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Abstract

This document discusses enabling technologies for 6G radio above 100 GHz, including channel modeling, radio architecture, signal processing, and localization and sensing. It summarizes testbed measurements, proof-of-concepts, and current research trends in 6G radio design and related technologies, such as optical wireless communications. The report provides a radio technologies roadmap, outlining technical challenges and key technologies beyond Hexa-X. It also shares perspectives on enabling technologies for above 100 GHz radio and the role of D-MIMO in 6G, based on a project-internal questionnaire. Lastly, it highlights the impact of 6G on future markets.

Keywords

6G markets, D-MIMO, localization, mmWave, optical wireless communications, proof-of-concepts, radio technologies, roadmap, sensing, sub-THz

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Executive Summary

This document presents the outcomes of WP2 and WP3, focusing on key enabling technologies for 6G radio above 100 GHz, including channel modeling, radio architecture, signal processing, and localization and sensing. The report explores material parameters for the 2-260 GHz range and stored channel models at 140 GHz based on measurements. It examines RF transceivers for the 100-300 GHz frequency range, evaluating hardware models and D-MIMO architectures, and provides guidelines for waveform and digital transceiver design, beam management techniques in sub-THz systems, and studies of D-MIMO and integrated access and backhaul.

The document delves into testbed measurements, evaluating the proposed radio and baseband architecture from proof-of-concepts implemented using prototyping hardware. The sub-THz communications proof-of-concept demonstrates a high data rate over-the-air radio link at a 150 GHz carrier frequency and a signal bandwidth of up to 10 GHz. The joint communications and sensing proof-of-concept reveals that the same hardware and signal design can be utilized for both at a 60 GHz carrier frequency and 800 MHz signal bandwidth. The flexible baseband proof-of-concept showcases the feasibility of exploiting ultra-wideband at various frequency bands using a unified transceiver at carrier frequencies up to 26 GHz and a signal bandwidth of 640 MHz.

The report offers a comprehensive overview of current research trends and challenges in 6G radio design, emphasizing advancements in other technologies, such as optical wireless communications. Key areas of focus include channel modeling, radio architecture and models for D-MIMO, localization and sensing, signal processing techniques, and optical wireless communications. Specific topics explored are near-field and wide bandwidth effects at (sub-)THz, small-scale fading, signal processing options, functional splits, reconfigurable intelligent surfaces, machine learning techniques, and the combination of THz and optical wireless communications to enhance performance.

Additionally, this report shares a view on the expected evolution of 6G markets, highlighting the potential to revolutionize various sectors. Hardware, software, and services will be crucial for 6G development, driving growth in healthcare, transportation, entertainment, manufacturing, and agriculture. Addressing challenges like legal frameworks, security, and infrastructure will be essential for successful adoption and realizing the full potential of 6G technology.

The project-internal survey findings on radio technology highlight the challenges in developing radio hardware, waveforms, beamforming, and channel modeling for utilizing frequencies above 100 GHz. Organizations vary in their involvement, with some focusing on research and development, while others prioritize commercialization and marketing. The success of distributed large MIMO systems, a clear 6G technology candidate, will depend on addressing challenges through research, development, and collaboration with key industry players. The report concludes with a radio technologies roadmap and an outlook on 6G applications and their impact on new markets.

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List of Acronyms and Abbreviations

Term	Description
3GPP	3rd Generation Partnership Project
5G	5th Generation Mobile Communication System
6G	6th Generation Mobile Communication System
ADC	Analogue to Digital Converter
AI	Artificial Intelligence
AoA	Angle of Arrival
AoD	Angle of Depature
AP	Access Point
AR	Augmented Reality
ARB	Arbitrary Signal Generator
ASK	Amplitude Shift Keying
B5G	Beyond 5G
BLER	BLock Error Rate
BS	Base Station
BSE	Beam Squint Effect
BW	BandWidth
CAGR	Compound Annual Growth Rate
CDF	Cumulative Distribution Function
C-JT	Coherent - JT
cmW	centimetre Wave
CoMP	Coordinate Multi-Point
CSI	Channel State Information
DAC	Digital to Analogue Converter
DFTS-OFDM	Discrete Fourier Transformation Spread - OFDM
DLT	Distributed Ledger Technology
D-MIMO	Distributed - MIMO

DPD	Digital Pre-Distortion
DSP	Digital Signal Processing
DU	Distributed Unit
Dx.y	Deliverable x.y
E2E	End to End
EC	European Commission
ETSI	European Telecommunications Standards Institute
EVM	Error Vector Magnitude
FFT	Fast Fourie Transformation
FPGA	Field Programmable Gate Array
FR2	Frequency Range 2
FSOC	Free Space Optical Communication
H2020	Horizon 2020
HPBW	Half Power BeamWdith
HW	HardWare
HWI	HW impairments
IAB	Integrated Access and Backhaul
ICT	Information and Communication Technologies
IF	Intermediate Frequency
IFFT	Inverse Fast Fourie Transformation
IoE	Internet of Everything
IoT	Internet of Things
ISG	Industry Specification Group
ITU	International Telecommunication Union
JCAS	Joint Communication And Sensing
JT	Joint Transmission
KPI	Key Performance Indicator
KVI	Key Value Indicator

LiDAR	Light Detection And Ranging
LiFi	Light Fidelity
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line-Of-Sight
LP	Low Pass
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
ML	Machine Learning
mmW	millimetre Wave
MR	Mixed Reality
NC-JT	Non-coherent JT
NCR	Network Controlled Repeater
NFV	Network Function Virtualization
NR	New Radio
OCC	Optical Camera Communication
OFDM	Orthogonal Frequency Division Multiplexing
OTA	Over The Air
OWC	Optical Wireless Communication
PA	Power Amplifier
PADP	Power Angular Delay Profile
PAPR	Peak to Aver Power Ratio
PHY	Physical Layer
PN	Phase Noise
PoC	Proof of Concept
QAM	Quadrature Amplitude Modulation
R	Reflection
R&D	Research and Development

RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RU	Radio Unit
RX	Receiver
SC	Single Carrier
SC-FDE	SC – Frequency Domain Equalization
SDN	Software Defined Network
SDR	Software Defined Ratio
SFN	Single Frequency Network
SLAM	Simultaneous Localization And Mapping
SNR	Signal to Noise Ratio
SNS	Spatial Non-Stationary
STFBC	Space Time Frequency Block Coding
SWM	Spherical Wave Model
T	Transmission
TRL	Technology Readiness Level
TRP	TX/RX point
TX	Transmitter
UE	User Equipment
USD	US Dollar
VLC	Visible Light Communication
VNA	Vector Network Analyser
VR	Virtual Reality
w.r.t	with reference to
WP	Work Package
XLAA	eXtra-Large Aperture Array
XR	Extended Reality
ZXM	Zero crossing Modulation

1 Introduction

1.1 Objective of the Document

This report aims to benefit a wide range of stakeholders, including companies and researchers. Companies can use a technology roadmap to align their business strategy with the latest technological developments and identify areas for investment and growth. Researchers can use a technology roadmap to identify areas of research that are relevant and impactful, and to stay up-to-date on the latest technological trends and developments. Society can benefit by gaining insights into the potential impact of new technologies on the economy, the environment, and society, and by identifying areas where new technologies can help address societal challenges [UN23]. In addition, other stakeholders such as policymakers and government agencies can also benefit from this report to guide the decision-making and policies related to funding and regulatory frameworks for technology development. Investors can use the roadmap to identify promising areas for investment and to make informed decisions about where to allocate their resources.

1.2 Hexa-X Objective on Radio Performance towards 6G

WP2 focuses on the project objective 2 "Radio performance towards 6G". This section provides a summary of the work performed in WP2 towards this objective. The work is reported in four deliverables:

- D2.1: Towards Tbps communications in 6G: use cases and gap analysis, [HEX21-D21].
- D2.2: Initial radio models and analysis towards ultra-high data rate links in 6G, [HEX21-D22].
- D2.3: Radio models and enabling techniques towards ultra-high data rate links and capacity in 6G, [HEX23-D23].
- D2.4: Enabling radio technologies and roadmap towards 6G (this document).

Complementary to the work done in this work package, additional related results can be found in [HEX22-D32], [HEX23-D33] and [HEX22-D13]

In the remainder of this section, references to sections and tables refer to the respective external deliverables.

1.2.1 Outputs

The following outputs are presented in WP2 deliverables related to the objective "radio performance towards 6G".

To develop key radio technology for supporting seemingly infinite capacity, with special focus on wide-spectrum access development going from GHz-bands approaching to THz and optical frequencies, taking energy efficiency into account.

D2.1 [HEX21-D21] provides technical requirements of the relevant sub-THz use cases and identifies gaps of state-of-the-art technology. Initial technical requirements in terms of range and data rate are evaluated in Section 3.1 and listed in Table 3-1. Based on that, the radio design considerations are discussed in Section 3.2, where the PHY parameters (code rate, modulation order, bandwidth) are summarized in Table 3-2. Section 3.2.3 focuses on the link performance and the impact of the radio HW components to system design considerations, summarizing the main parameters in Table 3-4. A power consumption model is derived in eq. (3-6). Section 3.3 provides insight on current state of technology for wireless in the frequency range 100 - 300 GHz and investigates enabling technologies. In particular, Section 3.3 introduces a gap analysis in terms of the required components: transmit power, receiver noise, phase noise, data converters, DSP, antenna approaches. An initial transceiver architecture is presented in Section 3.3.7, with a summary of device classifications in Table 3-6. The waveform gap analysis is discussed in Section 3.4, presenting the relevant waveform design KPIs in Section 3.4.2 including coverage and energy efficiency. A summary of waveform candidates is provided in Table 3-7. Section 3.5 provides an overview of beamforming showing the impact of the system and link KPIs in Figure. 3-23, and summarizing potential design options in Table 3-8. The gap analysis of the shortcomings of current channel models as well as required measurements are described in Section 3.7.

D2.2 [HEX21-D22] presents initial simulation models and frameworks for the performance analyses of the 6G radio PHY, in addition to waveform comparison and channel modelling and measurements. Section 3 focuses on radio system level considerations, where the RF architecture is defined in Section 3.1, different modelling approaches are discussed in Table 3-1, a RF calculation example is given in Table 3-2, a summary of the RF impairment in Table 3-3, and an example of power consumption modelling in Table 3-4. Initial models for RF components are provided in Section 3.6, including ADC, PN, PA, LNA, other losses, in addition to beamforming nonidealities corresponding to quantized gain control and the noise added by the phase shifter. Section 4 reports performance analysis of different waveforms. Namely, evaluation of DFTS-OFDM considering channel measurements with iterative receiver in Section 4.2, impact of phase noise and PA non-linearity in Section 4.3, initial results on zero-crossing modulation in Section 4.4, and performance results of constrained-envelop in Section 4.5. Beamforming analysis is reported in Section 5 depicting a generic hybrid architecture in Fig. 5-1. A reference ideal model is presented in Section 5.2 with analysis of the theoretical limits w.r.t. channel characteristics, bandwidth, and array size. The impact of HW constraints and implementation aspects are summarized in Section 5.3. A study on beam training is reported in Section 5.4, and the evaluation of beam training interval in different mobility models is reported in Fig. 5-7, 5-9. A generic E2E simulation framework is given in Table 5-1, listing the beamforming parameters in Table 5-2, and other system parameters in Table 5-3. Channel measurements and modelling results are reported in Section 7, with wave-material interaction analysis from 2 GHz to 170 GHz in Section 7.1, multipath measurement data at 140 GHz are reported in Section 7.2 with analysis of the data in Section 7.3.

D2.3 [HEX23-D23] presents 6G radio system design aspects and involved enabling technologies for fulfilling the requirements of emerging use cases, especially, link data rate of 100 Gbps. In Section 2.2, the use cases enabled by sub-THz communication in the band (100 GHz-300 GHz) are reviewed and mapped to three scenarios (mid-range, short range, and very short range) with technical details listed in Table 2-1. For each scenario, several radio options are expected depending on the operating band and device class (user equipment (UE), or access point (AP)) as depicted in Figure 2-2 in [HEX23-D23]. High-level radio design methodology is presented in Section 2.2.2 and illustrated with a flow chart diagram in Figure 2-3, considering the role of different enabling technologies in the radio system design. Technical details of RF design with examples in each step are presented in Section 4.1.1. Section 3.1 presents extended channel measurement for wave-material interaction analysis from 2 GHz to 260 GHz, and a comparison with ITU model for the estimation of primitivity and conductivity for different materials in Table 3-1. The material primitivity dependency on the frequency is shown in

Figure 3-8. Results on wideband MIMO channel model at 140 GHz based on measured spatial-temporal channel data in indoor and outdoor environments are reported in Section 3.2. The data are available in Hexa-X Zenodo community [DHK23]. Based on these data, Section 6.2 provides statistical modelling for path loss in Figure 6-7, evaluation of number of independent beams in Figure 6-9. Section 4.1, presents RF implementation aspects and strategies to optimize the system such as channelization and carrier aggregation, where sub-array-based RF transceiver, illustrated in Figure 4-2, is considered as a practically feasible architecture for above 100 GHz radio. The technical requirements for achieving 100 Gbps are listed in tables for OFDM and SC waveforms; Table 4-2 for the bandwidth, Table 4-4 for ADC dynamic range, Table 4-5 for the minimum SNR. Several hardware models are refined and described in Section 4.2; for local oscillator phase noise in Eq. (4-5), which is compared with 3GPP model in Figure 4-12. The impact of phase noise on link performance is illustrated in Figure 4-14. Several power amplifier models are presented in Section 4.2.2; for saturated output power of different technologies in Figure 4-16, simplified memoryless model at 300 GHz in Table 4-10, and behaviour modelling with memory is described in Figure 4-19. An example of link analysis is presented in Section 4.1.2 to determine the radio design parameters (number of antennas, and bandwidth at different bands) considering different hardware models, modulation schemes, waveforms, as shown in Figure 4-8 and Figure 4-9. Section 5.1 reports additional performance results on waveform candidates under individual or combined hardware models. Section 5.1.2 focuses on SC-FDE and DFTS-OFDM performance in different settings, Section 5.2.2 presents results on phase noise impact on zero-crossing modulation, and Section 5.1.4 provides an overview of spatial and carrier aggregation waveform designs. The analysis of beamforming management for the frequency range from 100 to 300 GHz in Section 5.2 shows the need to exploit side information to reduce the training latency.

To develop distributed MIMO antenna technology for radio access in higher frequencies, as well as for increased efficiency and flexibility in lower bands, converging fronthaul, backhaul and access.

Literature review of D-MIMO and the area of research relevant to 6G is summarized in D2.1, Section 3.6.

In D2.2 [HEX21-D22], Section 6, different aspects of D-MIMO have been studied. Section 6.1 identifies the challenges at different bands, the potentials and deployment options. Section 6.2 elaborates on the HW constraints, and Section 6.3 discusses architectural options with simulation examples, analogue, digital, hybrid, and integrated access and backhauling.

D2.3 [HEX23-D23] presents a comparison of cellular-based and D-MIMO deployment options and highlights the potential of D-MIMO technology to optimize for coverage, enhance the capacity and reliability by cooperative transmission over multi-links. Section 4.3 provides insights on D-MIMO architectures, showing architectural options in Figure 4-25 for fronthaul, transmission, processing, and deployment. Analogue and digital approaches for different options are discussed in Section 4.3.4 and Section 4.3.5 to cope with the increased processing costs at high data rates. Integrated access and backhaul is discussed in Section 4.3.5, as shown in Figure 4-31, and the optimization of access and backhaul resources and deployment are presented in Section 5.3.4 and Section 5.3.5. Moreover, Section 5.3 provides several performance analyses in terms of spectral efficiency considering mobility and non-coherent joint transmission in Section 5.3.1, channel estimation and pilot schemes in Section 5.3.2. Furthermore, a comparison of network-controlled repeater and RIS to tackle blockage is presented in Section 5.3.4.

1.2.2 Measurable Results

The following measurable results are achieved in WP2 and reported in the deliverables.

Technical components targeting new use cases and performance metrics.

- Flexible radio design: An initial radio architecture for the frequency range 100 - 300 GHz and RF HW components models are presented in D2.2, Section 3. The RF architecture is refined with detailed modelling methodology in D2.3, where Section 2.2 provides a conceptual design guideline and Section 4.1 focuses on technical details. A refinement of the HW complements with further analysis is provided in D2.3 Section 4.2, focusing, in particular, on phase noise and PA models.
- Hybrid beamforming architecture is presented in D2.2, Section 5. This has been considered in the radio architecture in D2.3, Figure 4-2.
- Several waveform candidates are studied in D2.2, Section 4. Based on these studies and considering the HW models in D2.3, the selected waveforms are limited to DFTS-OFDM, SC-FDE due to their robustness, in addition to ZXM, due to its role in improving energy efficiency. A qualitive assessment is presented in D2.3, Table 5-1.
- E2E simulation framework is developed in D2.2, Table 5-1.
- D-MIMO components, e.g., beamforming methodologies, scheduling, analogue/digital approaches, integrated access and backhaul are presented in D2.2, Section 6. Architectural D-MIMO components (Fronthaul, transmission, a processing, and deployment) are presented in D2.3, Section 4.3, and transmission schemes (channel estimation techniques, non-coherent transmission) in Section 5.3.
- Stored channel model for simulation is provided in D2.2, Section 7.2, Section 7.3, and in D2.3, Section 3.2. Simulation code written in MATLAB and the data are published in Hexa-X Zenodo community [DHK23].
- Model for material-wave interaction, in particular, for permittivity of different material is presented in D2.2, Section 7.1 for the frequency range (2 GHz -140 GHz). The range is extended to 260 GHz in D2.3, Section 3.1.

