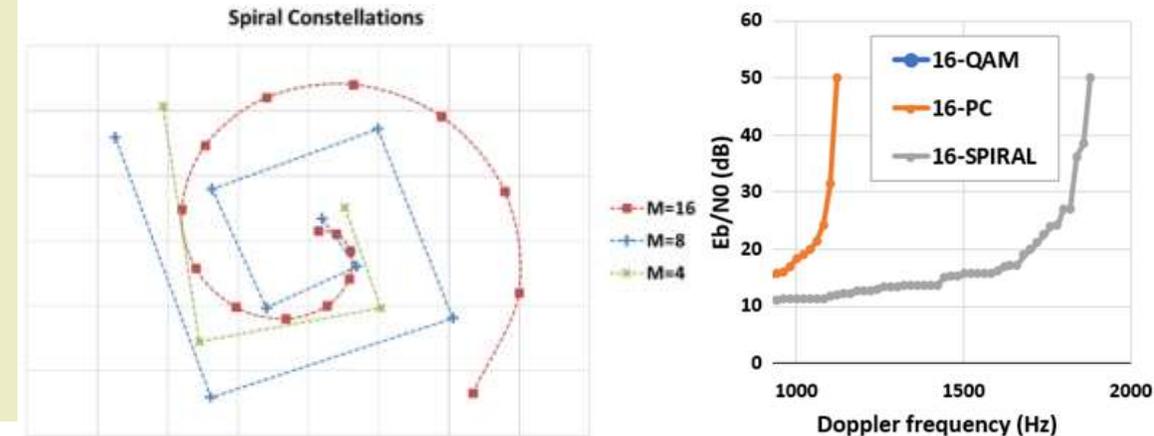
Chapter outline

- Sub-THz waveform and constellation candidates
 - Evolution of NR numerology and waveforms towards sub-THz
 - Polar constellations
 - Hardware-friendly waveforms
 - Energy-efficiency of 1-bit quantized zero-crossing modulation
- Waveform and modulation enhancements
 - Adaptive multi-carrier modulation
 - New LDPC code parity matrix design

Key findings

- A careful design of the waveform and modulation schemes can lead to efficient power consumption, and low phase noise (PN) & out-of-band radiation.
- Sub-THz communications would benefit from supporting CP-OFDM and DFT-s-OFDM, allowing larger bandwidth and enhancement to PN mitigation.
- Polar constellations can integrate FR2 and sub-THz systems due to their high resistance to white noise and Doppler shifts, achieving better performance than M -QAM.
- One-bit quantised zero-crossing modulation is found to be more energy-efficient than M -QAM modulations at 120 GHz.
- An Adaptive multi-carrier modulation was proposed to address the stricter spectrum mask regulations in 6G and was found to outperform conventional OFDM.
- Lastly, a new LDPC code parity matrix showed a remarkable decoding performance with reduced complexity.

One of the proposed polar constellation for Sub-THz transmission (left), and the corresponding performance gains (right)



Intelligent Radio Air Interface Design



Chapter outline

- The framework to enable AI-driven air interface
- Learning for waveform, modulation and coding
 - MIMO waveform for communication
 - waveform and precoding for JCAS
 - AI for LDPC matrix structure optimization
- AI-based CSI acquisition
 - ML-based channel state feedback compression in a multi-vendor scenario
 - Intelligent CSI compression
 - CSI prediction
 - Antenna muting
 - User pairing for MU-MIMO
 - Power control for D-MIMO
- AI solutions for hardware impairments
 - AI-driven PA-nonlinearity compensation
 - Generative AI for hardware impaired communication

Key findings

- **AI-Driven Waveform and Coding:** Leveraging AI in waveform, modulation, and coding design offers substantial improvements in spectral efficiency and reduces transmission overhead.
- **AI-Based CSI Acquisition:** AI-based CSI acquisition and compression can significantly enhance network spectral efficiency while minimizing the feedback overhead. These are especially advantageous in dynamic and multi-vendor scenarios.
- **AI-Based MIMO Transmission:** Applying AI to optimize MIMO transmissions, from power control and user pairing to antenna management unlocks the potential for more efficient communication schemes, including pilot-free transmissions, and introduce flexible strategies for maximizing throughput and user quality of service.
- **AI Solutions for Hardware Impairments:** Finally, AI provides innovative solutions to manage power amplifier non-linearities and other hardware impairments, ensuring stable performance in the presence of non-idealities.