Performance key value indicators (KVIs) and key performance indicators (KPIs).

- Sub-THz use cases analysis and derived technical KPIs are presented in D2.1, Section 2. Based on these use cases sub-THz communication scenarios and related KPIs are reported in D2.3, Table 2-1.
- Initial technical requirements for radio design focusing on communication are presented in D2.1, Table 3-1, and refined in D2.3, Table 2-1, with additional localization and sensing KPIs for joint communication and sensing radio design.
- Additional radio performance metrics are defined and listed in D2.3, Section 2.3, including KVI-specific (coverage (inclusion), energy performance (sustainability), link reliability (trustworthiness)) in additional to technical KPIs (latency, beam failure rate, positioning accuracy, orientation accuracy, and positioning latency).
- Waveform performance analysis in terms of BLER, PAPR, complexity is presented in D2.2, Section 4.2, and Section 4.3, and in D2.3, Section 5.1.2.
- Performance evaluation of D-MIMO schemes is presented in D2.3, Section 5.3 for spectral efficiency, coverage, and achievable rate.
- D2.3, Section 6.1 presents several performance examples to demonstrate that optimizing deployment scenarios, transceiver configurations, and ADC resolution can significantly impact the power consumption and improve performance. Figure 6-3, and

Figure 6-4 show the area throughput, and Figure 6-6 shows power consumption examples for different ADC resolutions.

World's first measurement-based multi-path channel model above 100 GHz, parameterised hardware impairment models.

- Measurements of wave-material interaction in the frequency range 2-170 GHz is presented in D2.2, Table 7-1, Table 7-2, and Figure 7-3. The measurement is extended to 260 GHz in D2.3 Table 3-1 and Figure 3-8.
- Multipath channel measurement data at 140 GHz is reported in D2.2, Section 7.2 for indoor and outdoor scenarios. MIMO channel model implementation based on the measured channel data are provided in D2.3, Section 3.2, and are published in Hexa-X Zenodo community [DHK23].
- Hardware impairments are summarized in D2.2, Table 3-3, and preliminary models are presented in D2.2, Section 3.6 for ADC/DAC, power amplifier, noise figure, beamforming phase and gain corresponding to the analogue phase shifter, and phase noise. The models for phases noise, and power amplifiers are refined in D2.3, Section 3.2.

Novel waveform candidates and beamforming algorithms for communications above 100 GHz.

- Waveform candidates are explored in D2.1. The summary of the results is available in Table 3-7. Initial evaluation results of the waveforms under HW constraints and channel measurements are reported in D2.2, Section 4. Three waveforms, namely, DFTS-OFDM, SC-FDE and ZXM are considered for further analysis in D2.3, Section 5.1 based on qualitative assessment listed in Table 5-1.
- Beam training strategy is studied to reduce the initial beam access latency and reported in D2.2, Section 5.4. Further assessment of beam management in the frequency range from 100 to 300 GHz presented in D2.3, Section 5.2, suggests utilizing side information to reduce the training latency.

10-year technology roadmap including both system and hardware design aspects.

- Analysis of current state of research w.r.t. enabling radio technologies (this report, Section 2)
- Measurements from proof-of-concepts (this report, Section 3)
- Assessment of current research trends incl. 10 years outlook (this report, Section 4)
- 6G markets evolution and economic impact (this report, Section 5)
- Radio technologies roadmap incl. insights from internal survey in this project (this report, Section 6)

Novel techniques enabling scalable multi-user distributed large MIMO systems (D-MIMO).

- Several D-MIMO architecture options are explored in D2.2, Section 6. These architectures are studied and reported in D2.3, Section 4.3, and signal processing techniques with performance analysis are reported in D2.3, Section 5.3, and AI-based compressed sensing techniques for beam selection are studied and reported in D4.3, Section 3.1. These include radio stripes enabling cost and energy-efficient D-MIMO deployment for high bandwidth applications, coordinate transmission under mobility (not roaming), deployment constraints in IAB, multiuser channel estimation for D-MIMO, and network-controlled repeaters and RIS.

1.2.3 Quantified Results

The following quantified results for the objective are completed in the WP2 deliverables.

(>0.1 Tbps) achievable rate for access

The modulation parameters and required bandwidth to achieve 0.1 Tbps are summarized in D2.1, Table 3-2. The required SNR and the impact on the link budget are discussed in D2.2, Section 3.3, where an illustrative example is listed in Table 3-2, with detailed parameters. Detailed link analysis is provided in D2.3, Section 4.1.2, considering HW models, channel, and different frequency band in Table 4-6, and showing different radio design options to achieve link rate of 0.1 Tbps in Figure 4-8, Figure 4-9 at different ranges according to the scenarios described in D2.3, Table 2-1.

(<0.1 ms) RAN latency

In D2.3, Section 5.1.1, an analysis is provided as to methods to achieve a latency below 0.1 ms. It shows that the main factors influencing challenging latency targets are the processing time and the slot duration, and it requires reliable link to reduce the number of retransmissions. This assumes that the communication link is established. However, under mobility, when the beam training is considered, the study in D2.3, Section 5.2, shows that there is a need to exploit side information rather than following conventional beam training approach based on probing a large number of beams.

1.3 Structure of this Document

Section 2 provides a holistic evaluation of enabling radio technologies for Beyond 5G/6G wireless systems, with subsections focusing on channel modeling, radio architecture and models, key signal processing techniques, and localization and sensing.

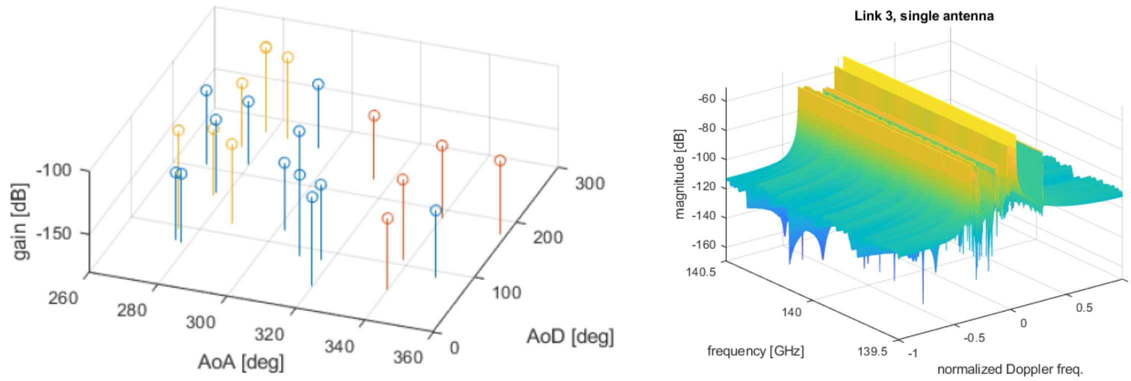
Section 3 covers measurements from testbeds, while Section 4 explores current trends in radio research, including channel modeling, radio architecture and models, key signal processing techniques, localization and sensing and additional research trends towards 6G.

Section 5 provides an economic forecast with respect to radios, while Section 6 outlines a radio technologies and application fields roadmap towards 6G. Section 7 derives a conclusion.

2 Holistic Evaluation of Enabling Radio Technologies for B5G / 6G Wireless Systems

This section provides an overview of research findings and performance assessments on the 6G radio system, aimed at attaining ultra-high data rate connections and capacity within the scope of Hexa-X WP2. For a more in-depth analysis, please refer to the documents D2.3 [HEX23-D23], D2.2 [HEX21-D22], D2.1 [HEX21-D21] and D3.2 [HEX21-D32].

$$P_q(\Omega^{\mathrm{rx}}, \Omega^{\mathrm{tx}}, \tau) = \sum_{l=1}^{L_q} P_{l,q}\delta\left(\Omega^{\mathrm{rx}} - \Omega_{l,q}^{\mathrm{rx}}\right)\delta\left(\Omega^{\mathrm{tx}} - \Omega_{l,q}^{\mathrm{tx}}\right)\delta\left(\tau - \tau_{l,q}\right). \quad \textbf{(2-1)}$$



(a) (b)

Figure 2-1: (a) Exemplary representation of a measured multi-path channel at 140 GHz; colour coding denotes three different links. (b) Doppler channel spectrum across 140 GHz band reproduced from the measured channel data.

2.1 Channel Modelling

2.1.1 Channel Model at 142 GHz based on Measured Multi-Paths

Measured multi-path channels at 142 GHz in discrete path formats are available in in Hexa-X Zenodo community [DHK23] for an entrance hall and outdoor scenarios such as suburban, residential, and city centre; details of the measurement channel sounder and measurement sites are available in [HEX21-D22]. Even though the measurements are single-directional, double-directional data were derived by exploiting the available detailed geometric database of the measurement environment and measured channels using a tool called measurement-based ray-launcher [DKH21].

The multi-path data cover several TX and RX locations in different environments. Each link, i.e., with TX and RX locations, is characterized by a double directional power angular delay profile (PADP).

The RX and TX antennas are specified by complex radiation patterns $\mathbf{g}_{\mathrm{rx}}(\Omega^{\mathrm{rx}}) \in \mathbb{C}^{M\times 1}$ and $\mathbf{g}_{\mathrm{tx}}(\Omega_l^{\mathrm{tx}}) \in \mathbb{C}^{N\times 1}$, respectively, where M is the number of RX antennas and N is the number of TX antennas. Now the channel frequency response matrix is determined as

$$\mathbf{H}_q(f) = \sum_{l=1}^{L_q} \mathbf{g}_{\mathrm{rx}}\left(\Omega_{l,q}^{\mathrm{rx}}\right) \sqrt{P_{l,q}}\, e^{-j2\pi f \tau_{l,q}}\, \mathbf{g}_{\mathrm{tx}}\left(\Omega_{l,q}^{\mathrm{tx}}\right)^T \in \mathbb{C}^{M\times N}. \quad \textbf{(2-2)}$$

Random snapshots of MIMO frequency response matrices can be generated by introducing random initial phase $\theta_{l,q}$ to each multi-path, where phase terms are drawn from the uniform distribution in $[0,2\pi)$. Moreover, the temporal dimension and time variability can be included by introducing small Doppler frequencies $\nu_{l,q}$ for each path. This models a small-scale virtual motion of a mobile, where only phases of path component change over time, but other propagation parameters remain constant. The resulting snapshot/time variant frequency response matrix is

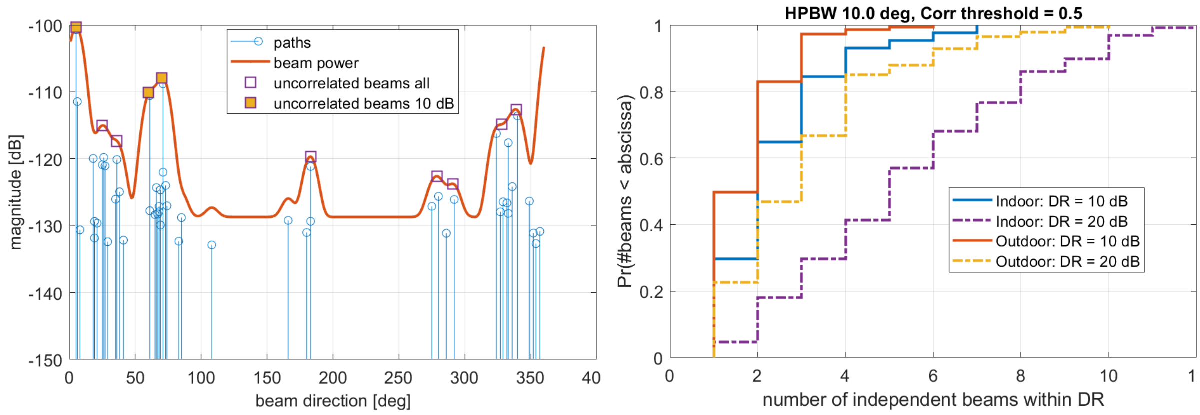


Figure 2-2: Measured path powers, the beam power and found independent beam azimuth directions in an example link (left). CDF of the number of independent beams in 132 indoor and 157 outdoor links using either 10 dB or 20 dB dynamic range (right).

$$\mathbf{H}_q(t,f) = \sum_{l=1}^{L_q} \mathbf{g}_{\mathrm{rx}}\left(\Omega_{l,q}^{\mathrm{rx}}\right) \sqrt{P_{l,q}}\; e^{j(\theta_{l,q}+2\pi\nu_{l,q}t)}\; e^{-j2\pi f\tau_{l,q}}\; \mathbf{g}_{\mathrm{tx}}\left(\Omega_{l,q}^{\mathrm{tx}}\right)^T \in \mathbb{C}^{M\times N}. \qquad \textbf{(2-3)}$$

Figure 2-1 (b) illustrates a Doppler spectrum across the frequency band of 140 GHz, which was derived from the measured multi-path data by (2-3) and the Fourier transform to convert from time to Doppler domain.

2.1.2 The Number of Independent Beams

Wireless communication over sub-THz radio frequencies demands very directive antenna patterns, which illuminate only sub-sets among all available propagation pathways. At sub-THz, partly due to the channel sparsity and mainly due to foreseen RF technology limitation, flexible beamforming schemes utilising all degrees of freedom provided by the propagation channel might not be possible. Hence, it is interesting to study how many independent beams of a practical beamwidth does the propagation channel support. Directional wideband propagation measurements are used for this study. One can rather easily estimate how many significant paths are present in a measurement location but interpreting that to separable beams is not evident. Three methods to assess the number of useful beam directions are introduced in [KGH+22]. The second method is based on measured power angular-delay profiles (PADPs) and a synthetic beam pattern defined in [38.901].

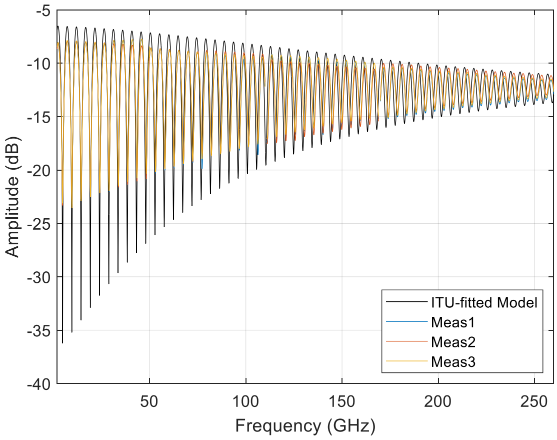
Measured PADPs were evaluated using 10° HPBW, 10 dB dynamic range, 2 GHz BW, and 0.5 correlation threshold. An example PADP, beam power and identified beam directions are illustrated by blue circles, a red curve and orange squares, respectively, in Figure 2-2 (left). Figure 2-2Figure 2-2 (right) depicts empirical cumulative distribution functions (CDF) of the number of independent beams in 132 indoor and 157 outdoor locations using both 10 dB and 20 dB dynamic range. Median values of the number of independent beams are 2 in both environments using dynamic range of 10 dB and using 20 dB they are 5 and 3 in indoor and outdoor environments, respectively.

2.1.3 Comparison with Below-100 GHz Bands

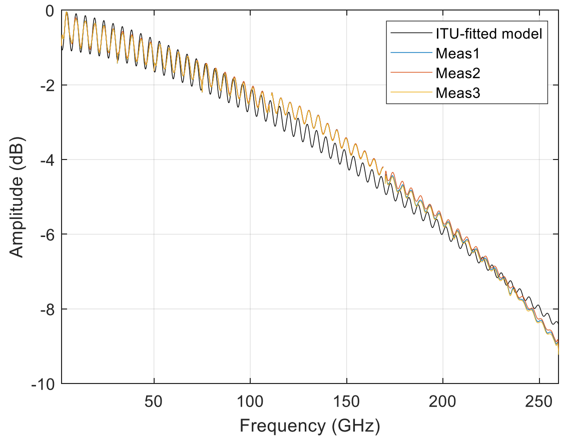
Comparing the radio performance between current cmW or low mmW wireless communication systems and future 6G systems operating at frequencies between 100 GHz and 300 GHz requires the knowledge of the propagation channel from a few GHz to 300 GHz. The propagation channel frequency-dependency may be analysed by a pure theoretical approach in free space but needs to be analysed in more practical and complex environments. Performing wideband channel measurements in real environments over such a bandwidth of several hundred of GHz is technically and organisationally challenging therefore a more practical approach is to focus on the material characterization. Knowing the transmission and reflection losses frequency-dependency of usual building material is the first step to assess the potential differences between a propagation channel below 100 GHz and above 100 GHz. A propagation measurement campaign was performed using a VNA and frequency extenders to measure continuously from 2 to 260 GHz the reflection (R) and transmission (T) losses of common building material slabs at normal incidence. Figure 2-3 shows results from 3 typical material compared with an ITU-like model that keeps the ITU theoretical framework for a slab [ITU] but with proposed new parameters fitted by the measurements.

Homogeneous and flat surface materials such as the plexiglass are well modelled by the ITU model. The observed fluctuation of the measured reflection and transmission gains is due to the interference between the direct reflected (or transmitted) path and the multi-paths created inside the material by multiple reflection/transmission on the two air-material interfaces. The fluctuation decreases with the frequency as multi-paths travelling inside the material are attenuated but the R loss average value is constant indicating a constant permittivity. Mortar represents a non-homogeneous material with a rough surface. Above 100 GHz, R losses are impacted by the scattering and may be higher than 10 dB compared to a similar material with flat surface. T losses can be still calculated from the conductivity σ expressed as $\sigma = cf^d$, f being the frequency and c and d two parameters according to the ITU model. But above 100 GHz, there are strong variations up to 10 dB around the fitted model. For composite materials such as chipboard or glasswool, R losses can decrease with the increasing frequency.

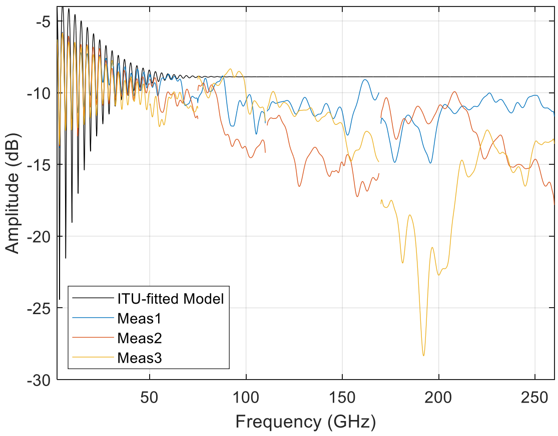
The ITU model is defined up to 100 GHz and needs to be improved for frequencies above 100 GHz from a point of view of accurate wave-material interaction modelling but could be used as it is in many communications channel simulations related to 6G sub-THz scenarios. Reflection loss errors of the ITU model due to rough surfaces may be not a concern in office environment, shopping mall, airport, etc as most of the material are quite smooth. Transmission loss errors due to the material inhomogeneity may not be a concern either as the losses are anyway too high to allow penetration of waves through materials at the high frequencies. Simulating a transmission loss of ~20 dB instead of ~30 dB may not significantly impact system simulation if we consider that a transmission loss higher than 20 dB corresponds to a blockage. Dedicated multi-frequency measurements at cmW and sub-THz frequencies in complex environments are required to check these assumptions.



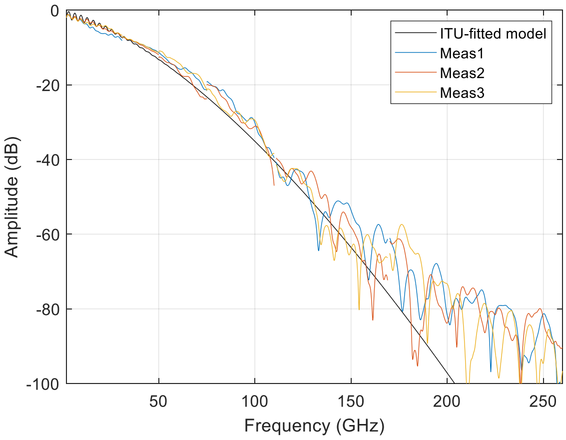
(a1)



(b1)



(a2)



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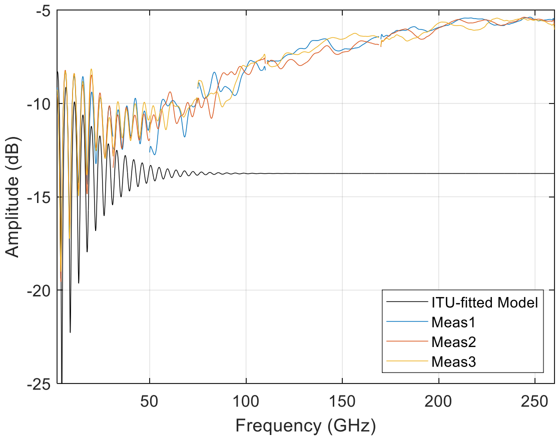
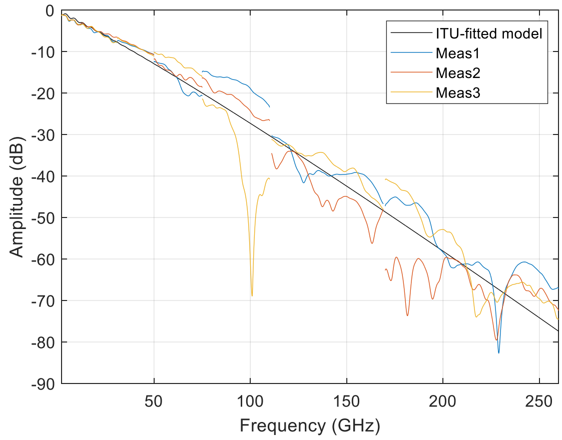


(a3)



(b3)

Figure 2-3: Material reflection (line a) and transmission gain (line b) compared with the ITU-fitted model fitted by the measurements. Plexiglass (a1, b1), mortar (a2, b2), melamine chipboard (a3, b3). The measurement is performed at 3 different points separated by 10 cm on the slab.

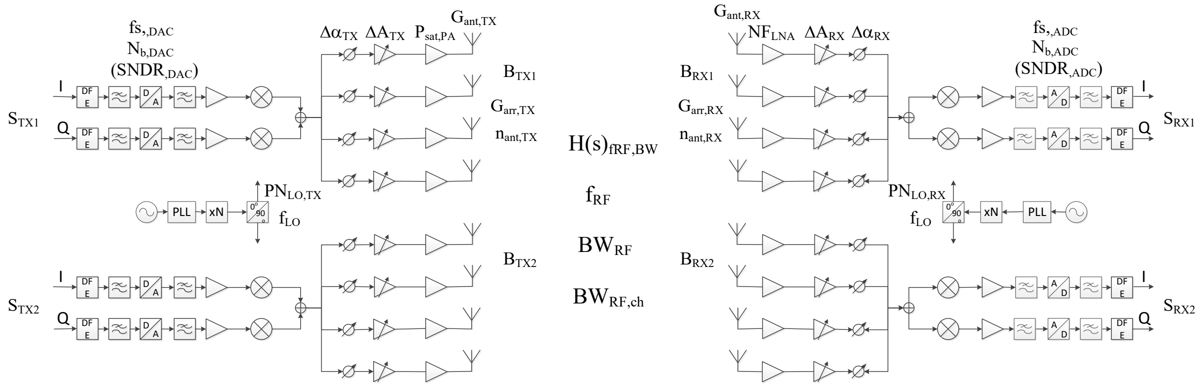


Figure 2-4: RF transceiver reference architecture for hybrid beamforming based on sub-array per beam principle. Key parameters for model abstraction are named.

2.2 Radio Architecture and Models

The targets of analyses for radio architectures and hardware models in D2.1 [HEX21-D21], D2.2 [HEX21-D22], and D2.3 [HEX23-D23] is to support 6G communication flexibly at sub-THz frequencies (100 – 300 GHz) and to provide data rates up to 100 Gbps in the first wave of 6G.

Fully digital MIMO is naturally the preferred option from the flexibility perspective, but it suffers from high power consumption and computational complexity especially at high data rates and bandwidths. Moreover, already in the FR2 bands of 5G NR most transceivers moved to sub-array-based RF architecture, where each sub-array consisting of multiple phase and amplitude steered antennas is pointed towards a beam containing one data stream (or sometimes multiple streams).

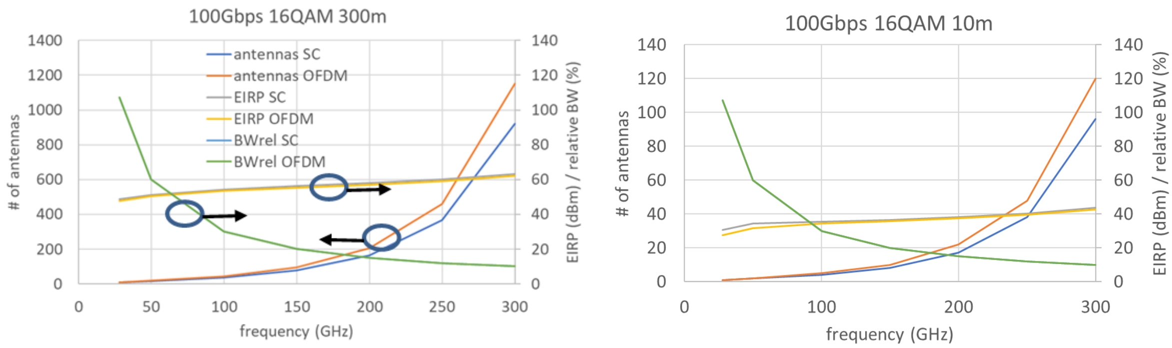
However, the technology evolution in the area of RF and mixed-signal processing is moderate (or one could say sometimes even slow) compared to pure digital (Moore's law), and therefore, when moving towards higher data rates, and thus higher carrier frequencies, it is anticipated that sub-array-based RF transceiver architectures are likely to be de facto also in extreme data rates in 6G. The sub-array-based approach is sometimes called as a hybrid-MIMO architecture. The sub-array-based hybrid architecture is the best reference for the architectural studies for the 6G transceivers. A general RF reference architecture illustration of hybrid-MIMO architecture for 6G transceiver is shown in Figure 2-4.

One of the main challenges in 6G high data rate radios is the conversion between analogue and digital domains with converters. The bandwidth (BW) and the (data converter) sampling rate vs. data rate has been analysed for various modulations in D2.3 [HEX23-D23]. The analysis is in a relative scale for single carrier and OFDM modulations. A summary of the analogue to digital (ADC) requirements to support 100 Gbps radio link is shown in Table 2-1 as an example of multiple analyses presented in D2.3 [HEX23-D23]. The needed 6G ADC sampling clock frequencies are significantly higher than in current 5G systems.

The link range analyses for the 6G radio for 100 Gbps data rates are presented in D2.2 [HEX21-D22] and D2.3 [HEX213-D23]. The detailed link budget model is presented in Table 4-6 in D2.3 [HEX23-D23] and two link range analyses for 10- and 300-meters links at different frequencies are shown in Figure 2-5.

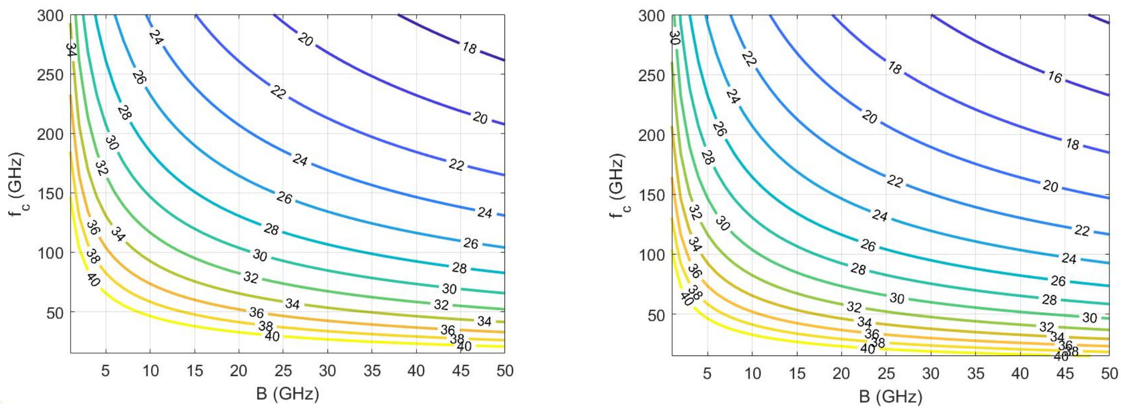
Table 2-1: ADC dynamic range (SNDR) and sampling rate (fs) requirements for various combinations resulting to 100 Gbps data rate with 5/6 coding rate.

OFDM					SC (r =0,35)				
	RF BW factor	**BW GHz**	**fs GHz**	**SNDR ADC**		**RF BW factor**	**BW GHz**	**fs GHz**	**SNDR ADC**
16-QAM	0.33	33	60	44.6	**16-QAM**	0.41	40.5	60	41.7
64-QAM	0.22	22	40	48.4	**64-QAM**	0.27	27	40	45.7
256-QAM	0.17	16.5	30	55.7	**256-QAM**	0.20	20.25	30	53.1



(a) 16-QAM, 300 m distance **(b) 16-QAM, 10 m communication distance**

Figure 2-5: Number of antennas, EIRP and relative bandwidth as a function of frequency for 100 Gbps target data rate with different modulation orders and link distance. Legends and axis are shown in (a).



(a) Single link end **(b) Whole link with equal PLL performances in TX and RX**

Figure 2-6: Phase noise-limited SNR. The different curves in the figure indicate the different phase noise limited SNRs.

The system phase noise behaviour and limitations on the achievable performance and bandwidths in 6G high data rate radios are analysed in D2.2 [HEX21-D22] and D2.3 [HEX23-D23]. The performed phase noise analyses highlighted that the phase noise impacts differently

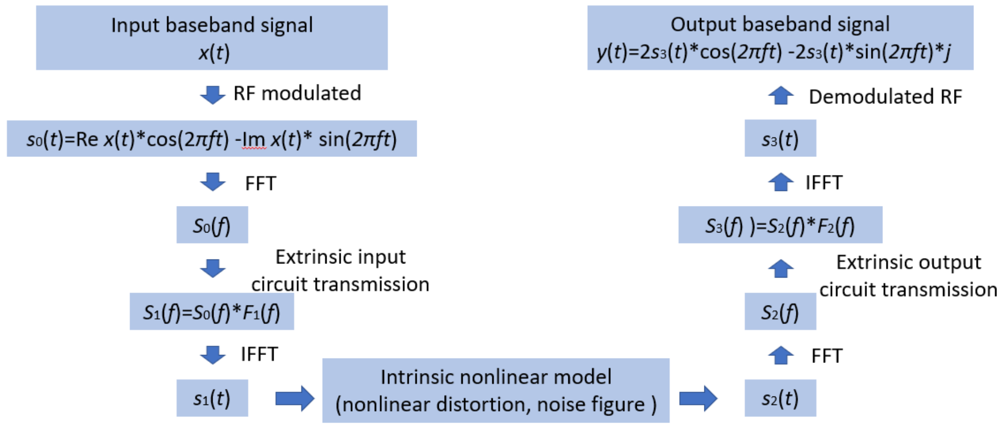


Figure 2-7: Structure for PA equivalent circuit simulation.

to SC and OFDM waveforms. The whole link phase noise simulations for high data rate radio have been performed and one selected result is shown in Figure 2-6.

Power amplifier models for memoryless and with memory effects and output power models with technology dependencies have been presented in D2.2 [HEX21-D22] and D2.3 [HEX23-D23]. The memoryless amplifier models for 300 GHz RF amplifier have been presented in D2.3 [HEX23-D23]. The memory effects of the amplifier have been simulated based on a flow chart presented in Figure 2-7. The proposed method was validated with 2 GHz amplifier, and it was used for 300 GHz amplifier, as well.

2.3 Signal Processing Techniques

Signal processing topics for B5G/6G can be separated into waveform-related and beamforming-related groups of topics. Although there is a need for a holistic view on the beamforming and waveforms, the first step is to analyse them separately.

On a general note, and very importantly, the choice of signal processing techniques for B5G/6G depends heavily on the frequency band in which the standard will operate. As of 2023, frequency bands being considered for 6G span everything from sub-GHz to THz. It is likely that the choice of frequencies will be narrowed down as time progresses towards the roll-out of 6G, but the frequency dependence of signal processing concepts will largely remain.

2.3.1 Waveform-related Signal Processing

It is likely that, to a large extent, the physical layer design based on the OFDM waveform will be the primary candidate for 6G operating in frequency bands adjacent (or overlapping) with 5G NR frequency bands, i.e., bands up to and including the 60 GHz band. A logical conclusion is that the changes to waveform-related signal processing for 6G operating in < 60 GHz bands will likely not be fundamental. One aspect that needs to be considered is the stringent latency requirements in 6G to support use cases such as VR or XR; to this end, the current state-of-the-art in baseband processing of data necessitates a significant increase in speed to meet the demands, as shown in D2.3 [HEX21-D23, Section 5.1.1].

The situation is different when frequencies higher than 60 GHz are considered, especially the so-called sub-THz bands (100 – 300 GHz). Well known hardware impairments and limitations at sub-THz include:

- Limited peak PA power;
- Low PA power efficiency;
- High levels of phase noise;
- Pronounced non-linear effects of the PA and frequency-selective non-linearity at very high bandwidth;
- High ADC power consumption from operating with very high bandwidths.

Combined with high pathloss (due to shrinking of effective antenna aperture with frequency), the limited peak PA power creates problems with range and coverage. One solution to this problem is choosing waveforms with small envelope variations, such that mean power can be brought as close as possible to the peak power and as result improve coverage (and as side effect, also PA power efficiency). As identified in D2.3 [HEX21-D23, Sections 5.1.2 and 5.1.4], to this end, there are several interesting waveforms and modulations to choose from:

- DFTS-OFDM with and without frequency domain filtering;
- Single carrier with frequency domain equalization;
  - Modulation here be square QAM or APSK, where APSK results in lower envelope variation
- Multi-antenna outphasing transmitter, i.e., a transmitter combining the outphasing approach (synthesizing a complex waveform as a sum of two constant-amplitude waveforms) with analog beamforming, such that one half of the antennas carries one component constant-amplitude waveform.