Joint Communications and Sensing



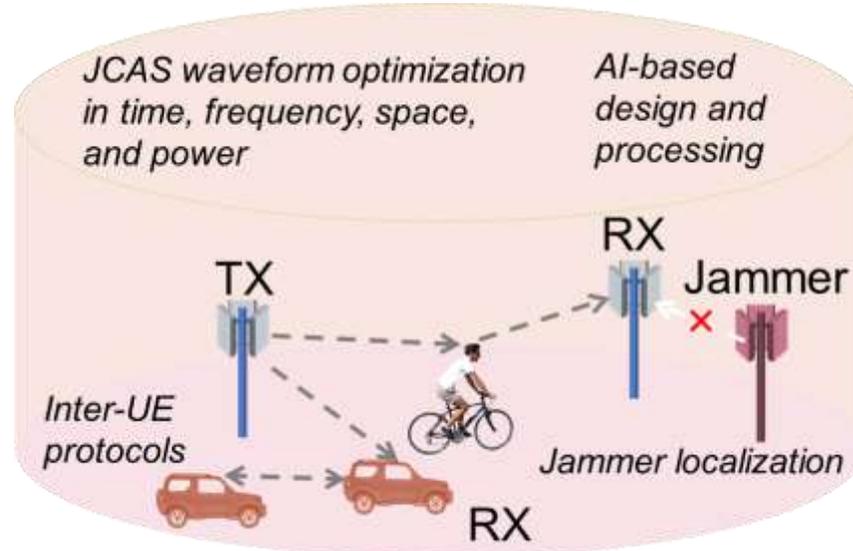
Chapter outline

- JCAS deployments
 - NTN and RIS-aided localization
 - Multi-static sensing
 - Evaluation of bistatic sensing performance in indoor scenarios
- JCAS resource optimization
 - Optimization of OFDM-based bistatic sensing
 - Resource allocation and protocols for inter-UE sensing

Key findings

- Optimizing the beamforming configuration in NTN and RIS-aided localization significantly enhance estimation accuracy compared to random configurations, particularly in estimating RIS-path delay and the angle of departure.
- In the case of multistatic sensing for UAV detection, 3D positioning accuracy is heavily influenced by cellular.
- Bistatic sensing in indoor scenarios at higher frequencies require higher bandwidth and more antennas to be able to resolve closely packed multipath signals and achieve adequate sensing accuracy.
- Extending the cyclic prefix or utilizing double OFDM symbol transmission were shown to effectively overcome traditional CP limitations with OFDM-based bistatic sensing.
- In the absence of cellular infrastructure or GNSS signals, inter-UE sensing protocols for bi-static ISAC was found to enhance sensing related security and privacy measures.

Example of the studied JCAS protocols: JCAS waveform optimization, AI-based algorithms and inter-UE jammer localization in a bistatic sensing environment



Flexible Spectrum Access Solutions



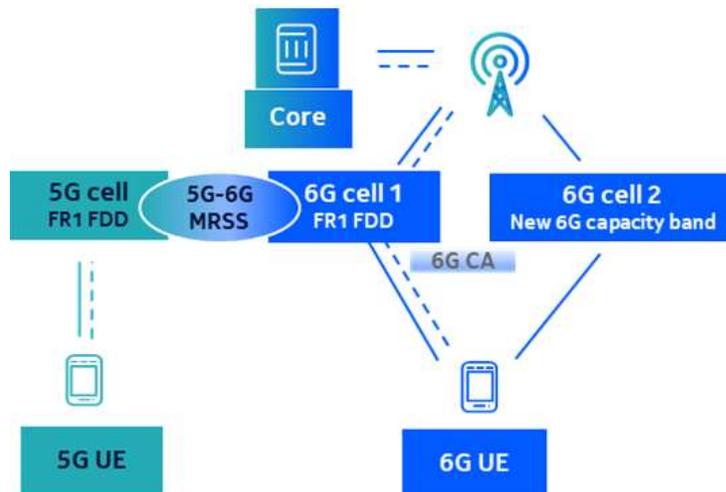
Chapter outline

- Spectrum sharing and coexistence
 - Assumptions and models to determine sharing possibilities with fixed satellite service (FSS) earth station (ES)
 - Spectrum sharing between 6G and FSS uplink
- Multi-RAT spectrum sharing (MRSS)
- Low-latency spectrum access
 - Sub-THz booster RAT
 - Risk-informed random access
- Inclusive radio interface via TN/NTN enhancements
 - NTN handover methods
 - TN/NTN radio interference mitigation
 - Inclusive radio interface via high altitude platforms (HAPS)

Key findings

- Multi-RAT spectrum sharing between 5G and 6G was analysed, showing that only a small control overhead is needed to enable a smooth migration to 6G.
- Risk-aware access was shown to improve the reliability of local spectrum access in uncoordinated scenarios.
- Moreover, NTN coexistence can be supported by modem-internal measures like antenna and circuit techniques and signal processing.
- HAPS in comparison to satellites was shown to offer improved coverage and performance.
- For FSS ES (3-4 GHz, C band), by taking more realistic assumptions into account the required coordination distances between FSS ES and cellular BS can be reduced significantly.
- For FSS coexistence (13-14 GHz, Ku band), additional enablers such as scheduling restrictions or power control are required, if a high BS Tx power is desired.