Uncompensated (residual) phase noise will be a significant limiting factor at sub-THz, as shown by the analysis in D2.3 [HEX21-D23, Section 4.2.1.2]. To this end, it is important to compensate the effect of phase noise as much as possible, and to this end, increasing the density of pilot symbols dedicated for phase noise estimation is instrumental, as demonstrated in D2.3 [HEX21-D23, Section 5.1.2.3]. Another approach to deal with uncompensated phase noise is to optimise receiver to perform signal detection in the presence of phase noise, e.g. using context-aware ML/AI-based receiver in [FS20].

PA nonlinearity problem has, to a large extent, the same solution as the limited peak PA power, namely, the envelope variation needs to decrease. Another way of dealing with PA nonlinearity is to perform digital pre-compensation, but at very large bandwidths assumed at sub-THz, that approach will likely be energy inefficient. An alternative approach to deal with PA non-linearity problem is to perform post distortion compensation at the receiver side, e.g. using AI-empowered receiver in [FHS23], [HEX23-D43] Section 3.1.4. This approach is specially feasible at high frequency bands where the inband distortion is a limiting factor rather than the out of band emissions.

As means of dealing with ADC/DAC power consumption, using a smaller number of quantization bits may help and the waveform can be co-designed with that constraint. Specifically, a novel waveform called zero-crossing modulation (ZXM) combines faster-than-Nyquist signalling and runlength-limited sequences to encode the information in the zero-crossings of the waveform, which allows for implementing the receiver with a 1-bit ADC [FDB+19]. Another way of dealing with high ADC power consumption is to divide the signal bandwidth into sub-bands and assign a separate transceiver chain to each sub-band; in so doing, the information signal in each sub-band has lower sampling rate than the full signal and thus the associated ADC/DAC has lower power consumption. This approach, under the name "analogue multicarrier" is described in D2.1 [HEX21-D21, Section 3.4.3.2].

2.3.2 Beamforming-related Signal Processing

Beamforming at lower 6G frequencies (especially sub-mmW) is not likely to dramatically change compared to how it is done in 5G in setups using one radio unit with one antenna array at each side of the link. At lower frequencies, systems can enjoy the benefits of fully digital antenna array processing, enabling spatial multiplexing of users.

What is likely to introduce a significant paradigm shift in 6G is use of several radio units (with different degrees of coordination) at the network side. Going under the umbrella name of distributed MIMO, the approach of having coordinated radio nodes distributed across space combines the elements of small cells, massive MIMO and coordinated multipoint, and was shown to outperform traditional small cell and cellular massive MIMO [BS20]. In order to achieve the promised levels of performance with acceptable levels of complexity, important technical challenges have to be resolved, such as:

- Achieving good time synchronization between distributed network nodes;
- Distributing the control signals between the distributed nodes and the central processing unit in an efficient way;
- Mobile device – distributed node association.

For more detail on signal processing and architectural solutions developed within Hexa-X and addressing the challenges listed above, one is referred to D2.2 [HEX21-D22, Section 6] and D2.3 [HEX21-D23, Section 5.3].

Another beamforming-related challenge is efficient beam management when analogue beamforming is used. Namely, with large bandwidths, a fully digital antenna array implementation becomes prohibitively power consuming and beamforming needs to be performed in an analogue domain with only a few transceiver chains. This in turn complicates the updating of beams as large-scale parameters of the channel change with movement. As shown in D2.3 [HEX21-D23, Section 5.2], beam management (and, with the same reasons, initial beam alignment between the user and the network) becomes prohibitively slow and require a prohibitively high signalling overhead. The solution to this issue is use of side information, such as position information or information collected through sensing, to reduce the beam search space and thus make the beam search feasible in terms of signalling overhead and latency.

2.4 Localization and Sensing

Localization, positioning, and sensing are anticipated to be tightly integrated with communication in 6G systems. This integration can take various forms, such as device-level, waveform-level, and resource-level, and will have significant implications in terms of new services and applications that can be supported, as well as improvements in the communication capabilities themselves [HEX23-D33].

For a successful integration, localization and sensing must be intrinsic components of the 6G architecture. The system must ensure sufficient localization and sensing infrastructure, optimized and adaptive space-time-frequency resources, as well as computational and storage resources for signal processing methods with different interfaces. These interfaces, ranging from raw data to processed object trajectories, must be able to support external services and sensor fusion. Since sensing and localization services may sometimes reduce available resources for communication, effective management and orchestration should guarantee that all services and applications, both from within the network and external to it, can be fulfilled by the network [HEX23-D33, Section 3.1].

Meeting the Key Performance Indicators (KPIs) of the Hexa-X use case families places demands on the infrastructure, hardware, bandwidth, and time resources. Suitable allocation, optimization, and selection of all these resources are required to meet the stringent localization and sensing KPIs. Real-world demonstrations have shown that a large contiguous spectrum is necessary, as well as large arrays at both the transmitter (TX) and receiver (RX) sides, to achieve both extreme location and extreme orientation accuracy. Infrastructure placement and space-time-frequency resources can be determined by formulating suitable optimization problems, which can consider both the KPIs and key value indicators (KVIs), such as energy consumption [HEX23-D33, Section 3.2].

6G localization and sensing will support use cases with extreme KPI requirements, but Hexa-X took a broader approach and examined the implications in terms of KVIs, namely trustworthiness, sustainability, and inclusiveness. Localization and sensing play a dual role in each of these KVIs, contributing to improved trustworthiness, sustainability, and inclusiveness while ensuring the localization and sensing processes themselves adhere to these values. Focusing on the latter role and trustworthiness, there are crucial issues related to security (protection against attacks on sensing signals and processes), dependability (ensuring the integrity of sensing information), and privacy (of both connected users and assets) [HEX23-D33, Section 3.3].

Hexa-X contributed to the development of models for hardware impairments and propagation channels suitable for analysing localization and sensing algorithms. The use of geometric channel propagation models is recommended, providing consistency across time, space, and frequency bands. Additionally, since localization, sensing, and communication will all occur over the same channel, unified channel models supporting traditional communications as well as localization and sensing should be further developed. Complementary to channel models, realistic hardware models play a vital role in the development and analysis of localization and sensing methods and designs. Several such models have been presented, including phase noise (PN), power amplifier nonlinearity (PAN), and array element perturbations. Regarding both channel and hardware models, fundamental differences have been identified between monostatic sensing and communications, resulting from the use of a shared oscillator in a co-located monostatic sensing setup as opposed to communications. This causes channel/hardware impairments, such as PN and inter-carrier interference, to depend on sensing target parameters [HEX23-D33, Section 4.1].

In terms of methods, both localization and sensing results have been reported, considering model-based and machine learning-based approaches [HEX23-D33, Section 4.2]. When hardware impairments are not present, high accuracy can be achieved, including centimetre-level and decimetre-level localization accuracy under line-of-sight (LOS) and obstructed LOS conditions. ML-based methods have revealed innovative signal designs and signal processing techniques, even in the presence of hardware impairments. Coverage analyses with one and two base stations (BSs) were conducted to provide a uniform quality of service. The impact of location information on improving communication was also studied, aided by the introduction of a Reconfigurable Intelligent Surface (RIS) [HEX23-D33, Section 4.2.5].

Hexa-X bridged the gap between theory and practice by providing both an in-depth analysis of the impact of hardware impairments and by listing the achievable performance from over-the-air (OTA) demonstrations [HEX23-D33, Section 5]. Hardware impairments can be transformed into higher noise floors, leading to masking effects, which are important for safety-critical applications. It was also demonstrated that, in most cases, hardware impairments tend to be more detrimental for localization and sensing than for communication. However, there are certain exceptions, and in some rare cases, impairments can even be harnessed to improve performance [HEX23-D33, Section 4.2.2].

The OTA demonstrations of new localization beams show that conventional communication beams, corresponding to Signal-to-Noise Ratio (SNR)-maximizing directional beams, are suboptimal for localization and sensing. Specifically, the combined use of standard directional beams and newly proposed derivative beams leads to optimal performance for localization and sensing, while using only directional beams is optimal for communications as they maximize SNR at the targeted angle. For sensing, results from a bistatic setup at 60 GHz showed that even with simple signal processing, localization errors between 0.1 and 0.3 meters were achievable for passive objects. For localizing User Equipment (UEs), Angle-of-Departure (AoD) errors of around 0.01-0.2 degrees were reported, which can be related to positioning errors around 0.2-3.5 cm at a range of 10 meters, assuming known base station position and orientation [HEX23-D33, Section 5].

To further improve localization accuracy, three interrelated aspects must be considered: better hardware impairment mitigation, better algorithms, and better system calibration. Overall, the integration of localization, positioning, and sensing within 6G systems promises to unlock new services and applications while improving communication capabilities. As the 6G landscape evolves, further research and development will continue to refine and optimize these integrations to ensure a more robust, efficient, and trustworthy network that meets the needs of a diverse range of use cases.

3 Measurements from the Proof-of-Concepts

The previous section provided a comprehensive assessment of current research related to enabling radio technologies. This section supplements that evaluation by presenting data collected from test environments.

3.1 Mapping of Proof-of-Concepts to Radio Architecture Model

In [HEX23-D23] a general radio and baseband architecture for high data rate communication and sensing was proposed. Different aspects of this architecture have been demonstrated in PoC hardware setups. These demonstrated concepts are:

1. Flexible baseband architecture
2. Communication at sub-THz frequencies
3. Joint communication and sensing
4. Sub-THz communication using flexible baseband

The relation between these PoCs and the architecture of [HEX23-D23] and the PoCs is illustrated in Figure 3-1 for the TX part. Note that the TX architecture is a simplified version of [HEX23-D23].

In the following subsection, selected results and illustrations from the demonstration are summarized.

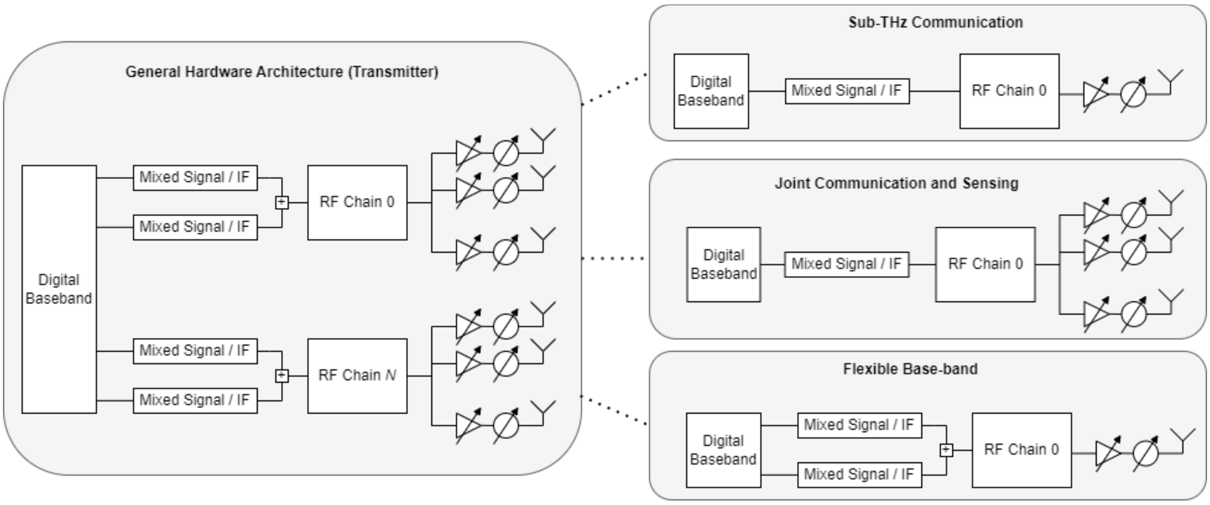


Figure 3-1: Relation of PoCs to general hardware architecture (only transmitter part is illustrated).

3.2 PoC Results

3.2.1 Flexible Baseband Architecture

Ultra-wideband is a key enabler for ultra-high data rate transmission. However, generating ultra-wideband waveforms, such as OFDM and its variant, with a single transceiver chain is challenging because of the need for high speed and high-resolution DAC/ADC. Alternatively, channelization can be employed, where the large bandwidth is split into multiple narrower-band channels, each using a dedicated transmit chain on each channel (carrier). The signals from the channels are superimposed (analogue multicarrier) and can be used as an intermediate frequency (IF) signal to high-frequency frontend, such as mmW or sub-THz, for over-the-air transmission (OTA), as illustrated in Figure 3-2:. The receiver employs multiple chains corresponding to the narrowband channels after the down-conversion from high-frequency. The individual channel waveform, bandwidth, and centre frequency can be reconfigured, which allows the use of a non-contiguous frequency band. Moreover, the same architecture can be adapted to different bandwidth requirements by switching off unneeded transceiver chains for power savings.

This PoC provides an implementation of the analogue multicarrier system with four channels, each with a bandwidth up to 160 MHz as shown in Figure 3-3. The IF transceiver chains are implemented using software-defined radio (SDR) platforms in the frequency range 0-6 GHz. A real-time flexible digital baseband transceiver is implemented on FPGA for waveform generation and signal detection at the receiver. Video broadcasting is used as an example for data transmission. This PoC demonstrates the feasibility of exploiting ultra-wideband at different frequency bands using a unified IF transceiver, where the system is evaluated for OTA transmission using a 2.4 GHz IF signal that is directly fed to an antenna module using a 26 GHz mmW frontend. The extension from 26 GHz to sub-THz is presented in Section 3.2.4.

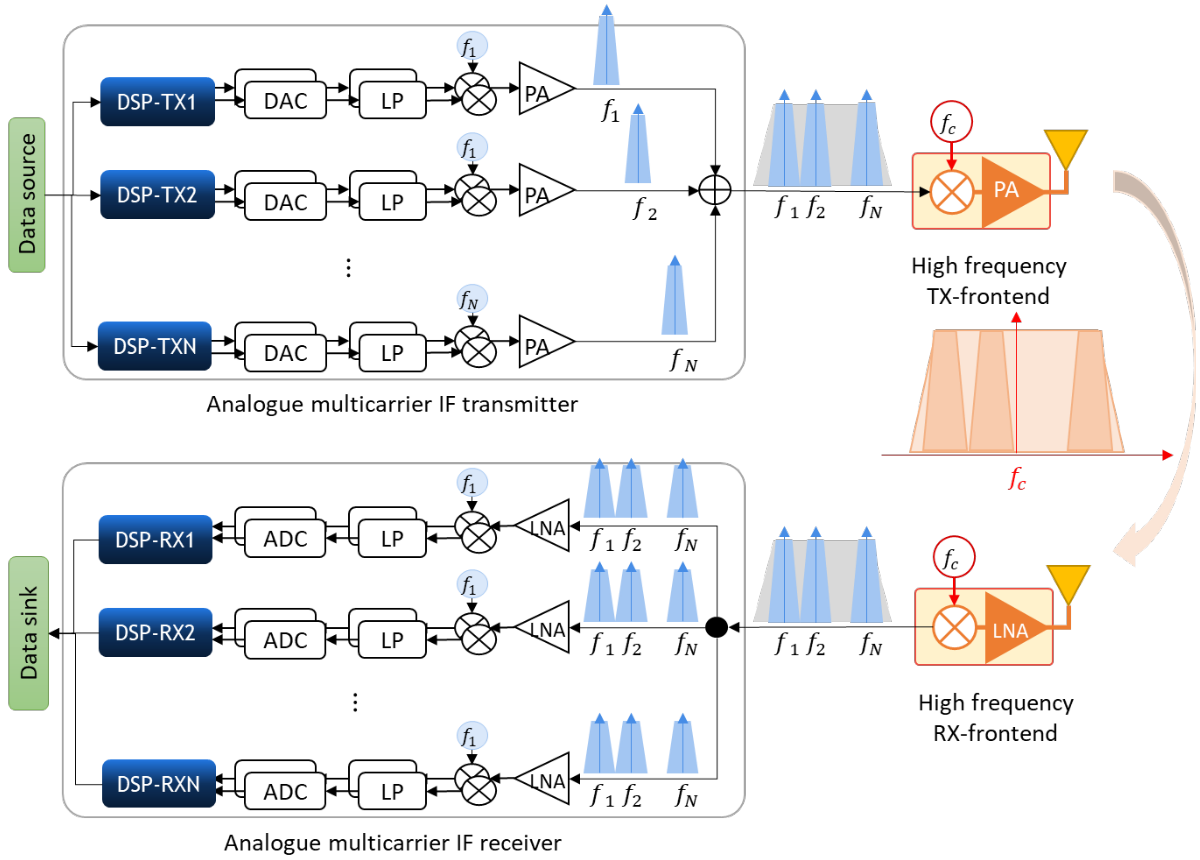


Figure 3-2: Block diagram of flexible analogue multicarrier system for ultra-wideband communications.

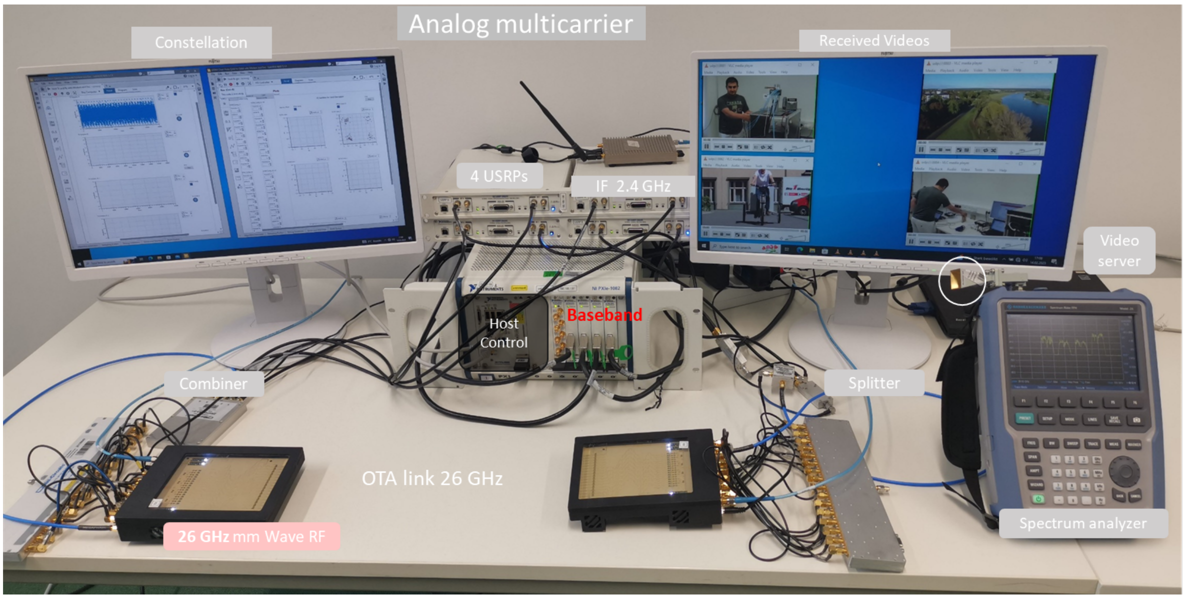


Figure 3-3: PoC implementation of analogue multicarrier system with SDR platform and 26 GHz frontend.

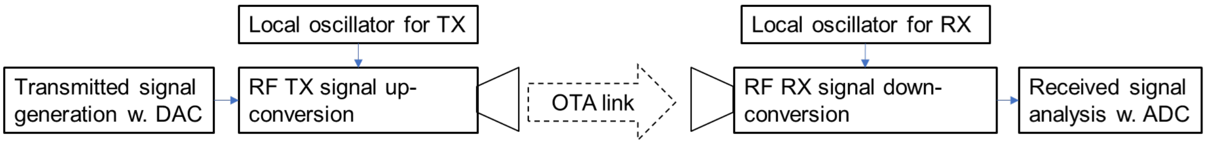


Figure 3-4: High level block diagram of extreme data speed proof-of-concept demonstrator arrangement.

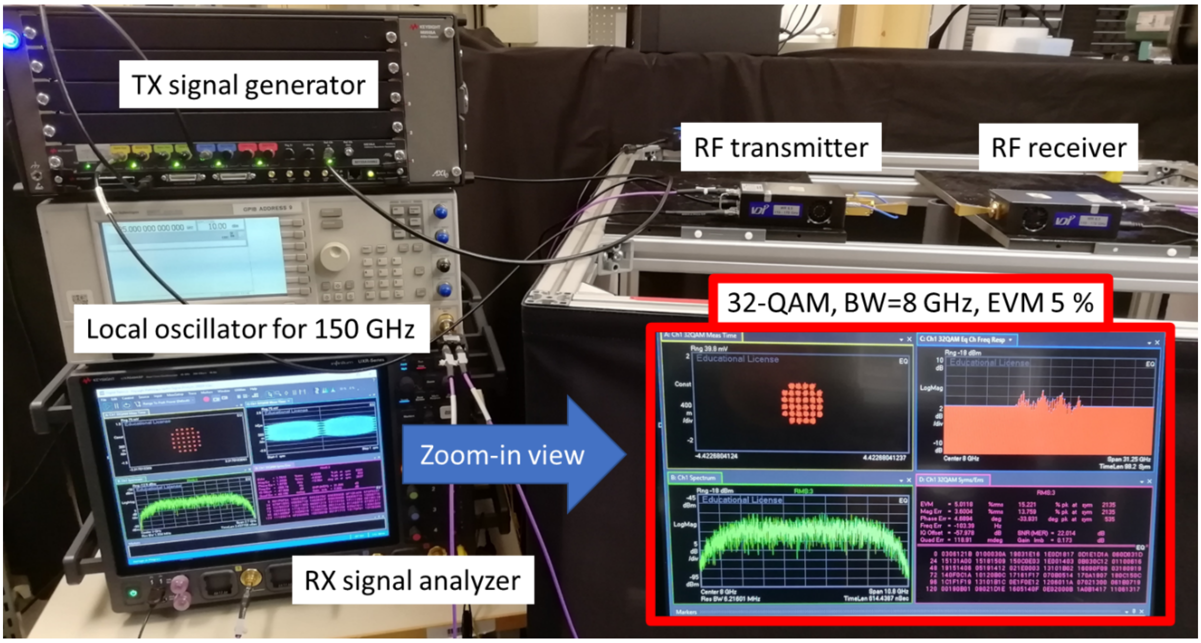


Figure 3-5: OTA arrangement for 150 GHz link with 32-QAM high-order modulation.

3.2.2 Communication at sub-THz Frequencies

A high data rate over-the-air (OTA) radio link at 150 GHz has been implemented with available laboratory equipment and components to demonstrate the feasibility of beyond current 5G communication systems. The signal generation and the analysis in the PoC are based on Keysight commercial measurement equipment. A high-level block diagram of the PoC is shown in Figure 3-4.

The transmission signal is generated by arbitrary signal generator (ARB) M8195A which supports 65 GSa/s sample rate and 25 GHz analogue signal bandwidth (BW). The signal analysis is performed with UXR1104A real-time RF oscilloscope with sampling rate of 256 GSa/s and is supports 40 GHz analogue signal BW. The RF transmitter (TX) and receiver (RX) are using Virginia Diodes Inc. (VDI) wideband frequency extenders which operates from 110 GHz to 170 GHz frequencies, and it has analogue BW of up to 17 GHz. The local oscillator (LO) of TX and RX extenders are implemented with Keysight E8257C RF signal generator which has frequency support to 40 GHz.

An overview of the PoC implementation with OTA link is shown in Figure 3-4. The setup supports a signal bandwidth of up to 10 GHz at 150 GHz carrier frequency. The LO signal is multiplied by six in the extender and thus 25 GHz input LO corresponds 150 GHz LO in the extender. The RF link operates at 158 GHz when the frequency offset is 8 GHz as in the example case shown in Figure 3-5. The error vector magnitude (EVM) of a 32-QAM signal using single carrier modulation with a BW of 8 GHz has been measured and the result of 5% fulfils the EVM requirement for signal detection. The maximum signal BW of 10 GHz with

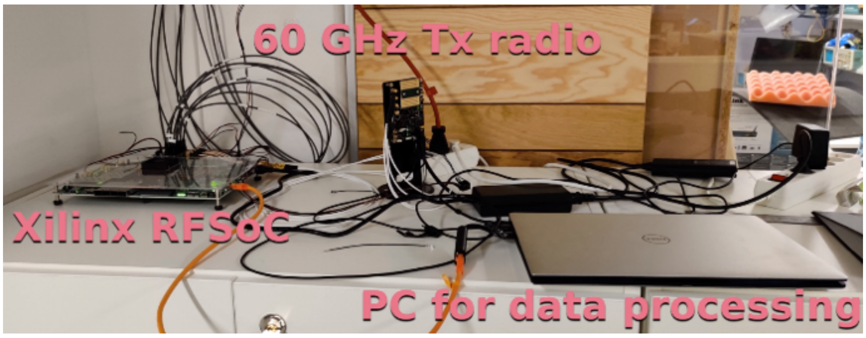


Figure 3-6: Hardware setup

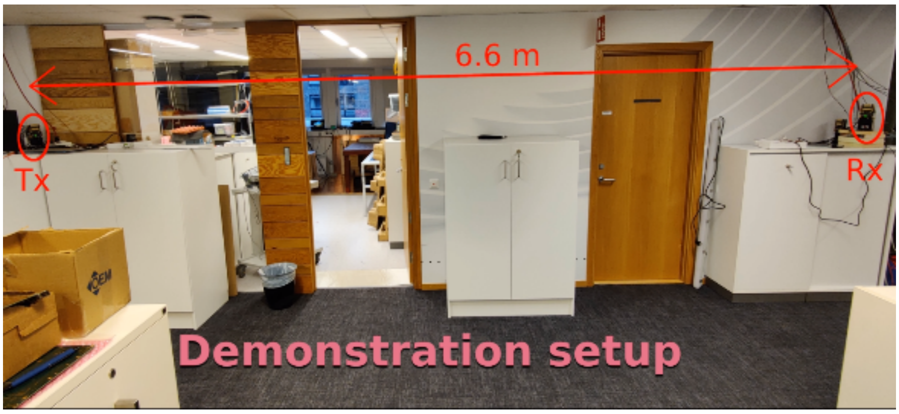


Figure 3-7: Demonstration setup

QPSK modulation was measured over the OTA link. If the signal bandwidth is limited to 2 GHz then 1.7% EVM with 32-QAM was reached and this result is shown in Figure 3-5, as well.

3.2.3 Joint Communication and Sensing

An indoor bi-static demonstration was developed to illustrate the feasibility of i.) sensing using hardware designed for communications, and ii.) signals designed to carry information. In Figure 3-6, the hardware setup is illustrated. It consists of 60 GHz transceivers, that can support analogue beam steering and a baseband interface implemented on a commercial FPGA platform. Parts of the signal processing were implemented on a standard computer. Two copies of the setup where placed ca. 6.6 m apart in an office environment as illustrated in Figure 3-7. Communication signals were transmitted between the transceivers and using the same signals, the two transceivers were operating as a bi-static radar. The setup properties were as follows: Carrier frequency 60 GHz, signal bandwidth 800 MHz, 64-QAM modulation using OFDM, 64 beams in the beam-book at the TX and 64 beams at the RX. A sub-carrier spacing of 960 kHz was used.

In order to combine communication and sensing, 16% of the time was used for communication (strongest LOS beam, random data). The remaining 84% of the time were used for beam-sweeping with a known pilot signal. Thus, communication and sensing were time-interleaved.

In Figure 3-8, the constellation at the input to the QAM demodulator is illustrated for the communication signal. As can be seen, the link supports 64-QAM, and is limited by hardware impairments. This can be identified by the secondary effect of an amplitude dependent noise level in the constellation.

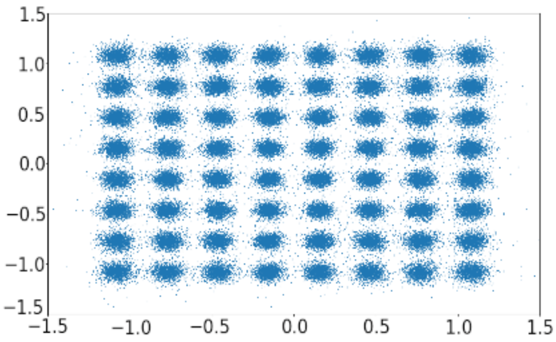


Figure 3-8: Communication constellation

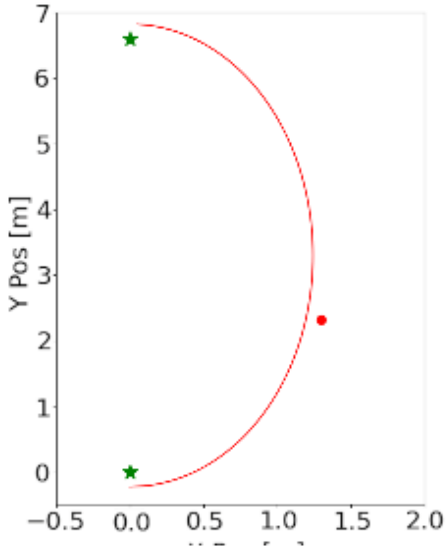


Figure 3-9: Position estimate based on communication signal

In Figure 3-9, the sensing performance is illustrated, which was obtained using the same signal characteristics. A person was moving according to the red line, and the red dot indicates a position estimate by the radar function. More details on the sensing performance can be found in [HEX23-D33].

In the demonstration setup it has been shown that the same hardware and signal design can be used for communication and sensing. The demonstration was performed using commercial hardware, meaning that typical hardware impairments have been taken into account.

3.2.4 Sub-THz Communication using Flexible Baseband

In this demonstration, real-time transmission is conducted over 140 GHz link, by integrating the IF transceiver detailed in Section 3.2.2 with the sub-THz frontend from Section 3.2.1. Several showcases highlight the feasibility of communication at sub-THz at different ranges by controlling the transmit power, and the impact of blockage and penetration through different materials. Figure 3-10 shows the laboratory setup in detail. The transmitted IF signal combined from 4 channels is upconverted by the TX frequency extender, and the IF received signal at the output of the RX frequency extender is split to 4 receive channels. The carrier frequency at 140 GHz is generated using an external oscillator, which consists of a programmable LO tuned at 11.66666 GHz feeding a frequency doubler resulting in 23.33333 GHz input to the frequency extenders, where 140 GHz is obtained from X6 internal multiplier.

This demonstration enables qualitative assessment of sub-THz communication by observing the quality of the video streams at different conditions. For instance, by changing the range, examination of beam misalignment, establishing a link via reflector to overcome blockage, and the impact of different reflector materials. In addition, the platform enables evaluating different OFDM-variant waveforms.

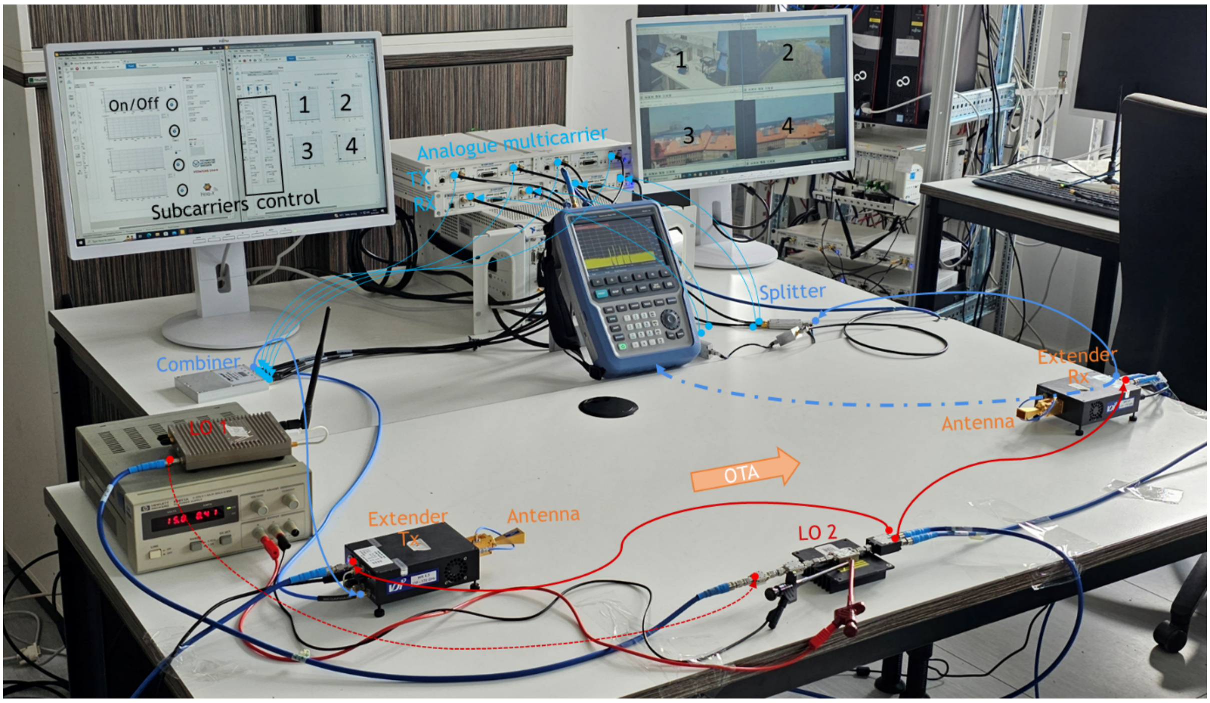


Figure 3-10: Integration flexible IF transceiver with sub-THz frontend for OTA transmission at 140 GHz.

4 Current Trends in Beyond 5G / 6G Radio Research

This section presents a selection of current research trends in the field. Where confidence is established, an estimated technology readiness level (TRL) and a projected timeline for developments and advancements are also provided.

4.1 Channel Modelling

4.1.1 Sub-THz Channel Modelling

Sub-THz radio frequencies are gaining high interest among research institutes and channel sounders are introduced more in numbers and capability. Channel measurements remain still very laborious and slow to conduct. However, with the current trend one can expect rapid increase of measured propagation data and consequently cumulating amount of extracted channel parameters. This development also allows us to study more realistic dynamic channel environments such as high pedestrian and industrial areas where human blockage, and other moving objects are expected.