Illustration of a network architecture supporting MRSS between 5G and 6G.



Trustworthiness



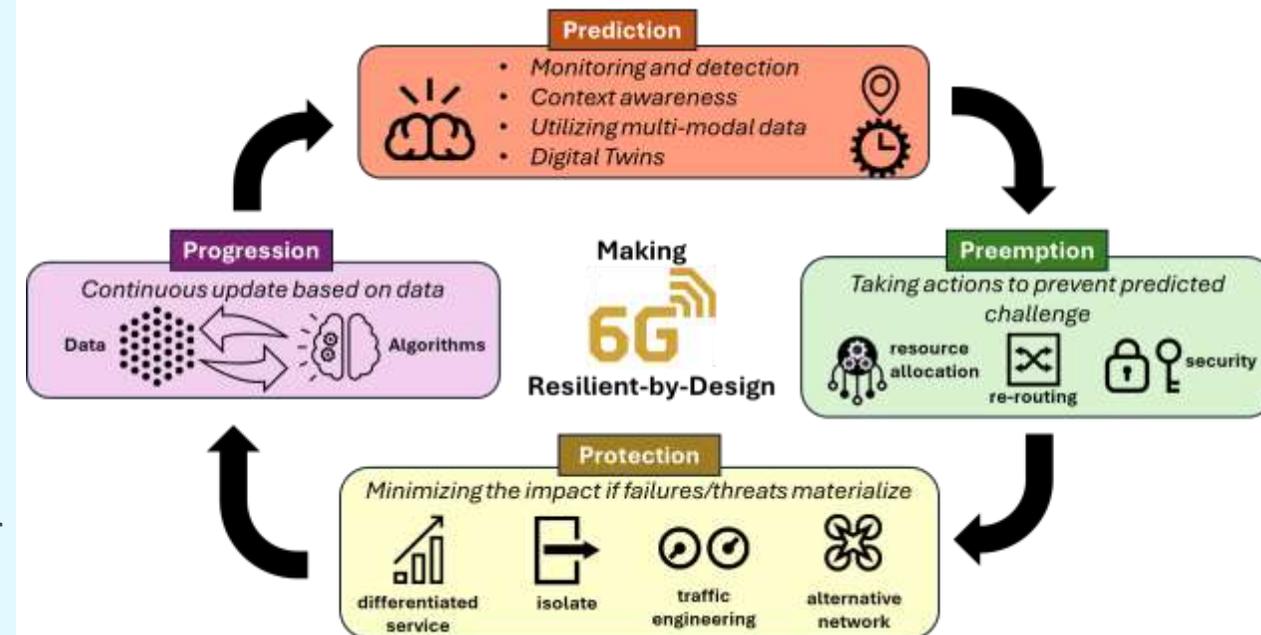
Chapter outline

- Resilient-by-design framework for 6G
- Jamming analysis
 - Impact of jamming as a foundation towards resilience
 - Indoor jammer localisation
- Security and privacy analysis of a general cellular JCAS system deployed for cross-road monitoring

Key findings

- **Resilient-by-design framework for 6G:** Any disruption in 6G networks would have significant impact with overreaching consequences. Such risks can be minimized by designing 6G to be resilient against internal and external disruptions.
- **Jamming analysis:** Coding alone is not sufficient to mitigate jamming. Hence, additional safeguarding strategies, such as passive localization of potential jammers, are needed.
- **Security and privacy analysis of JCAS:** The integration of the sensing functionality of cellular JCAS systems in 6G will impose new challenges in terms of privacy and security, which can be addressed by identifying potential threats through a thorough security and privacy threat mapping.

Illustration of the proposed resilient-by-design concept for 6G networks



Proof-of-Concepts and Simulators



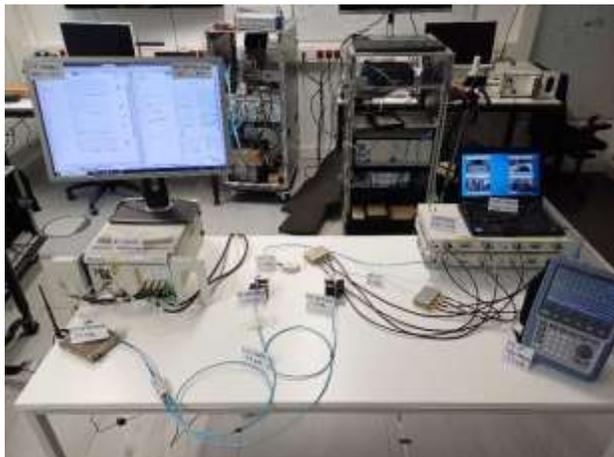
Chapter outline

- Link modelling of 6G physical layer
- Flexible modulation and transceiver design
- AI-native air interface
 - ML-based channel state feedback compression in a multi-vendor scenario
 - Pilotless operation with a partially learned air interface
- Bistatic joint communication and sensing
- Power consumption of JCAS
- EMF assessment for D-MIMO
- Channel measurements and data models
- Phase noise modelling