There are many future directions ahead in channel modelling. One of them is the development of a statistical channel model for system and link level simulations. The next step to that direction is to collect data sets and parameters from as many sources as possible and to perform statistical analysis on them. The purpose is to extract probability distributions of various channel parameters for different environments, deployment schemes, and radio frequencies. Next, existing, standardized channel models, targeted for lower frequencies, must be revised in the light of collected THz insight. Model components, frameworks and mathematical descriptions needing modifications must be identified and updated. Complementary propagation measurements might be needed in this phase, e.g., to understand validity of so called intra cluster parameters or the applicability of the cluster concept overall. In addition, since high-frequency approximation is becoming more relevant in sub-THz regime, site-specific ray-based methods can also be exploited to support the analysis and to complement the statistical channel model. Finally, with the new parameterization by the mentioned probability distributions and updated model components, a new or at least a revised stochastic channel model can be introduced.

Related, but slightly different aspect is the modelling of near-field and wide bandwidth effects at THz. With the high frequencies the near-field distance can approach or exceed the practical link distances. Existing channel modelling frameworks may need upgrading in these aspects and one future research direction is to explore suitable methods for the upgrading.

4.1.2 Wave Scattering

It has been shown in [HEX23-D23] that the conductivity and permittivity for homogeneous materials with flat surface can be simply modelled by equations introduced in the ITU-R 2040 recommendation for frequencies between 100 and 300 GHz. However, some materials such as concrete or relief wallcovering cannot be considered anymore as optically smooth at frequencies above 100 GHz. Several papers highlight the scattering effect created by the surface roughness and propose different theoretical or measurement-based models to simulate the power angularly spreading around the specular direction. Averaged power scattering profile obtained by measurements and simulations show that the specular reflection dominates even if it is attenuated in the case of rather rough materials for frequencies below 300 GHz. An interesting research direction to complement the existing knowledge on the scattering would be the small-scale fading analysis over the frequency and space due to the multi-path created by rough surfaces. This fading that can have the coherence bandwidth greater than a few GHz may impact the sub-THz wireless system performance as very small antenna displacements may introduce additional losses.

4.2 Radio Architecture and Models

Commonly adopted D-MIMO architecture includes distributed Radio Units (RUs) connected to a Distributed Unit (DU) via wired/wireless fronthaul links. Critical baseband processing operations can be performed at the DU to optimize the resources in a more centralized way and reduce the cost of RUs by making them simpler. On the other hand, it may be beneficial to keep some baseband operations at RUs to achieve a balance between resource allocation performance and latency. There are many ongoing investigations to compare different processing options in D-MIMO and as in 5G NR [SAR+21], it would be better to design different functional splits for different purposes.

To ease the deployment, a serialized fronthaul interface can be an enabler at the expense of some extra sequential operations at the RUs. Another option to make the deployments more flexible can be to use a wireless fronthaul. Some less critical part of the spectrum can be allocated for fronthaul signals to realize the wireless fronthaul. Compared to a wired fronthaul, this solution can be cost effective (considering that the cost of deployment of fibre cables is very high [ZHA+21]) but will result in a lower capacity. To support fronthaul links (or backhaul links in IAB) RIS can be used, which can potentially change the channel characteristics by increasing the channel amplitude [BJÖ+19], increasing the channel rank [OZD+20] and hence can enhance the capacity of wireless fronthaul/backhaul links. RIS can also be used to support access link service quality especially in high frequency bands by covering blind-spots. It is expected that it may be possible to use several RISs in a D-MIMO network to improve the performance without increasing the energy consumption and the cost of deployment much. To cover comparably larger and farther areas, one can also use network-controlled repeater (NCR) and make use of the amplification ability of these nodes. In a heterogeneous network with several RIS, NCR, IAB, and classical D-MIMO nodes, it would be possible to obtain extreme performance with an optimized algorithm design supported by a very flexible architecture. On the other hand, processing, e.g., beamforming, in different nodes can either be performed in the analogue or digital domain. In case of limited bandwidth, local processing would be feasible at RUs. A further distinction can be made between centralized and distributed processing, e.g., digital processing will be power consuming and increases the size and cost of the nodes that requires moving the processing to the DU.

TRL and timeline: The concept of IAB has achieved TRL 5-6, nonetheless NCR has only conceptual studies resulting with TRL 2-3. D-MIMO systems, i.e., combinations of D-MIMO with IAB, NCR and RIS have conceptual studies where it is presumably around TRL 2.

4.3 Signal Processing Techniques

4.3.1 Distributed MIMO (D-MIMO)

Simultaneous multi-node connectivity, i.e., macro diversity, to large number of coordinated Radio Units (RUs) will not only provide higher data rates everywhere, but also robust access links, especially for mmW/sub-THz operations [HEX21-D21]. coordinated multi-point (CoMP) flavours with coordinated beamforming, scheduler and joint transmission (JT), where 3GPP has defined CoMP schemes in LTE and New Radio [36.741]: (i) non-coherent joint transmission (NC-JT Case 1), where different streams are transmitted from different TX/RX points (TRPs), (ii) NC-JT Case 2a, where different layers are transmitted across TRPs with spatial diversity/multiplexing, e.g., space-time block codes, (iii) NC single frequency network (SFN) JT (NC-JT Case 2b) where same layer is transmitted across TRPs, (iv) Coherent JT.

TRL and timeline: D-MIMO concept and related signal processing techniques have achieved different TRL, where it is presumably around TRL 3-4. Some precoding and interference management techniques with clustering approach has experimentally validated with a PoC, and some C-JT demonstrations has been validated in a lab environment. Nonetheless, given that multi-TRP is the current version of ultimate D-MIMO networks, one can argue that multi-TRP with NC-JT is at TRL5. We expect (best guess) D-MIMO can change to TRL 5/9 by the year 2025/2030. Frequency bands up to mmW [HEX21-D21], are expected to reach the higher TRL sooner.

New research trends and possible extensions for D-MIMO are given below:

Enhanced non-coherent operations: Most of the existing transmission techniques require instantaneous channel state information (CSI) to form precoders. There may be challenging conditions due to, e.g., high mobility, lack of uplink/downlink reciprocity, pilot contamination, where a robust transmission mode would be preferrable. Non-coherent techniques may offer several advantages in a D-MIMO system due to the lesser feedback requirements, lower complexity, and robustness against channel variations. These approaches may be applied, e.g., in joint transmission, beamforming, modulation and coding schemes. As an application of NC-JT transmission scheme, space time frequency block coding (STFBC) schemes exploiting multiple transmit antennas, e.g., Alamouti-like orthogonal codes, can be utilized in a D-MIMO network to increase the diversity at the UE side when instantaneous CSI is not available at RUs. Opportunistic beamforming and other robust beamforming techniques also allow transmitting over multiple beams simultaneously that can be coordinated over multiple RUs.

Multi-band operations: Signal processing algorithms, e.g., RU-UE association, beamforming, resource allocation, power pooling across multiple frequency bands will potentially enhance gains in both spectral and energy efficiency.

Multi-antenna UEs: UEs operating at high frequencies with directive antenna arrays may also impact the requirements put in the D-MIMO network that might reduce the amount of coordination between RUs. Precoding and other resource allocation schemes as well as UE beamforming capabilities are some topics to be studied.

Heterogeneous nodes: There might be heterogeneous deployment of various RUs and DUs with different capabilities and functionalities, where multi-DU cooperation is important that would require advanced coordination and processing methods, e.g., interference management and load balancing among same or different DUs.

D-MIMO extensions: The role of reconfigurable intelligent surfaces (RISs) and network controlled repeaters (NCRs) is appealing to assist D-MIMO networks from the perspective of integrated access and backhaul/fronthaul (IAB), which would be regarded as a D-MIMO system where advanced signal processing techniques would be required. Three-dimensional (3D) distributed massive MIMO networks employing vertical coordination/cooperation would need novel processing methods, e.g., interference management, IAB techniques, etc.

D-MIMO extended capabilities: Distributed nodes will enable better angle of arrival (AoA) resolution, macro diversity which will enhance the accuracy and reliability of localization and radio sensing capabilities.

Context-aided communication: Localization and sensing information help enhance D-MIMO capabilities, e.g., directive beams, better sleep modes, proactive D-MIMO communications. Out-of-band information can assist D-MIMO beamforming. Herein, data-driven methods can be utilized to harness hidden correlation between in-band measurements and out-of-band measurements and information sources.

4.3.2 ML-assisted Compensation of RF Hardware Impairments

RF hardware impairments impose significant constraints on the performance of wireless communication systems, particularly at higher frequency bands like sub-THz. However, leveraging ML-based techniques offers a promising solution for effectively compensating these impairments. This approach unlocks opportunities to enhance performance, improve efficiency, and reduce costs in future wireless communication systems [HEX23-D43], [FS20], [FHS23], [KHH+21], [PKH+21]. Machine learning has shown potential in compensating for oscillator phase noise, leading to performance enhancements and cost reductions in transmitters/receivers. A context-aware receiver for DFTS-OFDM modulation, incorporating trained models, is proposed for improved performance in phase noise-limited scenarios with manageable complexity in [FS20]. PA non-linearity distorts transmitted signals and degrades throughput. Traditional compensation methods, such as power back-off or digital pre-distortion (DPD), have drawbacks like reduced energy efficiency or increased complexity. ML techniques optimize transmitter and/or receiver functionalities to compensate for PA nonlinearity. ML-empowered receiver methods, such as learning demapper for DFTS-OFDM signal in [FHS23] and joint waveform optimization and learned receiver for CP-OFDM signal in [KHH+21], [PKH+21] confirmed potential performance gains in terms of throughput, reliability, and energy efficiency for this approach.

TRL and timeline: ML-assisted techniques for compensating RF hardware impairments have achieved different TRL, where it is around TRL 4-6. We expect ML-assisted techniques can change to TRL 7/9 by the year 2025/2030. Higher frequency bands (e.g., mmW) are expected to reach the higher TRL sooner.

New research trends and possible extensions for ML-assisted RF hardware impairment compensations are given below:

ML frameworks: The adoption of ML-assisted techniques in 6G networks would require frameworks for data collection, training, model monitoring, and inference for operation at physical layer that need to be developed.

Scalable solution: The ML-assisted techniques provide an opportunity for a scalable solution to compensate the impact of multiple types of RF hardware impairments.

Coordination: Depending on whether the ML functionality is at the transmitter or receiver side or both the network nodes (UE and BS) may need to coordinate their operations for compensating RF hardware impairments.

4.4 Localization and Sensing

Research has shown that 6G JCAS systems can utilize communication infrastructures and signals to enable synergies with localization and sensing for diverse applications by exploiting the large antenna array sizes and wide bandwidth. However, further research efforts are still needed to improve localization and sensing accuracy, service coverage, and practicability, and to meet the stringent requirements for new use cases.

4.4.1 D-MIMO and Near Field Localization

Existing localization and sensing works typically use a narrowband far-field (FF) model due to its simplicity in algorithm design and performance analysis [CEG+22]. This model works well in conventional communication systems with limited bandwidth and antennas. However, to combat high path loss with signals at high carrier frequencies, extra-large aperture arrays (XLAAs) will be deployed, resulting in several features: (i) spatial non-stationarity (SNS) [DAA+20] indicates that the complex channel gains between different antennas at an XLAA BS and the UE are different; (ii) spherical wave model (SWM) [AAG+21] captures the curvature of arrival/departure waves to/from the UE such that the steering vector is position-dependent instead of angle-dependent; (iii) beam squint effect (BSE) [TD21] caused by wide bandwidth results in different beamforming directions for different parts of the band. Ignoring these features can simplify the channel model and localization (and sensing) problem formulation, but it will result in performance degradation. Accounting for these features, however, can provide extra location-related information such as curvature of arrival [GGD+21], opening opportunities for localization and sensing. In addition to XLAA, distributed MIMO systems (which are expected to provide larger spatial diversity and higher data rate [MYS11]) could also be considered another type of large array, if the phase coherence is maintained between different antennas [ADK+23]. Such a cell-free setup (e.g., radio stripes) can provide a low-cost solution for localization and sensing without deploying multiple BSs as anchors.

TRL and timeline: The concept D-MIMO and near field localization has been validated in lab reaching TRL 4, we expect (best guess) this technology can change to TRL 5/8 by the year 2026/2030.

4.4.2 Reconfigurable Intelligent Surfaces (RIS)

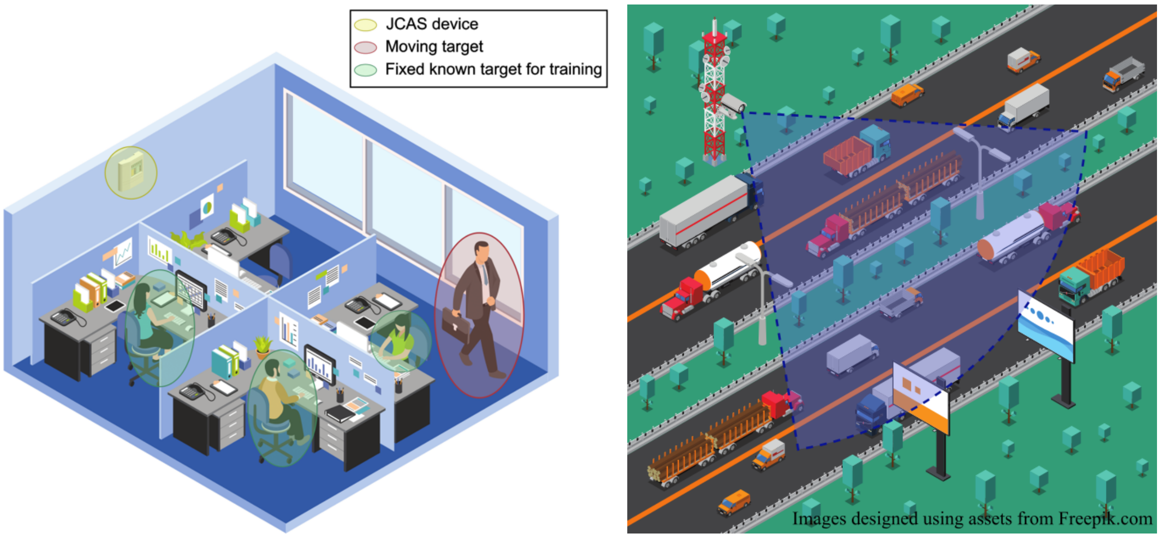
In existing system setups, localization functions require access to multiple BSs, and sensing requires combating the attenuation of transmitter (TX)-object-receiver (RX) links, which limits service coverage [CKA+23]. Considering the deployment of power-hungry BSs with full communication capabilities is costly, reconfigurable intelligent surfaces (RISs) are a potential alternative that can passively reflect radio waves in preferred directions and actively sense their environment in receive and transmit modes [WHD+20]. With the introduction of RISs, new localization and sensing application scenarios have emerged: (i) improving existing localization and sensing system performance by boosting signal energy and acting as extra anchors; (ii) enabling low-cost systems, such as single-input single-output (SISO) systems, to perform localization tasks due to high angular resolution introduced by RIS [KKS+22]; (iii) facilitating cooperative positioning to estimate the position of multiple user equipment (UEs) via sidelink communications without the involvement of BSs [CZK+23]; (iv) enabling self-localization and sensing using a full-duplex array with only a single RIS acting as a passive anchor [KCK+22]; (v) sensing-aided communications using RIS: to reduce the overhead of acquiring channel state information, the BSs could exploit the user and dynamic blockers speed/location information by sensing to pre-define the RIS service region [GMA+22]. These new scenarios provide opportunities for ubiquitous localization and sensing services to realize 6G connectivity.

TRL and timeline: RIS protypes have been developed by several companies for communication services reaching TRL 3, we expect (best guess) this technology can change to TRL 4/7 by the year 2026/2030.

4.4.3 Calibration

While most of the localization and sensing algorithms are developed considering ideal channel models, hardware impairments (HWIs) distort the transmitted and received signal and hence degrade localization and sensing performance [GAI+22]. Therefore, impairment modelling and calibration methods are required to compensate for HWIs, either offline during calibration or online, using dedicated signals and routines [Sch08]. Both offline and online calibration methods have residual errors, which can be modelled as random perturbations around the nominal values. Localization and sensing have different requirements for residual error levels, and dedicated calibration algorithms for each task are necessary. Another type of calibration error that is often overlooked in communication systems is the geometrical state of the anchors (BSs and RISs) [MA18]. Even small errors in the position or angle of the anchors can result in significant localization and sensing errors. The calibration of anchor states can be performed similarly to localization tasks using calibration agents with known states (e.g., GPS or extra sensors) [GKJ+23]. Furthermore, joint localization and calibration methods (taking one anchor as the reference and calibrate other anchors) are emerging as more practical solutions for anchor geometrical state calibration in 6G JCAS systems [ZCB+23].

TRL and timeline: Calibration is a relatively mature technology in wireless communication systems, reaching TRL 5, however, the requirements for calibration error is more stringent than



(a) (b)

Figure 4-1: Indoor JCAS system (a), where some targets can be in known positions with respect to the JCAS system; and outdoors JCAS system (b), in which the labels are obtained from camera measurements knowing the relative distance of the base station and the traffic lanes.

communications with more efforts needed. We expect (best guess) this technology, for localization and sensing services, can move to TRL 6/7 by the year 2026/2030.