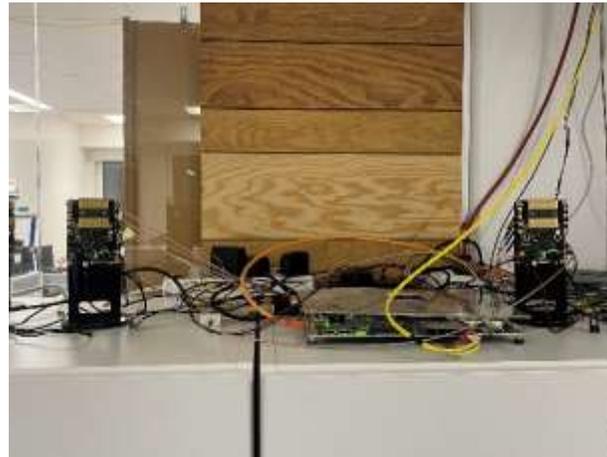
Chapter summary

- This chapter gives proof for some of the emerging concepts in 6G proposed within this WP.
- Some validation are done through system level simulations, whereas others include practical experimentation in lab setups.
- The methodologies and results are detailed in the chapter.

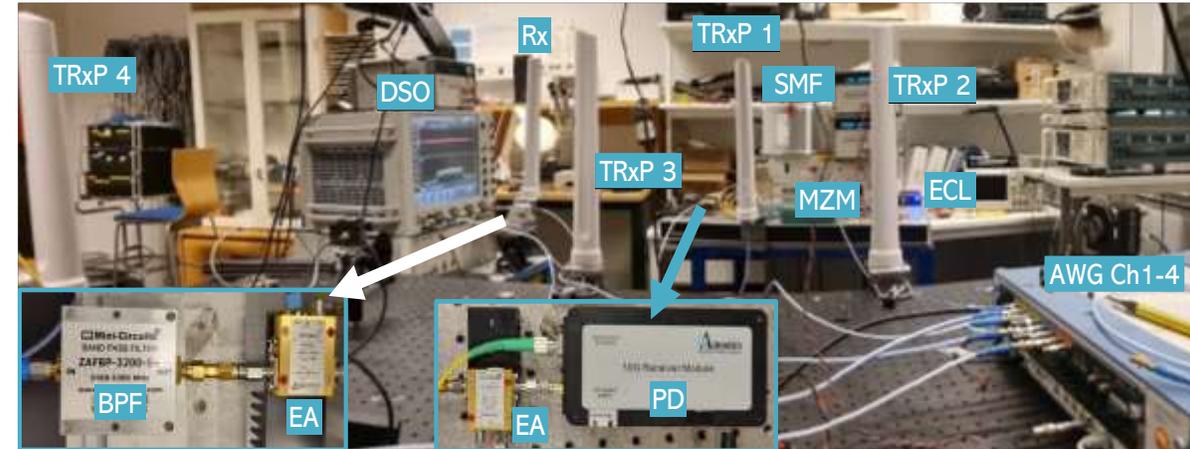
Selected evaluation setups



Flexible modulation and transceiver design



Bistatic JCAS scenario



Distributed-MIMO testbed

Key Take-Aways



- It is important to consider a holistic radio design framework for 6G as it ensures future-proof 6G networks that combine performance, scalability, efficiency, sustainability, and trustworthiness.
- The design process must consider propagation environments, hardware constraints, and deployment strategies for optimal performance.
- 6G TNs will need to support global and seamless connectivity. Hence, 6G design must consider flexible topologies, including TN/NTN integration, device-to-device communication and centralized/distributed RAN architectures.
- Sustainability, encompassing environmental, social, and economic sustainability, will be a cornerstone of future 6G design. This can be achieved through energy-efficient hardware, resource allocation, and deployment, alongside novel materials for reduced environmental impact and recyclability.
- In terms of new spectrum for 6G, the FR3 band is the most attractive for its initial implementation, while the sub-THz spectrum remains crucial for the long-term development of 6G and future generations. The interplay between channel modelling, RF transceiver design, and physical-layer enablers for sub-THz communications is still an open question.
- The transition to 6G requires advanced spectrum management technologies to address spectrum scarcity, coexistence with incumbents, and low-latency spectrum access.
- In case of NTN integration, open questions remain with regards to handover management, network architecture, efficient signalling design, and adopting to the particular characteristics of ground-to-satellite channels.



HEXA-X-II.EU //   



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6GSNS

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