4.4.4 Machine Learning

Typically, machine learning methods assume labelled data is available for training [HEX22-D32]. However, it should be considered how such data is collected and used. The use of simulation setups can be advantageous in generating synthetic data for pre-training models that can be transferred to fine-tune systems with limited real-world data available [SFY+22] (however, it is important to note that real-world errors are crucial for obtaining labelled data that is representative of actual operating conditions). Similar approaches can be employed for JCAS. For example, in Figure 4-1 (a) the deployment of known targets in fixed positions gives reliable labelled data (see also [MSR+19]). However, in certain other environments (cf. Figure 4-1 (b)), it is not always possible to place a target in a real environment, or it is too costly. In such cases, external sensors, e.g., camera measurements, can be used to obtain labelled data for the training stage. This data may not be as accurate as the data collected from known targets, but it can still be useful to fine-tune pre-trained ML models.

On the other hand, it is common in machine learning works applied to JCAS to assume that the gradient of the loss function with respect to the network parameters does not vanish when training the networks [WLH+22], [MGZ+21]. However, in end-to-end learning of practical scenarios, the channel model is unknown, and the gradient cannot be propagated back to the transmitter. Reinforcement learning can be applied to these kinds of scenarios, in which the system can still be end-to-end optimized, based on a reward value. In the case of bistatic sensing, this reward will be relayed back to the transmitter from the receiver. Hence in these scenarios, the potential error in the feedback should also be considered. End-to-end reinforcement learning has already shown promising results in communication systems [AH19], [WSH+22].

TRL and timeline: Machine learning for positioning has been studied in experimental setups, reaching TRL 4, we expect (best guess) that this technology can change to TRL 5/7 by the year 2026/2030.

4.5 Optical Wireless Communication

Optical wireless communication (OWC) encompasses different technologies able to address distinct use cases, e.g., visible light communication (VLC), light fidelity (LiFi), optical camera communication (OCC), free space optical communication (FSOC), and light detection and ranging (LiDAR) [HEX21-D21].

Looking at a major research trend on this topic outside of Hexa-X, 6G BRAINS (Internet of Radio Light - Bring Reinforcement-learning Into Radio Light Network for Massive Connections) project foresees that future wireless communication systems will rely on heterogeneous networks with the simultaneous utilization of multiple bands, namely sub-6 GHz, mmW, sub-THz, and OWC bands. It then aims at combining spectral links like THz and OWC to enhance the performance in terms of capacity, reliability, and latency [6GB21]. Thanks to the adoption of THz and OWC, 6G BRAINS technologies may also be used for e.g., vital data monitoring, communication-enabled radar, ultra-precise localization, and secure distributed connections [BRA21-D21]. The further combination of ML-driven methods with THz and OWC also allows for performing resource allocation over and beyond massive machine-type communications, in conjunction with performance enhancements in terms of capacity, reliability, and latency, as required for future application scenarios like production manufacturing, automotive industry, and smart agriculture. The targets are to achieve up to 100 devices per m^3 network density, up to 99.999% reliability, up to 0.1 ms air interface latency, and high-resolution 3D simultaneous localization and mapping (SLAM) of up to 1 mm accuracy for the future industrial networks [6GB21, BRA21-D21].

TRL and timeline: the above mentioned OWC technologies (VLC, LiFi, OCC, FSOC, LiDAR) are already available reaching TRL 9 for basic requirements and functionalities. The innovative requirements and functionalities such as the ones addressed by 6G BRAINS need massive research and development still ongoing inside this project lasting until December 2023 and it might be expected the relevant technologies reaching TRL 4/6 by the years 2027/2030 and TRL 7/9 beyond 2030.

5 Evolution of 6G Markets

Analysis of a project-internal questionnaire related to this topic has shown that there is a scarcity of insights on the economic impact of sub-THz technology at this point in time. This can be attributed to the complexity that makes it difficult to predict with certainty and, especially for companies, the sensitivity of business-related topics. Furthermore, it should be noted that the economic impact of the survey may not be directly applicable to academic organizations. While academic institutions may be impacted by economic changes, their focus is often on research and education rather than on profit and loss statements.

As a consequence, thereof, the discussions in this section are based on existing public studies.

5.1 General Economic Impact of 6G

The race for the next generation of wireless communications technology is already in full swing, with 5G networks growing rapidly. The next wave of wireless connectivity, 6G, is expected to be a paradigm shift in the way we communicate and interact with technology. 6G is expected to deliver unprecedented speed, ultra-low latency, massive connectivity, and novel use cases [HEX23-D14], incl. holographic communications, immersive augmented reality (AR), smart cities and digital twins of the physical world, that will revolutionize many established industries. In this section, we look at the market evolution of 6G technology through 2040 and provide insights into potential opportunities and challenges. The development of wireless communication technology has been a driving force for the progress of modern societies. From 1G to 5G, each generation has brought significant improvements in speed, capacity, and performance. However, the increasing demand for higher data rate, lower latency and ubiquitous connectivity has paved the way for the development of 6G technology. To realize this vision, 6G requires advances in hardware, software and services that can meet its unique requirements.

It is currently assumed that 6G markets will open from 2028 and will have largely developed by 2040. The 6G market is expected to account for USD 13,690.9 million in 2030 and is expected to surpass USO 340,510.2 million by 2040, exhibiting a compound annual growth rate (CAGR) of 28.10% during the forecast period (2031 - 2040). [MRF23]

5.2 Hardware Development

Hardware will play a critical role in the development of 6G technology. To support the expected massive connectivity and ultra-low latency, 6G networks will require a significant increase in the number of base stations and access points, as well as advanced antennas and transceivers capable of operating at higher frequencies, such as THz and optical bands. In addition, new form factors and device designs may be required to enable seamless integration of 6G technology into various environments such as wearables, smart infrastructure, and internet of things (IoT) devices. In addition, advances in chipsets, processors, and memory technologies will be critical to handle the massive amounts of data generated by 6G networks and support complex computing tasks at the network edge. The 6G hardware market is expected to see significant growth as companies invest in research and development to develop solutions that meet the unique requirements of 6G networks. Companies specializing in advanced antenna technologies, THz communications, optical communications, and semiconductor manufacturing are expected to thrive in the 6G era. In addition, collaboration between hardware manufacturers, chip designers, and device integrators is likely to increase to accelerate the development of 6G hardware solutions.

Hardware accounts for almost 2/3 of the total market and is forecast to grow at rates above 30% between 2030 and 2040. [MRF23]

5.3 Software Development

Software will be a key enabler for 6G technology, providing the intelligence and flexibility needed to manage network complexity and support a wide range of applications. It is expected that 6G networks will be highly programmable and leverage software-defined networking (SDN) [TSM+21] and network function virtualization (NFV) [SZC20] technologies to enable dynamic network slicing, intelligent routing and optimized resource allocation. In addition, advanced machine learning (ML) [ALS+18] will be essential to enable autonomous network management, predictive analytics, and intelligent decision-making. The 6G software market is expected to be highly competitive, with companies specializing in SDN, NFV and ML technologies at the forefront. In addition, collaboration between software vendors, network operators, and application developers will be critical to create a vibrant ecosystem that can foster innovation and enable the development of novel 6G applications.

Market volume will be around 14% of the total market in 2040, growing at around 40% annually between 2030-2040. [MRF23]

5.4 Development of Services

Services will be a key driver of the 6G market, opening up new business opportunities and revenue streams. The 6G services market is forecast to experience significant growth, driven by increasing demand for advanced applications and services that leverage the unique capabilities of 6G technology. The market is expected to be diverse as a variety of service providers, including traditional telecom operators, technology companies, cloud service providers, industry verticals, and start-ups, will enter the 6G services space.

One of the key drivers for 6G services is likely to be the healthcare sector. With the ability to enable remote surgeries, telemedicine, and real-time monitoring of patients, 6G is expected to revolutionize healthcare. Similarly, in the transportation sector, 6G can enable autonomous vehicles, connected roads, and intelligent transportation systems, leading to greater efficiency, safety, and reduced congestion.

Significant growth in 6G services is also expected in the entertainment and media industry. With 6G's ultra-high speeds and low latency, immersive augmented and virtual reality experiences, holographic communications, and advanced content delivery services are expected to become mainstream and change the way we consume and interact with media.

In addition, the manufacturing sector is expected to benefit from 6G services by enabling advanced industrial automation, robotics, and supply chain management, leading to increased efficiency, productivity, and cost savings. In addition, the agriculture sector can leverage 6G services for precision farming, remote monitoring, and smart irrigation, enabling sustainable and efficient farming practices.

Healthcare, transportation, entertainment, manufacturing, agriculture, and other sectors are expected to benefit greatly from 6G services by creating new business opportunities and transforming industries. However, overcoming challenges and creating an enabling ecosystem are critical to the successful development and adoption of 6G services in the market by 2040. Additionally, the development and deployment of 6G services may face challenges, such as legal and policy frameworks, security and privacy concerns, and infrastructure requirements. Overcoming these challenges will be critical to the widespread adoption of 6G services and realizing their full potential.

A detailed discussion of envisioned 6G services and corresponding requirements can be found in [HEX21-D12] and [HEX23-D14].

Overall, the market for 6G services is forecast to grow significantly around 50% between 2030 and 2040, driven by increasing demand for advanced applications and services that leverage the unique capabilities of 6G technology. [MRF23]

5.5 Sustainability

Ultra-high availability Internet is still an unachieved goal and offers many research directions. 5G has brought some improvements, but a cost-efficient, fast and latency-free Internet with cyber-physical fusion and terrestrial communications (air, space) is not yet a reality. In the future, there will most likely be a densely connected world with energy-efficient, self-charging nodes and smart and automated devices. 6G is an important element of a new era of hyper-digitization in a hyper-connected world, which will not only bring technological benefits but also contribute to societal megatrends such as the United Nations SDGs, green energy and clean atmosphere at the same time. Interesting approaches in this direction are offered by the vision of Embodied Intelligence [DDK+22]. Here, the benefits to humanity, the growth of businesses, and the thriving of industries are propagated based on a fully connected, intelligent, and automated ecosystem with minimal functional costs as well as minimal transaction costs. This on the other hand requires a new 6G ecosystem, and new architectures which have to be developed, especially for hardware.

5.6 Global Development towards 5G and 6G

Current discussions and visions about the future of 6G reveal fundamental differences in the way the three major economic blocs - the U.S., China, and Europe - are driving 6G development. The U.S. vision of 6G emphasizes leadership in the wireless ecosystem and security at all levels [IISS22]. The Chinese vision emphasizes sovereignty, global initiatives, and the digital Silk Road [IISS22]. The EU vision emphasizes research sovereignty, the United Nations Sustainable Development Goals, and the central role of people [ELF22, pp. 11-14 and pp. 31-33], [ELF22, p. 33], [ELF22, p. 35]. Given current geopolitical tensions, many researchers and companies are concerned about the fragmentation of global 6G markets, technologies, and regulations, especially with regard to the use of artificial intelligence [SCJ21]. Europe is well-positioned to compete globally with its strong ecosystem of technology vendors, mobile operators, and end users in various industries.

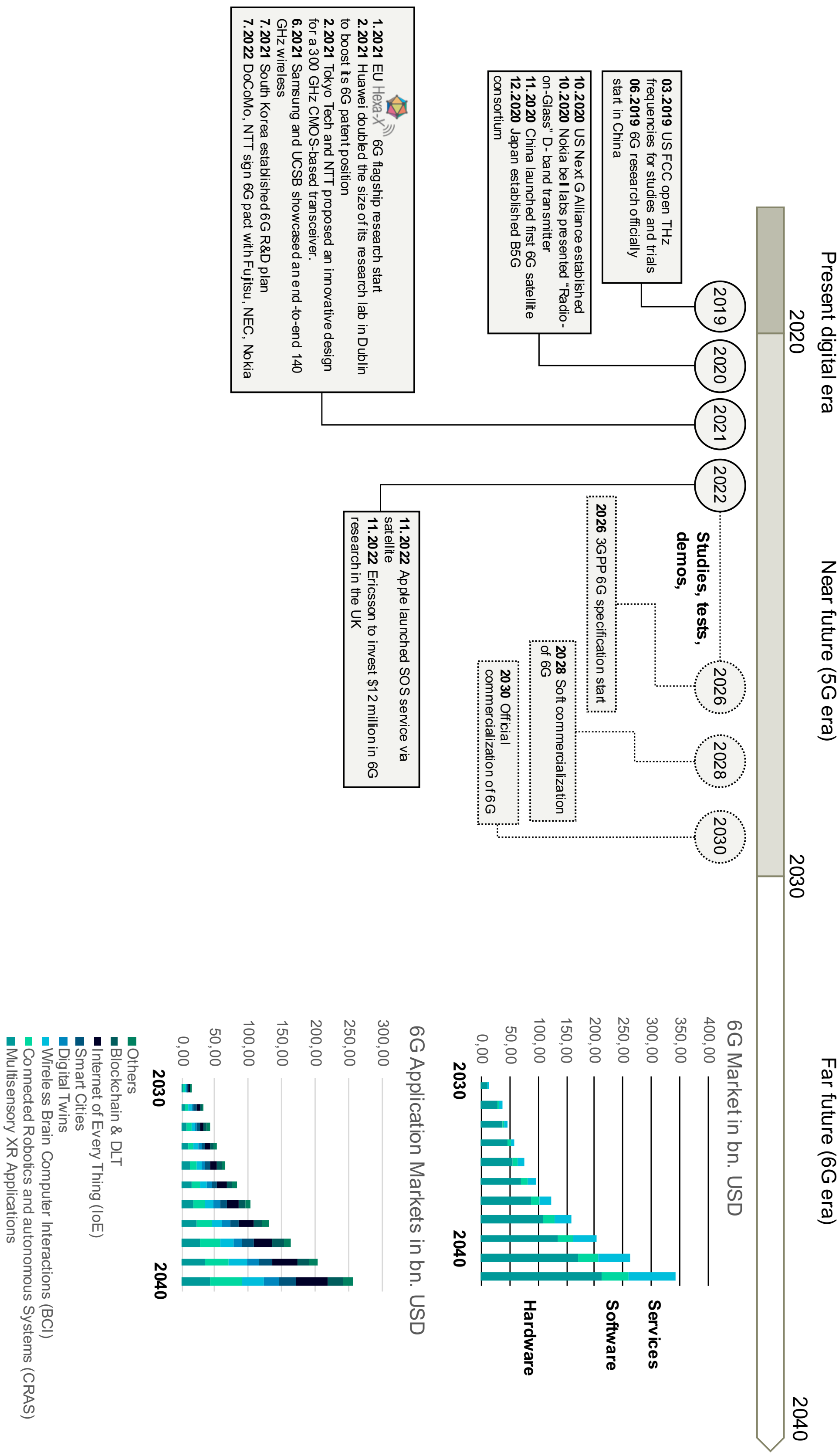


Figure 5-1: 6G Market Development, based on [ITX22a] and [MRF23]

6 Radio Technologies Roadmap towards 6G

6G is expected to be a key enabler of the future internet, enabling a range of new services and applications that were not possible with earlier generations of wireless technology. The future of the internet is closely tied to the evolution of wireless technology, as more and more devices become connected and require high-speed and reliable Internet connections. 6G will play a significant role in shaping the future of the internet, particularly in areas such as virtual and augmented reality, digital twins, and the internet of things (IoT). With its faster speeds and lower latency, 6G will enable new forms of immersive experiences that rely on high-quality video streaming and real-time interactions. It can also support the deployment of advanced IoT applications that require low-latency connectivity and high-bandwidth data transfer.

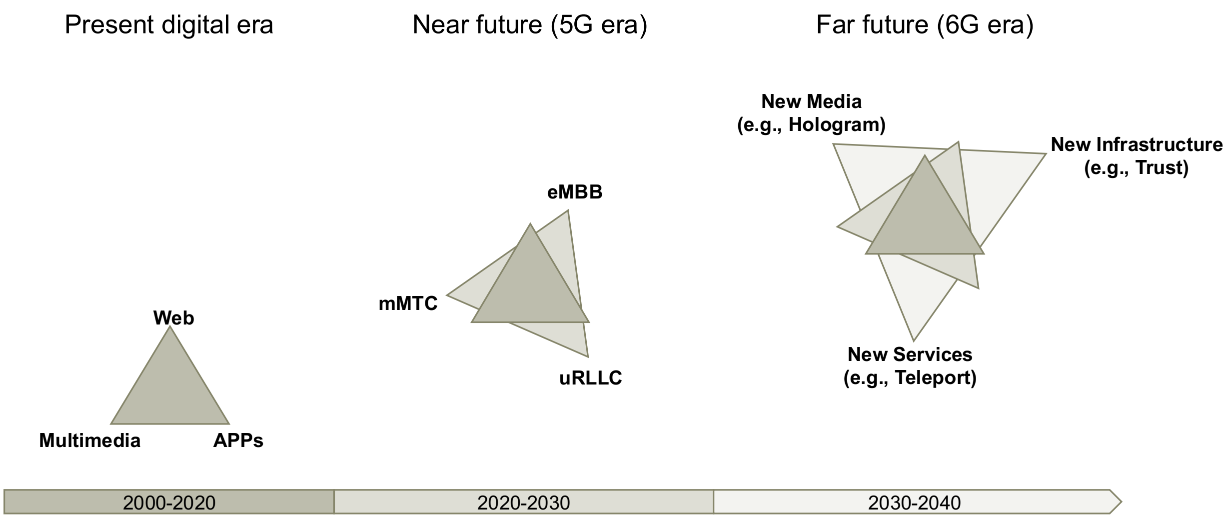


Figure 6-1: 6G as key enabler of the future internet [LYX+20]

6.1 6G Technology Challenges

The development of 6G radio hardware is a critical step for the next generation of mobile technology. With the introduction of 6G, significant improvements in speed, capacity, reliability, latency, and connectivity will be achieved. However, there are a number of challenges that must be overcome to realize the visions of 6G.

As part of the Hexa-X work, the challenges and opportunities associated with 6G radio hardware development and implementation have been analysed in detail. Technical challenges such as frequency spectrum, energy efficiency, and miniaturization and integration of radio hardware were discussed, and promising approaches to address these challenges were identified.

- *Frequency spectrum*: One of the critical challenges in the development of 6G radio hardware is the use of THz frequency bands. Compared to the frequencies currently used by 4G and 5G, THz frequencies are much higher and present technical challenges. Attenuation of signals by the atmosphere and propagation of signals over short distances are challenges that must be overcome. Innovative approaches such as the use of metamaterial-based antennas and research into new modulation schemes are needed to make THz frequencies usable for 6G radio hardware.

- *Energy efficiency*: With the massive number of devices and sensors expected in 6G networks, energy efficiency is a critical factor. Radio hardware must be designed to minimize energy consumption and extend the battery life of devices. Advanced technologies such as energy-efficient amplifiers, dynamic power control algorithms, and adaptive communication protocols can help improve the energy efficiency of 6G radio hardware. In addition, innovative solutions such as energy recovery systems or wireless power transmission techniques could also be considered to optimize energy consumption.
- *Miniaturization and integration*: Miniaturization and integration of radio hardware are other challenges for 6G. With the expected introduction of even smaller and more compact devices and sensors, radio hardware components will need to be adapted accordingly. This will require the development of miniaturized and flexible antennas, amplifiers and other components that can be integrated into different form factors. New materials and manufacturing processes could also be explored to support the miniaturization and integration of 6G radio hardware.

Going forward, beyond the scope of this project it may be beneficial to explore other avenues to collect data on the economic impact of sub-THz technology, such as conducting in-depth interviews with key stakeholders or analysing publicly available financial reports. Such approaches could help to provide a more comprehensive understanding of the economic implications and should also account for the unique characteristics and challenges of different organizations/stakeholders.

ML will support the 6G software and services market through intelligent network management, automated service orchestration, contextual and personalized services, intelligent computing, edge intelligence, and advanced security and privacy solutions. However, in recent decades, there has been a neglect of security and privacy concerns in wireless communications to some extent, despite the close relationship between data security, privacy, and users' daily lives. As a result, ensuring data security and privacy has become a crucial aspect of human-centric 6G communications. One significant advancement in 6G is its high intelligence, which enables the provision of high-quality, personalized, and intelligent services to users. This high intelligence encompasses operational intelligence, application intelligence, and service intelligence, as described below.

ML has the potential to revolutionize the way services are provisioned, managed, and delivered in 6G networks, unlocking new opportunities, and driving innovation in the software and services market. It is very important that new business models can be developed. Security, confidentiality, and privacy must be guaranteed in the process. Once security, confidentiality and privacy are guaranteed, consumers can exchange the available anonymized data for a reduced data price. Based on current research and industry trends, the following key technologies are expected to play a significant role in shaping 6G software and services markets:

- *Operational intelligence*: Traditional network operation involves optimizing resources and performance using methods such as game theory and contract theory. However, these optimization theories may not provide optimal solutions for large time-varying variables and multi-objective scenarios. With the advancements in deep learning technologies, advanced machine learning techniques can now address these challenges. Additionally, federated learning has transformed linear multi-objective optimization problems into nonlinear optimization problems, allowing for optimal solutions in complex and time-varying decision-making scenarios.

- *Application intelligence*: While 5G networks are gradually incorporating intelligent applications, they are expected to be foundational for 6G networks. One example being intelligent voice assistants for daily tasks.
- *Service intelligence*: As a human-centric network, 6G's high intelligence will provide intelligent services in a personalized and satisfactory manner. For example, federated learning can enable personalized health services, recommendation services, and intelligent voice services for users. In the future, intelligent services will be seamlessly integrated with 6G networks, further enhancing user experience.
- *Heterogeneous Networks*: Heterogeneous networks, which include the integration of various wireless technologies such as 5G, satellite communications, and terrestrial networks, are expected to be an important technology for 6G. Heterogeneous networks can enable seamless and ubiquitous connectivity and provide improved coverage, capacity, and reliability in 6G networks.
- *Secure multi-party computation*: 6G may enable secure multi-party computation, where multiple parties can collaborate and process data without revealing sensitive information to each other. This can facilitate secure and private data sharing among different entities, such as organizations and individuals.
- *Quantum computing*: Quantum computing, which uses the principles of quantum mechanics to perform calculations beyond the capabilities of classical computers, is expected to be a transformative technology for 6G. Quantum computing has the potential to significantly improve the processing power and capabilities of 6G networks and enable new applications and services such as quantum cryptography, quantum communications, and quantum sensing.
- *Blockchain and Distributed Ledger Technology (DLT)*: Blockchain and DLT are expected to play an important role in 6G by enabling secure, transparent, and decentralized operations. Blockchain and DLT can be used for various purposes, including secure and traceable data sharing, decentralized identity management, and smart contracts, which can improve trust, security, and privacy in 6G networks.
- *User-centric control*: 6G may empower users with increased control over their personal data and privacy settings. Users may have the ability to define their own privacy preferences and control the sharing of their data, allowing for more transparent and user-centric control over their information.

6.2 Insights from the Project

This section presents a high-level overview of project-internal survey findings on radio technology.

6.2.1 Radio Hardware, Waveforms, Beamforming and Channel Modelling to Enable Utilization of Frequencies Above 100 GHz

The development of radio hardware, waveforms, beamforming, and channel modelling is critical in enabling the utilization of frequencies above 100 GHz.

It is the consensus among the respondents that conquering these frequencies is a highly challenging task that requires significant expertise and resources. This task requires not only a thorough understanding of the underlying technologies but also the ability to navigate the complex and dynamic ecosystem in which these technologies operate. The involvement varies considerably across the different respondents of the survey. While some expressed that they were not involved in this area, others have highlighted its significance, with a few indicating a very high importance.

This can be attributed to the fact that organizations often address different parts of the value chain when it comes to this topic. Some organizations are heavily focused on the research and development of fundamental technologies (TRL 1-4), while others are more focused on the commercialization and marketing of products and services (TRL 5-9). Additionally, the level of involvement may also depend on the specific application or domain in which the organization operates. For example, individual organizations that address consumer markets may have different views on its relevance to their products and services.

This variation in responses further underscores that frequency bands above 100 GHz pose unique and complex challenges in terms of their propagation characteristics, signal processing, and hardware design. Furthermore, the varying levels of importance also reflect the dynamic nature of this field. The significance of this topic can change over time as new technologies emerge, market demands shift, and regulatory policies evolve. As a result, it is critical to continuously monitor the developments in this area to stay abreast of the changing landscape.

In terms of knowledge regarding the frequency bands above 100 GHz, the survey has confirmed that organizations are mainly focused on radio and antenna implementation, hardware component models, as well as in-depth insights on hardware impairments and their impact on potential architectures. The questionnaire also highlights the need for increased research on waveforms and modulations, beamforming, distributed massive MIMO, along with a strong emphasis on channel characterization. Many organizations aim to distribute the knowledge gained from this project internally and use it to select external partners for future R&D projects.

In terms of technology, the goal is to drive internal R&D towards making THz technology a reality, with focus on performance assessment of technologies for the radio interface in bands above 100 GHz. Exploitation of this technology will focus on enabling above-100 GHz services and is expected once products such as modules and hardware are available.

There is a call for further development of methods related to radio hardware, waveforms design, and beamforming methods. Additionally, the usage of machine learning is suggested for anticipating optimum parameterization for THz related products, and there is a need for a simulation and modelling framework for RF impairments.

One of the noteworthy highlights of the project is the creation of ETSI ISG THz. Looking ahead, there is a strong expectation that it will yield impactful work that will drive innovation and progress in the field, in particular related to channel and propagation models for 3GPP to define a THz Access Layer. There is also interest in key building blocks for the radio hardware. However, THz technology is still in its early stage, and the evolution of semiconductor components and other materials and technologies is still unclear, hence it remains a big challenge of predicting radio hardware evolution in this field.

6.2.2 Studies on Radio Technologies Towards Distributed Large MIMO Systems

Distributed large MIMO systems a clear 6G technology candidate. The current estimate of the TRL of the topic varies, with some participants stating a TRL of 6 and others a TRL of 3. However, despite this variation, researchers and engineers have the clear vision of reaching a TRL of 9 by 2030, which would signify that the technology is fully developed and ready for commercialization, with the potential to make a positive impact on a range of industries and applications.

The success of this technology will hinge on the specific needs and circumstances of individual organizations, as well as the availability of viable products and solutions. In order to address these challenges, component manufacturers should prioritize the implementation of related accelerators and supporting functionalities in silicon, which is a pressing need in the industry. To achieve this, it is crucial to understand the direction of the industry and collaborate with customers who are working in this field.

Additionally, the deployment of distributed large MIMO systems will require highly complex signal processing, which in turn will pose significant energy consumption challenges. To overcome this, it will be important to conduct research and development efforts that focus on improving the energy efficiency of these systems. Such efforts can be aided by partnerships with key players in the industry, and by participating in standardization and regulation discussions.

Moreover, collaboration with customers in this field are on the way, which will eventually enable the evaluation of the developed methods in live networks. This is a crucial step towards ensuring that the technology can be effectively integrated into various use cases and domains.

6.3 Outlook for 6G Technologies

6G technology is still in the early stages of development, and the actual implementation and applications may vary as technology progresses. The roadmap presented in Figure 6-2 and the implementation of 6G applications will depend on various factors.

6.3.1 New 6G Application Markets will trigger new Technology Demand

In 2030, 6G will be more than a radio network as we know it today. The challenge is to seamlessly develop and integrate mobile communications, sensor technology and computing power. New e-health concepts will enable e-health services worldwide, even for remote or hard-to-reach regions. Local trust zones will create secure spaces for IoT microgrids of smart cities. Simple IoT devices autonomously connect to each other and form local mesh networks without the need to densify the network infrastructure. Edge, fog and cloud computing are supporting technologies. Which application fields will drive the upcoming technology developments most?

- Telemedicine is already being used in some areas, but 6G could enable more advanced telemedicine services that require real-time communication, high-quality video streaming, and low latency.
- The deployment of smart city infrastructure is already underway in some cities, but the full-scale deployment of 6G-enabled smart city infrastructure could take several years, depending on the readiness of the technology and the availability of funding.
- Remote education is already being used across the globe, but 6G could enable more immersive and interactive remote education experiences.
- 6G will enable the implementation of high-quality XR applications that provide multisensory experiences. These might include VR training, AR-based maintenance, or MR-based product visualizations.

- Immersive gaming experiences are already available, but 6G could enable more complex and interactive gaming experiences that rely on real-time communication and low latency.
- Interactive live streaming experiences are already available, but 6G could enable more seamless and interactive live streaming experiences that rely on real-time communication and low latency. This could be implemented as early as the mid-2030s, once 6G networks are widely deployed.
- 6G will support the implementation of connected robots and autonomous systems that rely on real-time communication and low latency. These systems could be used for media production, such as drones that enable live broadcasts of events.
- The Internet of Everything is an extension of the internet of things (IoT) that includes not only devices and sensors, but also people and processes. 6G will support the implementation of IoE infrastructures based on real-time communication and low latency.
- Digital twins as digital representations of a physical object or system are playing an increasing role. 6G could support the implementation of digital twins used in industry to monitor and optimize systems.
- Blockchain and DLT technologies could be widely used in many industries, including finance, insurance, and supply chain management. By 2040, blockchain and DLT-based solutions could be used also in new areas such as healthcare and education.
- Edge computing infrastructure is already being used in some industries, but the full-scale deployment of 6G-enabled edge computing will still take several years, depending on the readiness of the technology and the availability of funding.

It is important to note that technology development after 2030 is very dynamic and depends on various factors, such as research breakthroughs, market demand, regulatory considerations, and societal factors. Therefore, actual progress and implementation of 6G technology by 2030 may differ from these general expectations. The central logic between 6G and further technology development lies in leveraging 6G's advanced connectivity, low-latency communication, and edge computing capabilities to enhance the perception, decision-making, collaboration, and overall performance of a future solution. By leveraging the benefits of 6G, modern machine type systems will become more intelligent, adaptive, and capable in interacting with the physical world.

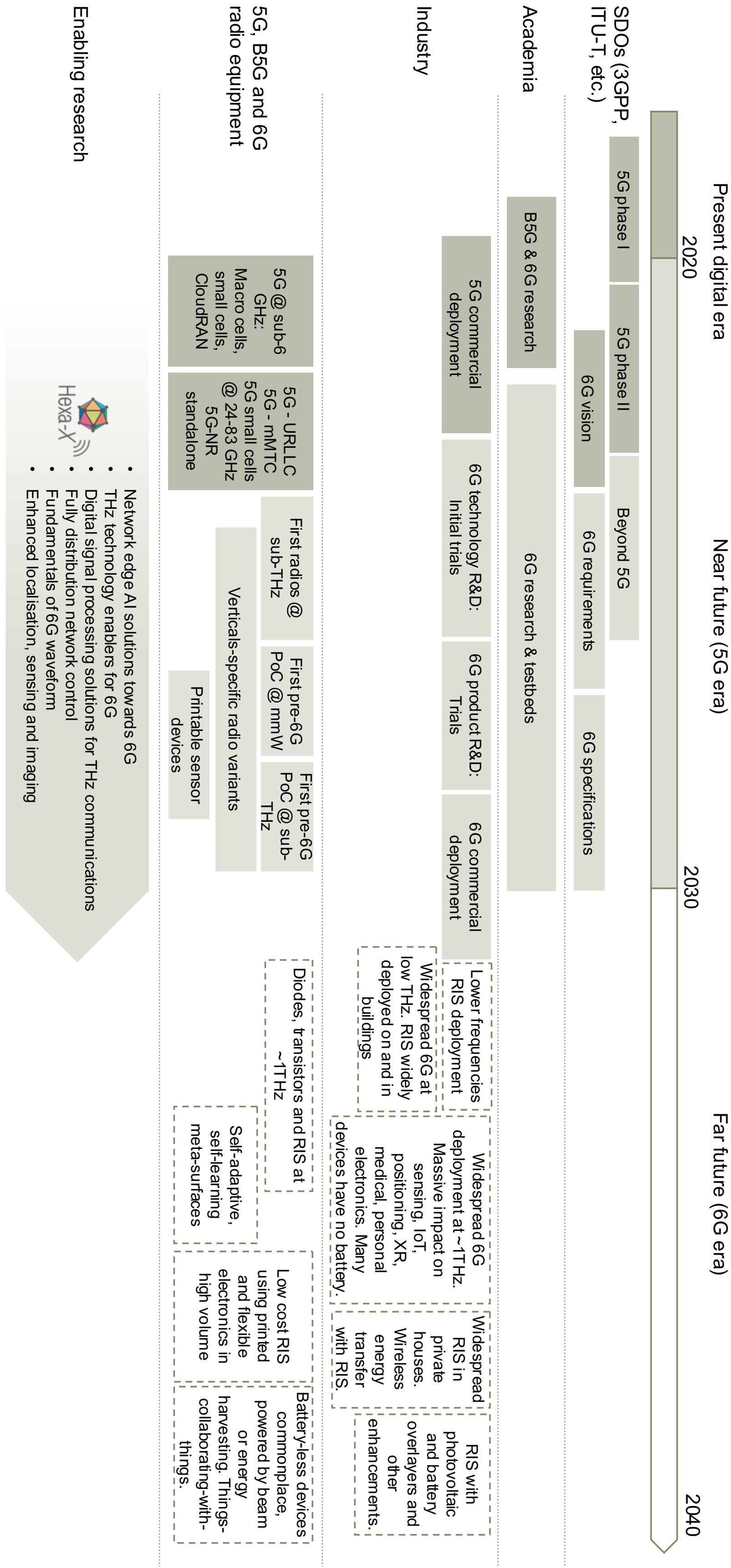


Figure 6-2: Estimated 6G Technology Roadmap [LYX+20], [PBP+20], [ITX22b]

7 Conclusions

Because end users in various industries will be the main drivers for new value creation and use in 6G industrial structures will lead to massive changes. Through 6G, connectivity will be integrated with sensing and precise positioning by 2030. 6G will allow connectivity platforms to converge with other digital platforms, creating a platform economy with corresponding ecosystems. The importance in the socio-technical transformation process as a whole and the role of 6G are very important in its scope. New infrastructures are the basis of any transformation process. [For22] For example, 6G will be an indispensable platform for autonomous devices and multisensory applications such as virtual reality, while ensuring user security, privacy, and sustainability. However, in order not to fall behind in the 6G competition, a clear, strong, holistic vision for European infrastructure systems 2035 is needed. Here, an integrated approach for information processing, communications and energy infrastructure needs to be pursued, which enables decisive and timely policy decisions that can then be combined with coordinated funding and lead to effective investments.

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